GRINDING MACHINERY

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BY

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WITH 200 ILLUSTRATIONS

LONDON
EDWARD ARNOLD
1915

PREFACE

The subject dealt with here is that of grinding as employed in engineering machine shops, and is one which is, for several reasons, of continually increasing importance to manufacturers.

The book has been written in response to the frequently expressed wishes of engineers, works managers, and machine operators, that I should give them detailed information, often of a character beyond that which could easily be dealt with in conversation or by letter. As such readers are familiar with ordinary workshop practice and tool details, these matters are as a rule only referred to briefly; but the nature of many of the inquiries addressed to me for advice—not on grinding only, but on many other questions as to plant and methods of production—has led me to the conclusion that the subject of grinding could not be adequately presented without some brief treatment of various topics connected with it.

The book has been planned so that the whole subject is presented as systematically as possible, and so as to lay bare the reasons underlying the various matters. Upon a knowledge of these depends a sound judgment as to what is suitable plant, of the possibilities of the process, and concerning the best mode of using the machinery. The Table of Contents fully indicates the arrangement of the book.

I have treated the vexed subject of work speeds first from the point of view of the best modern practice, and then introduced my theory of grinding. This was first published in a paper before the British Association for the Advancement of Science in September 1914. It dispels the current belief in a standard work speed, but offers in return an explanation of the phenomena encountered, and supplies the best methods of meeting the various difficulties.

The machines illustrated have been carefully chosen with regard to the ends in view, and in the selection a preference has always been given to those of the pioneer firms; machines of my own design have, however, only been introduced as illustrating special points, e.g. the automatic steady, which could not otherwise be shown. Machines have throughout been treated from the point of view of the grinding process, and not as interesting examples of mechanism, so that unless the detail is directly connected with grinding the description is as brief as is compatible with lucidity.

The various problems presented by different classes of work have been treated in the same manner. The reader will detect these various phenomena under other guises and, understanding the nature of the case, will treat it appropriately.

The feeds used and the errors involved in grinding are so small that in a number of the illustrations some of the dimensions are very much exaggerated for the sake of clearness; in all cases, however, the fact is quite evident, and can lead to no misapprehension.

Where the best method of presenting any matter has involved the use of equations, the results have been also given in ordinary language so as to be available to any reader.

Where my opinion is expressed, particularly if opposed to current belief, I have written in the first person.

My thanks for photographs of and information concerning their products are due to the following firms and their agents: Messrs. The American Emery Wheel Works Co., Sir W. G. Armstrong, Whitworth & Co. Ltd., Charles H. Besly & Co., Beyer, Peacock & Co. Ltd., The Blanchard Machine Co., The British Abrasive Wheel Co. Ltd., Brown & Sharpe Manufacturing Co., The Bryant Chucking Grinder Co., The Carborundum Co., The Cincinnati Grinder Co., The Daimler Co. Ltd., Greenwood & Batley, Ltd., A. Harper, Sons, & Bean, Ltd., The Heald Machine Co., Alfred Herbert, Ltd., John Holroyd & Co., The London Emery Works Co. Ltd., Lumsden Machine Co. Ltd., The Newall Manufacturing Co. Ltd, The Norton Grinding Co., and the Norton Co., Pratt & Whitney Co., Hans Renold, Ltd., R. Sterne & Co. Ltd., Walker Grinder Co., Willmarth & Morgan, and more especially to Messrs. The Churchill Tool Co. Ltd. and the Landis Tool Co., who made a number of drawings especially for this volume.

The beautiful microphotographs of Figs. 2 to 8 were kindly made for me by Mr. O. F. Hudson, Lecturer in Metallurgy at the University of Birmingham. I am further obliged to the authorities of the Municipal Technical School, Birmingham, for the loan of the apparatus with which I made the microphotographs of Figs. 13 to 15.

J. J. G.

LEAMINGTON, 1915.

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GRINDING MACHINERY

CHAPTER I

GRINDING AND MANUFACTURING

Grinding.—In modern machine-shop practice the term 'grinding' has now acquired a definite meaning, and is confined to the shaping of material by means of rotating abrasive wheels of practically rigid substance. The shaping may be done by hand, as in sharpening a lathe tool on a grindstone, or may be a mechanically guided operation, as in the truing-up of a hardened steel mandril in a grinding machine, but owing to the importance of the latter work the term 'grinding,' or more definitely 'precision grinding,' as an operation, is practically confined to it. As opposed to turned or milled work the quality of ground work which first makes itself appreciated is fineness of surface; this, however, is surpassed by that of polished work, which does not possess the first characteristic of ground work—namely an accuracy considerably surpassing that of work produced by ordinary cutting tools.

Polishing and Lapping.—Polishing consists in removing the small inequalities of surface by rubbing the work with soft material charged with abrasive powder. By using successively finer powders the material is removed by smaller and smaller amounts with a corresponding improvement in the quality of the surface. To do this work rapidly the soft material is made into bobs or belts and run at a very high rate of speed, but as this soft material follows the larger irregularities of the surface of the work, the result is that accuracy is not a feature of the process.

The accuracy given to certain work by machine grinding can be improved by lapping (Chapter XII), which consists in making a lap (or piece of metal, or other material softer than the work) to envelop the work, charging it with abrasive, and working the two together until a better fit is obtained. This is a slow process, and demands much care. It consequently is only used in those operations for which the accuracy of form or the quality of surface given by grinding is insufficient.

Both grinding and lapping are really cutting processes when closely looked into, and in the heavier kinds of grinding chips which can be handled are produced.

Although the use of grinding or abrasive processes is of primeval antiquity, and grinding machines have long been in use, it is only of recent years that machine grinding has become one of the recognised shop operations. At first applied to the manufacture of gauges, hardened steel spindles, and to the cutters and mandrils of the shop, now all the more accurate parts of engines, motor cars, machine tools, sewing machines, and machinery in general are ground, and the use of the process is extending to pieces in which the precision is not of such importance.

A number of causes have combined to effect this rapidly, and a review of these will assist in the formation of a broad judgment of the possibilities of the process, of its nature, and of its limitations.

Mechanically guided Grinding.—It is not so long ago that turning was a mechanically guided operation only in so far that the work was carried between centres, as the slide rest dates back only to Maudslay; yet now the art of turning metal by hand exists as a commercial process in very few trades—such as axle box making—and almost all manufacturing machines using steel tools have them mechanically guided.

That this substitution of mechanically guided for hand guided tools has taken place is, by the nature of commercial progress, due to the fact that it results in a cheaper product, and this economy is due to the comparatively unskilled labour which can be employed, and to the opportunity it offers of speeding-up the process. After mechanically guided tools became usual, the appreciation of accuracy became more possible, and so a way was opened for the employment of grinding as a productive method. The replacement of a steel tool by a grinding wheel was first adopted to deal with the problem of hardened work—the correction of distortion due to the process of hardening; in France grinding machines are still termed 'Machines à Rectifier.' In its early days the process, although it gave more accurate results than turning, and produced a superior surface, was so tedious that it was confined to those cases where the requirements warranted the expense, e.g. the spindles of machine tools. Single point diamond tools were sometimes used on very small hardened work, but the expense and difficulties encountered were great.

Modern Manufacturing.—Following the development of the steam engine and machine tools, with the resulting spread of the facilities for making machine parts, came the development of modern mass production, involving the use of special small tools of advanced accuracy. This called again on the use of mechanically controlled grinding for the purpose of finishing and sharpening these tools, and for the production of the gauges simultaneously required. The old process of making a reamer, for example, necessitated several careful annealings and operations removing little metal, and a then-satisfactory reamer was an inferior and expensive tool compared with those finished by the grinding operations of to-day.

These demands resulted in the production of machines—the universal grinding machine and the cutter grinder—for the manufacture and sharpening of the special tools, and the production of gauges and other hardened parts. The capability of dealing with hard steel (due to the very much harder nature of the abrasive particles of the wheel and their freedom from heat effects), and the adaptability to precision work (due to the sharp edges of the particles taking a very fine chip with little normal force), are the properties which render the grinding process especially suitable to the requirements of tool manufacture. From this footing in the tool-room, the process of grinding has extended, aided by improvements in both wheels and machines, until to-day mechanically guided grinding machines have a place in all manufacturing shops where accurate work is required, and not on hard steel parts alone, but on many classes of material. This could not be so unless the grinding machine produced work of certain required accuracy or of other desired qualities, at a cost unmistakably less than it can be produced at by other processes.

It would be premature to discuss here the question of the advisability of adopting the process and installing the machinery in any special case; knowledge to this end is to be gathered throughout the book, and the matter is again referred to in the conclusion, after the nature of the process, the trend of modern development, and the reaction of this art upon other manufacturing methods have been considered.

For reasons which can be easily understood, the process of grinding is more accurate than that of turning, and less accurate than that of lapping under proper conditions, and the surface produced corresponds fairly with the accuracy. When using these three processes within limits of accuracy easily attained by them, the cost is generally least in the roughest process—that is, with the single point cutter—and is greatest with lapping; but as any particular limit of accuracy is made finer the cost of finishing by the rougher processes increases very rapidly. Hence if we are fixed to certain limits of accuracy it will prove to be cheaper to finish by grinding than by turning, or by lapping than by grinding, according partly to what these limits are, and partly to the character and condition of the machines and appliances available. Speaking generally, therefore, work necessarily of a very high degree of accuracy should be first turned, then ground, and finally lapped.

Accuracy is compulsory.—The limits of accuracy required are therefore of primary importance in determining what processes should be used in the production of a part of a machine, and whether grinding is desirable or necessary.

In order to be satisfactory, to run and wear well, machinery demands in its construction certain accuracies, due to properties inherent in the nature of the materials employed, the use to which they are put, the oil to be used in the bearings, &c. These are the primary factors which enforce limits upon the dimensions of machine parts. These limits may be very liberal, and attainable by mere careful casting or forging, or they may be very narrow, and require very accurate workmanship to meet them. Of the former, many loom and agricultural machine parts are illustrative: and as an example of the latter we may take the case of a forced fit, where a cylindrical piece is forced by a press into a hole slightly smaller in diameter than itself—say a wheel and axle which rotate together. Consider this case more closely.

Supposing that the female part or hole is made first, it is necessary that the plug should be made a certain amount larger in diameter than the hole, else it will be loose, or at any rate insufficiently tight when forced in: on the other hand, it must not exceed it by a certain (other) amount (dependent on the external and internal diameters of the female piece and the material of the parts), else it will be impossible to force the plug into the hole, or damage will result in doing so. These considerations determine certain dimensions between which the diameter of the plug must lie; the stresses in the parts of the forced fit, and the force necessary to press the parts together, or to turn the plug inside the hole, will depend upon the particular diameters to which the parts are formed, but their amounts must be within a satisfactory range. The margin of diameter or the limits are therefore determined for any particular case by the elastic properties of the material used.

Beyond this, the quality of the surfaces, and the nearness of the material surface to the ideal geometrical surface (if one may express it so), affect the problem; more so, however, in cases of running fits where there is wear than in the forced fit example which we have taken. In all cases, however, a certain maximum and minimum difference of size is entailed by the physical properties of the materials.

Limits, Tolerances, and Allowances.—When the problem is extended from the production of a single shaft for one particular hole to the case of manufacturing these parts in quantity, the matter becomes a little more complicated, as the holes will vary in diameter amongst themselves in whatever way they are produced, and it is very desirable that manufactured parts should be interchangeable.

Our physically controlled limit of difference of fit has then to be divided into two parts applicable to the two parts of the fit. From the point of view of manufacturing one particular fit, the division of the allowable margin (between the male and female parts of a fit) should be such as to make the cost of manufacturing the particular parts of that fit in quantity a minimum; but for manufacturing reasons the margin is divided according to broader considerations, with the result that it has become possible to make 'limit' gauges for the different classes of fit commercial articles.

It should be observed that owing to the difficulty of working close to the actual size of a gauge, parts—whether male or female—made to limit gauges come regularly well within the limits, so that when a physically determined margin is divided between two sets of limits, a little may safely be added to its amount.

We have considered the hole to have been produced first; if a shaft had been required to be a running fit in the hole it would have been made to a somewhat smaller diameter than a shaft to be a press fit, so that it would rotate easily and provide room for oil. In quantity manufacturing the holes would all be made the same size within the small limit allowed, but the shafts would have different diameters (each with its limits) according as they were to be press or running fits. It would, however, be a matter of indifference whether the holes or shafts were actually made first.

The sizes in this case are said to be on the hole as a basis, and there is one set of limit gauges for the holes for whatever purpose they are intended; the variations for the various types of fit being made on the shaft, there being different sets of limit gauges for the shaft according to the purpose of the fit.

The Hole and Shaft Basis.—This is shown in Fig. 1, in which the proportions are distorted for the sake of clearness. There is here one gauge A for the hole, the nominal size of

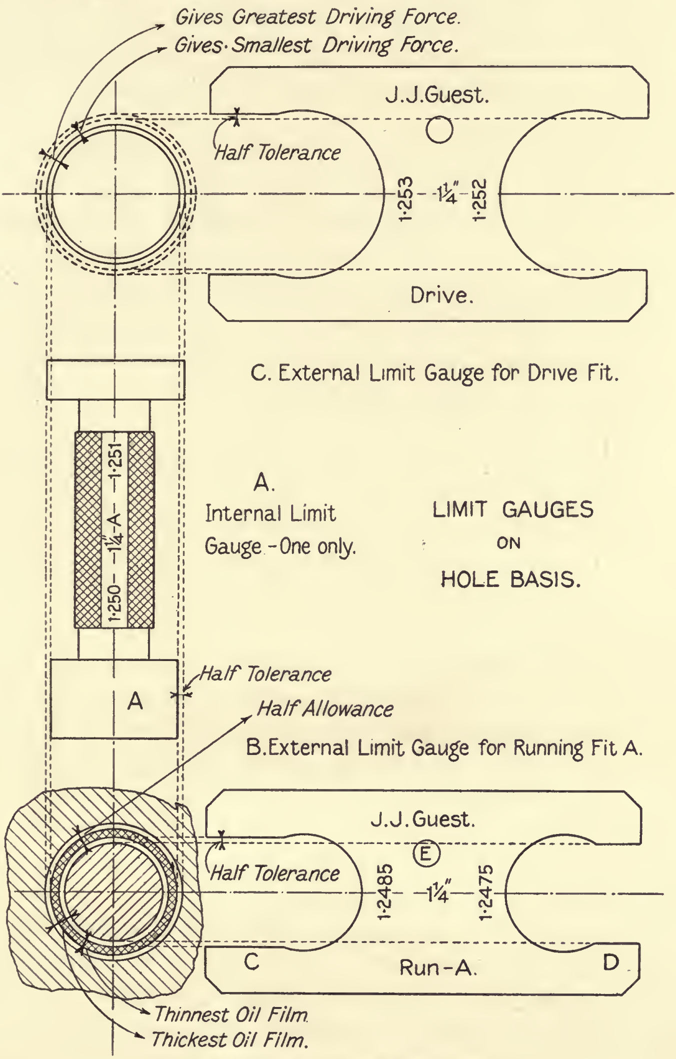


Fig. 1.—Gauges on the Hole Basis

which is $1\frac{1}{4}$ inch. To be satisfactory the hole must be such that the long end of the gauge, 1·250 inch in diameter, must go into the hole, while the short end, which is 1·251 inch in diameter, must not go in. The hole is made of a size within these limits, whatever the purpose for which it is to be used.

Shafts to be a running fit in the hole are made to the flat gauge B, the large end of which, 1·2485 inch across, must pass over the shaft, and the smaller end, 1·2475 inch across, must refuse to do so.

The shaft is drawn inside the hole, the sectioned circle showing the smallest shaft which will pass the gauge, and the circle just outside it the largest; the largest hole is shown in a part which is sectioned, and the smallest hole which will satisfy the gauge indicated by the circle just inside it. Thus the cross-hatched portion shows the oil in the case where the fit is the closest; if the fit were the slackest which would pass, the two clear rings will also represent oil. Actually the fit will not be near these extreme cases.

The difference between the two ends of a gauge is called the 'tolerance,' being the error allowed in the work. For example, the tolerance on the Internal Limit gauge is here 1·251 − 1·250 inch, or 0·001 inch. The difference between the size of the hole and of the shaft is called the 'allowance' for the particular purpose of the fit.

The upper External Limit gauge C represents the gauge for a shaft to be a driving fit, necessitating a press to force it into the standard hole. Here the widths across the gauge faces are 1·252 inch and 1·253 inch respectively, and the shaft will be on the average 0·002 inch larger than the hole. On the left the two full circles indicate the limiting sizes of the hole, and the broken circles the extreme diameters (greater) of the shaft which is to be forced into the hole.

Here the shafts are made of different sizes for different purposes, while a hole of the same size is used for all purposes.

The shaft may, however, be used as a basis; in which case all shafts would be the same size (within the invariable limit), and the holes would vary between different limit ranges according to the type of fit required.

Opinions are divided as to the merits of the two systems. As the great majority of holes are conveniently produced close to size by reaming or broaching, and as the cost of extra sets of these tools for producing the holes, of mandrils to cope with the various diameters required by the shaft-basis system, and the difficulty of storing them is considerable, the hole-basis is initially the less expensive, and I consider it the more suitable for firms manufacturing in moderate quantities. To meet the requirements of such customers, the firms making a speciality of the production of limit gauges are inclined towards the hole-basis system. It is initially convenient, which leads to its establishment, and hence to its permanent use.

For very large quantities the shaft-basis presents the advantage that tools made originally for the larger holes (i.e. the running fits) can, when worn, be reground for the smaller allowances (e.g. a press fit), which is a saving, and the initial expense is not of such serious import with the quantities. As regards the effect on design, there is little difference in the systems ; the shaft-basis makes less machining with a little more trouble in fitting. Limit gauge sets are rather cheaper to make on the hole-basis.

While many engineering firms work upon the hole-basis system, the shaft-basis has received the seal of the approbation of the Engineering Standards Committee, who have carefully considered the opinions and practice of many firms. They have issued a list of allowances for the various running fits.

Some years ago Messrs. The Newall Engineering Co., Ltd., then of Warrington, but now a branch of Messrs. Peter Hooker, Ltd., compiled from general British and Continental practice the sets of limits given in Table I and II, pages 423–4, which result in satisfactory fits on the English and Metric systems. They should be compared with Table III, which represents Messrs. Brown & Sharpe's practice. I have ventured to rearrange the form of the matter which these firms courteously allowed me to use. I have used the limits given by the Newall Engineering Co. for much of my manufacturing work, and have found them to be satisfactory.

Practically for manufacturing purposes specially fixed limits have often to be used, and also the two systems may be combined when appreciable advantage is to be obtained by it. For example, the hole-basis system may be used in the manufacture of a machine, and the shaft-basis for the counter-shafting.

In working to these or such limits, various gauges and measuring contrivances are used, and it must be borne in mind that these gauges and the tools used must possess a higher degree of accuracy than that of the limits themselves.

The limits and tolerances are fine, running into fractions of the thousandth of an inch—this being rendered necessary, as explained above, by the elasticity of steel, the thickness of the oil film in the bearings, &c.

The fineness of these commercially necessary limits tends to make good machine work expensive, and puts a premium on the use of machines and tools which have initially high accuracy, and in which it will not be impaired with undue rapidity in use. These machines and gauges make the capital cost of plant for interchangeable manufacturing very high, but it is to be remembered that accuracy of parts to limits materially reduces assembling costs. It is cheaper to make to a fine limit, using a gauge, than to a wider one and trying the actual parts to fit, so that the product may be not only superior but cheaper. The controlling factor in these cases is the quantity of the repetition work.

It will be seen that these naturally (physically) enforced limits are such as tend to make work expensive when the finishing is done by turning, assisted by filing and the use of emery cloth for finishing. As shafts and external work, however, within these limits can be easily produced very economically by grinding, now that the principles underlying the successful employment of the process are becoming understood, and wheels and machines made in accordance with them, the grinding machine finds an increasing field of usefulness In soft metals such as mild steel and cast iron, holes within the limit can be cheaply produced by reamers and broaches ; when the material is very hard, grinding frequently proves more economical, while holes in hardened steel must be ground where truth and economy are requisite. It is essentially the demands for these degrees of accuracy, and for the corresponding quality of surface involved, which is extending the use of the grinding machine so rapidly, since it here shows economy over lathe work.

As accuracy is the first quality looked for in ground work, it follows that fine workmanship is essential in a grinding machine. To explain what is meant by fine workmanship is impossible in a book, and to this extent any literature on the subject is bound to be defective. Appreciation of it is not attained by every one in the shops. The accuracy of the work produced by any machine depends upon the design, material, and workmanship, condition and the handling of the machine; and to produce work economically the machine must possess such accuracy in itself and be such as to perform the work with little trouble. Apart from the requirements of accuracy, grinding machines have to meet the question of protection against grit, the problem of high spindle speeds, and other difficulties, so that the selection of grinding machines requires particular care.

The substitution of a rotating abrasive wheel for the tool in a lathe produced the first form of grinding machine, and such a substitution is still useful in many cases, although machines specially designed for grinding produce better work much more rapidly. Let us now see what conclusions can be arrived at by comparing the action of a rotating wheel with that of a single-point cutter in removing material from the work.

The grinding wheel may be regarded as consisting of a number of very small tools held in position in the wheel by a cement. The wheel is 'trued' by means of a diamond tool, so that the points of a very large number of the small tools lie on the wheel surface. By the rotation of the spindle the particular particles in use are brought into action, and each takes a cut on the metal of very small depth and width. The length of the cut depends on the length of the path of the particle in contact with the work. Thus in external grinding the length is short (say $\frac{1}{32}$ inch or $\frac{1}{16}$ inch); in internal grinding it is usually longer (say up to $\frac{1}{8}$ inch), while if a cup wheel is used, grinding upon its flat face, the length of cut is considerable and may be several inches. Photographs of the small chips produced by these fine cutting points are shown in Figs. 14 and 15, and resemble the larger swarf from lathe tools.

The Action of a Grinding Wheel.—The particles of abrasive are bonded or cemented together indiscriminately in the wheel, so that the angle at which the cutting surface of a particle meets the work—which corresponds to the top rake of a tool—varies over a wide range, instead of being correctly suited to the material, as a shaped tool can be. It is the same with the angle of clearance behind the edge of these cutting points. On the whole, therefore, the cutting edges of the particles are presented to the work at most unfavourable angles. In the truing of a wheel by means of a diamond tool, the projecting edges of the abrasive particles are turned off, so that, regarded as cutting tools, their rake angles are unaltered by the process, but their clearance angles are made zero.

The net result of this is that it requires much more force per given area of cut, and therefore much more work, to remove the metal by grinding than by turning, planing, or milling. This difference of the amount of work is further increased by the very small chip taken in grinding (as a chip of small area requires relatively more force than a chip of larger area) and by other causes. The work represents that part of the cost of the operation which comes in the power account, and these costs are difficult to allocate. When, however, it is a question between roughing off a large quantity of metal by ordinary tools and finishing by grinding, and doing the whole operation from the rough by grinding, such as producing parts from the forging, this cost is to be borne in mind, as it may turn the scale in favour of the double operation.

In the case of finishing work by grinding, this extra cost is very slight, and need not be considered.

Although the cut is very fine, as there are a number of cutting points in action at once, and as the speed of the cut is so high (about a mile a minute), the power which must be supplied to a grinding machine intended to give a rapid production is very high ; but with sufficient power the time taken

—and hence the total cost—need not be unfavourable to the grinding machine.

The edges of the particles, being very keen (see Fig. 5, page 19), will take a very fine cut, and the cut can only be very fine, as it is controlled ultimately by the size of the particles of the abrasive in the wheel, and their bondage in the wheel; and this fineness enables dimensions to be obtained accurately, not only by its own nature, but also because the total force of the fine cut is small, and therefore less force is put on the piece of work and on the machine than where a cut of greater sectional area is taken by an ordinary cutting tool at a very much slower speed. This taking of a very large number of very fine cuts, enabling accuracy of size and quality of surface to be obtained, and the comparatively small cutting force in action, are the features which lie at the base of precision grinding. The particles of grit are so keen that they will cut steel when the depth of cut is of the order of a hundred thousandth, and work can be ground to the ten-thousandth part of an inch.

The rapidity of working will depend upon the number of cutting points in action per minute, and accordingly high wheel speed is of great advantage, for the number of small cuts made per minute depends directly on the speed. It is, therefore, customary to employ as high speeds as are consistent with safety. The number of cutting points also depends directly upon the width of the wheel, and this reasoning leads to the employment of wide wheels, and arranging that as much as possible of the width of the wheel shall be in use.

As the depth of cut is so small (of the order of $\frac{1}{1000}$ inch usually), in order that there should be a large number of cutting points coming into action as the wheel revolves, the wheel must be turned very true on its axis, for which purpose a diamond tool is necessary. A diamond is so hard that it cuts the particles of abrasive across while the cement or bond retains them in position. For making a wheel sufficiently true for rough purposes a 'wheel-dresser' (see Fig. 11, page 37)—which acts by dislodging the outstanding particles of abrasive from the wheel—is cheap and effective. Soft cup wheels may also be trued by its use or with a piece of hard carborundum block.

For wheels working on the edge a diamond tool is essential when good work is requisite.

Continuing the comparison with a single point cutting tool, we next observe that the chip in a lathe, whether it breaks off short or forms a long spiral, usually has no difficulty in finding room to dispose of itself in ; room must also exist for the chips in the case of grinding, and unless there is room trouble must result. One of the great improvements in wheels has been the reduction of the amount of bond necessary so that the space between the particles of abrasive is not filled up, but the wheel is open and porous, affording space for the chip as it is produced.

Grade.—As the edge of a lathe or other cutting tool gradually becomes blunt, so do the edges of the particles of abrasive which project slightly from the geometrical surface of the wheel, and act as cutting points. Although the material of these is extremely hard and uninfluenced by any temperature attained, the keenness of the small parts is gradually lost, and the force at the cutting point necessary to take the chip increases, not only owing to loss of keenness, but since the area of the chip section for a given depth of cut consequently increases. If the amount of bond or cement is suitable, the increasing force dislodges the cutting particles from the wheel, and as this takes place all over the surface of the wheel, new cutting points take the place of the worn ones, and the action of grinding proceeds. If, however, the particle is held in the wheel more firmly, the forces involved, the power required, and heat produced continue to increase until the work is burned, or other trouble occurs. It is evident that the amount of the bond or cement which holds the small cutting particles together, and the corresponding hardness of the wheel (called its 'grade') should vary with the nature of the work.

Grit.—As mentioned above, the depth of cut possible with a wheel depends upon the size of the particles of abrasive of which the wheel is composed; this is termed the 'grit' of the wheel, and is usually the same throughout the wheel, though for some purposes a mixture is used. The large grits suitable for heavy cuts are distinguished by low numbers, and the small grits which yield fine finish by means of light cuts, by higher numbers. It is not essential, however, to use fine grits to secure a satisfactory and fine surface, as by carefully truing the wheel—which is equivalent to shaping the cutting points into 'broad cutting' tools—a fine finish can be obtained with very coarse grits.

Basis of the Accuracy of Grinding.—As the work proceeds, the wheel loses particles from its surface and wears down, and it is sometimes asked how it is possible to produce straight parallel work with a wheel which is continually losing its size by disintegration.

Suppose that the wear of the wheel alone affected the result, and that everything else was ideal in the case of grinding a piece of work round and straight in a machine such as is shown in Fig. 29. The travel of the work would be exactly parallel to its axis, and the result would be that the work could be ground true within any limit which could be assigned, however small. For after the wheel has passed over the work and the cut for the next travel put on, the wheel cannot wear down by more than the amount by which it has been fed forward, as if it wore down this amount it would no longer touch the work. So that by reducing the cross-feed as the work is ground nearly to size, the amount of want of parallelism, being less than the final amount of the cross-feed, can be made as little as is desired.

This finishing of the work surface by an exceedingly fine cut which produces an insignificant amount of alteration in the shape of the wheel, is one of the fundamental points of precision grinding. Further, the cut being very fine, it produces little force, so that the errors due to springing of the work are small.

For example, a hole might be ground out by a wheel taking a deep cut and fed once slowly through; this would not make the hole parallel or to the taper for which the machine was set, for the wheel would wear in the process—and the work would also distort with the removal of the metal. On some external work, where the wheel is large compared with the amount of metal ground off—so that the wear of the wheel is small—traversing is dispensed with, without the loss of commercial accuracy.

At these fine feeds (say $\frac{1}{4000}$ inch on the work diameter) the amount of wear on the wheel is very slight, and the effect on the work is commercially unnoticeable. In fact, when a number of pieces have been rough ground to within a thousandth or two of an inch of size, they may often be finished to size without any apparent wear on the wheel; the number depending upon the area of the surface to be ground.

It is not always possible to arrange matters so that the wear of the wheel has no effect on the work shape, sometimes for reasons of productive economy, but in general the method of working should be arranged with that point in view.

These considerations of the nature and requirements of the process of grinding lead on to the methods by which they are met in the manufacture of the wheels and in the construction of the machines.

CHAPTER II

THE ABRASIVES AND THE WHEEL

As the distinctive feature of grinding machines is the wheel, it is well to consider the properties and mode of action of it first.

From the earliest days tools and weapons have been made and sharpened by grinding, at first by rubbing on flat stones, and later by the use of rotating wheels; also fine particles of hard materials have been used for purposes of abrasion. Most of these natural abrasives are composed of either silica or alumina.

Natural Abrasives.—Among those stones and abrasives which owe their hardness to silica may be mentioned mill-stones and gritstones, quartz and quartz sands, tripoli, and pumicestone. The hardness of crystalline silica is 7 on Mohr's scale, which is rather harder than Fe_3C, the cementite of carbon steels. Crystalline alumina is much harder, being 9 on Mohr's scale (see page 438), and furnishes the natural abrasives known as Emery and Corundum. The diamond, which is crystallised carbon, is 10 on Mohr's scale, but the difference in hardness between Corundum and the diamond is very great. This step in the scale is considerable compared with the others.

Silicates.—The effective abrasive stones consist of silica particles held together by a cement of carbonate of lime, and occur in great variety. The finer are used as hones, and the coarser, used as grindstones, hold their place in many manufacturing processes. The principal hone and oilstones are the German, Washita (of various grades), Turkey, Canadian, and Arkansas; they are expensive, and seldom used except for smoothing the edges of tools. Some of the abrasive wheel makers have placed artificial oilstones on the market, and they possess advantage over the natural stones in their convenient shape, uniformity, and freedom from flaws. For producing a fine smooth edge on workshop tools such as scrapers I have not so far found anything better than Arkansas stone, which, however, is unfortunately very expensive and also needs care in selection. The principal sources of grindstones in this country are Yorkshire and Derbyshire, from the quarries of which qualities suitable for mill- or grind-stones are produced. Stone of a finer grit is suitable for woodworking tools, the most famous quarries being at Bilston, which are unfortunately now beginning to be exhausted.

Grindstones.—In Fig. 2 is shown the grit of which a Bilston, and in Fig. 3 that of which a Derbyshire, stone is composed. They are magnified 20 diameters so that they may be conveniently compared with the photographs of other abrasives shown in the corresponding figures.

For manufacturing purposes gritstones, compared with artificial wheels, are at a disadvantage in that the grit itself is comparatively soft, and in that their smaller tenacity renders it dangerous to run them at surface speeds such as those which a modern abrasive wheel will safely withstand. They are, however, comparatively very cheap, and have a 'grade' particularly suitable for some work, and which the manufacturers of abrasive wheels have only recently been able to produce with success.

The stone is soft when quarried and hardens somewhat on exposure to the air. Owing to the mode of natural formation, grindstones may contain soft spots and be otherwise irregular in structure; in the work for which they are employed this is usually of little moment. Mounted grindstones tend to come to rest regularly in a certain position, so that one portion may be immersed in water for long intervals; this should be avoided, as it softens that part of the stone.

The stones from the same district vary very considerably in hardness; the sand grains in some are closely bonded together, and the stone is so hard that it is also used as building material. From this the hardness varies until there is so little cementing material that the stone can be easily disinte-

FIG. 2.—BILSTON GRIT.
20 DIAMETERS

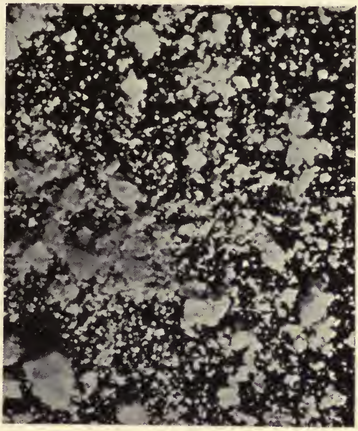


FIG 3.—DERBYSHIRE GRIT.
20 DIAMETERS

FIG. 4.—EMERY, No. 60.
20 DIAMETERS

FIG. 5.—CORUNDUM, No. 60.
20 DIAMETERS

grated by the pressure of the fingers. Where the work consists of parts with delicate edges or points (e.g. razors and needles), such stones are used, the harder stones being used on the rougher work.

A surface speed of 800 or 900 feet per minute, circumferential speed, is suitable for grindstones, although in manufacturing processes they are frequently run very much faster. In these cases they must be held in a strong mounting, such as is shown in Fig. 10. This compares unfavourably, in the light of what has previously been said about the advantage of high speed, with the corresponding 3500 to 7000 feet per minute at which artificial wheels are run.

As particles of crushed emery are so very much harder than the sandstone grit, it would appear to be an easy matter to produce artificially very much more effective wheels than those of natural stones, especially as with a strong cement or bond a much higher speed could be used. That particular quality of softness of the natural stone, considered as a whole, in virtue of which the particles of grit are torn from the stone directly they become slightly blunt, so that the face of the wheel always contains sharp grit ready to cut, proved to be difficult to imitate.

Emery.—Until recent years the principal abrasive used for wheels was emery, an impure form of corundum, that having the highest reputation coming from the Island of Naxos. Other sources occur in Smyrna, in the Pfalz district (Vosges), in Massachusetts, and in Ceylon. Naxos emery contains from 55 to 65 per cent. of corundum; other emerys from 30 to 55 per cent., usually about 40 per cent. only. About two-thirds of the impurities consist of iron (magnetite), and the remainder of tourmaline, of which the hardness is 7·5 (Mohr). The emery is obtained in masses, either shaly or having no definite structure, and without definite planes of cleavage. It is not only hard but also close grained and tough; the iron gives it a black colour. When crushed the particles retain these characteristics. The excellency of the Naxos material and the small source of supply resulted in the supply being 'cornered' about the middle of last century; the Greek Government now work the mines, and make considerable reductions to their National Debt as the result. Since the discovery in Canada of large deposits from which nearly pure (90 per cent. or more) corundum can be obtained, the importance of Naxos emery has rapidly declined, although the price of the corundum is about two and a half times that of the emery.

Corundum.—In Fig. 4 is shown emery and in Fig. 5 Canadian corundum grit, both being of size No. 60, and magnified 20 diameters. The emery particles appear to be somewhat smaller than the corundum—due to the mesh of the sieve having actually smaller spaces than in the case of the emery.

Corundum is crystallised alumina (Al_2O_3), and when crushed the particles have semicrystalline appearance and sharpness. Pure crystalline alumina is colourless; the natural corundum usually has a faint yellow tinge, but when the clear crystal is coloured by nature with certain metallic oxides, the result is a gem, and such are the ruby, sapphire, and topaz. The turquoise also is mostly alumina.

The density of emery varies according to the impurities—from 3·65 to 4·05; pure corundum has a density of 4. The Canadian Corundum Company state that their product is practically pure, as they allow 2 per cent. of impurity only. This is an extraordinarily perfect refinement, and a much less, say 5 to 10 per cent., might be expected.

As corundum is practically colourless, wheels made from it are coloured by the bond only, and are of a light colour: if emery be used in admixture the wheels are of darker shade, darker in proportion to the amount of emery, and the dark particles can be easily seen. As corundum is the natural product which stands next to the diamond in hardness, and as emery contains 35 to 65 per cent. of impurity, it seems evident that an admixture of emery will not improve the cutting properties of the wheel; it should, however, considerably lessen the selling price.

Artificial Abrasives. Carborundum.—In 1891, by the use of the electric furnace, Acheson first commercially prepared a new abrasive, which was christened Carborundum, and chemically was carbide of silicon (SiC), the weight analysis being $Si = 69·10$; $C = 30·2$—impurities 0·64 per cent. It had previously been prepared in the laboratory by Moissan, without its value being recognised. It is produced by mixing in the furnace, carbon 50 per cent., silica or aluminum silicate 25 per cent., and common salt 25 per cent. by weight, fusing and then allowing the mass to cool. On the resulting mass being broken it is found to consist of crystals of a purple blue colour, formed on the hexagonal system. The sp. gr. varies from 3·171 to 3·214, and the hardness lies between 9 and 10 on Mohr's scale, so that it stands next to the diamond. It is, however, brittle, while corundum is comparatively strong and tough. Acheson has made numerous improvements in the furnaces for producing the material, and considerable quantities are now produced by the Carborundum Company at Niagara, where advantage is taken of the low cost of electric power. Carborundum is now also produced in France, Germany, Austria, and Canada, and for trade purposes sometimes masquerades under other names.

When the crystals are crushed into fine particles for wheel-making and other purposes, the fragments are irregular in form, partly of a glassy and partly of a crystalline fracture, and very keen edged, so that with its special hardness carborundum would seem to be an ideal abrasive for the formation of wheels. In practice the wheels made of it are the most efficient for work on cast iron. The glassy smooth surface of carborundum makes it difficult for the bond to adhere to it, and hence wheels made of this abrasive are apt not to be so regular in the grade as those of other abrasives. Particles of 60 grit are shown in Fig. 6, magnified to 20 diameters : larger grits are more prismatic and irregular in shape.

Alundum.—The electric furnace has since been employed in the manufacture of artificial corundum, denominated Alundum, by the Norton Manufacturing Co., who manufacture considerable quantities. Artificial corundum has been made in a small way for nearly a century, and for some years artificial rubies have been manufactured by a building-up process, and were placed on the market as gems without reference to their origin. The curious fact that in the rubies offered from certain sources the flaws were all spherical, while generally they are of distorted shapes, led to the tracing of the former to an artificial source. Alundum is produced from bauxite—

a pure form of clay. It is said that traces of chromium can be introduced into artificial corundum and render it harder than the naturally produced material. Corundum and alundum almost always contain traces of iron, which renders it much tougher than if it were purer ; the pure crystals are colourless and rather brittle. In their endeavours to improve the quality of their products the British Abrasive Wheel Co. have experimentally purified some of their artificial alumina ; but it is questionable whether it is as good an abrasive as crystals of usual impurity. In Fig. 7 is shown alundum size

Fig. 6.—Carborundum, No. 60. 20 diameters

Fig. 7.—Alundum, No. 60. 20 diameters

No. 60 grit and magnified 20 diameters, for convenient comparison with Figs. 2 to 6 showing other abrasives. The fracture is similar to that of carborundum, but the fragments are rather less angular. Like carborundum, alundum is sold under other names.

Abrasives differ in hardness, in tenacity, in angle of natural crystallisation, in fracture, in specific gravity, in resistance to high temperatures, and also in their purity. It is necessary that they should be unaffected by high temperatures, not only that the fine edges of the fragments should withstand the heat produced by metal cutting, but also that they may not be injured by the temperature (about 3000° F., or 1650° C.)

necessary to fuse the bonds employed in the vitrified process—which produces the wheels most generally useful in precision work. The specific gravity affects the speed at which the wheels can safely be run, but on these points there is so little variation between abrasives that the toughness and hardness of the material and the type of fracture of the particles are the important differences.

Grits.—After the abrasive is crushed into small particles they are separated into sizes, first by the usual rotating sieve process, and afterwards by rocking sieves, and the pitch of the mesh of the sieve gives the name to the particles which pass through it, but which did not pass through the one size smaller mesh. For example, the particles which passed through a sieve with 36 wires to the inch but which did not pass through the preceding finer mesh is called 36 grit, No. 36 emery or carborundum as the case may be, and a wheel made of that size abrasive is said to be of 36 grit. The illustrations of grit (magnified 20 diameters) show No. 60 grit, that size being selected as one in general use for many purposes. This method of sizing is not a very definite one, as the diameter of the wires of the sieve is not specified, and larger particles pass if the wires are thin than if they are thick, either originally or from wear. Also the arrangement of the wires in the mesh gets out of shape, thus altering the size of the particles which pass through.

The crushed abrasive is separated into grits varying from No. 6 to No. 250, beyond that finer particles are separated by the time they take to settle in a liquid, as explained in Chapter XII; for commercial purposes a stream of water is used. The very fine grits are distinguished by letters F, FF, &c., and 'flour.' The sizes usually employed in wheels used on grinding machines run from 24 to 80, but as coarse as No. 6 is used for some purposes, and No. 250 is employed on glass work. The size of the grit controls the sectional size of the small chips which can be produced by the wheel, so that wheels of the coarser grits grind more quickly, and wheels of fine grit produce a higher finish. Some wheels are made with a mixture of grits termed 'combination,' with a view to combine the features of rapid cutting and fine finish.

It is, however, to be noted that good workshop finish is obtained easily with the coarser wheels, provided the machine and wheel are in good condition. Commercially very fine finish, such as requires wheels of 80 grit, is only needed in special cases ; accuracy, within the limits considered in Chapter I, is usually the chief consideration.

Bonds.—In a wheel these particles of abrasive are joined together by a cement or bond. Originally shellac or some gum was used, but the bonds now chiefly in use are the vitrified, silicate, and vulcanised, though others of various natures are employed by some firms.

Usually a wheel is of uniform grade throughout, which is attained by very complete mixing of the wheel substance before moulding the wheel shape and careful after-treatment. That disc wheels are often considered to be softer towards the centre is partly due to their circumferential speed diminishing as they wear down, and partly to the same amount of work necessitating a greater radial wear, since the circumference over which it is distributed is less.

For some purposes a wheel with different grades is required ; for instance, if it is important that a disc wheel should keep the corners sharp and free from roundness, the sides of the wheel may be made with more bond than the intermediate portion.

Grade.—The greater the amount of bonding material the more firmly are the different particles of abrasive held together, and the greater the force required to detach them from the wheel. When in use the particles get blunt gradually, and as they do so the force of the cut they take increases until it becomes so large as to dislodge the particle from its hold. The property of the wheel by which this disintegration takes place is termed its 'grade.' It depends on the amount of bonding material, the more there is the harder the nature of the wheel is. The 'grade' of a wheel must be such that in use the disintegration of the wheel only just takes place, and different grades are necessary for wheels to be used on different materials. The grade is usually denoted by a capital letter, the early letters of the alphabet being usually used for the soft grades and the later ones for the hard grades; this is not, however, the invariable practice, though it is to be hoped that it will be universally adopted. A chart showing the relation of the grades is given on page 427.

The grade of a wheel is not a very definite quality. The properties of a wheel depend partly on the abrasive and partly on the bond and its amount, so that, for example, wheels of tough corundum and harder, but brittle, carborundum, if made with equal amounts of the same bond, would not behave in the same manner when used on mild steel. The amount of the impurity in the abrasive also affects the matter: for example, emery is corundum with an equal amount of impurity, and accordingly is softer than corundum. Wheels are tested for grade by ascertaining the force which is necessary to dislodge the particles at the surface; this is done by using the end of a file or hardened screwdriver, pressing it on the wheel surface and then pushing it until some particles are broken out of the surface. The grade is estimated by the amount of force required. If the force were measured it would determine the tangential effort necessary to disintegrate the wheel surface, and this may be considered as approximately deciding the grade of the wheel. But the actual behaviour of a wheel in use depends also on other factors—the rapidity with which the particles become blunt, for example.

The desirable properties of a bond are that it should have a high tenacity, should resist the action of water, soda water, oil, or other fluid used in grinding, should be easily controlled in quantity and distribution in the wheel, and should not be subject to atmospheric influences.

Vitrified Process.—The wheels most usually employed in machine grinding are made by the vitrified process, in which the bonding material is a felspar or kaolin. This is mixed with the crushed abrasive into a wet mass, and moulded to shape. After the wheels are dry, they are rough turned and stacked in a kiln, which is fired. When the bond has fused and run, the whole is allowed to cool slowly. The bond is of the nature of porcelain, and very little is necessary to cement the particles together firmly enough to give the requisite hold on the particles for producing the useful grades. This gives a very open nature to the wheel, the bonded particles having much free space between them, as can be seen in Fig. 8, which is a photograph of a wheel of alundum No. 60 grit, such as is shown in Fig. 7, magnified also 20 diameters. The wheel has been

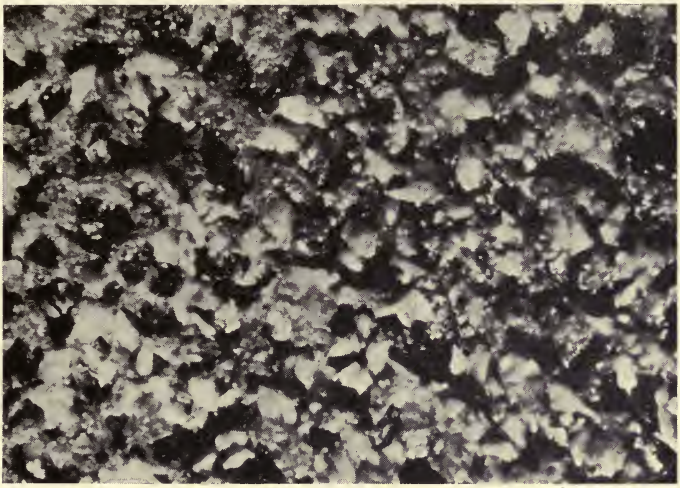


Fig. 8.—Vitrified Wheel Surface, Trued. 20 diameters

trued and the surfaces of the particles as cut by the diamond can be traced. The wheels are turned true after vitrifying, and the centre holes lined with lead in the larger sizes.

Wheels of this bond cut very freely, and are unaffected by any of the fluids used in grinding. They are the most generally useful for machine grinding, presenting the cutting points openly, and holding the particles with the minimum of bond.

Elastic Wheels.—Wheels made with elastic or vulcanised bonds are about twice as strong as those with the vitrified bond, so that where a thin wheel is necessary or where side-thrust is likely to come upon the wheel, this bond should be selected. The bond is rubber, masticated, and the wheels are shaped, pressed firmly, and vulcanised. The process produces wheels with the material close up, which lack the porosity of the other bonds and cut best when worked hard.

Silicate Wheels.—Silicate wheels, in which silicate of soda is used as the bond, require more bond than in the vitrified wheels to cement the particles together so as to constitute the same grade, so that they are not so open in texture. Also for an equal degree of safety they must not be run so fast as the vitrified wheels. Where soft grades are required, as in surface grinding with cup wheels, this bond is very suitable, as there is not then too much bond to hinder them cutting very freely, but there is sufficient to secure a fair hold on the particles, and the correct grade can be accurately obtained. This is important, as with such wheels a very little difference in the grade leads to rapid disintegration if it is too soft, or to glazing if it is too hard.

Larger wheels can be made by the silicate than by the vitrified process, owing to the manufacturing risks of the latter.

Some silicate wheels are affected by atmospheric influences, and lose their strength in course of time.

The material of a wheel consists of particles of abrasive held together with certain forces by the bond, and alters as these are changed. Many bonding materials have been tried—those given above being in general use. The vitrified bond is used for free-cutting wheels of moderate dimensions; the silicate where soft wheels are required, the extra amount of bond holding the particles uniformly, but not being of sufficient amount to clog up the wheel; and the vulcanised for wheels where greater strength is requisite. Experiment may yet lead to better bonds; the amount of hold which a certain proportion of bond should have, depends ultimately on the hardness and toughness of the abrasive. The vitrified and silicate bonds are well suited to the present abrasives, but elastic bonding offers opportunity for improvement.

Strength and Surface Speed.—Upon the strength of the bond and its amount depends the speed at which a wheel can safely be run, and upon the wheel speed depends the output of the machine, so that the strength of the bond is a factor in grinding efficiency.

It can be proved that the stress in wheels depends upon the square of their circumferential speed (provided we disregard the small variation of density due to the different bonds and their amount), so that for any allowable stress in the wheel there is a corresponding definite circumferential speed. Wheels should usually be run up to this speed, and hence the revolutions per minute at which a wheel should be run is inversely proportional to its diameter.

To ascertain the manner in which the size of a wheel affects the permissible speed of running, consider the case of similarly shaped wheels, that is wheels whose external and internal diameters and width of face are all proportional. Let ω be the permissible angular velocity for a wheel of outside radius r, (so that ωr is the peripheral speed), then ω will depend upon r, upon the strength f per unit area of the material of which the wheel is composed, and also upon its density ρ. That is, we have—

$$\omega = \Sigma a f^l r^m \rho^n$$

where l, m, n, and a are constants, and Σ indicates that the sum of a number of terms may have to be taken. If L, M, and T are the dimensions of length, mass, and time, we shall have—

$$\frac{1}{\mathrm{T}} = \Sigma\left(\frac{\mathrm{M}}{\mathrm{T}^2\mathrm{L}}\right)^l . \mathrm{L} \; . \left(\frac{\mathrm{M}}{\mathrm{L}^3}\right)^n$$

or $$\mathrm{T}^{-1} = \mathrm{M}^{l+n} . \mathrm{L}^{m-3n-l} . \mathrm{T}^{-2l}$$

$$\therefore l = \tfrac{1}{2};\ l + n = 0;\ m - 3n - l = 0$$

$$\therefore n = -\tfrac{1}{2} \text{ and } m = -1$$

$$\therefore \omega = a f^{\frac{1}{2}} r^{-1} \rho^{-\frac{1}{2}}$$

or $$\omega r = a\sqrt{\frac{f}{\rho}}$$

Thus, the limiting value of the circumferential speed (ωr) is proportional to the square root of the permissible stress (f) if we regard the density as constant; and conversely the stress in a wheel depends on the square of its circumferential speed—and not on its diameter.

Tenacity and Bond.—As the tenacity of a wheel depends upon the amount of bond, and the greater the amount the harder and stronger the wheel, a greater stress can safely be allowed in a hard wheel than in a soft wheel, and therefore a higher circumferential speed can be permitted. It is usual, however, in practice to neglect this, and to consider that the safe circumferential velocity of all disc wheels is the same, and this is taken to be from 5000 to 7000 feet per minute. Cup wheels, however, especially if silicate, should be run at a lower speed ; from 3500 to 4500 feet per minute is suitable.

For wheels which have not the same ratio of inside to outside diameter the size of the hole has an effect, but as the wheel has to be driven by flanges holding it on the two sides, this effect also is usually not considered.

The best makers test all their wheels before dispatch by running them at a high speed (usually 9000 feet per minute peripheral velocity), and in this connection it is to be noted that if under test a wheel is run at double the speed at which it is to run in use, it has been subjected to four times the working centrifugal stress, and if to two and a half times the speed to over six times the working stress.

In Table VIII, page 431, will be found the number of revolutions per minute at which wheels of different diameters must be run in order to attain various circumferential speeds from 3000 to 7500 feet per minute.

A number of experiments upon the strength of wheels have been made by professors of engineering both in America and on this side of the Atlantic. Unfortunately the grade of the wheels is never stated, so that the results are of little value ; a firm desiring a test strikingly in their favour as regards wheel safety might make wheels of a very hard and useless grade for the purposes of the experiment. The strength chiefly depends on the grade, but to some extent on the grit of the wheel as well.

The tensile strengths of the material of vitrified wheels is approximately as below for various bonds of 60 grit. The amounts are in pounds per square inch.

Grade	H	I	J	K	L	M	N
Strength	600	800	1200	1350	1500	1750	2000

The amount of variation with the size of grit runs about as below—

M Wheels—grit		60	46	36	
Strength—pounds per sq. inch .		1750	1550	1450	
Q wheels—grit	8	12	14	20	24
Strength—pounds per sq. inch	1150	1400	1550	1750	2000

so that for equal factors of safety the circumferential speeds in feet per minute should be as follows—

Grade	H	I	J	K	L	M	N
Circumferential speed	3500	4000	5000	5250	5500	6000	6500

The stress may be found from the equation—

$$\text{stress} = \frac{v^2}{6400}\left(1 - \frac{1}{3} \cdot \frac{d_2^2}{d_1^2}\right)$$

where v is the circumferential velocity in feet per minute and d_1, d_2 the diameters of the wheel and flange respectively. In deducing the formula, the density of the wheels has been taken as $\frac{1}{10}$ lb. per cubic inch, and in the absence of any knowledge $\frac{1}{3}$ has been taken to be the value of σ (Poisson's ratio). Calculation of the stresses will show that the factor of safety is rather over three, which is sufficient in machines of this class.

Wheel Speeds.—In use, a disc wheel gradually wears down, and as its diameter decreases so the circumferential speed falls. As the limiting factor to the circumferential speed is the safety necessary, the rate of rotation should be increased as the wheel wears, otherwise the wheel will appear to be of a softer grade owing to the ratio of work speed to wheel speed increasing, and if the diameter is much lessened without increasing the number of revolutions per minute, the wheel will wear away rapidly.

In order to be able to raise the rate of revolution as the diameter decreases, so as to keep the circumferential speed nearly the same, some speed variation device, such as a pair of step cones, should be included in the drive. The number of speeds which should be provided depends upon the amount the wheel is intended to be worn down. In precision grinders the hole in the wheel has usually to be of considerable size, so that the wheels can be held in collets for the purpose of changing them rapidly and without loss of wheel substance, and in this case a reduction of the wheel to two-thirds of its diameter is about as much as is obtained: two or three speeds are then sufficient. In some machines, such as ordinary tool grinders, where the wheel is not changed until used completely or to some arranged diameter, the hole in the wheel may be comparatively small. Owing to the prices at which these machines are usually sold, step cones cannot reasonably be looked for in the drive, although they would be a good investment for the user. Where the speed can be increased so that the fastest speed would give so high a circumferential velocity to the largest wheel used as to be dangerous, some arrangement should be included to prevent the fast speeds being used when large diameter wheels are on the spindle. The best method of all is to use simple single speed machines, and as the wheel wears down transfer it successively to machines with faster running spindles: this method is, however, only available in few cases.

Mounting Wheels.—In mounting a wheel upon a spindle it is very essential that it should go on easily but without appreciable play, and for this end the holes of all wheels but the smallest should be brushed with lead, which can be quickly scraped if necessary so as to allow the wheel to fit easily. If the wheel be forced on the spindle or collet, bursting stresses, similar to those due to rotation, are caused, and there is considerable risk that the cumulative effect will render the wheel unsafe.

Before mounting a wheel it should be examined for cracks, and tapped lightly with a hammer, so as to judge by its ring whether it contains an unperceived crack. Even then a new wheel should be started with care, as it is not absolutely certain that a flaw will be detected.

It may be noted that at the speeds employed the bore of pulleys expands so that unless they are originally a very close fit they may be loose when running. For this reason collets should have a taper fit on the spindle; they are then tight when running and can also be easily removed. The amount of this enlargement of the bore at a given speed can easily be calculated from the elastic properties of the material of the

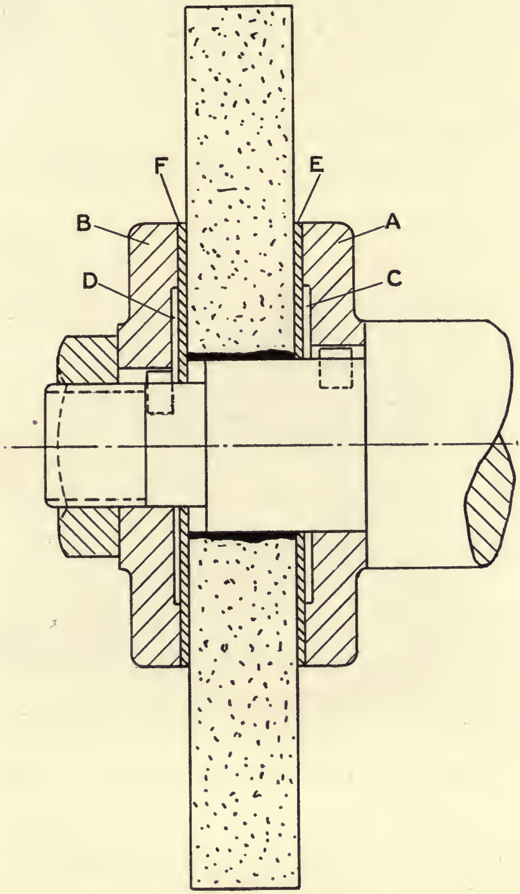


Fig. 9.—Wheel Mounting

collet, and the correctness of the amounts found have been confirmed by direct measurement on the expansion of the holes in steam turbine rotors.

Wheels should be mounted between flanges arranged to bear on the wheel near their circumference only. If the flanges are flat, tightening the nut to close them tends to make them a trifle concave, which would be dangerous; they should therefore be distinctly recessed towards the centre, and sufficient flat bearing area provided at the outside. Machines of the better class are all fitted with collets designed on this principle, and one such is illustrated in Fig. 35, page 126. For the sake of clearness the mounting of a wheel is also shown in Fig. 9, where the flanges A, B, bear on the outer part only, and are recessed at C and D towards the centre.

Between the wheel and the flanges, washers E, F, of soft

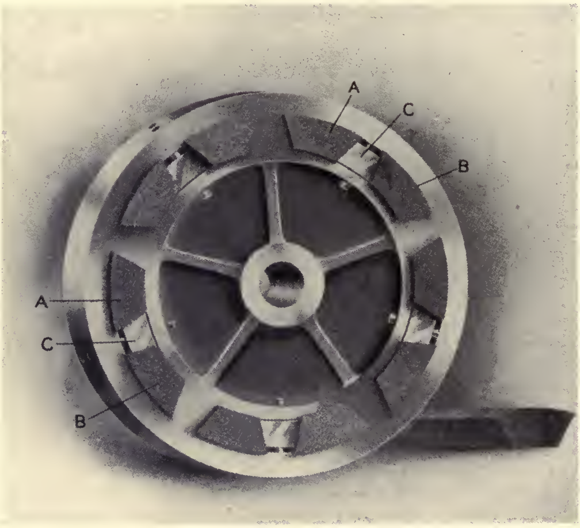


Fig. 10.—Inserted Segment Wheel

material, such as blotting paper or cardboard, should be placed, so as to distribute the pressure, where the wheel is gripped. Some makers send out their wheels with stout paper washers already fixed to the sides, which is a great convenience. Preferably the flanges should be keyed.

If the wheel is likely to receive sidethrust, the flanges should extend to as near the edge of the wheel as is practicable.

Cylinder and cup wheels are mounted in recessed flanges, and held by plates, between which and the wheel washers of soft material must be placed, or they may be held in special chucks. Examples of the construction are given in Figs. 37 and 38. Cylinder and cup wheels are expensive, and for large work, such as surfacing armour plate, chucks with inserted segments are used. Such a chuck is shown in Fig. 10, in which the segments A, B, are secured by the wedges C, which bind the segment on three faces, and thus hold it securely.

Segments of artificial material are very expensive, and those of natural grit stone much cheaper, even when due allowance has been made for the greater amount of work done by the artificial material. Accordingly in these machines the natural stone is used, and its softness enables the cutting to be done rapidly.

Balancing.—The circumferential speed of wheels being about 5000 feet per minute usually, the rate of rotation of the wheel spindle is very high, and hence the centrifugal effects of any want of balance and truth in the wheel or spindle are very considerable, and form the cause of some of the difficulties encountered in grinding.

The wheel spindle itself and all the rotating parts attached to it must be in balance and run steadily by themselves; if, when the wheel is mounted, vibration then occurs on running it, the trouble lies in the wheel.

The amount of these forces can be judged from the force necessary to prevent a mass of one ounce, at a distance of 3 inches from the axis, from flying outwards when it is moving round the axis at 1900 r.p.m. (the rate for a 10-inch wheel). This force is almost 20 lb. weight.

The expression for the effect of want of balance is—

$$4\,\pi^2 n^2 r \,.\, \frac{m}{g}$$

where n is the number of revolutions per second, m is the mass of the out-of-balance part (the difference from uniformity), r the effective radius in feet at which it acts, and g the acceleration due to gravity, which is 32·2 feet per second per second.

The effect is equivalent to a periodic permanent force of this maximum amount, and under certain conditions it can enforce vibrations of the same frequency as the revolution of the wheel, or a simple fraction thereof, on the machine and on the work, causing chatter. This subject is referred to more fully later.

Some makers balance their larger wheels before passing them for delivery by adjusting the lead in the central hole, and this is convenient initially. As the want of balance is sometimes caused by want of uniformity in the material of the wheel, this is not a perfect arrangement, and a wheel of such a nature will go out of balance as it wears down. Small amounts of want of balance are quite unavoidable, and the best way of meeting them is to make the wheel head so heavy that the effects are reduced to insignificant amounts. Where there are sufficient machines to warrant it, the wheels may be balanced periodically on parallel ways.

In the machines constructed by the Landis Tool Company, the collet is made with a groove containing movable weights, which can be adjusted until balance is obtained. To give a correct dynamic (as opposed to a static) balance, these weights should be in the plane of the wheel; they are placed as close to it as constructive details will allow.

Besides the usual disc and cup shaped wheels a number of shapes are used, suited to the various purposes for which the wheels are employed. Most of the wheel makers give drawings in their catalogues of the shapes they supply, and will make wheels to such shapes as are desired. Wherever possible disc wheels should be used, as they are the cheapest form, and also cause less delay in delivery.

Silicate wheels take a few days in making, but the vitrified wheels take several weeks, and there is also the chance that after that time just what is desirable is not obtained, so that care is necessary in ordering wheels for any particular purpose.

In specifying a disc wheel the diameter, face, hole, abrasive, bond, grit, and grade should be stated; with seven different factors varying, a great number of wheels are necessary to meet possible requirements. Machine makers are tending to use wheels of fewer combinations of diameter, face, and hole, but the recognition and adoption of a uniform system would be advantageous, and it could be revised at such intervals as progress might dictate. One of the difficulties is that in cases where the requirements of the work necessitate the changing of the wheel, collets are used, so that the collet with the contained wheel is changed. This necessitates a larger hole in the wheel than if it is to be mounted directly on the spindle. To meet the case it might be arranged to make the hole in wheels of a particular diameter of one of two sizes according to the purpose for which the wheel is needed. I have suggested* the following series—

Wheel Diameter (inches)	6	8	10	12	14	16	18	20	22	24
Size of Hole (inches) either	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$	1	$1\frac{1}{4}$	$1\frac{1}{2}$	$1\frac{3}{4}$	$1\frac{3}{4}$	2	2
or	2	3	4	5	5	7	8	8	8	10

Truing Wheels.—To render the working portion of a wheel true enough to be serviceable in precision grinding it must be turned true by use of a diamond, which in almost all cases must

Fig. 11.—Wheel Dresser.

be mechanically guided. The diamond is so very much harder than the abrasive materials that it cuts the particles of the wheel across without dislodging them from the bond, so that they become—as remarked earlier—small tools without clearance. The chip taken is so fine, however, that this does not matter. 'Wheel dressers' of various kinds have been invented, consisting of discs with plane or corrugated edges which rotate when in contact with the wheel, and so dislodge the projecting particles; they cannot, however, cut them, and do not produce a wheel surface comparable with that produced by a diamond, and not good enough for regular grinding work except in the case of soft cup wheels. A typical wheel dresser is shown in Fig. 11. A more effective one is provided by mounting a sharp-edged hollow steel washer on the end of a spindle mounted on ball bearings. The disc rotates freely as the friction is so small, and presented properly

* Inst. Automobile Engineers, 1911.

to the wheel disintegrates its surface easily. For truing grindstones a similar but more substantial tool is useful, and the rotating disc here is usually hollow, and its axis nearly at right angles to that of the stone; or the end of a tube is used, the tube being rolled by hand along the rest set close to the wheel. A piece of hard carborundum block is very effective in truing ordinary wheels, and in removing glaze from small wheels by hand.

Diamonds.—Diamonds are of two very different kinds, crystalline and amorphous, both being allotropic forms of carbon, as is also graphite. They are natural products, the crystalline being found principally in South Africa, Australia, and Brazil, a few only now coming from India. The amorphous diamond, carbonado, or carbon, is found in Brazil. Diamonds have been produced artificially, but so far only in very small sizes and at excessive cost, and larger diamonds have not been produced from smaller ones in the manner in which artificial rubies are made. The crystalline diamond is of the octohedral system, and, when pure, is transparent and colourless. It can be split by means of a sharp blow on the back of a knife, the edge of which is held against the crystal, along the planes of cleavage, and by this means splints suitable for diamonds, to be used as small tools, are made. Sometimes diamonds are tinged with a yellow or brown colour, and rarely with blue or red, which latter colours enhance their value as gems. The crystalline diamonds used as gems and for manufacturing purposes are of the same nature; the latter simply have such defects as spoil their value for decorative purposes. The crystalline diamonds, then, which are offered for commercial purposes, all have defects, and the question of their suitability and comparative value is of importance in their selection, and can only be judged after experience. Those with incipient cracks should be avoided, while an elongated shape renders setting easier and more secure. While those of a good crystal shape generally give the best service, they are also the most expensive. Diamonds appear to vary considerably in hardness. I have a preference for those from Brazil. It is advisable to supply at first tools containing cheap small diamonds (say $\frac{1}{4}$ ct.), as the stones sometimes fall or are ground out of their setting and are lost; when this risk is reduced by experience, larger diamonds should be used, as they are more economical, although the price per carat is greater. Diamonds weighing 1 ct. are suitable for wheels up to about 2 inches wide. As a diamond cannot be inspected well, nor weighed when it is mounted into a tool, it is well to buy the diamonds loose and mount them afterwards.

The amorphous diamond or carbonado is black and opaque, and shows no structure under the microscope. It is very considerably harder than the crystalline variety, but it is also more expensive. When the wear and cost are taken into account I consider that the crystalline diamond is the more economical.

When a wheel is to be trued straight across (as a disc wheel trued cylindrical, or a cup wheel, flat) the position of the corner of the diamond which operates is of no importance, but if a complex shape (e.g. a gear tooth space) is to be produced accurately on a wheel for reproduction on the work, the position of the working corner is very important, and it is difficult to adjust it accurately. In such cases a carbonado should show to its best advantage.

Setting Diamonds.—For use diamonds are set at the end of a cylindrical rod of steel or brass, thus forming diamond tools, and precision machines are provided with means for clamping the tool to the work table in order to true the wheel parallel to the main ways of the machine. The axis of the diamond tool should be presented to the wheel face at an angle, and not normally, so that when a flat is worn on the point of the diamond, a fresh corner may be presented by turning the tool round in the clamp.

It is to be noted that setting the diamond off the axis of the tool, or bending the tool, has not the same effect.

There are several ways of mounting diamonds for the purpose of tools, some of which are shown in Fig. 12. I have a preference for setting them as at A, using a brass holder and solder (preferably hard) as the operation is easily and quickly performed, and there is no risk of injuring the diamond. A bit of swarf dropped in the hole keeps the diamond up while soldering. Brazing into a steel holder is more troublesome, and although it makes a stronger setting, hard solder is amply strong enough for the purpose. In the holder C, the diamond is held by the screwed cap, and in that shown at D by the cross screw springing the split holder.

In truing the wheel plenty of water should be used. The action of the diamond cuts the particles of abrasive across, but in doing this the edge of the diamond gradually gets worn away and blunt. If too great a flat is worn on the diamond and presented to the wheel, the particles are no longer cut across, but are splintered and dislodged bodily, and the truing is no longer satisfactory. When this occurs the diamond has to be reset. In the initial setting the diamond

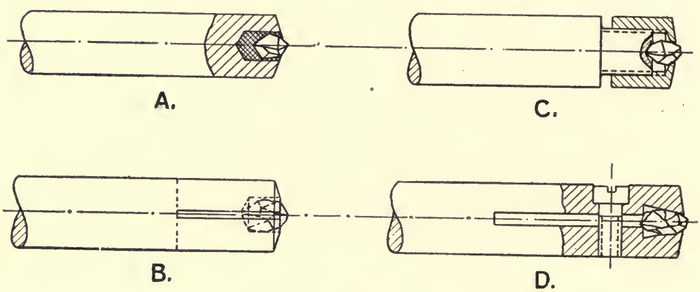


FIG. 12.—DIAMOND TOOLS

is presented in the most satisfactory manner, so that resetting does not make matters as favourable as they might be. Again, in setting, the diamond should not be presented to the wheel with the planes of cleavage parallel to the wheel face, as it may break; so that the amount of resetting is limited, and diamonds should be treated carefully from the beginning.

In Fig. 8 the wheel surface shown has just been trued with a diamond tool, and the surfaces where alundum particles have been cut across and the small splinterings are visible.

Diamond Laps.—In internal grinding the problem of the wheel and of the method of holding it on the spindle increases in difficulty as the diameter of the hole decreases, and for small holes wheels are replaced by diamond 'laps.' The lap is made of soft steel, and, as it is necessary that it should run very true, it should have a taper fitting to the spindle. It is charged with diamond powder by rolling it with the powder and oil between hardened steel plates. The diamond powder is made by crushing up small diamonds: the resulting powder is mixed with oil, and the particles separated into various sizes by the time they remain in suspension. In rolling between the hardened plates the soft steel is penetrated by the particles which remain embedded in it, and project very slightly from the steel. The lap, after being charged, should be tapped and brushed to remove the particles not firmly embedded. Laps charged with the coarser particles—those first deposited from the oil emulsion—naturally cut the most rapidly.

When the lap is rotating and brought to the work, the diamond points projecting from the lap cut the work in exactly the same manner as the particles of emery or corundum projecting from the surface of a wheel do, so that the process is really a grinding and not a regular lapping (see Chapter XII) operation. The speed should be as high as possible, and the lap should run perfectly true. The cut can only be exceedingly fine from the nature of the lap: it must not be forced; the diamond powder, however, is so very much harder than any other abrasive that these laps cut fairly quickly and last a considerable time. The truth of the lap depends upon its original form: it cannot be 'trued.' Neither could a wheel made of diamonds (if they could be manufactured cheaply) be trued, so that, without the discovery of a very much harder substance for truing them, they would be of little use in precision grinding.

CHAPTER III

THE WHEEL AND THE WORK

The Material of the Work and the Various Abrasives.—To deal with the various materials used in engineering manufacture and construction, and to grind them efficiently and to a desired quality of surface, there is a choice of four variations in the nature of the wheel: the nature and size of the abrasive grit, and the nature of the bond and its amount.

The abrasives may be divided into the Oxide of Aluminium (Al_2O_3) group and the Carbide of Silicon (SiC_3) group. Of the former emery is now little used in machine shop grinding, as the amount of impurity lessens its value as a cutting agent considerably, and the cost of making it up into wheels being the same as that of making up the purer materials, the wheel cost is not lessened much, although the natural abrasive is much cheaper. The grading is also affected by the impurity. There remain natural corundum and its artificial equivalent, alundum, which is also sold under other names. Although one is inclined to prefer a manufactured material as being more under control as to quality, there seems little difference between these abrasives.

Corundum and alundum are the best abrasives for working on steel, whether mild, high tension, or hardened, and on brass. They are also used for grinding bronze, rubber, celluloid, and such materials.

Carborundum (also sold under various trade names), the carbide of silicon abrasive, is the best for grinding cast iron, whether soft or chilled; and it is also used for grinding bronze castings, glass, &c.

Carborundum, from its hardness, is the best abrasive for use on materials (e.g. cast iron, hard rubber and fibre, glass, &c.) which are not strong enough to fracture it, but the toughness of the alumina abrasives renders them the more suitable for those materials which only yield under a high shearing stress (see 'Phil. Mag.' July 1900, and 'Engineering,' July 8, 1908), or in which there are constituents of such different hardnesses as ferrite, cementite, austenite, and martensite, arranged in dimensions (as will be seen later) comparable with the section of the chip taken in grinding.

Quality of Finish and Size of Grit.—The number of the grit (or the size of the particles to which the abrasive material is crushed) which should be used depends partly upon the nature of the material to be ground and partly on output or the finish required. The tougher the material the coarser the grit which will be suitable.

The rate of removal of material increases regularly with the coarseness of the grit, so that generally in manufacturing coarse grits are desirable.

The quality of surface produced, while it depends upon the fineness of the grit, depends to a far greater extent on the condition of the wheel and the machine, and for engineering purposes an entirely satisfactory finish can be obtained with wheels of from 24 to 80 grit, the finer grits being used on the smaller work.

In ground machine parts two qualities are looked for—accuracy of surface and smoothness of finish. If the surface be examined closely it will be seen to be covered with a multitude of small scratches, which are the marks of the cuts made by the particles of abrasive in the wheel. If these marks are uniform, clear and sharp as if made by a keen cutting point, it implies that the force of the cut has been small, and hence probably the work is round and otherwise true, and accordingly this finish is to be regarded as that of a good ground surface. This class of finish can be obtained from wheels of the above-mentioned grits by carefully truing the wheel. If the marks are too deep or conspicuous for the purpose in view, the next finer grit should be selected; with 60 to 80 grit, however, the surface obtainable is good enough for workshop gauges. By slightly polishing the wheel after truing it a smoother surface can be produced—a small piece of hard carborundum oilstone is convenient for the purpose; it must be used very lightly, or the polishing will be overdone. One half-thousandth of an inch is the most which should be left on the diameter of the work before smoothing the wheel for this finish.

If smoothness of surface as well as precision is necessary—as in fine gauges and important bearings—the work may be touched-up with some very smooth emery cloth, or, what is much better, lapped a little as described in Chapter XII.

Possibility of Grit being embedded in the Work.—It is occasionally stated that emery (and I suppose other abrasives) are retained in the surface of ground shafts, and destroy the bearings in which they run. This objection is the same as that which used to be raised to cut gear teeth—it often means that the objector has not got a grinding machine, just as it used to mean that he had not a gear cutter.

A piece of abrasive is cemented into a wheel, and cuts a piece of steel with its projecting point; the point wears a little, and then the cut is wider. The force of the cut thereby is increased, and tilts the piece of abrasive from its setting, and it falls away. The particle of abrasive cannot get embedded in the steel unless it is forced in. The easiest way to do this is to roll it in; if the wheel itself were used to do this the force necessary would destroy the wheel face first, as the bond is only sufficient to withstand the force due to a very fine cut. As there is no other way of embedding the particle, it may therefore be concluded that abrasive material cannot be retained in the ground surface. It is not too easy to roll the very fine abrasive into the soft steel of 'diamond laps,' using hard steel plates for the purpose. I have examined ground parts for embedded abrasive, using a microscope, but have never found any, and chemical analysis has been applied with the same result.

The only case which seems possible is with such cast iron as contains open pores in which fine abrasive dust might lodge; the best safeguard against the possibility is to grind with plenty of water, and to rinse the work in clean solution afterwards before it dries. The finer particles remain suspended for a considerable time in a fluid, and so would not have settled to the surface.

Turning now to the nature of the bond, three choices are open: the vitrified, the silicate, and the elastic.

Uses of the Various Bonds.—For general purposes the vitrified bond is the most serviceable: it is strong though brittle, and very little of it is necessary to hold the particles together, so that the wheels are porous and open-grained, allowing plenty of room for the chips and solution, and so cutting freely.

The bond in silicate wheels is weaker, so that more of it is necessary to hold the abrasive particles together with the same strength; this makes the harder wheels too compact to cut freely in machine grinding, but the soft wheels are very satisfactory, and they have the advantage that the desired grade can be secured more exactly in their manufacture than in the case of the vitrified wheels.

They are therefore to be considered for cup wheels and for the small wheels for internal grinding. The manufacture of the latter by the vitrified process appears to present some difficulty, as small wheels made out of fragments of larger vitrified ones always seem to work better, although nominally of the same grit and grade.

Another advantage attaches to the silicate process—namely, that wheels can be produced by it in a short time, while vitrified wheels of usual size require two or more weeks in the making alone.

When a wheel is likely to be called upon to encounter unusual forces in its use, as when a disc wheel is used upon its side near the edge, or when a thin wheel is necessary, elastic wheels should be used, as they are much safer under such circumstances, owing to their greater strength. Their elasticity also makes them useful in grinding very thin work.

Grade.—Whatever bond is used the grade of the wheel depends on the amount of the bond used, but the working of wheels of the different abrasives, or of the same abrasive of different purities (corundum and emery), varies, although the kind and amount of bond is the same in each. In use the projecting points of the particles in the wheel gradually become dull—the forces on them then increase ; the amount of bonding material used must be such as to hold the particles in the wheel until they are worn a suitable amount, and not to be capable of retaining them there much longer.

The desirable amount of bond varies with the material on which the wheel is to be used, and how it is to be used. With hard materials the particles should only lose their edge slightly before they are released from the wheel, but with softer materials they should be retained longer, partly for economy, and partly because the very sharp particles cut the work very easily and produce a rather scratchy surface. Thus wheels with little bond, and which are therefore 'soft,' are to be used on hard materials, and the harder wheels on the softer materials. Wheels are therefore classed according to their softness or hardness, and separated into 'grades,' usually distinguished by letters of the alphabet.

The grade of a wheel may be judged by the force required to dislodge the particles of its substance, using the end of a file ; with a little experience the grade of a wheel can readily be ascertained in this way. The behaviour of a wheel in use, however, somewhat depends on the purity of the abrasive, so that this method cannot be entirely relied upon in selecting a wheel for a particular purpose, although it depends upon the force required to disintegrate the wheel—which is the meaning of grade.

Unfortunately different wheel-making firms express the same grade by different letters, and even in opposed sequence. Probably the 'Norton' system of grading is most used. It is used throughout in the text of this book, and it is to be hoped that it will be soon recognised as the standard, and accepted by wheel makers generally.

In this method of grading the early letters of the alphabet represent the softest wheels of the Vitrified and Silicate grits, and the later letters are used successively as the hardness increases. For Elastic wheels numbers are used, the number increasing with the hardness. This is shown in the following table—

Wheel Grades—Norton System

Hardness.	Very Soft			Soft				Medium			Hard		
Vitrified and Silicate Wheels	E	F	G	H	I	J	K	L	M	N	O	P	Q
Elastic Wheels .			½	1	1½		2	2½	3	3½	4	5	
Suitable for .	Face Work.				Hardened Steel.		Cast	Mild Iron.	Steel.				

A comparative table (No. V) of the grading by several firms is given on page 427, to meet the difficulty of the present disorder. It is particularly misleading that the Carborundum Company use the early letters of the alphabet for the harder wheels, reversing the usual system.

The British Abrasive Wheel Company's grading is identical with that of the Norton Company. Many firms prefer to make wheels of their own special bonds and grades to suit the particular requirements of each case, no particular grade being stated, but a reference being kept for future use. Some engineers used to make threads of peculiar pitch and shape long after the Whitworth standard was accepted, the taps being preserved.

Selection of the Grade.—For external work on wrought iron and mild steel (0·15 to 0·40 % carbon) grades L and M are most suitable, M generally, and L for large diameters of work and rigid machines; as the hardness of the steel is increased L becomes generally the correct grade. On hardened steel K is to be used generally, but where accuracy and very high finish is required a J wheel of a finer grit is better. For cutter sharpening J and K grades work well on carbon steels, but even softer can be used on high-speed tools. For brass and bronze L is usually right. For cast iron of customary hardness L and M grades are best, but for chilled cast iron the much softer wheels H or I. For internal grinding wheels of slightly softer grades are desirable, as the contact of the wheel and work extends over a longer arc.

For cup wheel grinding, where the contact is over a considerable area, still softer wheels have to be used, G and H being usual grades, and at the same time a coarse grit is used. For work on the same material, however, wheels of two or three grades are necessary, as the area of contact here depends on the width of the work, and the greater this is, the softer the wheel which must be used. The grade of the wheel in cup wheel grinding must be carefully chosen, as if the wheel be only just too soft it wears away rapidly, while if it be too hard it refuses to cut.

The increase of the power and rigidity of machines has made the selection of grade of wheel an easier matter than it used to be, for the permissible range is extended in both directions. If a wheel giving trouble on a light machine by being on the point of glazing be transferred to a more rigid and powerful machine, the cut can be made heavier, which will stop the glazing tendency ; but on the other hand a soft wheel which works satisfactorily on a rigid machine, may, if transferred to the same work on a light machine, have its surface disintegrated by the vibration.

Selection of the Wheel.—Table VII, page 430, shows the various grits and grades of wheel suitable for work on a number of materials. In selecting from it the influence of the machine and quality of work required should be borne in mind. Usually as soft a wheel as is consistent with the requisite finish should be used, for with a given power the output is then greatest.

Wheel Speeds.—The speed at which the wheel should be run is the highest consistent with a proper factor of safety : and this leads to the rule that they should run at a certain circumferential velocity, which varies according to the strength of the wheel material, so that it is higher for hard wheels than for soft, and for elastic than vitrified or silicate bonds. Elastic and vitrified wheels of L and M grit can be run safely up to 7000 feet per minute, though a rather slower speed is usual ; K wheels up to 6000 and J up to 5000 feet per minute. Soft silicate wheels, G and H grade, can be run at 4000 feet per minute. Some silicate wheels have a brass wire mesh inserted in them in the process of manufacture with a view to safety, but I cannot speak from experience with regard to them.

It should not be forgotten that the wheel should be examined and tested, by tapping it with a hammer, for cracks before mounting it, and that the spindle should be started slowly and the wheel watched, as occasionally, though very seldom, they run dangerously out of truth.

When a wheel glazes, it is frequently recommended that its circumferential speed be lowered; this tends to check the glazing, but it can be checked in other ways, and then if these are insufficient the wheel can be changed.

In turning the speed of cutting is limited by the heat produced, which draws the temper of the tool and spoils it. In grinding there is no such limit, as the cutting particles can withstand the temperatures produced, although it may fuse the metal being ground. As the wheel diameter lessens by wear the surface speed unavoidably drops, until it is possible to use the next faster spindle speed; but otherwise it should not be reduced except in the case of trouble from vibration.

In circular grinding, external or internal, the work and wheel should run to meet one another, otherwise the wheel may drive the work at intervals, producing a bad surface.

Work Speeds.—The question as to what is the best speed for the work in circular grinding is one upon which there are many and conflicting opinions. It appears to be invariably accepted that the work surface speed is the controlling feature, and that if, for a particular material, a satisfactory surface speed is found for any diameter of the work, then that surface speed will be correct for all diameters—provided that no trouble arises from the slenderness of a particular piece of work, or such causes. This corresponds to lathe work, where the surface speed at which a particular tool will cut continuously for a reasonable time, is a mark of the quality of the tool. Some little time ago Messrs. Brown & Sharpe stated that a somewhat slower surface speed should be used on large diameters than on small, but in their latest notes they return to the previous point of view, and advocate the same surface speed, whatever the diameter be.

Formerly it was the practice to run work at surface speeds from 150 feet per minute upwards to twice that amount or more. To-day the speeds used are much lower, but are very varied, some authorities advocating speeds from 10 to 20 and others from 60 to 70 feet per minute. The intermediate portion of that extreme range is that which is most usually used.

The following firms, who manufacture and use grinding machines, recommend the work surface speeds given—

Authority.	Work Surface Speed in Feet per Minute.
Brown & Sharpe	35–65
The Churchill Tool Co., Ltd.	35–70
Greenwood & Batley	25
Alfred Herbert, Ltd. (Mr. Darbyshire)	25
The Landis Tool Co.	25

This idea of a constant work surface speed (i.e. independent of the work diameter) I consider, for reasons which I give later, to be incorrect. For moderate diameters (say 2 inches to 4 inches) I think that speeds of 30 feet per minute with 24 to 36 grit wheels, and 40 feet per minute with the finer grits, are suitable for mild steel; for cast iron 40 and 50 feet per minute respectively in the same cases; but my views are given fully later.

Table IX, page 432, gives the number of revolutions per minute at which work of various diameters is to be run in order that the work may have a selected surface speed.

The first part of the grinding operation is to remove the metal left on in turning for the purpose primarily of ensuring the work being properly ground, and the second part consists in securing an accurate and well-finished surface. With regard to the removal of stock, it is not to be immediately concluded—though it has not unfrequently been regarded as self-evident—that the higher the work speed the more rapid the grinding; later considerations will show that the reverse is more nearly the case, and it will be noticed that the firms making the heavier machines recommend the lower work speeds.

Finishing Speeds.—When the work has been rough ground to within a thousandth of an inch or so on the diameter, it becomes a question of finishing, and whether the work speed should be changed, and, if so, whether it should be increased or diminished. On this point again there are diametrically opposite opinions.

Where the quantities are small it is not usual to change the work speed, unless the machine in use is provided with a quick-change device so that no time is lost, for the work can quite well be rough ground and finished at the same speed. Where the quantities are large (25 or more, but it depends upon the size and the allowances) it is advisable to put the work through the machine twice, and in this case a different work speed should be selected for finishing.

With the very fine cut of finishing grinding, it is evident that the quality of surface primarily depends upon the number of the cutting points of the wheel which have gone over any portion of the work surface. Hence the time taken simply depends upon how long it takes a certain amount of wheel surface to pass the work; that is, the time taken does not depend at all on the surface velocity of the work, but only on that of the wheel. At these small finishing cuts no difficulty occurs in either increasing or diminishing the work speed as regards the behaviour of the wheel; increasing the work velocity, however, distributes any errors better, and should the wheel be worn to a (very slight) curve it lessens the faint spiral mark which is seen (Fig. 27), and considerably reduces the effect. With the higher finishing speed, moreover, a surface of sufficiently good quality may be produced in less time. The sole objection to the higher speeds for finishing appears to be that they are more likely to cause vibration troubles; but with the slight cuts used these very seldom occur if they are absent in the rough grinding.

Where then a different work speed can be used for finishing it should be higher than for the roughing out; from 25 to 75 per cent. increase is reasonable, but I believe that still more may frequently be used with advantage and without introducing troubles from vibration. With this view I believe that most authorities agree, but I would mention that others (Mr. Darbyshire, of Messrs. Alfred Herbert's, and Mr. Edge, of the British Abrasive Wheel Co., among them) advise a 25 per cent. reduction of the work speed for finishing.

Difficulties and Change of Speed.—After starting the work, trouble may occur in the grinding, which necessitates a change of work speed. If the wheel glazes, increasing the speed of the work may prevent it; and, on the other hand, if the wheel wears away too rapidly, the work speed should be reduced. Vibration may occur between the work and the wheel, causing chatter marks (see page 104); the work speed should then be changed. If it is due to a synchronous effect a slight alteration, either increase or decrease, of the speed may stop it. Generally a decrease is advisable. The vibration is usually originated by a want of truth or balance in the wheel, which should be trued with a diamond before restarting the work.

As the time taken in the actual grinding of a part consists of two parts—that of removing the allowance left on the work for grinding, and that of finishing to the requisite degree of accuracy and quality of surface—a machine may fail in efficiency in either of these two divisions of the work. To turn out work quickly, it must be convenient to manipulate; to finish accurately and well, the machine must be sufficiently rigid and accurate and in good condition; while for removing the stock left on from the turning rapidly it must have a sufficiency of power and weight, with rigidity enough to correspond to the forces involved.

The rate of removal of the stock also depends very largely on the wheel and on the speeds and feeds used. They should be selected so as—if possible on the particular piece of work—to use the machine to its full power capacity.

Theory of Grinding.—I have mentioned that I do not consider the work surface speed in cylindrical grinding to be independent of the work diameter. The theory which I advance (Brit. Ass. Report, 1914) is that the controlling factor is $v^2 \frac{d+D}{d\,D}\,t$, where v is the surface velocity of the work, D and d the diameters of the wheel and work respectively, and t the diametrical reduction of the cut. For internal work the wheel diameter is to be considered to be negative. If the quantity $v^2 \frac{d+D}{d\,D}\,t$ exceeds a certain amount, the wheel disintegrates too rapidly, failing to size the work properly, and wasting away; if on the other hand it is less than another certain quantity, the wheel surface glazes, and it fails to cut. The range between these quantities is that in which grinding can proceed satisfactorily.

Number of Cutting Points on a Wheel.—To arrive at this result it is necessary to consider the action of the wheel on the work closely. The wheel surface consists of a large number of cutting points, which take chips of very small section at a very high speed. Behind these points lie other arrays gradually taking up the action as the former are broken off or get worn down and finally dislodged from the wheel. As an increase in the depth of the cut brings more points into play, and as truing the wheel increases the number it previously had, the number of points 'on' the surface of a wheel is a rather indefinite number. Taking a 60-grit wheel I estimate the number of cutting points at about 1500 per square inch. This estimate may be objected to, the more especially as the Norton Company estimate the number at 3300 points for a wheel of this grit. If the particles which have passed through a square mesh the spacing of the wires in which is $\frac{1}{60}$ inch, but had failed to pass one of $\frac{1}{80}$ inch spacing, were neatly and compactly arranged side by side, the number of points would be not so very much more than the latter estimate; but an examination of a wheel shows that the particles are attached together in a very open architectural style (see Fig. 8), giving plenty of free space. Also in use a particle gets dislodged from the wheel before it is much worn, and this leaves an empty space. By glazing a wheel slightly the points on or near the surface can be counted; or they can be counted from a record of the surface such as is shown in Fig. 13, A and B.

The depth of the cut which a point takes is very small, much smaller than the one or two thousandths of an inch which is usually regarded as the thickness of the chip taken.

The number of points depends on the size of the grit, being inversely proportional to the square of the average linear dimension. Hence the number of points per square inch varies as the square of the number of the grit; e.g., if

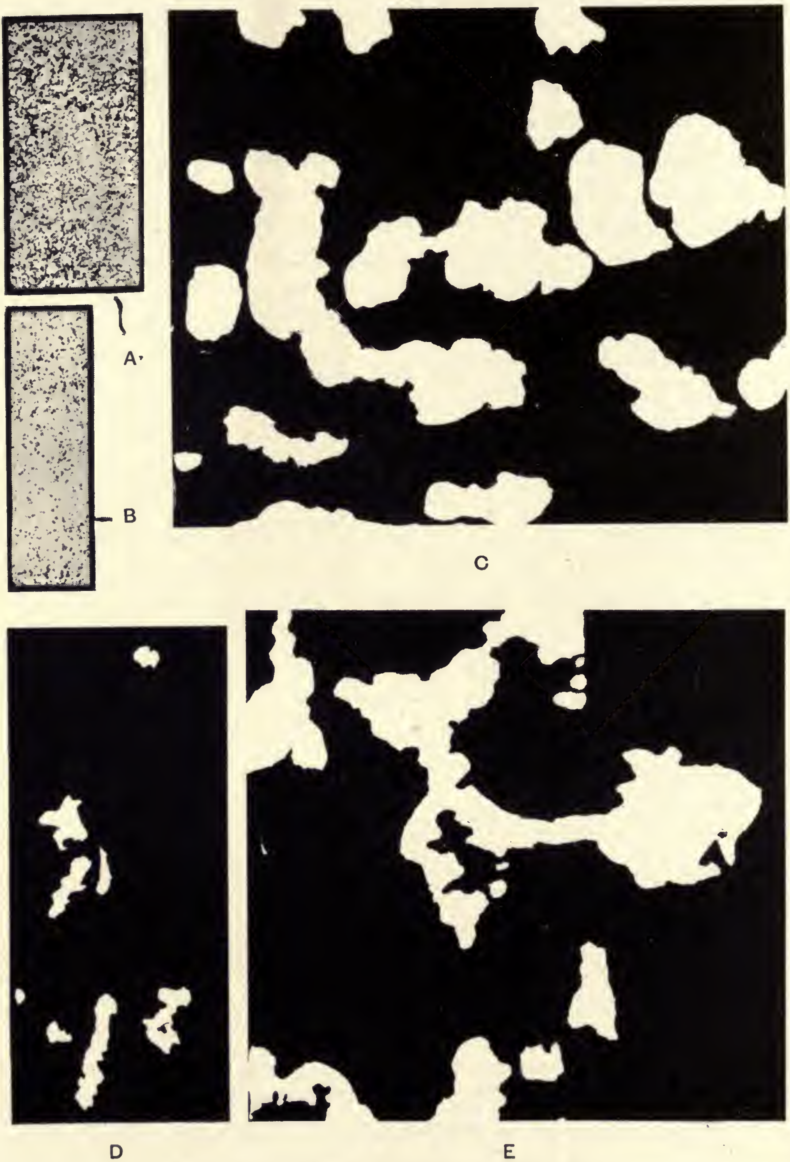


Fig. 13.—Cutting Points on Wheel Face

there are 1600 with 60 grit there are $1600 \times (\frac{24}{60})^2$ or 256 with 24 grit.

If the wheel be trued, the projecting points are turned off the particles, the diamond being so hard that it cuts the corundum or other fragments right across; this brings more points up to the wheel surface, so that there are more active points on a wheel when it has just been trued than there are after it has been in use. Also the width of the trued points is much larger, and there is no clearance behind the edge. When a wheel glazes the same occurs, and the glazed points are smoother. In Fig. 13 at A is shown the particles on the wheel face of a 46-grit wheel after it has been trued with a diamond, and the result of use of the wheel on the number of effective particles is shown by the corresponding view at B. At A there are not only very many more particles effective, but the areas presented by the various particles are greater as the projecting edges are trued off. This is well seen at C, which gives a view of the trued surface magnified fifty diameters, and the flat, trued-off facets are of definite area. The joining of the particles is the bond, which is also trued off flat. At D is shown a used wheel surface magnified also fifty diameters. The grit in all these cases is 46 alundum. At E is shown a carborundum wheel surface, 36 grit, turned with a diamond and magnified to the same extent. The diamond cuts the abrasive grit across, splintering it slightly with the alundum, but considerably in the case of the carborundum. In A and B the grit particles are black for sake of clearness; in C, D, E they show as white, and the recesses of the wheel face as black.

The Chips in Grinding.—The chips produced by a cup wheel, with plenty of water, can easily be seen and handled; though of very small cross section they may be some inches long, and in heavy work collect in the separating channels of the machine as a kind of steel wool. Such chips are shown in Fig. 14; they resemble turnings closely. The chips produced by a disc wheel in circular work are very short, but are thicker than those from a cup wheel. If the work is done dry the chips are ignited by the heat, and are mostly consumed as sparks. With a good flow of water, however, they can be collected, though some will be found melted into

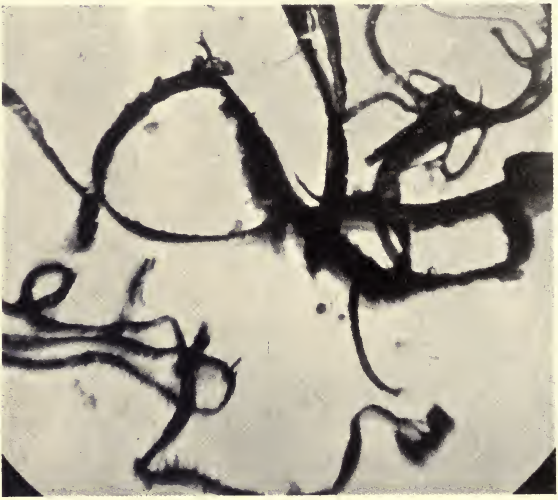


Fig. 14.—Grinding Chips, Cup Wheel. 50 Diameters.

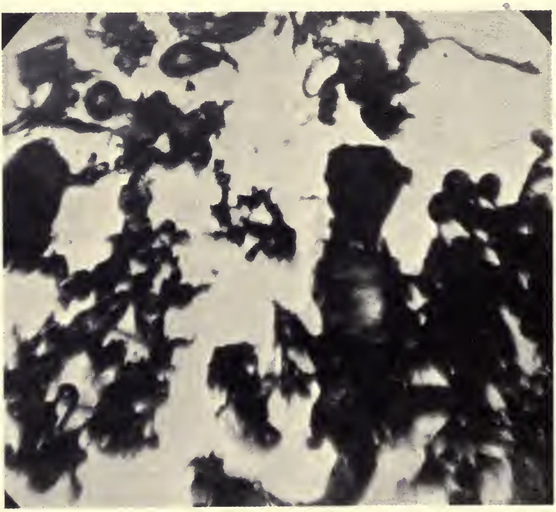


Fig. 15.—Grinding Chips, Disc Wheel. 50 Diameters.

round globules. In Fig. 15, which is a photograph of the chips from a plain grinder, the swarf, fused globules, and some broken abrasive can be seen. The magnification is 50 diameters. These chips present just the appearance of the larger chips taken by a lathe tool, but it is curious that the grinder chips from hardened steel resemble those from a tough mild steel instead of from a hard and brittle material; probably this is accounted for by the high temperature produced at the cutting point.

Normal Velocity of the Material.—Now consider a small area on any wheel face at which grinding is taking place.

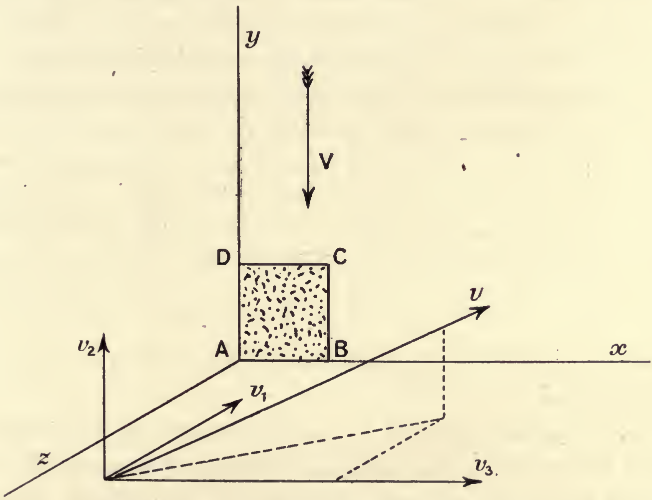


Fig. 16.—Velocities of Wheel and Material

This is shown at ABCD in Fig. 16, and may be regarded as a space across which a large number of cutting points travel with a high velocity V in the direction shown. The material of the work here fits the space ABCD and has a velocity there, which we will suppose to be of the amount v, and in the direction shown. Suppose this velocity split into three velocities, v_1 normal to the area ABCD, v_2 parallel to it and to V, and v_3 parallel to the area and perpendicular to V. Now if v_2 alone existed, the work would just move along the surface of the wheel without getting ground away; and the same if v_3 alone existed. All that v_2 would do would be to make the particles of the wheel appear, as viewed from the work, to move faster (or slower) than V by the amount v_2. As shown, it would be faster, as v_2 and V are opposed in direction. Similarly all that v_3 would do would be slightly to increase the apparent amount of V to $\sqrt{(V + v_2)^2 + v_3^2}$, and to alter (slightly) by angle $\tan^{-1}\frac{v_3}{(V+v_2)}$ its direction as viewed from the work. This leaves v_1 alone as the effective velocity, and upon this normal velocity of the material of the work into the wheel face the grinding action must depend. If a steel rod were placed with its end on the surface of a wheel, and with its length perpendicular to the wheel face, and then pushed lengthways slowly into the wheel, it would be ground away and have normal velocity only.

As the particles of the wheel passed the grinding space they would be taking cuts, and the depth of these cuts would depend upon the rate v_1 and on the time since a cutting point passed nearly enough along the same path. This time—very small—would be equal to the average distance between the following cutting points divided by V, their velocity. The depth of the cut would therefore be equal to $\frac{v_1}{V} \cdot p$, where p is this average distance, which is evidently proportional to the size of the grit of the wheel.

Now the force exerted by and on the cutting point depends upon the section of the chip, and therefore—in a certain wheel run at a definite surface velocity (V)—it depends upon v_1. When this force reaches a certain amount it is sufficient to break or dislodge the particle, and hence the disintegration of the wheel face depends upon the normal velocity v_1 of the material. Hence v_1 must not exceed a certain amount.

If v_1 were very small the points of the particles would become worn down by the rubbing action before there was enough metal projecting over them to enable them to cut. Thus to have v_1 very low tends to make the wheel glaze. These two quantities—the force on the cutting points and the amount of rubbing—control the breaking up and glazing of the wheel face, and they depend on v_1, the normal velocity of the material.

If we alter V we shall somewhat alter the force necessary to take the same cut; experiments on the variation of cutting force with speed in lathes show that it rises with the speed, but only slightly. It is therefore best to make V as high as is reasonably safe, as the output is thereby increased, since v_1, and therefore v, is in proportion to V.

Disc Wheel Grinding.—To illustrate more fully what is proved here and just how the chip is formed, suppose that A, B, C (Fig. 17) are three points on the circular surface of a disc wheel, and that they follow one another along the path CBA. This path is really curved, but it is supposed to be magnified so highly that the small piece of it at which we are looking is practically straight. AD, BE are two particles following the same track with velocity V. Now let the work in contact with the wheel face along A, B, C be fed into it with the velocity

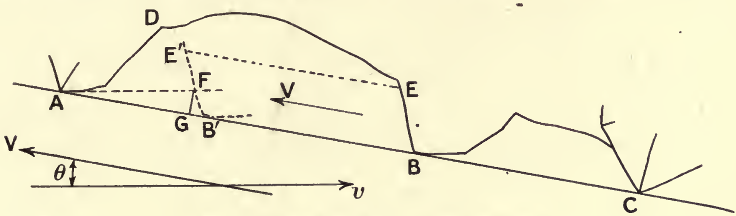


Fig. 17.—Feed as in Disc Wheel

and in the direction v, which is inclined at an angle θ to V, and we will suppose this angle θ small as sketched, and the resolved part of v perpendicular to the wheel face, only 1 per cent. or less of V. Directly A passes the point at which it is sketched, and moves off, the point A of the work moves along AF, and meets the cutting particle EB which has come up to the position E′B′ at F. If this takes the small time t, then $BB' = Vt$, $AF = vt$, $AG = v_2t$, and $GF = v_1t$, where v_1 and v_2 are the components of v along and parallel to V, since AFG can be taken to be the triangle of velocities. Since GB′ must be a small quantity compared with AB, we can consider that $AB = AG + BB' = v_2t + Vt$, and $\therefore\ t = \dfrac{AB}{V + v_2}$.
Hence the thickness of the chip which the tooth E′B′ is taking (which is FG) $= v_1 \cdot \dfrac{AB}{V + v_2}$.

That is, the thickness of the chip depends on v_1, since AB evidently depends on the size of the grit only, and v_2 is only a small fraction of V; that is, the thickness depends on the normal velocity of the material into the wheel face. This confirms the previous proof.

Face Wheel Grinding.—As another illustration, consider work fed into the face of a cup wheel; we shall again find that the size of the chip depends on the normal velocity of the work. This is shown in Fig. 18. Here ABC is again the wheel face, and the work is feeding into it with velocity v in the direction shown, but the cutting points are moving upwards from the plane of the paper with velocity V. The work which passes the point A of the particle AD feeds along AF until it comes

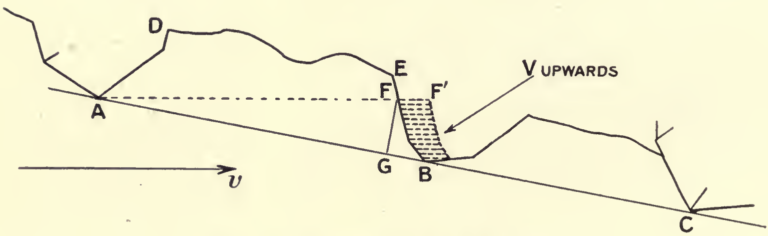


FIG. 18.—FEED AS IN FACE WHEEL

to the particle BE which cuts it and passes on upwards. The work continues to feed on until the next particle comes up along the path of BE, and in that time feeds into its path a distance FF′, which is vt, where t is the time taken for the second particle at BE to follow the first. If p_1 be the pitch of the particles this way, then $p_1 = Vt$. The area of the chip, shown shaded, is then FF′ × FG. We have $FF' = vt = v\frac{p_1}{V}$. Also $FG = AF \times \frac{v_1}{v}$, since AFG is the triangle of velocity for v and its components along the wheel face ABC and perpendicular to it. Hence if $AF = p_2$, the pitch of the particles the other way, we have for the area of the chip the value

$$FF' \times FG = v \, . \, \frac{p_1}{V} \times p_2 \, . \, \frac{v_1}{v} = v_1 \, . \, \frac{p_1 p_2}{V}$$

The expression $p_1 p_2$ evidently depends on the grit in the wheel only, and therefore again the chip section depends on v_1, the component of the work's velocity normal to the wheel face.

The cutting particles are distributed very irregularly in the wheel face, and some take deeper chips than others, but the above shows what happens in a case we may regard as typical of the average, although the action of the points of particles below ABC is not considered. In both of these cases the size of the chip depends on the normal velocity v_1 of the

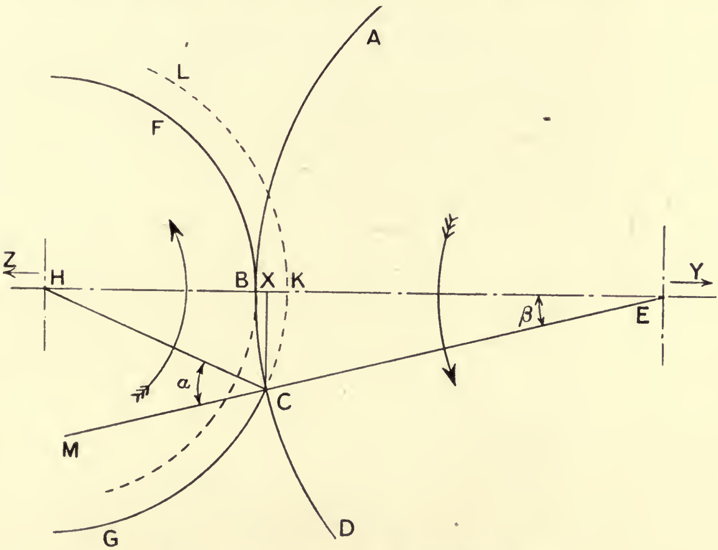


Fig. 19.—Contact in External Work

work to the wheel face, and therefore the force on the cutting particle and the disintegration of the wheel face depend upon it.

Theory of Disc Wheel Grinding. The Arc of Contact.—Returning to the case of a disc wheel used to grind circular work, consider what happens where the wheel touches the work. The contact is an area or surface, with a breadth equal to that of the wheel and a certain length, small it is true, but still to be considered. It is sometimes referred to for convenience as a line, but if it were merely a line no metal could be removed in the grinding process. Everywhere along the arc of contact except on the line joining the centres of work and wheel, the work has a normal velocity to the wheel face. In Figs. 19 and 20 is shown the nature of the contact, Fig. 19 showing it for external and Fig. 20 for internal grinding. The corresponding parts are indicated by the same letters, so that one description applies to the two cases. The wheel ABCD, whose centre is at E, grinds the work FBCG, whose centre is at H, and the broken line CKL shows the work surface as it would have been if the wheel had not ground it, so that BK

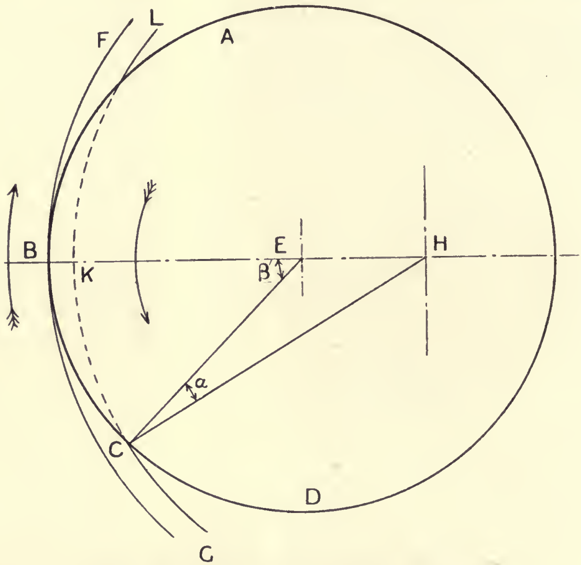


FIG. 20.—CONTACT IN INTERNAL WORK

is the depth of cut. The directions of rotation of the wheel and work are shown by the arrows, and the depth of cut is particularly exaggerated for the purpose of making matters clear. The arc of contact is BC, and the area of contact has a length BC with a width equal to the acting width of the wheel.

The wheel and work surfaces run to meet one another, and owing to the closeness with which the particles of abrasive follow one another owing to the high speed, the part FBKL of the work above the line of centres EKBH is ground almost entirely away, and contact only takes place below, along

BC. Since the work rotates in the direction of the arrow the cut begins just above the point B, so that the length of cut can be taken as BC, though it is a little more, and the length of the chip is rather shorter, as it is compressed while being made.

To obtain the length of BC, let $D \equiv 2R$ be the diameter of the wheel, $d \equiv 2r$ that of the work, and t the amount being ground off the diameter of the work, so that $BK = \frac{1}{2}t$. Then calling the angle HCM, where M is on the prolongation of EC, a, we have by the trigonometry of the triangle HCE—

$$HE^2 = HC^2 + CE^2 \pm 2HC \cdot CE \cos a$$

where the minus sign refers to internal grinding, Fig. 20.

Or $$(r \pm \overline{R - \tfrac{1}{2}t})^2 = r^2 + R^2 \pm 2rR\cos a$$

$$\therefore\ rR\cos a = rR - (r \pm R)\frac{t}{2} + \frac{t^2}{8}$$

or $$\cos a = 1 - \frac{r \pm R}{rR} \cdot \frac{t}{2} \quad \text{since } \frac{t^2}{8} \text{ is so small.}$$

Or expanding $\cos a$, by trigonometry, it being a small angle—

$$1 - \tfrac{1}{2}a^2 + \frac{1}{12}a^4 = 1 - \frac{r \pm R}{rR} \cdot \frac{t}{2}$$

$$\therefore\ a = \sqrt{\frac{r \pm R}{rR} \cdot t}$$

Now if angle HEC be β, we have—

$$\frac{\sin\beta}{HC} = \frac{\sin a}{HE}$$

or $$\sin\beta = \frac{r}{r \pm (R - \frac{1}{2}t)} \cdot \sin a$$

and $\therefore$ $$\beta = \frac{ra}{r \pm R}, \text{ since both } a \text{ and } \beta \text{ are small angles,}$$

and $\therefore$ $$\text{arc } BC = R\beta$$

$$= \sqrt{\frac{Rr.t}{r \pm R}} \quad \text{or} \quad \sqrt{\frac{D.d.t}{2(d \pm D)}}$$

So that the length of BC depends on the diameters of both wheel and work, upon the depth of the cut, and whether the grinding is external or internal. To illustrate the actual lengths involved, a few cases are given in the following table for different diameters of wheel and work. The depth of the cut has been taken as $\frac{2}{1000}$ inch on the work diameter.

LENGTH OF ARC OF CONTACT FOR $\frac{1}{1000}$ INCH ASIDE CUT

	EXTERNAL.				INTERNAL.			
Diameter of wheel .	14 in.		18 in.		1 in.		3 in.	
Diameter of work .	1 in.	6 in.	2 in.	12 in.	$1\frac{1}{8}$ in.	2 in.	$3\frac{1}{2}$ in.	5 in.
Length of contact .	0·0306	0·065	0·0425	0·085	0·095	0·045	0·145	0·087

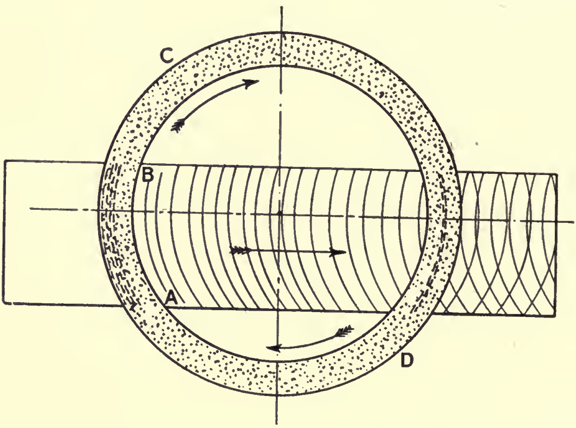


FIG. 21.—CONTACT IN FACE WORK

The arc of contact is thus longer than it is usually assumed to be, and is much longer in internal than in external grinding. If the depth of the cut in the internal cases be reduced to $\frac{1}{2000}$ inch on the diameter (that is, to a quarter of the previous amount), the length of the arc of contact is halved, so that they are 0·0475, 0·0225, 0·0725, and 0·0435 respectively, or about the same average as the external examples given.

As a contrast, the case of the face wheel is shown in Fig. 21, which is a plan view supposing the wheel spindle to be vertical. The wheel ABCD shows in section as a ring, and the grinding takes place mainly over the area marked with broken circular marks at AB, though a little is done on the opposite side of the wheel. The length of the cut AB is now considerable, being rather longer than the width of the work. To secure flat work the work must not be much larger than the diameter of the inside of the cup wheel, the limit being the diameter of the highest circle of cutting points when the wheel has worn a little. The cutting points are indicated in the figure by the broken arcs, and the work is shown travelling under the wheel

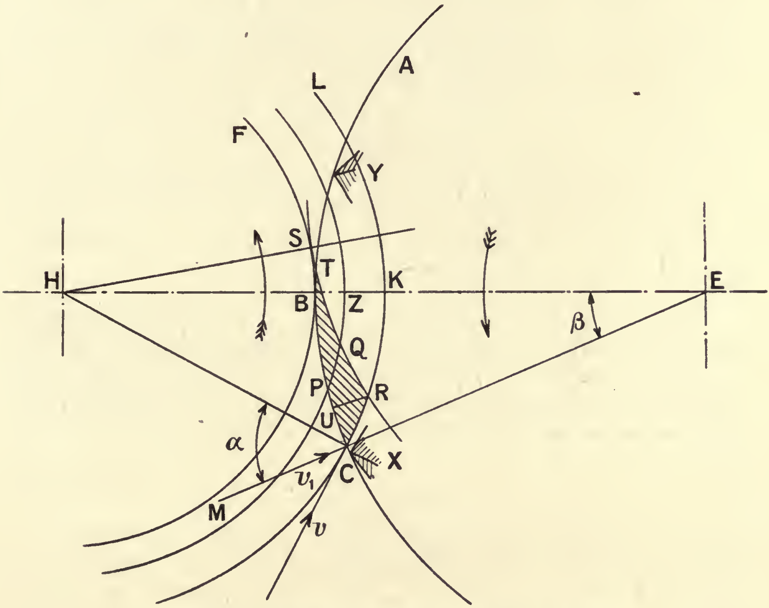


Fig. 22.—Formation of Chip by Disc Wheel

in the direction of the arrow. The marks of the grinding on the work are also indicated.

The chips produced in the two cases are shown in Figs. 14 and 15 respectively.

Normal Velocity of Material.—Now consider how the chip is formed. In Fig. 22 is shown a figure like Fig. 19, but to it are added lines showing the formation of the chip. The cutting point X has just moved over the arc BC, and the point Y is following it. Immediately X has passed any point P on the arc BC, the material at P begins to move along the arc

PQ of a circle with centre H; and if t be the time after which Y follows X, then PQ will be $2\pi nt$HP, where n is the r.p.m. of the work. Thus B will get to S, where BS $= 2\pi nt$HB, and C to R, where CR $= 2\pi nt$HC in the short time t. The cutting particle Y will meet the metal very nearly at SQR, and its extreme point will move along BPC, so that the shape of the chip will be of the curved triangular shape shown shaded. The particle Y never touches S, and T is the nearest point it gets to it. The distance of T from BS, however, is so small as to be practically immeasurable.

Now if v be the velocity of the surface of the work, CR $= vt$, and if RU be drawn perpendicular to PC, then UR $= v_1 t$, where v_1 is the component of the work velocity at the point C, which is normal to the face CP of the wheel there; v is along the arc CK, and v_1 along the line MCE, hence $v_1 = v \sin \text{HCM} = v \sin a = va - \frac{1}{6} va^3 = va$ (very nearly).*

* The values of the expressions for s and v_1 can easily be proved geometrically, a method which appeals more to engineers than the algebraic one given in the text. In Fig. 19 draw CX perpendicular to HE, and let Y and Z be the ends of the diameter BEY, KHZ. In any circle the product of the segments of intersecting chords are equal (see Euclid III. 35), so that—

$$\text{XB} = \frac{\text{XC}^2}{\text{XY}}$$

and

$$\text{XK} = \frac{\text{XC}^2}{\text{XZ}}$$

and ∴

$$\text{XB} + \text{XK} = \text{XC}^2 \left(\frac{1}{\text{XY}} + \frac{1}{\text{XZ}}\right)$$

But where, as in our case, BK is only a few thousandths of an inch and XY and XZ several inches, we may take XY as equal to BY or D and XZ as d; and in the same way BC and XC are exceedingly nearly equal, so that we can consider that XC is equal to BC or s, and hence—

$$\text{BK} = s^2 \left(\frac{1}{\text{D}} + \frac{1}{d}\right)$$

or

$$s^2 = \frac{d\text{D}t}{2(d + \text{D})}$$

Now draw HM perpendicular to CM; then the sides of the triangle CHM are perpendicular to the directions of v and its components v_1 and v_2, and therefore—

$$\frac{v_1}{v} = \frac{\text{HC}}{\text{HM}}$$

Hence $v_1 = v\sqrt{\frac{r \pm R}{rR}.t} = v\sqrt{\frac{d \pm D}{dD}.2t}$ . . (1)

The thickness of the chip depends on v_1, but as the cutting particle takes a chip the width of which increases with the breadth—and in proportion to it—unless the cutting point has been turned by a diamond tool so as to cut at once over a comparatively considerable breadth, the area of the chip will depend on v_1^2; and as the force tending to dislodge the particle varies nearly as the area of the chip, therefore it varies as v_1^2, or, since we can drop the constant 2, as—

$$v^2 . \frac{d \pm D}{dD} . t$$

The Controlling Factor.—Also, if $s = BC$, we have—

$$s = \sqrt{\frac{rR}{r+R}.t} = \frac{v_1}{v} . \frac{Rr}{r+R}$$

so that v_1 is proportional to s, and hence the v_1 at any intermediate point P is proportional to s, the arc up to P measured from B. Hence the total disintegrating action must be dependent on the maximal normal velocity at C, so that in reckoning up all the action along the arc the total effect depends on $v^2 . \frac{d+D}{dD} . t$.

The first part of the action from B towards P has no tendency to disintegrate the wheel; it tends to glaze it, as the normal velocity is so small, and is zero at B. The action in this early part of the arc is the same as in finishing with a small cut BZ. When the particles of a wheel are glazed a little they tend to push the work away during the early part of the arc BC, and so increase the rubbing and glazing further unless it be checked.

It can be checked by increasing $v^2 . \frac{d+D}{dD} . t$—that is, by

---

But HM . EC = 2 × area of triangle HCE = XC × HE

$$\therefore \quad HM = \frac{s(r + R - \frac{1}{2}t)}{R} = s . \frac{d+D}{D} \text{ (very nearly)}$$

$$\text{and } \therefore \quad \frac{v_1}{v} = \frac{2s(d+D)}{dD}$$

$$\therefore \quad v_1 = v\sqrt{\frac{dDt}{2(d+D)} . \frac{4(d+D)^2}{d^2D^2}} = v\sqrt{\frac{d+D}{dD} . 2t}$$

increasing either v or t, but it is to be noticed that increasing v is far more effective than increasing t: for example, if v be increased 30 per cent. the effect is increased 69 per cent., and it would require that increase of t to produce the same effect. Conversely to check wasting of the wheel $v^2 . \frac{d + D}{dD} . t$ must be lessened, and it is more effective to reduce v than t. There will be in different cases a more or less wide range over which the quantity may vary, and yet the wheel work reasonably; it is best that its value should not be near either the glazing or wasting points, else a little difference anywhere may cause trouble.

Since $v^2 . \frac{d + D}{dD} . t$ contains both v and t it can be varied by changing either quantity; hence we see that the actual work surface speed is not definitely controlled by this quantity, and therefore may vary over a considerable range.

Maximum Output.—Now the two quantities v and t can be arranged, while keeping this factor constant, to meet some other condition. As $\frac{1}{2}vt$ is the rate of removing material, and since this is ultimately limited by the power which can be taken by the machine for unit width of wheel face we have

$$vt = c \quad . \quad . \quad . \quad . \qquad (2)$$

as the condition for reaching the greatest output. Hence the most rapid output would be obtained by decreasing v and increasing t, in such a way as to keep $v^2 . \frac{d + D}{dD} . t$ constant. Pushed to its limit with a machine having indefinitely great power, this would indicate that the most rapid method of grinding is to remove the material at a single traverse, using a slow surface speed and a heavy cut. Besides other difficulties, however, this would be directly opposed to that fundamental principle of grinding which secures accuracy, although the work may change its shape slightly (see page 93), by taking a number of finer cuts. It is in any actual machine definitely limited by the fact that vt is (nearly) proportional to the power supplied to the machine per unit width of wheel face, and this is the deciding factor, so that the limit is expressed by equation (2) above.

We then have for a given machine and width of wheel face $vt = c$, a constant, and for a particular kind of wheel and material $v^2 . \frac{d + D}{dD} . t$ must lie between two limits which we will call a_1 and a_2; then by dividing we see that $v . \frac{d + D}{dD}$ must lie between $\frac{a_1}{c}$ and $\frac{a_2}{c}$, which gives the limits for the efficient surface velocity. If we find some value b between a_1 and a_2 as actually the best, then we shall have—

$$v . \frac{d + D}{dD} = \frac{b}{c} \quad . \quad . \quad . \quad . \quad (3)$$

as the best surface velocity.

We notice that it depends immediately upon the power factor c, and the higher this is the lower the values of the best surface velocity. The tendency to reduce work speeds of recent years is thus shown to be (in part) a direct consequence of the greater power factor of the machines.

Magnitude of the Quantities involved.—It will also be noticed that the best value of v depends upon the diameters of both work and wheel, but before considering this more closely let us consider the magnitudes of the various quantities involved in the action. These can easily be estimated in a particular case. As an example, suppose that the wheel be 14 inches diameter by 1 inch face, of 36 grit, and be running at 5000 feet per minute circumferential speed; and the work be 2 inches diameter running at 30 feet per minute surface speed, with a depth of cut of $\frac{1}{1000}$ inch on the diameter.

The rate of removal of material $= \frac{1}{2} vt$

$= 0{\cdot}18$ cubic inches per minute.

The length of the arc of contact $= \sqrt{\frac{d . D . t}{(d + D) . 2}}$

$= 0{\cdot}0296$ inch

(rather less than $\frac{1}{32}$ inch).

The maximum normal velocity of the material v_1

$= v\sqrt{\frac{d + D}{dD} . 2t}$

$= 12{\cdot}3$ inches per minute.

The number of cutting points per square inch we will take as 600, though it is not a very definite number. The shape of the chip will be a wedge on a base which we may take to be roughly rectangular with an average width of n times its depth. Its length will be 0·0296 inch, or $\frac{1}{34}$ inch. If its depth be x and width nx the average volume will be $\frac{1}{2} \cdot x \cdot nx \cdot \frac{1}{34} = \frac{1}{68} nx^2$. There will be $600 \times 5000 \times 12$ chips taken, and their volume will amount to $\frac{1}{68} \cdot nx^2 \cdot 600 \cdot 5000 \cdot 12$ cubic inches, which must be the same as 0·18 cubic inch. So that $nx^2 = \frac{0{\cdot}18 \times 68}{600 \times 5000 \times 12} =$ 0·00000034 cubic inch. If we take $n = 3$, then $x = 0{\cdot}00033$ and $nx = 0{\cdot}001$, so that the base of the chip would be one-thousandth of an inch wide and one-third of that amount deep. If n were larger the chip would be wider and thinner. If we had—still taking n as 3—calculated the depth from the maximum normal velocity, we should have arrived at the same figures. The average 'pitch' of the consecutive cutting points on the wheel face would be about $1\frac{2}{3}$ inches.

The Force at the Grinding Point.—Several machines use a wheel 14 inches by 2 inches, and they are arranged to take, and do take, about 5 h.p. Of this a portion is used in driving the machine parts and absorbed in the belting, the remainder alone reaching the cutting point. Probably more than 1 h.p. is absorbed in the belts, friction, &c., but assuming that that amount only is absorbed, it leaves 2 h.p. per inch of wheel face at the cutting point, so that (as 99 per cent. of this goes through the wheel) the force at the edge is 13 lb.

This force is the tangential force ; the normal force tending to separate wheel and work is very small, but its ratio (about one-eighth) to the tangential force depends on the condition of the wheel particles, and is higher if they are glazed.

The area of contact is 0·0296 square inch, and therefore contains usually 18 cutting points, so that the force on each averages 0·72 lb., and the final force on each 1·45 lb. Experiments on cutting tools in a lathe show that the force per square inch of chip section increases as the area of the section diminishes. Taking some experiments by Prof. R. H. Smith, an average value of the cutting force on a chip of 0·001 square-inch section was 290,000 lb. per square inch, which would give about 0·1lb. on a 0·00000034 square-inch area, while the average rate of increase of force per square inch of cut as the area of the cut diminished would increase this to 0·35 lb. This force would be that on a properly shaped cutting point presented correctly to the work ; the shape and presentation of the edges of the abrasive particles would very considerably increase this value, so that within the limits of our knowledge the forces on the point calculated from the opposite points of view agree fairly well. Nothing is known as to the effect of taking the cut at so high a rate as 5000 feet per minute, instead of at a hundredth or even a fiftieth of that amount.

Judging from the stress strain curves, the high speed would make little difference in the case of hard materials, but might reduce the work on tough metals, e.g. copper and bronze.

The chips in Figs. 14 and 15 were made with coarser grit wheels, but bear out the above calculations as to the size of section. In cutting steel the cutting point has to meet alternate layers of ferrite (soft) and cementite (hard material) in the pearlite, and these layers are of a thickness about that of the chip taken in grinding. The distribution of martensite and austenite is of a similar order of size. The changing force on the cutting point, exceedingly rapid though the variation is, may be one reason why the harder carborundum does not work so well on steel as the softer but tougher alumina abrasives.

Temperature Rise.—In considering the temperature effects, it does not matter whether we deal with the chips individually or in bulk, and taking the latter view as the simpler, if H be the horse-power expended at the grinding point, m the number of cubic inches of metal removed per minute, and supposing that half the heat goes into the chip, then the temperature rise of the chip in degrees Fahr. is—

$$\frac{H \times 33{,}000}{2\,J\,k\rho m}$$

where k is the specific heat of the material, ρ its density, and J, Joule's mechanical equivalent, which is equal to 778 ft.-lb., For steel $k = 0{\cdot}113$ and $\rho = 0{\cdot}284$ lb. per cubic inch. So that if $H = 2$ and $m = 0{\cdot}18$ as in our example, we have for the temperature rise $\frac{2 \times 33{,}000}{2 \times 778 \times 0{\cdot}113 \times 0{\cdot}284 \times 0{\cdot}18}$ or 7250° F. As the metal melts at 3250°, this temperature would fuse it easily.

Fused and Ribbon Chips.—In dry grinding the metal is ignited and burns as sparks, but in wet grinding the water carries away the heat and keeps the temperature down. In Fig. 15, which represents chips from a heavy plain grinder, it will be noticed that most of them are fused somewhat, and some have been melted completely and then chilled by the water into small globules.

The temperature rise depends directly on the power used, and inversely as the rate of removing metal, so that it is greatest with hard wheels. It is higher with fine grit wheels owing to the extra force per square inch of chip section as the size of the chip diminishes, and also higher with the harder steels. By combining these factors ' ribbon ' chips can be produced, in which the chips are fused together and come from the machine as a ribbon of steel.

Grinding Hardened Steel.—The heat produced cannot be lessened by any application of cooling water; the latter simply carries away the heat produced, and so reduces the temperature to which the metal rises at the cutting point. In grinding hardened steel there is thus considerable risk of drawing the temper of the metal at the surface if the work is hurried; so that just at the surface the steel would be softened, although remaining hard inside, owing to the mass of metal absorbing the heat with a less rise of temperature. Thus the temper could only be drawn for a few thousandths of an inch deep, but this is sufficient to spoil a hardened surface, and this must be avoided by taking light cuts, and using plenty of water applied right at the grinding point when removing the last few (five is sufficient) thousandths from the diameter of the work.

The above estimation of the quantities in a particular case puts us in a position to consider another point with regard to the derivation of equation (1)—namely, the effect of the length of the chip; for if the chip were indefinitely long, as it might be supposed to be if we took a cup wheel and fed it parallel to its axis into some stationary work, there would finally be no room for the swarf, and the wheel would clog. With the dimensions of the chip found, it is now clear that nothing of this nature will take place. In modern open texture wheels there is abundant room for the length of the chips in circular grinding, especially when it is remembered that their greatest thickness is only a fraction of a thousandth of an inch. In using cup wheels for surface grinding, the length of the chip is considerable—some inches it may be—but if the area of the chip be fine enough trouble seldom arises.

Effect of Length of Arc of Contact.—A question may also be asked as to what is the effect of a longer or shorter arc of contact in these cases, and more particularly in internal grinding, where it is considered to have a very undesirable effect. The action, however, is similarly distributed in all cases. We have—

$$v_1 = v\sqrt{\frac{d + \mathrm{D}}{dD} \cdot 2t} \quad \text{and} \quad s = \sqrt{\frac{\mathrm{D}dt}{2(d + \mathrm{D})}}$$

so that, eliminating t—

$$\frac{v_1}{s} = v \cdot \frac{d + \mathrm{D}}{d\mathrm{D}}$$

That is to say, the normal material velocity at any point P (see Fig. 22) of an arc of contact is proportional to the length BP; hence whatever the history of a cutting point, whether it goes a greater number of times over a short arc or a fewer number over a longer one, it gets just the same amount of each kind of action. A cutting point as it passes along the arc BPC encounters the material at grazing incidence at B, and rubs and glazes: then as the normal velocity increases along the arc it cuts. As the wheel rotates the particle makes a succession of cuts, gradually getting blunter until it is finally fractured or torn out of its bond by the force of the cut. The particle, however, comes into action before it becomes, as the wheel wears, one of the prominent surface particles; near the centre line HBE it does not cut; later it begins meeting the material first at almost grazing incidence. If the arc were longer, with the same final normal velocity v_1, practically the same would happen, all in proportion; but the arc being longer, the particles would require proportionally fewer turns before they became blunted and dropped out of the wheel.

Area of Contact is proportional to the Power.—Now, taking the same equations for v_1 and s, let us eliminate d instead of t; D also goes out, and we have—

$$s = \sqrt{\frac{d\mathrm{D}t}{2(d+\mathrm{D})}} = \sqrt{\frac{t}{2} \cdot \frac{v^2 . 2t}{v_1{}^2}} = \frac{vt}{v_1}$$

This shows us that whatever the diameters of work and wheel, the length s of the arc of contact is proportional to vt, or to the amount of power supplied per unit width of wheel face.

Now in our case of a machine with a certain wheel and a certain amount of power available at the wheel face, vt is constant, and has been taken to be c: so that in all cases derived from the conditions (1) and (2) the arc of contact has the same length.

Hence, if we base a series of work speeds for different diameters upon the formula of equation (3), the arcs of contact will all be of the same length, and the action at each point of these arcs will be the same; while the fact that the power at the wheel face is the same, tells us that the total force on the work will be the same in each case.

Alteration of Speeds to check Wear of Wheel and Glazing.—Before considering the work speeds based upon equation (3) it will be convenient to consider what is to be done if, after a work speed v has been selected, trouble occurs.

Suppose that the wheel wears unduly. To prevent this, the quantity $v^2 . \frac{d+\mathrm{D}}{d\mathrm{D}} . t$, or, since $\frac{d+\mathrm{D}}{d\mathrm{D}}$ is a constant, as we have our work and wheel in the machine, the quantity v^2t is to be reduced. At the same time vt is to be kept constant—that is to say the maximum output is to be still obtained. To do this we must reduce v and increase t in the same proportion;

this will keep the output vt as before, but will reduce the normal material velocity which is disintegrating the wheel surface.

As an illustration, consider the case previously taken, and suppose the wheel so soft that it wore badly under the speed (30 feet per minute), and the cut ($\frac{1}{1000}$ inch on the diameter). The normal material velocity was 12·3 inches per minute. Now, if the speed be reduced to 15 feet per minute, and the cut put up to $\frac{2}{1000}$ inch on the diameter, the rate of removing stock will be the same, but the destructive normal velocity is reduced to 6·15 inches per minute, which the wheel will probably withstand.

Conversely, if the wheel be glazing, the work surface velocity must be increased, and the depth of cut decreased; this increases the normal material velocity, and disintegrates the face of the wheel faster, preventing glazing.

The simplest way to reduce wheel wear is to reduce the cross-feed; when, however, this has been reduced sufficiently to check the wheel wear satisfactorily, the possible output from the machine has been very much lessened. It has gradually been found from experience that it is better to reduce the work speed than the cross-feed, but this also lessens the output possible. The correct method is that given above—to reduce the work speed far more than is sufficient to regulate the wheel wear, and to increase the cross-feed simultaneously.

The normal material velocity, $v\sqrt{\frac{d+D}{dD}\,.\,2t}$, which is possible is a function of (i.e. depends on) the nature of the wheel and work material only; it may be said to express the grade of the wheel. It is not an exact quantity—a wheel disintegrates, and it is a question whether it is doing so too rapidly for economy. The amount in the example, 12 inches per minute, is suitable for a 36 K wheel; with 16 inches the wheel face usually loses too much to be satisfactory, but with 3846 K alundum wheels Messrs. Brown & Sharpe run at 20 inches satisfactorily. For economy a wheel must disintegrate, and the best rate is a matter of the ratio of wheel and labour cost.

Deduced Work Speeds.—Now, considering equation (3), we have $v = \frac{b}{c} \cdot \frac{dD}{d + D}$ and taking the example given as satisfactory we obtain the quantities in the following table as corresponding.

WORK SPEEDS AND FEEDS IN CIRCULAR WORK

Work diameter—inches . .	½	1	2	4	8	16	
Surface velocity—feet per minute	8·3	16	30	53·3	87·7	128	For 14-in. wheel.
Cross-feed—thousandths of inch on diam.	3·6	1·87	1	·57	·34	·23	For 14-in. wheel.
R.P.M.	63·5	61	57·4	50·6	42	30·6	For 14-in. wheel.
Surface velocity—feet per minute	8·2	15·6	28·6	49·	76·3	106	For 10-in. wheel.
Cross-feed—thousandths of inch on diam.	3·66	1·92	10·5	·61	·39	·28	For 10-in. wheel.
R.P.M.	62·7	59·7	54·7	47	36·5	25·2	For 10-in. wheel.

In this table I have taken a very wide range—in practice such different diameters as ½ inch and 16 inches would be done on very different machines—in order to show where difficulties arise in carrying out the natural formula of equation (3). The table shows the speeds and also the corresponding feeds for the various work diameters with a 14-inch wheel, and again with it supposed worn down to 10 inches diameter. The difference of wheel diameter has not very much effect.

It will be noticed that the r.p.m. are much more nearly constant than the surface speeds; further considerations will, however, make an alteration.

Changes to meet Vibration of Slender Work.—Work of ½ inch diameter according to the above table runs at 8·3 feet per minute, which is within the limits of modern speeds, but the amount of cross-feed—0·0036 inch on the diameter—is very high, and the slender work would vibrate under the cut, the force due to which is the same in all the series of diameters. To check the vibration and chatter the force of the cut must be reduced, and hence vt must be made smaller. But $v^2 . \frac{d + D}{dD} . 2t$ must be the same, so that v is to be increased and t diminished. As an example, suppose that the force be halved: the velocity must be doubled and the cross-feed reduced to one quarter, so that they would be $16\frac{1}{2}$ feet per minute and $\frac{1}{1000}$ inch or less on the diameter. The tendency to vibration here limits the output and not the power which is conveyed to the machine. To what extent the velocity has to be raised and feed reduced depends on the length of the part and the efficiency of the steadies. Thus on small diameter work the speed usually has to be raised above the speed given by equation (3), and it is done at a sacrifice of the rate of removing material.

Effect of changing Width of Wheel Face.—At the other end of the scale we have a different set of conditions—the work speed is very high and the depth of cut small, and this is also the case with internal grinding. Now high work speed may mean trouble from vibration, due to the work being out of balance; also such fine cuts as those indicated are the finest for which a machine is usually arranged, or less still, and with a slender internal spindle difficult to use for other reasons; it is, therefore, desirable to be able to use less work speed and deeper cuts. Keeping to the same grit and grade of wheel, there is only one way to do this, which is by increasing the value of vt; then v can be reduced in just the ratio in which vt is increased, and t can be increased in the square of the ratio, since $v = \frac{b}{c}$ and $t = \frac{c^2}{b}$ and c is increased. Now the maximum power delivered to the machine is fixed, and hence the only way to increase vt is to decrease the width of the wheel used, as vt is the power per inch width of wheel face. So that for large diameter work a narrower wheel should be used than for medium sizes. Again considering our example, if we used a wheel of 1 inch face instead of 2 inches, the work speed to suit it would be 44 feet per minute for 8-inch work and 64 for 16-inch diameter work, and the cross-feeds $1\frac{1}{4}$ and 1 thousandth on the diameter. The disintegrating effect is just as before, and the power employed and the output are similar. The total force of the wheel on the work is the same, but it is concentrated along one inch length instead of along two inches. The cross-feeds would now be of amounts suitable for use; while the previous small amounts could only be employed advantageously as the accuracy of the work was improved by the grinding.

The effective width of wheel face in use is that of the traverse per revolution of the work, so that the power used per width of wheel face may be increased by using a slower travel. In the next chapter, however, it is shown that the traverse should be between $\frac{5}{8}$ and $\frac{7}{8}$ of the width of the wheel face, and it is seldom that more than one such rate is available; and I have accordingly, for the sake of simplicity, taken the effective width as proportional to the actual width of the wheel face, in the above considerations.

The influence of wheel diameter change, due to wear or actual change, on the correct work speeds and on the desirable width of wheel face, is little in external grinding, but becomes very important in the case of internal work. In Chapter VII, accordingly, the matter is dealt with more fully.

Effect of Change of Grade.—Another way of overcoming the difficulty is to use a softer grade wheel; by this the value of $v^2 \frac{d+D}{dD} . 2t$ is lowered, as a less normal material velocity is suitable. This is not the only effect, though, of a change of grade, as for the same h.p. supplied the value of vt—twice the material removed—increases; so that a change of grade is effective in a double way, and the variation of a single letter in the grade makes a considerable difference. Since vt is now increased the output is increased.

This is generally the effect of changing the wheel for one of a softer grade. The normal material velocity must be less, and also vt is increased, giving a double effect in lowering the correct surface speed. If by means of a more powerful machine we further increase vt, the surface speed is lowered further still. The depth of cut and the output are increased by both alterations; the particles of abrasive do not do quite so much work, and more are used. This has been the trend of development of wheels and machines for some years; the correct surface speeds have therefore been considerably lowered.

From the output point of view soft wheels of a coarse grit should be used; if the work is to be finished with the same wheel, the quality of surface desired controls these points.

If the wheel wastes away the work speed is to be lowered, and the depth of cut increased. Lowering the work speed alone is effective, but it sacrifices output, which can be maintained by lowering the speed more and simultaneously increasing the depth of cut. The converse is to be done if the wheel glazes. For finishing, the work speed should be increased if the amount of grinding warrants the change, as here the depth of cut is small, and the tendency to glaze increases. This increase is an advantage in finishing work, but a considerable increase of speed is permissible, as the depth of cut is so small. Work of small diameter usually necessitates a reduction in the rate of removal of material, even if it be well steadied. On large work, to secure cross-feeds of amounts which can be reliably maintained, softer or narrower wheels are to be used ; the same applies to internal grinding and also to flat surface grinding with a disc wheel, which is the same case with d made very large indeed.

My conclusion then is that no correct work speeds can be given when the material of the work and kind of wheel alone are specified, as the power supplied and diameter of the work affect the matter very considerably.

The attention now paid to particular work surface speeds and the advocacy of certain rates is due, I consider, to a misapprehension of the real nature of disc wheel grinding and to a desire to bring the practice into line with lathe work, to which it is only superficially akin. The adverse criticism of the high surface speeds used in the past is mistaken ; men were just as capable then as they are to-day, and it can be taken as certain that they adopted the speeds most suitable for the appliances available. The generally accepted views of what are suitable speeds to-day are given earlier in this chapter, but are based upon the prevailing idea that there is one suitable work surface speed.

With the understanding of the principles elucidated above, readers should not have much difficulty in arriving at the best speeds after knowledge of the particular machine in use has been acquired. Figs. 199 and 200 will be useful.

Though the normal material feed will have certain limits between which it must lie, it is best to work well away from them—alterations being made when an indication is shown that the speed is near one of the margins. Neither glazing nor wasting occur at once, and can usually be checked by attention; it takes more to break up a glazed wheel surface than to check it from glazing. Neither is it well to run too near the limit of the power supplied by the belt to the machine; it may hasten matters for a time, but invites trouble, e.g. if the machine slows so much as to check the water supply, the work may be spoilt.

Effect of Wheel Velocity.—The wheel velocity simply enters into everything—except vibration effects—as a ratio; if it is increased or decreased all velocities and outputs change in the same ratio. The fall of wheel velocity as its diameter decreases has not the same effect as speeding the machine differently. The power delivered to the wheel is the same, so long as the belt is on the same steps of the cone pulleys, and the output possibility is not altered, but feeds would need modifying to meet the lessening of V—and hence the normal material velocity—while vt was constant. To lessen V has the same effect as increasing v; it should therefore be done only to meet troubles due to synchronous vibration.

Effect of Traverse.—So far we have merely considered the work to rotate; the sideways traverse introduces the velocity v_3 of Fig. 16, as is shown in Fig. 23, where along Ox at the lower edge OA of the area of contact OABC the normal velocity is v_1; v_2 is very nearly equal to the surface velocity, and v_3 is the travel velocity; the latter produces very little effect, as its value is so small compared to V, which it alters relatively to $\sqrt{V^2 + v_3^2}$.

The grinding at the point here depends on v_1—the effect of v_2 and v_3 is to present surface of the work to the wheel. The extent of ground surface depends upon the v_2, and the volume of material removed on v_1, while v_3, the travel, merely serves as a mechanical device for continuing the action. If v_3 acted alone a hollow flat would be ground along the circular work; the shape of the edge of the wheel would wear to a shape which would give a feed corresponding to that described in Fig. 24 as relating to a face wheel, the feed to which takes place as below.

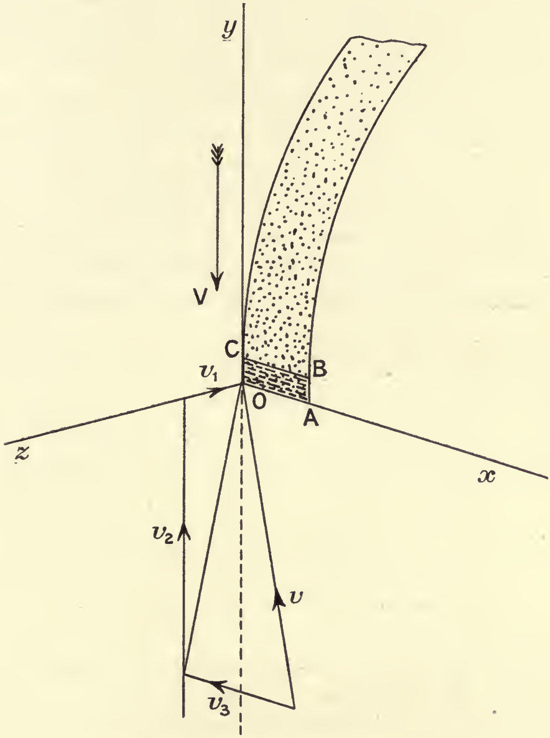


FIG. 23.—FEED IN CLYINDRICAL WORK

Cup Wheels.—In grinding with a cup wheel, the work is simply fed to the face of the wheel parallel to the face itself, either by a slide or rotatory motion. If the wheel axis is perpendicular to the slide, the work is flat, and the wheel face is frequently considered to be flat, as its defect from flatness does not produce marks similar to the visible helical marks produced on cylindrical work when the wheel wears slightly round. Actually the wheel face is slightly curved, as is shown in an exaggerated manner in Fig. 24, where the material is feeding with velocity v, parallel to the line AB touching the wheel face. The outside AC of the wheel face does most of the work, and wears to such a shape as that shown, while the inner face AD wears a little, as some grinding always takes place along EB. At any point then the velocity v can be resolved into v_2 along the wheel surface and v_1 normal to it, which latter controls the cutting. The whole curve AC is very shallow, as CF is the depth of the feed, which is only a few thousandths of an inch, so that v_1 is very small indeed. The width of the work which can be ground flat is AB, which is a little more than the inside diameter of the wheel. The area of contact which is the width of the work by AC, can be anything up to AB × AC, and is very considerable, and contains a very large number of cutting points, necessitating a very small chip for each of them, else an unpracticably large driving force would be required.

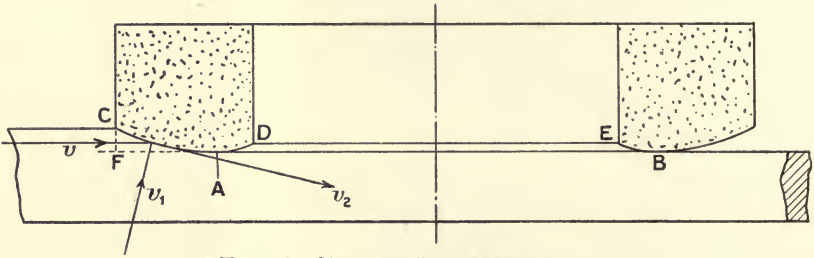


Fig. 24.—Feed in Cup Wheel Work

In disc wheel work the grazing incidence of the cutting points in the first part of the contact, BP in Fig. 22, tends to glaze the particles, and this is corrected by a suitably high normal velocity at the point C; in the plane ABC this grazing incidence does not occur, but the unavoidably small normal velocity over the whole surface makes the wheel likely to glaze. The wheels used therefore must be of soft (about H) grade, and they should be of coarse grit, so as to keep the number of cutting points small, so that the share of the driving power which each point gets is as large as possible.

For simplicity the section in Fig. 24 is supposed to be taken through the axis of the wheel spindle, and the velocity of any point on the section CAD of the wheel face is normal to the paper, as in the case sketched in Fig. 18. At other parallel sections the cutting particles have a velocity inclined to the paper surface, giving a lesser component perpendicular to that surface and a component parallel to v. The value of v_1 is thus affected indirectly, being the velocity of the material normal to the wheel face. It decreases continually (at any radius) as the point we are considering departs from the section taken; when it reaches the plane at right angles to that its value is zero. This variation of the action, however, makes no difference to our ultimate conclusions, which must be similar to those deduced for disc wheel grinding.

By using cup wheels with thin walls the number of cutting points is kept small, but a limit is soon reached in this direction, owing to risk in making and using the wheels. In any particular case the wheel may be bevelled on its cutting edge to reduce the number of points and prevent glazing, but so wasteful a measure should only be resorted to under necessity.

The wheel surface has less power per square inch of contact when the work is wide, so that it is least under control in that case, and the wheels need then to be softer and coarser than are suitable for narrower work.

The rate of removing material is btv, where b is the breadth of the work and t the depth of the cut: for example, on work 10 inches wide, with a depth of cut of 0·002 inch, a work velocity of 50 inches per minute would remove a cubic inch in that time. If AF were then $\frac{3}{4}$ inch (say for a wheel having walls 1 inch thick), the normal velocity would be $50 \times \frac{\cdot 002}{\cdot 75}$ or 0·133 inches per minute, or only $\frac{1}{90}$ of the rate in the example of circular work taken. If the grit were 24 with about 250 points per square inch, and the wheel speed 4000 feet per minute, there would be $250 \times 4000 \times 12$ chips taken in that time, so that their sectional area would be about $\frac{1}{12000000}$ square inch, which is much less than the section of the chips taken by the smaller grit wheel on circular work in the previous example. An examination under the microscope of such chips as are shown in Fig. 14 shows them to be of this order of size, but usually rather larger in section, which indicates that fewer cutting points are in action than has been estimated.

CHAPTER IV

THE WORK AND THE MACHINE

The Development of Machine Grinding.—The difficulties which had to be overcome in order to make the success of the modern grinding machine, come into two classes: those inherent in the process of grinding, and those involved in the necessary mechanism of the machines to attain the desired ends—accuracy, finish, and quantity. Some of the difficulties of the process and the ways of overcoming them have been described in the preceding chapters; others will be best illustrated in connection with the consideration of the development of the machines and of the details involved.

As the process of machine grinding was first applied to work of circular section, such as shafts and spindles, and as these still form the most important application, we shall consider the process principally from that point of view.

The earliest grinding machines consisted of lathes with a grinding head and spindle mounted on the slide rest and driven from overhead. This is a practice still followed occasionally, either by reason of its small initial cost as plant, or for the advantage of performing lathe and grinding operations at one setting of the work. Its advantages are most apparent in the case of small work, such as is done in watch lathes, when several opaertions can be performed on a piece of work without resetting by means of attachments (such as grinding spindles) to the lathe, or by transferring the work by interchangeable quills from one machine to another. The highly finished surface of watch lathe beds and parts enables them to be kept fairly free from grit, which sticks to and rapidly ruins the oily ways of an ordinary lathe. Hence dry grinding is not so detrimental to these small tools, and can be commercially used on them.

Dry Grinding.—In such arrangements and in some of the earlier machines which followed them the work is ground dry. This makes it necessary to use wheels with comparatively narrow faces, and to employ light cuts, otherwise untrue work results from the effects of the heat produced.

As the grinding head in lathe grinding is carried on the compound rest, it has several sliding surfaces between it and the bed, which is not a suitable arrangement to withstand the tendency of the spindle to vibrate; for this reason, and because the fine adjustments desirable in a grinding machine are not provided on lathes, it is not easy to obtain first-rate work quickly in this manner.

Furthermore, the dust from dry grinding consists partly of exceedingly fine particles which float in the air, and are carried to all parts of the machine and lodge on them, especially if these parts are oily. Bearings can be very effectively guarded from the grit, but sliding surfaces are far more difficult to protect. Examples of guarding are seen later, but the best practice is to extract the air and dust away with an exhaust fan (see Fig. 122), and thus protect not only the machine but the operator from the ill-effects of the grit-laden air. Where the amount of dry grinding is considerable, suitable provision for dust extraction must be made to meet the requirements of Factory legislation.

Protection against Dust.—With these points in view it is evident that the first call in a grinding machine is for the protection of its parts from the waste abrasive. For other reasons modern manufacturing grinders work with an abundant flow of water, or some other fluid, over the cutting points of the wheel; this at once simplifies the problem of protection very considerably, and in many machines practically perfect protection is obtained. In the case of small machines which work dry, such as small internal grinders and cutter grinders, the difficulties are considerable, but unless they are carefully considered and met in the design, the machine can preserve its accuracy for a short time only.

Wet Grinding.—Wet grinding meets the dust difficulty, but its employment is essentially due to the need of keeping the temperature nearly constant, and so permitting the work to be ground accurately far more rapidly than if done dry, and to its lubricating properties, which enable a fine finish to be obtained quickly. In dry grinding the temperature rises very considerably, and trouble is caused by the work changing its shape, and causing inaccuracies in the product. Actually the material can be removed more quickly by dry grinding, but as the accuracy and finish are lost the process is without its chief merits, and is uncommercial.

Grinding Solutions.—The solution used must be thin, and may be either plain water, water with soda dissolved in it, or a solution of soluble oil, or one of the preparations now on the market for this special purpose. For cast iron and for hardened steel work the soda solution is to be used, but the soluble oil or special preparations give the best finish on softer steel work. For the soda solution, sufficient soda must be used ($1\frac{1}{2}$ to 2 oz. of soda to the gallon of water) to leave an efflorescence when the solution evaporates; this solution is quite 'thin,' and the wheels cut freely when it is used. So with soluble oil just sufficient is to be used to prevent the parts or machine from rusting. The great disadvantage of plain water is that it rusts the machine and the work (the latter unless it is oiled immediately it is taken from the machine), and for that reason I consider it uncommercial and undesirable. However, there are advocates of its use, chiefly urging that the grit contained in a solution pumped over the work continuously, and the gradual rise of temperature, affect the work.

As the first requirement is dust protection, so the second is the provision of arrangements for dealing with an ample supply of liquid. The use of solutions involves the use of a pump, and the provision of a tank (which is frequently formed in the body of the machine); the apparatus used, nozzles, and systems of guarding the working parts from the solution, are described later on, as they vary somewhat in different machines.

Beyond the dust difficulty, the chief one encountered in dry grinding is that of the effects of the heat produced, and with the early hard wheels it was greater than with the modern free-cutting wheels. Further, the grinding machine was then used for work on hardened steel almost entirely, and a piece of hardened steel is practically never straight. In grinding it between the centres much more would be ground off one side than off the other, and when the work was finished it would be straight and true, but its temperature would be unequal, one side being much hotter than the other, and as the work cooled and the temperature became equalised, the contraction of the side previously the hotter would bow the work, making it concave on that side.

In the absence of cooling liquid, the solution of the difficulty is to take plenty of time over the work, or to let it have frequent intervals of rest, which is not an economical course. In order to distribute the cutting, and so the heat produced, as uniformly as possible over the work longitudinally, and thus to minimise these bad effects, the work was rotated rapidly (about 150 to 250 feet per minute, circumferential speed), and a narrow-faced wheel used. This practice has endured long after the difficulty it was intended to overcome had been removed by the free use of water, although for heavy cutting slower speeds are advantageous, as previously shown.

Distortion in Dry Grinding.—The amount of bowing is very conspicuous when the accuracy aimed at in ground work is considered. Suppose, for example, a piece of work $\frac{3}{4}$ inch in diameter by 9 inches long be ground, and that when it is finished the temperature varied uniformly across the piece, one side being 60° F. hotter than the other; then when cold this side will be shorter than the other side by $9 \times 60e$ inches, where e is the coefficient of expansion of the material (see Notes, page 438). The result would be that the piece would warp, as it cooled, into an arc of a circle, and the eccentricity at the centre would be $\frac{1}{8}\frac{l^2te}{d} = \frac{1}{8}\frac{9^2.60.e}{\frac{3}{4}}$

For steel, for which e is about 0·0000065, this is rather more than $\frac{1}{200}$ inch.

If l be the length, d the diameter of the piece, and t the difference of initial temperature of the two sides, the difference of contraction is lte, and this results in the part cooling to an arc of a circle of radius R, where $R = \frac{d}{te}$, since the inside circumference is then shorter than the outside circumference, in the ratio of the sides of the cooled work. An arc of this radius of length l is bowed an amount

$$\frac{(\frac{1}{2}l)^2}{2R} \text{ or } \frac{1}{8}\frac{l^2}{R} \text{ which is equal to } \frac{1}{8}\frac{l^2 . te}{d}$$

Work Expansion and Spring Tailstocks.—Besides this bowing, the work, if the temperature rose uniformly or irregularly in it, would expand longitudinally as a whole. To prevent this giving rise to large axial forces the tailstock barrel was arranged, to be held up to its work by a spring, and not clamped, so that the expansion would press the barrel back. This construction is now employed as the best, although water is used; for heavy work the tailstock barrel is usually clamped, and occasionally released and re-tightened.

When water was first introduced to keep the temperature of the work low or constant, it was applied in a small stream, and the above difficulties were reduced, although they were not entirely overcome, for the heat produced caused effects during the grinding as well as afterwards.

'Change of Axis.' Temperature Effects.—When a piece of work, particularly if of hardened steel, is placed in a grinding machine, it will not run true, and as it revolves and traverses past the wheel some parts of the skin will be ground before others. These parts will then be the hotter, so that if they occur along one side of the work that side will expand, and the work as a whole will be bowed, that side becoming convex. The result is that this side will be ground still more, and the other side will not be touched. As the temperature equalises itself by conduction through the work, the work tends to become straighter, and then the opposite side of the work, which so far has not been ground, becomes the farthest from the axis, and is consequently ground. The work then is not round. Later the two parts at right angles to the line joining the parts first ground will be ground. Thus the grinding proceeds irregularly and unsatisfactorily as to accuracy of work shape.

When any such irregularity in grinding occurs the attention should first be paid to the centres.

Advantage of 'Dead' Centres.—If the work head centre is live, as in a lathe (and as is used for convenience in some grinding work), it may run out of truth, thereby throwing a previously truly turned piece of work out of truth at that end. In grinding machines, to prevent such irregularities both centres are made dead wherever it is possible, and the work driven by means of a dead centre pulley or gear, revolving round one of them, as is illustrated in Figs. 69 and 117. In that case, if the centres and centre holes in the work are properly shaped, and free from dirt, any defect in the roundness of the work must be due to some change of the shape of the material as the grinding goes on.

So, when such an irregularity occurs, it is best first to examine the centres themselves, and then to clean the centre holes (see Fig. 87, page 214), and try whether the effect is then removed. If it is not, and the water supply is as full as is provided on the machine, the cut must be reduced and the work done more slowly. If the wheel is not cutting quite freely it should be changed for one of a softer grade, or if one is not available, the width of the face of the wheel reduced.

If it is the bowing or 'change of axis' of the work which causes this effect, it is most conspicuous at the centre of the length, and the position of the greatest irregularity is a guide as to whether the trouble is due to 'change of axis' or is connected with the centres.

This trouble is accentuated in thin hollow work, as then the heat generated has to be conducted round the circumference through the thin metal instead of through the whole section when it is solid, thus it takes longer. In grinding thin work it is well to go slowly, and not rough out with a heavy cut.

The energy brought to the grinding point (about 99 per cent. coming through the wheel spindle) is turned into heat as the metal is removed; this heat immediately raises the temperature at the point to a very high degree, so that the ground-off particles burn as sparks and the spot on the work becomes very hot. The chief function of the water is to cool this spot promptly and carry away the heat before it has time to spread by conduction into the body of the material, and so distort it ; hence the fluid should be applied as directly to the grinding spot as is possible. This presents no difficulty in external, but is not so easy on internal, work.

When the grinding is dry the ground-off metal is sometimes entirely burnt away, only abrasive dust being left ; even under a heavy flow of water some of the small chips are burnt as sparks or fused into spherical globules.

Effect of Internal Strains.—The abundant water supply used on modern machines and the free-cutting wheels have almost eliminated this change of shape due to temperature, but a similar effect, though it is less in amount, is due to another cause—the existence of internal stresses in the material of the work. Such stresses are produced and left in the material by any mechanical treatment severe enough to produce permanent set. Upon the results of this cause no water supply or grade of wheel can have any effect, as they are due to the removal of material which carried stress, and so kept the work in its original shape.

Neither the temperature effect nor the relieved stress effect occur until turning marks are ground out, and both are most conspicuous at the centre of the length, so that they are difficult to distinguish, and also the latter may induce the former. The stress effect is to be suspected if the work is from the unturned bar, particularly if it is bright drawn.

Distribution of Internal Stress and its Magnitude.—To illustrate the manner in which relieved internal stress produces its effect, let us consider a rectangular bar which happens to be bent (say into the arc of a circle), and is then free from internal stresses and strains. Now straighten this bar by bending it very slightly beyond the straight line (the opposite way to which it was initially bent), and then releasing it, so that its elasticity restores it to the straight line, and it remains there. This bar has then internal stresses in it. What they are and their distribution depends upon how much bent the bar was at first, and its particular cross-section. If the bar was originally bent to any degree exceeding a small amount, the internal stress left on the outside is compressive stress on the side where the bar was previously concave. Fig. 25 shows a typical case, and gives the stresses in a rectangular bar. It is drawn to scale for a square bar 3 inches by 3 inches section and 2 feet long, originally bent so as to be $\frac{3}{16}$ inch out of straight (i.e. the distance between the hollow of the concave side and a straight-edge placed across the end is $\frac{3}{16}$ inch). The material of the bar has a yield-point at 40,000 lb.

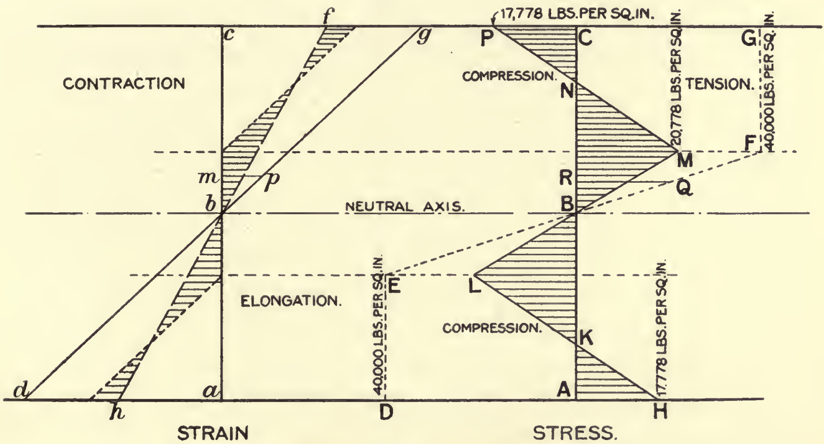


FIG. 25.—STRESS IN A STRAIGHTENED BAR

per square inch. The figures are supposed drawn on a line of section of the bar—that is, ABC is a line across the bar, and the length QR represents the stress at that point; *abc* is the same line, and *pm* the strain, extension or contraction. When the bar is bent for straightening, just before it is released, the stresses are given by the broken line DEBFG, the corresponding strain line being *dbg*; that is, the stress is zero at the centre of gravity of the section—here the centre—and increases both ways till it reaches 40,000 lb. per square inch at one third the distance out, and then remains the same to the outside. After release the stress left in the bar takes the figure HKLBMNP, and the strain the line *hbf*; that is, the stress is zero at the centre, runs up to 20,778 lb. per square inch at $\frac{1}{2}$ inch from the centre, then diminishes to zero at a little over 1 inch from the centre, and then is of the opposite nature and increases to 17,778 lb. per square inch at the outside. In mild steel the state of stress left is symmetrical. The more the bar was bent initially the greater these stresses are at the skin; they do not in a bar of rectangular or circular section approach the yield-point stress of the material. Calculation shows that in a rectangular bar the maximum amount is half the yield-point stress, but in a bar of cruciform section the stress can reach the yield-point.

Now suppose that we mill a piece off the side of this bar in which there is a compressive stress. The bar will shorten as a whole—but this will be a very small matter and will not concern us—and will bend up, this side becoming concave. If on machining the machined side becomes convex, it will show that it had internal tension in it before machining. The whole distribution of stress alters on machining; for example, the zero stresses are not afterwards at the same points of the material as before. The amount such a piece of work may buckle depends on its length and thinness, and upon the yield-point of the material; as an example, some cold rolled strips 32 inches long by 0·2 inch thick, machined on one side to $\frac{3}{32}$ inch, buckled, when released from the miller, into an arc $1\frac{7}{8}$ inches high.

Usually the amount of distortion can only be small, but it is very perceptible in grinding. If a round piece of work contained such stresses as above described, and the side with the compressive stress touched the wheel first, the bowing would make it tend to shrink away from the wheel; when the side with the tensional stress was ground it would tend towards the wheel, so that effects in grinding would be somewhat similar to those due to heat effects.

Type of Stress frequent in bright Drawn Steel.—If, however, the whole of the outside circumference initially had tensile internal stresses, and the interior compressive, the longitudinal results balancing, immediately any part of the bar was ground it would bend towards the wheel and be ground more, and when the bar was so reduced that another part of the circumference was ground, the bending would take place in that direction. This is the state of stress which occurs in bright drawn steel when drawn with a heavy reduction; and renders grinding difficult. The initial states of stress in bright drawn steel have been found experimentally to run up to 50,000 lb. per square inch tensile and 54,000 lb. compressive, and such amounts render the distortion as grinding proceeds very conspicuous.

I have found that reeled bars and hot worked bars grind without any trouble from this source. The reeled bars have internal stresses ; it is the screw symmetry of the distribution of the stress caused by the rotation in reeling which causes this freedom from trouble.

Both temperature and relieved stress effects are due to the elongation (or contraction) of the length of parts of the material. Under a rise of temperature of 100° F. a steel bar expands 0·00065 of its length, and about the same elongation is produced by a stress of 20,000 lb. per square inch, which is less than half the yield-point stress of regular mild steel. The distortion effects due to the relief of stress are, however, much the smaller, as they are due to the removal of a small portion only of the material.

Remedies.—The greater part of the change of shape takes place the moment the material is removed, and is permanent, but there is a small after-effect which takes place very slowly. The easiest way to meet this difficulty is to rough grind first and allow an interval before finish grinding, but where very precise work is required (e.g. machine tool spindles) the most satisfactory method is to anneal them slightly. Very little is necessary (boiling for a short time in water I consider is sufficient); so that the hardness will not be affected. It has been shown that the crystalline structure of overstrained mild steel reforms itself when annealed even in this slight manner, but further investigation into the subject, especially as regards hardened steel, is desirable.

Although a piece of work may show irregularities in the grinding, it does not always mean that there is any real trouble ;

errors are shown up so conspicuously in a good grinding machine that the amount involved is apt to be over-estimated. If the work grinds regularly it may be taken to be right; if there are slight irregularities it is a question of the particular requirements whether they are sufficient to be of importance.

Necessity for True Wheels.—In the early machines the width of the wheel used was small, chiefly for reasons of the heat effects, but with the provision of good water supplies and the improvements in wheels, the width employed has been much increased, with the advantages of bringing a larger number of cutting points into action. To bring the width of the wheel effectively into action it must be trued so that where it touches the work it is parallel to the surface it is producing, otherwise the traverse of the work as it rotates will produce a screw thread mark down the work, and part of the wheel may not come into action at all. As the depth of cut is only a few thousandths of an inch at most, and in finishing is very small indeed, the diamond tool for turning the wheel true should be mechanically guided, so as to have the same movement relatively to the wheel as the work has; this is most perfectly attained by simply attaching the diamond tool to the work table, whether the machine be for external, internal, or surface work. It should cut the wheel as near as possible to the place where the wheel cuts the work, otherwise —if the wheel spindle be not parallel to the line of travel of the work—it will not true it quite as correctly as it ought to be done (see pages 150–2).

Rate of Travel.—After the wheel has been turned true in this manner, when it is brought up to the work (supposed rough ground), it will cut right across its face. In order to keep it cutting right across its face as the work rotates and travels across the wheel, the travel must be such that one revolution of the work brings an entirely new portion of the work to the wheel face. The traverse movement must not be such as to leave any portion of the work unground, and in order to have a margin the travel per revolution should be decidedly less than the width of the wheel, say $\frac{7}{8}$ of it at most.

If the travel per revolution is small compared to the width of the wheel face, as is shown in Fig. 26 at A, the leading edge of the wheel does the principal work. The spiral line is drawn to

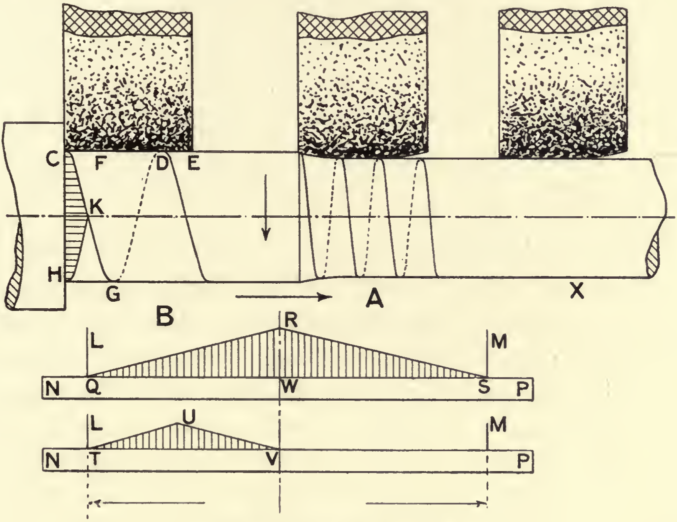


FIG. 26.—RATES OF TRAVERSE

indicate the track of this leading edge, but this track will not be marked on the work. The work is supposed to be travelling to the right (or the wheel to the left), and the left-hand portion of the wheel is doing the cutting, and the remainder, at most, just grazing the work. As a result, the left side wears; on the reverse travel the right side of the wheel face wears, with the result that the wheel face wears into a curve as shown. This curve is very shallow; the amount of curvature could not exceed the depth of the cut, say $\frac{1}{1000}$, but a fraction of this amount (0·00005 inch) will produce conspicuous travel marks

FIG. 27.—SPIRAL MARKING

such as are shown on a ground bar in Fig. 27, where the optical effect is striking.

Therefore, in order to keep the wheel as flat as possible, the traverse should exceed half the width of the wheel, as is indicated at B in the figure, where the spiral line indicating the (unmarked) track of the leading edge shows a traverse movement CD of about $\frac{4}{5}$ of the wheel face. The part CD of the wheel is now doing the work, and wearing; on the reverse traverse the corresponding part EF wears, and the wheel tends to keep flat. The travel then should be between $\frac{5}{8}$ and $\frac{7}{8}$ of the wheel face.

For the finishing travel or two it is best to travel less, by increasing the rate of rotation of the work without altering the travel speed ; the wear under the finishing travel is infinitesimal, and the effect of any slight rounding is minimised.

This applies also to internal grinding and to flat grinding when the curved edge of the wheel is used (see machines in Figs. 121 and 124), but in the cases in which the flat face of a cup or cylinder wheel is used for surface grinding this arrangement is impossible, and the cutting face of the wall of the wheel wears to a curve. This curve is so slight, only one to two thousandths of an inch in depth, that the wheel face is usually considered to be flat, but trial shows that it is curved to this extent.

Double Copying Principle.—In a lathe, where the traverse of the tool per rotation of the work is small, the truth of the work may be regarded as a direct copy of the truth of the lathe bed, but in grinding, where large traverses per rotation of the work are used, there is a double copying principle involved. The truth of the ways is first copied on to the wheel face, and then series of the wheel face copied on to the work, using the truth of the ways for the formation of the series, as in broad-cutting with single tools. The exactness demanded makes it necessary that the wheel face truth is derived directly from the machine ways.

Pause, or Tarry.—In Fig. 26 the wheel at B is shown up against a shoulder of the work. If, with this large traverse, the reverse took place promptly on the shoulder being reached, a certain portion of the work, CGH, and the corresponding portion on the other side of the work, would remain untouched by the wheel. It is advisable then for there to be a pause or tarry at the reverse of the motion of the table. If this pause lasted for half a revolution of the work, there would be only one quarter as much surface left unground; this part is shown shaded at CKH.

These unground portions are shown developed in the lower part of the figure: LM is the work and NP the shoulder; the shaded part QRS shows the unground part for no tarry, and TUV for a tarry of half a revolution. RW is half the traverse per revolution of the work.

To leave no portion of the work untouched the tarry should continue while the work makes a complete revolution, but it is not advisable that it should last so long, as there being little material opposed to the wheel towards the end it then is apt to cut a little deeper.

If the machine is not fitted with a tarry mechanism—most are not—it is well to throw the traverse motion out at the shoulder now and then to avoid the accumulating effect of the unground parts.

Where there is not a shoulder no tarry need be used; the edge of wheel should be set to run beyond the end of the work by about half the width of the wheel, so as to produce the same effect.

In internal grinding there should be no tarry, and the wheel should not be run so far out of the work, as there is a tendency for this to produce 'bell mouthing' in the hole, owing to the spring in the spindle and supporting sleeve.

Grinding Parallel close to Shoulder.—Sometimes it is very essential that the diameter of the work should be uniform right up to a shoulder, and free from the slight effect of rounding of the wheel face. This can be secured by throwing out the cross-feed at the other end of the work and feeding at the shoulder end only. This throws the wear on the other (left hand, as shown) edge of the wheel as at X, and keeps the side towards the shoulder flat. The feed may be heavier than is normal at the shoulder end, and little or nothing at the other.

Vibration.—Besides the general truth of the work produced, there is a truth of surface which is necessary—that is, the surface of the ground work must be free from blemishes, particularly from series of regular marks known as chatter. These are due to vibration of the parts of the machine and of the work. The actual modes of preventing these defects are described later, but as vibration is a phenomenon much more frequent, and of greater importance in grinding machines than in other machine tools, its nature is here of particular interest.

The characteristic of a vibratory motion is that it repeats itself after a certain interval of time (known as the period), and the motion may be either the same in all particulars, or its magnitude (termed the amplitude) may gradually increase or diminish. The period or time taken to go completely through the motion once may be many years, as in the precession of the earth, the second or two of the swing of a clock's pendulum, or the inconceivably small time of a such a vibration as constitutes light. In grinding, the important period is that of the rotation of the wheel, varying from $\frac{1}{10}$ to $\frac{1}{300}$ of a second; in this small time there must take place all the changes of force and resulting small movements, due to any want of balance in the wheel. The movements must be small, but the forces involved may be large, and that they almost certainly will be large when any conspicuous vibration takes place can be ascertained by calculating the values of the centrifugal forces $\left(4\pi^2n^2r\frac{m}{g} \text{ or } \frac{v^2}{r}\cdot\frac{m}{g}\right)$ for a few cases.

Free Vibrations.—If we support a weight by a spring, and, after it has found its position of rest, give it a vertical blow, it will oscillate up and down through a greater or less space (the amplitude), according to the strength of the spring and the amount of the blow. When the weight is at its farthest distance, either up or down, from its position of rest, the spring is extended or compressed (from the configuration of rest), and has stored in it a certain amount of work or energy, and just for the instant the weight is at relative rest and has no kinetic energy. As the weight approaches its central position it gains velocity and kinetic energy, while the spring is less extended or less compressed, and the energy stored in it becomes less, until at the central position it becomes zero. Its energy has now been transferred to the weight as kinetic energy. If the strength of the spring is slight enough in comparison to the weight, the motion will take place slowly enough to be easily observed, as the period may be made some seconds. If the spring were stiff and the weight small, the rate of vibration would be rapid. Such an interchange of the form of the energy is typical of vibratory motions such as we have to consider. The amplitude depends on the amount of energy involved, but the period in which the whole motion takes place does not depend on the amplitude (unless it increases to a large amount), or on the blow originally given to the weight. After a time, chiefly owing to the resistance of the air, the extent of the vibration will be found to have lessened, and finally the weight will come to rest. Such damping resistances are proportionate to the velocity of the weight at any time.

The force with which the spring acts in accelerating or retarding the motion of the weight is (by Hooke's law) proportional to the distance the weight has moved from its position of rest.

If the weight consisted of a heavy central part of a steel bar, and the springs of slender ends to the bar, the same kind of vibration would take place if the bar were placed between the centres of a grinding machine and struck a blow. The amplitude of the vibration would now be small, and the period probably too small for the motion to be satisfactorily observed; the elastic restoring force would, however, be again proportional to the displacement of the heavy part from its position of rest, and the period would not depend upon the amount of the blow. The movement would be damped out quickly.

Similar vibrations take place in uniform bars and in masses of metal, which vibrate elastically and change shape (very slightly) during the vibration. The restoring forces, which depend on this distortion of shape, cannot be expressed so simply as they can in the examples above taken, and in considering the character of a vibratory motion we shall treat of such examples for the sake of simplicity.

Vibrations of a weight or a bar struck and left to itself are termed 'free' vibrations, in contrast to other vibrations, which may be caused by alternating forces continually acting on the parts, and which are termed 'forced' vibrations. In order to 'force' a body to oscillate, the disturbing forces must themselves be regularly repeated and periodic; they may, however, be gradually applied or abrupt. Considering the bar previously mentioned, if it were set to rotate, and a wheel somewhat out of truth were brought up to grind it, such disturbances would be caused. In reckoning these the average cut can be taken as a uniform smooth effect, while the forces above and below the average would be an alternating disturbing force. It would be periodic, the period being that of a revolution of the wheel, but would vary irregularly, and not according to a simple rule, like the spring in our previous case did.

However such a periodic disturbing force or disturbance varies, smoothly or abruptly, it can be built up (as was proved by Fourier) by the addition or superposition of a number of constituent disturbances, each varying with the time according to a simple sine or cosine law—that is, in the manner in which the position of the vibrating weight above-mentioned would change in the absence of resistance. The period of each of these constituents is a simple fraction—the half, third, fifth, &c.—of the period of the total disturbing force, here the period of the rotation of the wheel. Thus each constituent can be expressed in the form $P_n \cos nkt$, where t is the time reckoned from when a particular point of the wheel touches the work, $\frac{2\pi}{k}$ is the period of revolution of the wheel, P_n is the greatest value of this constituent disturbing force corresponding to the number n, and n is successively 1, 2, 3, 4, &c. Reckoning the time t in seconds (that is, in fractions of a second), if the wheel be making 1400 r.p.m. (suitable for a 14-inch wheel), the wheel period would be $\frac{6}{140}$ second, and k would be 146·5. The value of P_n cannot well be found in this particular case, but from our point of view that is not a matter of importance. These constituents are usually termed harmonics, from their importance in sound vibrations.

The effect of such a disturbance on a part which can vibrate, is best considered by writing down the fact that the acceleration is produced by the forces acting on the body, as an equation. This takes the form—

$$m\frac{d^2x}{dt^2} + a\frac{dx}{dt} + bx = \Sigma\, \mathrm{P}_n \cos nkt \quad . \quad . \quad (1)$$

where x is the amount the part we are considering has moved from its undisturbed position in the time t. The first term expresses the acceleration forces, the second the damping resistances to the motion; the third term is the force which tends to restore the body to its undisturbed position, and the right side of the equation represents the disturbing forces, the symbol Σ being prefixed to indicate that we must add all the simple constituents together—or take as many of them as matter for our purpose. The second term is the velocity multiplied by the damping constant a, and the third the movement x multiplied by the force which, acting alone on the body, would move it through unit distance (usually 1 inch), or, if the body would only move a small distance, a hundred times the force required to move it one hundredth of the unit ($\frac{1}{100}$ inch).

The advantage of expressing the relation of the acceleration and forces algebraically lies in the fact that if the equation be solved, we then know just what the resulting motion is, and can ascertain what happens, and can trace the causes of the results. Without such aid vibration effects are difficult to consider accurately. The result of solving the equation gives us—

$$x = \mathrm{A}\epsilon^{-\frac{at}{2m}} \sin\left(\sqrt{\frac{b}{m} - \frac{a^2}{4m^2}}\,.\,t + a\right) +$$

$$\Sigma\frac{\mathrm{P}_n}{\sqrt{(b - mn^2k^2)^2 + a^2n^2k^2}}\,.\,\cos\left(nkt - \tan^{-1}\frac{ank}{b - mn^2k^2}\right) \quad (2)$$

The movement therefore consists of two portions, which are added together to give the value of x at any time; each of these portions is a vibratory motion, as each involves a sine or cosine of the time, and therefore repeats itself at intervals.

The Damping out of Free Vibrations.—The first term $A\epsilon^{-\frac{at}{2m}}\sin\left(\sqrt{\frac{b}{m}-\frac{a^2}{4m^2}}.\ t+\alpha\right)$ is an oscillating motion which has an amplitude $A\epsilon^{-\frac{at}{2m}}$; this is not constant, but gradually diminishes, for as t gets larger $\epsilon^{-\frac{at}{2m}}$ gets smaller, unless a is exactly equal to zero, when it remains equal to unity. As there is always some damping resistance, a cannot be zero, so that after a time the vibration represented by this first term dies out, however large A may be. This is the chief effect of the damping; it damps out the vibration represented by the first term of the solution of the equation. It also slows the rate of vibration somewhat, and makes the vibration lag behind the force. Bearing this in mind, we will first consider a to be very small, and omit it, and the solution then takes the simpler form—

$$x = A\sin\left(\sqrt{\frac{b}{m}}.t+\alpha\right)+\Sigma\ \frac{P_n}{b-mn^2k^2}.\cos nkt \quad . \quad (3)$$

Suppose that the disturbing forces P did not act, then the solution would represent the motion without them—that is to say, the 'free' vibration. Hence the free vibration has an amplitude A, and will repeat itself when $\sqrt{\frac{b}{m}}.t+\alpha$ has increased by four right angles, or after a time $T_1 = 2\pi\sqrt{\frac{m}{b}}$. This is the period of the free vibration, and depends only on m and b—in our first example—the weight (m), and the strength of the spring (b). The factor A depends on the amount of the blow which started the motion, and α on just when the blow was struck.

Our damping factor $\epsilon^{-\frac{at}{2m}}$ tells us that the free vibration dies out, however large A is—that is, however large the original free motion may be, and a trial shows us that with the parts of a machine these vibrations die out very rapidly. After this free vibration has died out we are left with only the second term on the right in equation (3), which represents the effect of the periodic disturbance—in the case we have mentioned, an untrue grinding wheel.

Forced Vibrations.—In considering the effect of any constituent P_n of the disturbing force, it is to be first noticed that the period of the vibration which it enforces is $\frac{2\pi}{nk}$ — that is, its own period, and not the natural period of free vibration of the part affected. Secondly, the amplitude (or magnitude) of the forced vibration due to the various constituents P_n are not directly proportional to the values of P_n, but to those values divided by $\frac{b}{m}-n^2k^2$. Hence, although in practical cases the values of P_n get smaller, as n is made successively 1, 2, 3, 4, &c., their effect in enforcing vibration will not necessarily do so, and will not do so if $\frac{1}{k}\sqrt{\frac{b}{m}}$ is nearly a whole number; for in that case some value of $\frac{b}{m}-n^2k^2$ will be small, and the resulting amplitude large. Now $2\pi\sqrt{\frac{m}{b}}$ and $\frac{2\pi}{nk}$ are the periods of the free vibration of the part, and of the constituent P_n of the disturbing force, and if they are nearly equal the forced vibration produced will be large.

There are then two causes of considerable vibration, a very large periodic disturbing force, and a near approximation of the period of a constituent of a periodic disturbing force to that of a free vibration of a part. The first is easily detected and removed, but the latter is more difficult to deal with.

It might be thought that if perchance $n^2k^2=\frac{b}{m}$ that the vibration caused would at once be exceedingly great, but this is not the case. From the equation point of view the solution fails, and has to be taken to a closer value, with the result that the expression for the forced vibration becomes—

$$x=\frac{P_n}{2nkm}\,t\,.\sin nkt$$

Again the period is the same, but the amplitude $\frac{P_n}{2nkm}t$ starts by being very small, and increases gradually but continuously as t increases. The chatter and vibration caused eventually becomes so great that the cause has to be remedied before work can be proceeded with.

With sound vibrations the effect is known as 'resonance,' and this term is now applied to such phenomena generally, whether of sound, electricity, or mechanics.

The importance of these constituents of quicker period than that of the actual total disturbance is now clear. These quicker periods are the $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, &c., of the total period, and practically these are more likely to coincide nearly with a free period than is the full period of the disturbance. The free period may be either one of the machine or of the work: if the work be stiff it will be a period of the machine, if thin it may be either.

When vibration and chatter occur, the source of vibration—a flapping belt or untrue wheel—should first be ascertained, and the cause removed. This is equivalent to making the term P zero in the equation. Then some period in the machine or work should be altered, so as to change this nearness of the period of the forced and free vibrations. As the period of the effective constituent of the disturbance is frequently $\frac{1}{3}$ or $\frac{1}{4}$ of the full period, only a moderate alteration is necessary or desirable.

Supposing that the chatter marks on a bar are due to vibration enforced by irregularities in the wheel, their pitch indicates which of the constituents is the effective one. For, supposing that the work surface speed be 40 feet per minute, and that the wheel speed is 1400 r.p.m., the wheel period is $\frac{1}{1400}$ min. ($\frac{6}{140}$ sec.), and if the chatter marks were due to the first term they would be spaced by the distance which the work surface would move through in that time, or $\frac{40 \times 12}{1400}$ inch, or about $\frac{3}{8}$ inch. If they were due to the second term containing $\cos 2\,kt$, they would be spaced half this distance apart; if to the third term, one-third of the amount, &c.

Transverse vibrations of the work itself are checked by steadies; except on slender work the period is very rapid, and is given, in seconds, by the expression $\frac{l^2}{80000d}$, where l is the length and d the diameter in inches of a steel bar supported by the centres only. As an example, the period of a bar 4 feet long by 1 inch diameter placed between the centres is $\frac{48 \times 48}{80000}$ $(= 0{\cdot}029)$ of a second, or rather over 2000 vibrations per minute. A mass, such as a piston, at one end of a bar, will reduce the rate of vibrations to about one half.

Summing up, then, we see that to produce continuous vibration there must be some cause of a periodic nature, which enforces the vibrations by reason of a relation of its period with that of some natural period in the machine or work. When the action starts, free and forced vibrations of nearly equal period are produced; the free die out, but as they do so the movement then arranges itself, so that the accelerations and forces satisfy equation (1), and the forced vibration assumes a permanent condition. When such happens the periodic effect is to be removed if possible, and also some periods altered to prevent recurrence of the action.

Balancing.—One of the chief causes of vibration is want of balance in the wheel, its spindle, or other parts of the grinder, including even the countershafting, and the problem of balancing is further of interest in much of the high-speed machinery the parts of which are produced by grinding.

A machine is said to be 'balanced' when its parts are so made and arranged that it is free from the dynamic effects of the movements of its parts, but the term is applied in two ways. In machinery, such as steam engines, containing parts moving in straight lines or oscillating through angles, many of the undesirable dynamic effects may be eliminated by a careful arrangement and proportioning of the parts in the original design. In this procedure the materials are supposed uniform and the construction perfect; the 'balancing' is here done before the machine is made. When simpler spindles are run at very high speeds, however, the effects are so great that even defects of density in the materials are of importance, and a spindle may be out of balance although in design it is symmetrical about its axis. This is the case which is of interest in grinding, and by ' balancing ' is then meant the addition of small weights (or the making of other adjustments) so that the spindle will run without vibration.

Suppose that a spindle is itself perfect in every way, but that when a thin wheel is mounted thereon it runs out of balance. The error must be due to one part of the wheel being heavier than another, and as an illustration suppose that the wheel contained a part having extra mass m situate at a radius r; the ' centrifugal ' force at a speed of n revolutions would be $4\pi^2n^2rm$, which would be balanced by that of a mass m, placed at a radius r, at all speeds, provided only that m_1 were selected so that $m_1r_1 = mr$. It does not matter what the value of r_1 is, so that the balancing may be done by replacing a little of the wheel material near the hole by some lead. This is the method adopted by manufacturers who balance those of their wheels which happen to have such error. In course of wear the irregular part of the wheel may be used up, so that it is again out of balance and requires correction in the same manner. Plenty of mass in the wheel heads of grinders is very desirable, as it reduces the effects of small unavoidable errors of wheel balance.

The simplest method of testing for such want of balance and of correcting it is to mount the wheel on a parallel spindle known to be in balance, and to place it to roll on parallel ways. If it rolls so that one part of the wheel always tends to rest at the bottom, that part is the heavier, and correction is made by adding weight to the other side until the spindle comes to rest indifferently in any position. The wheel is then in ' static ' balance, and when mounted on a true spindle will run steadily. As the forces due to high-speed rotation are greater than those due to gravity in the ratio $4\pi^2n^2r$ to g (where $n =$ revs. per sec., $r =$ radius at which mass is in feet, and $g =$ 32·2, so that the ratio for a mass at a radius of 2 inches running at 1000 r.p.m. is 57), static balancing must be very carefully done to be dynamically efficient, and hence wheels are often balanced dynamically.

If, however, the part which is out of balance is not thin like a disc wheel, static balance may fail dynamically in another manner, and it may even make the vibration worse. This is illustrated in Fig. 28, where a perfect spindle ABCD is supposed to be supported in a horizontal position in bearings at A and D. Suppose that a mass m be fastened to the spindle at C: the spindle will tend to turn round and set itself with C as low as possible. It could be balanced statically by placing a mass equal to m anywhere along the line at the bottom,

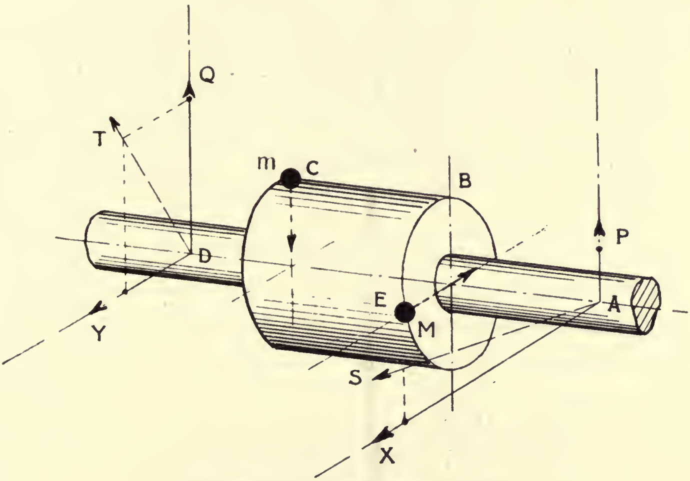


FIG. 28.—BALANCE OF SPINDLES

opposite either to B, to C, or to any other point in BC. If the spindle with the mass m at C where the radius is r were rotated at n revolutions per second, a force $4\pi^2 n^2 r \frac{m}{g}$, indicated by the broken line with an arrow head, would be exerted by the fastening to prevent m flying off; this force would be transmitted by the shaft and produce reactions P and Q at the bearings A and D respectively—P and Q bearing the inverse ratios of the distances of C from these forces. Now if the spindle were balanced statically by a mass m placed opposite to B, on rotation, the forces produced at the bearings, although (as the figure is drawn) opposed to P and Q, will not be equal to them in magnitude owing to the different distances of C and B from the lines of P and Q ; thus the spindle will not be in balance nor run steadily. It will only be in balance if the position selected for the balancing mass be exactly opposite to C, and in an actual spindle the position of this mass variation (here *m* at C), which renders the spindle out of balance, is unknown.

Now suppose that in addition to the mass *m* at C the spindle carried a mass M at E on a plane AED different from ACD. In rotation there will be additional forces, indicated by X and Y, at the bearings. Combined with P and Q these give S and T as the resultant reactions, the planes APSX and DQTY being perpendicular to the axis AD ; so that S and T will be the rotating reactions at the bearings. It will be noticed that these forces have a lead and lag on the positions of the masses *m* and M. No single mass placed anywhere on the spindle can balance these non-parallel forces, and two masses must be used. Although an actual spindle will not be out of balance in so simple a manner as this, the same conclusions are true; two masses are necessary which may be placed at predetermined distances along the length of the spindle, but their angular position must be correct.

The problem of actually ascertaining this correct position and the amount of the balancing masses is no easy one. In cases of built-up masses intended to rotate at a high speed, such as the rotors of steam turbines and dynamos, want of dynamic balance is to be expected. Flanges are frequently provided for the reception of the necessary masses, but both the amount and the angular position of these masses must be determined from experiments on the shaft rotating in its bearings. These are suspended or mounted so as to be capable of horizontal side movement, controlled (usually) by springs, and observations are taken on the amount of movement of the bearings and the corresponding angular position of the shaft, from which the position for the correcting masses can be deduced.

As the shaft rotates, the want of balance sets up vibrations, which may be of two types, corresponding to the side movement of the shaft as a whole (and will not exist if the shaft be in accurate static balance) and to its angular movement. At two corresponding critical speeds there will be greatly increased vibration, owing to the period of natural vibration of the shaft as it runs, approximating to the period of the force causing vibration—that is to the period of revolution. In experimenting, the observations are naturally taken at one of these critical speeds, as the phenomena are then the most conspicuous. To ascertain the angular positions at which the correcting masses should be applied, a scriber is adjusted just to touch the shaft (usually at or near a bearing), leaving a short mark on surface previously coated with raddle. The shaft is then rotated in the opposite direction at the same speed, and another mark scribed. These marks will be found to be at different portions of the circumference, and the angular position at which the correction is to be made is taken to be half-way between them.

The preceding section indicates that considerable errors may easily arise here, as the angle between the scribed mark and the position of the correction to be made, varies rapidly with changes of velocity near the critical value. In equation (2), page 101, the angle between the displacement x and the alternating force is found to be $\tan^{-1}\dfrac{ank}{b - mn^2k^2}$. If a were zero, no angular difference of position of the scribed marks would occur ; this damping coefficient—due to friction at the bearings and air resistance—always exists, so that the numerator of the fraction always has some (small) value, and hence there is always angular lag. The denominator depends upon the difference of the squares of the periods in question, and this is very small in the neighbourhood of the critical speeds, so that at them, although the damping is small, the angle $\tan^{-1}\dfrac{ank}{b - mn^2k^2}$ approaches a right angle, and a little difference in the rate of revolution in the two directions will make much difference to the position midway between the two marks.

These various difficulties lead to a method of trial and error in the balancing of high speed rotating parts, the shaft being tried and balanced, and then tried again until a sufficiently accurate running balance is attained.

The Universal Grinder—Description.—From the lathe fitted with a grinding head on the slide rest to modern manufacturing grinders has been a long development, first resulting in grinding machines, termed Universal, and capable of dealing with very varied work, for the tool room, and later in machines for more specialised purposes. As the Universal Machine was developed first, and presents many typical features, it will be well to consider it first, taking as illustrative of modern practice Messrs. Brown & Sharpe's machine, No. 1 size, which is illustrated in Figs. 29 and 30. This machine is capable of grinding external work, parallel and of any angle of taper, internal work, flat work held on a face-plate or in a chuck, and of sharpening certain classes of cutters. In Fig. 33 outlines of the machine and countershafting are given, showing the arrangements for driving the various parts.

The development, it is seen, has produced a machine with practically no resemblance to a lathe, carrying a grinding head; this is accounted for by the very different forces involved, and the special need in grinding for accuracy, freedom from vibration, dust protection, for dealing with a large water supply, and general convenience.

The illustrations show the machine arranged for external grinding. The work is carried between the centres A, A′ of the workhead B and the tailstock C, and is rotated by means of the dead centre pulley E, which is driven by the belt *u*′. The tailstock C carries the diamond tool by means of the clamp D, which holds it firmly while the wheel is being trued.

The tailstock barrel is held up to the work by a spring having an adjustable tension, and can be withdrawn from the work, to free it for removal, by the lever C′. For the purposes of face-plate and chuck work, when the pulley F is used for driving, the headstock spindle is rotated in bearings (see Fig. 117, page 279) but for work between centres the spindle is locked by the plunger G, and the pulley E revolves upon the fixed spindle. The accuracy of the roundness of the work thus depends upon that of the centres themselves only. These can easily be ground

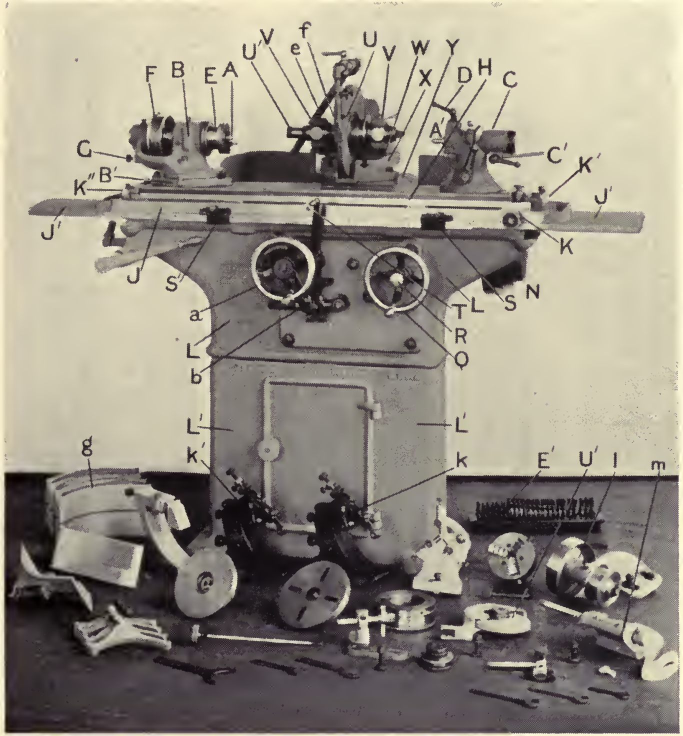


Fig. 29.—Brown & Sharpe No. 1 Universal Grinder

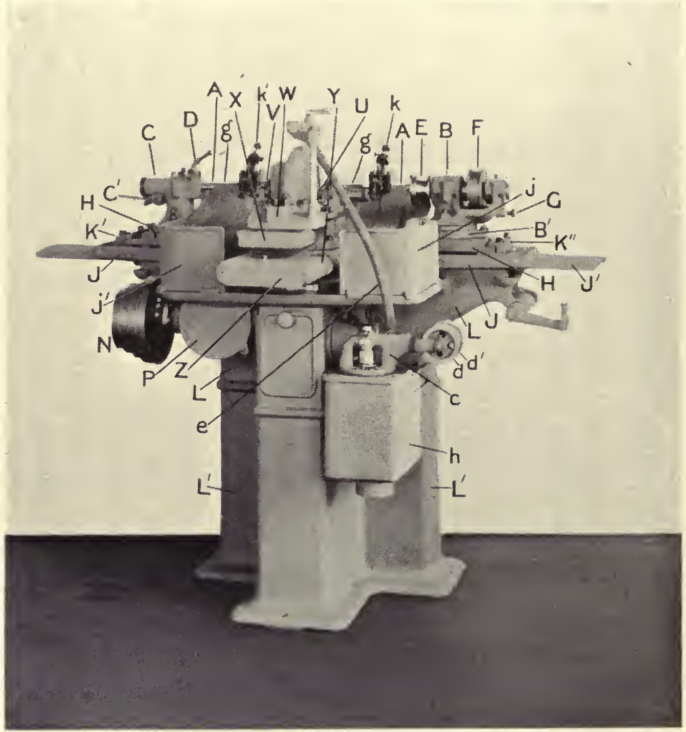


Fig. 30.—Brown & Sharpe No. 1 Universal Grinder

up true by swivelling the workhead B over on its base B′ to the correct angle, as indicated by the graduations, putting the centre in the centre hole of the spindle, and driving the latter by the pulley F. The headstock BB′ and tailstock C are carried on a table H, which swivels about a vertical stud at its centre, upon the main slide J, the angular adjustment being controlled by the knob K. Two plates K′, K″, hold the table to the main slide, and the plate K′ carries a divided plate giving the amount of the angular adjustment. The main slide J slides on the body L, L′, which, for convenience, is made in two parts, the upper L containing the feed mechanism, while the lower L′ is fitted as a tool cupboard. The work is thus carried, as it rotates, to and fro in front of the wheel, which is stationary.

Travelling Wheel and Travelling Work.—In the lathe it is the tool, and the grinding wheel where that is substituted for the tool, which is traversed over the work. Geometrically it does not matter which is traversed relatively to the other, and grinding machines are manufactured on both systems; one in which the wheel traverses is illustrated in Fig. 110, which is a view of the No. 3 Universal Grinder of the Landis Tool Co. The parts are lettered to correspond with those of the machine now being described, and some further reference to them will be found on page 270.

Practically each system has its advocates, both among manufacturers and among users, and which is the better is an undecided point, or perhaps a matter of personal preference. My preference is for the moving work type for all but very large work: partly because I consider it better to have the position of the cut stationary, so that one can watch it if need be without oneself moving, and because I prefer to have the cross-feed handwheel and gear in one fixed position; partly because I think that the accuracy of response of the wheel to the movement of the cross-feed hand wheel and ratchet is more accurate if it is not subject to the stresses involved in the reversal of movement; partly because vibration arises more frequently from the wheel than from the work, and that therefore the less freedom it has the better; and partly because, according to my calculations, wear, provided the design is correct, produces less inaccuracy in the work. On very large machines the travelling work type, however, is more expensive to construct, and it also occupies much more shop room. As representing the other point of view, the arguments are, first, that the work is supported directly on the body of the machine, as the work table, even when swivelled, has no overhang, and is practically solid with it, and secondly, that there is considerable saving of floor space. Also occasional very long work can be ground, supported by external temporary fittings. Strenuous advocates of the system further claim that the weight of the moving parts being fixed, the reversals are more accurate (for reversing, see page 116), and also it does not overstrain the reversing mechanism, as the slide carries a constant load; that the design 'favours a heavy main and cross slides to reduce vibration of the wheel head'; and that unequal wear on the main slide is avoided.

Taper Work by Swivelling Work Table.—The headstock BB′ and tailstock C are adjustable along the table H to suit work of various lengths, and are guided by tongues in a T slot, so that the axes of the centre points lie on one line. For taper work the table H is swivelled on the main slide J, and this setting of the axis of the work at an angle to the line of travel produces the taper of the work, whether the work or the wheel has the traversing motion. This is shown in plan in Fig. 31, where the wheel is supposed stationary, and the work to be moved parallel to the line of the main slide—the lowest line on the figure. This shows how the taper is produced, and as the motion is a relative one between the work and the wheel, it is clear that this applies to either of the two cases—the work or the wheel actually travelling. This device of swivelling the table keeps the centres in line with one another, which is necessary to avoid trouble in attaining the accuracy desirable.

If the machine were required for parallel (i.e. straight) work only, still it would be necessary to have a fine adjustment for parallelism; for on moving the headstock or tailstock, microscopic particles of grit might lodge on the aligning surface, and thus disturb the position on clamping. Any error would be doubled on the diameter of the work, and hence the necessity for a fine adjustment to correct for this. On large machines,

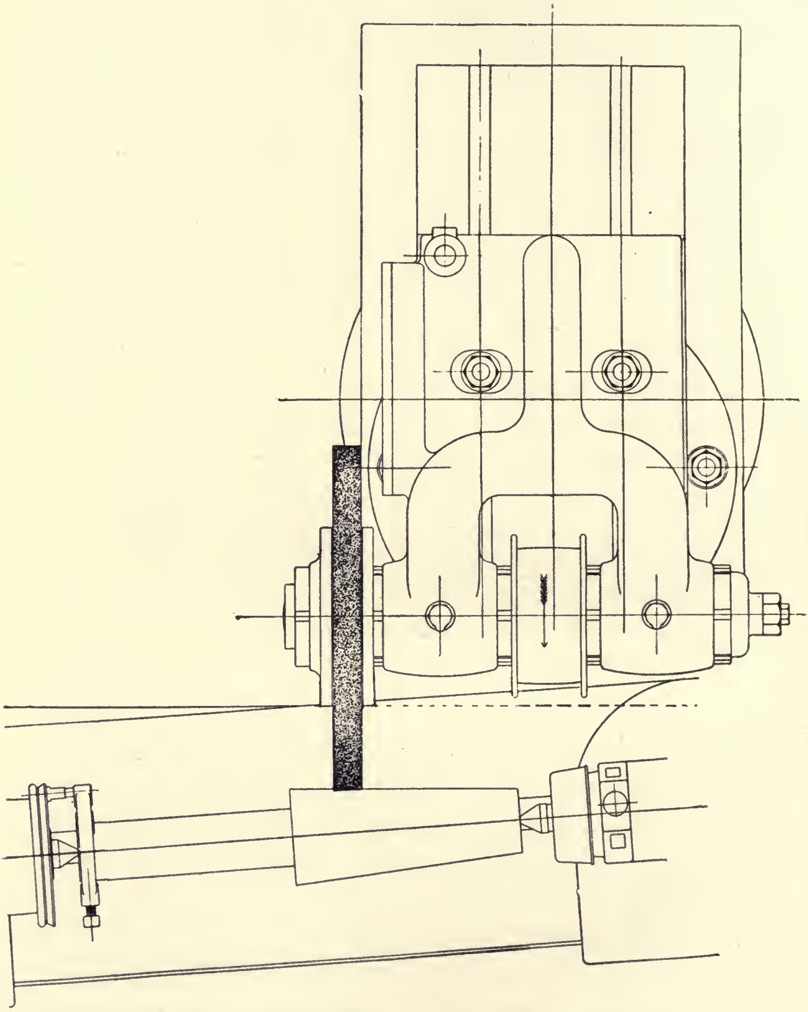


FIG. 31.—TAPERS BY SWIVELLING THE WORK TABLE

designed for parallel work only, this adjustment is made (as is usual in lathes) by fitting the tailstock to set over.

For taper work the wheel has to grind the work at a point 'level' with its axis, else errors similar to those produced by setting a lathe tool below the centre on taper work are produced.

Where the machine is designed for quite small work the table may be swivelled, if provided with a suitable fine adjustment to the movement, to 45°, and so all degrees of taper ground. On larger machines this would involve much overhang and liability to vibration, so that the more abrupt tapers are obtained by swivelling the wheel slide, as described later.

The ways by means of which the body L carries the main slide J consist of a vee M and a flat M′, as can be seen in the view in Fig. 33, and also in Figs. 75 and 76. While main slide ways are often of other types (see Fig. 105), this is a very convenient one. There are no gibs, and the surfaces are kept in contact by the weight of the parts only, with the result that the slide runs freely, and is not subjected to the forces which are liable to be introduced by the adjustment of a gib.

Types of Ways—Slide Fitting.—For precision work the ideal method of producing a slide is by the simple intersection of two planes; on scraping up these a straight line way is produced, accurate to the degree of accuracy of the planes. This construction, if suitably arranged for a grinding machine main slide, would present difficulties in the lubrication, and accordingly the vee and flat is preferable. On small hand-operated machines, where the pull of the work belt may lift the table and main slide, the latter is best gibbed. Whatever be the actual type of ways, it is upon the perfection of them that the straightness (i.e. uniformity of diameter if parallel, or straightness of generator if taper) of the work depends. In this machine the length of ways on the body and slide are nearly the same, which causes the least trouble from wear in the smaller machines; on large machines it is best that the body ways should be relatively longer. In the machine shown in Fig. 84 the body ways are very much longer, being nearly double the length.

The table motion is derived from the speed cone N, which drives a bevel gear reversing mechanism in the case P, and so ultimately the table by means of a pinion and a rack fastened to the main slide. For setting the work the table is operated by the hand wheel Q, which is connected through gearing to the table when the knob R in its centre is drawn out; when this knob R is pushed in the hand wheel Q is free, and the automatic feed is connected with the table. The movement of the main slide J is reversed by the action of the dogs S, S′, whose position is easily adjusted—and which contain in themselves a fine adjustment—operating the reversing lever T, the movement of which acts on a 'load and fire' mechanism, which shifts a clutch in the reversing mechanism at P. The action of such a mechanism is shown later (see Fig. 52, page 157).

Precision of Reverse.—As most work has shoulders upon it, and it is desirable to go close up to them in the reversing when grinding, the precision of the reverse is important. The variation of the position of the main slide at reverse is to be divided into two parts, one due to the reversing mechanism, and the other affected by the momentum of the main slide and what it carries. The latter depends on the table velocity and on the lubrication of the ways. Just after the clutch ceases to drive, the table is free and runs on a distance x given by the equation $\frac{1}{2}Mv^2 = \mu Mgx$, where M is the mass of the table and all it carries, v its velocity, μ the coefficient of friction of the ways, and g the acceleration due to gravity. Hence $x = \dfrac{v^2}{2\mu g}$ and does not depend on the weight of the slide or table, or of the work. If $v = 60$ inches per minute and $\mu = 0{\cdot}035$ inch, then $x = 0{\cdot}037$ inch, or about $\frac{1}{32}$ inch. In actual running at any speed this will only vary as μ varies, owing to the variation in the lubrication of the ways; but if the speed be altered to 80 inches per minute the new over run would be 0·065 inch, or $\frac{1}{16}$ inch, so that the table would run 0·028 inch, or nearly $\frac{1}{32}$ inch farther. It is wise, therefore, if the reverse is close to a shoulder, to make it a little earlier (by using the fine adjustment of the stops) before increasing the speed of the traverse. In the illustration it will be seen that the stops are located by a rack; this prevents their slipping when moving the reversing lever over, which happens if the stops are held by a frictional lock and the operator forgets to tighten it. If, however, such a lock is well designed, very little tightening will secure it against the risk of slipping.

Turning now to the wheel head, we see that the spindle is arranged to carry either a wheel U at the centre, or one overhung at one end of the spindle at U′. In the case of Universal machines the position between the bearings enables certain taper work to be done more easily, and it also (very slightly) reduces the effect of the oil film in the bearings. The overhung wheel is far easier to change, and in plain machines for external grinding it is practically exclusively used. In this machine the spindle with its bearings complete (see Fig. 34, page 125) can be removed from the machine by unclamping the caps V, V′, and after the wheel has been changed it can be replaced without distortion, as the outer cases of the bearings have spherical seats. The wheel head W which carries these bearings is adjustable on the plate X, which swivels on the cross slide Y. The lower ways Z of the cross slide can in turn swivel on the body of the machine; this adjustment is graduated, and is that used in grinding abrupt tapers on work between the centres.

Quick Tapers.—In Fig. 32 is shown a plan of the wheel head with the cross slide thus set over grinding a taper of 45° aside on work between the centres; the movement for traversing is in the direction of the cross slide travel as shown (parallel to the face being ground), and is operated by the cross-feed mechanism.

In grinding tapers by this swivel adjustment of the cross-ways the traversing is done by the regular cross-feed motion, which is very slow, and the cut is put on by the hand wheel, which in regular use traverses the main slide. The angle of the cross-ways is set as closely as possible by eye, but the exact taper is finally got by the use of the swivel adjustment K to the work table.

The wheel head is here shown swivelled on the cross slide, so that its axis is parallel to the cross slide ways. This is not necessary, but it is desirable, as otherwise all end play must be taken out of the spindle.

When the taper work (external or internal) is held in a chuck or on a face plate, the upper part B of the work head is swivelled, not the cross-ways. In this case the work is traversed by power, as the main slide is employed and the cut put on by

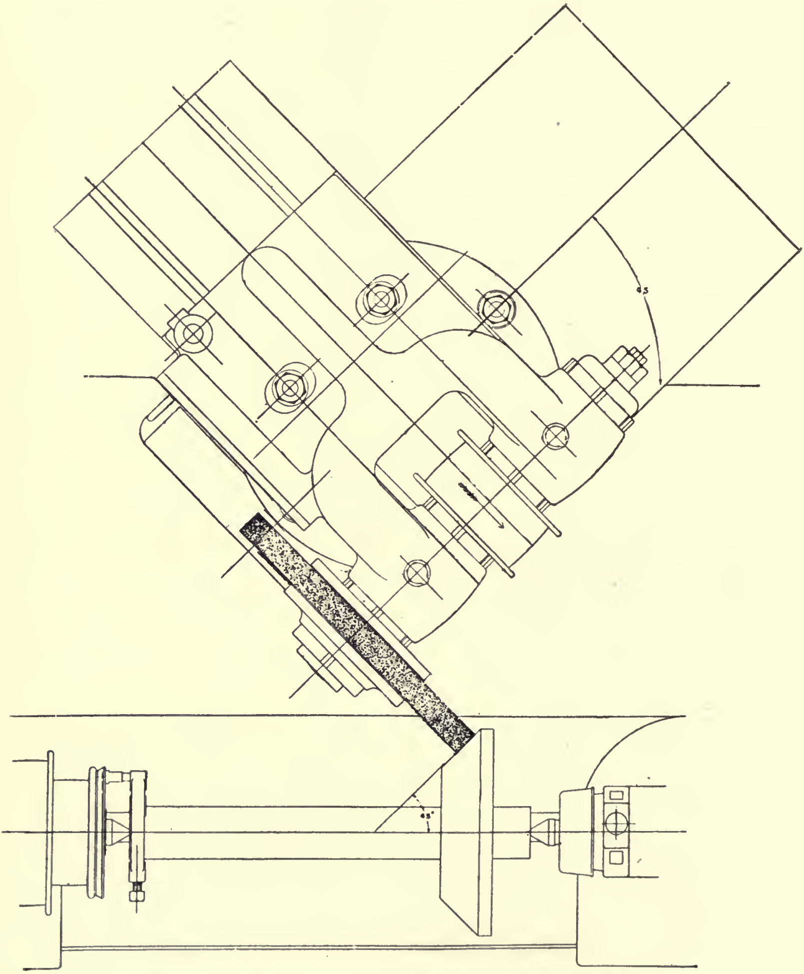


Fig. 32.—Tapers by Swivelling the Cross-ways

the regular cross-feed. This avoids the inconvenience of traversing by use of the fine cross-feed, and the difficulty of putting on the cut properly by tapping the main traverse hand wheel.

Without altering the setting of the cross slide the parallel portion of this piece of work could be ground, using the main traverse of the machine. In this case the reduction of diameter does not correspond to the graduations of the cross slide, but is less than these by the factor sin a, where a is the angle (aside) of the taper, which is shown as 45° in the figure. For example, at 30° the actual feed of the wheel normal to the surface of the straight portion of the work would be only half that indicated by the graduations, and at 14° 30″ it would be only a quarter. This is sometimes taken advantage of in grinding gauges where a fine cross-feed is desirable.

In all setting of the machine for tapers and back again for parallel work, the adjustment should first be made on the graduations as closely as possible by eye, but the final test has to be the fit to a gauge, or the measurement of the ends, and to make the final adjustment the knob K is used. As the accuracy aimed at is a fraction of a thousandth of an inch, setting by eye is not only hardly precise enough, but the result may be vitiated by the accidental presence of a particle of grit between the headstock or tailstock and the aligning ways of the table.

As the wheel head is used in various angular positions the spindle pulley has flanges. The cross slide is gibbed, as the tension of the belt driving the wheel head is in some positions considerable ; accurate response to the movement of the cross-feed disc is very desirable, and it is essential that the lubrication be not neglected, and the slide should be moved now and then over its whole range. The motion from the cross-feed hand wheel a is transmitted through a worm and worm wheel, through a vertical shaft along the axis of the swivelling adjustment of the cross-ways, and operates the cross slide by a pinion and rack.

The Cross-feed.—The cross-feed is arranged with an automatic feed, which is operated at the reversing of the table, through the cross-lever b, which by means of a ratchet and wheel turns the cross-feed shaft. The smallest amount of the cross-feed, which corresponds to one tooth of the ratchet, is the $\frac{1}{8000}$ of an inch movement, representing $\frac{1}{4000}$ of an inch on the diameter of the work, which is a convenient amount in view of the limits required by the conditions previously considered. An automatic throw-out consisting of a shield, which prevents the ratchet from action, is fitted, and its position is easily adjustable, both for considerable differences of position and for the small amounts corresponding to the wear of the wheel. On external work, where the size of wheel is not limited by the size of the work as it is in internal grinding, the wear of the wheel is in many cases negligible and, if the cross-feed mechanism sizes correctly, repetition work can be ground rapidly to size with hardly any time spent on measuring. Cross-feed mechanisms are referred to in more detail in a later chapter.

Provision for Wet Grinding.—The grinding fluid is circulated by means of a centrifugal pump *c*, having a vertical spindle, driven by the belt *r′* over the idler pulleys *d*, *d′*; it is delivered on to the work at the grinding point by the pipe *e* and the nozzle *f*, and then is drained away by the guards *g* to the channels and tray, whence it flows back into the tank *h*, in which the pump is placed. The guards *g*—which are shown loose in Fig. 29—consist of a number of joggled loose parts, which are built up on the table to suit any particular length of work, in the manner shown in Fig. 30. At the rear are two removable guards *j*, *j′*, to catch the spray and splash.

Steadies.—When slender work is being ground, although the force of the cut is small, it is apt to vibrate, which leads to chatter marks; to prevent this, and also to enable such work to be ground quickly, it has to be supported by steadies. Two of these, *k*, *k′*, are shown in position in Fig. 30, and on the floor in Fig. 29. They are adjustable, so as to support the work underneath and opposite to the wheel, and by their use the work can be sprung if desirable, as it sometimes is.

When the machine is used for internal grinding the work is done dry, all the water fittings being removed. The dead centre pulley is replaced by the chuck or face plate, and the wheel head by the counterhead *l* and internal grinding spindle and bracket *m*, all of which are shown on the floor in Fig. 29.

Arrangement of Driving Mechanism.—The machine is driven from the source of power by means of the fast and loose pulleys *n*, *n′*, on the first shaft. This drives the grinding wheel by way of the step cones *p*, *p′*, and the pulley *q* on the second shaft and the belt *q′*, thus providing two speeds for the wheel spindle. This second shaft also drives the pump by means of the pulley *r* and belt *r′*.

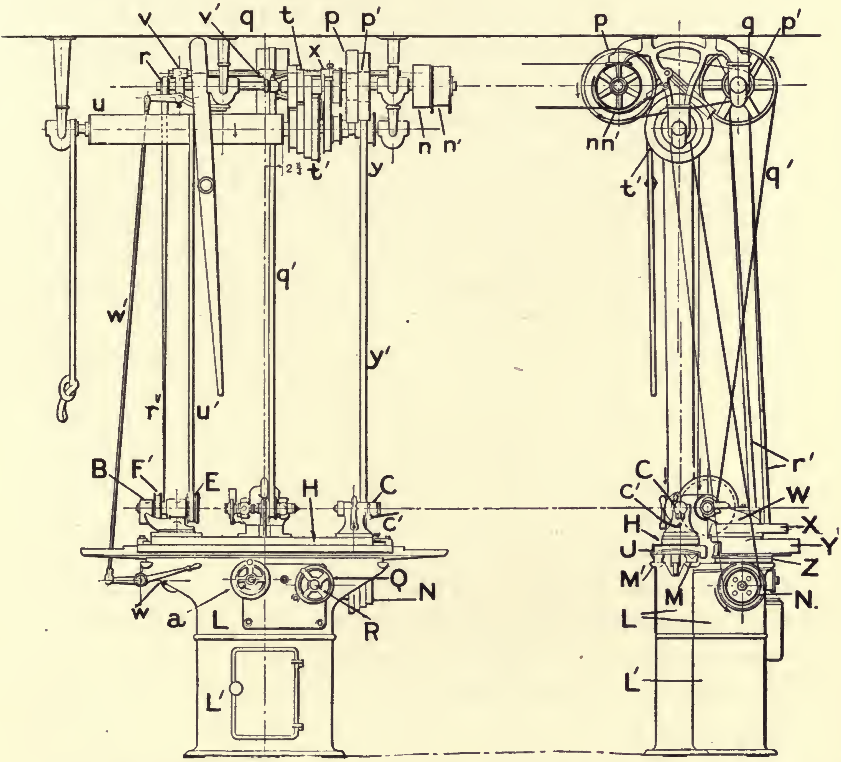


FIG. 33.—BROWN & SHARPE NO. 1 UNIVERSAL GRINDER. ARRANGEMENT OF THE DRIVE

The first shaft drives the work by means of the step cones *t*, *t′*, and the drum *u* on the second shaft and belt *u′*. An additional belt is shown on the left-hand hanger carrying the drum shaft, which is for use with the small size dead centre pulley, which is shown on the machine in Figs. 29 and 30. The step cones provide four work speeds, but the number is increased by the provision of two dead centre pulleys of different diameters. The step cone *t* is engaged by means of a friction clutch operated by the shipper bar and slider *v′*. This shipper bar is operated by the handle *w*, conveniently placed on the machine body, through the connecting rod (pipe) *w′*. After taking the friction clutch out of action, the continued movement of the lever *w* brings a friction brake *x* into play, and stops the rotation of the drum quickly, and prevents it having a tendency to start rotating while the work is being measured. The third (drum) shaft carries at its end a step cone *y*, which drives the traversing mechanism of the table through the belt *y′* and step cone N.

It will be noticed that here the work is driven by a belt which moves along a drum as the work traverses ; in the case of machines in which the wheel head traverses, it is the belt to the wheel head which moves along a drum. Here the change of speed for the wheel and the work are both obtained by shifting belts on step cones in the countershafting, but in Chapter VI some alternative arrangements are shown, which aim at rendering the change of speed easier and more rapidly effected. This Universal machine has been steadily developed to its present perfection by Messrs. Brown & Sharpe, and is intended for tool-room use. It should be compared with the Landis Universal Grinder (see Chapter VIII), which is designed for the same purpose. A knowledge of these types forms a convenient point from which to survey the trend of development of the modern manufacturing grinders.

Several of the arrangements on this and similar machines have been designed and developed to meet the particular needs of grinding machines, and these we will now proceed to examine more minutely, noting the variations produced by the modern trend towards the employment of machines of more limited scope, and towards the external, internal, and flat work being done on different machines.

CHAPTER V

DETAILS OF PARTS

The Wheel Spindle.—The quality of the work produced by a grinding machine largely depends upon the wheel spindle. Compared with the work spindle of a lathe, the wheel spindle runs at an exceedingly high velocity, but the direct forces applied to it are comparatively small; compared with other fast-running spindles (such as steam turbine shafts), the fit in the bearings has to be very close. In the design the protection of the bearings against the entrance of grinding fluid and grit, the lubrication, and adjustment must be efficiently provided for, and the material and workmanship must be of high quality.

In Figs. 34, 35, 36, and 37 are shown typical spindles, which illustrate modern practice, being the spindles of Messrs. Brown & Sharpe's No. 1 Universal, Messrs. The Churchill Machine Co.'s Plain, the Landis Tool Co.'s Universal, and Messrs. Pratt & Whitney's Vertical Surface Grinder. In the first three the edge of the wheel is almost always used; in the last the face alone. In all these the journals are parallel, and few makers use conical type bearings. One is illustrated in Fig. 38, the spindle of the Blanchard Surface Grinder. In the parallel type the side and end adjustments are quite independent, and when the wheel is used upon its edge, the play (side) of the spindle possible is only that due to the thickness of the oily film. If the journals are conical, the longitudinal expansion (differential only as it sometimes is) affects the side play, and difficulties in obtaining a high finish to the work are apt to occur; also the distribution of the oil in the film is adversely affected by the centrifugal effect, which tends to force the oil to the large end of the taper, and so out of the bearing. Constructionally parallel journals present the advantage that they can be properly lapped, while the conical type cannot be lapped so efficiently (see page 391). Practice differs as to whether the spindle should be hardened (as it is in the spindle of Figs. 34 and 36), or simply of heat-treated spindle steel. The former undoubtedly requires more care in the manufacture, but the hardened surface is very much harder, takes a better finish, and has a longer life, so that I consider it decidedly to be preferred. If the spindle is of hardening steel, the threaded parts must be made true after hardening, so that the parts where they occur must not be hardened, or must be softened afterwards, as the whole spindle must run very exactly true; if the journals are case-hardened (which I prefer), this difficulty does not arise, but the case-hardening must be properly conducted, otherwise surface defects may develop. It is often alleged against hardened spindles, particularly if of hardening steel, that the material tends to distort in course of time; if proper precautions (see page 93) are taken, this tendency is exceedingly slight, and the number of hardened spindles which are giving entire satisfaction in use is an answer to the argument. The journals should be lapped after grinding to make them as perfect as possible, and to remove the small marks of the grinding, which tend to cut the bearings. Some makers form oil grooves in the spindle, but regular practice is opposed to this, as are the phenomena displayed by oil in bearings in such experiments as those of Mr. Tower.

Wheel Spindle Bearings.—In the designs of Figs. 34 and 35 the bearings (bronze) are taper on the outside, and split through at one side; to adjust for wear, the nut A at the large end of the bearing is slackened, and then the bearing is drawn into its taper seat, and so closed to the spindle, by tightening the nut B at the other end. Finally, the adjustment is secured by locking with the nut A. The second bearing —in which the letters correspond but are marked with a dash— is adjusted in the same manner. In Fig. 35 the split in the bronze is dovetail shape, and the adjustment of the bearing further secured by tightening the dovetail clamps, LM, L′M′, by the screws shown at NP, N′P′.

Wheel spindle bearings should run warm, and the temperature attained is a convenient check on the correctness of the adjustment. The finer the finish desired on the work, the

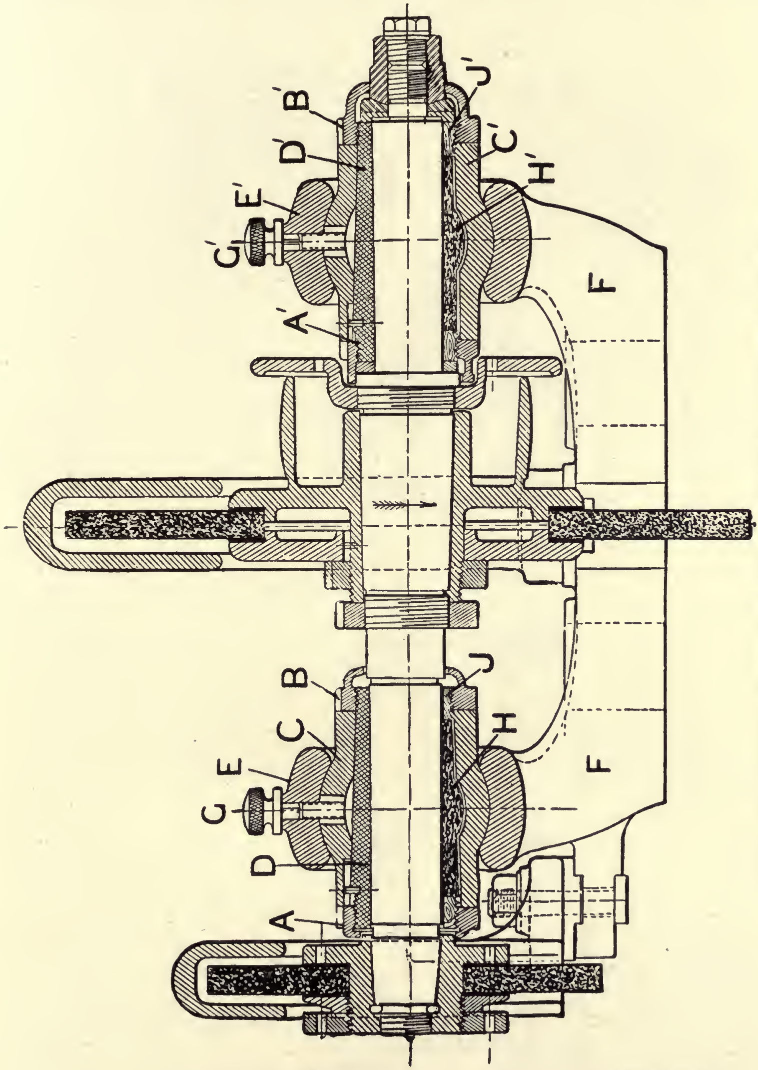


FIG. 34.—BROWN & SHARPE WHEEL SPINDLE (UNIVERSAL GRINDER)

closer should be the adjustment of the bearings, and the warmer they should run. This design of bearings renders adjustment very convenient, and lends itself well to lubrication arrangements. The split bushes with taper outside, I also consider as very suitable for the bearings of spindles for

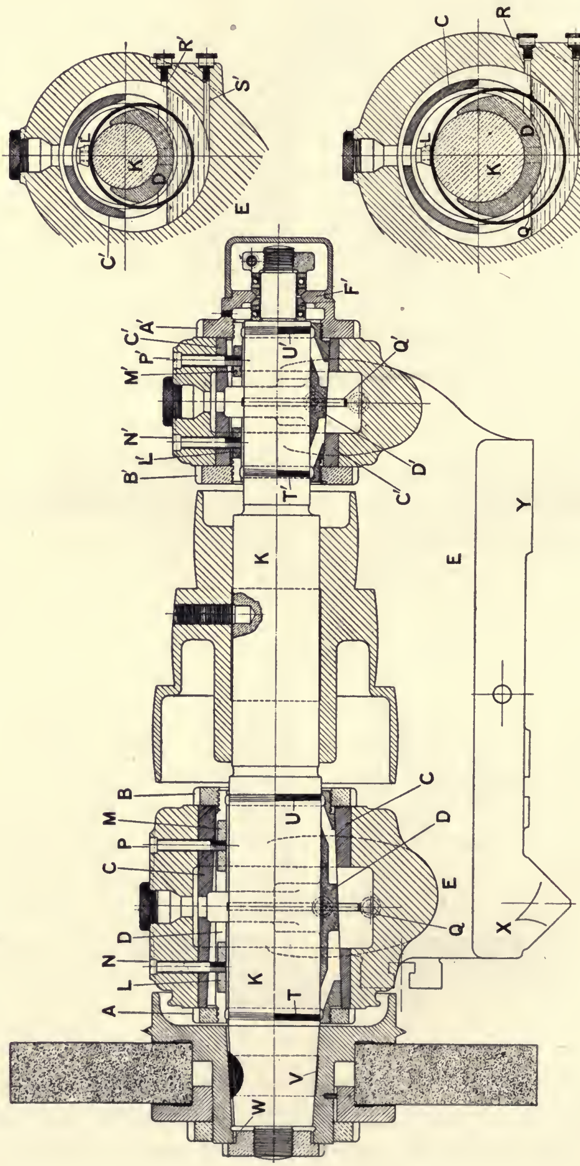


Fig. 35.—Churchill Wheel Spindle (Plain Grinder).

internal work, but the particular arrangements of the nuts above illustrated cannot well be employed.

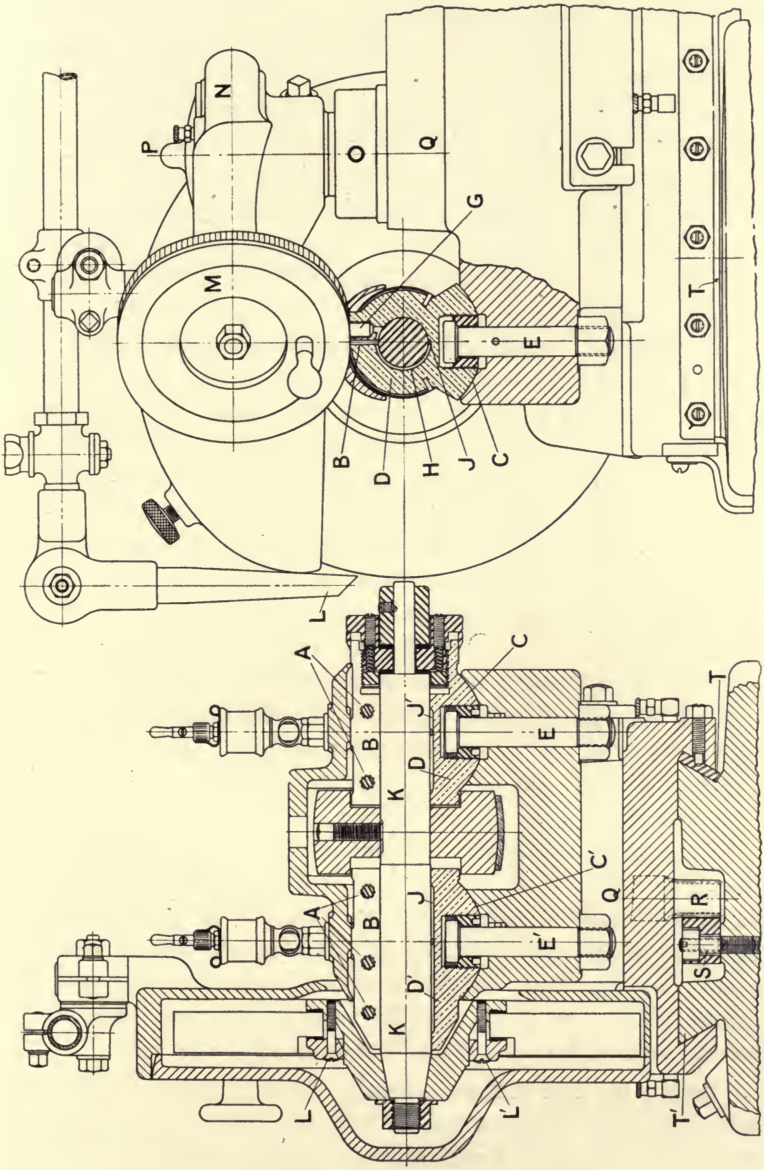


FIG. 36.—LANDIS WHEEL HEAD (UNIVERSAL)

In the spindle of the Landis Tool Co.'s Universal Machine, Fig. 36, the side adjustment is made by removing the screws A, taking out the liner B, scraping its surface, and then replacing and tightening up the screws. This type of adjustment is used frequently in the smaller machines, and the packing liner is often made of wood, or even hard felt, which can be compressed—in which cases the adjustment is controlled by secondary screws acting as a check and lock upon the closing screws, an arrangement which can be seen in Fig. 170. In the Pratt & Whitney Vertical Surface Grinder the bearings are of white metal, and are of the cap type. The same type is employed (see Fig. 127) in the Walker Single Stroke Grinder—also a vertical spindle cup wheel machine.

In both the Universal Machine spindles, Figs. 34 and 36, the bearings are self-aligning, the outer cases C, C′ of the bearings proper, D, D′ in Fig. 34, having spherical seats, where they are held by the caps E, E′ to the wheel head body F. By releasing the caps the spindle, bearings, and cases can be removed for changing the central wheel, and on replacement the bearings align themselves, and so do not strain the spindle. When removing the spindle and bearings for this purpose, it is very essential that no grit be allowed to get into them, and every care should be taken to prevent it—particularly at the bearing at which the end thrust is not taken, as it is free to slide along the journal when lifted out of position. In the Landis design the spherical seats C, C′ are formed on the bearings D, D′ themselves, which are drawn on to the wheel head surfaces by suitably arranged bolts E, E′.

In plain grinders the bearings D, D′ are usually drawn into tapers formed in bushes C, C′ let into the wheel head E, as in the Churchill design, Fig. 35, but Messrs. Greenwood & Batley employ a self-aligning type, somewhat similar to that of the Landis Tool Company, but with the bearings pulled up to spherical seatings opposite to the contact of wheel and work. In Fig. 63 the nuts of the bolts are to be seen.

Design for End Thrusts.—Ideally the end thrust should be taken up over a short length only, as at F in Fig. 35, and also in Fig. 36, but if it is taken over the whole length of a bearing, as at over D in Fig. 34, and provided with suitable collars, the result has always, so far as I am aware, been satisfactory. In the Landis design, Fig. 36, the thrust is taken by a stationary collar, which is provided with a fine longitudinal adjustment by means of a graduated sleeve; by this means the wheel spindle can receive a fine movement in the direction of its length, for the purpose of grinding snap gauges and such work, using the side of the wheel. In this case the end thrust must be taken up so as to leave no play, but in work where the curved face of the wheel is used, a slight degree of end freedom is best allowed; it produces no effect if the spindle is parallel to the main ways of the machine.

In machines where the flat face of the wheel is employed, such as cup wheel

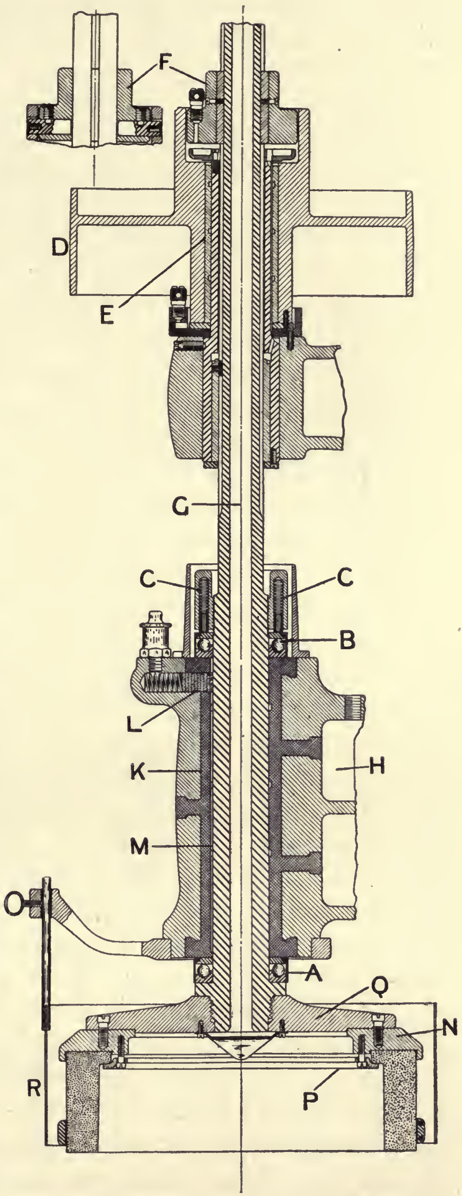


Fig. 37.—Spindle of Pratt & Whitney Vertical Surface Grinder

surface grinders, the provision for taking the end thrust is very important, and it should be taken up as close to the wheel as is possible, so as to minimise the effects of temperature change. This is so arranged in the Pratt & Whitney vertical surface grinder spindle, Fig. 37 ; the direct thrust is taken on a ball-bearing thrust washer A, and the end play is taken out by another ball and thrust washer B at the rear of the main bearing ; this is held up to position (and also thereby holds the main thrust in position, when there is no end thrust from work on the spindle) by means of a set of springs at C. This eliminates the effect of temperature on the amount of end play and—except so far as the initial tension in the springs is concerned—does away with the need of adjustment for end thrust. The spindle driving pulley D is carried on an independent bearing E, as is customary in good practice in belt-driven drilling machines, so that the belt pull does not come on the spindle and its bearings. The spindle is driven indirectly from the pulley through the collar F, and slides through the upper bearing, as the head H, carrying the lower bearing K, is adjusted vertically to suit different thicknesses of work, or for feeding.

In Fig. 38 is shown the spindle of another surface grinder, the Blanchard, in which the whole spindle head is carried on the vertical slide, and moves as a unit. The spindle A is carried in a taper bearing B at its lower end, and by a ball bearing C at its upper ; the direct end thrust of the wheel is taken on a ball thrust bearing at D as near to the wheel as possible ; the completion of the thrust bearing is at the upper end of the spindle by the spherically seated ball thrust washer E, which is held to its seat by the springs F, which thus keep the lower ball thrust D tight up, as in the previously described design.

The main bearing here is a taper bearing, and is adjusted to the spindle by the nut G : the raising of the bronze bush making it fit the spindle more closely, as the spindle A is held endways by the thrust at D. The centrifugal effect here carries the oil up the bearing, so that it aids the circulation of the oil, which follows the course indicated by the arrows. In this case the main journal here has an oil way cut in it. General views of these vertical surface grinders are given in Figs. 125, 126.

Lubrication.—Grinding spindles not only run at a high speed, but the fit of the bearings to the spindle is very close, so that the

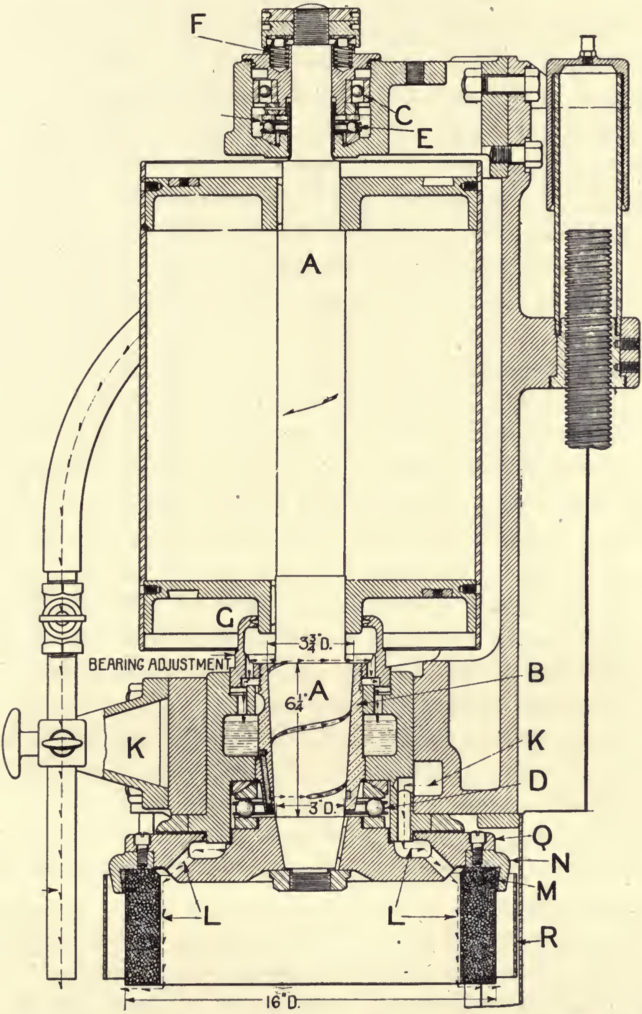


FIG. 38.—WHEEL HEAD OF BLANCHARD VERTICAL SURFACE GRINDER

arrangement of the lubrication is important. In Fig. 34 the oil supplied through the hole GG′ at the top runs round the bearing bushes D, D′, and is distributed along the length of the bearing by the capillary action of pads H, H′ in the slot, which is here arranged to be at the bottom of the bearing. It is prevented from flowing out by means of the wood strips J, J′.

In the Churchill spindle, Fig. 35, oil wells are provided, into which lubricating rings Q, Q′ dip and carry the oil to the top of the journal. After lubricating the spindle the oil is returned to the reservoir by the passages shown. By means of a neat but simple device of arresting the sideways motion of the ring by a suitably placed point, the rings are caused to twist slightly at each end of a sideways traverse. This twisting causes them to traverse axially over the width of the oil chamber, and so distribute oil over that length of the top of the journal. On reaching the end, and meeting the projection there, the ring is twisted so that it travels back again. In the sectional views, the spindle K, bearings D, D′, bearing bushes C, C′, and the wheel head E are shown, and also the holes R, R′ for ascertaining that the oil reservoirs are filled correctly, and the holes S, S′ for emptying them. The open slot of the bearings is here seen at the top. Shallow screw threads, shown at T, U, T′, U′ in the sectional view, prevent the escape of oil at the ends of the bearings.

In the Landis design, the oil supplied through the hole G at the top runs round the circumferential groove H to the longitudinal grooves J, J′ at the bottom of the spindle K, and so is distributed along the journal.

In the spindle design of the Pratt & Whitney machine, the oil for the main bearing is fed through an ordinary lubricator, and slowly passes through felt washers L, Fig. 37, into the longitudinal groove M. The upper spindle bearing and pulley bearing are lubricated in a similar manner, but felt washers are not employed.

In some cases I prefer direct oiling by means of sight feed lubricators, an arrangement which is seen on the Landis head, Fig. 36, and on Messrs. Greenwood & Batley's, Fig. 62. The oil can then be supplied at any desired rate continuously, and it is clean oil, provided the sight-feed lubricator itself is dust-proof; as such lubricators are usually intended for other purposes, and are subject to the conditions of competitive manufacture, such is not always the case. Grinding conditions require such accuracy that the cutting of a wheel is affected by the addition of oil to that already in the lubricating system, so that the rate of supply of oil must be uniform. If necessary the supply may be stopped while finishing a part.

Although the spindles are a very close fit in the bearings, there is some space between the surfaces which the oil occupies ; the spindle when running does not set itself exactly central, but the oil film varies in thickness round the circumference of the bearing. Varying forces, such as caused by vibratory jerks of the belt, or due to want of balance in the wheel, make the spindle alter its position in the bearing, the thinnest oil space changing its position. The result is a series of chatter marks on the work.

The spindles require good lubrication, as they run at a high speed, although the load is low ; and the oil used should be light, so that the space between the spindle surface and the bearing may be as small as possible. When a perfect oil film exists, it is not of uniform thickness all the way round, but the spindle sets itself so that the film is thickest on the intake side—that is, before the line where the resultant force on the spindle axis cuts the bearing. The pressure in the oil film also varies, and is a maximum behind this point where the resultant force on the spindle axis cuts the bearing, and the pressure diminishes from the centre towards the edges of the bearing. If a hole is drilled in a bearing to a point of high pressure, oil will flow out, and it is impossible to lubricate a spindle at such a point unless the oil is supplied at a head exceeding that which corresponds to the pressure. Thus the selection of the points at which oil is fed into bearings is very important, and should be made upon the principles mentioned above, founded on the researches of Mr. Tower (‘Proc. I. M. E.,’ 1883, 1885, and 1888), Prof. O. Reynolds, and Mr. Lasche. In these experiments, however, a half bearing only was used, and the fit was not close like that of a machine tool spindle. The first experiments were on slow speed bearings, but those by Mr. Lasche (‘Traction and Transmission,’ Jan. 1903) extended to the speeds used in grinding machines. The effect is most enhanced in the high speed bearings of spindles for internal grinding, where, if it be attempted to feed oil to the bearing at a high pressure point, it refuses to go near, and if the spindle be oiled when stationary the oil is promptly pumped out as the spindle gains speed.

Protection against Grit.—It will be noticed that in Fig. 34 the adjusting nuts are curved in towards the spindle at their sides; in Fig. 35 the headstock has a groove formed in it, which is covered by a projection of the wheel collet, and in Fig. 36 the wheel collet is deeply recessed, and the bearing projects into it, so that the bearing is protected from the entrance of gritty fluid. In the latter cases, Figs. 35 and 36, the end thrust bearing is completely enclosed. Similar arrangements are used on the spindles for internal work, shown in Figs. 42 and 43.

Position of the Wheel.—The central position of the wheel between the bearings, as in Fig. 34, makes it possible to grind some cases of taper work between the centres more easily; the effect of the oil film is also minimised, as there is no multiplication by the leverage of the overhang. The advantages, however, are so slight that it is generally considered that the convenience of easily changing a wheel at the end of the spindle without disturbing the bearings in any way, outweighs them, and in plain grinders, at any rate, the position of the wheel is so arranged.

Spindles for Internal Grinding.—Turning now to the spindles for internal grinding, we find very severe limitations and conditions are imposed on the design by the nature of the case. To produce a desirable circumferential speed at the wheel the rate of revolution of the spindle must be very high, and requires 6350 r.p.m. for a 3-inch wheel and 19,000 r.p.m. for a 1-inch wheel to give 5000 feet per minute to the wheel edge. Usually a somewhat lower speed is used, but still it is a very high one. As the wheel has to grind a hole, either the spindle must project from its bearings and carry the wheel considerably overhung, or else the support for the bearing at the wheel end must be small enough to go down the hole, which arrangement allows little room for the bearing and adjustment. In all but the smallest sizes such a supporting sleeve carrying a bearing near the wheel is desirable, as the amount of play at the wheel is then that due to the wheel end bearing, and is not intensified by the amount of overhang. There seems to be an 'impression' that the sleeve is a stiffer construction in itself, but this is not the case—a solid spindle of the sleeve diameter must be the stiffer, as splitting it up into sleeve and spindle would increase the number of degrees of freedom. The stiffness in any particular case can be calculated.

Whatever may be the opinion as to the desirability of hardened steel for the larger spindles, there seem to be few objectors, at any rate among the users, to its employment for these small spindles. The bearings are almost always of phosphor bronze.

Typical designs of internal spindles are shown in Figs. 39, 40, 41, 42, 43, 44, and 45, of which Figs. 39 and 40 are by Messrs. Churchill, Fig. 41 by Messrs. Brown & Sharpe, and Fig. 42 by Messrs. Heald, while Figs. 43, 44, and 45 represent two of my designs, given as illustrating special points.

In Fig. 39 the spindle A is supported close to the wheel by a bearing C, which is carried in the sleeve D; and as it wears the bronze bush C is closed by pressing it into the taper recess of the sleeve by means of the nut E. The other, enlarged, end F of the sleeve D, is gripped in the supporting bracket, and in it is carried the support G for the rear bearings H, K, of which there are two, on opposite sides of the driving pulley J. By removing the support G from the tube, and the cap L, the bearings H, K can be adjusted by the nuts M, N respectively. The chief force on these small spindles is that due to the wheel belt, particularly as the tightness of the belt is adjustable by the operator of the machine. Carrying the pulley between two bearings distributes the effect of the tension over them, and this construction is used also in the spindles of Figs. 29, 40, and 42. There is, however, in this construction a little more difficulty in the dust proofing, and the added difficulty of making three bearings collinear. A way out of this last difficulty is to make the pulley spindle co-axial with, but separate from, the wheel spindle, and to connect them with a flexible coupling; a simple form of

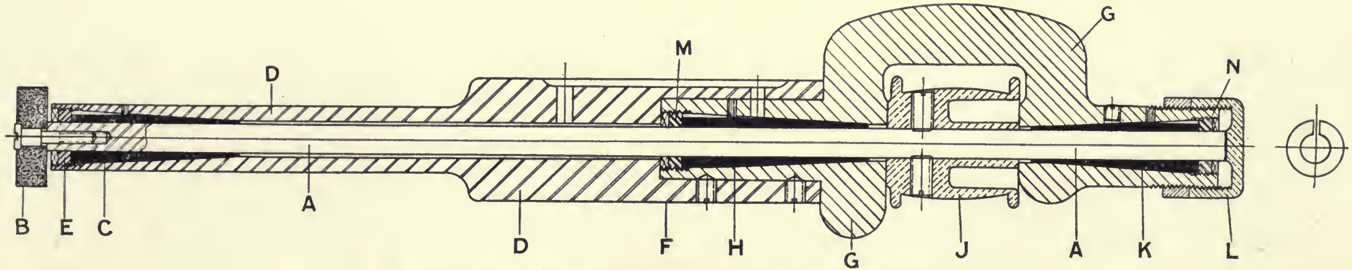


FIG. 39.—CHURCHILL INTERNAL GRINDING SPINDLE

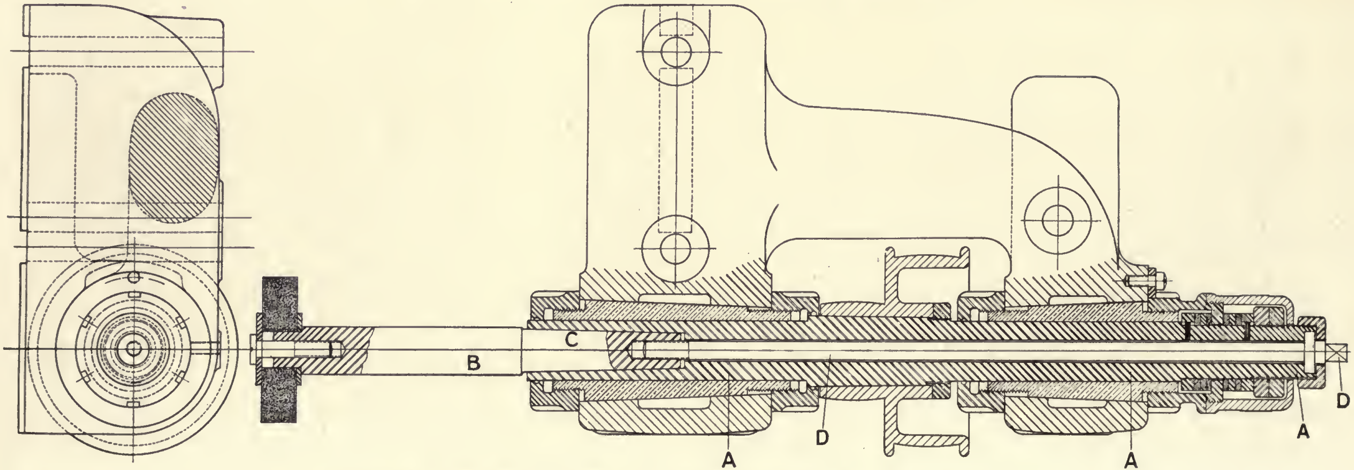


FIG. 40.—CHURCHILL INTERNAL GRINDING SPINDLE (ADAPTER TYPE)

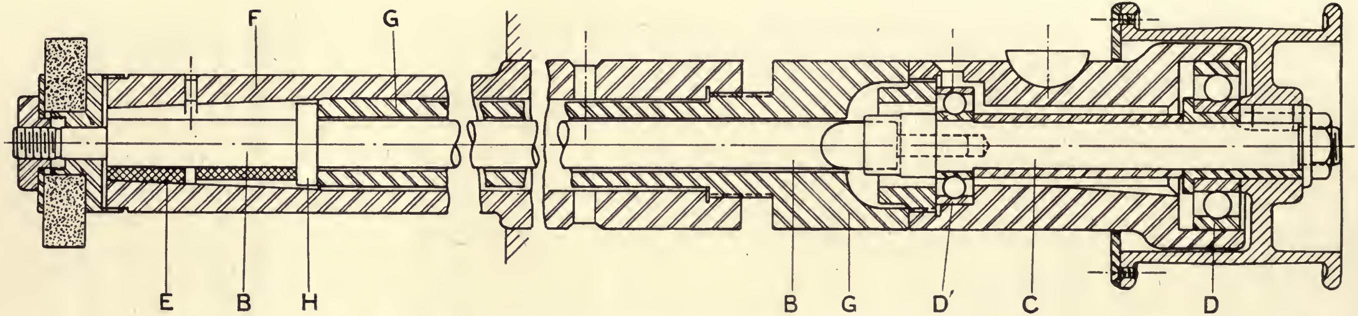


FIG. 41.—BROWN & SHARPE INTERNAL GRINDING SPINDLE

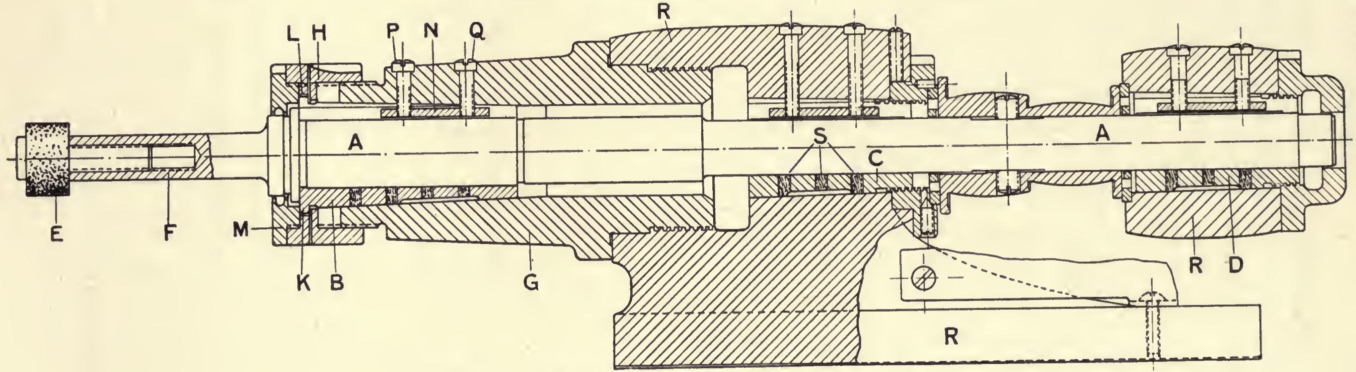


FIG. 42.—HEALD INTERNAL GRINDING SPINDLE

approximating to this is illustrated in Messrs. Brown & Sharpe's spindle, Fig. 41. Here the internal spindle proper B has a reducing projecting end centred in the pulley spindle C, and is driven by a tongue and groove. Here the rear bearings —those of the pulley spindle—are the regular ball journal bearings D, D′, and the larger is within the driving pulley, and thus takes the pull of the belt.

The front bearing E is of the outside taper type, and is adjusted by being pressed into the female taper of the sleeve F by the thrust of the collar H, when the sleeve F is screwed in—the collar H being prevented from moving by the inner tube G. This operation first takes out all the end play, and then closes the bearing E. The sleeve F is knurled on the outside so that it can be turned easily. When this has been adjusted, the sleeve F is unscrewed sufficiently to free the collar H, and make it a running fit. This sleeve F which supports the wheel end bearing is carried in the bracket, and is clamped after adjustment.

In both designs, Figs. 39 and 41, the wheel bearing is oiled from the bracket, the fluid travelling up the inside of the sleeve. Where the bearing is so close to the wheel, too much oil should not be given to the bearing, as a drop getting on to the work causes the wheel to choke, and hence delay. In the design of these spindles, there is a bearing close to the wheel, and the spindle is small there, but in Figs. 40, 42, and 45 are illustrated spindles in which the wheel is overhung from its bearing by the length greater than the depth of the hole.

Fig. 40 shows Messrs. Churchills' ' Adapter ' spindle, which is a heavy hollow spindle A of such dimensions that wheel holders B of various lengths and diameters can be fitted to it, and so that the projecting part of the spindle may be suitably stiff for the work being done. The wheel holder B is drawn to the taper seat C by the draw-in rod D running through the spindle A. The limitations on the bearing construction, which are enforced by the allowable size of the sleeve in Figs. 38 and 40, here do not apply, and the type of bearing is that previously described in connection with the larger spindles of Figs. 34 and 35, and has the advantages of easy adjustment and independence of the side and end play. It will be noticed that the pulley has a taper fit to the spindle, and is held by a nut. The end thrust is taken on the rear adjusting nut of the back bearing, and is entirely enclosed by the cap.

The Heald ' Style A 1 ' internal grinding spindle is shown in Fig. 42, where the spindle A is supported by three bearings B, C, and D, and carries the wheel E, overhung from the nearest bearing B, by the reduced part F of the spindle itself. The bearings are all of the parallel inside, taper outside, split type. The wheel end bearing B is carried in the sleeve G, and is adjusted by the nut H, the turning of which moves the bearing B both into and out of the taper of the sleeve G positively, the bearing and nut being connected axially, as the shoulder K of the bearing lies in the recess L in the nut H, and is held there by the retaining nut M. When the bearing B has been correctly adjusted it is locked into the taper of the sleeve G by the taper wedge N expanding the slot, on the screws P, Q being tightened, as in the bearings of Fig. 35. The sleeve G is screwed firmly into the bracket R, which supports the two rear bearings C, D, one on each side of the driving pulley. The lubricating oil is distributed over the journals by the wicks seen at S, and in the other bearings.

The spindle of Fig. 40 is fitted with wheel collets, so that the collet and wheel may be removed together. In Fig. 39 the wheel is carried on the plain part P of a screw, which fits the spindle nose by a plain part Q, and so is supported firmly. In neither case is the wheel put on the spindle nose itself; this should never be done, as small wheels cannot be held firmly against slipping, and if that occurs when the wheel is on the end of the spindle, the latter is worn away.

Reference can be made to Fig. 102, in which can be seen the spindle of Messrs. Healds' cylinder grinder; this is an altogether longer spindle, but the construction is similar to that of Fig. 42, there being three bearings, one close up to the wheel, but the driving pulley is (necessarily) overhung at the rear.

Supporting the Wheel Bearing in the most rigid manner.—In order to call attention to one or two points, a drawing is given in Fig. 43 of the wheel end of the larger internal grinding spindles of my design.

Here the bearing A is closed for adjustment by the nut B, and should the adjustment be carried too far, it is slackened by unscrewing the nut B slightly and pressing the bearing out by means of the collar C, the end adjustment of the spindle being released for the purpose. The oil is carried to the bearing A

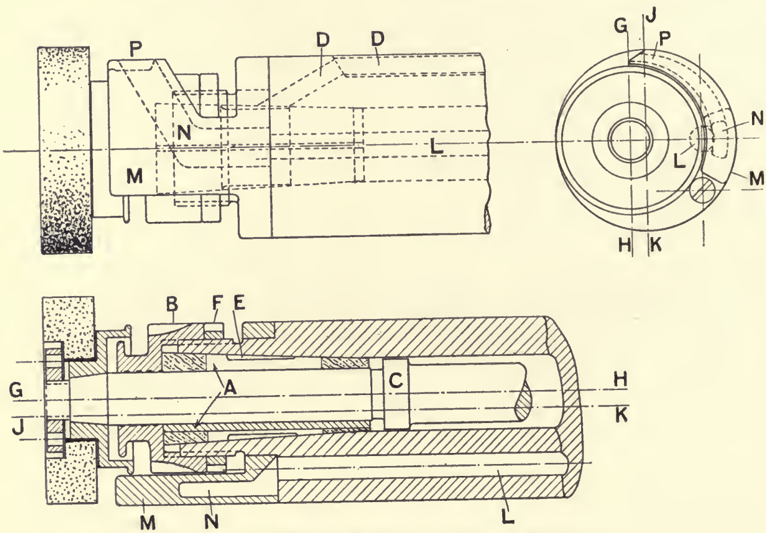


Fig. 43.—Guest Internal Grinding Spindle

down the independent oil way D, and is delivered to the central recess E of the bearing, and hence to the slot filled with a felt pad, the location of which, in regard to the point of the cut, is carefully arranged. The wheel collet has a conical fit to the spindle, and protects, in conjunction with the nut B, the bearing from the grinding fluid and grit. The nut has a projection which is turned up (instead of down as in the design of Fig. 34) so as to form a channel guiding the drops of gritty water away from the bearing. The inside of the nut B is just clear of the spindle, and has a shallow screw thread cut along it, so that the rotation of the spindle tends to take out any oil which gets there, and so prevents the ingress of any grit. The adjustment is locked by the nut F. The plan and end view show that the sleeve differs from those previously described, in that it is considerably eccentric to the spindle; GH is the axis of the spindle, while JK is that of the sleeve.

Before internal grinding was a manufacturing method, it might be held that the stiffest sleeve which could be used on a particular hole and the largest wheel were obtained when the wheel was nearly the size of the hole, and the sleeve just a trifle smaller. This, however, is not a commercial arrangement, as it allows for no wear of the wheel. If we arrange for a reasonable wear of wheel and then consider how to provide the utmost rigidity, we are led to a sleeve in which the spindle is carried off the centre of the sleeve. Suppose that ABCD, centre P, Fig. 44, is the smallest hole for which the spindle is intended; AEF, centre Q, the initial size of the wheel shown just grinding the work; and AGH, centre R, the size of the wheel when worn to its small limit, also shown just grinding the work. The adjusting devices and sleeve, if concentric with the spindle, must then all fall inside the circle AGH; but if the sleeve be not concentric, although the adjusting nuts will still have to fall within the circle AGH, the sleeve body can extend from A to J, where RJ= PC. Then the sleeve, when the full-sized wheel was in use, would just graze the work at C. Giving a little clearance, LJ, we arrive at AKLM, the circle indicated by section lines as the size of

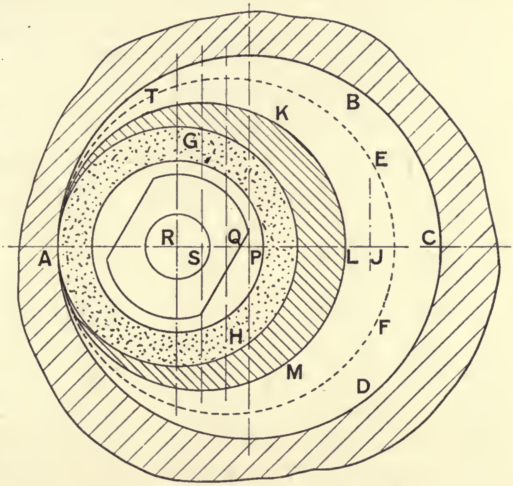


Fig. 44.—Arrangement of Guest Eccentric Sleeve

the best circular section sleeve. The centre is at S, offset a distance RS from the wheel centre. This is larger than the concentric sleeve, as indicated by the shaded portion outside the smallest wheel AGH. Its relative stiffness is very much greater than the difference suggests to many, for the rigidity depends on the moment of inertia of the section, and therefore is approximately as the fourth power of the outside diameter. With practical dimensions, allowing for the water way, it is about three times as rigid as a concentric sleeve. Advantage is taken of the facility offered for forming the water supply way in the metal of the sleeve; very little rigidity is sacrificed, as the position of the hole causes its sectional area not to have much effect on the moment of inertia of the total section. The water way in the sleeve is shown at L, the water is delivered through it to a nozzle, M, Fig. 43, which carries it round along NP and delivers it on to the work (not the wheel) at T in Fig. 44, and the direction of delivery is such that it runs along the work surface to the grinding point.

Ball Bearings.—Ball bearings have frequently been used for grinding machine spindles, but for the larger sizes are not desirable, except for thrust bearings and for polishing heads. They save power, and need less oiling, but this is of little moment. The best work, which is the chief consideration, is obtained with uniformity from parallel plain bearings. Where, however, the rotation is very rapid, as in spindles for small internal work, the quality of the work is less affected by the use of ball bearings, and they are justifiable. In Fig. 45 is shown my design for the bearings of these small spindles, in which certain difficulties arising in earlier types I constructed are avoided. In careful hands the previous type was quite satisfactory, but the design illustrated is proof against mal-adjustment. The bearings are of the three-point type, and the spindle A is one piece only. The wheel end cup B is fixed, the pulley end cup C slides, and is forced to position by the spring D. This keeps the balls at this end up against the cone E of the spindle, forcing the spindle to the left, and so keeping the cone F and balls at that end in position. There is no adjustment provided to be tampered with, and should any temperature rise occur, its effect is taken up by the action of the spring. The pulley is overhung, which makes the dust-proofing easy. Though a separate collinear end drive might be preferable, it would be far more expensive.

However an internal grinding spindle for small holes is constructed, no unreasonable life should be expected from it and its bearings. A spindle carrying an inch wheel, if the circumferential wheel speed be the same, makes as many revolutions in six months as the spindle of a 14-inch wheel does in seven years, and this fact is often overlooked. To my mind the best solution is—provided dust-proofing and lubrication are satisfactory—simplicity of design, and such that the wearing parts are of inexpensive construction. It will be noted that the wearing parts of the bearings in several designs illustrated are very simple and cheap to replace.

Condition for slipping in a high speed Ball Bearing.—In Fig. 46 is given a sketch of a ball bearing. The spindle whose axis is AB has the cone CD formed upon it, and EFGH is the 'cup.' A three-point bearing is shown, in which the ball touches the

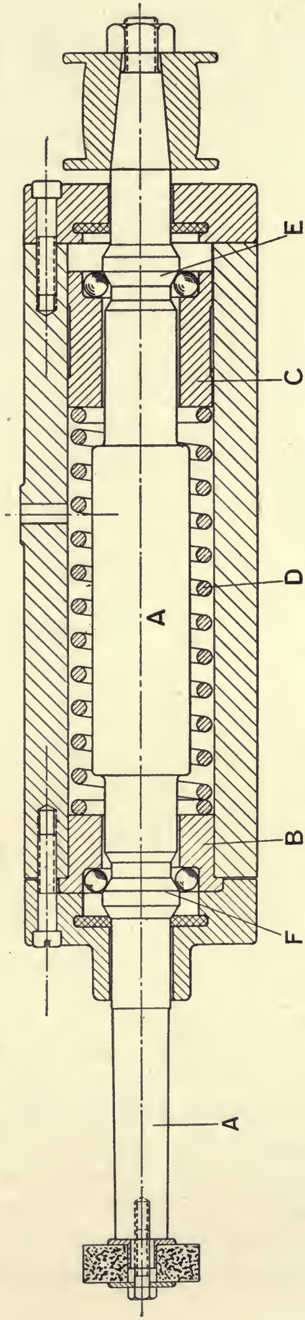


FIG. 45.—GUEST INTERNAL GRINDING SPINDLE (BALL BEARING TYPE)

cone at L and the cup at M and N. It is frequently stated by writers in engineering books and periodicals that unless the tangent to the ball at L, here CDB, meets the axis AB

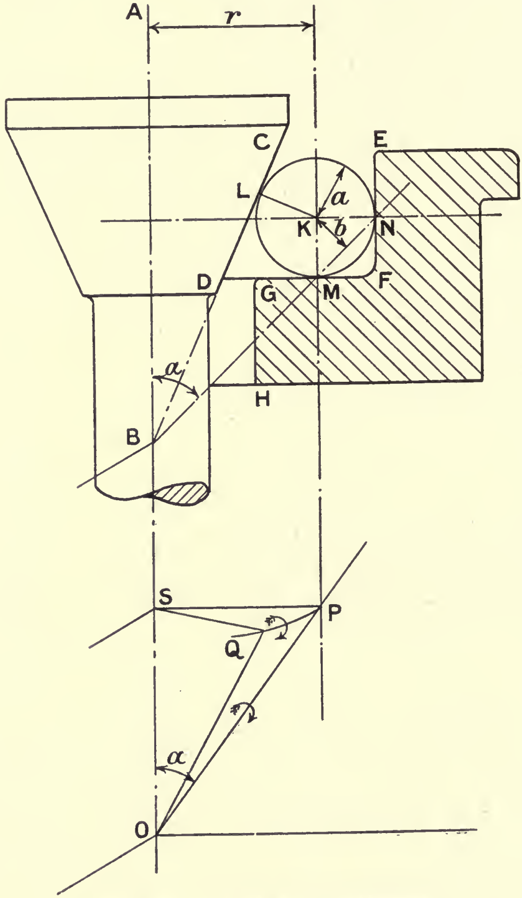


FIG. 46.—SLIP-IN BALL BEARINGS

in the same point that MN meets it, there will be side-slipping of the ball on the cone at the point L, though not at M and N; this, however, is not the case—there is no side slipping of the ball in three-point bearings at slow speeds. If CLD and MN do not meet the axis at the same point B, all that happens is that the ball has spin round the normal LK at L just as it always has at M and N. In a high speed bearing, however, the ball may slip on the cup and cone surfaces at all three points L, M, and N, by rotation round an axis perpendicular to the plane of the paper. The condition for slipping is to be found as follows from the couple necessary to change the axis of spin of the ball as it runs round. The cup is supposed fixed and the ball centre K to run round its track with angular velocity Ω. Let $a =$ angle ABM, r be the radius of the track of ball centre, Ω' the angular velocity of the ball round BMN, and mk^2 its moment of inertia. Then, in the lower figure, if P be the ball centre, draw PS perpendicular to the spindle axis OB, and PO parallel to MN, to meet it in O. After a short time δt let the ball centre get to Q. To do this and then to be rotating about OQ, that is not to slip, it must have angular acceleration $\dot{\omega}$ round QP, hence OPQ is a triangle of angular moments, and we have—

$$\frac{mk^2\dot{\omega}\delta t}{mk^2\Omega'} = \frac{\text{PQ}}{\text{OP}} = \frac{\Omega r \delta t}{r \operatorname{cosec} a}$$

and ∴ $$\dot{\omega} = \Omega \,.\, \Omega' \,.\, \sin a.$$

Hence from the upper half of the figure we have—

$$\Sigma\, \mu\, \text{F}a = mk^2\dot{\omega} = \Omega\Omega' \sin a \,.\, mk^2$$

∴ $$\Sigma\, \mu\, \text{F} = \frac{r}{ab} \,.\, \Omega^2 \,.\, \sin a \,.\, mk^2$$

or $$\Sigma\, \text{F} = \frac{r \,.\, mk^2}{\mu \,.\, ab} \sin a \,.\, \Omega^2$$

where Σ F is the sum of the three normal forces at the points L, M, N; a the radius of the ball; b the length of the perpendicular from K on MN; and μ the coefficient of friction. If Ω exceeds the value given by this equation the balls will slip on the bearing surfaces. Putting the equation in revolutions per second and F in pounds weight—

$$\Sigma\, \text{F} = \frac{8}{5\mu g} \,.\, \pi^2 n^2 rm$$

Wheel Collets.—As one particular grit and grade of wheel is not suitable for all the work which may be required, the wheel may have to be changed frequently. If this is the case several wheel collets should be provided, and the collets with the wheels in them changed, and not the wheel only, as is necessary if a single collet is used. This saves time and wheel material, as with a collet the wheels come up so true when put on the spindle that only a light cut with the diamond is necessary. It is equally important that small machines, such as cutter grinders, should be provided with spare collets, as on these machines the wheels are changed very frequently. To ensure a fit free from shake the collets for the disc wheels should have a taper fit to the spindle, and preferably the central portion of the bearing area should be removed, as shown in Fig. 35 at V. With the correct amount of taper no key is really necessary, though one is fitted in this case. On the larger machines the collet should have an inside thread, as shown at W, Fig. 35, so that it can be drawn off the spindle by screwing a recessed threaded plug down the collet until the inside of the plug meets the spindle nose and withdraws the collet from the spindle.

The collets should grip the wheel close to the edge of the flanges only, as is shown in Figs. 9, 35, 36, &c., and washers of some yielding substance, such as blotting paper, put between the wheel and collet flanges to distribute the pressure, or the collet may be lined with white metal for the same purpose. Wheels are now usually supplied with washers fastened to them ready. It has been pointed out that the wheel must be an easy fit, so as not to cause any bursting strains in its material by forcing it into position.

In Fig. 36 the wheel is shown reduced where the collet grips it, and the collet flanges are flush (or nearly so) with the sides of the wheel. This entails the necessity of using specially shaped wheels, which frequently take some time to procure, and so have to be ordered well ahead of requirements, but in some cases their use is very desirable. In crankshaft work, for example, a wheel has to reach a long way down to grind a pin, and recessing the wheel so that the collet flanges are below its sides enables a wheel of much smaller diameter to be used. In such collets the collet flange is tightened up to grip the wheel by four screws, as shown at LL′, more conveniently than by the single nut, shown in Fig. 35, securing the collet flange there.

Holding Cup Wheels.—Chucks or collets for cup or cylinder wheels are either mounted on a taper, as in Fig. 38, or screwed nose of the spindle, as in Fig. 37, or—what minimises the distance from the grinding edge to the thrust bearing—attached directly to a flat collar formed on the spindle itself. The chuck shown in Fig. 37 (the Pratt & Whitney Surface Grinder) is typical.

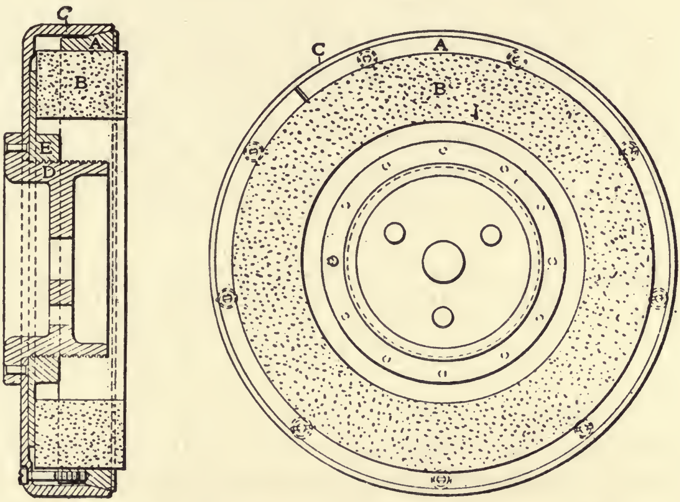


FIG. 47.—BESLY CUP WHEEL CHUCK

In mounting, the wheel is first placed on the plate N (removed from the face plate for the purpose), and secured there by shellac melted in position. It is then clamped down by the ring P, with leather pads between the metal and the wheel, and finally bolted to the face plate Q. The water supply in this case is carried through the spindle, which is hollow, and receives the supply from the tube, seen in Fig. 125, at the top of the spindle. In Fig. 38 the water is supplied also to the interior of the wheel by the passages shown at K and L. The wheel is secured by cement at M to the plate N, which again is mounted on the face plate Q. Owing to the porous nature of the wheels used, the inside of them is waterproofed with beeswax. In Fig. 37, close to the edge of the wheel is a metal band, which can be tightened on to the wheel by screws in its fastening; this should be set a short distance from the grinding edge of the wheel, and acts as a safety device.

Chucks are on the market in which the wheel is gripped a short distance from its working edge, and adjusted forward when worn. They are more complicated than a simple mounting, as described above, and, I consider, no more effective—in fact, the average overhang from the thrust bearing is much more. They have the small advantage of requiring no rear wall or projection. One such, illustrated in Fig. 47, is the pressed steel chuck of the Besly Grinder. As the wheel B wears it is adjusted forward by the flange E, which is threaded on D, and is then gripped by drawing the split ring A into its taper seat in the chuck body C, by means of the screws shown.

If the wheel is more of a cup shape—that is, has more wall at the back—the fixing with shellac or other cement can be omitted, but in large wheels the value of this extra piece has to be considered, as it cannot well be used on a Plain or Universal Grinder as a disc wheel, as the grade generally necessary in a cup wheel is much too soft for cylindrical work. For very large face wheels, such as are used for grinding armour plates, wheels built up of segments (either of natural or artificial stone) are used; the cost is less and the breaking-up of the wheel face enables them to cut better. Such a wheel is shown in Fig. 10; the segments are held in position by means of wedges, and can be adjusted as required.

Driving the Spindle.—In Figs. 34, 40, and 45, the driving pulley has a taper fit to the spindle, but the parallel fit shown in Figs. 35 and 36 is more usual. If the fit is a parallel one the pulley should be a light drive on the spindle, which should be designed to be withdrawn from its bearings without disturbing their adjustment. At the high speeds at which small internal grinding pulleys run, the centrifugal effect expands the hole in the pulley so that it floats on the spindle when running, and I consider that a conical fit is here much the better type.

For the usual proportions of diameter between pulley and wheel (0·35 to 0·45), the belt speed has not much effect, but when the pulley has the same or a larger diameter than the wheel (as in the case of some internal and cup wheel machines, see Figs. 45 and 37), the centrifugal effect affects the tension. In these cases the belt must be initially tight to pull well, but the centrifugal effect lessens the pull on the bearings as the spindle acquires speed. The effect is still further increased in the case of internal spindles, where the speed of the belt runs up to 5000 feet per minute. At high speed the belt must be wider than it need be at low speeds to give the same driving torque on the pulley, and to last well the belt must be pliable, as it has to run round a small pulley. The practical effect of running a belt at 5000 feet per minute is to add a tension in it of 125 lb. per square inch for the ordinary density of leather; if run at 2500 feet per minute the added tension is one quarter of this. The effect then is very considerable, and leather belts for driving internal spindles should be at least twice as wide as if calculated without allowing for the centrifugal effect.

Link beltings are so heavy in comparison with the working tension that they are of no use for driving wheel spindles, though their flexibility and being endless suggest their use. The centrifugal effect is easily calculated by integrating round the pulley, the relation between the tensional stresses p_1 and p_2 in the slack and tight sides being $\frac{gp_2 - \rho v^2}{gp_1 - \rho v^2} = \epsilon^{\mu\theta}$, where ρ is the density and v the velocity, using feet and seconds as the units.

Belts fitting on the sides of a vee groove are sometimes used for driving internal spindles: they run well, but I have no records of how they wear. Steel chains are used by Mr. Hans Renold for driving some of the grinding machines (both wheel spindles and feeds) in his factory. The wheel spindles are driven by 'silent' chains, as is shown in Figs. 183 and 124, which illustrate a rod grinder and a surface grinder respectively. The sprocket wheel need not be so large in diameter as a belt pulley, so that the chain would not run so fast as a belt. As a chain sprocket is really a many-sided polygon, the velocity transmitted by a chain is not quite uniform; the difference from this is, however, so small that no chatter marks are produced on the work thereby.

As a disc wheel wears down its circumferential velocity diminishes, and as the behaviour of the wheel and its factor of safety depends upon it and not on the diameter, this circumferential velocity should be kept constant by increasing the rate of revolution of the spindle. This is usually provided for by means of step cones in the countershafting, as shown in Fig. 33, where cones with two steps are shown.

If, however, an idler pulley be arranged on the wheel belt, as shown in Fig. 97, the speeds can be obtained by means of a step cone on the wheel spindle only. The driving pulley in the countershafting is then a flat-faced pulley only, and the spindle speed is easily changed by merely changing the belt from one step of the spindle cone to the other, and the tension idler takes up the belt difference. This arrangement has the further advantage that the tension in the slack side of the belt is controlled by this tension idler (the tension in the tight side is dependent on the power which is being taken), so that no great difference is made, as the wheel head moves in and out with the cross slide. The bearings then run under good conditions, and the slide itself need not be gibbed, but ways similar to those of the main slide used, and the wheel head kept down by its weight alone.

The spindle of Fig. 35 is driven in this manner, and the ways of the wheel head are as shown in the figure at X and Y, and the general arrangement of the drive is shown in Fig. 62.

In Figs. 79 and 82 are shown tension and idler arrangements on a self-contained machine. These general arrangements are more fully described in Chapter VI.

In face wheel grinding machines, the diameter of the grinding face does not decrease, and when one diameter of wheel only is used, one spindle speed only is necessary. Where, however, it is necessary to use cup wheels of other diameters, other suitable speeds must be provided, and this increases the range of usefulness of wheels of any particular grade.

Wheel Truing Arrangements.—It has been pointed out that in such cases as we are now considering the diamond or wheel truer should be attached to the work-carrying part of the machine, so that the relative motion of wheel and work will true the wheel correctly. In Figs. 29 and 30 the diamond tool is carried in a bracket on the tailstock. In this machine (Brown & Sharpe) the bracket shown is arranged to carry a tool for truing the side of the wheel, by aid of the cross-feed motion. Similar arrangements are shown in Fig. 77 and in Figs. 78 and 85, which represent the designs of the Churchill and Norton machines respectively. In all these the wheel is trued above the centre line, which is a matter of indifference if the spindle be parallel to the main ways, but if it be not it produces a slightly curved surface, so that the wheel does not cut over its whole face. To avoid this the Landis Tool Co. adopt the arrangement shown in Fig. 64, for holding the short diamond tool, which is here level with work centre. Although the arrangement does not appear so direct and substantial as when the diamond tool is held in a clamp on the tailstock, the diamond tool is here backed up by the work, as shown. The fitting is shown at D, in Fig. 110, detached from the machine. In the Cincinnati grinders, Fig. 112, the diamond tool is set 'level' with the axis by being put through the centre itself. Although these devices secure a theoretical point, I prefer supporting the diamond as rigidly as possible, with a minimum of overhang. The drawings show the axis of the diamond tool square with the face of the wheel, but it is rather better if arranged to be at a small angle (10° or 15°) to the normal to the surface, as the end is not worn flat so quickly.

It is not so necessary to use diamond tools on wheels for internal grinding and face grinding. In the former the wheels have frequently to be trued at short intervals, and it is easy to touch them up with a hard piece of carborundum where they are seen to be glazed, and it saves the time of bringing up the diamond tool. On the internal grinders of my design the diamond tool is provided with a fine adjustment, so that when one piece of a repetition lot is completed, the diamond point can then be set to the wheel, and serves as a kind of gauge, which prevents the hole being ground over-size, besides being always ready for use.

The act of truing a wheel brings a large number of facets into action, and makes the wheel more likely to glaze when it is on the point of doing so, than it is if trued by a rougher method. The best method is to have the wheel of the correct grade for the work, use the diamond tool, and the full face of the wheel; but as broken wheels have frequently to be used up on internal work this is not always possible, and wheels which are rather too hard have to be made to work, although the spindle is too springy to maintain the requisite disinte-

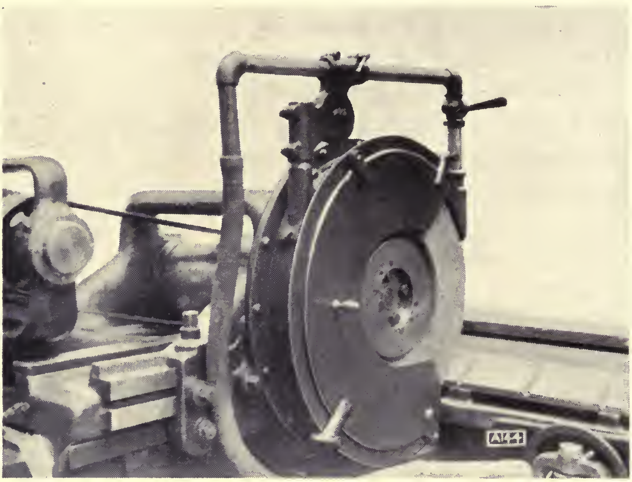


Fig. 48.—Steel Wheel Guard—Churchill

grating cut. Also owing to the exigencies of manufacture, small wheels made to an ordered grade are frequently somewhat too hard. Whenever possible water should be used on the diamond when truing the wheel. Where it is necessary to true a wheel to a particular shape to 'form' grind work, the diamond tool must be carried by a special mechanism, of which examples will be given later.

Wheel Guards.—Wheels may burst if run at excessive speeds, such as can be caused by the engine racing, or by mounting a wheel on a spindle speeded for a much smaller one. Forcing on too large a collet or an accidental injury may also cause a wheel to be unsafe. In machine shops doing accurate work such causes are infrequent, but the results are in any case to be guarded against, and the cast iron wheel guards employed are usually substantial. While the strength and inertia of such a guard are sufficient for wheels of moderate size, large wheels should have guards of wrought iron or mild steel. One such is shown in Fig. 48, which gives a closer view of the wheel head of the machine by Messrs. Churchill, of which Fig. 80 gives a general view.

To increase the capacity of steel wheel guards to take up the energy of a bursting wheel, the sheet is frequently bent into corrugations, as in the tool grinder by Messrs. Harper, Sons, & Bean, which is shown in Fig. 49.

FIG. 49.—CORRUGATED STEEL WHEEL GUARD—HARPER, SONS, & BEAN

Pumps and Nozzles.—The best type of pump for the circulation of the water is a centrifugal with its axis vertical, so that the bearings are above water-level. The flow is radially outwards, the water going into the pump disc at its centre, and being delivered at the increased pressure due to the rotation at the outer edge, and hence flowing to the delivery nozzle. The head against which a centrifugal will deliver depends (nearly) on the square of its velocity, and this makes it advisable that the speed should be constant, otherwise there is apt to be undue splashing at the delivery. The best arrangement of the piping is shown in Figs. 58 and 78, where the nozzle can be quickly swung out of the way, so that the work can be measured in comfort, and the nozzle then easily replaced in position.

The section of a pump is shown in Fig. 50. Here A is the body, B the paddle, and C the vertical spindle driven by the

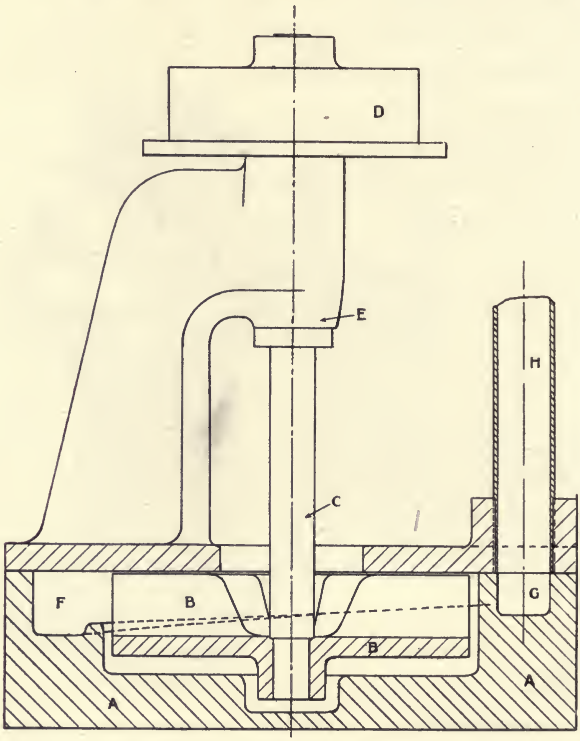


Fig. 50.—Centrifugal Pump

pulley D. The water-level must be well below the bottom E of the spindle bearing, but well above the top of the paddle. The fluid enters the paddle at the centre, and receives velocity by the rotation. It is delivered into a channel F of gradually increasing section, and finally delivered at the space G to the vertical pipe H. Pumps which require packing or have a definite contact in the working parts are rapidly ruined by the grit in the grinding fluid.

The simplest effective nozzle consists of a pipe cut off at about 45°, as is shown in Fig. 36 at L, and used with the lip nearest to the wheel. The pipe may be flattened towards the end. In small machines this is entirely satisfactory; larger machines usually have a special fitting, as shown in Figs. 57 and 58, or have an adjustable flap to the nozzle so that it can be spread as desired. It is very important that the fluid should be directed right on to the grinding point; the cutting points of the abrasive material ought to work in water, so that the heat produced is partly absorbed at once in the fluid. A certain velocity is needed in the jet to accomplish this, as the wind from the wheel blows the water about.

The speed of the wheel throws the water off as spray, the finer parts of which float as a kind of mist, and make such guards—as are shown at j, j' in Fig. 30, and in other illustrations—desirable. To reduce the spray to a minimum, traps for it are sometimes cast in the guards, as in Messrs. Churchills' machine on page 171, Fig. 58.

The Reversing Mechanism. — Two types of reversing mechanism are common in grinding machines: the trigger release and the plunger trip, which is usual in automatic slot drills. Of these the former requires less force, and has less wear. The chief cause of small variations in the reversing position is due to the momentum of the parts reversed, provided the trip mechanism is well arranged. The trigger release is shown in Fig. 51, which is a drawing of the reversing box of the Cincinnati Grinder, shown later in Fig. 112. The drive is through the pulley A seen on the left, which is fast on the shaft BC, on which the clutch D is keyed to slide. The shaft BC is enlarged where D slides, and two keys are shown fitted. The clutch D is alternately engaged with bevel pinions E and F by the clutch teeth on their faces; so that these alternatively drive the bevel gear G—indicated by its pitch circle—into which they both mesh, and thus give it, and through it the table of the machine, motion in alternate directions. When the top H of the reversing lever HJ is moved to the right, it moves the slider L on the bar MN to the left, carrying, by means of the springs P, Q, the bar with it, which thus moves the clutch D by means of the fork R, which is connected to it by means of a second bar, into engagement with the clutch teeth on E. The trigger S then falls with its tooth U behind the collar T, which is fast on the bar MN, and thus retains the clutch teeth in mesh. The table then runs towards the left, and when the stop moves the top H of the reversing lever to the left, the lower end J moves the slider L, which is

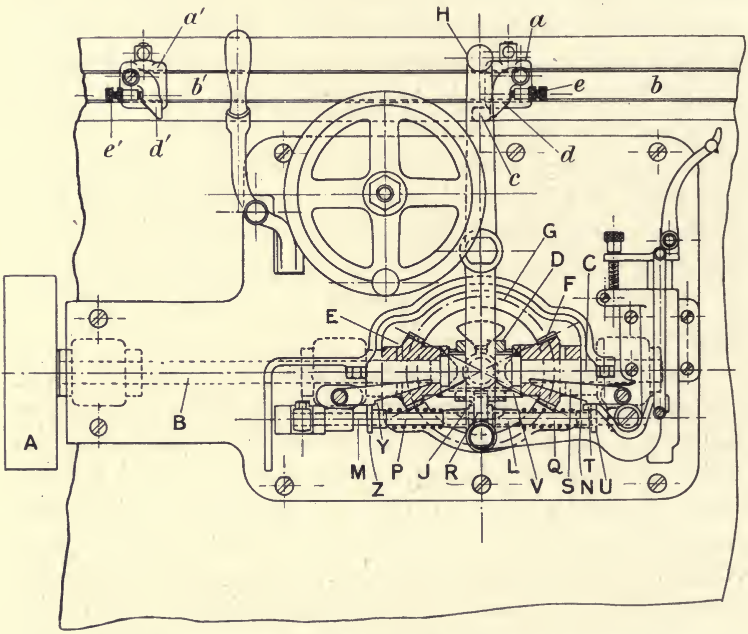


Fig. 51.—Trigger Reversing Mechanism—Cincinnati Grinder Co.

loose on the bar MN, to the right, compressing the spring Q. The rod MN cannot move, since the collar T is prevented by the tooth U of the trigger. The spring is compressed until the foot V of the reversing lever, after engaging the trigger S, lifts it so that the tooth U comes out of engagement with the collar T, and the spring then carries the rod MN, and with it the rear rod (which is connected to it), the fork R, and clutch D to the right, taking the clutch D from engagement with the bevel pinion E, and engaging it with the bevel pinion F; the tooth Y of the left-hand trigger then falls behind the collar Z, and so retains the clutch D in mesh with the right-hand bevel pinion, and the table now runs towards the right. If the motion is well made the moment of reverse is determined by the trigger edge, moved very directly from the table, passing the collar edge.

The arrangement is perhaps more clearly seen in Fig. 52, which is a photograph of the apron of a Guest No. 0 Grinder, taken during the erection of the machine. In designing, I

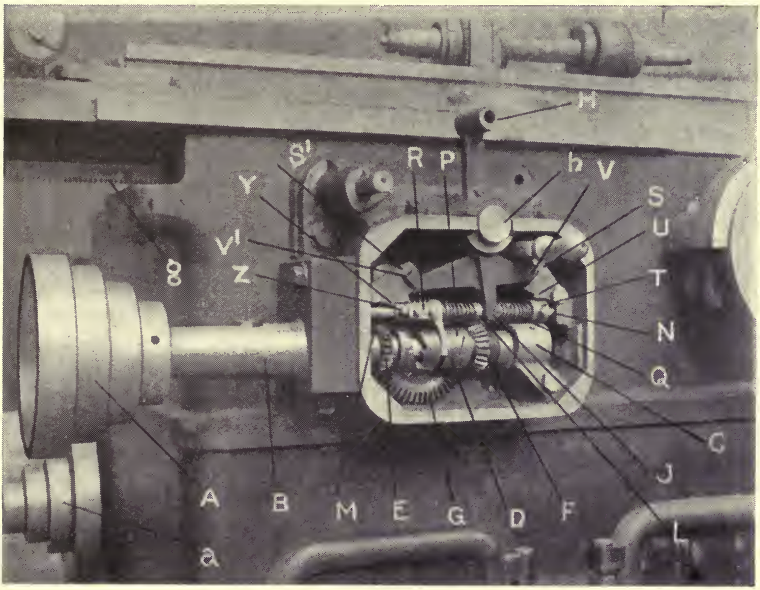


Fig. 52.—Trigger Reversing Mechanism—Guest

hold accessibility a cardinal virtue, and the removal of the apron cover accordingly exposes the whole reversing mechanism. The parts are lettered in the same manner as for Fig. 51, and the same description applies, except that here the fork R is carried directly on the rod MN to save shock. The step-cone A is driven from the step-cone *a* at the rear of the machine; the bevel gear G drives the rack *g* (and so the main slide) through intermediate spur gearing.

So far as the bevel pinions, gear, and clutch are concerned, the plunger type is the same; reversing is done by means of a plunger with a vee top which works against the foot of the reversing lever. This is illustrated in Figs. 53 and 96, where the reversing lever AB is shown with its top A to the right. The table is travelling to the left, and as the stop moves A over to the left, the bottom of the reversing lever B moves to the right, and in doing so forces the plunger D down, compressing a spring in the bracket E. When the bottom point of the lever has passed the vee of the plunger D, the latter rises and forces the reversing lever quickly over. The clutch F, which engages the bevel pinions G, H alternatively, is connected to the reversing lever through the lever J and bar K. This has two studs L, M, which the reversing lever AB moves, and there is a little slack between the lever and the studs, so that the clutch teeth keep in gear until the point of the reversing lever has passed the point of the plunger D, and then the reverse takes place rapidly. The sliding clutch F is slowly withdrawn from the bevel pinion clutch it is in engagement with till the moment of reverse, and is then quickly moved into engagement with the opposite bevel pinion. Once there the plunger retains it in engagement until the next reverse. The motion can be reversed by the lever N, which moves the rod K; by centralising N the clutch F can be centralised, and thus the travel motion thrown out of action. The motion from the bevel pinion is communicated to the table by means of gearing, the final movement to the table being given through a rack bolted to it. In small machines the small torque due to a screw and nut motion to the main slide has been found to produce inaccuracies in the work.

In the arrangements of various designers there are differences of construction in the reversing mechanism, but if the action is understood, any small matter getting out of order can be easily set right. One cause of failure to reverse in the trigger type may be noted, however—a trigger failing to fall owing to dirt or tightness due to any cause. The result is that, at the following reverse, as the spring is compressed, it slides the clutch out of engagement with one bevel pinion, without taking it over into the other, and the traverse motion stops; and as the defect is at the opposite side to the parts operating at the moment of failure, some time may be spent in locating

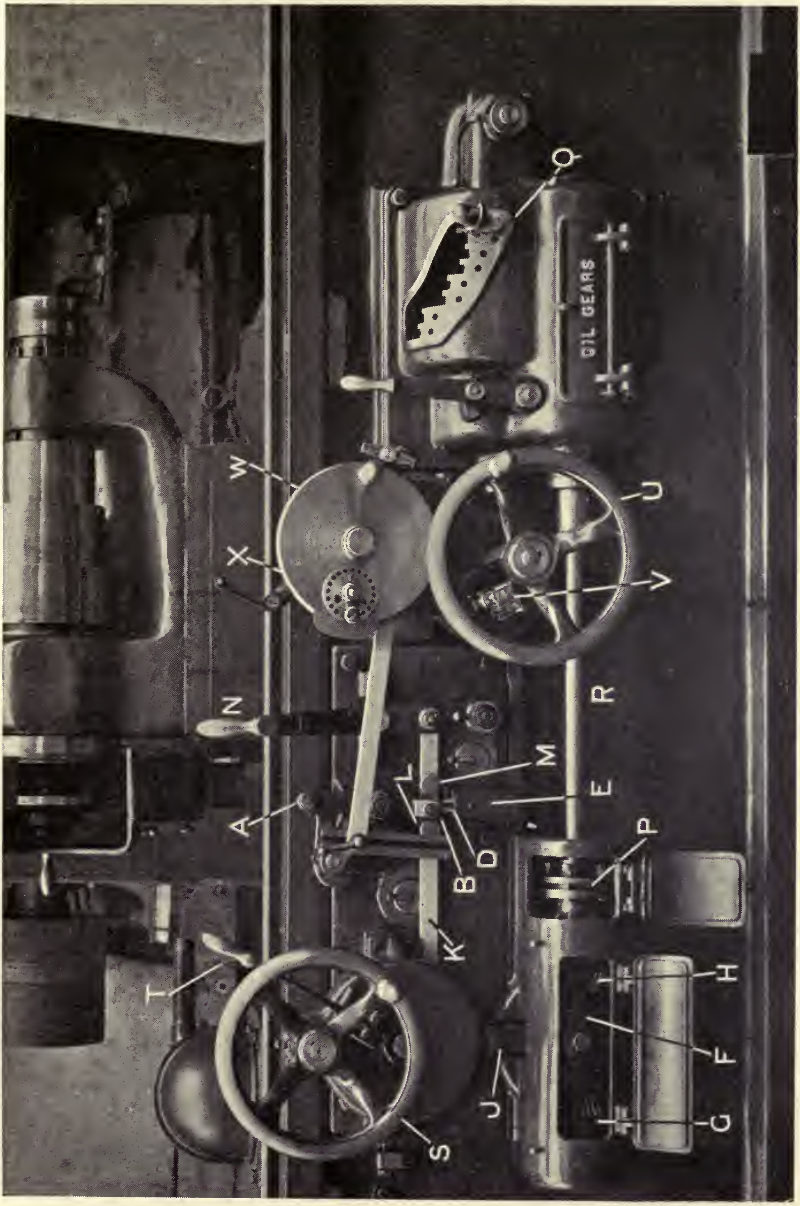


Fig. 53.—Feed Mechanism—Churchill

it. In these machines the reversing lever is operated by dogs seen at *a, a′* in Figs. 51 and 54. In the Cincinnati machine the stop bodies are clamped on to the vee *bb′*, and operate a fixed projection *c* of the reversing lever by means of swing pieces *d, d′*. These have a fine adjustment by means of the screws *e, e′*, and can be swung up so as to miss the projection *c*, so that the slide can be run beyond the reversing points when desired for gauging. On returning the table the projection *c* lifts the swing piece, which then falls into acting position again. In Messrs. Churchills' machines the stops are seen in Fig. 96, which is a view of an Internal Grinder, in which the traverse and reversing motions are the same as in the Universal and Plain machines. Here the stop bodies *a, a′* slide along a rack *bb′*, and have a fine adjustment by means of the screws *e, e′*, the flanges of which engage the rack. The stops operate on the withdraw pin *c* of the reversing lever, and by drawing it out against a spring the slide can be run beyond the reversing points. On returning the incline *dd′* pushes back the withdraw pin *c*. The engagement of the screw flanges with the rack makes it impossible for a stop to slip, although the operator may omit to clamp it.

Stops fitted to a rack are also used in Messrs. Brown & Sharpe's machines (see Figs. 29 and 54, in the latter of which the lettering is similar to that of Figs. 51 and 96); they are simply held by a clamp in the Norton Co.'s design, in which supplementary stops (see Fig. 56) for limiting the run of the table beyond the reversing points for gauging purposes are also fitted.

This direct connection between the main slide and the reversing mechanism is impossible where the main slide carries the wheel head, unless the machine were worked the wheel side of the machine. In machines for very large work this is probably the better arrangement, but in smaller machines it would be very inconvenient, and the mechanism for setting the reversing points is then provided on what is normally the front of the machine. The arrangement in the Landis machine is clearly seen in Fig. 98, which illustrates an Internal Grinder. The stops *a, a′* here are adjustable round a worm wheel *bb′*, and are given a fine adjustment by means of small worms c, c', which are in gear with the worm wheel. By lifting the small worms out of gear, the stops can be rapidly adjusted to the approximate position. The worm wheel is geared directly into the main slide rack and turns with it, making here nearly one complete revolution for the full main slide traverse—as is seen by the internal gear teeth at *dd′* on the worm wheel—which occupy nearly the whole circumference. The main slide is moved by hand by the wheel *f*, the shaft of which carries a pinion meshing, with the internal gear *dd.′* A similar arrangement is seen in the front view (Fig. 62) of the Greenwood & Batley Plain Grinder.

In plain grinders a pause or tarry device inserted in the gearing between the reversing mechanism and the main slide is an advantage: it should be adjustable as to the amount, and capable of being thrown out of action when required. For my machines I used a single-tooth clutch, which could be inserted more or less deeply in a clutch having steps of different height; this is an effective but simple device, as is desirable in mechanism which is enclosed.

The hand wheel for traversing the table should be geared so that its top moves in the same direction as the table moves. The action of throwing the automatic traverse into action should, on the larger machines, throw the hand wheel out of gear—for the hand wheel motion being geared down considerably to the table motion, its rim velocity is high when connected with the running table, and the momentum change at reverse causes severe forces on the gear teeth. I consider it to be advantageous if the movement of the throw-out motion normally causes the throw-out to take place at the next reverse, instead of immediately; thus the operator does not have to watch for that moment when he wishes to stop the wheel at the end of the work for gauging purposes.

The use of wide wheels and the recognition of the principle that the traverse per revolution of the work should exceed half the width of the wheel has led to rapid rates of traverse. The dynamic effects are the more considerable in the machines for work of small diameter. Although the main slide speeds are small compared with those of planing machines, the precision of reverse and absence of shock are so desirable that cushioning is being tried. The machine (Norton, 3 inches × 18 inches) of Fig. 85, has a cushioned reverse. The Greenfield Manufacturing Co. make a machine in which the main slide is driven hydraulically, the motion being controlled by a two-way valve, and in this they have the same end in view.

On all but the smaller machines it is desirable that an adjustable safety slip motion be fitted in the main slide drive, so as to allow the slipping to take place instead of serious damage. Such a slip motion is shown at P in Fig. 53, and consists of a flanged coupling between the shafts of the motion, driving by friction only. In this illustration (Fig. 53), it will be seen that the drive for the table traverse comes through a change speed box Q of the Hendy type, through the shaft R and friction P to the reversing box; S is here the hand traverse motion, and T the throw-out lever.

The Cross-feed Mechanism.—The lower end of the reversing lever in Figs. 29 and 51, the lower end of the plunger in some machines, and in Fig. 53 a rocking lever operates the respective automatic cross-feed mechanisms. These all consist of a ratchet wheel, operated by a pawl, to which a variable stroke can be given. A typical design is that of Messrs. Brown & Sharpe, shown in Fig. 54, and has been referred to on page 119.

The mechanism is operated by the vee point A at the bottom of the secondary lever B*c*, which, acting on the roller C, presses down the lever D to a definite position at each reverse of the table. After the point has passed the roller, the spring E pulls the lever D up until the end of one or other of the adjustable stops FG meets the curved arc B, near the bottom of the secondary lever. This limits the extent to which the spring pulls the lever up, and so the extent of movement of the ratchet H, which is operated through the link K; and this determines the number of teeth of the ratchet wheel L which the ratchet H will take at each reverse. The amount of feed is set by adjusting the position of the stops F and G, and can be arranged to be different at the two ends of the stroke, which is useful when it is desired to grind a diameter right up to a corner, as is described on page 97. The cross-feed is thrown out of action by putting the ratchet H out to the position H′, in which it is

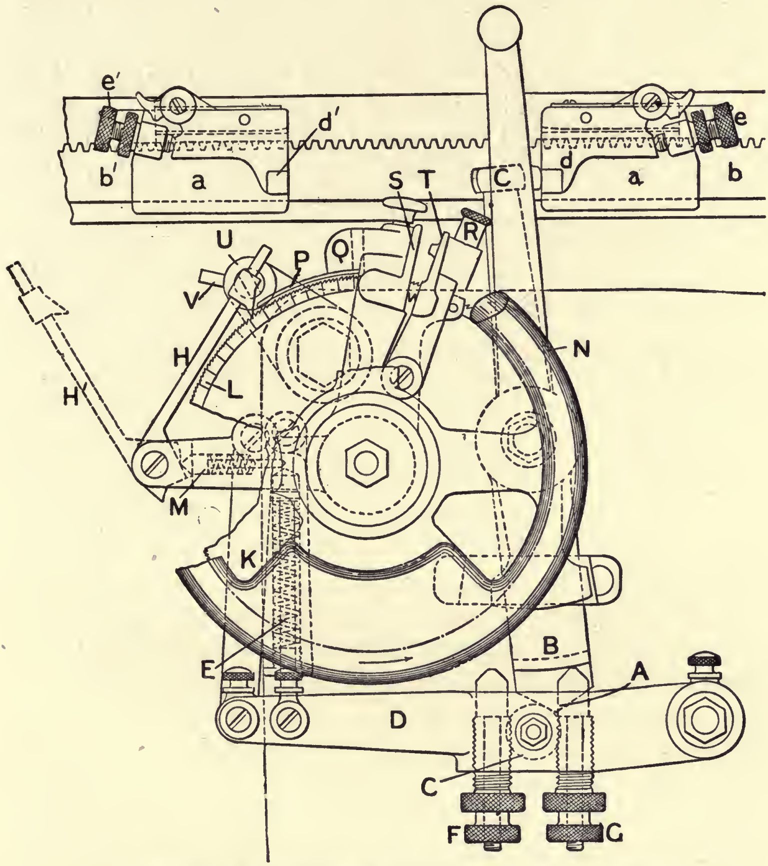


FIG. 54.—CROSS-FEED MECHANISM—BROWN & SHARPE

retained by the spring latch M. The wheel can then be run back by hand freely. As the feed takes place it carries round with the ratchet wheel KL, which is graduated and fixed to the hand wheel N, the shield P, which eventually comes underneath the ratchet H, and prevents it from acting, thus automatically throwing out the feed. This shield P is carried round by the arm Q, which is held in any desired position on the ratchet wheel by the plunger ratchet at R; it can be rapidly slipped round, moving it clockwise, and is provided with a latch adjustment ST. By squeezing ST together the part T containing the plunger ratchet R is approached to the grip S by an amount rather greater than the tooth space, carrying the tooth of the ratchet with it; on release it slips back over the next tooth, so that the result is that the shield has moved back through the space of one ratchet tooth.

Such a mechanical throw-out to the cross-feed action will trip the motion, so that the cross-feed disc is practically in the same position every time, and if the connecting mechanism to the wheel head is correctly designed and well made, work can be duplicated by such a device to an accuracy which is commercially satisfactory. The moment of the throw-out of the cross-feed movement may, however, be controlled from the size of the work itself, and the work size will then be independent of the wear of the wheel. Messrs. Pratt & Whitney and myself have independently brought out such devices; in both cases the control was electrical, the diminishing size of the work operating a lever which made an electrical contact when the work was to size, the resulting current energising an electro-magnet, which threw the feed out. Messrs. Pratt & Whitney employed a single diamond point to eliminate the effect of wear. In my arrangement the work was measured across a diameter by a lever caliper with hardened surfaces, and arranged to swing a little; this eliminated the effect of vibration, and made an accurate throw-out, although vibration was present. Electrical contrivances, however, make their way very slowly in workshops, and in connection with grinding machines there is the disadvantage that all wires and connections have to be very carefully protected from the soda water or oily solution used, as it is most destructive to the insulation.

To work satisfactorily any cross-feed must receive attention; the ratchet wheel and mechanism must be kept clean, and the cross-slide oiled and run to and fro over its full range occasionally.

In grinding one piece, after the work has been got parallel, the shield is set just short of the pawl H, and the automatic feed then takes off a thousandth or so, and is thrown out by the feeding up of the shield. The machine is allowed to run a few traverses more, and the diameter of the work is then measured, and the amount which it is over-size ascertained in quarter thousandths of an inch. The grips ST are then pinched once for each quarter thousandth of an inch the work is over-size, and the machine started again. The automatic feed is allowed to throw itself out, and the machine to take a few more traverses, and the work should then be to size except for the wear of the wheel. In most cases this is negligible, but if the work is large and the wheel has worn so that the work is still over-size, the grips ST are again pinched once for each quarter thousandth of an inch remaining, and the process repeated.

For repetition work, the ratchet H is thrown back from the wheel to the position H′ indicated by the broken line, and the wheel run back from the work one or two turns of the hand wheel. The next piece of work is then inserted in the machine, and the wheel brought up until it cuts, when the automatic feed is thrown in, and the machine left to its work. The position of the shield at which the wheel first cuts should be noted, so that the wheel may be brought rapidly up to it as the succeeding pieces are placed in the machine.

While the machine is grinding, the centres of the next piece should be cleaned and a carrier placed on it in readiness—two carriers are desirable for this purpose in small repetition work. In machines in which the accuracy of the cross-feed can be relied upon, when the automatic feed has been thrown out, and a few traverses more taken place, the piece of work may be removed without measuring it, and the next substituted, and the machine started. The piece removed can then be checked for size. If it is over-size beyond the limit, the cross-feed is at once compensated to take what may be allowed off, so that the piece then in the machine will be to size. After it has been finished the over-size piece can be returned for finishing.

Much work has one or both ends reduced for a short distance to take a wheel, or collar, or serve as a journal, and this distance is too short for traversing the table. The wheel is then fed in by hand, and to limit the cross-feed movement in this case a stop U is provided, which can be drawn forward by the handle V when required, and forms an abutment for a projection on the shield arm Q. This enables the diametral size of the short lengths to be duplicated easily; com-

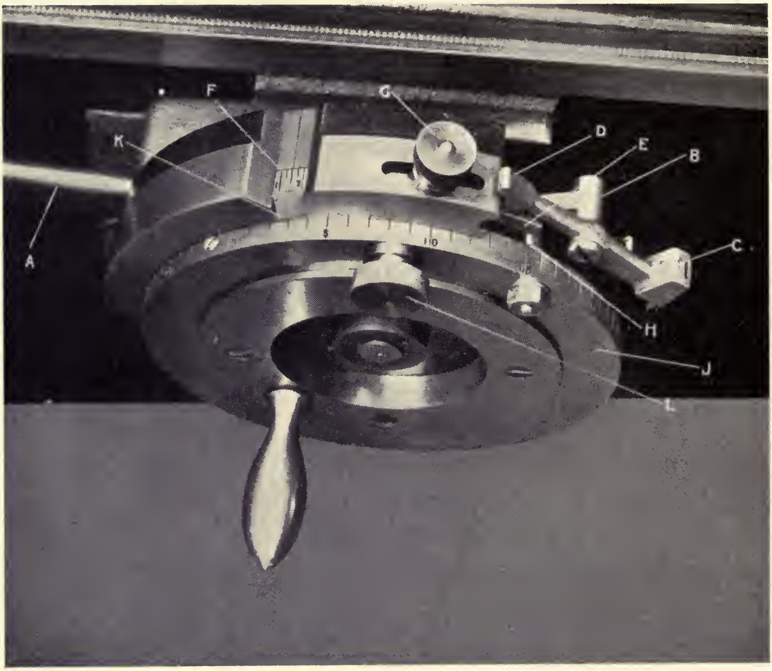


FIG. 55.—CROSS-FEED MECHANISM—GUEST

pensation for the wear of the wheel is made in the same manner as before.

In Fig. 55 is shown my design of cross-feed mechanism, illustrating some points which I regard as desirable. It is operated by the lever A, the other end of which is pressed down by an edge of the reversing dogs; by running the dog screw well out, the cross-feed action is thrown out at that reverse. The lever A rocks the arm B, pivoted concentrically with the spindle, so that the point C of the ratchet CD reaches a definite point each time. The amount of the return of the ratchet is controlled by the position of the end E of the arc EF, which is adjusted and locked by the knurled nut G. The graduations of this adjustment, seen at F, give the amount of cross-feed on the work diameter. The ratchet CD is shown retained in its out-of-action position by its end D. The ratchet is finally

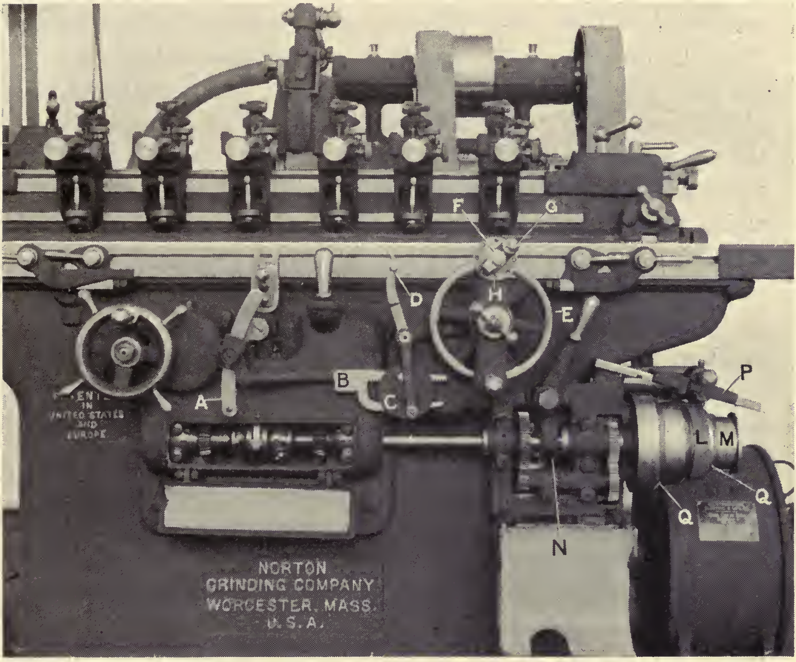


FIG. 56.—FEED MECHANISM—NORTON

thrown out of action by the stop H, carried by the graduated disc J; the throw-out takes place when the zero graduation reaches the fiducial mark K, so that the reading at any time gives the amount which the machine will feed before the throw-out takes place—as shown it is $3\frac{1}{4}$ thousandths of an inch on the work diameter. This enables the wheel to be brought rapidly into action in repetition work on which the grinding allowance is known. The knob L compensates for the wear of the wheel by shifting the disc J back on the ratchet wheel (not visible, and which is keyed to the shaft) one tooth at a time. The mechanism is enclosed to protect it from the grit.

The chief differences in the cross-feed mechanism consist in the driving of them. The Norton feed mechanisms are seen in Fig. 56: the drive is from a rocking lever A, through a sliding rack B and pinion C; this gives a considerable movement to the ratchet D, so that it first falls into engagement with the ratchet wheel E, then moves it, and then moves back to the position shown. This permits the wheel to be run back from the work at any time except when the ratchet is actually feeding, without the operation of throwing the ratchet out of engagement. The compensation for the wheel wear here is by a small pinion F, which meshes with the ratchet wheel, which is cut as a gear wheel for the purpose. The pinion is turned by the handle G, which has a plunger and a locating hole in the plate H corresponding to each tooth of the pinion; thus the movement from one locating hole to the next moves the shield back one tooth of the ratchet wheel, corresponding in this case also to 0·00025 inch on the diameter of the work. This is a positive device, and the position of the shield on the ratchet wheel cannot be moved without withdrawing the plunger and turning the handle G: it takes some time, however, to move the position of the shield far.

To adjust the amount of the cross-feed at each reverse, more or less movement is given to the sliding rack B by adjusting the position K, at which it is connected to the rocking lever A.

In the small Norton grinding machine shown in Figs. 85 and 86 a differential gear is included in the cross-feed mechanism, so that the usual movement through a ratchet tooth space is replaced by the larger one indicated by the notches at Q.

Where the wheel head and cross slide are the traversing part of the machine, the derivation of the speed motion has to be different, but the mechanism connected with the ratchet wheel is generally similar. In Fig. 57 is shown a side-view of the wheel head of a Landis Plain Grinder with automatic feed; here the ratchet wheel A, ratchet B, and the compensation latch C for the wear of the wheel, are clearly seen. The ratchet B is operated by the shaft D, which receives its motion from the lever E. At the reverse the plate F rises, pushes up the weight G, and feeds the ratchet; on the return of the plate, the weight G falls, carrying the ratchet back with it. The amount of return, and hence of the feed, is adjusted by the screw H. In Messrs. Greenwood & Batley's Plain Grinder (see Figs. 62 and 63), which is of the travelling wheel type, the attachments to the ratchet wheel are well enclosed, which is always a desirable

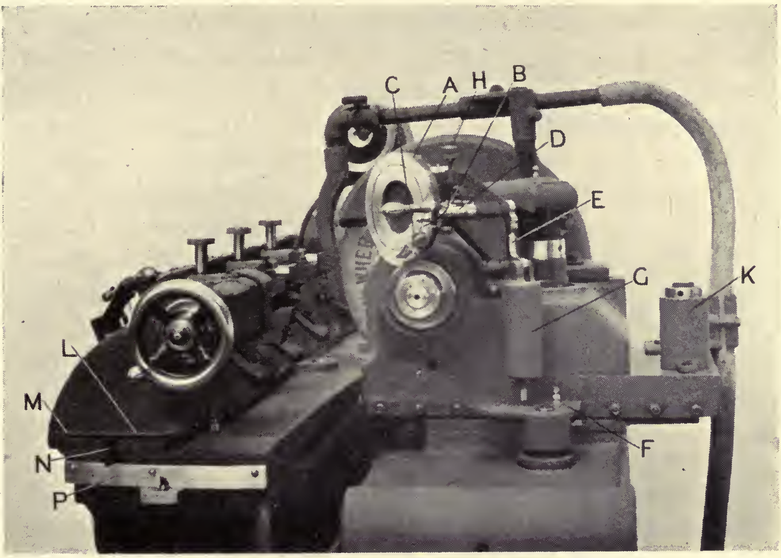


Fig. 57.—Landis Plain Grinder, End View

point in a grinding machine. The feed motion is arranged to operate at the end of the stroke, during the pause before reversing, by means of end movement of the main slide rack. The mechanism is carried on the main slide, so that the hand wheel and auto-gear do not move in and out with the cross slide. This is a desirable feature, particularly upon the larger sizes of machines.

It is very desirable that the movement given to the ratchet wheel corresponding to the minimum cross-feed should be an easily visible amount; also the operation of the ratchet wheel by the ratchet with certainty requires a reasonable pitch of tooth. This comparatively large amount of motion has to be reduced in a very large ratio to give the small movement (usually $\frac{1}{8000}$ inch) of the cross-feed, corresponding to a tooth space of the ratchet wheel.

This reduction is made by means of a worm and worm wheel in almost all machines, the final movement of the slide being produced by a rack and pinion. While this is undoubtedly convenient in the case of Universal grinders, I have a strong preference for a plain screw feed in the case of Plain grinders, though Messrs. The Norton Manufacturing Co.'s machines are the only machines, I believe—save those of my design—so fitted. Racks and pinions can be cut fairly accurately, but screws can be lapped to a very high degree of accuracy, as is described in a later chapter, and most measuring machines employ a screw as the final means of subdivision of the inch. The accuracy of the response of the wheel movement to the indications of the cross-feed disc is most important in manufacturing grinders, especially in repetition work where less skilled operatives are employed.

A cross section of the Churchill Plain Grinder, showing the arrangement of the cross-feed, is given in Fig. 58. The ratchet wheel A is fast to the pinion B, which is in mesh with the gear C, which is loose on the worm shaft DE. The worm F meshes with the worm wheel G, which is on a horizontal shaft carrying also a pinion H, which gears with the bull wheel, and this engages the rack L, fixed to the cross slide M. The backlash is taken out by the weight N, which holds the wheel head back from the work by means of the chain PP′. It will be noticed that the worm is fitted with ball thrust washers to lessen the friction, and runs in an oil box. The pinion R is keyed to slide on the shaft DE, and when moved to the right engages the gear C by means of the single-tooth clutch seen. The movement of the ratchet wheel A then operates the cross slide, the worm and worm wheel supplying the principal part of the reduction ratio. When R is in the position shown, it is out of gear with the automatic movement (but is always in mesh with the lower gear), and the wheel head can then be run rapidly to and fro by the hand wheel S, an indicator at T showing the movement.

This is very convenient when the work has considerable steps on the diameter, and also for truing the wheel.

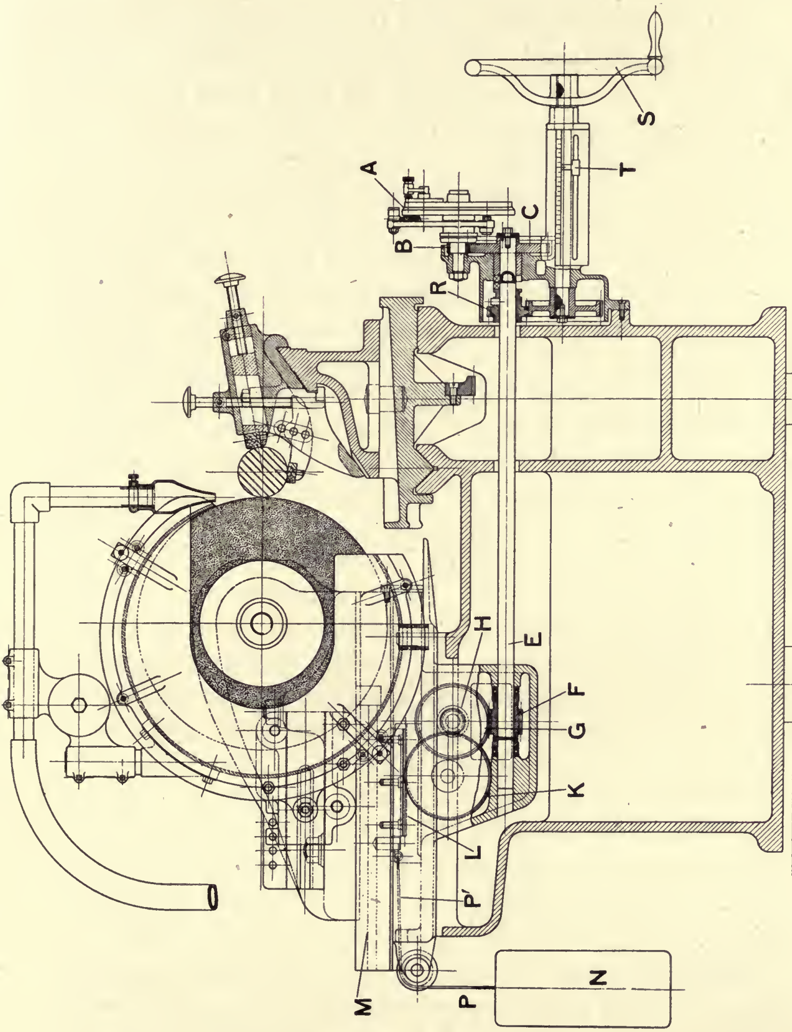


FIG. 58.—CROSS SECTION OF CHURCHILL PLAIN GRINDER

In Fig. 53 the front view of this mechanism is shown: U is the hand wheel for rapid movement of the wheel head, V the indicating slide, and W the hand wheel for fine movement of the wheel head. At X is an arrangement similar to that in

Fig. 56 for compensation for the wear of the wheel. The wheel head cross slide is not gibbed, but consists of a vee and a flat, as can be seen in Figs. 35 and 48.

In Universal machines, where the lower cross-ways swivel round a central point, this particular arrangement cannot be used; the only difference is that the worm wheel G then lies in a horizontal plane, and its vertical shaft is concentric with the stud about which the cross-ways swivel; the pinion at the upper end of the worm wheel shaft meshes directly with the rack. Many Universals have no arrangement for taking the back lash out of the rack and pinion, as a loose weight with its chain would be troublesome when the cross-ways were adjusted to an angle. Such an arrangement is very desirable, as precise correspondence of the cross slide position with the indications of the cross-feed wheel is very important in repetition work.

The arrangement of the mechanism between the cross-feed hand wheel and the rack in the Landis machines can be seen in Fig. 36. As shown, the cross-feed is not automatic. The feed disc M operates a worm shaft, the worm of which and the corresponding worm wheel lie in the casing N. The worm wheel shaft, the axis of which, PQ, is vertical, carries a pinion R on its lower end, which is in mesh with the rack S, which is bolted to the main slide of the machine by the screws shown. Here the feed motion moves with the wheel head. In Fig. 57 the part F operating the cross-feed automatically is seen to be elongated, so that it operates the feed in whatever position the wheel head happens to be. Here the slide is of the vee type, gibbed as shown at TT′ in Fig. 36. The cross-slide is here held back from the work by a spring enclosed in the case K, Fig. 57; the spring is helical, and used in bending (by twisting round its axis), so that its tension can be adjusted easily.

Steadies.—Another feature peculiar to grinding machines, though for Plain and Universal machines only, is the steady; of these a pair are shown at *k*, *k*′ on the floor in Fig. 29, and in position on the machine in Fig. 30. A line drawing of this steady is shown in Fig. 59, and is Messrs. Brown & Sharpe's design, used on all their machines.

Spring Type.—The object of steadies is to prevent vibration of the work and hold it firmly against the cut of the wheel. As the diameter of the work decreases by the grinding a little at each stroke of the main slide, steadies for grinding machines cannot be set once for all like a lathe steady, but must be arranged to keep in contact with the work continuously as its diameter decreases. Two types are in general use—those

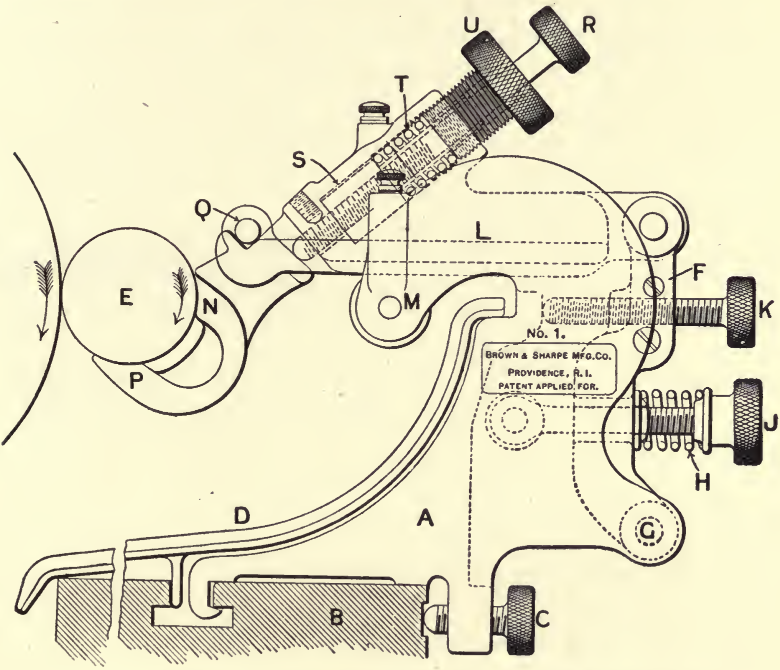


FIG. 59.—STEADY, SPRING TYPE—BROWN & SHARPE

adjusted by screws, and those held up to the work by springs; the steady of Fig. 59 is of the latter type.

Here the steady body A is clamped to the machine table B by the screw C; at D is shown a water guard, and at E a piece of work. A lever F is pivoted at G to the steady body, and is forced inwards by a spring H, the tension of which can be adjusted by the nut J; its forward motion is limited by the fine pitch screw K. This lever forces forward a sliding piece L, supported on a roller at M so as to move freely, and carrying a shoe which bears on the work at N and P. In order that the shoe should touch the work at both N and P it is pivoted to L at the vee Q, and adjusted by the screw R, the point of which bears on the rear part of the shoe. The nut S, in which the screw R works, is free to slide in the recess in L, and is kept down by the spring T, the tension of which is controlled by the nut U. The screw K controls the size of the work, and the

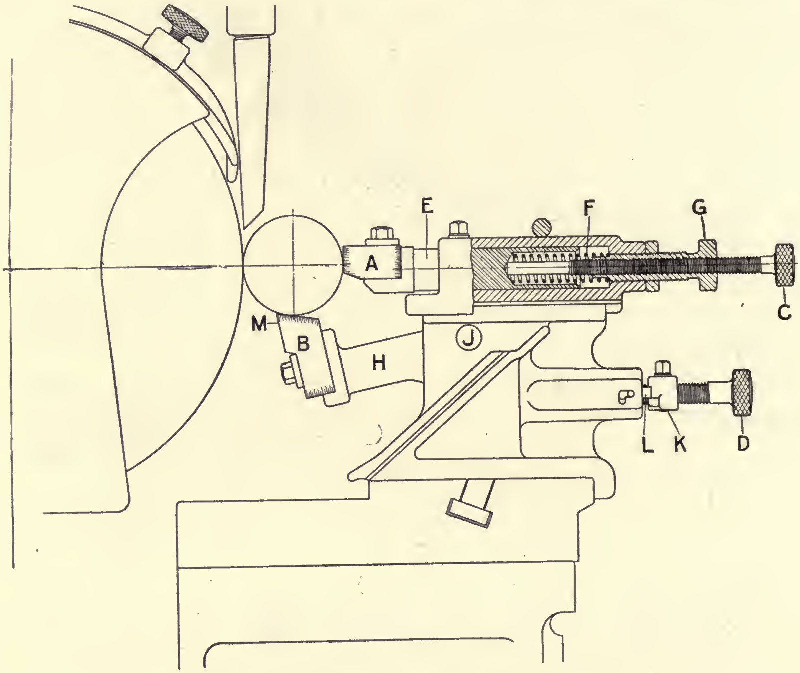


Fig. 60.—Steady, Screw Type—Landis

screw R adjusts the shoe so that it touches the work at the two points; both movements are spring controlled. When the work is to size the screw K is in contact with its stop and the nut S at the bottom of the chamber; while the work is being ground the shoe is forced into contact with the work at P and N by the combined action of the springs, neither the screw K nor the nut S being in their final position.

The shoes, though they are metal, wear as a number of parts are ground, and the screws K and R are adjusted to compensate for this wear. The screw K requires to be adjusted carefully, as it 'sizes' the work; thin work is sized at its ends by the cross-feed of the machine, the table being set correctly parallel first, but the intermediate parts are sized by manipulation of the steadies, using the screw K.

Screw Type.—In Fig. 60 is shown the steady of the Landis machines; here the shoes A and B are adjusted by the screws C and D respectively, which feed the screws up positively. The upper screw C is the more important, as it directly controls the work diameter: it acts directly on the sliding part E to which the shoe A is fixed. The shoe is moved positively by the screw C, but is pressed forward beyond the positive position by the spring F, the tension of which is adjusted by the screw G.

The shoe B is held by the bell-crank lever H, pivoted at J; it is operated positively forward by the screw D, the forward motion of which is limited by the adjustable nut K and withdrawable stop L.

Above the steady is the section of the rod on which the sheet steel water guards hang; the arrangement can be seen in Figs. 64 and 82.

In the Norton grinding machines the steady shoes are adjusted positively by screws, but no springs such as shown at F, Fig. 60, are employed; rollers are used to make the motion more sensitive. A series of steadies are shown in position on a machine in Fig. 66.

In these positively adjusted screw steadies the shoes are of wood; this supplies a certain degree of elasticity, which is desirable when the work is forced to the wheel by a hand operation. Should the force exerted be too great the wood yields and wears, while metal would present a firm support, and force the wheel to cut.

Brass or bronze shoes soon wear to a bearing on the work, and for repetition work are very desirable. When, however, the quantities are very great hard steel shoes are the best, and accurate stops should then be fitted. Occasionally brass shoes mark the work with a trace of colour, but it can easily be removed in finishing.

The shoes must bear as shown in Fig. 60—the shoe A opposite to the wheel, and B almost vertically beneath the centre of the work, but somewhat towards the wheel. After a little time the shoes wear at the contact points and provide bearing area; but there must always be a clear space between these areas, and when the shoe is in one piece, as in Fig. 59, this condition must be observed.

In machines of British manufacture (see Figs. 58 and 62) the simple screw steady without springs seems to be generally adopted. There is considerable difference of opinion as to

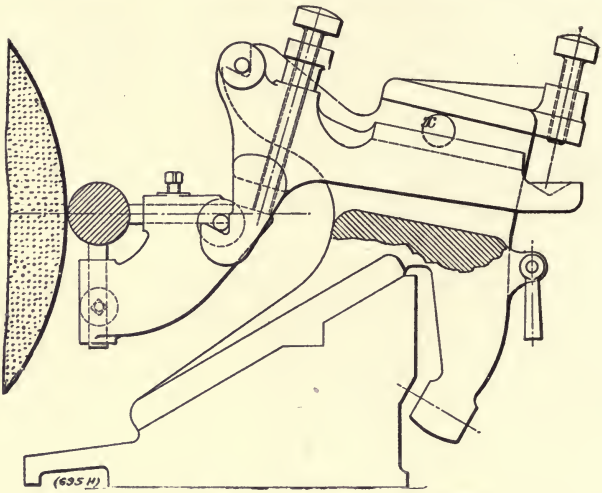


FIG. 61.—STEADY, AUTOMATIC—GUEST

what the pitch of the screws should be. If it is fine there is no sensitiveness to the touch—that is, the force with which the work is pressed cannot easily be felt when handling the steady screw. If the pitch is coarse, then the most minute amount of turn of the screw moves the steady block a very considerable (according to grinding accuracy) distance, and reliance has to be placed on the estimation of the force; as the effect of the force varies with different lengths and diameters of the work, each job requires a little practice.

The screw steadies need continual attention and adjustment, keeping the operator fully occupied. They are, however, very much easier to set up than the spring type.

Automatic Type.—The steady shown in Fig. 61 is one which I brought out and fitted to my machines (initially in 1904): it is arranged to work automatically. The main part is the rocker which swings in the top vees: as it swings forward one of the shoes (here pieces of rod adjustable for different sizes of work) touches the work, the second is then adjusted to touch it also, by means of a fine pitch screw bearing on the heel of the steady block holding the two shoes. As there is a 'change point' in the mechanism the moment the second shoe touches, this position is at once perceived, and the adjustment is very easy. The weights of the parts are so arranged that the shoes are pressed on to the work, but with a force of only a few ounces, so as not to spring it.

A steel ball is then placed in the inclined vee groove cut in the rear part of the rocker, and rolls down it until it touches the still more inclined surface above the vee groove, and takes a position as shown at x. Immediately a little has been ground off the work, the balance of the rocker causes it to move forward and to keep the shoes in contact with the work. The ball, however, acts as a continuous ratchet, and prevents the cut of the wheel forcing the work away. Although the whole steady is rigid, and metal to metal from work to machine table, the sensitiveness of the arrangement is such that no trouble occurs, though the shoes are metal. The swing latch at the back is to keep the rocker up and the steady block out of the way when inserting work. The action of the steady has proved to be sensitive and accurate.

The following records of tests indicate the degree of sensitiveness of this steady :—

	Test.	Maximum variation of diameter.
No. 1	Work $\frac{1}{2}''\times 9\frac{1}{2}''$—Bright drawn steel—3 measurements over $6\frac{1}{2}''$—1 steady ..	0·0003″
2	Work $\frac{1}{2}''\times 9\frac{1}{2}''$—Bright drawn steel—3 measurements over $6\frac{1}{2}''$—1 steady ..	0·0002″
3	Work $\frac{1}{2}''\times 9\frac{1}{2}''$—Reeled steel—3 measurements over $6\frac{1}{2}''$—1 steady	0·0001″
4	Work $\frac{13}{16}''\times 24''$ — Turned M.S. — 8 measurements over 20″—3 steadies .	0·0003″
5	Work $\frac{13}{16}''\times 24''$ — Turned M.S. — 8 measurements over 20″—3 steadies .	0·0004″

In these tests the steadies were adjusted to the work at the start, and not touched afterwards.

The steadies in position on a machine can be seen in Fig. 68. The block-adjusting screw is at K, and the block at M, while at L is the sizing screw for sprung slender work. Messrs. Pratt & Whitney more recently (patent of 1908) have brought out a similar, but not so sensitive, arrangement.

Follow Rest.—When work has already been ground nearly to size—within 0·001 inch—it may be steadied for finish grinding by a steady fixed at the wheel. The steady may be carried on the wheel head or on the body of the machine, if the wheel head does not traverse. As the steady is fixed at the wheel it is very efficient in preventing chatter, and highly finished accurate work can be obtained by its means. It can be used for parallel work only, and is best suited to large quantities of slender work of high accuracy.

In grinding rods and shafts a steady of this type is used; the rod is rotated and fed through the steady once only, the wheel being wide enough and of such grade and grit as to finish the work at a single pass. Such a machine is shown in Fig. 183; very fine adjustments are fitted both to the wheel and to the steady, and the latter is of hardened steel.

Machine Bodies.—It has been pointed out that the forces at the grinding point are very small compared to those occurring when cutting tools are used, but it will have been observed that the bodies or main frames of modern grinding machines are very massive, when compared with the bed of a lathe for work of the same size.

This is partly to meet the requirements of accuracy and partly to check vibration. To ensure the maintenance of accuracy of the ways the modern practice is to provide three feet to the machine body, and upon these it is to rest, and the remainder of the space beneath is to be clearance; the body is scraped and the slides fitted when it is resting thus, so that the machine works under the same conditions as it is manufactured. The feet are shown at U, V in Fig. 58, and also the clearance space between the rest of the machine and the floor. The machines are not to be bolted down, they merely rest by their own weight, which is arranged to be quite sufficient for the purpose.

When the machine is very long this method is not adopted:

a good concrete foundation is prepared, and the machine levelled upon it, supported by adjustable taper wedges. These can be easily seen in Fig. 83, which gives a view of Messrs. Nortons' largest machine. The wedge moved by means of a screw gives a very fine adjustment, so that the machine may be set true in itself and kept true, although the foundation may sink or distort. While rigidity in the vertical longitudinal plane is important, it is more so in the vertical plane perpendicular to that, and in the horizontal plane, although these rigidities appear to be sometimes slighted by designers.

Although these rigidities are always to be considered, in the bodies of the machines of my design, attention was especially paid to the breaking up of the vibrations by placing the stiffening ribs of the correct shape in suitable positions. By a suitable design both aims can be secured by the same metal correctly located, so that the machine while not increased in weight will be less subject to vibration troubles. The mechanical principles upon which vibrations depend are those given in treatises on dynamics, and are obtained from the general laws by neglecting, as far as is possible, the squares of small quantities. A brief treatment adapted to the scope of this work has been given in Chapter IV.

CHAPTER VI

PLAIN GRINDING MACHINES AND EXTERNAL WORK

Development of the Plain Grinder.—As the Universal Grinder was steadily developed, it gradually became evident that much of the unhardened steel work, previously completed in the lathe, could be profitably transferred to the grinding machine for the finishing process—that is, not only was the finish obtained of a higher quality, but that it often at the same time cost less. This opening up of the process of finishing by grinding as a manufacturing method naturally led to the construction of simpler but more powerful machines, for external work only, which machines hence acquired the name of Plain Grinders.

Compared with the Universal Grinder, work capacity for work capacity, the Plain Grinders are fitted with wider wheels, usually of greater diameter, have a more copious water supply, more rapid feeds, and generally are more stiffly built, and take much more power. The cross-ways, wheel heads and work heads have no swivelling adjustment, and in the larger machines, which are intended for parallel work only, the work table also does not swivel; the parallelism is then secured by use of a set-over tailstock.

The comparative simplicity has given the opportunity for certain improvements. In the Brown & Sharpe Universal Grinder, Figs. 29 and 30, the table H is flat on the top, which presents advantages in some work which these machines are occasionally called upon to do, but it does not offer a corresponding advantage for plain—that is straight or slightly taper—work done between the centres; and as a table section somewhat of a triangular or L section has a greater rigidity, and yet does not increase the height of the work from the main ways, such a section has become usual in Plain Grinders. In some designs the system of protecting the table by means of short pieces of telescopic guarding—as shown in Figs. 29 and 30 at *g*—which require arranging for each different length of work, also gives place to protection by arrangements requiring less attention. Where the wheel head travels there is more inducement to retain the flat-topped table which does not travel, and so can be easily made deeper. This is the case in the machines shown in Figs. 62, 63, and 110, which are a Plain Grinding Machine by Messrs. Greenwood & Batley, and the No. 1 Universal Grinder of the Landis Tool Co. respectively, in both of which the wheel traverses. The guards consist of sheet steel pieces bent to the requisite shape and hung from a rod, reaching from one end of the table to the other. The top of the table in these machines is flat, and the centres are aligned by the vertical scraped edge D (Figs. 62 and 63), against which the headstock and tailstock are pulled by the action of the bolts, the heads of which lie in an inclined tee slot, as is seen best in Fig. 64, which shows the section of the table in the Landis Plain Grinders, and the mode in which the parts are fitted to it. The parts are lettered to correspond.

The Table Section.—The table A has a flat top B, on which the tailstock C rests, and a vertical edge D, against which the aligning edges of the headstock and tailstock are pulled by inclined bolts E, E′—the slot F for the bolt heads being correspondingly inclined. The sheet steel guards G, H, K are shown, hanging round the horizontal rod J. These parts are also seen in Fig. 57, where LM is the flat top of the table, the slot in which is marked N. Two sets of graduations at P will be noticed. This is useful and customary, the graduations being in degrees and in inches per foot taper. Where the table, for the sake of rigidity primarily, is given a shape having a somewhat triangular section, the detail can be arranged—after providing suitable guiding edges for the headstock and tailstock—to assist in carrying off the water. In the case of small machines the headstock and tailstock may be of the 'swan neck' type, and overhung from ways on the side of the table farthest from the wheel, as is shown in Fig. 65, which gives the table section of

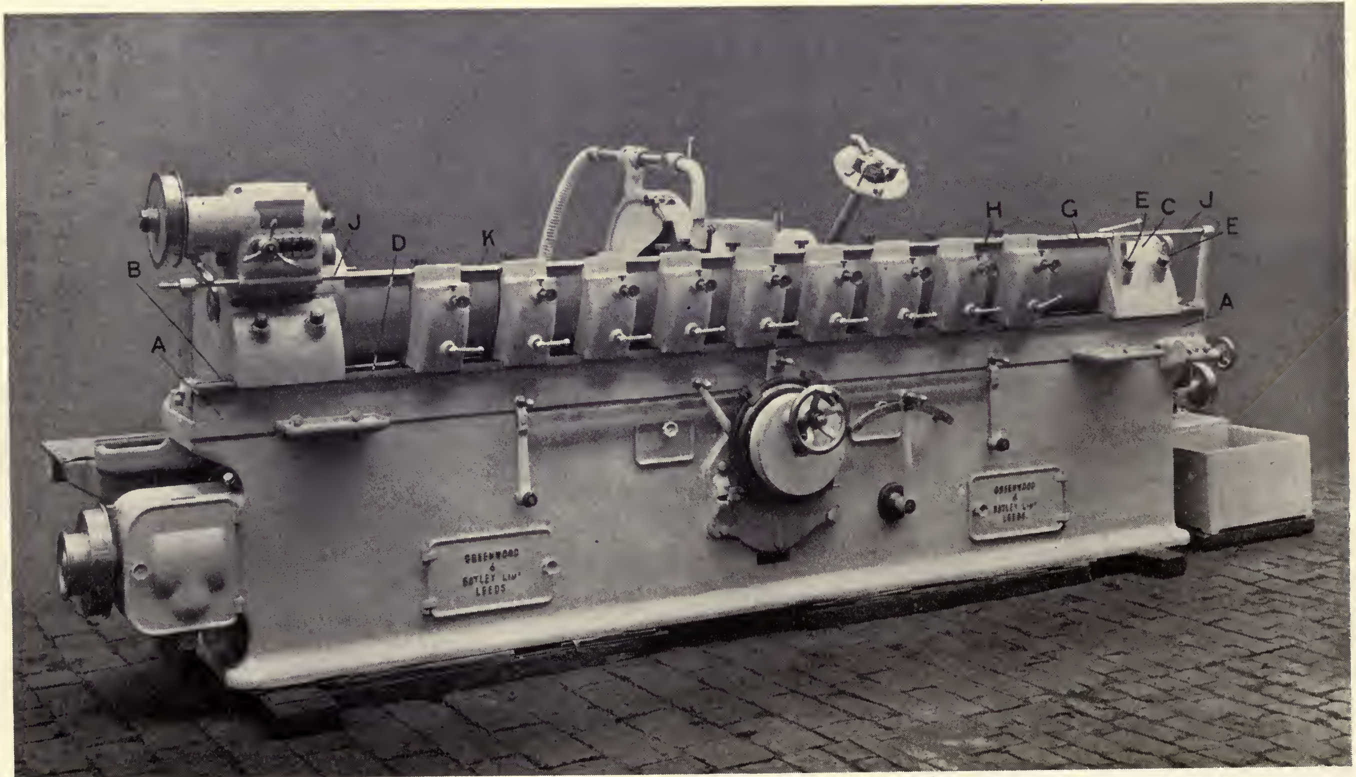


FIG. 62.—GREENWOOD & BATLEY PLAIN GRINDER

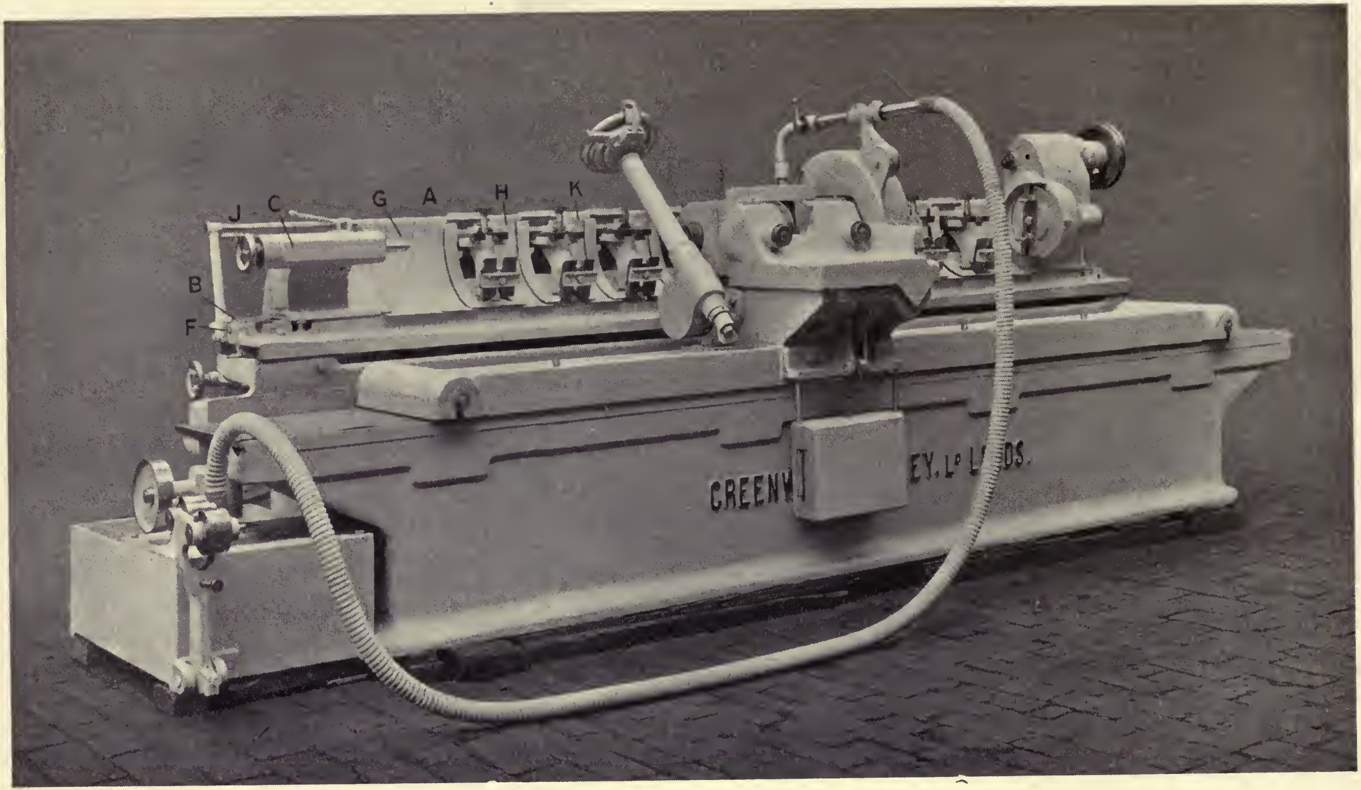


Fig. 63.—Greenwood & Batley Plain Grinder

Messrs. Brown & Sharpe's No. 11 Plain Grinder. Here the ways A, B which support and guide the headstock and tailstock are well protected from grit and splash by the sheet metal guard C. This guard with the inside DE of the table forms a surface off which the water runs to the channel F of the main slide G. In larger machines it is desirable that the supporting

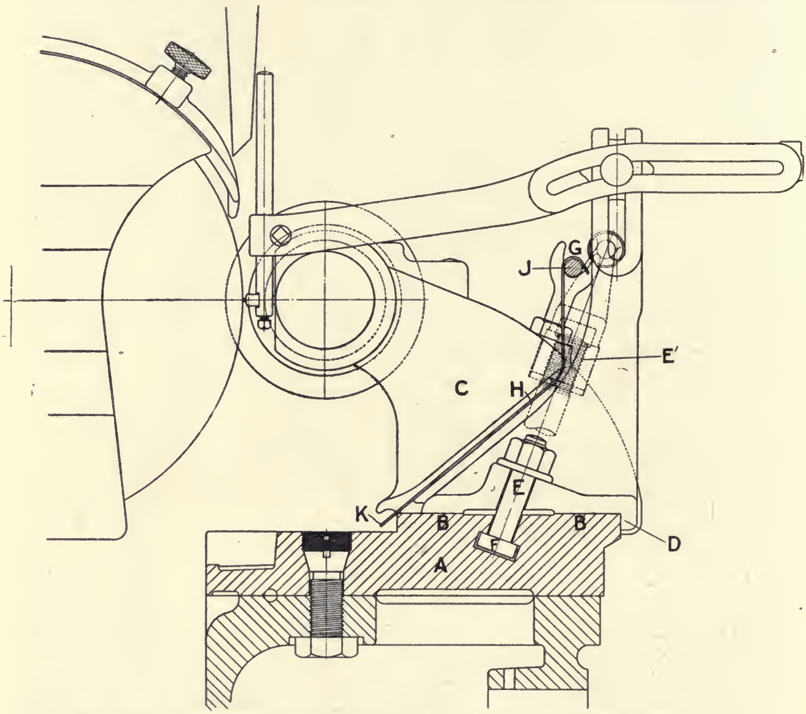


Fig. 64.—Headstocks, Table, and Guarding—Landis Tool Co.

parts for the work should have as little overhang as possible, and more rigid designs are adopted, Messrs. Brown & Sharpe then using the slip guards described above.

Mr. Norton's design can be well seen in Fig. 66. Here the upper ways A, B are protected by the vertical projection C, and the lower way D has the sheet steel guard E jutting out over it. The tailstock leg and foot F is doubled round the sheet steel plate E to rest on its way D. The groove G is merely for the heads of the clamping bolts to fit in, and it is a matter of indifference that the water flows on to it. The headstock and tailstock are bridged across from one way to the other by these curved legs, and the swan neck type of overhang is avoided.

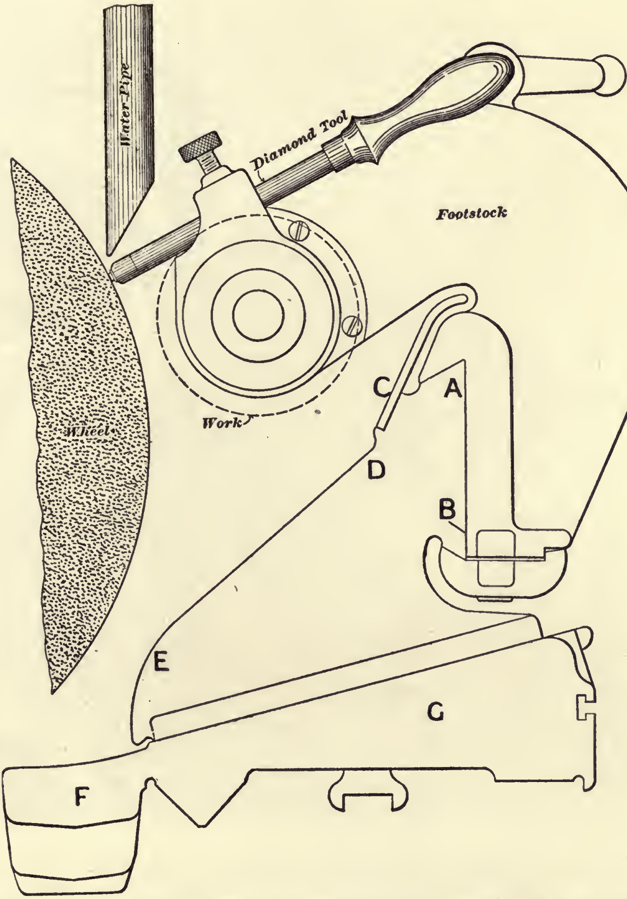


FIG. 65.—HEADSTOCK, TABLE, AND GUARDING—BROWNE & SHARPE

In Fig. 67 is a sketch of my design of table section and of method of protection of the ways. Here the guards consist of three pieces of sheet steel, one, ABCD, fastened to the table and reaching the whole length between the headstock and tailstock when separated to their limit, and pieces EF and GH about half that length—the former carried by the headstock and the latter by the tailstock. These three guards telescope as the headstock and tailstock are adjusted, and protect the table completely in all positions; to allow of this telescoping the

Fig. 66.—Norton Plain Grinder, End View

guard ABCD is joggled at the centre, the piece AC running towards the headstock and through it, and the piece BD towards the tailstock and beyond it. The object in enclosing the table so completely along the bottom edge at DF is to prevent the wind from the wheel blowing the gritty liquid round the guards to the grinding way. For work of large diameter these guards are easily removed; the table must then be cleaned up before replacing them. For purposes of rigidity the guards pass through a curved slot KL in the headstock, so that overhang is avoided. The tailstock is slightly inclined, to allow the lower

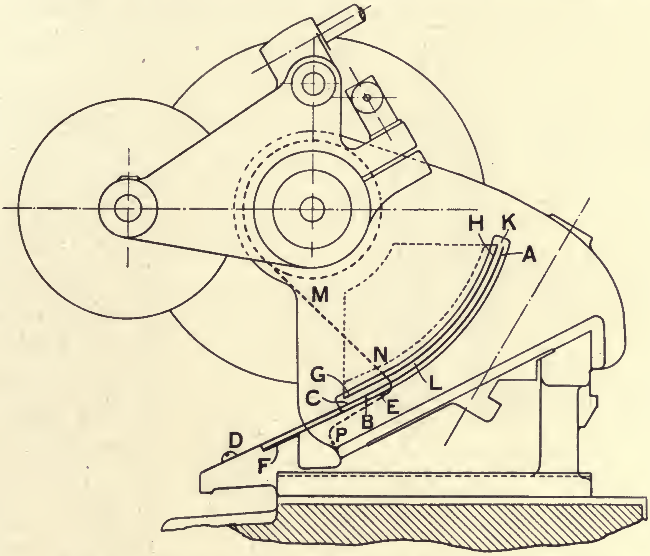


FIG. 67.—HEADSTOCKS, TABLE, AND GUARDING—GUEST

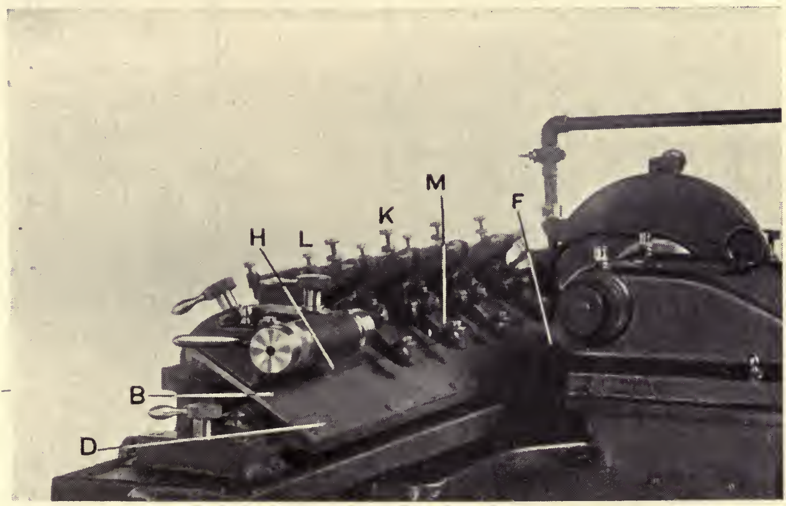


FIG. 68.—GUEST PLAIN GRINDER, END VIEW

parts of the guards to pass it. The appearance of a table so enclosed is seen in Fig. 68, which is a view of an 8-inch by 48-inch machine, and in which the lettering corresponds. A number of steadies are shown in position.

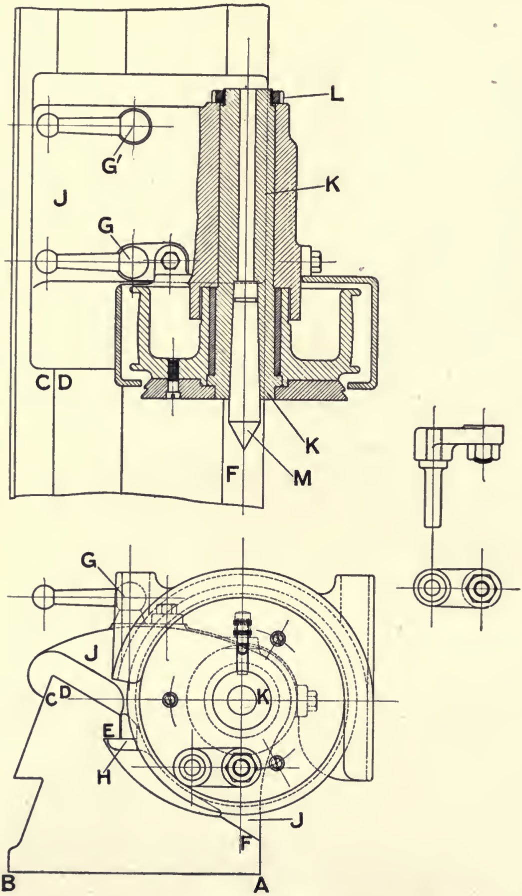


Fig. 69.—Plain Grinder, Work Head—Churchill

In machines where the table ways are well protected, a little attention is nevertheless necessary, as spray floats in the air and settles on surfaces, finally collecting into drops. These must be occasionally wiped up. Also a shoulder on the work or a keyway may cause splashing if the water supply has a slightly too high velocity.

In the machines of Messrs. The Churchill Machine Tool Co., the table is of a triangular section which carries off the flow of water easily, but no attempt is made to protect the table ways from fluid and grit except that drain gutters are cut across the lower ways. The table is quite open, and can be got at without difficulty for wiping up when the position of the headstock or tailstock is changed, as can be seen in Figs. 58 and 80.

The Work Head.—As Plain grinders are intended to be used for work between the centres only, there is no necessity for the work-head spindle to be fitted into bearings, as all it has to do is to support the centre, which is dead. Accordingly the headstock in these machines is simply a bracket into which the spindle, carrying the dead centre pulley and centre, fits tightly: and this construction has the further advantage that there is now no oil film round the spindle to produce its effect on the work. Fig. 69 shows the construction of the headstock of Messrs. Churchills' smaller machines. The table section is shown at ABCDEF, AB being the surface where it fits the main slide, CD the upper guiding way, and F the lower, and E the clamping edge, whereby the bolts GH, G′ clamp the headstock J in position. The spindle K is a tight fit in the headstock, and is drawn in by the nut L: it is bored through so that the centre M can be easily removed for sharpening. The dead centre pulley has a bronze bush, and rotates easily on the spindle; and a protection plate is screwed on to the front of it. It is surrounded by a fixed protecting casing with belt apertures; at the side is shown the driving pin, which can be adjusted to any convenient distance from the centre.

The Centre Grinding Head.—Since the work-head spindle does not rotate, a separate small running head is provided in Plain grinding machines for the purpose of receiving the centres and rotating them for grinding their points true. It is common practice to make these small heads with their axes at a fixed angle of 30° with their ways, so that when placed in position on the grinding machine table they sharpen the centre to an included angle of 60° when the table is straight; they may, however, be made adjustable, or at any angle to suit particular work.

Although the centre grinding head is a small attachment, it is an important one; the taper hole for receiving the centre must be run dead true, otherwise when the centre is placed in the main headstock it will be out of line, which will create trouble continuously.

The Driving of Plain Grinders. Belt Drives only.—In the headstock just described, which is typical of the headstocks of small Plain grinders, the dead-centre pulley is driven by a belt from a drum overhead, as is shown in Fig. 70, which gives the general arrangement of the whole of the drives for this machine —the Churchill 6-inch Plain Grinder—and may be compared with Fig. 33 giving the corresponding arrangement for Messrs. Brown & Sharpe's No. 1 Universal Grinder, both of which machines are of the travelling work type. Here the fast and loose pulleys A,B for the main belt are on the first shaft CC′, on which is also the pulley D which drives the wheel spindle. There are two speeds provided for the wheel spindle, obtained by moving the belt at the wheel head, and one two-step pulley EE′ only is used. The belt runs as shown under a tension idler F, which compensates for the difference of diameter of the steps on the wheelhead pulley, and also for the variable position of the spindle in and out, preserving a requisite tension on the slack side of the belt. Thus the adoption of a tension idler adds considerably to the life of the wheel spindle bearings, besides rendering the change of its speed easy.

The first shaft CC′ drives the second shaft at the rear by means of the pulleys G, H, so that it runs at constant speed. From the second is driven the drum for the work, the pump, and the feed: the pump from the pulley J, the feed by means of the step cone K on the second shaft and L on the machine, and the drum shaft by means of the step cones M, N, the latter of which is connected to the drum shaft P by means of a friction clutch Q. This is operated by the lever R on the machine through the connecting-rod S; the brake is shown at T. The drum P drives the dead centre pulley.

It will be noticed that the traverse is driven from a constant speed shaft (by the cone pulleys K and L), while in Fig. 33 it is driven (through the pulleys *y* and N) from the shaft of the drum which drives the work. In the latter case the traverses therefore are a definite amount per revolution of the work, and this possesses the advantages illustrated in Fig. 26 (page 95). Plain grinders, however, generally have the traverses driven independently, and the makers give various reasons for the

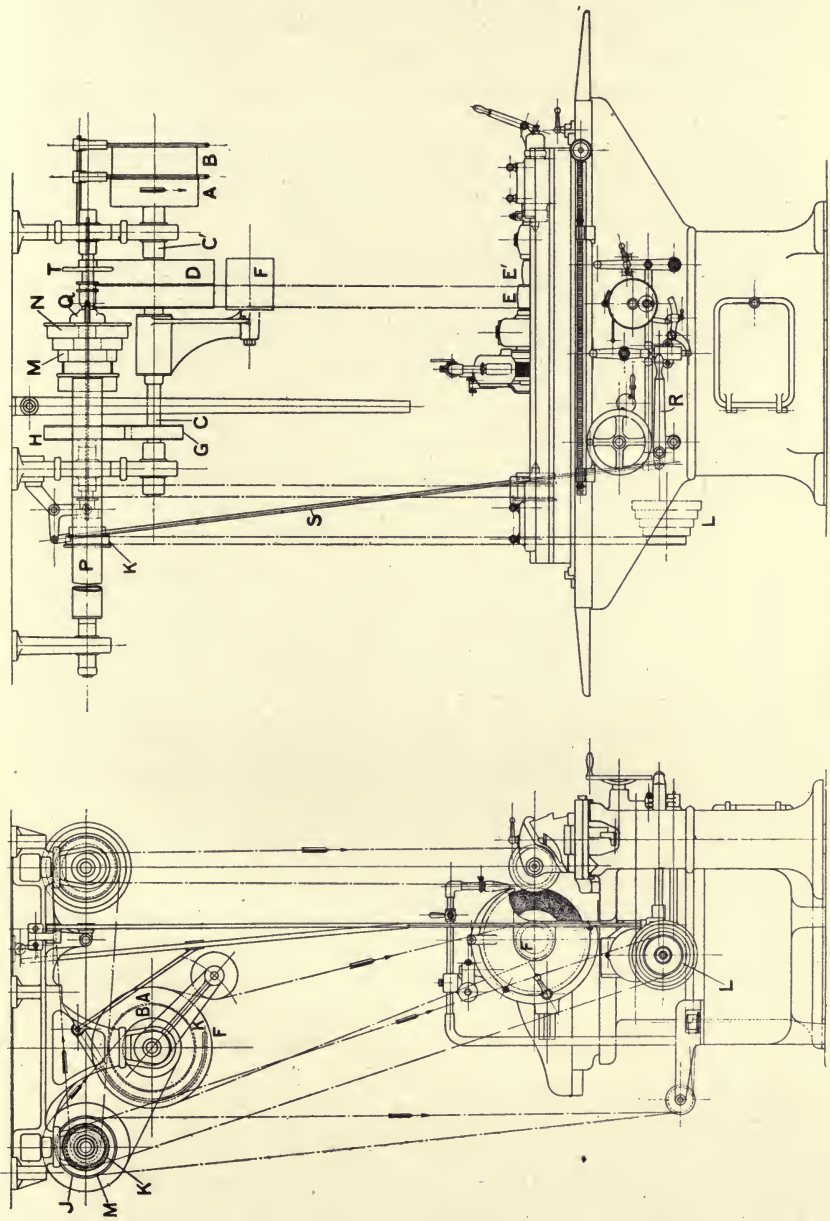


FIG. 70.—ARRANGEMENT OF DRIVE OF PLAIN GRINDER—CHURCHILL

arrangement ; one, however, does not appear to have been referred to—namely, that high rates of rotation must be provided for work of small diameter, and a traverse of nearly the wheel-width per revolution then gives so high a velocity to the main slide that the shock of the reverse must be cushioned, or will lead to trouble if used. If the traverses are independently driven, a limit of speed suitable to the machine and its gearing can be easily arranged.

Rapid Speed Changing Arrangements.—This drive is nearly the same as that shown for the Universal; it has added a tension idler to the down wheel belt, which permits the wheel speed to be changed easily, and adds some other advantages. Where speeds have to be changed frequently in manufacturing machines it is desirable that it should be an easy and quick operation, and on the larger grinding machines it is now customary to fit such arrangements, and is beginning to be so on the smaller sizes. They usually take the form of gear boxes of either the Hendy, the spring key, or sliding gear type, such as are in favour in modern machine tool practice. The operator of a grinding machine is continually making measurements to a fraction of a thousandth of an inch, and welcomes any convenience which makes it unnecessary for him to handle a greasy belt, so that the obtaining of the various speed changes by the movement of a lever has a secondary gain, besides that of the time directly saved.

As regards the change of work speed, there are two very different arrangements : according to the first, the speed of the belt to the dead centre is changed by a gear box through which the drive goes ; while in the second the gear box is on the work head itself, and the work is driven by a dead centre gear. The former type is used not only on Plain machines, but also on Universals, and is hence better illustrated by taking an example from among the latter. Fig. 71 shows the general arrangement of the drive of the Cincinnati Universal Grinder, in which the speeds are obtained by gear boxes carried at the rear of the machine. Here the main drive is to the pulley A on the first shaft BC. This shaft drives the wheel spindle pulley D by means of the pulley E, giving one speed only, and the gear box pulley F by means of the pulley G. From the left hand part of the pulley F the pump is driven by a belt to the pulley H and then through gears. The gear box is shown in Fig. 72. The pulley F drives the top shaft which, by means of the

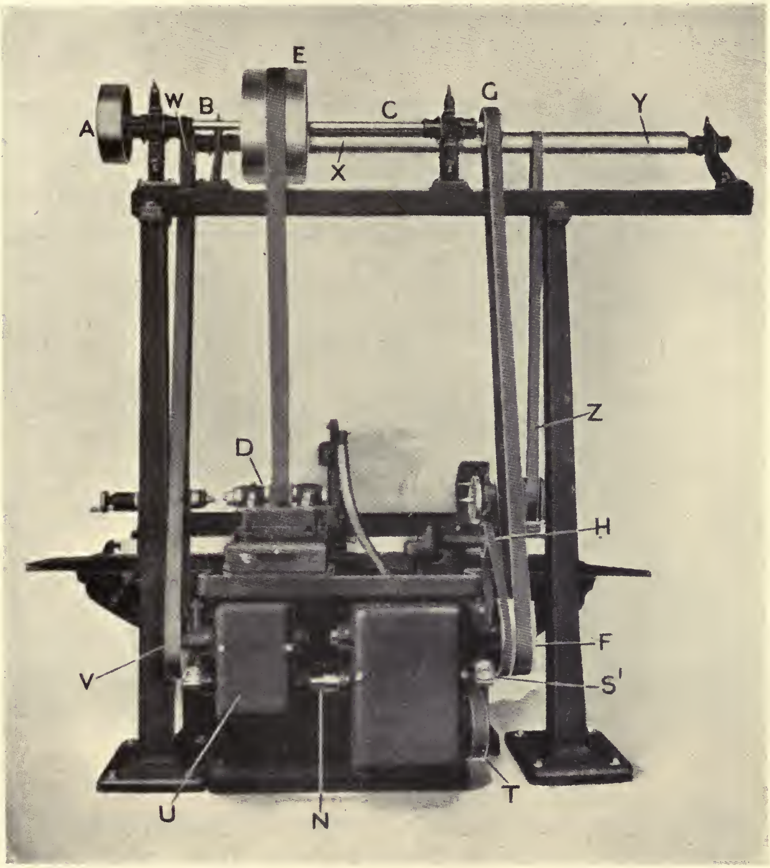


Fig. 71.—Arrangement of Drive—Cincinnati Grinder Co.

clutches J, K and the gears LL′, MM′ gives two speeds to the middle shaft N. For each of these speeds the lowest shaft P can have any of six speeds by means of the nest of gears Q, Q, Q, any one of which may be made the driver of the lower gears Q, Q, Q by means of the spring key R controlled by the rack sleeve and gear S, S′, the gear being operated from the front of the machine. The lower shaft on which are the fixed gears Q, Q, Q carries the pulley T, which drives the main slide traverse pulley A in Fig. 51. The middle shaft is carried through to a second speed box U on the

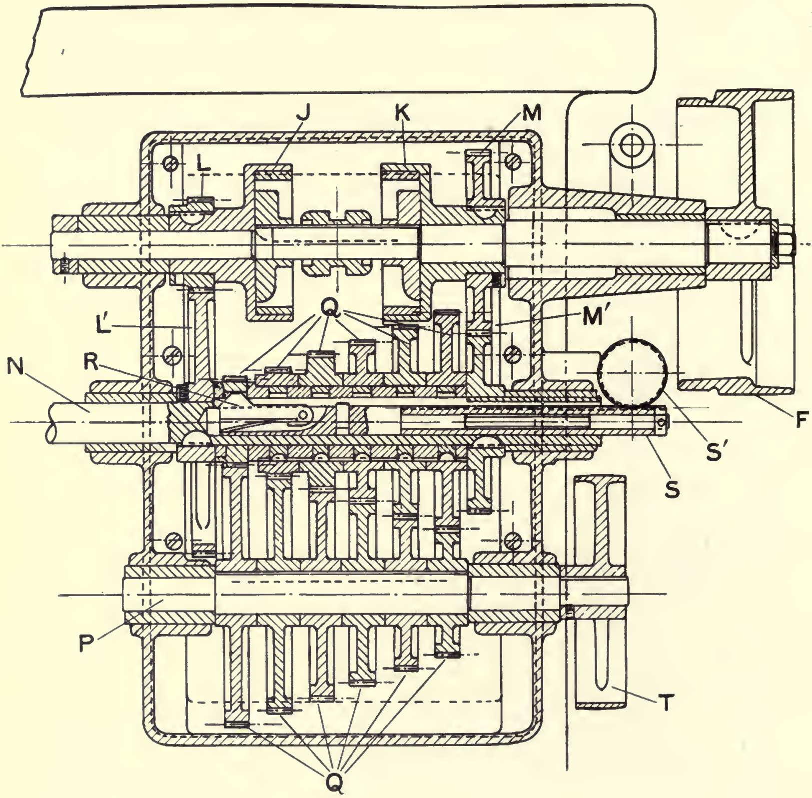


Fig. 72.—Change Speed Box—Cincinnati Tool Co.

left of the machine, containing a nest of gears controlled by a spring key operated in a similar manner to the other from the front of the machine. The secondary shaft—the upper one—carries a pulley V, which drives a pulley W on the drum shaft XY, and from this the work is driven in the usual manner by the belt Z. The countershafting is now very simple, and all the speed changes are controlled by two levers in the front of the machine, and both work and traverse can be stopped by a movement of the lever, which operates the clutches in the first speed box. The work spindle is belt driven, which gives a smooth motion, and is not liable to cause chatter marks. The drive shown gives one speed only to the wheel head, but it could easily be arranged for more.

The advantage of having all the work and table speed

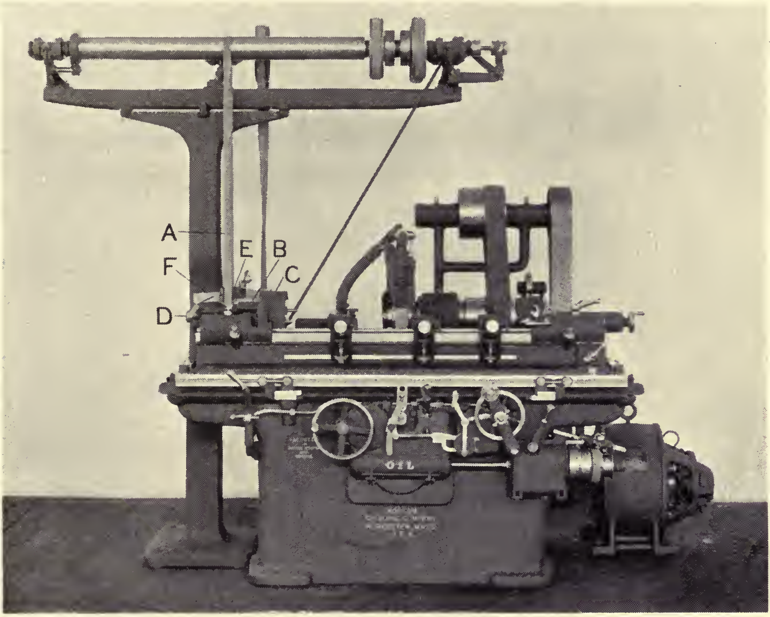


Fig. 73.—Norton Plain Grinder, 10″ × 36″

changes on the machine—instead of being obtained by shifting belts in the countershafting itself, or from the countershaft to the machine (Figs. 33 and 70)—has caused the use of this type of drive to extend rapidly. Messrs. Brown & Sharpe have adopted it on their Plain grinders, using speed boxes similar to those on their milling machines, except in the smallest size, where an adaptation of the Sellars friction drive is used. In Fig. 97 it is shown adapted to an internal grinder by Messrs. Churchill.

When the mechanism for changing the speed of the work is carried on the headstock itself, the arrangement is generally only suitable for a Plain Grinder ; the spindle could be either live or dead, but the change over from dead centre to chuck work would be a little troublesome if both were fitted. Figs. 73 and 74 show a 10-inch by 36-inch electric drive Norton Grinding Machine, and in this the change of speed for the work is got

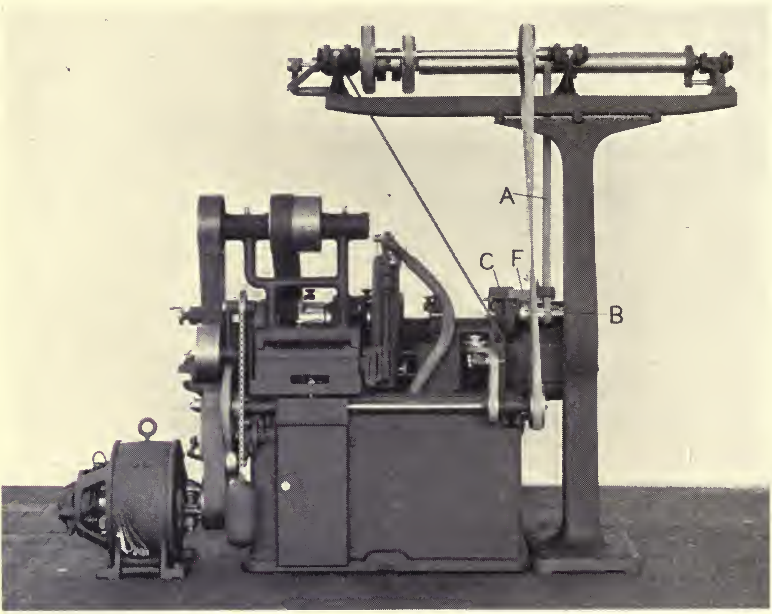


FIG. 74.—NORTON PLAIN GRINDER, 10″ × 36″

by moving the belt A from the drum to one or other of the steps of the cone pulley B, the shaft of which drives the dead centre gear in the casing C by a pinion. The shaft is carried in a swing frame about the spindle axis, so that the belt from the drum can be made tight, whatever the size of the step it is on. The tension is put on the belt A by the lever D—attached to the swing frame—which is locked when the belt is tight. The belt A passes through a guide E, which slides along a bar F, and can be located correctly for the various steps of the cone B. As a step cone driven from a drum cannot have a very wide range of speeds, the drum has two speeds, by countershafting pulleys with friction clutches. The feed is driven in a similar manner—shown in Fig. 56—the belt L which runs round a weighted tension idler drives the pulley M, the speed depending on the step of the cone upon which the belt is set. Here the range of speeds given by the cone pulley M, which is driven from a drum at the back, is increased by the gearing at N. To avoid handling the belt, the change of the position along the cone is made by the sliding fork P, the cones having inclined parts Q, Q′ between the steps, so that the belt L moves up and down the cone easily.

The more usual method is to drive a gear box on the work head by a constant speed belt from the drum, and obtain the whole range of speeds by the gearing. Examples are shown in Fig. 75 of a machine by Messrs. The Churchill Machine Co., where the gear box is of the spring key type, and in Figs. 62 and 63 of Messrs. Greenwood & Batley's machines, in which the gearing is of the Hendy type, but the design avoids the irregular slot opening of the Hendy box, and affords very complete protection.

Geared Dead Centre Drives.—In these cases, where the work is driven through a dead centre gear, there is always a possibility of the gearing producing surface marks on the work. The dead centre gear should be as large as possible, and the teeth numerous, cut spirally and of an overlapping width. Even then marks are sometimes produced in the work. They may also occur when the work is driven by a worm and worm wheel. In such designs as that of Mr. Norton, where the dead centre gear is driven by a pinion carried in a swinging frame, the frame may be unlocked for the finishing traverses—the weight alone makes a sufficient tension in the belt—and by its yielding produces a smoother surface on the work. It is frequently stated that gearing does not produce surface marks on the work, but so far as my experience goes, wherever a gear drive has been replaced by a belt drive, the quality of surface produced has been improved. For much work the surface marking, which is of very small depth, is not a matter of importance, and the dead centre gear drive is then satisfactory.

These improvements in Plain grinders to meet manufacturing requirements have made them continually more complicated,

Fig. 75.—Churchill Plain Grinder, 30″ × 120″, with Self-contained Work Drive

and the trend now is towards reducing the number of belts to the machine, and finally towards self-contained machines. The movement, commenced with the larger machines, has extended to the smaller, and now Messrs. Nortons' smallest machine (3 inches by 18 inches, Figs. 85, 86) is built self-contained.

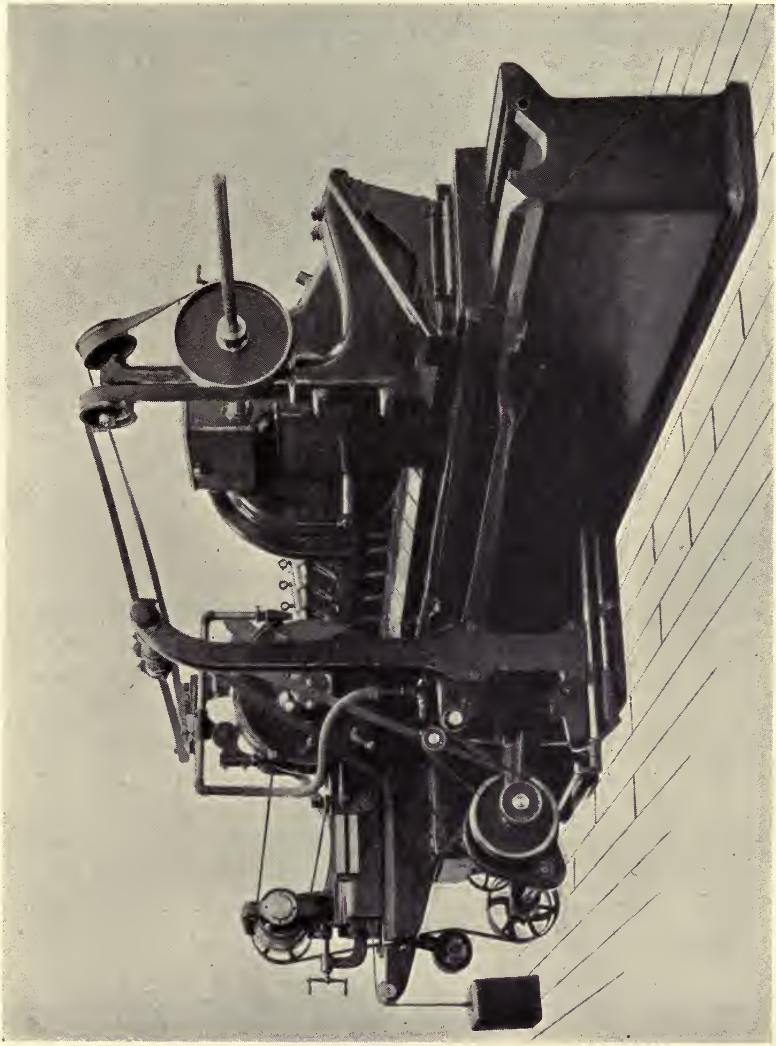


FIG. 76.—CHURCHILL PLAIN GRINDER, 30″ × 120″, WITH SELF-CONTAINED WORK DRIVE.

By driving the work from the body of the machine itself the countershafting is reduced to a single shaft, and by arranging the wheel drive on the machine it then becomes

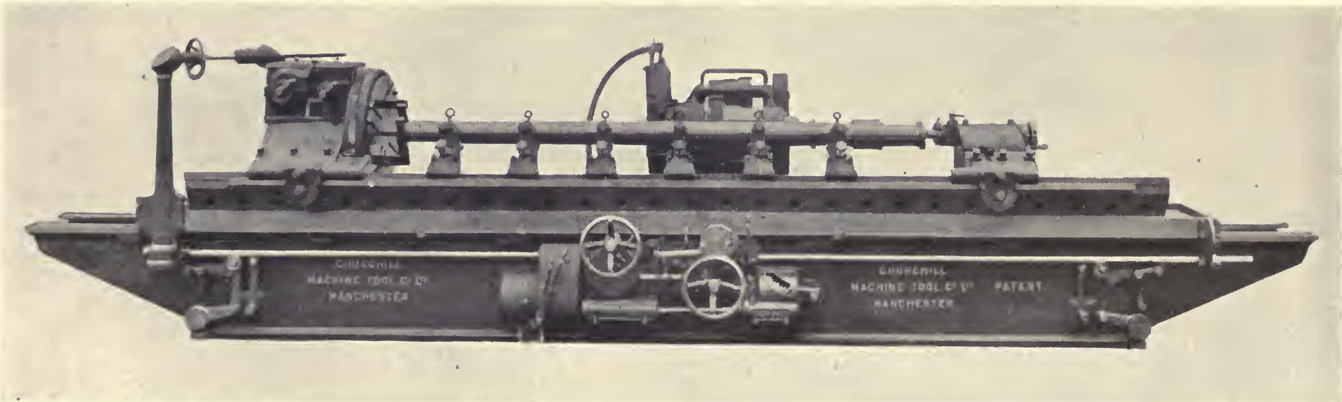


FIG. 77.—CHURCHILL PLAIN GRINDER, 36″ × 192.″ SELF-CONTAINED TYPE

self-contained; as these points are independent, machines which illustrate both are selected as examples.

In Figs. 75 and 76 are shown views of Messrs. Churchills' machine with self-contained work drive by means of a belt: the drive is from the pulley in the rear, round the two centrally situated idler pulleys, then round the work head idler pulleys and main pulley, and finally by the idler pulleys at the tailstock end of the table back to a central idler pulley and the driving pulley. One of the idler pulleys is made to keep the correct tension on the belt. In this arrangement the table may be swivelled on the central stud without affecting the running of the belt.

Another arrangement of the drive is seen in Messrs. Churchills' large self-contained machine of Fig. 77, in which the work drive is by means of a horizontal front shaft, a vertical shaft, and an inclined horizontal shaft to the work head. In both these machines the change of work speed is made by a gear box in the head itself.

A similar drive is used on Messrs. Nortons' large self-contained machines, Figs. 78 and 79, where the horizontal shaft is inside the body of the machines and drives the horizontal shaft, carried by the table and work head, by an inclined shaft. The work table in this case cannot be swivelled, and the tailstock has a set-over adjustment for securing exact parallelism. The change of speed is obtained by a cone drive similar to that previously described, and carried on the body of the machine. The machine shown is fitted with a gap to accommodate such work as pistons fixed to their rods.

The drive to the wheel spindle on these machines is similar: the wheel spindle itself is driven from a countershaft carried at the rear of the work head and adjustable—in Messrs. Churchills' design by sliding, and in Messrs. Nortons' by swinging—for the alteration in belt length; and this countershaft is driven from below by a belt at the side of the machine. A weighted tension idler pulley is contained in this drive, so as to allow the cross movement of the wheel head to take place without affecting the drive to the wheel. The direction of the belt pull is here almost directly away from the work, but this cannot be avoided on self-contained machines. Two belts

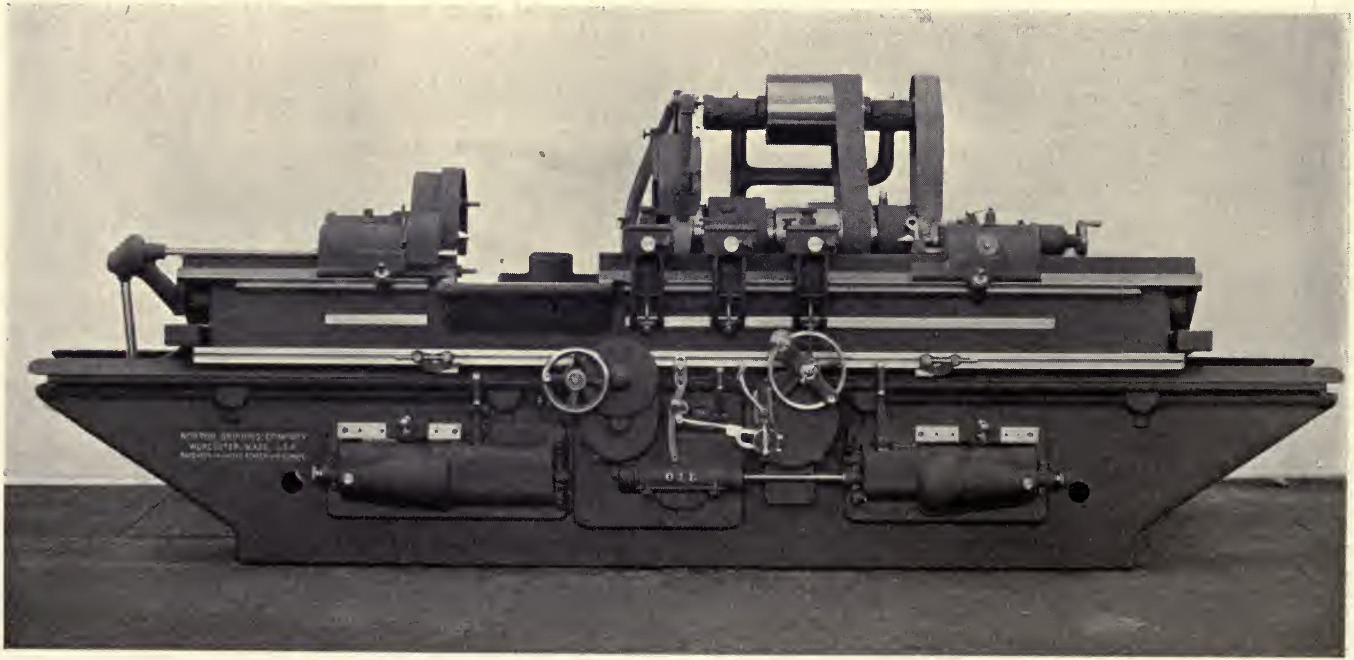


Fig. 78.—Norton Plain Grinder, 18″ × 30″ × 96″. Self-contained Type with Gap

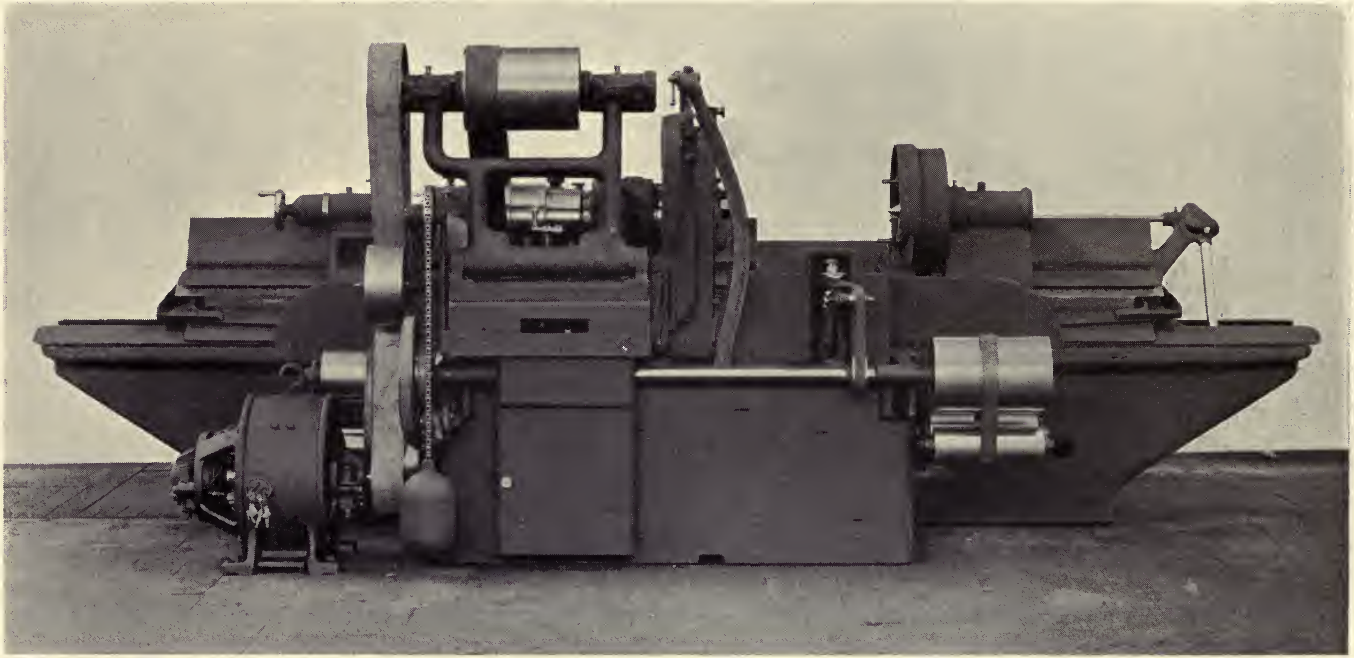


Fig. 79.—Norton Plain Grinder, 18″ × 30″ × 96.″ Self-contained Type with Gap

are used, but the drive can be arranged with one only, as can be seen in Fig. 82, which shows a very large machine by the Landis Tool Co. There are here two idler pulleys used, the belt to the wheel spindle being bent the reverse way in its

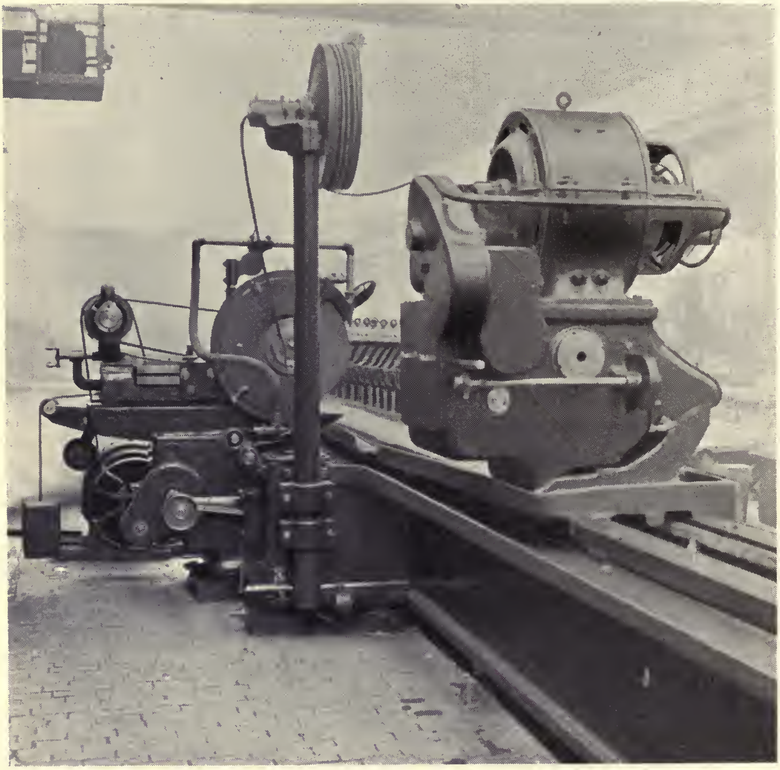


Fig. 80.—Churchill Plain Grinder, 30″ × 20′ 0″. Self-contained Electric Drive

circuit ; it has the advantage, however, of being a much longer belt than those of the system first described.

These machines are entirely self-contained, and are driven by a single pulley or a motor suitably placed. Where the size of machine is still greater, the arrangements for transmitting the motion to the work become cumbersome, and the work head is then most conveniently driven by an electro-motor, so that two or more independent electro-motors are employed in the driving of the machine. The greater the amount of power required at any point, the more suitable does the employment of a separate motor at that point become, so that the larger and more powerful the machine the more profitable is the employment of separate motors for the various movements.

In Messrs. Churchills' 30 inches by 20 feet Plain Grinder, Fig. 80, two motors are employed—one to drive the work and the other driving the wheel and other motions. The machine is of the travelling table type although the length is so considerable, and is generally of much the same design as this firm's smaller machines which have been previously illustrated. The work head motor is set with its axis at right angles to the work axis, so that any want of balance there may be in the armature does not produce direct effects on the work. The arrangement of the cable conveying the current to and from the work head motor as it moves can be easily seen. The wheel guard in this machine is of rolled steel instead of the usual cast iron.

A machine of the same capacity, 30 inches by 20 feet, by the Landis Tool Co. is shown in Figs. 81 and 82. It is driven by three motors. The wheel, 30 inches diameter, is driven from a variable speed motor, controlled from the front of the machine, by a belt running round two idler pulleys, as can be seen in the rear view. This grinding wheel motor is not carried on the main slide, but runs on the track seen at the rear of the machine, and receives the current from, and delivers it to contact shoes which run on the wires at the rear of the body of the machine. The grinding head cross slide has a rapid power movement controlled by the lever seen alongside the hand cross-feed ; this is in addition to the usual fine automatic cross-feed.

The motor at the work head end of the machine serves the double purpose of revolving the work and traversing the main slide, the speed changes being by change-speed gear boxes. The third motor is used to drive the pump, and is seen at the right-hand end of the machine, with its armature spindle vertical.

It will be noticed that in this machine the wheel slide is

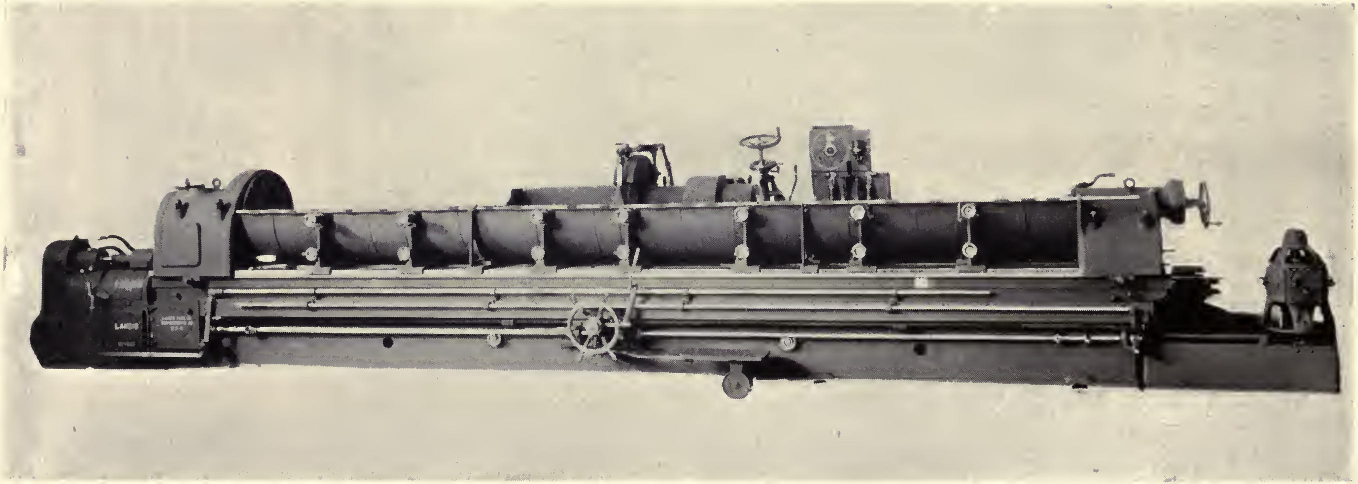


Fig. 81.—Landis Plain Grinder, 30″ × 20′ 0″. Self-contained Electric Drive

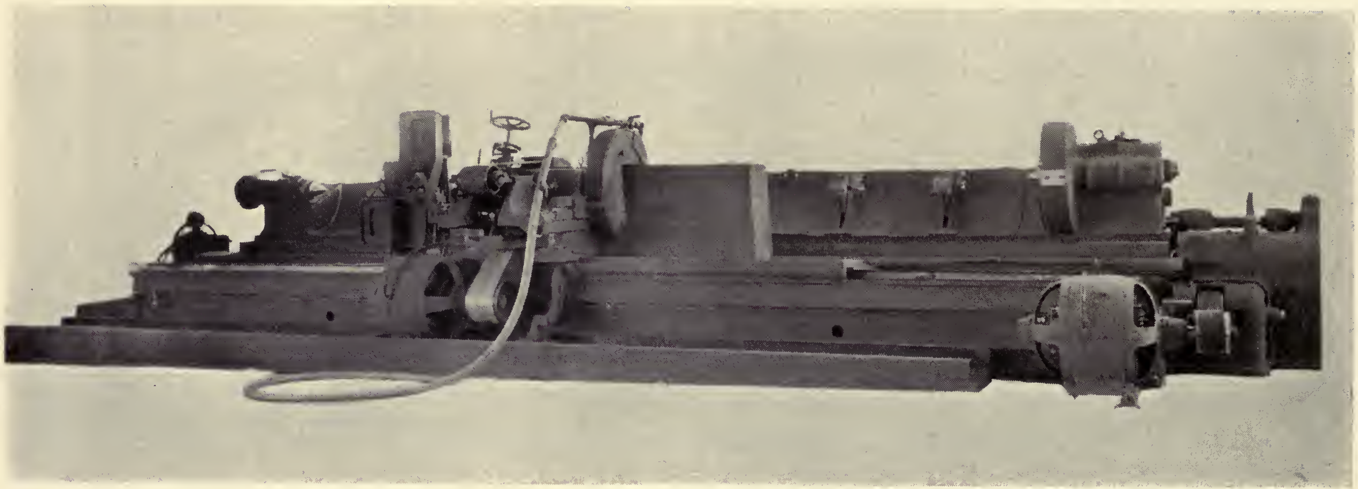


Fig. 82.—Landis Plain Grinder, 30″ × 20′ 0″. Self-contained Electric Drive

not gibbed down, but is guided by a vee and a flat way. The reversing stops are fitted on a rod at the front of the machine and tripped by contact with the travelling wheel and mechanism, which is moved in unison with the wheel by means of the screw to be seen just above the rod on which the reversing stops are fitted.

A very large roll grinding machine, taking work up to 50 inches by 17 feet, by the Norton Grinding Co., is shown in Fig. 83. Here the wheel head travels, and the motions are controlled from the wheel side of the machine, which is the best arrangement with work of large diameter. Here five independent motors are employed: a 40-h.p. motor for driving the wheel, one of 15-h.p. for revolving the rolls, and three 2-h.p. motors for moving the work headstock and tailstock along the ways to the different positions required, and for driving the pump. The wheel is 24 inches in diameter by 8 inches face, and weighs 200 lb.; the small crane seen at the wheel head is for lifting the wheel and its collet. The centre seen in the tailstock is 6 inches in diameter, but is not used for the work seen in the machine, which is ground supported in pillow blocks. The total weight of the machine is 100,000 lb.

In their largest machine, shown in Fig. 84, Messrs. Churchill have adhered to the travelling work type. This machine has a capacity of 50 inches by 25 feet, and takes wheels up to 50 inches by 5 inches. Its weight is well over 100,000 lb. and its bed is 50 feet long. It is driven by two electric motors, and the controlling mechanism and operating levers are brought to the front of the machine. The general details of the mechanism follow the lines of the smaller machines, but the rapid movement of the wheel head is power driven—by means of the open and crossed belts on the pulley to the right of the operating mechanism. When in use the lower part of this mechanism is covered and protected by a steel platform, above which only the lever handles and the hand wheels project. The mirror, carried on the steel wheel guard, gives a view of the approach of the wheel to the work. The staging carrying the conductors of the current to and from the wheel-head motor, which is of the variable speed type, is seen at the rear of the machine.

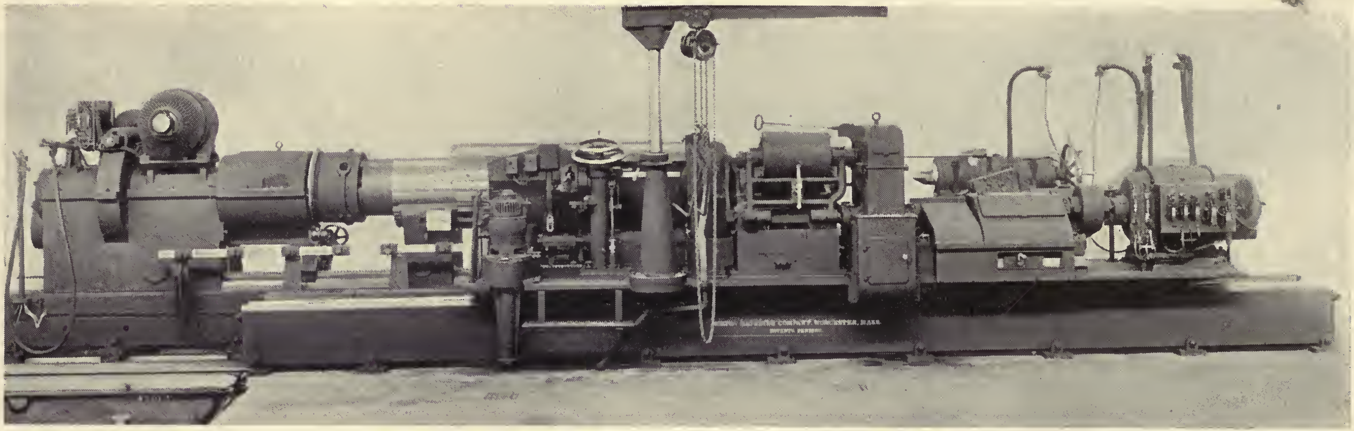


Fig. 83.—Norton Plain and Roll Grinder, 42″ × 18′ 0″. Self-contained Electric Drive

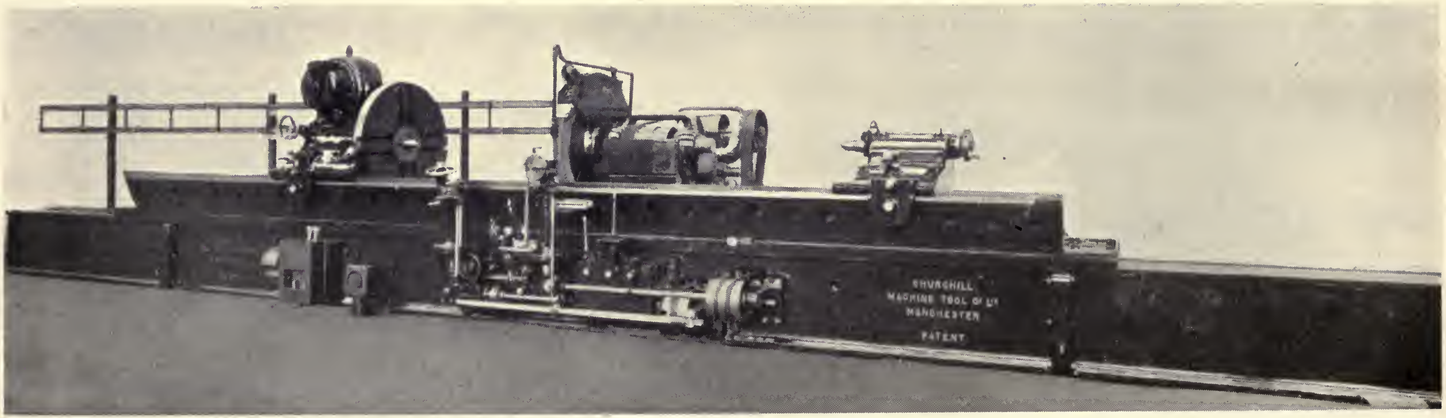


Fig. 84.—Churchill Plain Grinder, 50″ × 25′ 0″. Self-contained Electric Drive

The large machines illustrated above, which have been built in recent years, and their commercial success, show that there is a growing reliance in the suitability of grinding for work of large size, and a belief in its economy. All these machines are fitted with easily operated speed and feed controls, as on such sizes it is a necessity ; on the smaller machines such fittings are a great convenience, but they are expensive features when the total cost of the machine is considered, and this renders their acceptance into current practice slow. That they are becoming regular features of the machines indicates that it is now recognised that the handling time is worth saving.

As illustrating the extension of the fitting of such conveniences to small machines, views are given in Figs. 85 and 86 of the smallest machine made by the Norton Grinding Co. The main drive of the machine is at A (Fig. 86) and from the main shaft the belt B drives the pulley C on the wheel head countershaft, the correct tension being maintained by the spring-controlled idler pulley D. The countershaft pulley E drives the wheel spindle itself by a belt running round the tension idler F. The table feeds are driven from the pulley G on the main shaft, which drives the cone pulley H (Fig. 85). This in turn drives the cone pulley J, the various table speeds being obtained by shifting the belt along it. From J the table is driven in the manner adopted in the larger machines. The work is also driven from the main shaft through the double Hooke's joint telescopic shaft K and gears, the speed changes (4) being obtained by the cone pulleys L and M, the latter of which drives the dead centre gear by a pinion. The control rod for this motion is seen at N, the handle being in front of the machine. Below this is the handle P operating the main belt fork. The cross-feed contains a differential gear, so that the spaces seen at Q giving the minimum cross-feed movement are wide ; a substantial dead-stop is provided at R. The settling tank S is pivoted at its lower inner corner for convenience in cleansing. As the table movement on small work (the machine takes 10-inch by 1-inch wheels) is rapid, the reverse is pneumatically cushioned.

Such machines as described above indicate the development of the art of grinding as a manufacturing process. In the progress from the Universal Machine of the tool room,

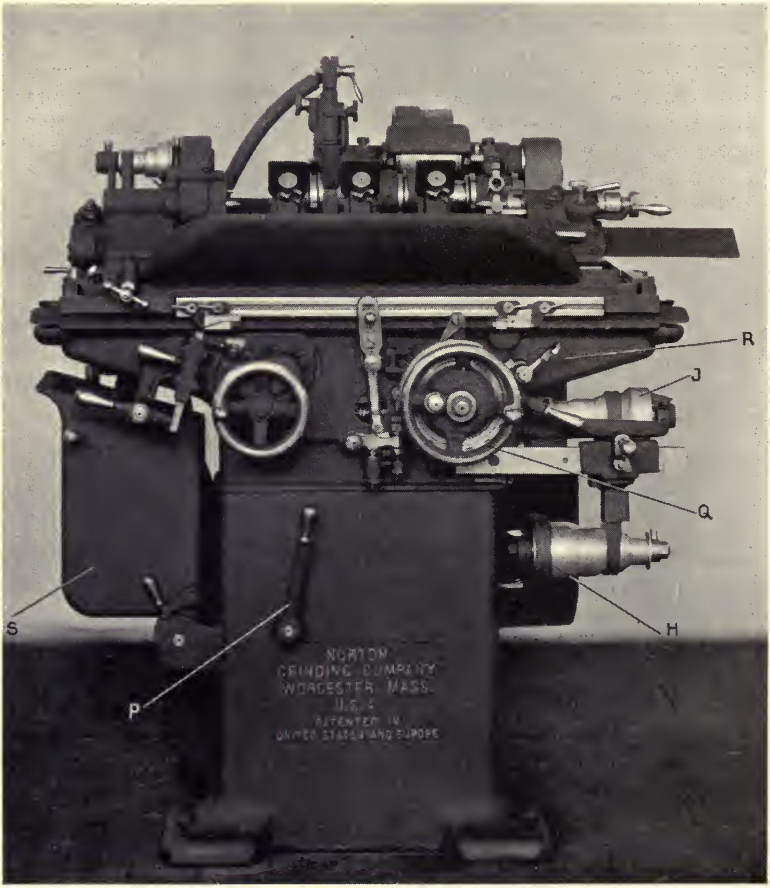


Fig. 85.—Norton Plain Grinder, 3″ × 18″. Self-contained

the desire for increased production was first met by the use of greater power by more rigid machines, and this has been followed by the employment of rapid speed changing and handling devices, while at the same time continual efforts have been made to improve the protection of the various parts against grit, and to increase the useful life of the machines.

From the machines we now turn to the work, and the actual process of the use of the machines.

Preparation of the Work. Centre Holes.—External cylindrical work is done between dead centres wherever possible, as it eliminates errors due to a live centre running out of

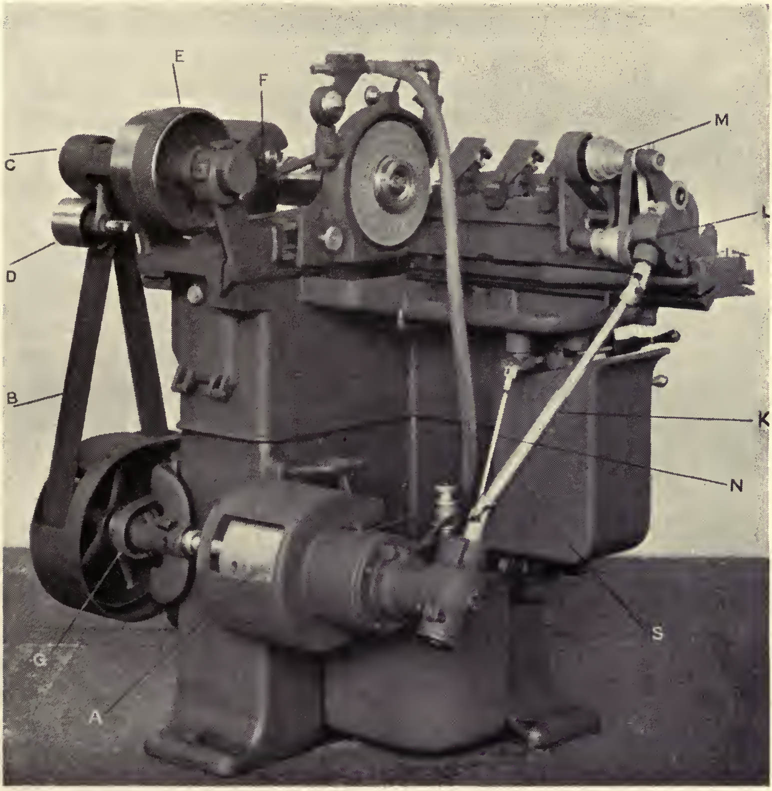


Fig. 86.—Norton Plain Grinder, 3″ × 18″. Self-contained

truth. In the preparation of the work the centre holes are important, and should be of the shape shown in Fig. 87, the centre hole A being drilled well beyond the vertex B of the taper C, and for this Slocomb centre drills are useful. The end of the work at D in the neighbourhood of the hole should be faced if there is much work to be done on the part, as otherwise the hole may tend to wear to one side.

For repetition work, if there are tapers or shoulders on the work, the centre holes in all the pieces should be drilled to the same depth, as the tapers can then be sized by the automatic cross-feed, and no readjustment of the reversing stops is necessary.

The angle of the taper is usually 60°, but some firms prefer to work with 75°; this is the greatest angle used in work to be ground. The diameter of the hole desirable depends upon the work: centre holes suitable for lathe work are large enough for grinding. When the part has no lathe work on it the centre holes should be as large as would be used on lathe work, if output be the consideration, but if it be precision they should be smaller. For gauge work $\frac{1}{8}$ inch on medium size and $\frac{3}{16}$ inch diameter on larger gauges is sufficient for the large end of the taper; and in work of this precision the holes should be lapped a little after hardening.

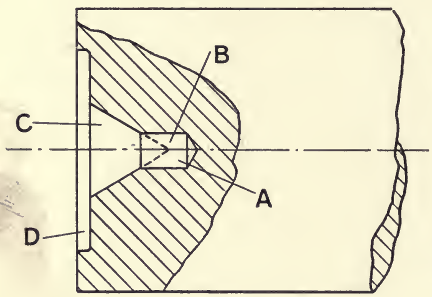


FIG. 87.—CENTRE HOLES

Key-ways may be filled with wood if they cause a tendency for the water to splash.

In some cases it is more profitable to grind direct from the rough, whether black bar, forging, or casting, than it is to turn first. In these cases care should be taken that the allowance is as little as is consistent with the work always cleaning up. Black bar should be reeled: $\frac{1}{32}$ inch is sufficient allowance for diameters up to 1 inch by lengths up to 4 feet. While it is impossible to give a general rule, shafts in which the ratio of length to diameter is 30 or more are usually economically ground from the black. The more slender the part and the harder and tougher the material, the more difficult the turning is, and the more likely it is that grinding from the black will prove economical. It may be noted that if the shafts be of tool steel for the sake of hardness they should be turned first, as the surface may have been decarbonised to some extent in the processes of manufacture, and requiring a diametral $\frac{3}{32}$ inch or so to be removed.

Automobile crankshafts and many other parts are frequently ground direct from drop forgings. The primary consideration here is the quantity, as the cost of dies is considerable. The forgings can be produced regularly within $\frac{1}{32}$ inch of size, and closer should it be desirable. The amount to be ground off is further increased by the allowance of 5° taper aside at shoulders and some other flat parts which is necessary, in order that the work may leave the dies readily.

Allowances for Grinding.—In preliminary turning a smooth quality of surface is not desirable; the ridges left from the tool are very rapidly ground off, and help to keep the wheel in good condition for rapid work.

The amount allowed for grinding in the turning is governed by the necessity for the work invariably finishing to size, and should be such as to leave no doubt in the mind of the grinding operator as to whether it will do so. The lower limit is fixed by this consideration, and an upper limit arranged so as to give such a margin that the turning can be done rapidly. As the finishing from 0·020 inch over-size takes only a little longer than from 0·015 inch over-size, the lathe limit should be wide with the aim of total economy on the whole of the work. The limits should be closer where the work is done on a capstan than on a centre lathe, as the cost of working to the finer limits is then smaller.

The practice of Messrs. Brown & Sharpe is to allow 0·008 inch to 0·012 inch on the work diameter for all sizes of work. This is an allowance only suitable for repetition manufacturing in quantity; for general work the allowance should be larger, otherwise too much time will be taken in the turning.

The Landis Tool Co. recommend the allowances given in Table IV, but do not suggest the limits.

The allowance given should depend not only on the size of the part, but also on the rate at which it is to be turned, and the purpose for which the part is intended. If the part is intended for strength, particularly against fatigue, and the turning rapid, not less than 0·01 inch for capstan or 0·015 inch for centre lathe work should be allowed, as it is important that all the material over-stressed (and perhaps therefore containing incipient flaws) in turning should be ground off. Reasonable regular tolerances (to be added to the minimum allowance, are 0·004 inch to 0·006 inch for capstan and 0·01 inch to 0·015 inch for centre lathe work.

Case-hardened Work.—For hardened work the limits can only be fixed after experience with the particular steel used, and depend on the shape of the part also. When work is desired to be hard in some places and soft in others it is usual to case-harden it on those parts only which are to be hard. Case-hardening for grinding cannot be done by 'potashing'—

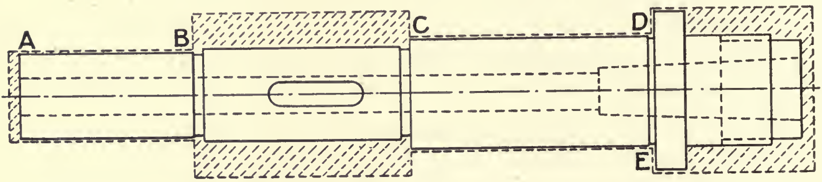


Fig. 88.—Turning for Casing and Hardening

that is, by making the work red hot and rubbing the surface with ferrocyanide of potassium, which fuses on the surface and carbonises the iron there into tool steel—as the effect of this only extends to a depth of a few thousandths of an inch from the surface. To case-harden to a depth suitable for grinding, the part must be heated in contact with carbonaceous matter or gas for several hours. To prevent the parts which are desired to be soft from becoming carbonised, they may be covered with clay—which is unreliable—or copper-plated (the whole is copper-plated and the plating afterwards polished off the parts to be hard), but preferably only the parts to be hard are turned, the whole cased, then the casing turned off the parts to be left soft, and finally the part hardened. This is illustrated by the sketch of a spindle shown in Fig. 88, in which the bearings AB, CD, and the face DE are required to be hard and the rest of the spindle soft; also suppose that the spindle is to be hollow as shown. The depth of the casing and the allowance for grinding will vary with the size of the spindle; for a length between one and two feet a depth of $\frac{1}{16}$ inch to $\frac{5}{64}$ inch of carbonising is sufficient, and a suitable grinding allowance is 0·020 to 0·025 inch on the diameter.

The stock is cut off and the ends faced so that the part is $\frac{3}{16}$ inch or $\frac{1}{4}$ inch longer than the finished spindle—suppose it $\frac{1}{4}$ inch over-length. The bearings AB and CD are then turned with the allowance above mentioned for grinding, and a little is left on the face DE, so that the part has the shape of the broken outline. It is best to turn off the skin of a bar; it is apt to be hard after carbonising. It is then carbonised by heating in contact with charred leather, granulated bone, or other suitable compound, at a temperature of 900° C. for about five to six hours. There are a number of mixtures on the market for the purpose of carbonising, but most of these are supplied in a state of fine powder, which is undesirable, as the carbonising is actually performed by the gas given off. Granulated bone contains phosphorus, and it is better to avoid it. Sulphate of barium mixed with the leather accelerates the process, but whether the result is as good as with charred leather alone is doubtful. The amount—percentage—of carbon absorbed in the steel depends on the depth from the surface, so that the depth of casing is not an exact figure, though a fracture shows a well-marked ring. The depth, which depends on the time of heating, may be anything desired—up to several inches in the case of armour-plate. As it takes time for the heat to penetrate the box and carbonaceous material, it is advisable to put small test pieces in the box of parts to be cased. These may be withdrawn hardened and broken, so that the actual depth of casing can be ascertained at various times, and the correct amount secured in the parts.

When the depth is sufficient the parts are allowed to cool slowly. Then the spindle is rough-turned to about 0·025 inch to 0·05 inch over-size, and the ends faced to size, and it is ready to be reheated and hardened. As all the outside of the part which was carbonised has been turned off except at the bearings AB, CD, and the face DE, these alone become hardened. The object of leaving so much on the ends is to make sure that the carbon does not reach a part to be machined in a lathe after the hardening process, and it should not be forgotten that deep centre holes should be drilled out before hardening, as the spindle is to be hollow.

In casing the part should be quite clean and free from oil.

When hardened steel has to be straightened, its temperature should be raised as much as possible without drawing the temper, and the straightening done at that heat.

Generally a little warping takes place, but the allowance given should cover the distortion in spindles of the length given, and over 1½ inch in diameter. Trial with the particular part is the only way to fix allowances, and once fixed the kind of steel used should be adhered to.

In grinding hardened work it is best to use a soda solution (not oil), so that the wheel cuts as freely as possible, and to use light cuts when within 0·005 inch of size (diametral), otherwise the surface hardness may be impaired (see page 72).

Specially Accurate Work.—Generally speaking, grinding should be the last process done upon any part required to be accurate; turning and milling operations, and particularly key-waying, are apt to distort the material. For particularly accurate work such as machine tool spindles the finish grinding should be done without removing the part from the centres, as there is always a chance of a minute particle of grit in the centre holes slightly altering matters.

Machine Centres.—The centres of the machine must be kept in good condition; they should be dead hard near the points. For work smaller at the last diameter than the centre is, it is most convenient to use a half centre in the tailstock barrel, so that the wheel can be run off the work without being run back. Female centres should be used on work (such as twist drills) where the centre hole must not be left, as the finished shape is definite as to length, and removing a tit is quicker than grinding the material away until there is no hole.

Driving the Work.—The carriers used for driving small work should be of the balanced type, and should fit the work nearly, as any out-of-balance effect may show itself in the work; for holding finished work carriers drilled and reamed to the size and split are useful. A sketch is given in Fig. 89.

When the machine is gear driven there is a chance of the teeth producing marks on the work; to minimise this effect a piece of rubber tube or leather may be put round the driving pin, or between it and the carrier.

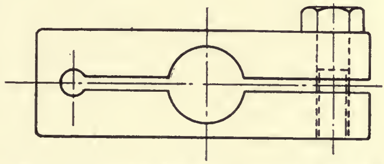


Fig. 89.—Carrier for Finished Work

When work is parallel from end to end (or parallel except that one part is a push fit and the rest is a running fit) it is best to grind the length at one operation, and then a carrier cannot be put on the work, but it is driven from the end either by a running square centre or by a special dog. For the first method

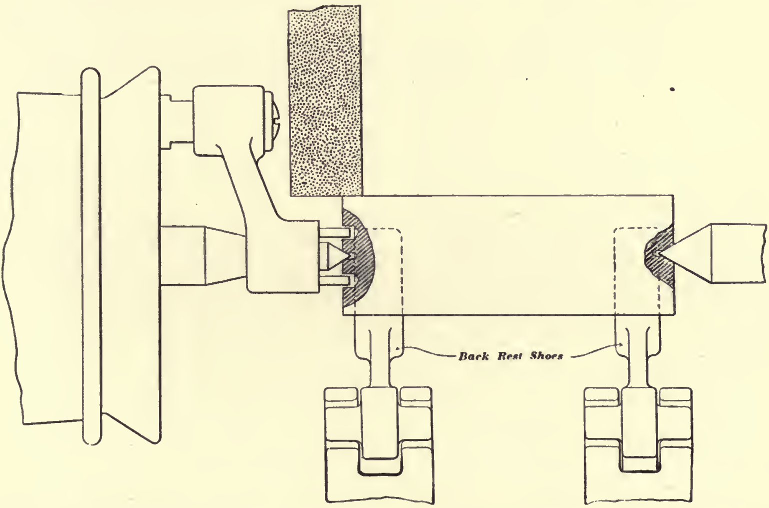


Fig. 90.—Driving Work for Grinding at Dog End (Browne & Sharpe)

a secondary head is used, in line with the regular dead centre work head, but containing a live spindle fitted with a square centre, and driven from the dead centre pulley in its rear. The angle of the square centre should fit the hole in the work, and for sharpening it, if the angle is 30°, the head should be set at an angle of 22° 12′.

In Fig. 90 is shown a dog arranged to drive shafts so that the wheel may pass over the whole cylindrical surface. Two holes have to be drilled (extra operation) in the end of the shaft. Two steadies are shown in position.

Mandrils.—The mandrils for holding hollow work are ground to a small taper, so that one end just fits, while the other is a very tight fit, and drives the work by friction. The correct taper depends on the ratio of diameter to length of the work; to meet the generality of work they are usually ground to a taper of 0·003 inch per foot. The centre holes should be formed and the ends recessed, as shown in Fig. 87; the large end should have a longer reduced part than the other end has, so that they can be at once inserted in the work in the correct way. The size

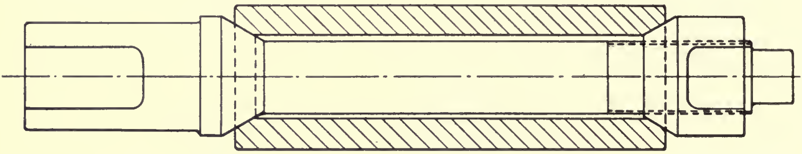


Fig. 91.—Hollow Work held by Cones

should be stamped on the reduced part so that it cannot be cut and effaced by the work slipping.

Hollow Work.—Hollow work is best held between cones, the ends of the work being bored to the angle; one cone is solid on a mandril, which goes freely through the work, and the other screws on it and is tightened to the work. If centred plugs are driven into the work, they may distort it, and the first one is difficult to remove. A sketch illustrating the arrangement is given in Fig. 91, and illustrates a case where the work can be ground completely at one operation.

When the work is thin, for example a tube or drum, the cut must never be forced; any appreciable rise of temperature distorts the work, which causes untrue grinding, and finally loss of time. As soft a wheel as possible should be used.

With an ample water supply the work does not rise in temperature appreciably as a whole, and so does not expand lengthways, and it is accordingly customary to clamp the tailstock barrel, since rigidity of the parts opposes vibration.

The barrel should be released and retightened at intervals, so that should there be slackness between the centres and centre holes, it will be corrected by the tailstock spring forcing the centres up to the work.

The centre holes should always be wiped and both oiled before putting the work into the machine : error produced by a particle of grit may not be detected until the piece is practically to size and it is too late to remedy it.

The tailstock barrel is held up to the work by a spring, and provision is made for adjusting its tension. When placing the work between the centres, it should be ascertained that the tension is suitable for the size of the work ; a considerable amount is desirable for heavy work, but slender work will stand a light end force only.

Setting the Stops.—After putting the work between the centres the stops are set by running the main slide to the position at which it is required to reverse, then the reversing lever is pushed over until the trip takes place, and the stop moved up to it and clamped. The fine adjustment screw should then be set out a little further and the reverse tested automatically to see that it is correct, and the position finally adjusted.

Shoulders.—In grinding to a shoulder the reverse can be set close to it, and the wheel brought right up to grind the shoulder by hand. If the machine is not fitted with a tarry motion the travel may be occasionally thrown out at the shoulder end, while the work makes two or three revolutions. If it is important that there should be no slight taper near the shoulder due to the wear of the wheel, the feed at the other end of the stroke may be thrown out, so as to throw the wear of the wheel upon that side.

When preparing work in the lathe the corners may be nicked in, as shown at B, C, and D in Fig. 88. It must be remembered, however, that any such nick very considerably weakens the shaft. Where strength is the consideration no nicking is permissible, and a radius corner is desirable, particularly when the value of the stress varies.

Setting for Parallel and Taper Work.—In setting the table for taper work, or for parallel work after taper, it is first set over to the correct position, as shown by the graduations on the plate; but this does not secure the correctness of the work, partly because of the difficulty of seeing to such degrees of accuracy as are aimed at, and partly from the chance of grit under the headstock or tailstock affecting the centre line position. The final appeal must be to the ground work itself, either by gauge or measurement by a micrometer, the former being best for taper work and the latter for parallel work. In adjusting the swivelling screw the amount of movement should not be overdone, as there is always a little slack in the fitting, and it is quicker to keep it in one direction.

Advantage should be taken of the fact that adjusting the taper screw does not move the work in the neighbourhood of the swivel pin much to or from the wheel.

Where long work of a particular length has to be done at intervals a bar of the same length as the work with short portions of equal diameters—rather larger than the rest of the shaft—at each end, is useful for setting the table accurately and quickly.

The Wheel.—The wheel for the particular work is to be selected according to the material and shape of the work, and data for facilitating the choice are given on pages 42–8, and in Tables VI and VII. A new wheel should be started slowly to make sure that it is not excessively out of truth.

In truing the wheel plenty of water is to be always used on the diamond, and the setting must be examined occasionally.

The wheel should be trued at the speed at which it is to be used ; if the spindle speed be considerably reduced, with the object of saving the wear of the diamond, the wheel may run very slightly out of truth when at the grinding speed.

Speeds and Feeds.—The speed for the work is to be selected on the principles given in Chapter III and the data of pages 432, 433, and the rate of speed of the main slide is to be adjusted so that the travel per revolution of the work is from $\frac{5}{8}$ to $\frac{7}{8}$ of the width of the wheel face.

Loading.—Very occasionally in grinding mild steel, but more frequently in grinding copper and soft bronze, the particles of metal become embedded in the wheel surface instead of falling freely away. The wheel is then said to be loaded, and is unable to cut; it is best in such cases to change the wheel, but if that is inconvenient the surface should be redressed, and a finer cut used. A high wheel speed lessens the tendency.

I have proved in the chapter on the wheel and the work that there is no definite correct work surface speed, but that its best value depends not only upon the material of the work and wheel, but also upon the diameters of each and upon the machine used. Thus the work speed selected may easily be incorrect and, if it be much out, the wheel will wear unduly or glaze; the speeds and feeds must then be corrected.

Checking the Wear of the Wheel.—If the wheel wears away too rapidly it is not at first evident unless very excessive. The diameter of the work should be measured and the cross-feed reading taken. After the work diameter has been reduced somewhat, the amount should be compared with the wheel movement as registered by the difference of the cross-feed readings; the difference gives the wear of wheel diameter, and should be very small.

When the quantity is sufficient for two handlings, the wheel wear should be quite appreciable in the roughing, else the grinding will take longer than is necessary; but if it is too great, not only is the wheel wasted, but it becomes untrue, and so time is lost. Rapid wheel wear is often accompanied by chatter and vibration; a want of balance may then be suspected, as it causes a wheel which is wearing a little to become untrue, and then chatter and waste commence.

The most obvious method of checking the wheel wear is to reduce the cross-feed; experience, however, has shown that it is better to reduce the work speed instead, as a better output is secured. This is regarded as the best modern practice. The correct method, however, is to reduce the work speed considerably more than is sufficient to stop the undue wheel wear, and to increase the cross-feed correspondingly. This method (see Chapter III) stops the waste, but does not sacrifice output, as the previous methods do.

Checking Glazing.—When, on the other hand, a wheel glazes, the speeds and feeds are to be changed in the opposite direction: the work speed raised and the cross-feed reduced, which is rendered necessary, as it is here supposed that the machine is already taking its working horse-power.

When a wheel face is thoroughly glazed it is difficult to break it up and to restore it to the proper condition, and it is frequently necessary to re-true it. At the first intimation that the wheel is glazing a good cut should be put on by hand to check it, and then the work speed increased and the feed reduced.

If the speed and feed alterations do not stop the glazing, more force must be used per inch of wheel face, which is done by reducing the width of the face. The effective width may be reduced by decreasing the traverse, but the wheel face then tends to wear convex.

The final resource if wheel wear or glazing persists is to change the wheel.

On any particular machine work of small diameter should run at a slower surface speed and with a deeper cut than is correct for work of moderate diameter; if the force of the cut is too great a higher velocity and less cross-feed should be employed. When the work is of large diameter, the surface speed should be higher and the cross-feed less; if the cross-feed thus becomes undesirably small, a narrower or softer wheel (see Chapter III) must be used. Either alternative will permit a heavier cross-feed and a slower work speed to be used (see Chapter III and page 264).

After experience with any particular machine, the correct work speeds should be selected without difficulty, as the variation of the size of the wheel as it gradually wears down produces no great effect. The influence of this factor is discussed in the next chapter, as it is of importance in internal work.

Fig. 199 is drawn to assist the determination of correct work speeds. In it the R.P.M. of the work is plotted against the ratio of work and wheel diameters by use of the formula deduced in Chapter III. The factor for the diagram has to be determined by trial for the particular machine in use.

Output.—After the work speed and cross-feed are satisfactory, trial may be made—by reducing the former and increasing the latter—to increase the output. The work speed must not, however, be so far reduced as to produce defects in the accuracy of the work.

For finishing—the last few traverses when the quantity is small, or the second handling when it is large—the work speed should be increased, as the cross-feed is now small. The restraining factor here is the greater tendency of higher speeds to produce vibration, and the speed should not be raised so much as to approach that which would produce vibration.

The rate of travel may be reduced, but there is little advantage in it except to minimise a travel mark.

Form Grinding.—Diameters of short length, frequent on the ends of shafts, are most quickly ground by feeding the wheel directly in without using the traverse ; if the length is greater than the wheel face, the wheel should be fed in twice, the outer side being done first and not quite to the full depth. After feeding in, the work is traversed off the wheel by hand, securing uniformity of diameter. With a reliable cross-feed it is not necessary to measure the work until it is finished, and a dead stop to the cross-feed is here useful, as it saves watching the graduations closely. This method of work may be termed 'form grinding,' as it can be used in the production of work other than of straight section. For accuracy reliance is placed on the wheel truth.

Cross-feed.—Traversing by hand tends to produce an illusive impression of greater rapidity of work, and generally both the automatic traverse and the autocross-feed are to be used : the latter should be adjusted as above, but it should not be such as to be close up to the limit either of the wheel or machine. Working near to any limiting conditions is not economical in grinding : the wheel face is not a permanent surface, but alterations in it are constantly taking place ; if for any reason trouble arises, as it probably then will, the loss of time more than effaces the gains previously made. What is to be aimed at is a steady condition which can be maintained in the face of unavoidable small variations, and not a condition of grinding a few parts in the minimum time with the maximum stress on the machine and operator. The most satisfactory adjustment of the cross-feed is to have it on the low side; it can be increased by hand, at any time when the work is being done, easily.

The water supply must be directed right on to the work at the grinding point, and the flow must be steady, as irregularities in it may cause irregularities in the work.

Errors of Roundness.—Troubles may occur either in the accuracy of the work shape or in the quality of its surface. The former takes the shape of want of roundness of the work. This is occasionally, but seldom, due to an unsuitable wheel, and the cause is generally to be found in the work itself.

If the error is at the ends of the work the centres or centre-holes are to be suspected; if at the centre then a heat or released strain effect. In the former case, it should first be noted whether the centres are right up to the metal of the work; if they are not this should be rectified, and another trial made. If they are, the work should be taken out and the centre holes carefully wiped and oiled, and it should be seen that their shape is correct, as in Fig. 87; another trial should then be made. If the centres themselves are worn, they must be reground.

Such trouble may also be due to want of balance in the work or carrier. If this is the case the work should be balanced and the carrier changed, but the effect may be considerably lessened by reducing the work speed, as want-of-balance effects vary with the square of the speed.

In the second case—where the trouble is due to heat effects—attention should be given to the water supply, and the rate of grinding should be reduced. If the cause, however, is the release of internal stress, nothing can be done except mildly to anneal the material.

If the work is not a straight parallel or straight taper, the defect is in the main ways of the machine, or may be due to forcing the rate of work. It is easily ascertained whether the latter is the case by taking more time in finishing. In work which is not too stiff this want of straightness can be corrected by manipulation of the steadies; when the work is too stiff the only method is to let the wheel traverse over the high parts and so reduce them. Appreciable error due to want of truth in the main ways should, however, never occur.

Vibration and Chatter.—The most serious defect of quality of surface is due to chatter, which causes a series of small flats on the work. This is due to vibration, which may arise from several causes.

The wheel spindle belt runs at a high speed, and a heavy lacing or fastener is quite sufficient to originate the vibration; the belt should preferably be an endless one, or if not, the lacing should be either a belt lace (without large knots) or else of the wire hook type. The belt may oscillate as it runs; if this happens it is probably due to insufficient tension in it, and the belt should be taken up.

The wheel spindle should run very nearly metal to metal with its bearings, and in satisfactory running the bearings are quite warm, and the motion of the spindle smooth. The correct adjustment of the bearings is best ascertained by their temperature rise, so that those bearings which can be adjusted while the machine is running, or at any rate immediately the spindle is stopped, are the most convenient. To produce a very fine surface on the work the bearings should run hotter than is necessary for ordinary work; they will not, however, have so long a life when set up closely. If, after these points have been attended to, the wheel head vibrates when the spindle is run without doing work, the wheel is out of balance. It should be trued and tried again, and if still out must be rebalanced. Occasionally wheels are so much out as to be unusable. If the work progresses satisfactorily for some time, and then chatter gradually begins and a kind of rumbling noise, due ultimately to irregularities in the wheel face, sets in, the depth of cut or the work speed is too great, or the wheel too soft. Immediately this occurs the work should be stopped and the wheel, as it will have lost its true shape, redressed, taking a fairly good cut over it: the work speed or cross speed should be reduced, and a fresh start made slowly so as to get rid of the marks on the work.

Vibrations set up in a machine from any cause, travel all over it, both through the body of metal and along surfaces, and are reflected from junctions or at variations of the section. In a thick, heavy section the vibration may not be apparent, as the movement will be so little, but the conveyed energy may make a slighter part vibrate conspicuously. Waves travel to and fro, and may reinforce or annihilate the effect of one another; it is only when the former occurs that the effect becomes conspicuous. The velocity with which a wave travels is independent of its size (amplitude), so that by varying the rate of the production of waves, the result may be very different, and very little difference may be necessary to prevent effects accumulating. Accordingly a simple change of work speed may be effective in stopping chatter.

As regards the work's part, marks may be due to irregularities in the drive if a dead centre gear is used. To prevent this, the driving pin may be cushioned by a bit of leather or rubber. The dead centre gear teeth should be spiral, but of not too acute an angle. Worm drives also may cause marks on the work. In either case, as a preventative measure, the teeth should be numerous. Probably the chief cause of chatter is vibration of the work itself, or the supporting centres, under the forced vibration of a heavy, irregular cut. The object of steadies is to prevent this, and whenever the work is of such dimensions as to render it likely that vibration will occur, they should be used. While a steady may permit a short, fairly stiff piece of work to be ground a little more quickly than it can be without one, the time of setting up and using the steady is to be taken into account, so that for small and moderate quantities steadies are not much used except where there is a suspicion of chatter. This is chiefly due to the continual attention and adjustment the present designs of steady necessitate, and which are not required by an automatic steady. The value of the use of steadies increases with the length of the work and also with the quantities ground at a time. The action of a steady consists in resisting vibratory motion of the work at the point of application of the steady blocks. If the steady block is held in contact with the work positively, by means of a screw or otherwise, the steady itself will have to spring if the work is to vibrate there. If it is held up into contact by a spring, the work is strained by the force of the spring and the vibration time greatly quickened, and the amplitude (amount) reduced; in the latter case there is always contact, and the blocks should be metallic, while in the former case unless the steady is constantly attended to there may be slack, and to prevent this wood blocks are used which yield elastically, and so take up small amounts of slack. For large quantities of repetition work steady shoes of hardened steel are the best; they must, however, be accurately made. In these cases dead stops to the steady movement are very convenient.

Steadying by Straining. Grinding Springing Work.—Between the steadies the work is free to vibrate, considered as fixed where steadied. The period of vibration is then very much shorter than that of the work as a whole, and the amplitude correspondingly reduced. Usually this checking of the vibration is sufficient, but in the case of thin work it is not so, and chatter marks occur between the steadies, though they are absent near them. In this case the period of vibration of these intermediate parts can be shortened by springing the bar so that it is bent into an arc. If a thin bar be placed between the centres and struck with the hand in the centre, it springs and vibrates easily. If then steadies (say two) be placed along it and set up to it, it will be found that an equal blow is resisted much more solidly, and the rod vibrates through a much less distance—the vibrations are much faster and die out more quickly. Now adjust the steadies so as to spring the bar upwards, and it will be felt that the resistance to a downward blow is again considerably increased and the vibration effects diminished. This is the state to be aimed at when long, thin bars are to be ground. If vibration occurs between the steadies, they are adjusted to spring the bar, until it feels nearly rigid at the intermediate points. The lower shoe of the steady should get well round the work, as at M in Fig. 60, for example.

When ground so sprung the section at any point will be circular and the bar straight (if previously free from internal stress) when released. To grind it parallel the steadies must be manipulated. In springing the bar it should be sprung nearly vertically upwards, but slightly outwards away from the wheel, and to effect this the lower shoe must reach beyond the centre. This is shown in Fig. 92, where A is the section of work near the centre, and the broken circle B indicates the section of the bar when it is sprung. Places should be ground for the steady blocks before applying them. On starting to grind the ends alone are ground first, as the effect of the steadies has been to draw the bar away from the wheel, and the bar is then larger at the centre than at the ends; the steadies are then adjusted as the grinding proceeds so as to push the bar into the wheel—as shown at C in Fig. 92—and to grind it there to the same diameter as it has at the ends. The diameter of the bar at its ends is then obtained by the use of the cross-feed, the table having previously been set parallel so that the two ends are the same; the diameter is made the same at each steady by using the adjustment, which moves the blocks towards the wheel. When these diameters are correct, those at intermediate points along the bar will be the same within insignificant amounts.

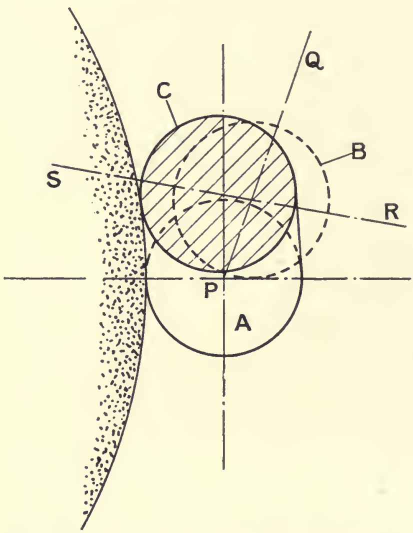


Fig. 92.—Springing Slender Work for Grinding

Thus the bar is first sprung up in the direction PQ and then pushed in towards the wheel along the line RS. The direction PQ should be slightly away from the vertical; that of RS is not of importance.

The being out of balance of work or carrier always produces an effect; whether it is noticeable or not depends on the amount of the want of balance and the stiffness of the work; and what is noticeable depends on how closely the work is examined and on what the requirements are. Defects of roundness are not visible from the optical appearance of the shaft (as traverse marks are), but a little lapping will show very conspicuously defects which cannot be detected with certainty by a micrometer, but which are of

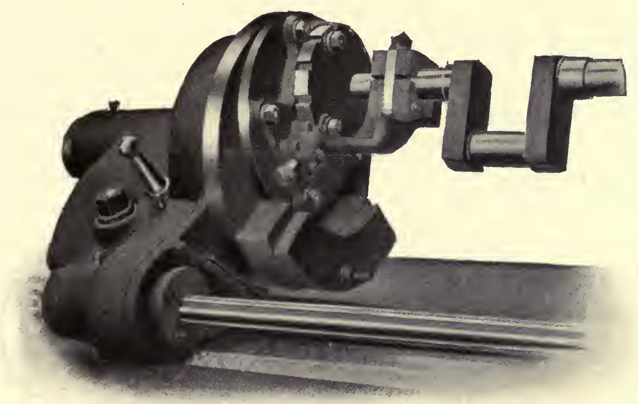


FIG. 93.—METHOD OF DRIVING CRANK SHAFTS—LANDIS

importance in journals. The application of steadies decreases the effect of this want of balance very considerably, and generally to very trifling amounts.

Crank Shafts.—Crank shafts are particularly springy, and liable to suffer from out-of-balance effects. For grinding the pins they are best held at the ends in collar grips and driven simultaneously from both ends, so that the shaft is stiffened in the same way as a column is, by fixed ends as against pin joints. The application of a steady to the part being ground then holds the whole shaft firmly, so that want-of-balance effects are reduced to as little as possible. The arrangement is shown in Fig. 93; the face plate carrying the jig with a throw adjustment and dividing plate is gear driven from the splined shaft seen in front. The other head is driven from this shaft, an adjustment being provided in the gearing for setting the heads in unison.

The pin of a crank shaft is an example of ' form grinding.' A wheel the width of the pin, shaped to the required radius at the corners, should be used and fed directly into the work. If the wheel is rather less in width the corners are not ground so easily, as they produce considerable side-thrust on the wheel. To reach down the webs to the pin in multiple throw cranks requires a very large wheel, even when the collet holds it by recesses so that the collet and its flange lie between the side surfaces of the wheel, and machines have usually to be specially fitted to give the correct speeds to the size. If possible the wheels for particular shape pins should be used for them only, and kept mounted in their collets, for to alter the radii, and especially to turn the wheel flat right across, is most wasteful. The roundness of crank pins can be tested by lapping with a half lap or bearing; for other parts a half lap is sufficient for testing the roundness and removing the cut marks from the surface, though a complete lap such as is shown in Fig. 187, page 394 is advisable—if it can be used—in order to obtain the best results. Unless the marks of the grinding cut are removed by a lap or smooth emery cloth the small sharp ridges may damage the bearing.

To true the wheel and form the round corners accurately the motion of the diamond tool must be controlled by a special jig. Such a radius truer is shown in Fig. 94, and is that fitted to the crank shaft grinding machines of Messrs. Churchill. It is arranged to bolt on the top of one of the steadies. Here the diamond A is carried on the pivoted arm B and moved by the handle C, so that its point describes a circle about the axis DE of the pivot. To enable it to be set at the correct distance from this axis DE, the arm B is hollow, and a stepped gauge F can be pushed along the axis DE until the step of the desired radius comes opposite the diamond A, which is then adjusted by means of the screw G just to touch the gauge surface. The amount of angular movement of the diamond and lever C is limited by stops at H, so that the corners of the wheel and its face can be dressed by continuous movement of the diamond, as is indicated by the broken line KLM indicating the wheel.

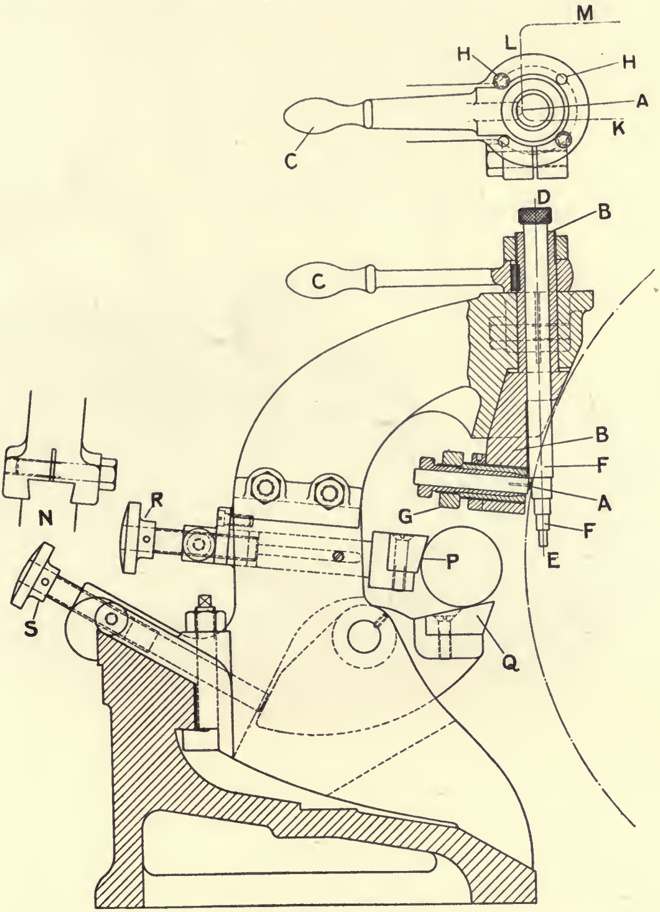


FIG. 94.—RADIUS TRUER AND STEADY—CHURCHILL

The fitting of the radius truer to the steady is shown at N. Ideally the diamond should work level with the work centre, but the error involved in the small displacement shown is insignificant owing to the large diameter of the wheel used.

The section of table adopted by Messrs. Churchill, the mode of clamping the steadies to the table, and the method of adjusting the steady shoes, are clearly shown in this illustration. The steady shoes P, Q, are adjusted positively forwards and upwards respectively by means of the screws R and S, and no springs are used.

Fig. 95 shows a crank shaft in a Landis Crank Shaft Grinder, and the radius truer in position for work.

After obtaining satisfactory accuracy and finish, output

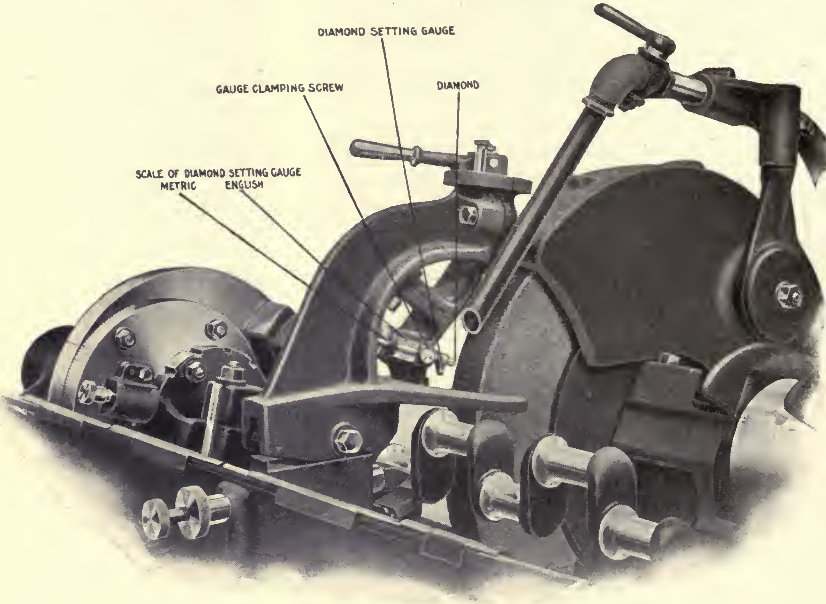


Fig. 95.—Radius Truer and Crank Shaft—Landis

is to be looked for. If it is evident from the running of the belts that the machine is taking as much power as they can supply, the only way to increase the output is to use a softer or coarser wheel, so that the same amount of power will remove the material more rapidly. If the wheel be changed for a softer one, the work surface speed should be reduced and the depth of cut increased at the same time, but after some experience the correct wheel will probably be selected. If the belts are not delivering as much power as they can be expected to, the work speed should be reduced and the cut increased but limitations as to accuracy and quality of surface must be borne in mind. Such trials take some time, for the results of small changes to improve matters already good are only slowly apparent ; hence for small quantities it is not economical to be over-anxious to make the actual grinding time the minimum, as the changes may easily run up the gross time taken, so that the net result of this is a loss.

Repetition Work.—In quantity work (say fifties or more according to the size) it is best to put the parts through the machine twice, for rough and finish grinding, and the best speeds should be ascertained.

Where each operation is done quickly, two or more carriers should be used ; while one piece is being ground the piece previously ground is checked for size, and if correct, the carrier removed to an unground piece, and the centre holes cleaned and oiled ready for the machine. When the cross-feed has been automatically thrown out on the part being ground, two or three more reverses (always the same number) should be allowed before stopping the work. The wheel should never be stopped unless it is necessary.

The wheel is then run back one or two complete turns of the cross-feed wheel, the work removed without measurement, and the next piece put between the centres and started. The wheel is then brought rapidly up to the work until the position corresponding to the maximum grinding allowance is reached, when it is moved more slowly. One advantage of a rough lathe finish is that the cut of the wheel shows when the tops of the ridges are touched, and when considerably more feed can be well put on without damage to work or wheel. The automatic cross-feed is then thrown in and the piece left to the machine.

If when measuring the piece, after removing it from the machine, it is large owing to the wear of the wheel, the cross-feed is adjusted by the compensation device, one movement of which usually corresponds to 0·00025 inch reduction on the diameter. In roughing the piece need not be returned to the machine, and in finishing it should not occur. Usually small pieces should be rough ground to within 1 to $1\frac{1}{2}$ thousandths of a inch of finished size: this will be sufficient to enable them to be finished with certainty.

If the grinding is close to size, and the wheel can be run off the work at the tailstock end, it need not be run back for finish grinding; and if the wheel is correct a considerable amount—say a square yard, but it differs with the grit and grade of the wheel—of work surface should be finished without readjustment.

Time Required.—The question of how long should be allowed for the grinding of a piece of work depends on the particular work, on the finish required, very greatly on the quantity to be done, on the machine, and on its operator. I have devised the following formula which will enable reasonable times for plain, straightforward work to be rapidly estimated. It is intended for quantities of from 10 to 20, and for normal skill in using the machine, and includes the time for setting up, measuring, truing the wheel, and to give a rate which can be maintained all day. This is the kind of estimate which I believe to be of most interest. The allowance for grinding is supposed to be 0·020 to 0·025 inch on the work diameter.

If d be the work diameter and l the length, in inches, of the portion to be ground, then the time in minutes is—

$$t = k\left(\tfrac{1}{2}\,dl + l + d\right)$$

where k is a factor dependent on the quality of the work and on the machine. For a machine such as Messrs. Brown & Sharpe's No. 2 Universal the values of k would be $\frac{1}{2}$ for running fits and $\frac{2}{3}$ for push fits. For more powerful machines the factor would be reduced—to about 0·4 and 0·55 respectively for machines using wheels of 2-inch face.

If the work is to be ground for a finish only and not to a limit size, two-thirds of the time derived from the above formula should be allowed.

The formula is based on the following considerations. The proposition is to grind so much off the surface and to give a certain finish to it. Now slender pieces of work cannot sustain so great a force at the grinding point as stiffer pieces can, and to allow for this, we may consider the effective diameter to be $d + x$ instead of x: and as short pieces take relatively a little longer than larger parts, except when 'formed,' we may take the length as $l + y$ instead of l. Now the time taken on both roughing-out and finishing will depend on the product of these, which is $(d + x)(l + y)$ or $dl + xl + yd + xy$. The formula must be very simple to be of any use, and of the simple numbers practice makes 2 as the most nearly correct figure for x and y—so that the time is proportional to $dl + 2l + 2d + 4$—and we may neglect the number 4 for simplicity, arriving at the expression—

$$k\,(\tfrac{1}{2}dl + l + d).$$

The values given for k are from practice, and suitable for the purposes named above.

The time taken in the actual grinding is very much less, and it can be greatly reduced if the quantities are large. In contrasting the times derived from this formula with those done as 'exhibition' times, or with those resulting from continuous experience in grinding one article, this must be borne in mind.

A collection of 'times' taken on a variety of work is given on pages 418–21. These are selected from a quantity of data kindly furnished by Messrs. Brown & Sharpe and the Landis Tool Co. They represent the result of considerable experience in the particular piece of work, and such times must not be expected to be obtained without it. For varying work the times given by the above formula will be found to be reasonable over a wide range of diameter and length.

Costs.—The cost of grinding must be taken as including the cost of the wheel material and power used as well as the labour charge, and this apart from dead expenses and establishment charges. The wheel cost in external grinding depends greatly on the management of the grinding; in roughing-out the wheel should wear, otherwise it will be found that the labour and power charges will be high, but it should not wear away too rapidly and waste. No fixed rules can be given, for the ratio of wheel and power cost to labour cost should evidently depend on the size of the machine, the larger machines taking the greater power and using wheel substance more rapidly.

The cost of the power is usually—one might say invariably

—neglected. It is difficult to ascertain, but a grinding machine requires so much more power than most machine tools of similar capacity that it should be debited with the cost, or part at least. Taking power at $\frac{7}{8}d.$ per electrical unit, a h.p. hour will cost $0 \cdot 65d.$ If we take a machine using 5 h.p. for half the time (that is, it takes 5 h.p. while roughing-out and very little the rest of the time), this then is about a quarter of the average rate paid for labour. With soft wheels the wheel cost is greater than with hard wheels, but at the same time the power required is less. Hence work can be done faster on a given machine with soft wheels; this lessens the labour charge, which is the highest charge. Soft wheels, therefore, provided that they are run in a manner which does not waste them, prove on the whole economical.

CHAPTER VII

INTERNAL GRINDING MACHINES AND WORK

Causes, similar to those which have placed the plain grinder in the manufacturing shops, have more recently led to the development of internal grinding machines. The progress made is slower, as the quantity of work is less, and the process more difficult.

Economic Production of Accurate Holes.—For the accurate sizing of holes in hardened metal the internal grinder is necessary, and from this its scope has gradually extended. In the softer metals small holes can be sized within very close limits, and inexpensively by the use of reamers. As the diameter of the hole increases the cost of the reamer increases very rapidly, and the number of holes representing the life simultaneously diminishes, since the number of teeth cannot be increased in proportion to the diameter; so that as the diameter increases, the advantages of grinding gradually make themselves felt. With the high tension steels the life of a reamer is shortened—in some cases to only a few holes—so that here reaming is expensive, although it follows in train with the preceding lathe operations. Broaching, where the quantities are large enough to warrant the expense of the tools, is satisfactory on the high tension steels: both broaching and grinding mean a second operation, transferring the work to another machine. For blind or slightly taper holes of accurate diameter, grinding usually offers considerable advantages.

Two Types—corresponding to Lathes and Boring Machines.—Internal Grinding Machines are divided by their general arrangement into two classes—corresponding to lathes and boring machines respectively—which have received the titles of Internal Grinders and Cylinder Grinders. In the former the work rotates, while in the latter it does not, although

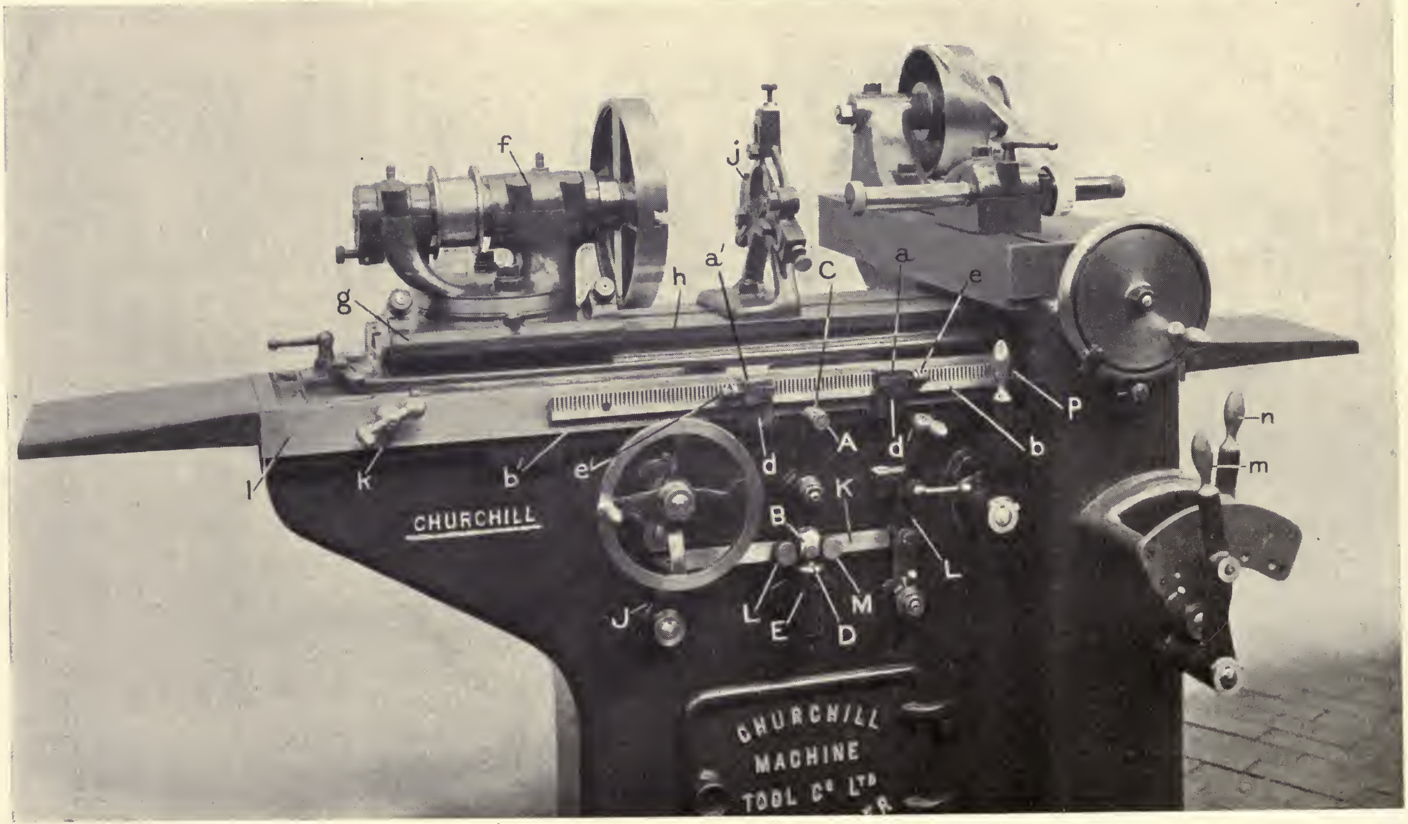


Fig. 96.—Churchill Internal Grinder

it may receive the travel movement, and have other adjustments. When the work is unwieldy or very large, the second class are advantageous, but for other work the lathe type is usually the better, and on them taper work is easily done, while it is impossible on the usual machines of the other type.

The arrangements of the parts in Internal Grinders may be made in a variety of ways—either the work or the wheel head traversing—and either of them receiving the cross-feed movement, the various arrangements having their particular advantages.

Internal Grinders. Travelling Work.—In Fig. 96 is shown Messrs. Churchills' Internal Grinder, in which machine the work receives the travelling motion, and the wheel head the cross-feed adjustment; and in Fig. 98 is shown the Landis Internal Grinder, in which the wheel head receives both the travelling motion and the cross-feed adjustment—as in their Plain Grinders. In some machines (Messrs. H. W. Wards' for example), the wheel head receives the travelling motion, and the work the cross-feed. In Fig. 96 the work head *f* can swivel on its base *g* through a large angle, and work of any taper can be ground. The whole head can be adjusted to any convenient position along the table *h*, which also carries the three-pin steady *j*, and which receives the fine adjustment for the taper by means of the handle *k*. The main slide *l* is provided with stops *a*, *a′* and with a traversing and reversing mechanism, the same as that fitted to the Plain Grinders of the same firm. This machine is also fitted with their change-speed gear box, of which the handle *m* changes the rate of revolution of the work, and the handle *n* controls, independently, the rate of travel of the main slide, while the handle *p* stops both motions simultaneously. The arrangement of the drive is shown in Fig. 97. The fast and loose pulleys A and B are on the first motion shaft CD, which drives the speed counter head E on the cross slide by the large pulley F; the pump, when wet attachments are fitted, by the pulley G, and the change-speed box by the pulley H. The power is received at the change-speed box by the pulley K; the main slide is driven by the shaft L, and the work driven from the final pulley M of the change-speed box. This pulley M drives the pulley N on the drum shaft PP, and so the work spindle pulley Q. The

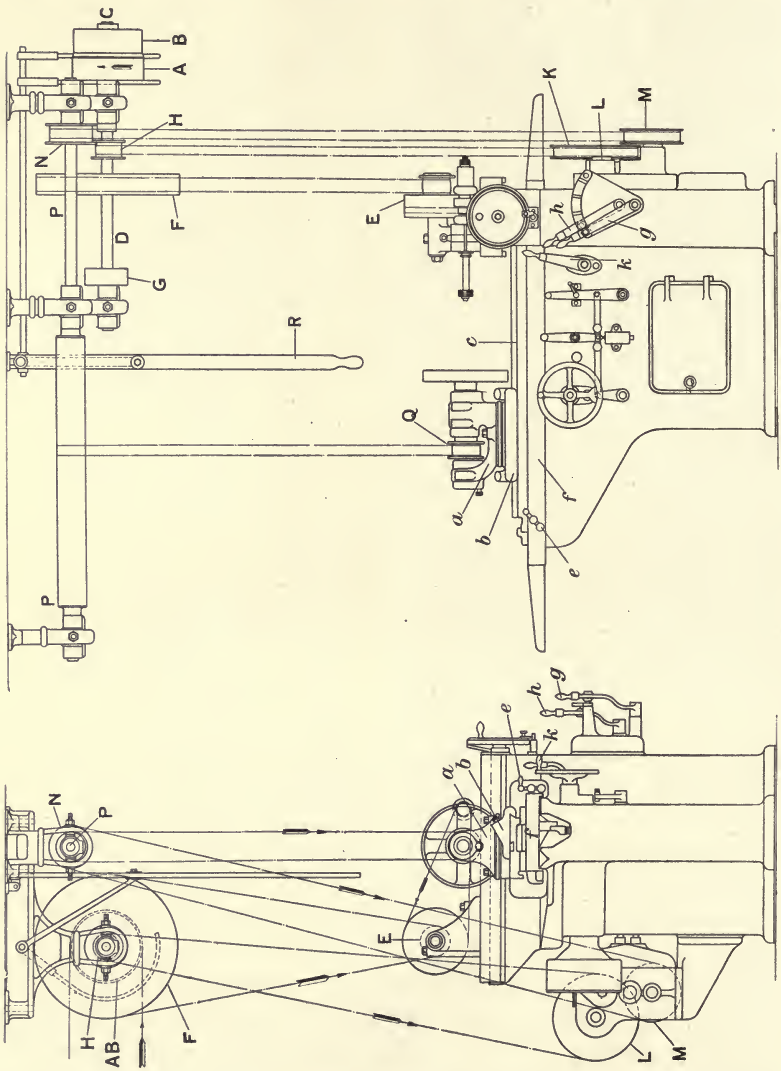


FIG. 97.—CHURCHILL INTERNAL GRINDER. ARRANGEMENT OF THE DRIVE

whole machine is stopped by the belt slipper R, while the work and table alone are stopped by the lever *k*.

This drawing shows clearly many of the features of the machine, and attention should be paid to the bridging of the cross slide ways over the main slide and table ; this is the most rigid method of supporting the cross slide, and at the same time it aids the protection of the parts. The device of mounting a secondary counter head on the cross slide is, it will be noticed, practically invariable practice ; the belt to the cross slide then does not run at the very high speed at which it is desirable that the internal spindle belt should run, so that the construction avoids the vibrations which these high-speed belts are wont to set up when they are long.

Travelling Wheel Type.—The Landis Internal Grinder, Fig. 98, corresponds closely to the lines of their Plain machines : here the work head A swivels on the base B, which is integral with the table BC, and not adjustable along it. The fine adjustment for the taper is obtained by swivelling the whole table BC by the screw D. The graduations are clearly seen here, on the vertical edge of the table. The traverse motion, power E, and hand *f*, the stops *a*, *a′*, the friction gear change speed G, and the cross-feed details H are the same as on the Plain Grinders ; the wheel slide has end covers K instead of the roller protection, as the stroke is short. The driving arrangements are similar to the Landis Universal Machine (page 272).

The machine is fitted for wet grinding, the supply being through the nozzle L ; the pump and tanks are seen in the foreground. This machine is fitted with a split chuck operated pneumatically. The compressed air is conveyed to the machine through the piping NN.

Dry and Wet Grinding.—There are many advocates of dry internal grinding as opposed to wet, and some think that a small quantity of water is satisfactory. Except for small holes I advocate wet grinding, with an ample supply of water directed on to the cutting point, as is usual in external work, and consider that the water supply must be so efficient as to keep the wheel quite clean, or that there should be none, and the work ground dry. When the amount to be ground out is large, it is sometimes best to rough out dry and finish wet, so as to eliminate temperature errors ;

when the work is ground dry for sake of quickness it must be cooled before finishing, as the expansion of the diameter due to

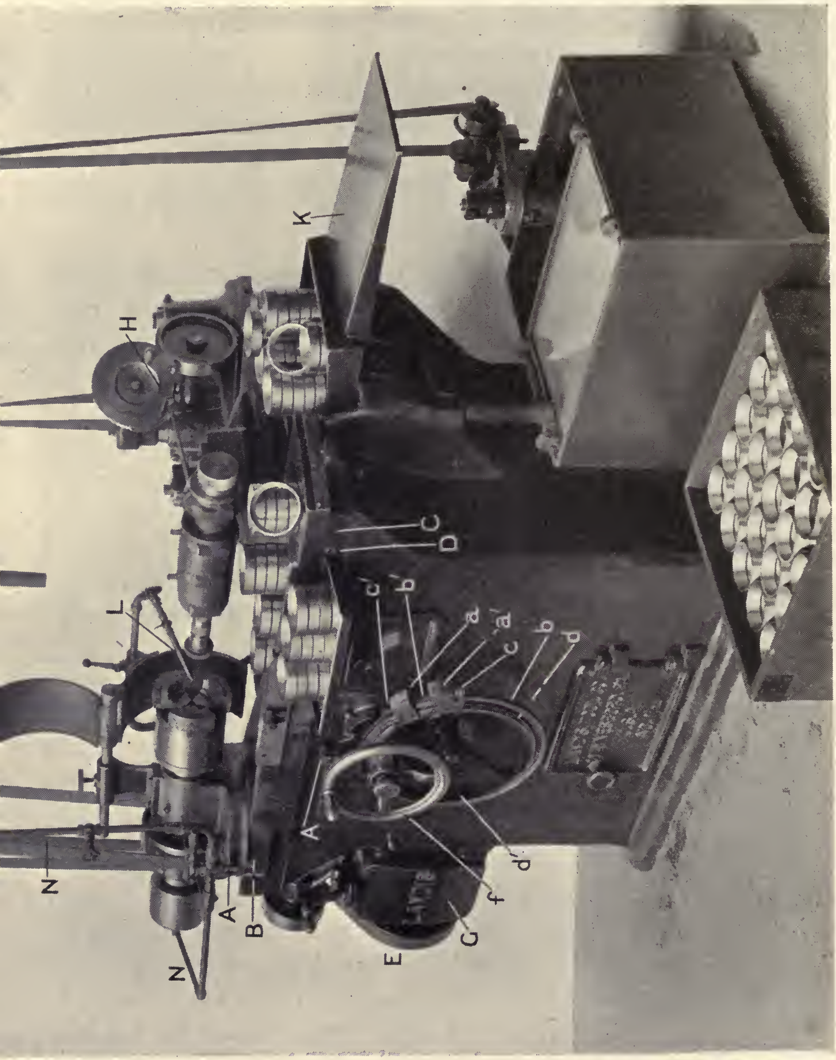


FIG. 98.—LANDIS INTERNAL GRINDER

the rise of temperature can easily be half a thousandth of an inch per inch of diameter of the hole. There is a certain loss of time in changing over from the dry to wet work owing to the contraction of diameter, so that even with large grinding allowances there is no certain gain to rough out dry and finish wet. When the hole is practically to size the water may be turned off, or very nearly so; the wheel then tends to retain the loose abrasion particles and to glaze, and so gives a smooth finish to the work surface. In dry grinding a spot of oil on the wheel in the final finishing will produce the same effect.

The water pipe should be carried down the spindle on the side farthest from the grinding point and then brought over and directed on to the work, so as to flow to the place of wheel contact. It is usually carried down on the same side of the spindle as the grinding takes place upon, but the water does not then reach the grinding area properly owing to the wind from the wheel.

The water may be fed over the outside of the work, but this does not meet the case effectively if the work is thick or irregular in shape, and is useless if the ground surface is to be dead hard, since the heat is not carried off before it has time to affect the body of the work, as it is when the water is supplied at the grinding point. Further, a small quantity of water is liable to get on to the wheel as it comes just out of the work at the reverse, and this spoils its cutting properties.

In my design (see Fig. 99) ample provision is made for the use of water, which is carried down a passage in the eccentric sleeve and delivered on to the work by a nozzle, as illustrated in Fig. 43. The nozzle is visible at A, Fig. 99, and the wheel B is seen to be placed eccentrically with regard to the sleeve C. The guard D is carried on the machine body, and the guard E on the main slide; these move telescopically while grinding is going on, and on running the work back make an open space for gauging conveniently.

The Cylinder Grinder.—Turning now to Cylinder Grinders, which correspond to boring or drilling machines, we see that the work does not rotate, and that the wheel spindle, in addition to its own rapid rotation, must at the same time be carried round another axis (corresponding to that of the boring bar or drill), so that the envelope of the wheel (i.e. the curve which it always touches) is a circle—namely, the section of the hole being ground out. Also some convenient means must be arranged whereby the size of this circle can be increased little by little, and so the cut of the wheel put on and the hole ground to size. This action is shown in Fig. 100, where the grinding wheel spindle A, rotating rapidly on its own axis, is itself carried round the main axis B,

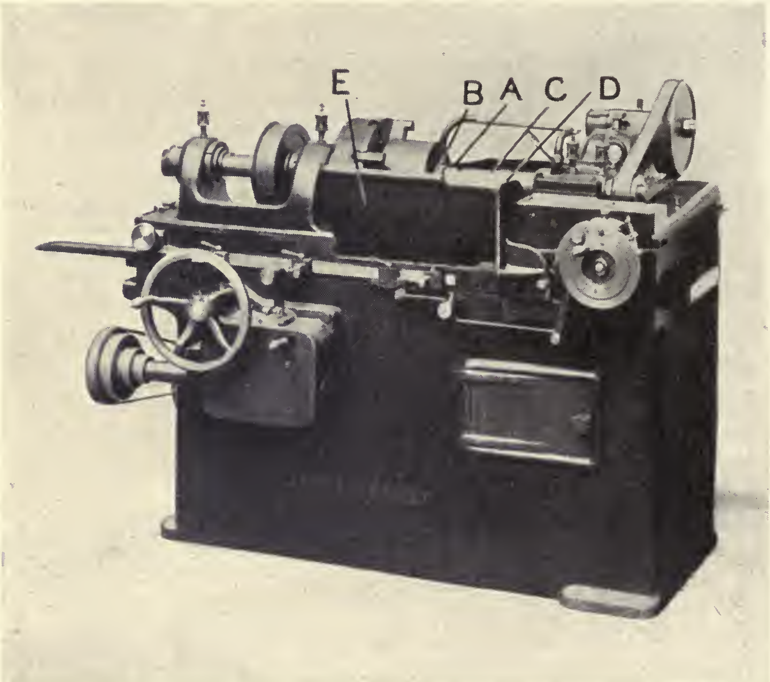


FIG. 99.—GUEST INTERNAL GRINDER. 16″ × 10″

so that the wheel takes successively the positions indicated by the circles C, C, C. These all touch the inside of the circle DD, whose centre is at B, and this circle represents the hole which is being ground out. If the distance BA is increased, as is shown at BE, the diameter of the corresponding circle FF is increased: this increase of the distance BA then puts on the cut and increases the size of the hole ground. It also compensates for the wear of the wheel and for different sizes of wheels and holes generally. Thus it corresponds to the cross-feed of an internal grinding machine.

Usually the wheel used in grinding a hole bears a larger ratio to the diameter than that shown in Fig. 100; but it is drawn small in this figure, partly for the sake of clearness, but also to indicate how some fixed external cylindrical work, such as locomotive connecting rod pins, may be ground in

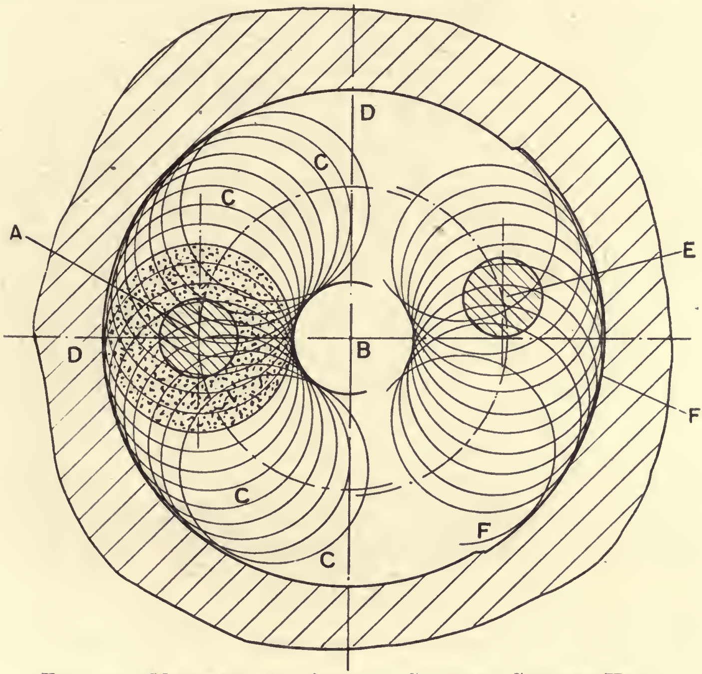


Fig. 100.—Movement and Feed in Cylinder Grinder Head

position. The successive circles C, C, C showing the positions of the wheel in its motion round the axis B, not only touch the inside of the circle DDD, but also touch the outside of the smaller circle, which thus represents a fixed pin ground externally in a machine of this nature.

Constructionally the rotation round the axis B is obtained by carrying the whole mechanism in bearings concentric with B—the wheel, its spindle, and pulley are all carried by the main spindle whose axis is B, as is also the mechanism for varying the distance AB. The usual construction is indicated in Fig. 101. Here A is the axis, and BCD the bearing of the main spindle. This main spindle is bored eccentrically for the second spindle EFG, whose centre is at H, so that the eccentricity is HA. This second spindle is also bored eccentrically at KLM to take the wheel spindle and its bearings, whose axis is at N, so that this second eccentricity is HN. By rotating the second spindle

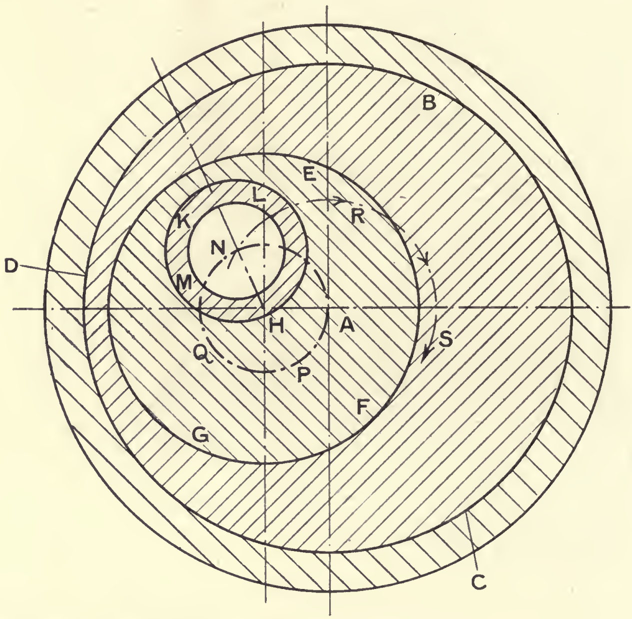


Fig. 101.—Construction of Wheel Head of Cylinder Grinder

EFG inside the first, BCD, the axis N of the wheel spindle is made to move round the broken circle QNAP, whose centre is H and radius HN; thus the distance AN changes as this rotation is made. Usually HN is made the same as HA, so that N passes through A as it travels round the circle NAPQ, and its greatest distance from A is then twice HA.

As the main spindle revolves, the wheel spindle N is carried round the circle NRS, thereby grinding the hole as already described; and the cut is put on by altering the radius AN of this circle, by turning the spindle EFG relatively to the main spindle ; and practically it is necessary to make this adjustment while the two rotations are taking place. This construction is simple and rigid : to make it convenient a mechanism must be added whereby the second spindle can be rotated inside the main spindle, while the latter itself is rotating, and while the spindle N is also rotating. Such a mechanism and the details of the whole arrangement are shown in Fig. 102, which is a drawing of the head of Messrs. Healds' cylinder grinder, of which Fig. 103 gives a general view.

The main spindle AAA′ revolves in the bearings BB′, CC′, which are of the capped type, as can be seen in Fig. 103, and are lubricated by felt pads as shown at D, D′. The end thrust is taken over the rear bearing CC′ between the flanged end A′ of the main spindle itself and the driving gear wheel E, which is adjusted by the nut F. The gear wheel E, which is keyed to the spindle, is driven by the pinion G which derives its power from the pulley H, while a hand wheel H′ serves for turning it by hand. The second spindle JJ is fitted eccentrically in the spindle AA ; the front bearing consisting of a taper hole KK in the spindle AA itself, and the rear bearing is parallel, the bush LL being taper on the outside, and adjusted by the nut M. The end adjustment is by means of the nuts NN′, while the nut P at the front end of the spindle, besides taking the end thrust, secures the correct fitting at the front taper bearing KK.

This second spindle JJ carries—eccentrically—at the front end the sleeve QQ of the internal grinding spindle, and at the rear end the rear bearing R of this spindle. The sleeve QQ is fitted to the second spindle JJ by a taper seat. The internal grinding spindle $S_1S_2S_3$ is very long and is provided with three journals—at S_1 near the wheel, S_2 in the rear of the sleeve QQ, and S_3 at the bearing R in the rear of the second spindle JJ. The construction of these bearings and the fittings of the spindle generally are easily understood from the drawing, and may be compared with Fig. 42, page 137, which illustrates a simpler spindle by the same firm.

The rotation of the spindle JJ within the spindle AA—by which the feed of the wheel is controlled—is effected by means

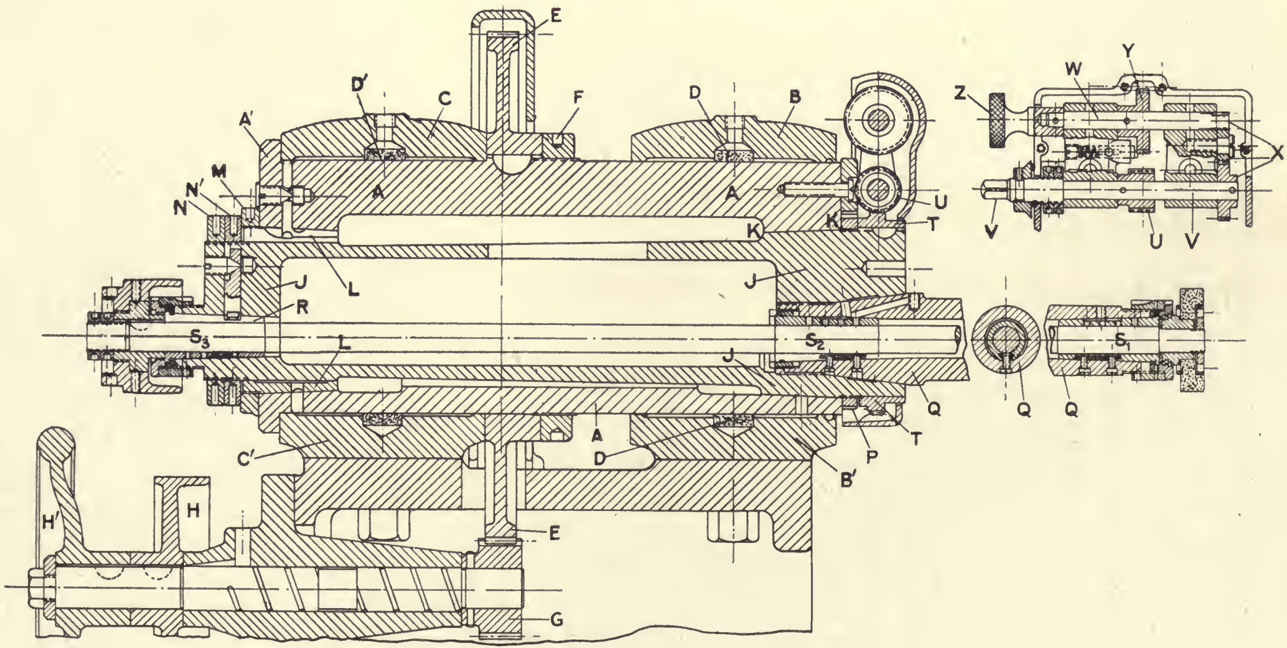


FIG. 102.—WHEEL HEAD OF HEALD CYLINDER GRINDER

of a worm wheel T keyed to the spindle JJ, and operated by a worm U carried in a casing fixed to the main spindle AA. The worm shaft VV has a squared end on which a handle can be placed for rapid adjustment, and is rotated automatically by the shaft W through the gears at X. The shaft W is turned

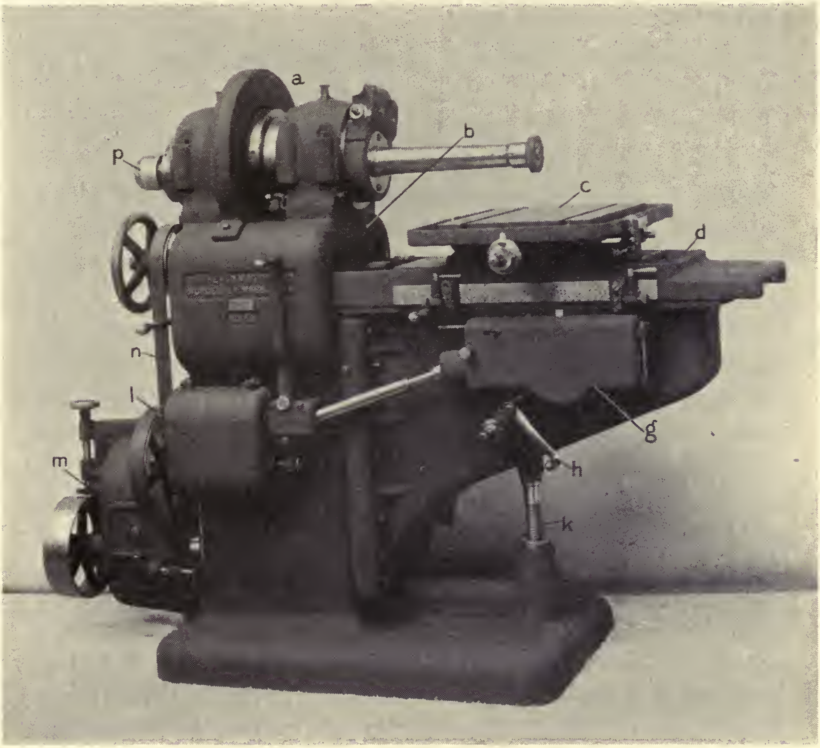


FIG. 103.—HEALD CYLINDER GRINDER

by a star wheel Y of many teeth, through the space of one of which it is moved by contact with a curved plate at each revolution of the main spindle A. The curved plate is seen in Fig. 103. This can be thrown in or out of action by the handle seen a little to the left of it. The knurled head Z gives a hand fine feed adjustment.

The movement of the second spindle inside the main spindle takes place—unless controlled by hand—at every revolution of the work. In some designs, such as that of Messrs. Brown & Sharpe, the feed is made to take place at each end of the traverse, as is done in Universal and Plain Grinders. This is probably the more convenient arrangement, but as in internal grinding wheels wear much more quickly than in external work owing to their small diameter and face, the advantage is not very great.

Arrangement of Machine with Travelling Work.—In Fig. 103 the general arrangement of the machine is easily seen. The head *a* already described is mounted on a bridge *b* over the main ways: the work, or jig for it, is bolted to the table *c*, which has a cross adjustment on the main slide *d*, which slides on ways formed on the knee, which itself is fitted to slide vertically on the body of the machine. The reversing motion, which is controlled by the stops on the front of the main slide, is contained in the case *g*, and the whole knee, main slide, cross slide, and work, can be raised by the handle *h* operating the screw *k*. The rate of traverse for the main slide is controlled by the change speed box *l*, the motion from which is transmitted to the reversing box *g* through the double Hooke's joint connection seen in front of the machine. At *m* is the change-speed box for the rate of rotation of the main spindle, the motion being transmitted through the belt *n* to the pulley H and then through the pinion G and gear E of Fig. 102. The wheel spindle pulley *p* is driven from the countershaft through a speed counter which swings, since the position of *p* varies as it is being carried round by the rotation of the main spindle, and a spring is arranged to act on the swinging link and so keep the belt driving *p* at the correct tension.

By means of the cross and vertical adjustments to the table *c*, a series of parallel holes can be ground in a piece of work—e.g. the cylinders of a monobloc petrol engine—and for this purpose such a machine is very conveniently adapted. Single cylinders for such engines, however, are preferentially ground in the former type of Internal Grinder, as in that type the slight taper (which is about 1 in 1000, and is desirable, so that the cylinder is parallel when the head end is hot as it is in use) can easily be set and ground. Taper holes cannot be ground in machines of the boring type, although some have been made with arrangements for the purpose. This introduces further complications into the mechanism, and the results have not so far, I believe, been encouraging.

The increase in the distance AN between the axes of the main and wheel spindles (see Fig. 101) is not proportional to the angular movement of the second spindle EFG in the main spindle BCD—that is, it is not proportional to the change of the angle AHN, or to the amount of turns of the worm wheel, and hence to the amount of turn of the worm.* The amount of cut put on then is not proportional to the movement which puts the cut on, but depends upon what angular position the second spindle then has with the main spindle. Although with practice the amount of metal being removed can be judged, this is not very reliable except where a number of parts are done under exactly the same circumstances, in which case the amount removed can be fairly well estimated by the time taken if the appearance of the grinding be kept uniform. The difficulty of estimation is greater with wet grinding than with dry.

When the feed is proportional to the movement producing it, as is the case with internal grinders of the first type, the wear of the wheel alone affects its sizing properties, and although in internal grinding the wheel wear is sometimes as much as the increase of work diameter, it can be allowed for, and the proportional cross-feed is a good indication as to the increase of the size of the hole, and is a desirable feature, provided in attaining it the simplicity and rigidity of the above type are not lost. In Fig. 104 is shown the line drawing of an arrangement giving a proportionate feed.

In the line drawing it will be seen that the main spindle H is bored through at an angle to the axis; the secondary spindle J fits this bore, and can be adjusted lengthwise in it, but is prevented from turning by means of a key. The grinding wheel spindle is carried in the secondary spindle, and in the

* $AN = 2\,AH \sin \frac{1}{2}\theta$, therefore $\delta\,.\,AN = AH\,.\cos \frac{1}{2}\theta\,.\,\delta\theta$, so that cut varies as worm turn and $\cos \frac{1}{2}\theta$.

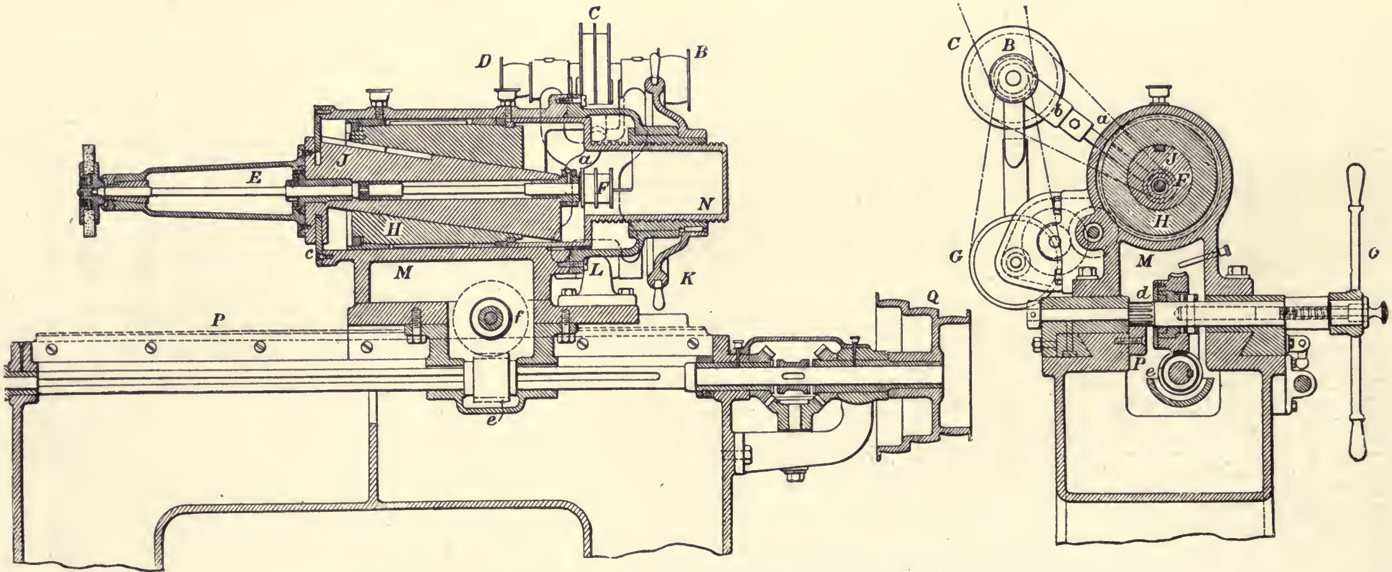


FIG. 104.—CYLINDER GRINDER WHEEL HEAD. PROPORTIONAL FEED

bracket E bolted to it, and its axis is parallel to the main spindle; adjustment of the secondary spindle along the inclined hole in the main spindle then alters the distance between the main and wheel spindles, and so adjusts the cut. The adjustment is simply performed by the screw mechanism shown at N, and is proportional to the movement producing it. The actual construction is practically more difficult than that previously described. The screw N does not rotate; it moves endways only, carrying the main spindle H with it; as the secondary sleeve J cannot move endways it has to move transversely, and so puts on the feed.

Arrangement of Machine with Travelling Wheel Head.—When the work is small it is best that it should travel, as there is then less tendency to vibration, but with large machines the wheel spindle is frequently arranged to travel. This type of internal grinder is made up to large sizes, and one such machine is shown in Fig. 105. Here the wheel head traverses and the work remains stationary; the main ways consist of two flats and two vertical surfaces, and are protected by roller blind devices at the wheel end. The arrangement of the mechanism in general can be traced in the illustration.

The Bases of Accuracy.—The accuracy of the work from both types of internal grinding machine, depends immediately upon the straightness of the ways of the main slide and upon the perfection of the main spindle and its bearings, together with the distance apart of the latter and the closeness of their adjustment. The uniformity of size of a parallel hole, or the straightness of side of a taper hole depend on the perfection of the main ways and upon the correctness of the wheel 'height,' while the roundness of the hole depends upon the truth of the main spindle and its bearings.

In both types there is overhang, the work from the main spindle bearings in the lathe type and the wheel from the main spindle bearings in the boring machine type; so that as regards this point of view, supposing that the bearings are equally good and far apart, the two types of machine may be regarded as equally good. Generally speaking, however, the lathe type is

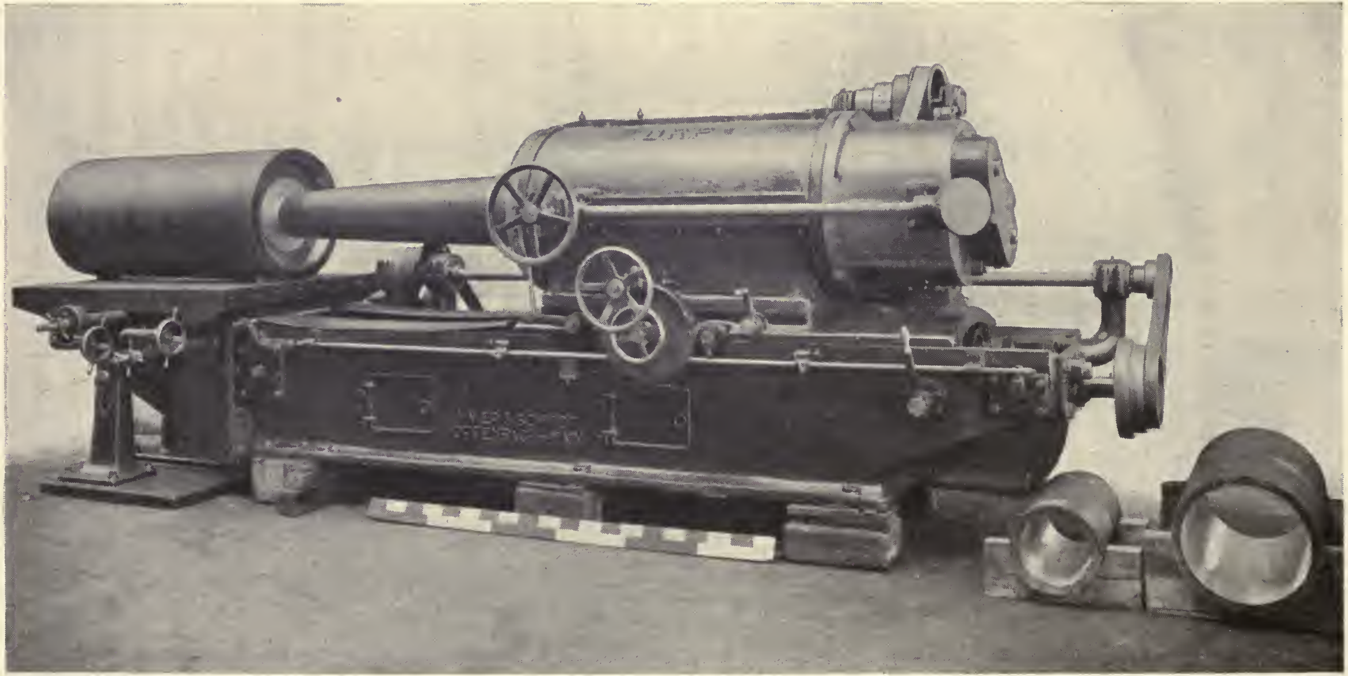


Fig. 105.—Mayer & Schmidt Cylinder Grinder

the better as regards these points. In machines for special purposes, and in which the work rotates, where the work is comparatively small, it can be arranged to be held inside the main spindle, and so this overhang avoided, but for machines for general use this is impossible.

Setting the Work Head Parallel.—When the work revolves, if its axis be set at an angle to the line of the main ways, the hole will be taper. This is shown in Fig. 106, where the taper is small. The work axis is AB and the line of the main slide is CD, making an angle θ with AB. The wheel grinds the side EF parallel to CD so that the work is ground to a cone of included

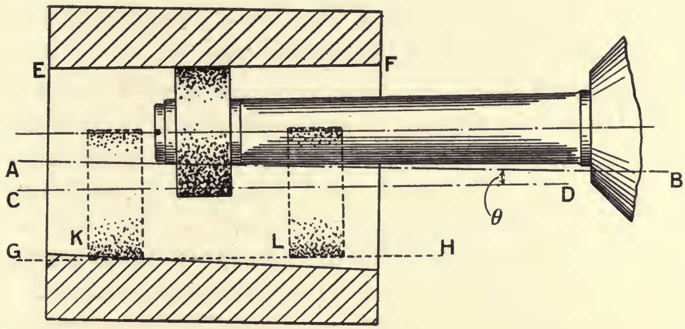


Fig. 106.—Setting Internal Work Parallel

angle 2θ, with the greater diameter to the right in the illustration.

The angle at which the wheel spindle happens to be set makes no difference, but unless it is parallel to the main ways all end play should be taken out. If it be not, the spindle will move in its bearings at each reverse, and the cut will then be heavier when the traverse is in one direction than in the other.

If the wheel in Fig. 106 is moved over to grind the work on the opposite side of its diameter, the relative movement will now be along the broken line GH parallel to CD, and the wheel will cut at K and be clear of the work at L. If the lines AB and CD be parallel, however, the hole will be parallel, and the wheel when moved over will cut equally all along the side GH ;

this is a delicate test for parallelism, and is useful in setting the work head to the parallel position.

There is no corresponding adjustment in machines of the boring type, and the work from them is parallel. Should the axis of the main spindle be out of line with the main ways the work is still parallel, but its cross section is not circular. The error is very small, however, since the principal component of it is proportional to the product of the width of the wheel and the angle between the axis of the main spindle and the line of the main ways.

The straightness of the parallel hole or the taper depends on the straightness of the main ways geometrically; practically it is affected by the spring of the slender spindle and the oil films, tending to produce 'bell-mouthing.'

Holding the Work.—For internal grinding work can be held, as for turning, in three or four jaw-chucks or on face plates, but as the work has already been machined there is a wider field for the use of collet chucks and fixtures. Ordinary chucks cannot be expected to be very accurate, as they are manufactured under competitive conditions to meet the requirements of lathes for which their precision is almost always ample. The jaws of a concentric chuck can easily be ground out true for any particular diameter. When doing this it is best to grip a piece of material in the chuck in the rear part of the jaws, so as to force the jaws into the holding position. Work such as gears can be held in a chuck with independent (preferably four) jaws, and set true. Cutters may be held in the same manner, but usually holding to a face plate is preferable. Work which is likely to be pressed out of truth by the force of the jaws should be held to a face plate, or—if it is circular on the outside—may have a fairly thick split collar slipped over it for the chuck jaws to grip upon. Holding work tightly in an ordinary chuck will distort it, with the result that the ground hole will go out of shape when the work is released from the chuck.

Where the quantities warrant it split chucks and holding fixtures are very desirable, as they reduce the time of setting so considerably. If a piece is to be ground both externally and internally, it is frequently best to put it on a mandril and rough grind the exterior first; on putting it into a collet chuck the inside, which was in contact with the mandril, now runs true, which lessens the time of internal grinding. It is finally put on another mandril, and the exterior finished.

Gears.—It is a matter of varied opinion as to how hardened gears should be held; generally it is considered that they should be located by the points on the pitch line, which is rather indefinite in some cases. I think, however, that it is preferable to hold by the bottoms of the tooth spaces (always machined at the

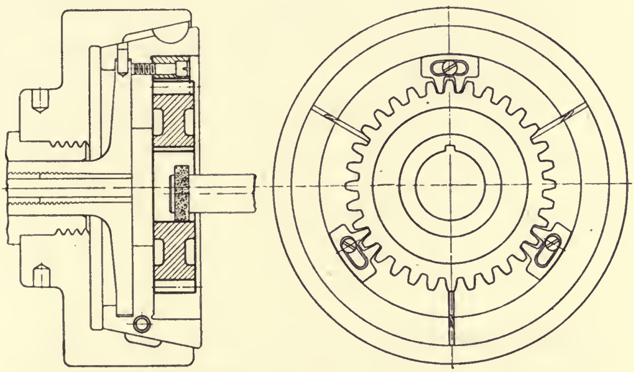


FIG. 107.—HOLDING SPUR GEARS—HEALD

same time), as defects in the grips and grit produce less errors in the averaging of the distortion due to hardening. At least six equally spaced (or nearly so) grips should be used. Fig. 107 shows a suitable arrangement given by Messrs. Heald, but here only three spaced gripping points are used.

Jigs should be made to locate the previous machining of the hole to be ground as accurately as possible, and should be arranged to hold the work without distortion. For example, a jig for petrol engine cylinders should hold the cylinder by the ring and face (machined at the same time as the cylinder was bored), by which it is held to the base plate, and it should be fastened in the same way. It is quite free elsewhere, and free from holding strains. Quicker gripping devices can easily be arranged, but not with so perfect a location and freedom from strain.

Jigs for thin work should hold it by compression on the ends, so as not to spring it across any diameter.

Belts.—The belt to the wheel spindles for internal grinding usually runs at a very high speed. Considerations of the centrifugal effect in leather belting as it runs round a pulley shows that a belt transmits most power at a speed of about 5000 feet per minute, and in this case the pulley would be the same size of the wheel, or rather larger, as the wheel surface speed is usually somewhat below that amount, as the spindle speed is so high. My practice used to be to run the belts to internal grinding spindles at this speed, with the easily remembered rule that the wheel used was not to exceed the pulley diameter. With these high speeds it is necessary that the belt should be endless: raw hide or orange tan belting is best for all but the smallest size spindles, for which cotton belts, woven endless, are most suitable.

Water is to be used in quantity or not at all; the wheel must be clean, and a meagre water supply tends to choke it.

Width of Wheel.—The width of the wheel must be less than that for external grinding for the same power delivered to it. This is explained in Chapter III, but as the difference is considerable in internal grinding, I refer to the subject again.

The relation between the work speed and the depth of cut which must hold in order that the wheel face may neither glaze nor disintegrate too rapidly is that $v^2 \frac{d \pm D}{dD} t$ should lie between two limits, and preferably it should have a certain value, which depends on the nature of the wheel (which is supposed to be run at a fixed speed) and the material ground only. To get the output of which the machine is capable, we also have vt having another constant value, dependent on the machine and wheel. From these we get the values of v and t.

Now vt is to be reckoned per unit (i.e. per inch) width of wheel face, and we can increase the value of vt for any machine by decreasing the width of wheel face. If in any case we have obtained the values of v and t and find them unsuitable, we can alter their values by altering vt for the case—that is, by altering the width of wheel.

If, taking a case of grinding which gives good results in external grinding, and using the same values of the above, we consider a case of internal grinding for which the values of the diameter of wheel and work are different (and the negative sign in the formula is to be taken), we find that very much higher work speeds and very fine depth of cuts are requisite. Now fine depths of cut are undesirable or even impossible with a small spindle, supported at best by a bearing in a sleeve which can easily spring. We must therefore increase the depth of cut, and to meet the wheel condition we must decrease v to an extent which makes $v^2 \frac{d-D}{dD} t$ the same as before. This will increase vt, and to do this we must reduce the width of the wheel. Taking the same power and using it on a narrower width increases vt at the wheel face.

This does not mean that we are going to lose output, which depends on vt: it alters neither the output nor the total force on the work, nor yet the final force on the wheel particles tending to dislodge them from their setting. What it does is to increase the length of the arc of contact, keeping the average force the same, but since the width of the wheel used is less the net result is the same. Generally speaking, the output is proportional to the length of the arc of contact multiplied by the wheel face, or to the area of contact.

Consider the same example as was taken in Chapter III, page 69. Here in external work, where $d = 2$ inches, $D = 14$ inches, $v = 30$ inches per minute, and $t = 0{\cdot}001$ inch on the work diameter, the grinding was satisfactory. If our internal work were 3 inches diameter and the wheel $2\frac{1}{2}$ inches, we should then find that $v = 257$ feet per minute, and that the corresponding cut would be $0{\cdot}000115$ inch on the work diameter.

Suppose that we increased the feed to one thousandth of an inch on the diameter, then the corresponding velocity would be v, where—

$$v^2 \frac{1}{1000} = 257^2 \times 0{\cdot}000115$$

or

$$v = 257 \times \sqrt{0{\cdot}115}$$
$$= 87 \text{ feet per minute}$$

The value of vt would now be increased in ratio 3·15, so that we should have to reduce the wheel face to $\frac{1}{3}$ inch. Actually if the same power were delivered to the machine we should have to reduce it further, as less of the power reaches the wheel in internal than in external grinding, owing to the greater loss in the belting and journal friction. The spindle bearing also is to be considered, and hence less power is usually delivered to the machine.

Treated thus, wheels of the same grits and grades will suit internal, as suited external work, but considering that the wheel is not supported so rigidly, a slightly softer wheel is desirable for internal work. The cubic amount of wheel wear should be the same, but as it is distributed over a much smaller circumference and width the effect is much more conspicuous, and leads to the impression that the wheel material does less work.

The wheel must not be too soft, otherwise it tends to pull into the work and have its substance wasted. This action is probably due to a gyroscopic effect. Suppose the spindle AB, Fig. 108, is running free in the bearings with an oil film round the journals, and that the force P of the cut acts at the point C of the wheel B and acts upwards, the spindle running in direction DC. Then if the spindle can bend or move about the point A, the force P produces a moment P . AB about the line AX, in the sense indicated by the arrow; which combines with $I\omega$ round AB to make the axis of rotation move towards C, as shown by the broken line, and so carries the wheel into the work. This increases P and tends to continue the motion of the wheel into the work with increasing rapidity, until it reaches a point where it quickly destroys the surface of the wheel. This will not happen if the wheel is near to the glazing point, as the normal force then checks the action. With springing spindles, therefore, the speeds and feeds must be more nearly what is just correct.

Work Speeds and Wheel Action.—Excessive wheel wear and glazing are to be checked by the same methods as have been given for the case of external grinding, but speeds and feeds are much more difficult to select correctly, and require much more manipulation than in external grinding. This is due to the influence of the changing diameter of the

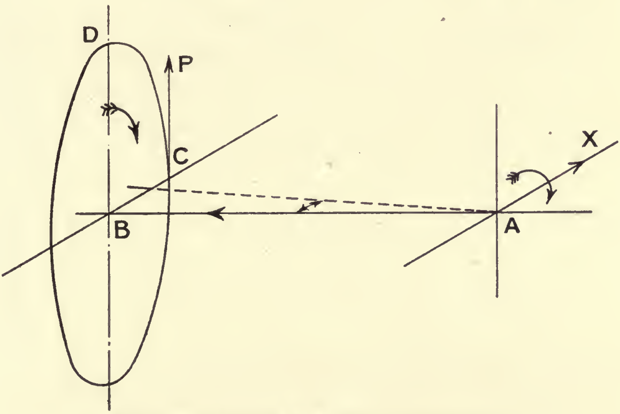


Fig. 108.—Spindle Action—Pulling in

wheel as it wears down in use, which is here very great, while in external grinding it is very small.

Suppose that a piece of work 4 inches in diameter is being ground externally with a 36 K wheel, 14 inches in diameter, taking 2 h.p. per inch of wheel face, and that a work surface speed of 30 feet per minute with a feed of $1\frac{1}{4}$ thousandths of an inch (mils) on the diameter is found to be the most perfectly satisfactory. The corresponding work surface speeds for wheels of different diameter can be calculated from equation (3), page 69. By setting off the various wheel diameters along OA in Fig. 109 and the corresponding work surface velocities parallel to OB, we obtain the broken curve OCD, which shows at a glance the effect of any change of wheel size. As the

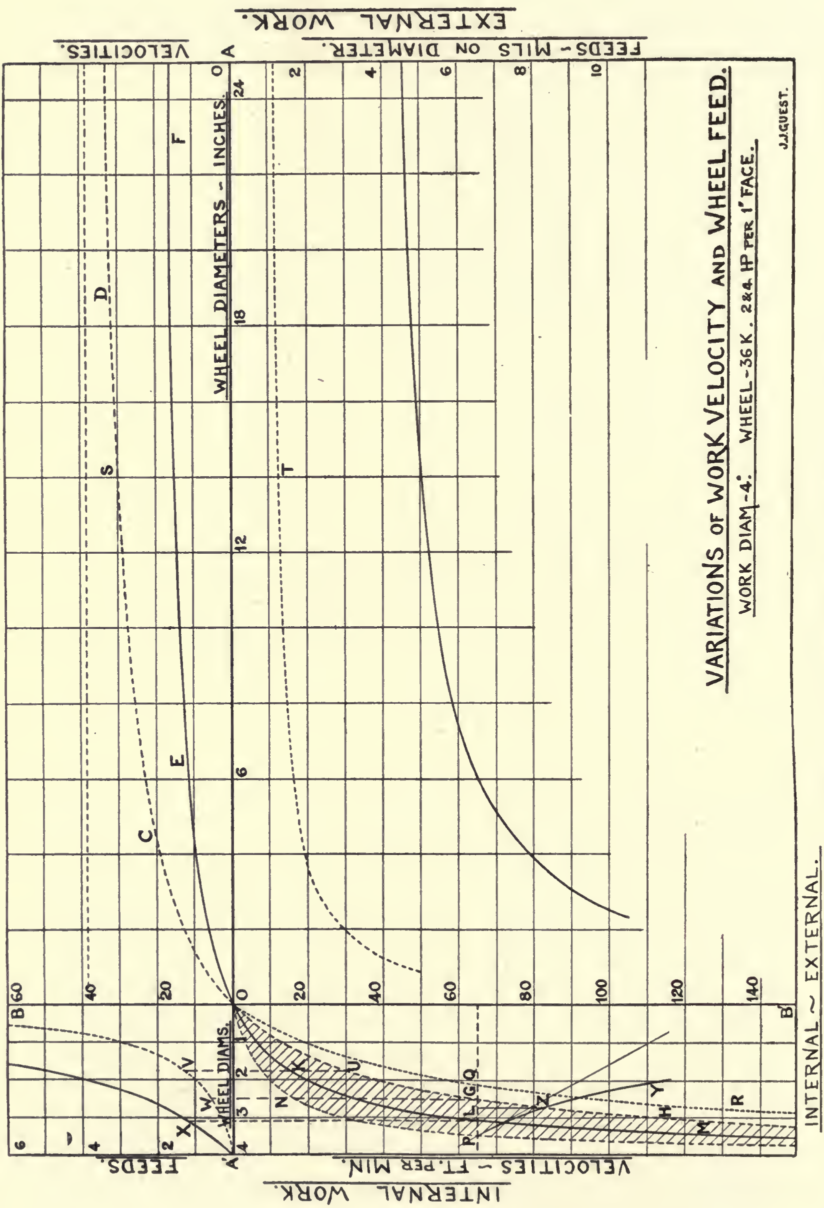


Fig. 109.—Effect of Wheel Wear on Speeds and Feeds

wheel diameter decreases the work surface speed should also be lowered, but the effect of wearing the 14-inch wheel down to 10 inches would cause only a small fall of the best work velocity from 30 feet to 27·5 feet per minute. If the wheel were changed for one of 6 inches diameter the best work surface velocity would fall to 23, and if a 24-inch wheel were used it would rise to 33 feet per minute. However the wheel diameter were increased the corresponding work speed would never rise above the value 38·6, indicated by the broken horizontal line to which the curve CD is asymptotic. The corresponding feeds are shown by the broken line T in the lower part of the figure, and are obtained from the fact that *vt* is constant.

It will be seen that wheel wear has no practical effect on work speeds or cross-feeds in external work.

If the h.p. per inch of wheel face were doubled, we should obtain the full line curve OEF giving the work velocity, and the feeds would be given by the full line curve below. This shows the influence of increased power in slowing work speeds.

Now suppose that the work be internal instead of external. The wheel diameters are set off to the left along OA′ and the corresponding work surface velocities parallel to OB′, while the feeds are in the remaining quadrant of the diagram. The curve OGH giving the natural work speeds is a continuation of the curve OCD, but its inclination is very different, and for wheels not much less than the size of the hole the work speed is very high, and the corresponding feed, given by the curve A′WV so very low, as to be unusable. This, as explained previously, necessitates the use of a narrower wheel, using more power per inch of face. Suppose that the wheel face be halved; the work speeds are then given by the full line curve OKLM, which is a continuation of FEO, and the feeds by the curve A′X. Thus a work surface speed of 65 feet per minute (the point L), with a feed of 0·001 inch (the point X) would be the best for a wheel just over 3 inches in diameter.

This condition allows certain margins, and may be departed from on one side until the wheel glazes, and on the other until the wheel wears unduly. Both these conditions are expressed by different values (a_1 and a_2, page 69) of the quantity b in the equation $v\frac{d+\text{D}}{d\text{D}}=\frac{b}{c}$, so that by drawing further curves of a similar nature (rectangular hyperbolas) to those already drawn, we shall obtain the limiting lines on the figure. If the work speed were reduced by a particular amount it will cause glazing; the broken curve ONP, drawn for a ratio of one-half, indicates this condition. The original curve OGH represents a condition of wheel waste at this amount (4) of h.p. per inch of wheel face, and the dotted curve OQR will represent one of excessive wheel waste.

Accordingly the area of the figure in which grinding can proceed is that between the curves ONP and OGH, and this I have shaded.

Suppose that a speed of 65 feet per minute be selected for the work, which gives a feed of 0·001 inch on the work diameter. This is represented by the line PLGQ on the diagram, and we see that the largest wheel which could be used is $3\frac{1}{2}$ inches diameter, and that it is just on the point of glazing.

As the wheel wears down its action improves, until at the point L, which is on the full line curve FEOKM, it would be at its best, the diameter then being just over 3 inches. Further reduction of diameter would make it wear more rapidly, and at the point G, $2\frac{1}{2}$ inches diameter, it would be wasting unduly.

If the use of the wheel be continued further, using the same work speed—that is to Q—the cross-feed must be reduced and the output sacrificed.

The short length of the line PLG (and for clearness wide margins have been taken) in which the wheel successively glazes, works well, and wastes, shows that the regimen in internal grinding is not constant—as it practically is in external work—and that the difference between the diameter of the wheel and of the hole has a great effect. With the limited number of work and speed changes on a machine it is impossible to obtain any particular speed and feed desired, but what is to be aimed at is to start with a wheel just on the point of glazing, and it is then known to be on the curve ONP. When a condition corresponding to the point G is reached the work speed is to be lowered, and if it were lowered so as to reach the point N (15 feet per minute) it would then again be on the point of glazing.

In external grinding a 14-inch wheel, using 2 h.p. per inch of wheel face, was at its best when the work velocity was 30 feet per minute and the cross-feed 0·00125 inch; if we take the same velocity for internal work (the point U) at the same h.p., we shall find by drawing UV vertically upwards that the feed (the point V) is the same as in the external work. For this to be the case the particular wheel diameter would be only 1·75 inch, and so not suitable for a 4-inch hole.

So far the wheel surface speed has been supposed to be kept constant, while in practice the wheel spindle speed would probably be constant. The effect of this is still further to reduce the range over which the wheel can be used without altering the work speed. It can be easily shown that by drawing a rectangular hyperbola PZY through P to OA′ and OB′ as asymptotes, the limiting diameter of the wheel is given by the point Z on the curve OUGZH, and the wheel diameter is then $2\frac{3}{4}$ inches instead of $2\frac{1}{2}$ inches, as it would be if its surface speed were kept constant.

In grinding holes, then, we see that comparatively narrow wheels must be used, and from the nature of the case a wheel of a diameter somewhat approaching that of the hole must be used. The work should then be started with as high surface velocity as is consistent with a workable cross-feed, the wheel being bevelled at its edge if necessary to stop glazing. This gives the best starting condition. After the wheel has worn down a certain amount it will begin to wear away too fast, and the work speed should then be lowered—which permits an increased cross-feed—and this restores the wheel action to the conditions in which it tends to glaze, and so the cycle begins afresh.

I have drawn Fig. 200 with a view to assisting in the selection of work speeds, the revolutions per minute obtained from the formula being plotted against the ratio of wheel to work diameter. It is to be observed that the regimen has a gradual change as the wheel wears down, and that this is to be counteracted by altering the work speed. The wheel speed should be kept constant so far as the arrangements of the machine permit.

It will be gathered that conveniences for easily changing the work speed are especially desirable on internal grinders.

The wheel should be trued with a diamond tool mounted on the work slide. It is convenient to have a fine adjustment to the diamond tool so that it can be set just to graze the wheel when the work is to size, thus serving as a gauge to prevent the work being ground over-size.

The stops should be set so that the reverse at either end takes place before the wheel gets more than half clear of the work, otherwise bell-mouthing is apt to occur.

As small wheels (an inch or so in diameter) seem to be regularly harder than their supposed grade, it is customary to make them out of larger wheels worn down or accidentally broken. These always seem to me to work better than those supplied to the size. The pieces of large wheels can be drilled with an old three-square file and turned up by a boy, at a fraction of the cost of the equivalent small wheels from the wheel factory.

Times for Internal Work. — Times on internal grinding depend on many factors. Setting the work takes little time with good appliances—e.g. spring collet chucks for ordinary work and special jigs for such work as motor cylinders, &c., but for work which requires to be set closely when held in a chuck or strapped to a face plate, some time is necessary. For such work as cutters or hardened steel gears five to ten minutes or even more is reasonable setting time, the amount depending on the size of the work and the accuracy required. Cutters are far more easily set on the face plate of a vertical internal grinder than on a horizontal spindle machine. Apart from this the time depends on the amount to be ground out of the hole, the material, and on the machine and the spindle.

On small holes especially it is desirable that the spindle and sleeve should be so large in diameter as only to allow a good initial clearance and reasonable wear for the wheel, and the less overhang from the support the better. An unsuitable spindle greatly increases the time required to grind the hole; a wheel of unsuitable grit and grade has a like effect.

The wheel should not come far out of the work, for much is apt to produce bell-mouthing; the time for gauging is usually small compared with the actual grinding time, and may be taken as proportional to it, so that the time may be written—

$$T = kdlt + a$$

where d = work diameter, l = length of work, t the allowance on the diameter for grinding, and a is a constant allowing for attention to the machine, setting, &c., and k a constant varying with the spindle. For work which requires small time in setting, if d and l are in inches and t in thousandths of an inch; the time in minutes will be obtained if $a = 5$ and k is taken as follows for spindles reasonably suited to the following holes—

Up to a diameter of	1″	$1\frac{1}{2}$″	$2\frac{1}{4}$″	$2\frac{3}{4}$″	$3\frac{1}{2}$″	6″
$k =$	·4	·3	·2	·15	·125	·1

The length is supposed not to be so long as to cause trouble from excessive spindle vibration.

The times thus calculated are suitable for work on hardened steel; for cast iron or bronze the time will be shorter, a little so on the small work increasing to one half or more on the larger sizes. For example, automobile cylinders from $2\frac{3}{4}$ inches to $3\frac{1}{2}$ inches diameter and from 5 inches to 8 inches long are usually ground in from 10 to 25 minutes, depending on the size, the allowance, and the quality of the cast iron. As in external work, carborundum is the most satisfactory abrasive for cast iron. A few examples of times, kindly supplied by the firms mentioned, are given (page 422) later.

CHAPTER VIII

THE UNIVERSAL GRINDER AND ITS WORK

Travelling Wheel Type.—'Universal' grinding machines are arranged to be able to do both external and internal work, and are usually able to do some other work in addition. The Brown & Sharpe Universal Grinder is illustrated in Figs. 29, 30, and 33, and described in Chapter IV; the description there and also the lettering in general fits the Landis Universal Grinder, illustrated in Fig. 110, which is of the opposite type, in that the wheel head with its cross slide is mounted on the main slide and traverses. The principal details of the machine have already been noted. The diamond tool holder is seen at D on the floor, and a drawing of it in action is given in Fig. 64. The speed variation for the rate of travel of the main slide is by means of friction wheels in the case N, their position being controlled by the lever N′. In the Landis Internal Grinder, Fig. 98, this controlling lever is at the friction box, and the friction wheels are of the concave recess type, with the leather-covered friction wheels arranged to swivel to give the speed alteration. In this internal machine the main slide movement is short and the main ways are protected by cast iron covers, but in the Universal, where the movement is longer, a spring roller blind cover, shown at J′, is used. The countershafting is shown in Fig. 111; the wheel head is driven from it by means of a belt *q*′ from a large high-speed drum *qq*, along which the belt travels to and fro, following the movement of the main slide. The work head is driven by a belt *u*′ from a short drum *u*, so as to allow for different positions of the head BB′ along the work table H. The fast and loose pulleys *n*, *n*′, cone pulleys *p* for driving the wheel drum *qq*, cone pulleys *t*, *t*′ for driving the work drum, and the pulleys *r* and *y* for driving the pump and traverse respectively are all lettered in accordance with the description in Chapter IV.

The Cincinnati Universal Grinder is shown in Fig. 112, and

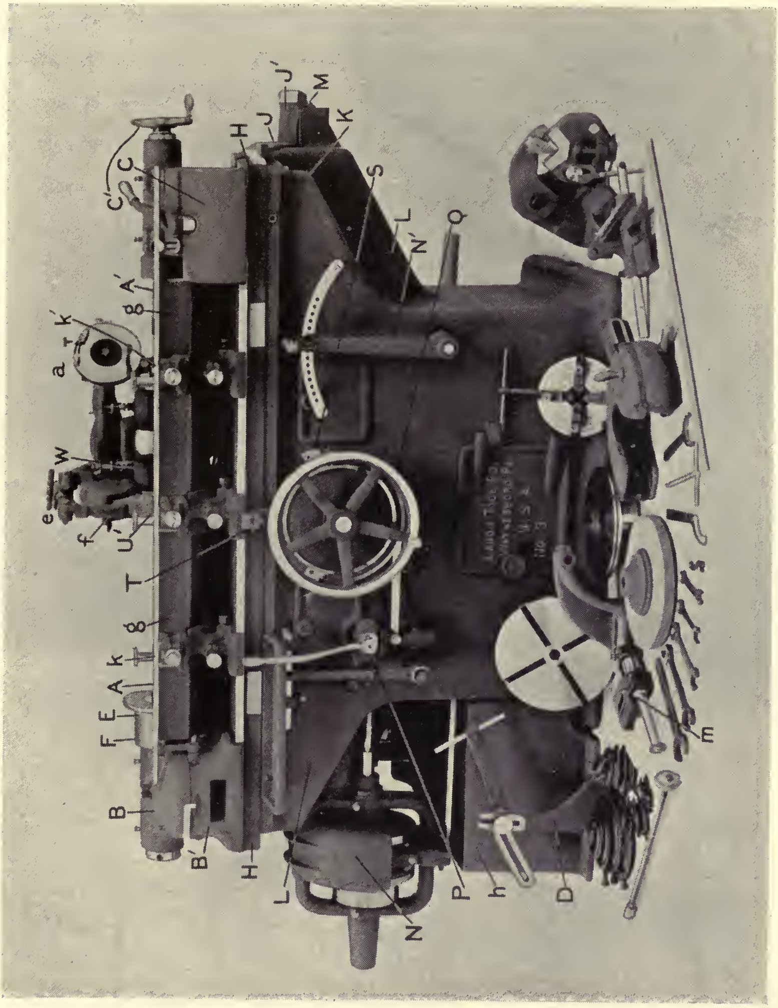


Fig. 110.—Landis Universal Grinder

the arrangement of the drive which was brought out by this firm has been already described in Chapter VI, and is being adopted on other machines owing to its convenience,

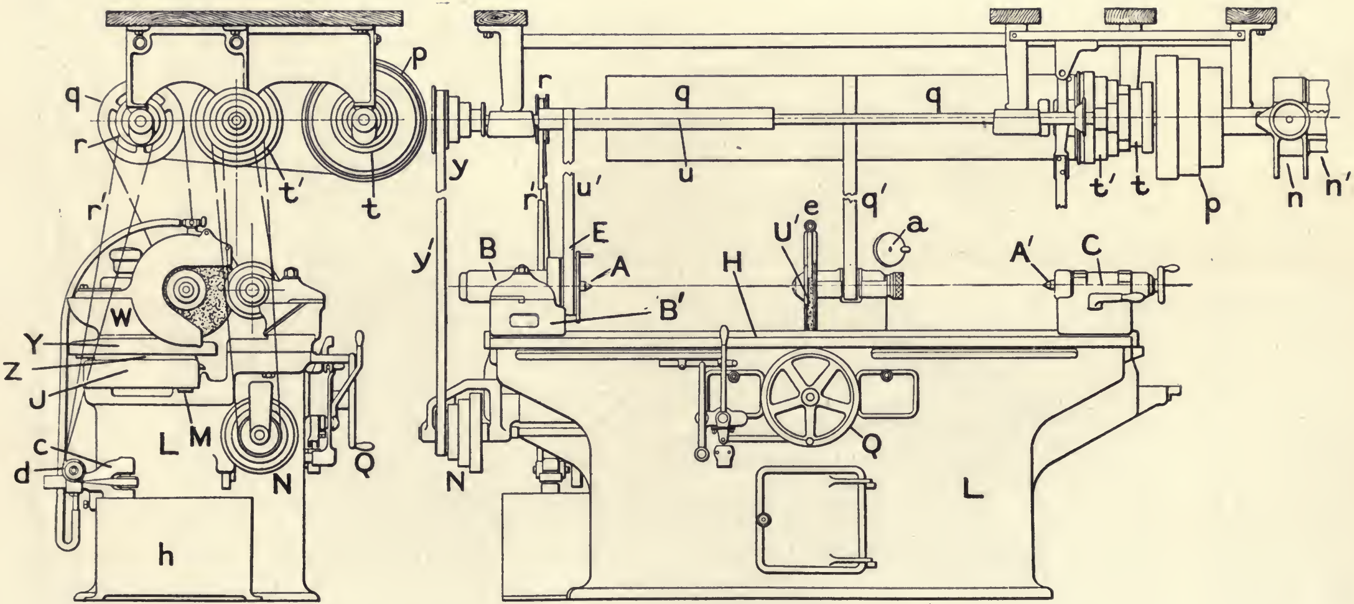


Fig. 111.—Landis Universal Grinder. Arrangement of the Drive

as the countershafting is simple, and all speeds of the work and table are obtained by the manipulation of handles on the machine itself.

Speed change boxes carried on the machine itself are also a feature of Messrs. Alfred Herberts' large Universal Grinder (24 inches by 12 feet capacity) shown in Figs. 113 and 114. Various differences of arrangement are noticeable, which adapt the machine to larger universal work and to such as is done in

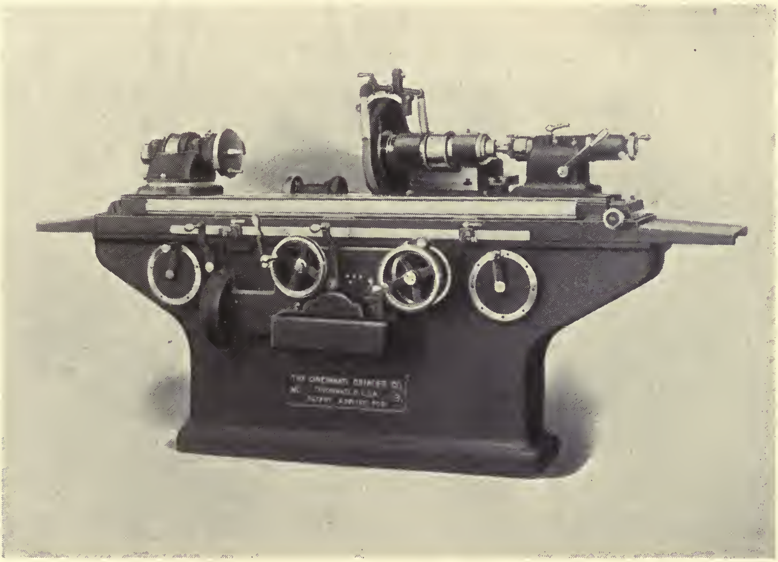


FIG. 112.—UNIVERSAL GRINDER—CINCINNATI GRINDER CO.

Messrs. Alfred Herberts' shops. The work head is driven by spiral gears set at 45°, so that in moving the head through 90° the belt is stretched as little as possible, as the headstock pulley A changes its angular position. The headstock and tailstock fit the table by means of a vee B and flat C; the vee is gashed at intervals to permit the grinding solution to flow away, and the table is open and not protected. The headstock and tailstock are traversed along the table by means of the wheels D, the shafts of which terminate in pinions meshing with the rack E. The guarding of the main ways is effected by sloping sheet steel guards F, G, after the same manner as in the Norton machines. The vee G of the main slide is here at the side of the ways nearer to the operator, an arrangement which was also adopted on the earlier Norton machines. My preference is for the vee on the inner side, as is the practice of Messrs. Brown & Sharpe, Churchill, &c. The steadies H are arranged so that the three shoes used bear at points on the work circum-

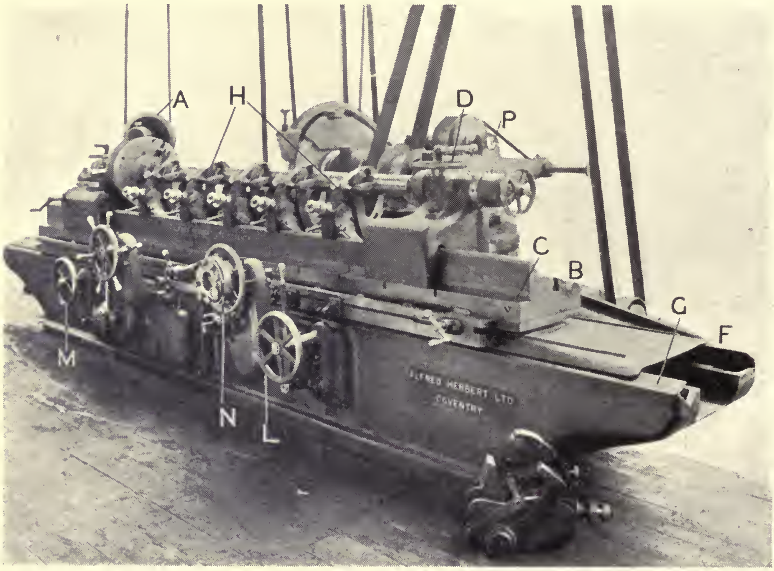


FIG. 113.—HERBERT UNIVERSAL GRINDER, 24″ × 12′ 0″

ference which are well apart. The speed change boxes J, K are controlled by wheels L, M at the front of the machine. The automatic throw-out to the cross-feed contains a number of independent plates at N, so that several different diameters can be duplicated on work without removing it from the centres. The wheel head carries the internal grinding spindle bracket integral with itself, and also a separate countershaft P for driving it, with an eccentric mounting to the shaft so that the belt from its pulley to the internal spindle can be easily tightened. The backlash is taken out of the wheel slide by means of a secondary rack, capable of sliding but held up to its pinion by a spring; the tension in the spring is adjusted until its force moves the wheel slide with certainty along its ways—which are of the vee and flat type. The adjustment of the cross slide to any desired angle is made by the lever Q at the rear of the machine, which operates the pinion above it through a ratchet.

The Swivelling Cross-ways.—The work of the Plain Grinder

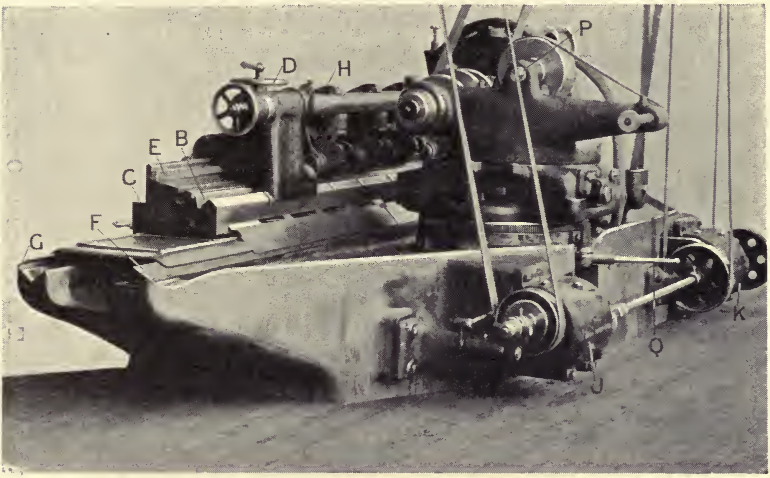


FIG. 114.—HERBERT UNIVERSAL GRINDER, 24″ × 12′ 0″

is limited to tapers of slight angle, the maximum amount of which depends on the size of the machine, being 6° or 7° only in the larger machines, but much more in the small machines. The complementary taper can also be ground by traversing the wheel with the cross-feed. The cross slide in Universal grinders is arranged to swivel as a whole, so that tapers of any angle can be ground on work between the centres or held in a chuck. The arrangement is described in Chapter IV, and illustrated in Fig. 32.

Double Taper Work.—Occasionally it is convenient to be able to grind two tapers on work at a single setting, and the

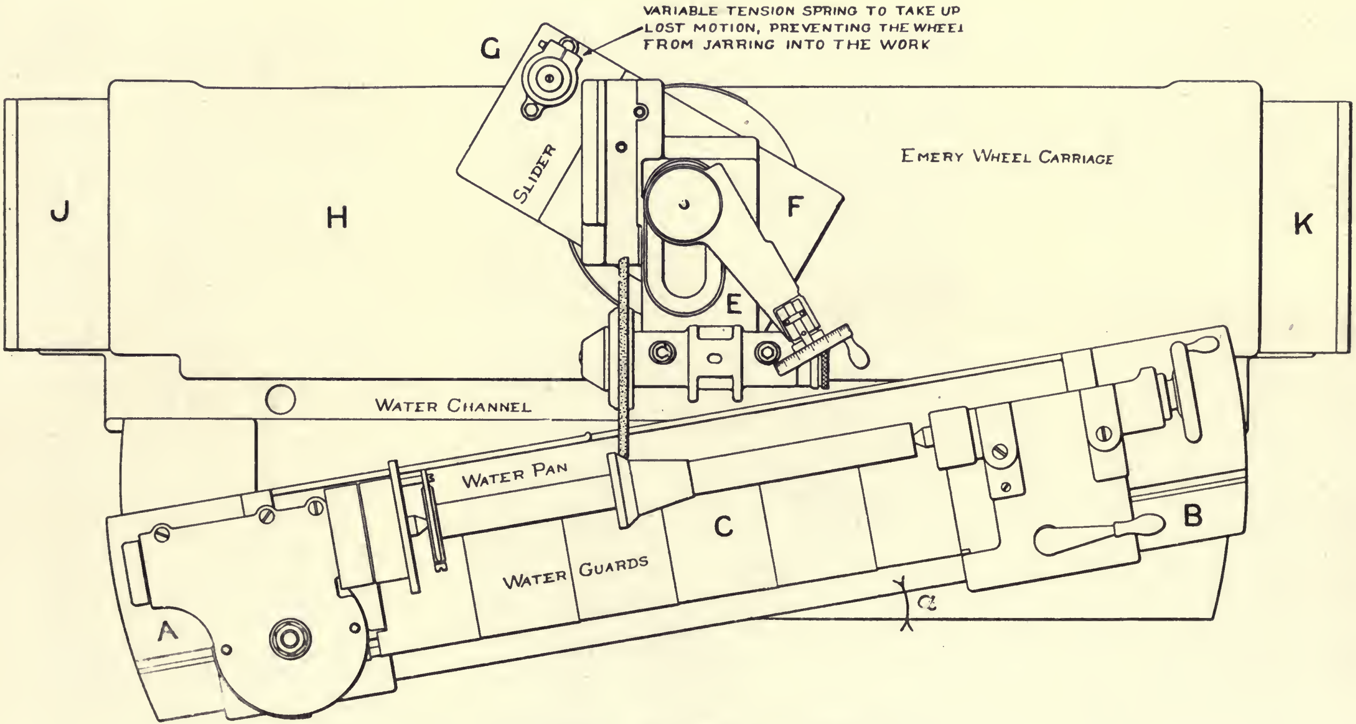


Fig. 115.—Grinding Two Tapers at One Setting

method of doing this is illustrated in Fig. 115, which shows a plan view of a Landis Grinder arranged for the work. The table AB is first set over to the angle a so as to grind the slight taper C, the included angle of which is $2a$; and the cross slide is then set over as shown to grind the abrupt taper. To do this it has to be set over to the angle $a + \beta$, where 2β is the included angle of the abrupt taper. The taper C is ground, using the automatic feeds, but for the abrupt taper the wheel has to be traversed over the work by the cross-feed motion. The wheel head E is shown swivelled on the top of the cross slide F to about its usual position. The spiral spring which takes up the backlash of the cross-feed in these machines is contained in the case G. All the cross slide and its mechanism is carried on the main slide H, and the roller protecting guards for the main ways are seen at J and K. Although quick tapers in internal work can be done by swivelling the wheel slide, it is better to do them by swivelling the work head, as then the automatic feeds can be used. When it is desirable to grind two tapers at one setting on work held in a chuck, the cross slide is swivelled as above described for work between the centres.

Facing Shoulders. — For facing shoulders, the swivel adjustment of the wheel head on the cross slide is useful. Suppose that a collar has to be faced square on a parallel shaft, as shown in Fig. 116. At X is shown the case of a plain grinding machine, where the wheel axis AB is parallel to the work axis CD. The edge of the wheel grinds the work along EF, and the side of the wheel the shoulder along FG. To prevent untruth or want of squareness of the side of the wheel grinding the shoulder out of truth it is advisable slightly to recess the side of the wheel, as indicated by the broken line HJ. At Y is shown the same case, but the corner of the wheel has been rounded by wear, the amount being much exaggerated: to keep the corner square it is usual to recess the work slightly in the lathe, as indicated at KL: or sometimes as at MNP in the figure Z. Such recessing cannot, however, be done when the strength of the shaft is of importance: in such cases a filet corner should be employed. In the figure Z the wheel axis QR is shown slightly inclined, so that only the corner of the wheel touches the shoulder on the work, and touches it along a line in the plane of the paper, and not along an arc at right angles to it as in the figure X with the wheel recessed. The edge of the wheel touching the shoulder is trued and the shoulder ground by traversing the wheel out by the cross slide in the direction indicated by S ; this produces

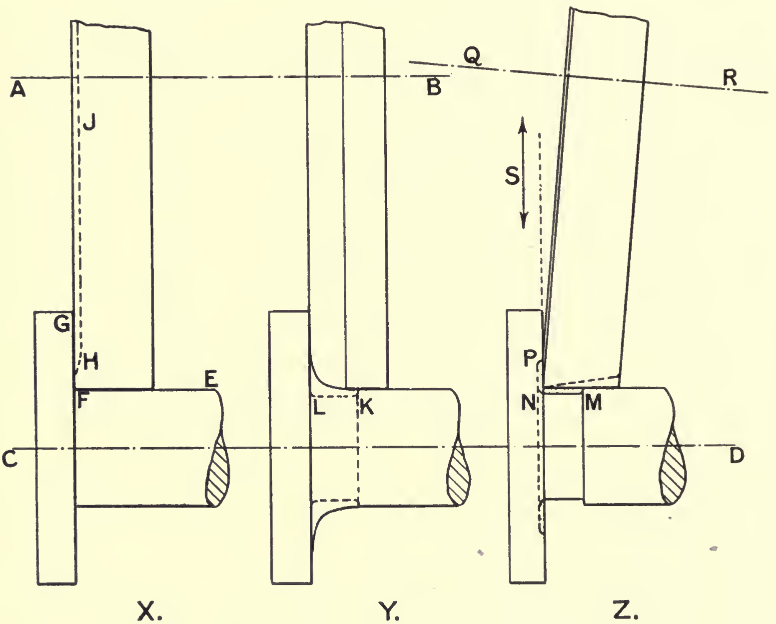


FIG. 116.—GRINDING SHOULDERS

a true conical or flat (according to the setting of the cross slide) surface of much better quality than that produced by the method shown at X.

When the wheel spindle is thus set inclined slightly to the main ways, it is important to take the end play out of it, and the diamond when truing the wheel should be as nearly ' level ' with the axis as possible.

The Work Head and Running Spindle.—Since the work head spindle is used for chuck work it is fitted to rotate in bearings, and since it is also used for dead centre work it

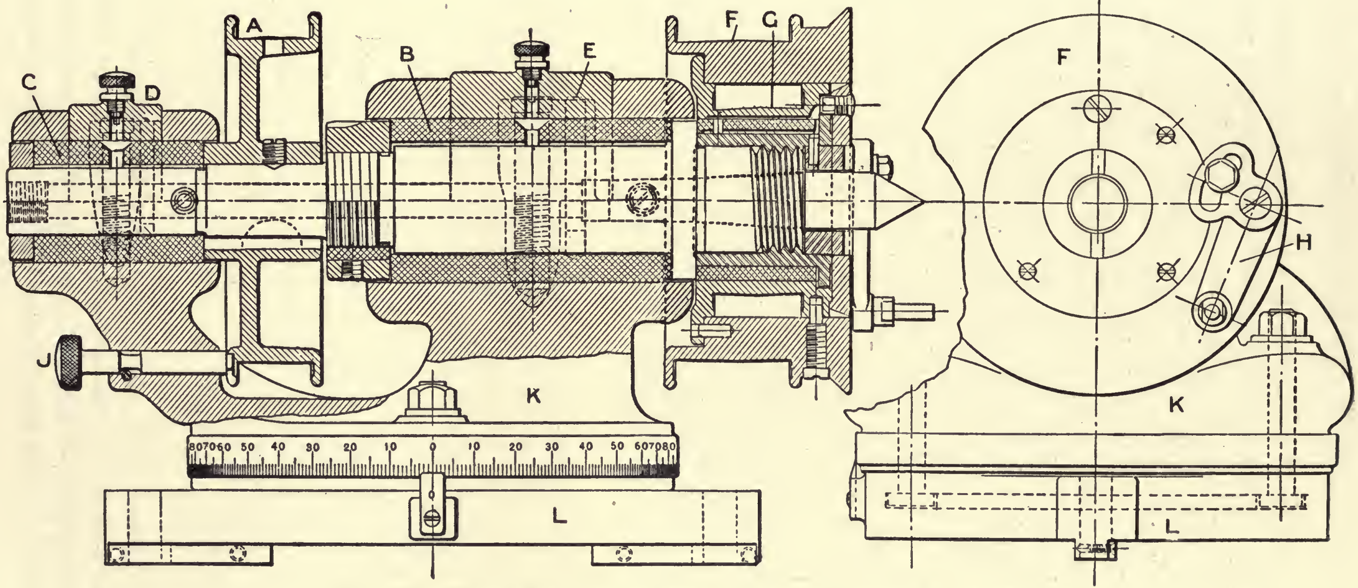


FIG. 117.—WORK HEAD OF UNIVERSAL GRINDER—BROWN & SHARPE

must be capable of being locked, while the dead centre pulley rotates loose upon it. Messrs. Brown & Sharpe's design is shown in Fig. 117. For chuck work the spindle is driven by the pulley A, between the bearings B and C, which are bronze bushes split along one side, and are closed by the caps D, E, and are prevented from closing further by wedges in dovetail slots. The spindle nose has a parallel part and a thread for receiving chucks and face plates, and also the dead centre pulleys shown in position. The outer pulley F can be removed, leaving the smaller one G which will give a higher speed to the work. An adjustable driving pin as shown at H is a convenience. When the dead centre is used the spindle is locked by the plunger J engaging a hole in the pulley. The whole upper part K of the head has a swivel adjustment on the base L, so that taper and flat work can be done.

Dead centre pulleys have non-adjustable parallel bushes which are cheaply replaced. They are not to be expected to have a very long life, as it is difficult to protect them perfectly against the fluid, and the best way to meet the difficulty is to adopt a design with the wearing parts as simple as possible.

Collet Mechanism.—The spindle is hollow, and Universal machines are usually supplied with a draw-in collet mechanism as is shown in Fig. 118, and is very useful for holding washers, saws, and other parts to be ground upon the face. The work is placed upon the split collet C, which is expanded by the screw B until the work is gripped tightly. The screw B works in the sliding sleeve D, which is prevented from turning by the pin E, and by turning the rear hand wheel A this sleeve is drawn into the face plate, and carries the collet C and the work with it, and draws the work up against the face plate F. The face plate can easily be ground in position, and so the two faces of the finished work will be true with one another.

Flat Work.—The best flat or nearly flat work is done by swivelling the work head through a right angle and using the automatic feeds. It must be remembered that as the feed is indexed as a certain amount measured on the diameter of the work, the actual movement of the wheel head and amount ground off a collar in this method is only half that shown on the graduations. A diagram of the arrangement is given in Fig. 119, where the wheel A takes successively the positions shown at B and C relatively to the work DEPF, whose axis is PQ. The surface produced is here a male taper, and the wheel cuts from E to P and then becomes clear of the work towards C. If the work head is swivelled so that the axis takes the position PR, then the surface ground would be a hollow cone, and the wheel would cut into the work in the position C, as the surface of the

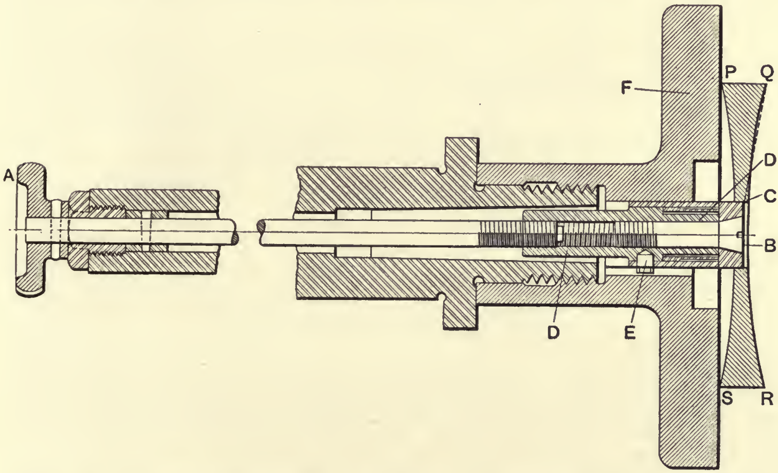


Fig. 118.—Collet Mechanism of Universal Grinder—Brown & Sharpe

work would be that indicated by the broken line PG, so that the corner of the wheel must not be traversed beyond the centre. If the work axis PS were exactly perpendicular to the wheel travel EP, then the wheel would continue cutting the same when in the position C, and so an even light cut of the wheel over both sides of the work—particularly at the circumference E and H—indicates that the work is flat, and furnishes the best method of setting the work head axis perpendicular to the main ways of the machine. The final adjustment of this is made by the aid of the screw K (Figs. 29 and 110), which swivels the work table and the work headstock which it carries.

Work can be ground similarly by keeping the work head axis parallel to the main ways, and setting the wheel head round through a right angle. In this case, however, the wheel has to be traversed over the work by the cross-feed and the cut put on by the main slide motion, both of which are inconvenient; the work, however, is more easily set in the machine and is

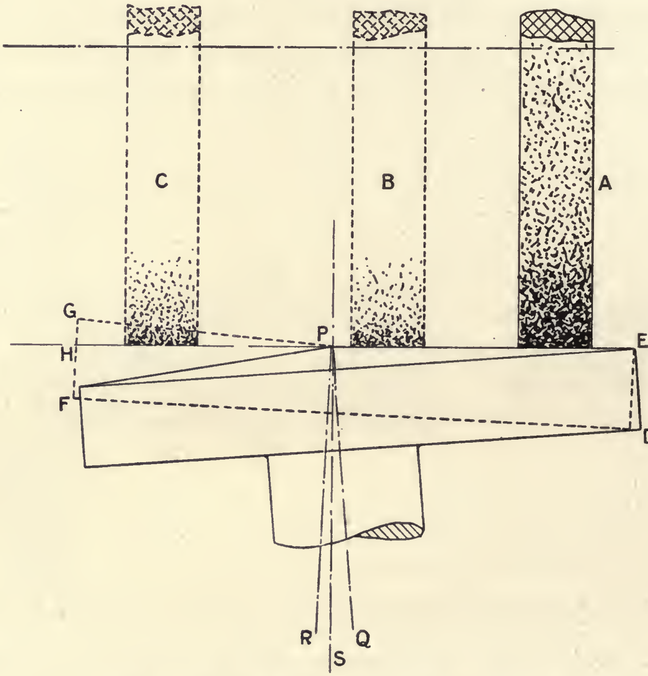


FIG. 119.—FACE WORK IN UNIVERSAL GRINDER

easily seen. When such work is needed in quantity one of the machines illustrated in the succeeding chapter is more suitable.

Flat or nearly flat work may also be produced in a Universal grinding machine by the use of a cup wheel, the face of which is brought up against the work. If the work revolves, as in the above cases, the work will be flat when the axes of the wheel and work are parallel; the quality of the surface produced is not so good as that produced by the method previously described. Machines specially adapted for the purpose are described in Chapter IX. Cup wheels can be used to produce flat work, such as square and hexagonal shafts, knife edges, &c., in a Universal Grinder by suitably mounting the work and using the traverse motion. Fig. 120 shows a Landis grinding machine set up for grinding a square shaft. The table is first set so that the work is parallel to the main ways and then the wheel spindle set square with the work, or rather very

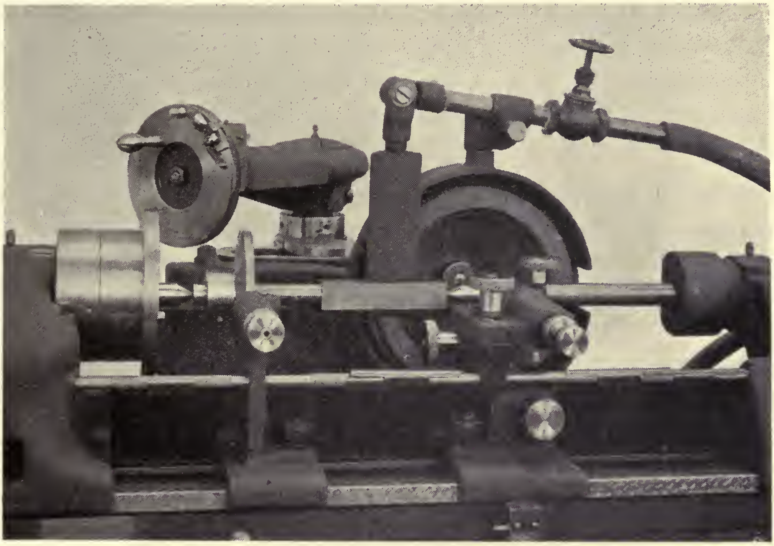


Fig. 120.—Grinding Square Shafts—Landis

nearly square, so that it cuts at one side only. If it is set decidedly off the perpendicular position the sides of the square are ground slightly hollow. On the left is to be noticed the index plate and plunger for locating the sides of the work correctly. When the side of the square is less than the diameter of the tailstock it is necessary to use a long centre as shown, otherwise the wheel will foul the tailstock. A steady is shown supporting the long centre.

It is convenient to be able to sharpen large cutters in a Universal Grinder, as they are frequently beyond the capacity of the regular shop cutter grinder. For any parallel cutters all that is needed is an adjustable tooth rest such as is seen on the floor in Figs. 29 and 110; but for face and angular cutters it is necessary to have an auxiliary wheel head which can be inclined and adjusted vertically. Such a head as fitted by the Landis Tool Company is shown in Fig. 162; it takes the place of the bracket for the internal grinding spindle, and is adjusted to grind the clearance on the cutters according to the principles explained in Chapter X.

CHAPTER IX

SURFACE GRINDING

NEXT to work of circular section the production of flat surfaces is of most importance in engineering, and such work may be produced by grinding in several ways, each having work to which it is best suited. These methods may be divided into two classes, employing the edge and face of the wheel respectively, and these subdivided further according to the method of producing the flat surface.

Edge Wheel Machines—Planer Type.—In Messrs. Brown & Sharpe's No. 2 Surface Grinder, Figs. 121 and 122, the edge of the wheel is used and the work traversed beneath it. At the end of the stroke the work is traversed sideways for the next cut, so that the surface is produced in a manner geometrically that of a planing machine. The surface produced is one parallel to that containing the lines of the main and cross slides, and its accuracy, so far as geometry goes, depends solely on the straightness of these two lines.

The main slide ways consist of two vees, but cannot be seen well in the views; the cross-ways are of similar type, and are clearly seen in Fig. 121. The main slide A can be traversed by the hand wheel B or by power, the reversing being done by stops, one of which is seen at C, acting on a plunger trip mechanism. The main slide is carried on the cross slide D, the movement of which is controlled by the hand wheel E, and can be operated automatically by the gearing shown at F. This cross-feed is rapid, as the cross slide must be quickly moved through a space from $\frac{5}{8}$ to $\frac{7}{8}$ of the width of the wheel at each reverse, so as to keep the wheel face flat, as explained in connection with cylindrical grinding (page 95); it involves much more strain on the mechanism than the small amount of cross-feed of the machine we have previously considered. The wheel spindle G is horizontal, and is supported by a bearing close up to the wheel; the whole wheel head H has a vertical adjustment by means of a screw J, the nut of which is rotated by the hand wheel K through bevel gearing. The ways of the vertical slide, which are of a very unusual type, are clearly seen in the

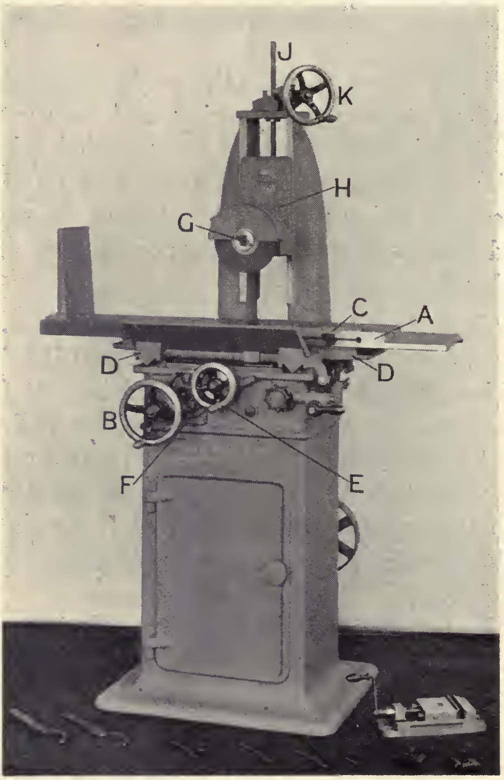


Fig. 121.—Brown & Sharpe No. 2 Surface Grinder

illustrations. The machine is driven from an overhead countershaft by means of a belt running round the pulley L, then round the wheel spindle pulley, and finally round the pulley M to the overhead driving pulley; the pulleys L and M are carried by a swing frame N, which is pivoted at P, and the weight of which preserves a suitable tension in the belt. In Fig. 122 the machine is shown equipped with a dust extractor; the machine is used dry, and the grit-laden air drawn away by an exhaust fan. Much of the dust and grit can be caught on a wet belt running slowly on the side of the machine towards which the wheel runs as it cuts.

In larger machines of this planer type, the wheel head

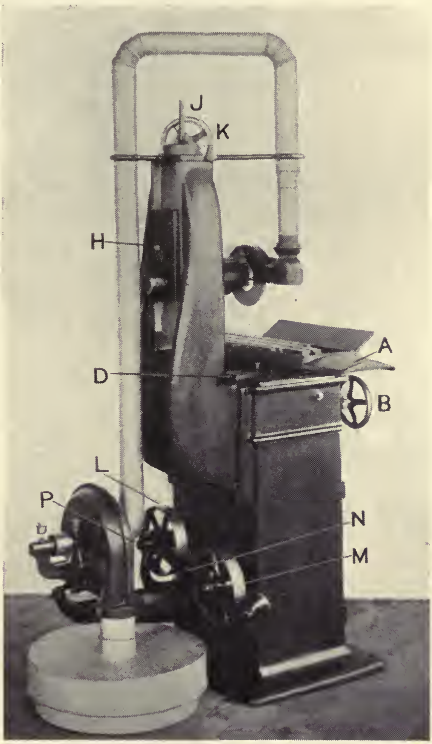


FIG. 122.—BROWN & SHARPE NO. 2 SURFACE GRINDER

may be carried between two uprights, as is the tool in regular planing machines, or it may be carried as in Fig. 123, giving an open-sided machine. The machine shown in this illustration is by the Norton Manufacturing Co., and has a capacity of 15 inches by 8 feet by 17 inches, and takes a wheel 14 inches diameter by 6 inches face. The sheet guards A, A′ protecting the main ways, the reversing stops, and mechanism are similar to those on the plain grinders by

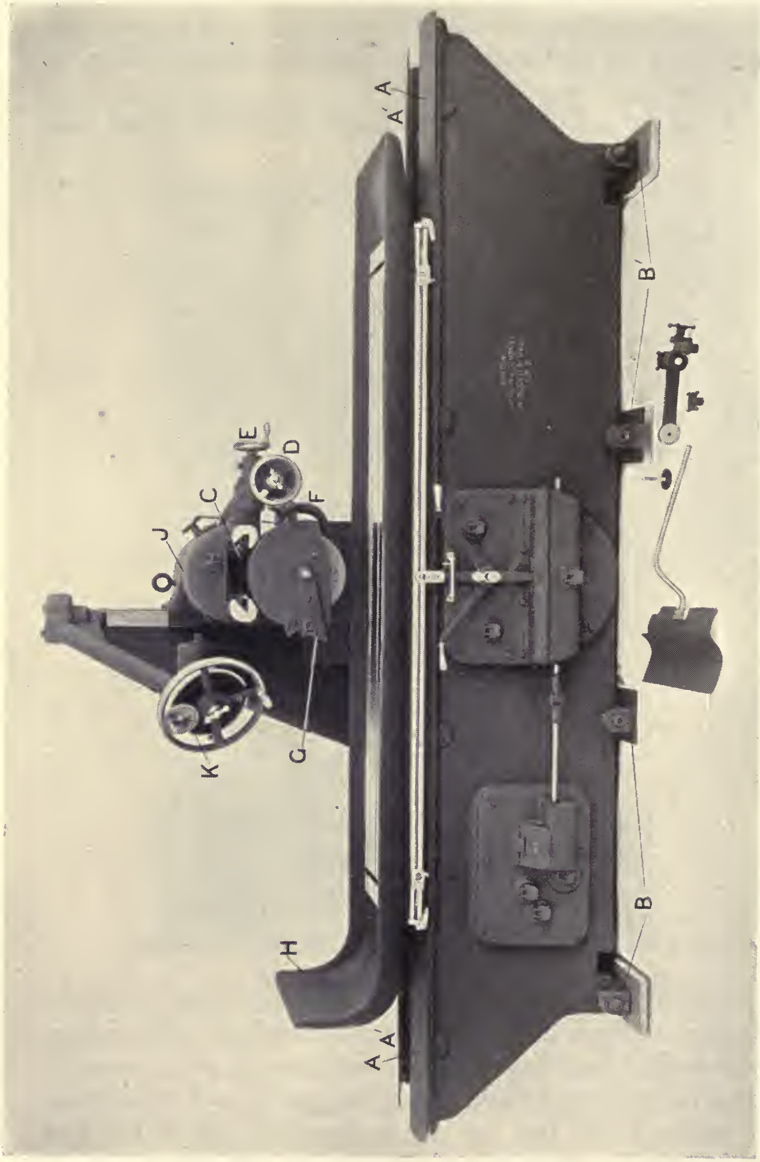


Fig. 123.—Norton Surface Grinder

the same firm. The bed is supported on a series of taper wedges B, B, so that the effects of settlement of the foundation at any time can be corrected. The wheel head is carried on a horizontal slide C, and has a rapid cross movement by the hand wheel D—no automatic movement is provided; the width of the wheel necessitates considerable cross movement in surfacing, and this is left to be operated by hand. There is at E a second hand wheel—geared into the shaft of D by means of a worm and worm wheel—whereby a slow cross motion can be given to the wheel for truing it. A large supply of water is arranged for, delivered by the pipe F, and guards at G and H are provided to deal with the spray. Power is provided to raise and lower the vertical slide J, and fine adjustment for setting is provided at K. The machine is self contained, the countershafting being within the machine body, and requires 15 h.p. for regular work. The width of the wheel enables formed straight work to be ground, up to 6 inches wide; for such work special arrangements are necessary for mechanically guiding the diamond tool in truing the wheel.

In neither of the machines of Figs. 121 and 123 can the wheel be inclined in a manner corresponding to the setting of a planer tool-box; should pieces of material require to be ground in such a manner on these machines, the work has to be set up as necessary, or suitable jigs made. The efficient driving of a wheel spindle which can be inclined and moved in such positions is somewhat difficult, and although it has been tried the other method is preferred. Undercut surfaces, such as the vees of ordinary machine slides, have not been ground with commercial success.

The same observations apply to the use of water in surface as in circular grinding, but small machines are seldom fitted for wet grinding. As only one side of the work—instead of all sides as in cylindrical grinding—is ground at a time, temperature effects are large in dry surface grinding, and the wheels used must be very soft so as to minimise the effect.

In Fig. 124 is shown a special Surface Grinding Machine constructed by Hans Renold, in which again the edge of a disc wheel is used in the grinding, but the surface produced in a different way—namely, by rotating the work round an axis, here vertical, and traversing the wheel across by a slide

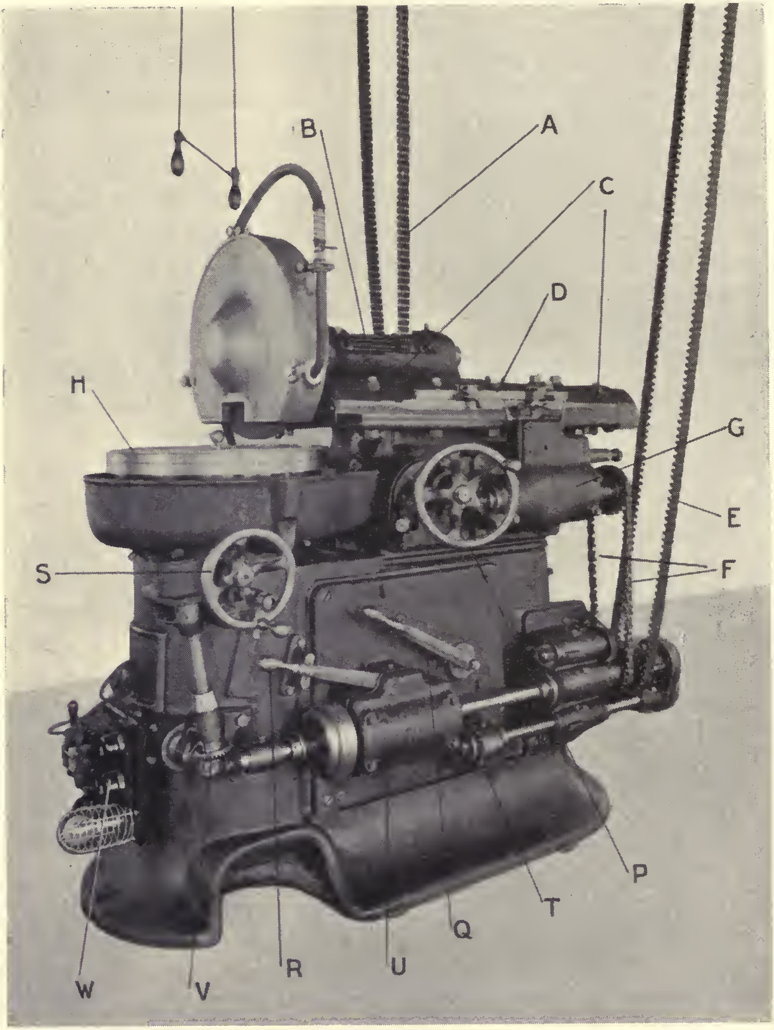


FIG. 124.—SURFACE GRINDER—HANS RENOLD

at right angles to the axis. This corresponds to face work on a lathe or vertical boring mill, and the accuracy obtained depends geometrically on the straightness of the cross slide, and the perfection with which its line is perpendicular to the axis of rotation. If this angle is not a right angle the work is ground conical, either male or female; and as this is sometimes useful—in such work as metal slitting saws—a small adjustment of the angle is provided for in such machines, usually by tilting the work spindle and face plate round a horizontal axis. The work is fed up to the wheel and the cut put on by the vertical movement of the work, which is controlled by the hand wheel at the front of the machine.

The wheel spindle is driven by a 'silent' chain running from overhead; the chain wheel B is so long that, as the wheel slide moves to and fro automatically, it only slides through the chain which is driving it. The wheel head C slides horizontally, and the rack D with the reversing dogs are seen at the front of the machine with the reversing mechanism in the box G below them. The feeds and work are all driven by the chain E, and from this motion the chain F drives the reversing box G. The vertical work spindle carries a magnetic chuck H for holding the work; its speeds are obtained through the change-speed gear box U, which is controlled by the lever R, the motion being transmitted through the gearing at V. The cut is put on by raising the work spindle and magnetic chuck by means of the hand wheel S. The pump, driven by the sprocket T, is on the far side of the machine with the water tank; at W is the control switch for the magnetic chuck, and the lamp seen is inserted in the circuit to reduce the current by means of its resistance. The driving of such machines by chains is unusual but illustrative. The corresponding machines, placed on the market by the Churchill Machine Tool Co., and other firms, are all belt driven.

This method of grinding flat work corresponds exactly with chuck work done by setting the work head round (page 281), so as to be square with the main ways in a Universal Grinder.

Work Speeds.—In these cases, where a flat or nearly flat surface is ground by the edge of a disc wheel, the arc of contact is small and is equal to $2\sqrt{Dh}$, where D is the diameter of the wheel, and h the depth of cut. This value can be obtained from the formula of Chapter III, by putting $\frac{1}{2}t = h$, and making the diameter of the work infinite, or it is at once evident from the geometrical relation that the products of the segments of chords in a circle are equal. The limiting velocity and depth of cut depend on $v^2 \frac{h}{D}$ (to which $v^2 \frac{d + D}{dD} t$ reduces on making d infinite), and the best velocity on $\frac{v}{D}$ (to which $v \frac{d + D}{dD}$ reduces). Hence we see that the table speed should be diminished as the wheel wears smaller, and the depth of cut increased proportionally. As the wheel approaches the centre of the work as the table rotates, it is desirable that the rate of rotation of the work be increased, so as to keep the work surface velocity at the wheel edge constant, but this is seldom done.

Cup Wheel Machines.—Until comparatively recently cup or cylinder wheels of a nature suitable for accurate work were difficult to obtain, but with their development the progress of machines employing them has been steady and rapid. Owing to the very large area of contact the grit used must be large and the grade soft, and truing is usually done with a piece of hard carborundum block, as if the wheel is carefully trued with a diamond tool it is more apt to glaze. For such reasons the surface produced is marked, more or less deeply, by the circular marks of the cut, and is not of so high a quality as that produced by the edge of the wheel.

Large cup wheels are very expensive, and wheels built up of suitably shaped pieces of grit stone, held in a chuck, are used on large work. Artificial abrasive slabs are also used in such chucks, but for this work the gritstone at present is holding its position, for the cost is very small compared with that of the artificial material.

As the arc of contact—see Fig. 21—increases with the width of the work, the grade of the wheel should be softer the wider the work, and it is necessary that the grade should be right to prevent glazing or wearing away; hence it is necessary to keep wheels of various grades mounted ready for use, even although one kind only of material is ground.

The power required to drive a wheel effectively with such areas of contact is very high, although soft wheels are used, and the water supply must be plentiful to carry away the heat correspondingly generated. Soda water is to be preferred to a soluble oil mixture, as owing to its 'thinness' the wheels cut with rather greater freedom. Also the total amount of grinding solution (and the tank) should be large, otherwise its temperature rises undesirably when the work is continuous. In Fig. 125 is shown a view of the Pratt & Whitney Vertical Surface Grinder, which uses a cup wheel 14 inches diameter with a $1\frac{1}{4}$-inch wall, so that work up to 12 inches wide (see page 64) can be done. The work is carried by the main slide A under the wheel B, so that the geometrical accuracy of the surface depends upon the straightness of the main ways, and on the accuracy with which the wheel spindle is set perpendicular to them. The wheel is fed to the work by the use of the vertical slide C, so that the machine is simple, in that it only contains two slides and a spindle as the main parts. Mechanically it corresponds to a Face Milling Machine. The table has power feed, with two speeds, 34 inches and 102 inches per minute, with reversing mechanism operated by the stops, and one of which, D, can be raised, so that the table can be run beyond the stops for examining the work. At E is the hand traverse motion for the main slide. The vertical feed, which puts the cut on, is operated automatically by the usual type of mechanism, or by the hand wheel F, which gives the fine feed; rapid adjustment of position can be made by the hand wheel G. The movement of the vertical slide is by rack and pinion, and the wheel head is held back by its weight being over counterbalanced by the chain H and a weight, the force being applied by the chain. The design of the spindle is shown in Fig. 37, page 129; it will be noticed that the spindle itself is relieved from the heavy pull of the driving belt, which is 4 inches wide, as the pulley runs on an independent bush, as is usual in drilling machine practice. The spindle is hollow, and the water is supplied by the pipe J through the spindle to the inside of the wheel. Owing to the porosity of the wheel, the water can be forced through it and spun off by the centrifugal effect,

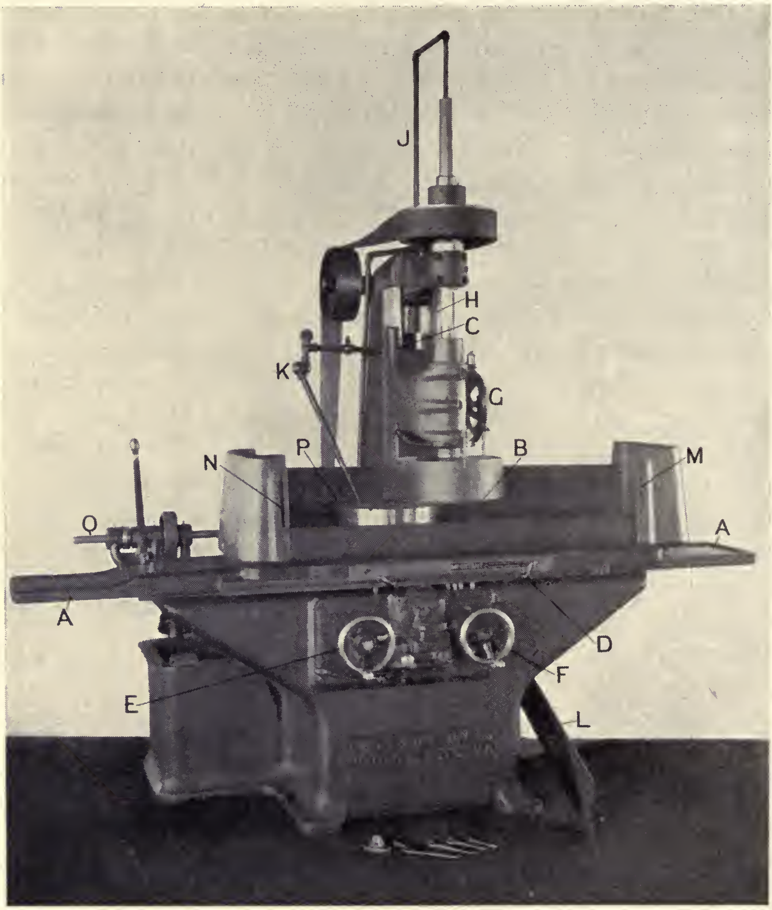


Fig. 125.—Vertical Surface Grinder—Pratt & Whitney

and to prevent this the inside of the wheel is coated with bees'-wax. The water supply through the pipe shown at K is useful for washing grit and swarf from the table when setting work.

When in use the guard shown at L is placed in front of the machine, and slides up and down in the slots M, N. When it is down work can be conveniently set, and when raised it catches the spray from the grinding.

The machine is shown fitted with a removable rotating table P, driven from the shaft Q. For flat, circular work this is desirable, and it can be tilted so that metal slitting saws can be hollow ground. For general flat work, for which the machine is essentially designed, a magnetic chuck fixed to the table is very desirable, as it saves a considerable amount of time in setting most work.

In Fig. 126 is given a view of the Blanchard Surface Grinder, in which the work is carried on a rotating magnetic chuck A and ground by the cup wheel B. The magnetic chuck, with its spindle and bearings, are arranged to slide under the wheel, but merely for purposes of convenience in setting and examining the work, and not for traversing it. The water guards have been removed for sake of clearness and to show the measuring device C, which consists of an Ames Indicator suitably mounted, and by which the thickness of the work is indicated at any time during the grinding, as it passes on the face of the magnetic chuck outside the wheel. The wheel spindle, shown in detail in Fig. 38, with its pulley and bearings, is carried on the slide D, which is adjustable vertically by the handle E, and can be fed by power through the change-speed box F. At G is the change-speed box for the rotation of the magnetic chuck, and above it at H and K respectively the valve handle for the water supply to the inside of the wheel, and a demagnetising switch. The belt for driving the spindle is a 5-inch double belt, the pulley being $14\frac{3}{4}$ inches diameter, and runs at 1000 r.p.m for a 16-inch diameter wheel; a 20 h.p. motor is recommended.

Machines using very much larger cup wheels are used for grinding armour-plate which has been hardened, but have few features of interest other than their size. The largest size in use takes up to 80 h.p. The wheels used are of the inserted segment type (see Fig. 10) and natural stone is employed.

In Fig. 127 is shown the Walker Single Stroke Surface Grinder;

in this the work is carried on a rotating magnetic chuck and ground by simply bringing the cup wheel down to it by means of the slide. When the surface is to be flat its accuracy depends geometrically upon the parallelism of the axes of the wheel and the work. As in other machines the work head, which is here carried in the lower knee, can be set at a small angle to the wheel spindle, as it is pivoted by screws to the knee and adjusted about this axis by means of an adjusting

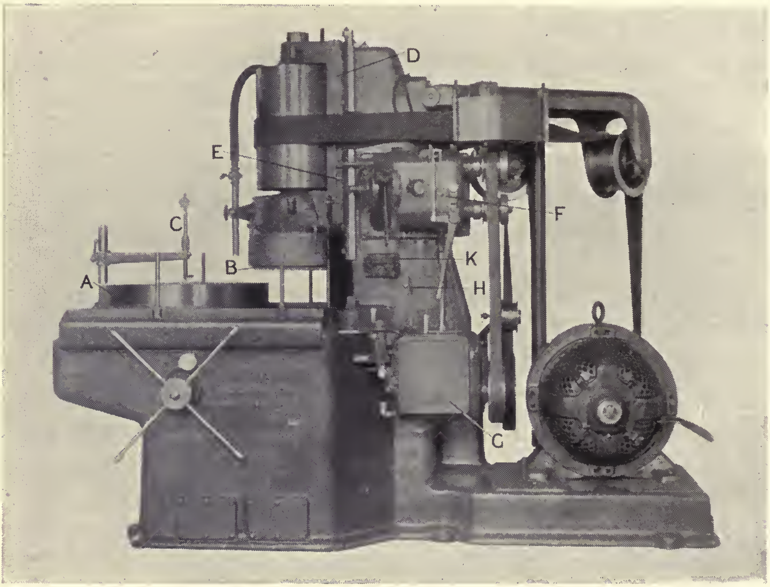


FIG. 126.—BLANCHARD VERTICAL SURFACE GRINDER

screw. In this machine only one slide is actually necessary; the wheel can be raised by the lever, the work set in position, and the grinding done by simply bringing the wheel down upon it; but in order to make the machine into a more efficient manufacturing machine, the magnetic chuck with its spindle and tilting arrangement is carried on a second slide. In working, the wheel head is always brought down to one position defined by a fixed stop: it is raised for removing the work and setting the next piece and then again brought down, grinding the work, to the same position. The knee carrying the work is adjusted vertically, by a graduated hand wheel, to suit the thickness of the work and to compensate for the wear of the wheel; the work spindle pulley is driven from the vertical drum at the rear, and is made long for the purposes of driving in all positions of this vertical adjustment. The movement of the wheel head by the lever always takes place over the same range, and controls the current magnetising the chuck, making it as it descends and breaking it as it rises. It also controls the rotation of the chuck by means of a linkage, which clutches the drum on to the rotating vertical shaft by means of the clutch as the slide descends and withdraws the clutch as it rises. Thus a single movement of the lever alone is necessary to magnetise the chuck, set it rotating, and bring the wheel down until the work is ground to a definite size. The wheel pulley is driven by a belt from the pulley on the rear shaft. In the linkage is a stop, by moving which the clutch is not thrown out when the head is raised; the magnetic chuck then continues to rotate, and can be easily cleaned. The water tank, the supply nozzle, and discharge can be clearly seen. The machine illustrated is fitted with a ventilated magnetic chuck, the blower for which is driven by the small electric motor.

Magnetic Chucks.—For the purpose of surface grinding, parts may be held in vices or by any of the devices which are usual in planer or shaper work, but for much work the most convenient method is by means of magnetic chucks, as previously mentioned. These hold the iron or steel by a magnetic pull to the face of the chuck, and all else that is needful is a stop to prevent it moving in the direction of the cut. The pull takes place on to the surfaces round the gaps wherever the work is there in contact with the chuck; the pull is considerable, and unless the side of the work towards the chuck is true, thin work is apt to be sprung towards the chuck.

When a magnetic chuck is set on a machine with its face true, or ground in position, work can be taken off and replaced with practically perfect accuracy and no trouble, and parts can be duplicated as regards thickness with little difficulty.

The chief matter of importance is that the face of the chuck be swilled and wiped clean from grit before the work is set on it. The resulting saving of time is so great that a surface grinder for general use can hardly be considered to be complete without one, and in some machines, such as shown in Figs. 124, 126, and 127, a magnetic chuck is built in as an integral part of the design.

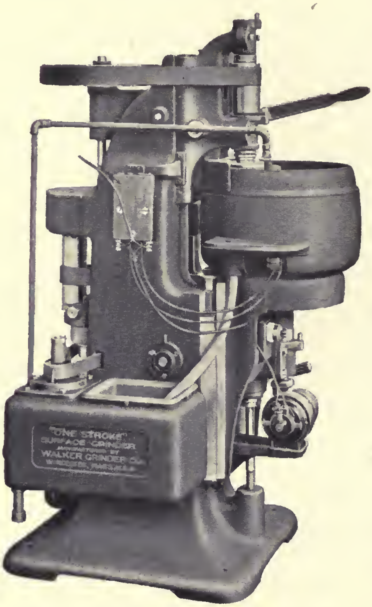


Fig. 127.—Walker One-stroke Grinder

Fundamentally, a magnetic chuck is merely an electromagnet with suitably shaped pole pieces. In Fig. 128 is an explanatory sketch of a magnetic chuck. The current enters the chuck by the wire at A, circulates round the central part B as indicated in the plan view, and leaves by the wire C; a switch for making and breaking the current is shown at D. When the circuit is made, a number of closed lines of magnetic force arise in circuits, as indicated by the broken lines in the side view, up the central part B and along the top F, across the gap GG, down the sides H, H, and across the bottom to the central part again. The irregular shaped top FF, and the correspondingly shaped top of the sides H, H, form the two poles of the magnet. The gap GG is filled up with non-magnetic substance, usually white metal, so that the top of the chuck is continuous. If the chuck rotates the leads have to be carried to rings, and the current brought to them through brushes, similar to those of a small dynamo or motor.

Any piece of steel put across the two poles is attracted to them, and forms an easier way for the magnetic lines than the non-magnetic gap does, so that the number of lines considerably increases as the way becomes easier. The pull on the steel part depends on the number of magnetic lines passing through it.

Iron and steel can only accommodate a certain number of lines per square inch, so that if the part be very thin (say less than $\frac{1}{32}$ inch) the number of lines through it may not create

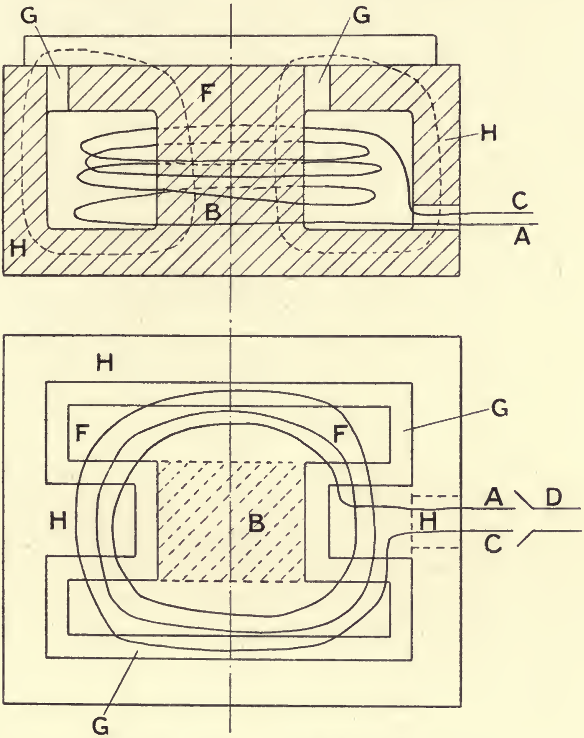


Fig. 128.—Diagram of Magnetic Chuck

sufficient holding force; hence thin pieces are more difficult to hold than thick, and may necessitate chucks of special design with narrower and more numerous gaps.

The shape of the gap GG varies in different chucks according to the work for which they are intended; circular chucks may have the gap arranged in many ways—it may be a series of radial lines connected by arcs, or a number of circles arranged concentrically or otherwise.

The coil of the chuck has to be wound to suit the voltage of the electric supply; too high a voltage would overheat the coil in a chuck designed for a lower voltage, and might fuse the wires. Continuous current is almost always used; chucks can be made for alternate current, but are more complicated and do not hold so well; hence if the current supply is alternating, it is better to run a small continuous current dynamo to supply the chuck current. Very little current is needed, so that the low efficiency of the small dynamo is not a matter of much moment.

There is a considerable amount of energy involved in the production of the system of magnetic lines, and some precaution is needed in breaking the circuit; a secondary resistance should be fitted, or at any rate the switch should be of the quick break double pole type. As the magnetic lines rapidly decay on the electric circuit being broken, they produce an electromotive force round the wire circuit, which tends to generate a powerful but temporary current.

High voltages should not be used, as the operator's hands are usually wet, and shocks are then severe.

Soda water and oil are very destructive to (electrically) insulating materials, and it is necessary that the chuck should be quite waterproof, and no holes, tapped or otherwise, should lead to the interior, other than that necessary for the leads (wires conveying current to and from the chuck). The leads should be encased in a tube or lie within the machine, protected against injury from grinding solution or accident.

In Fig. 129 is shown a magnetic chuck by the Walker Grinder Company; the interior is ventilated in order to prevent deterioration of the insulation by the grinding solution. The machine spindle A carries a chuck plate B, to which the magnetic chuck C is fastened. The ventilating air passes through the spindle—which is hollow—at F, circulates in the chuck and escapes at the holes E, E, which have gauze across them to prevent the entry of dirt. The current is conveyed to the chuck coil through the rings G and H, on which brushes rub. At P is some of the non-magnetic material in a gap in the chuck face. The forced draught is usually produced by a small blower driven by a motor; such an arrangement is shown in Fig. 127.

In chucks of my design—one of which is shown in Fig. 130—there is no aperture whatever in the chuck face, the central hole being a blind one and used only for the insertion of plugs to centre the work. The current is carried to the chuck by leads through the hollow spindle of the machine, and the slip rings are two small rings at the rear of the spindle, well away from grinding fluid and spray.

Hardened steel work which has been held on a magnetic chuck is apt to remain magnetised. To remove the magnetisation it is necessary to magnetise it in alternate directions with a gradually decreasing intensity of magnetisation. Instruments for the purpose are called demagnetisers, and consist of an electro-magnet, with a revolving switch for alternating the current and a resistance which can be gradually increased to a large amount, so as to reduce the current and the magnetisation. For small numbers the parts can be simply rotated in a magnetic field, and then moved away from it while they are rotating.

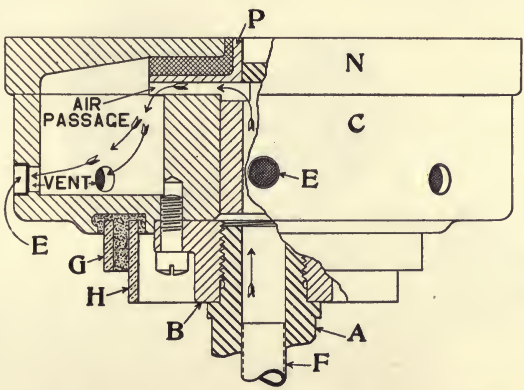


Fig. 129.—Ventilated Magnetic Chuck—Walker

Metal Slitting Saws.—The sides of metal slitting saws are usually ground with cup wheels on machines such as are illustrated in Figs. 125 and 130, and are made slightly hollow so that the saw clears itself sideways. This can be done by using the edge of the wheel as is shown in Fig. 119, page 282, and adjusting the setting of the work head so that the side of the saw is ground to the shape of a hollow cone; the cup wheel method has some advantages, and the operation presents some instructive points.

Whenever grinding is being done there is some normal force between the wheel and the work; it is slight, but as the wheel runs off the work it tends to cut a little deeper, as it is not kept out so effectively as the area of contact lessens; thus internal work tends to bell-mouth, and the wheel should not be run very far out of the hole at either end. So in hollow

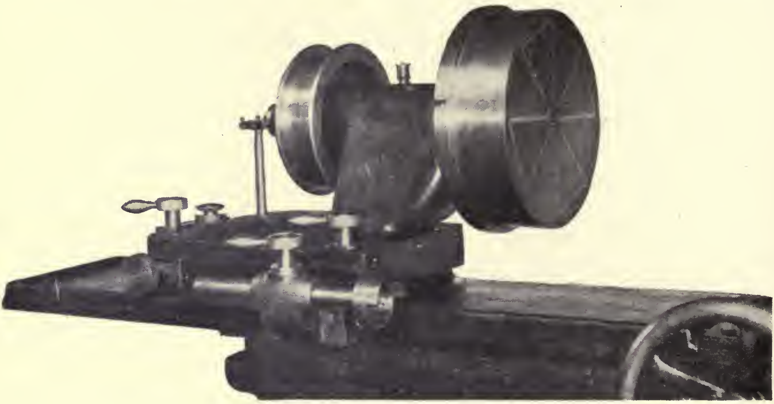


FIG. 130.—MAGNETIC CHUCK—GUEST

grinding metal slitting saws with the edge of the wheel, if the wheel is run off the teeth the slight hollowness may be lost just at the edge by the action of this small spring of the wheel towards the work, so that the saw may tend to bind in the cut when used. If, however, the wheel be not run off the saw—since the clearance at the edge depends on the straightness of the wheel—the result may be the same. When a cup wheel is used it is brought practically normally up to the face of the saw, and the grinding is done in that position; as it is never run off the edge there can be no rounding, and the relief is obtained with certainty.

It should be noticed that this small action also affects such tools as twist drills; the edge along the flutes is ground and made taper along the length of the drill, the shank end being a few thousandths of an inch less in diameter than the lip, so that the drill clears lengthways. In grinding this edge (clearance is usually milled or ground at the rear of it) the drill should be rotated so that the rear of the edge strikes the wheel first; it tends then to spring out from the wheel a very little, so that when the cutting edge is being ground it is just a bit farther from the drill's axis, as there is no time for the springing to return before the edge has gone past the wheel. The amount of this action depends on the springiness of drill and machine: it is always exceedingly small, but drills ground that way (it is unusual, requiring a left-hand grinding machine for right-hand drills) cut a little more freely than if ground using the customary direction of rotation.

If the sides of a saw are ground by the first method, the angle of the side is constant—that is, a line drawn from the centre to the outside of the saw surface is straight; but when ground by the cup wheel method the line will be a circular arc. For the same clearance this leaves the centre of the saw much thicker, which is desirable, and since it removes less metal the grinding can be done more quickly.

That the shape of the ground surface in this case is spherical is not difficult to see. Let ABCD in Fig. 131 be the edge of the wheel face and EF the axis of the wheel spindle, and let the work axis be FG. In the machines these are in one plane, and intersect at the point F. Since EF is a perpendicular at the centre of the circle ABCD, then all the lines FA, FB, FC, &c., are equal, and hence as the work revolves round FG all the lines from F to the ground surface are equal—that is, the ground surface is a piece of a hollow sphere, and therefore any plane section, radial or not, of the ground surface is a circular arc.

The sketch shows FG to miss the circle ABCD, which is the case of a saw with a raised collar at the centre; usually there is no collar, and the wheel is set so that the circle ABCD passes across the hole in the cutter.

The advantage of this spherical clearance is shown in Fig. 118, where it is much exaggerated; the full line PQRS shows a saw with the spherical clearance, and the broken line from Q a straight (conical) relief. The spherical clearance gives a greater relief at the edge, and at the same time the centre of the saw is thicker.

In the figure the saw is shown held on a drawback expanding collet, which is the best method for the roughing operations. The saw is first placed on the collet C, and the latter expanded by the screw B. The collet carrying the saw is then drawn into the spindle by the screw A, operated from the rear of the

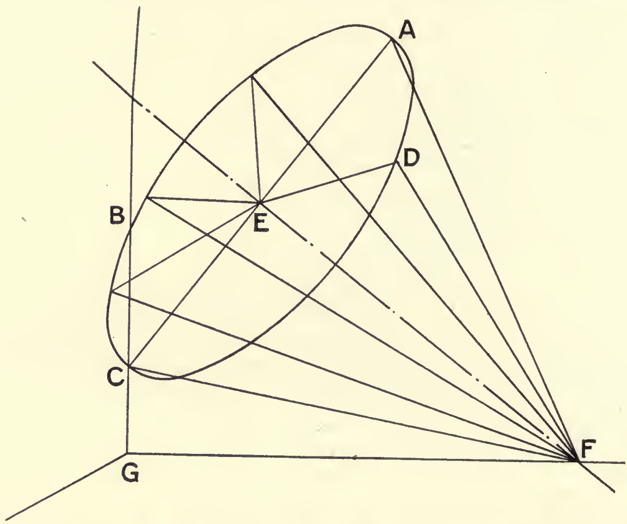


Fig. 131.—Grinding Saws, Concave

spindle, until the saw comes against the face plate F. Owing to the warping in hardening the saw usually will not touch the face plate all the way round, and it is packed where necessary with paper, until on drawing the saw up tightly to the face plate all is firm. After grinding this side is practically true, and will need no packing when reversed for grinding the other side. Although the saw is hollow where ground, no packing piece is really essential, although one is used sometimes.

The resultant cut of the wheel passes fairly close to the collet, and it acts as a stop. I have ground the sides of circular cigarette knives 9 inches diameter by $\frac{1}{16}$ inch thick, with a

$\frac{3}{8}$-inch central hole, holding them in this manner firmly under a heavy cut.

After a saw has been roughed out, the best means of holding it for finishing is by means of a magnetic chuck. If a magnetic chuck be used initially the saw must be reversed a number of times, and a small amount of stock removed at each. For when a thin untrue piece of steel is placed on a magnetic chuck, the pull all over its face pulls it flat against the chuck face, straining it. When the exposed side has just been ground it is true, but immediately it is released from the chuck it

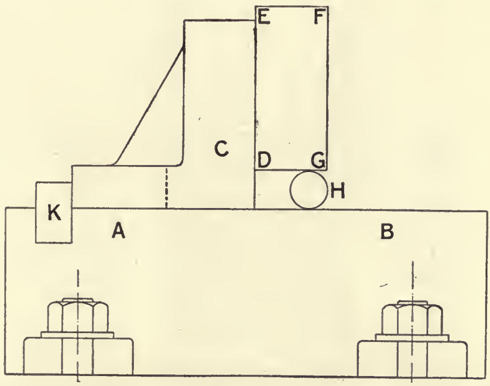


Fig. 132.—Secondary Pieces on Magnetic Chuck

springs back, and the ground face becomes untrue. This repeats itself at each grinding, but the amount gradually diminishes, so that the ultimate result is satisfactory.

Such precautions are to be taken when magnetic chucks are used for holding any springing parts for grinding.

Secondary pieces can be set on the top of a magnetic chuck, and themselves become conductors of the magnetic lines, and so magnetic. These are frequently useful, for example in grinding a strip square, as is shown in Fig. 132. Here the chuck AB carries the secondary piece C, of which the holding surface is square with its base, set on it, and which holds the work DEFG by the face DE. Short pieces of wire H should be placed underneath the work at G. The pull of the piece C strains the work in a horizontal plane, so that when the piece is released after grinding the top EF, this surface is still flat, and can be used for holding the piece magnetically while the other sides are ground. At K is a stop to prevent side motion. The piece C should have saw cuts, the ends indicated by the broken line, to direct the magnetic lines advantageously.

Disc Grinders. — Work of a somewhat lower degree of accuracy can be done rapidly and conveniently on disc grinders,

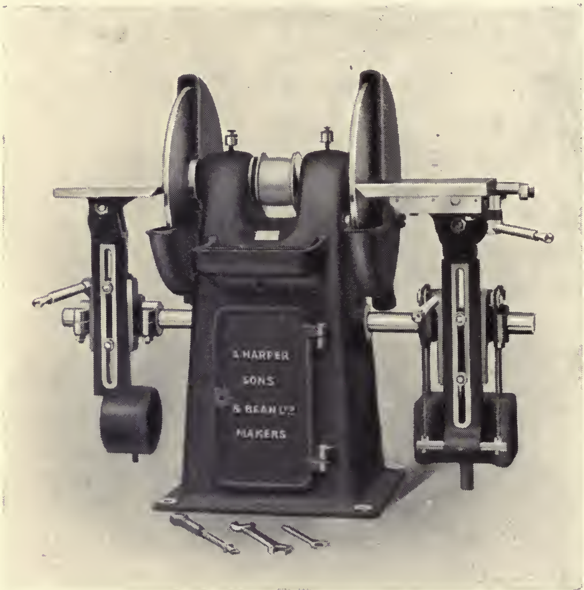


Fig. 133.—Disc Grinder—Harper, Sons, & Bean

and one such by Messrs. Harper, Sons, & Bean, is illustrated in Fig. 133. In these machines the grinding is done by a sheet of emery cloth glued upon a steel disc, which is rotated at a very high speed. As steel is stronger in proportion to its weight than is the material of an emery wheel, the discs can be run at a higher speed, gaining the advantages so involved. Peripheral speeds of 7500 to 8500 feet per minute are used.

The surface speed diminishes with the radius, so that the inner part of the disc is not so effective as the outer portion. The circles, of cloth or paper, coated with suitable abrasive material, are glued to the steel disc and kept in a press, which is a necessary part of the equipment, while the glue sets, so that the abrasive surface is flat. In coating the fabric with abrasive more or less glue may be used, as with the bond in wheels, producing circles of different grades. In use the circles cut best initially, gradually lessening in efficiency; finally they are removed by soaking in hot water.

Generally these circles are coated uniformly with abrasive of one grit (usually 16 to 24 for cast iron, and 24 to 60 for steel or brass), but when the work presents a considerable amount of surface to the grinding disc—and especially if this surface is unbroken—it is better that the abrasive be distributed in some pattern, presenting lines of abrasive and free space alternatively. This reduces the actual area of contact, and also provides plenty of room for the swarf. The Besly Company supply discs in which the abrasive is arranged in a spiral line; other firms have patterns in which different abrasives alternate.

Owing to the use of glue in the preparation and mounting of the circles, water cannot be used in the grinding, which is accordingly done dry. The heat produced is often considerable, and may cause the finished work to be objectionably distorted; this, however, can easily be avoided by grinding in two or three operations.

The accuracy of the flat surfaces produced is dependent on the flatness of the grinding disc, and is of the order of one thousandth of an inch, while an accuracy of dimension between one and five thousandths of an inch is to be expected.

The work may be presented to the disc by hand only, or use may be made of the work tables, such as are shown in Fig. 133. These are adjustable as to height and as to distance from the disc, and are balanced. Any work, while it is being ground, must be moved across the face of the disc, so as to distribute the wear evenly. This is done by swinging the work table on the shaft upon which its carriage is mounted; the shaft must be parallel to the wheel spindle in order to secure satisfactory results.

The left-hand table in Fig. 133 can be canted at an angle, so that work can be ground to a bevel easily. The work is placed upon the table, held in position, and pressed against the disc by hand only; this is only suitable for small quantities, or where little material has to be ground off. When the work is more severe, the right-hand work table—which is fitted to slide towards the wheel, and is moved by the lever below it—is used; the work is carried on the table, usually in a jig, and the extent of the grinding is controlled by an adjustable stop. In Fig. 134 is shown the stop of the Besly Disc Grinder. The actual stop screw AB is hollow, and can be firmly clamped by the locking screw C. The screwhead A is graduated, and the reading is taken against the edge of the plate D. Inside

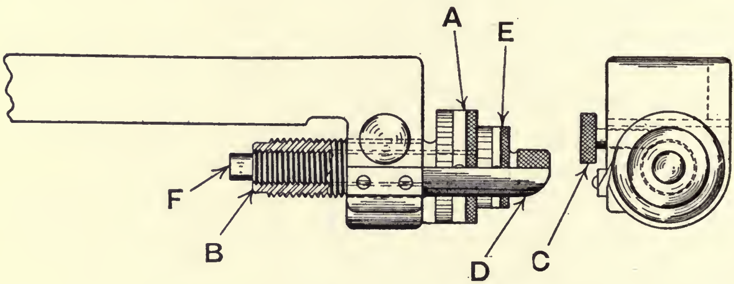


Fig. 134.—Adjustable Stop of Besly Grinder

this screw is a second screw EF, which limits the grinding when its end F comes in contact with the fixed abutment; by slacking it back the grinding is allowed to proceed gradually until the end B of the actual stop screw AB is left in contact with the abutment, the work being then ground to size.

Disc grinding is usually done from the rough, and the allowances should be as little as possible. In machining cast iron it is necessary for the tool to get well under the skin, especially if the work be not pickled, and accordingly a machining allowance of $\frac{1}{8}$ inch is given, even on small work; for grinding this is unnecessary, and from $\frac{1}{32}$ inch to $\frac{1}{16}$ inch is ample. The same, or less, is satisfactory for brass or bronze castings. Drop forgings usually need a $\frac{1}{32}$-inch allowance. Stampings vary considerably; frequently, however, the surface need merely be cleaned up and made true.

To reduce the amount of material ground off, surfaces should be recessed wherever possible; this makes the grinding much easier, as room is provided for the swarf, and it may be essential to the success of the process. The small difficulty of machining narrow surfaces which occurs in planing does not here exist; an extra core is, however, sometimes needed.

The simplest mode of producing a flat surface is to hold the work to the wheel by hand, allowing it to take its own seating on the grinding surface. This presents one of the principal advantages of this system of grinding—namely, that the surface is cleaned up with the removal of the least possible material and in the least time, for as the major prominences are ground off the work reseats itself. In manufacturing so many surfaces have merely to be cleaned up and made flat that the point is important.

In Fig. 135 is a drawing of the Besly Vertical Spindle machine, which takes a disc 53 inches in diameter; heavy articles rest upon the surface by their weight only, and being prevented from moving round, have the lower face ground flat in the most economical manner. Using a large disc with surface sufficient to accommodate a large number of articles, the labour cost of grinding them may be reduced to little more than that of placing and removing them. The method is common in optical work, in which the parts are loaded, as they are light.

In order to secure the above advantage, when work has to be held in a fixture carried on the sliding work table, the work holder should be of the floating type. An illustration of such a jig, by the Besly Company, is given in Fig. 136. An angle plate is carried on the work table, and carries the work holder by means of a ball-and-socket joint, so that the work can accommodate itself to the grinding disc. The ball is pulled into its socket by a spring, and the work holder is tilted conveniently by another which forces its lower edge towards the wheel.

Although the disc grinder affords a convenient means of doing various work in the tool room and fitting shop, the fact that no truing is required renders the process suitable for comparatively unskilled use, and it is well adapted for quantity

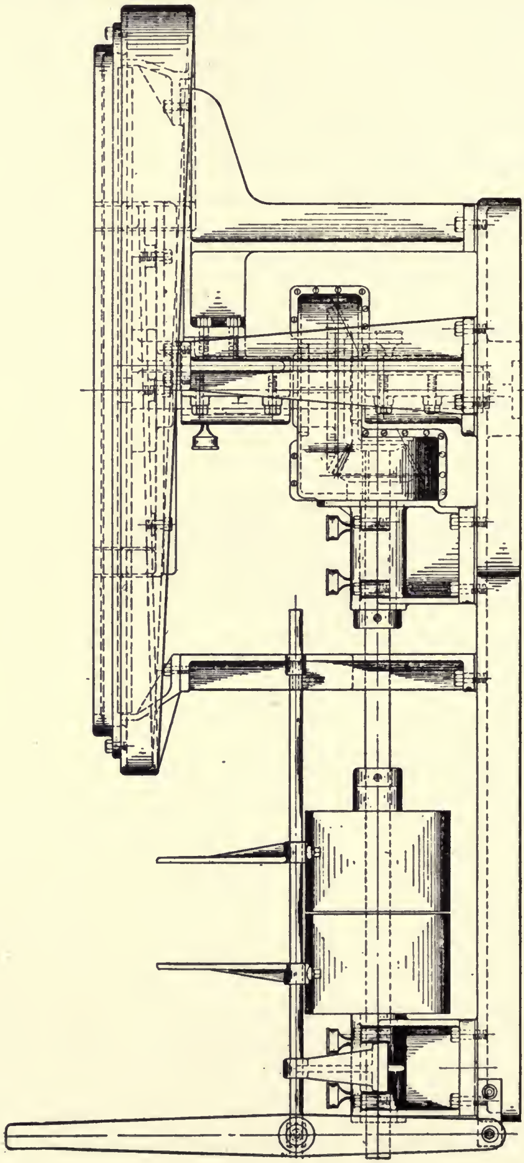


Fig. 135.—Besly Vertical Spindle Disc Grinder

manufacturing. The process shows its greatest economy on small parts which can be ground in a minute or less, and accordingly efficient jig design is essential to obtain the best results.

As the force on the work is moderate, and is downwards and outwards from the disc, it is frequently possible to arrange the jig so that no clamping is necessary, the work being merely dropped on to the locating points. Where the grinding time is very short, work carriers, which can be loaded with a quantity of work, and then placed in the machine, can be arranged for.

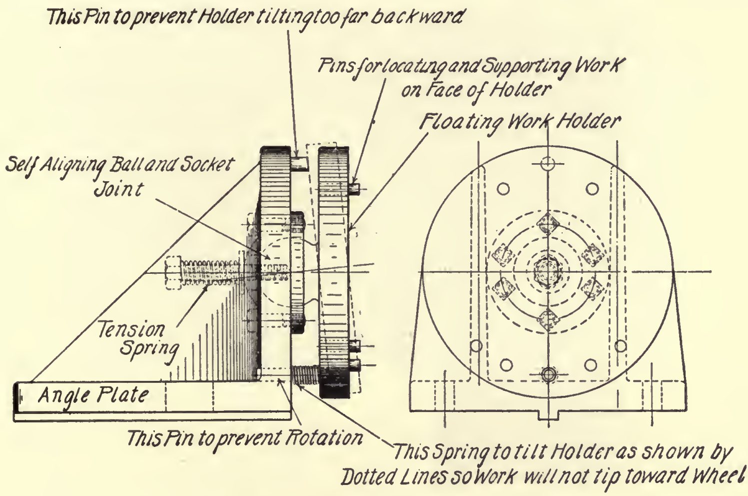


Fig. 136.—Floating Work Holder—Besly

Convenience and simplicity—for there is plenty of grit about—are the chief considerations.

When the area to be ground, or its over-all dimensions, is considerable for the size of the machine, the work may be carried on a rotating work holder, consisting of a spindle carrying the work by means of a face plate or magnetic chuck. In order to produce flat work the spindle axis must be set accurately parallel to the disc spindle. The arrangement then becomes geometrically equivalent to that of the machines of Figs. 126 and 127. In Fig. 137 is shown a Besly Disc Grinder fitted with such a rotating work head.

Thin work may be distorted by being clamped in a jig, so that after being released the ground surface is not flat; in such cases, as in those where the distortion is caused by temperature effects, the surface may be corrected by being held lightly against the wheel by hand.

When a considerable amount of metal has to be removed cup wheels are more economical than cloth or paper discs, but the work has then to be fed or rocked right across the edge of the disc. In Fig. 138 is shown a Guest Double Head Grinder, which illustrates a further point. When two parallel

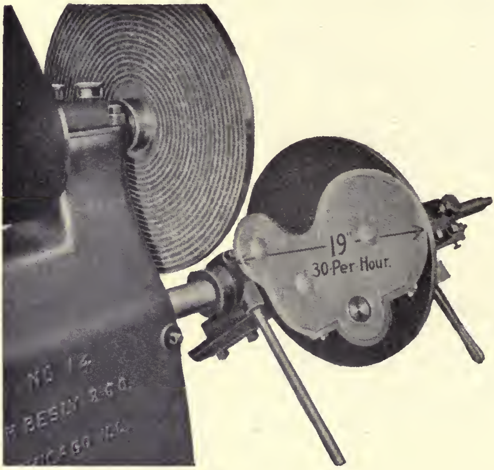


Fig. 137.—Rotating Work Head on Besly Grinder

surfaces are to be produced on the work they may be ground at one operation by the use of two wheels or discs. The work is carried by a jig mounted on the table on the front of the machine, or stretched between the wheels to a similar table on the other side. In the former case rotating fixtures with several work holders are convenient, the parts being inserted at the top, carried across the wheels and out again by the motion. In the latter case a roughing and a finishing cut can be given by adjusting the screws seen at the end of the wheel head, so that the wheel spindles are very slightly out of parallel. The wheels are fed up independently, so that the wheels cut equally, but it is best that the jig should permit the work a slight lateral movement to ensure this.

The work from disc grinders presents the curved marks of the path of the cutting particles, and these are sometimes considered undesirable. They may be polished out or, instead of a disc grinder, a belt charged with abrasive, or an emery

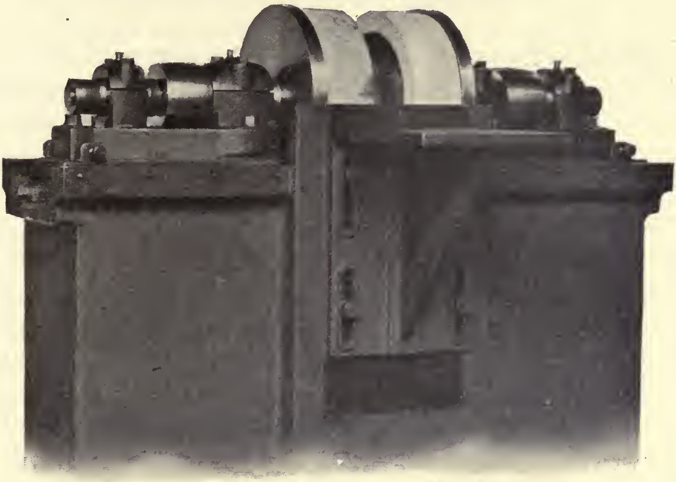


Fig. 138.—Guest Double Head Grinder

cloth band, running over pulleys (see Fig. 184) may be used. The belt is supported by a flat plate where the grinding takes place so that the work is flat. Such an arrangement, however, is not nearly so efficient as a disc grinder.

The time occupied in grinding such work as is suited for disc grinding depends largely upon the article itself, and no general rule can be given; the process should be considered whenever there are small surfaces to be machined or cleaned up flat on work which can be easily jigged.

CHAPTER X

SHARPENING CUTTERS AND TOOLS

In General.—The sharpening of milling cutters and other tools is an essential part of the work of a manufacturing shop, and a number of machines are on the market for the purpose. If the edges of a cutter's teeth become dull they rapidly become much more so, hence frequent sharpening prolongs the life of a cutter, very little being ground off each time. Some cutter makers stamp this advice on their products, considering it so important. Owing to the diverse forms of the cutters and various modes of presentation of the edge to the grinding wheel, a considerable number of movements or adjustments are necessary in a machine which will meet all demands, and cutter grinding machines vary from simple forms to sharpen a few of the more generally used types of cutter to Universal cutter grinders which, in addition to sharpening all standard types of cutter, will do external, internal, and surface grinding. Some machines normally are adapted to sharpen a few types of cutter, and by the addition of various attachments the range can be extended as desired ; this is an arrangement alluring to optimistic small firms, although the initial cost is higher than that of a simple machine.

The amount of metal removed in sharpening a cutter is small, as it is only along the edge, either in front of, or at the back of the tooth that grinding takes place, and as the work is so small the machines need not be very substantial. It is this fact apparently which tempts designers into the employment of unnecessary and very undesirable amounts of overhang, which not only tend to inaccuracies initially, but lessen the life of the machines from wear and the extra difficulty of the dust protection. It is the best practice that the parts moved in passing the cutter across the wheel should be as light as is consistent with reasonable rigidity, so as to secure sensitiveness ; the rest of the machine should be substantial, so as to minimise vibration.

Machines intended to grind the shanks and holes of cutters and for manufacturing small parts require to be much more rigidly and accurately built than if intended for cutter sharpening only ; otherwise they will not size the work easily, and will lead to various other troubles. It is also desirable that the use of water should then be provided for, and such machines conveniently fill a place in factories where little general machine grinding is done.

For convenience most cutters are ground dry, and as it is of first importance not to draw the temper of the edge, the wheel must be of a soft, free-cutting grade. For the same reason the cut must be light and never forced. The wheel must be kept clean and never become glazed or smeared with the thick oil from a cutter. The wheel face used should not be too wide, as this increases the rate of production of heat. Cup wheels may be bevelled inside to reduce the width in action. In cases where water is used the same precautions are still to be taken, as the use of water does not prevent the heat from being generated ; it only keeps the work cool by abstracting the heat from the metal. This takes a certain small time, and if the heat is not conducted away sufficiently rapidly the temper of the tooth is drawn by the increasing temperature. Unless the water is guided right on to the grinding point it is practically useless. Wheels of a soft grade suitable for cutter sharpening are now easily obtainable, and trouble arising from hardness of grade is almost a thing of the past. The use of water, although in several ways inconvenient, has the advantage that rather harder wheels, which keep their shape longer, may be used than is possible in dry grinding.

Types of Cutters.—For the purpose of sharpening, cutters may be divided into two classes : (1) those sharpened on the back of the cutting edge, so that the clearance is produced by the grinding, and (2) those sharpened on the front of the face forming the edge, chiefly in order to preserve a particular shape of tooth, and in which the clearance is produced by relieving in the manufacture of the cutter.

The first class may be further subdivided into (1) parallel cutters with straight or spiral teeth, (2) angular cutters, face cutters, rose reamers, and end mills. The second class includes formed cutters, gear cutters, taps, and reamers when sharpened on the face of the tooth, and also formed tools for lathes—whether circular or flat.

Clearance.—In Fig. 139 is a sketch of the teeth of these

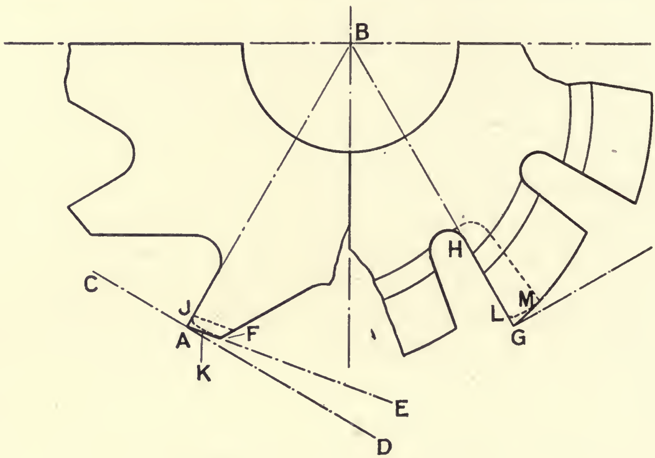


FIG. 139.—CLEARANCE ON CUTTERS

cutters; that of the first type is shown at A. The face angle BAC, where B is the cutter axis and CAD the tangent, is almost always 90°, although it may be, and generally is, less when inserted teeth are used; for reamers it may be a little more. The clearance angle DAE, at the back of the edge between the tangent AD and the cutter surface AF, is produced by grinding the facet AF, the width of which is termed the 'land.' This should be narrow, and should not exceed $\frac{1}{8}$ inch on cutters up to 6 inches in diameter; for reamers to be used on steel the width should be about $\frac{1}{100}$ inch, and for those intended for cast iron or bronze from $\frac{1}{20}$ inch to $\frac{1}{25}$ inch. With these small dimensions it is impossible to judge the angle closely by eye, and to obtain satisfactory results a reliable method of securing the correct angle of clearance must be employed.

A tooth of the second class is shown at G, and is supposed to have some particular section which it will produce on the work in milling. The clearance behind the cutting edge is here fixed by the curved arc, and is produced in the manufacture of the tool. When dull the cutter is sharpened by grinding the front GH of the tooth. It is usually arranged that the face of the tooth is ground radial, as the section of work produced is then easily maintained accurately. When a tooth gets dull and rubs, the edge is worn away as indicated by the broken line JKF on the first tooth, and LM on the second ; it will be noticed that, if there is much rubbing, in cutters of the second class a very considerable amount of the face GH has to be ground away to bring the edge up sharp. The tooth of the first class is not damaged so seriously. The broken lines indicate the amount to be ground off in sharpening in the two cases. It is therefore to formed cutters and gear cutters that the recommendation to keep sharp particularly applies.

Principles of Cutter Sharpening.—In sharpening cutters of the first class either the edge of a disc wheel or the face of a cup or dish wheel may be used, sometimes one and sometimes the other being the more advantageous. Whichever is used the clearance must be formed by the motion of the wheel, and not allowed to be dependent on the shape to which it wears. The correct methods are illustrated later, but attention is called here to Fig. 140, in which are shown incorrect methods, where the clearance obtained depends on the wear of the wheel. The cutter is supposed to be moved perpendicularly to the plane of the paper, and the clearance depends both on how the wheel is trued and how it wears afterwards. At the top AB is shown the edge, and at the side the face CD, of a wheel in use, both incorrectly applied. The broken lines indicate how the wheel wears and the effect on the cutter edge. In the example of the cup wheel it is the back part of the land which is chiefly affected ; but if the cutter tooth faced upwards, or if it were being sharpened at the top of the wheel, it would be the cutting edge which would be rounded. So that the position shown is the best to use, lest the wheel face at C should be too wide.

As the clearance on this class of cutter is produced by the

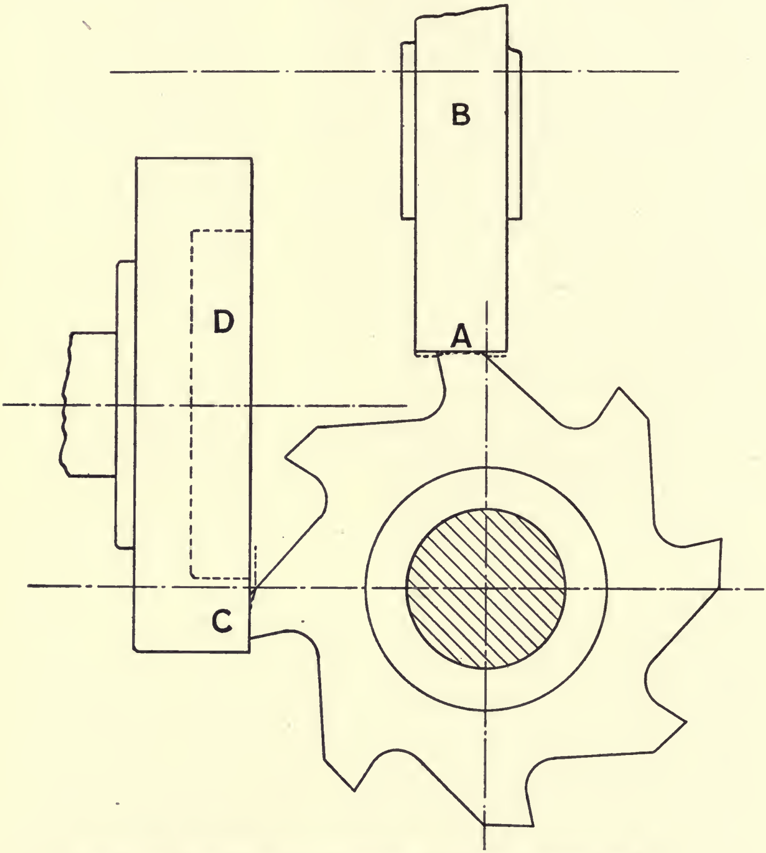


FIG. 140.—SHARPENING CUTTERS—INCORRECT PRINCIPLES

grinding, the 'setting' of the machine to obtain the correct amount is important; for if it is insufficient the cutter does not work freely, and if it is too much the edge does not stand up as long as it ought to do. In practice the error is always made on the side of too much clearance, as too little leads to immediate trouble.

Hardly any cutter grinders are provided with efficient means of securing the correct clearance, although sharpening a cutter at different angles at different times implies that more is ground off than is necessary to sharpen the cutter.

Amounts of Clearance.—From experience with lathe tools it is known that 3° is sufficient clearance, but as cutters have frequently to be fed into the work normally to the surface, and this feed is equivalent to reducing the clearance, it is well to regard a cutter as requiring rather more clearance, say 4° or 5°. The ideal amount would depend upon the material and upon the particular work. In setting up a machine to grind the clearance a further allowance must be made for small errors of adjustment, so that the actual clearance produced may not be too small; for this reason the 'charts' of settings which give the amount of adjustment necessary are usually based upon a clearance of from 5° to 9°. Such a chart for edge wheel grinding is given in Table X, page 434, with a corresponding chart for face wheel work in Table XI opposite to it. Because of the effect of errors of adjustment, it is well to set small cutters to receive the larger angles of clearance, and large tools, in which the effect of these errors is relatively less, for the smaller angles. For face cutters 3° is sufficient.

Secondary Clearance.—Besides this normal clearance immediately at the back of the cutting edge it is sometimes necessary to grind a second clearance, of an increased angle, a little farther back, as is shown in Fig. 141. For the width of the land increases with each sharpening of the cutter, and as it does so the chance of drawing the temper of the edge in the operation increases. Before the land becomes large (say over $\frac{1}{8}$ inch) it is well to reduce its width by grinding this second clearance of an increased angle a little farther back. Also in reamers, where the land must be very small—else they will not cut well—this second clearance is ground. It is shown in Fig. 141, where A, B, C, D, E, F are points of the cutter teeth, AG the too wide land, which is reduced to AH by grinding off the shaded portion HGK by means of the wheel LMHK.

For the sake of clearness the figure is exaggerated, but it shows that a comparatively small wheel is necessary to grind this clearance, and yet to miss the next tooth B. This second clearance or relief can, however, easily be ground by using a dish wheel, such as is shown operating on the tooth P, grinding away the part PQR, and reducing the land from DR to DQ without endangering the cutting edge of the next tooth E, or it may be ground by the method explained on page 335. The figure (141) shows the tooth C before grinding and the teeth E and F afterwards. The angle of the secondary clearance is not important; after it has been ground the cutter

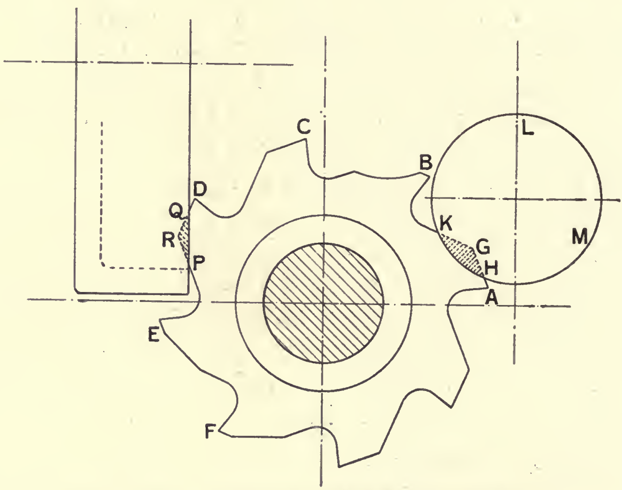


Fig. 141.—Grinding Secondary Clearance

can be resharpened at the normal clearance angles for a number of times.

The simplest form of cutter grinder consists of a wheel head, a cross slide for approaching the wheel and work, a means of travelling the cutter relatively to the wheel, and a tooth rest for locating the position of the tooth of the cutter. With the addition of a tooth rest a Plain or Universal Grinder will serve to sharpen certain classes of cutters. In some cases cutters are best indexed round by a division plate on a live spindle in the work head, but not frequently, and in this case a tooth rest is not required.

Parallel Cutters — with Holes. — Generally the cutter is traversed past the wheel by means of a slide, but in the particular case of cutters having a parallel hole they may be traversed by sliding them along a parallel mandril. This method is only applicable to cutters of uniform diameter on the outside, for however the wheel and tooth rest are placed, the distance from the axis to the ground tooth edge is the same all along the cutter. The great advantage is that the method produces parallel cutters without a chance of error in setting, and where parallelism is important, as it so often is, the method should be used. The cutter may either be moved along a parallel mandril fitting its hole or may be mounted on a collet sliding along a bar.

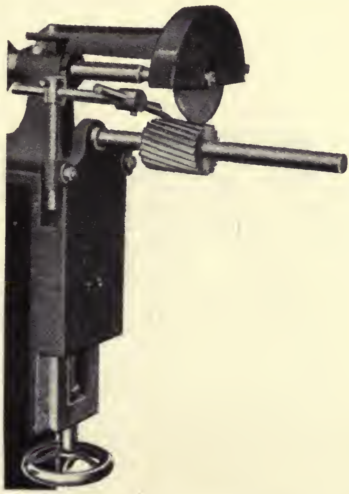


FIG. 142.—SHARPENING PARALLEL CUTTER—LUD. LOEWE

Fig. 142 shows a cutter in position for sharpening, using this method, on the Loewe cutter grinder; Fig. 143 shows a parallel inserted tooth cutter being ground on a Landis Universal machine, the main slide in this case traversing the wheel over the cutter, and here the table must be set parallel to make the sharpened cutter parallel.

Parallel Cutters—with Shanks.—Parallel mills with shanks may be sharpened in a similar manner, the shank being held in a mandril which itself slides through a hole in a small headstock. The face of the tooth being sharpened is kept in contact with a tooth rest in the usual manner by twisting the knurled handle of the mandril. A plan view of the arrangement is given in Fig. 144; the cutter A is carried in the shaft BB, which slides and can rotate in the bracket C; the shaft BB is hollow so that the cutters can be easily removed. This arrangement was an attachment on the cutting grinders which I used to make in Birmingham, but, although it is useful, I have not seen it elsewhere.

Tooth Rests.—To locate the tooth of a cutter in the correct position and to hold it there, tooth rests, consisting of steel blades, usually adjustable, are necessary. These may be attached either to the wheel head, where they are set to act on the cutter just in front of the wheel, or they may be carried on the support of the cutter. In the former case they may be used for all kinds of cutters, but in the latter only for cutters where teeth are straight. The latter is preferred where it can be used,

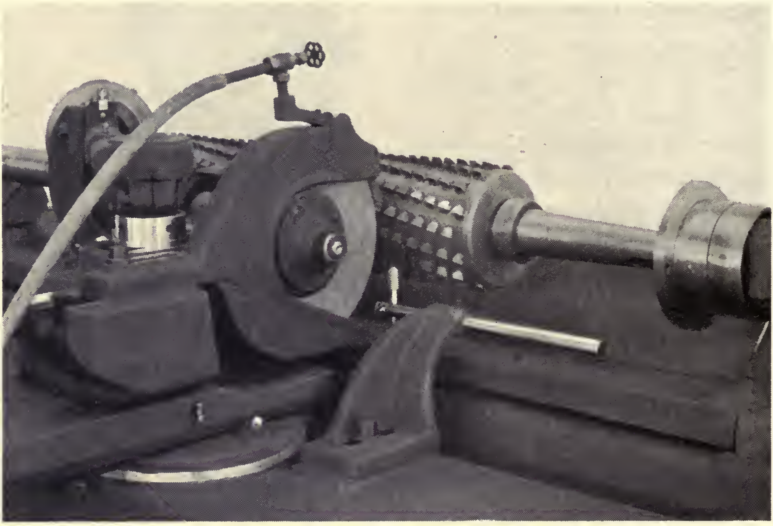


FIG. 143.—SHARPENING PARALLEL CUTTER ON LANDIS UNIVERSAL GRINDER

since the cutter tooth does not, in its motion, slide along the tooth rest as it does in the former case. The construction of the tooth rests for the two cases is a little different.

Fig. 145 shows a tooth rest carried on the wheel head; it is set in front of the wheel AB, and the central part CDE must be wider than the wheel, and should be quite stiff and rigid. It is shown swivelled to match the angle of spiral of the tooth of a cutter GH, which is shown in section above the tooth rest. On each side of CDE is a strip KL, MN, made thinner than CDE so as to spring easily; the top KCDM should be smooth and the corners slightly rounded. As the cutter edge GH slides over the top of the rest the grinding takes place; when H has got clear of CD on to K (the slide stop being set so that it does not go beyond it), the cutter can be turned, springing KL to K′L alongside the wheel as shown in the end view, allowing the next tooth to come on to the top of the rest, and not damaging the rest by springing the part CDE into the wheel. One side, KL or MN, may be omitted, and the cutter turned when at the other end only.

When a tooth rest is carried on the work table and moves with the cutter, it will be clear of the wheel when the cutter is

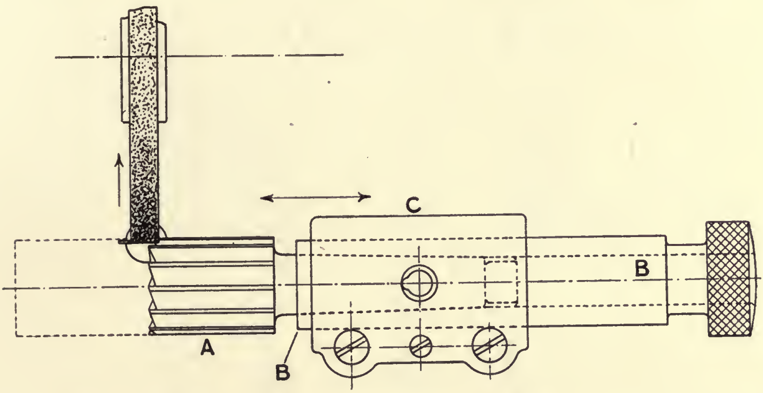


Fig. 144.—Head for Sharpening Parallel Mills—Guest

turned to bring the next tooth into position, and so consists simply of a strip of steel sufficiently thin to spring easily as the cutter is turned, but sufficiently rigid to support it firmly when in action. The blades should be easily replaced, as they are apt to get damaged by unskilful use, since they go close to the wheel. Such tooth rests are seen in Figs. 156 and 162. As the parts are rather close together it is well to traverse the cutter slowly across before actually grinding, to ascertain that all is right.

Both types of tooth rest need mounts so that they can be easily adjusted; these are seen clearly in Figs. 157 and 162. The nuts and locking parts should be case-hardened, as an adjustable tooth rest which will not adjust is dangerous to the temper—not of the cutter only. In certain cases it is impossible for the simple spring blade to be at once sufficiently flexible and rigid; a more expensive hinged blade must then be used, as is shown locating a gear cutter in Fig. 159.

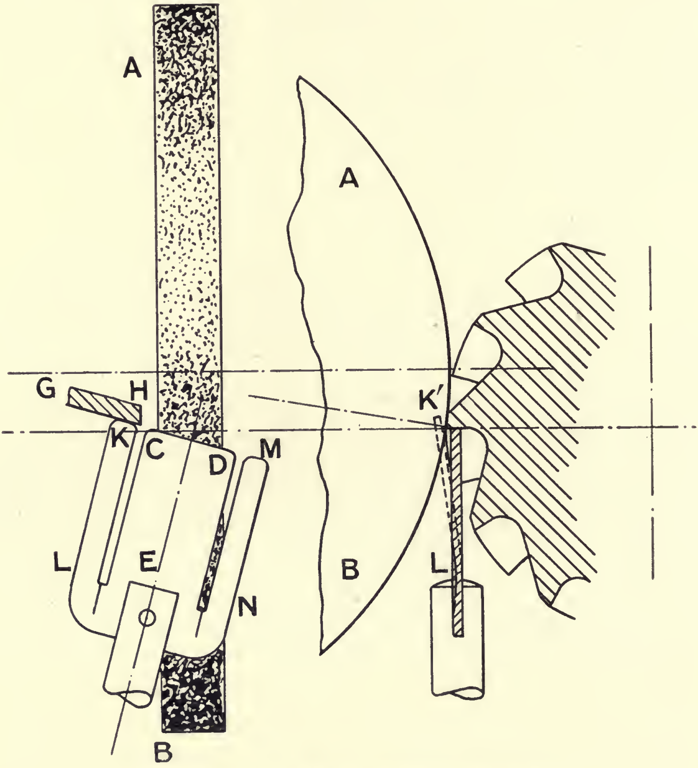


Fig. 145.—Tooth Rest for Spiral Teeth

The clearance ground on the cutters of Class A depends as a rule on the position of the edge of the tooth, and hence on that of the tooth rest which fixes it. To see how to adjust the tooth rest position, first consider the case of a cutter ground in a Plain or Universal Grinder, using a disc wheel as in Fig. 146, which shows an end view. If A be the axis of the cutter BCD, of which B is a tooth point and E the centre of the wheel BFG, then B must be off the line of centres AE, and the farther it is from AE the greater the clearance which will be ground.

Setting for Clearance with Disc Wheels.—The angle of clearance is the angle at which the edge of the wheel cuts the circle round the points of the cutter teeth, and this is equal to the angle EBG. In very simple cutter grinders and in Universal grinders there is only an adjustment of the points (lines) A and E towards one another, and the position of B

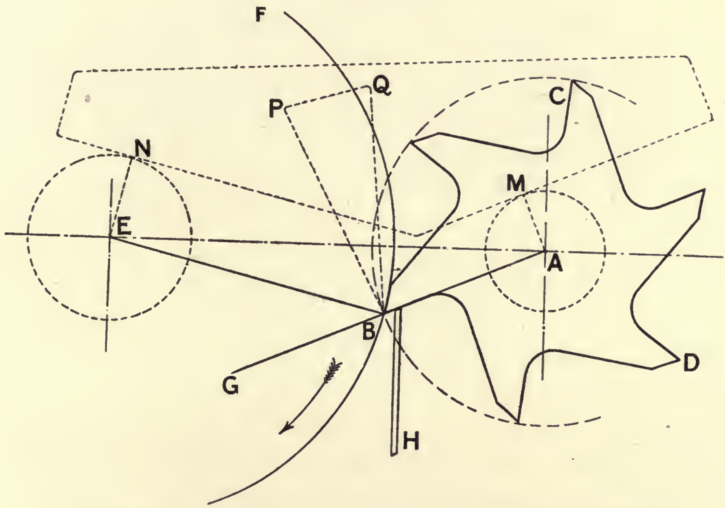


Fig. 146.—Setting for Clearance in Universal Grinder

below (or above) AE for a desired clearance depends on both the diameter of the wheel and of the work. The tooth rest BH is adjusted vertically and set to keep the tooth point B in position. This position is usually determined by eye, but the length of the land is normally so short as to make it difficult to judge correctly.

For a definite angle of clearance, EBG, the angle EBA is fixed, and if a gauge be made of this angle, its point would indicate the correct position of the tooth point B when its sides passed through A and E respectively. To make it easier to use, the sides might be stepped back by the radius of the mandril or work head centre AM, and by the radius EN of the end of the wheel spindle and the apex B consist merely of a sharp point, so that the gauge would take the shape of the figure shown in broken lines. When its edges rested on the mandril (or centre) and the spindle end respectively, its point would indicate the correct position for B, and the tooth rest could be adjusted with certainty. If the point B be made adjustable, formed on a plate PQB on the gauge plate, it can be set so that EN and AM have any values, and will therefore suit any spindle diameter and any mandril diameter.

In a machine with only the movements of a 'Universal' Grinder, not only is accurate setting difficult, but the tooth rest must have a different height from the table for each diameter of cutter; furthermore taper cutters or reamers can only be sharpened by using a cup wheel (otherwise the edge is not straight), and face cutters cannot be ground without special attachments. To meet the requirements of more easy setting, cutter grinders have an additional vertical adjustment, and usually, to permit cup and dish wheels to be conveniently used, an angular adjustment round a vertical axis, besides adjustments, for making some settings still more convenient, which vary with particular machines.

The terms 'vertical' and 'horizontal,' it must be remembered, are used for the sake of clearness, as in the great majority of cutter grinders the movements are arranged so that these terms, as used in the text, are correct. Generally, however, they refer to planes and lines at right angles.

As illustrating different types of these machines, views are given in Fig. 147 of the upper part of a Cincinnati Cutter Grinder, in Fig. 148 of a Brown & Sharpe No. 3 size, and in Fig. 149 of the No. 1 size of the Universal Cutter Grinder, which I used to make in Birmingham. In Fig. 147 the main slide movement is in the line AB, and is operated by the handle C or lever D, through a vertical shaft; the cross slide is in the direction EF, and is operated by the handle G, for the movement of which a graduated disc is fitted. The vertical adjustment is made by means of the handle H, which raises or lowers the vertical piece JK, which carries with it the main slide and fittings; the amount of this adjustment is indicated by the graduated disc L. When a cup wheel is to be used, the whole of the knee M and what it carries is swung round the vertical column NP, through a right angle, or nearly so. The work is carried on a table Q—corresponding to the table of a Universal Grinder—which is swivelled about a vertical axis

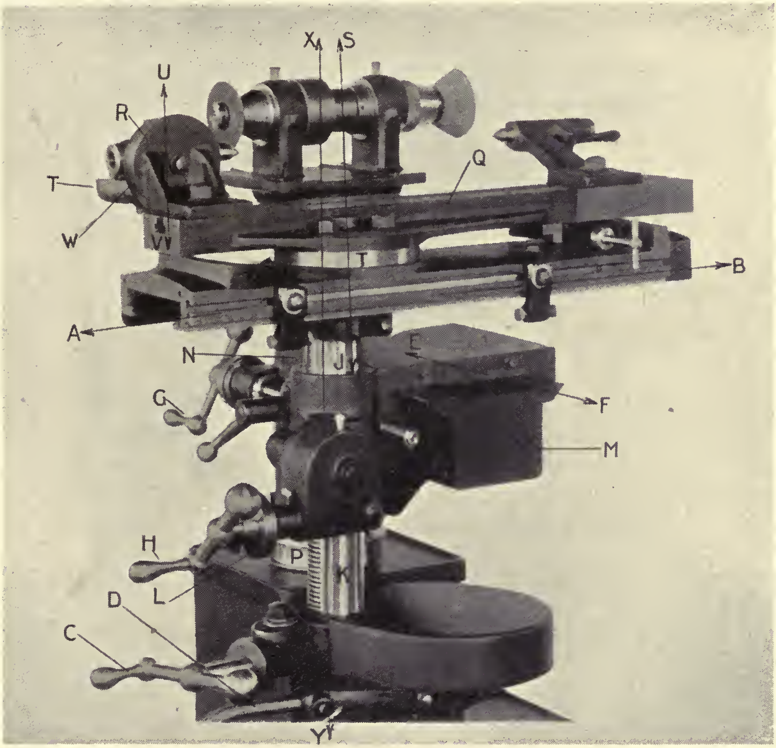


Fig. 147.—Cincinnati Cutter Grinder

ST for taper work, and for short work, held on the head R, this may be swivelled about a vertical axis UV; the angle of movement is shown by the graduated circle T. In addition it will be noticed that the head R can swivel about a horizontal axis, for which movement the graduated circle is that shown at W.

A reference to Fig. 160 will assist in rendering the construction clear. Lines indicating the sliding movements and angular adjustments are drawn on Figs. 149 and 156 also.

In the Brown & Sharpe Cutter Grinder, shown in Fig. 148, the main slide consists of a cylindrical bar A, which can slide in bearings, one of which is seen at B, and it is prevented from

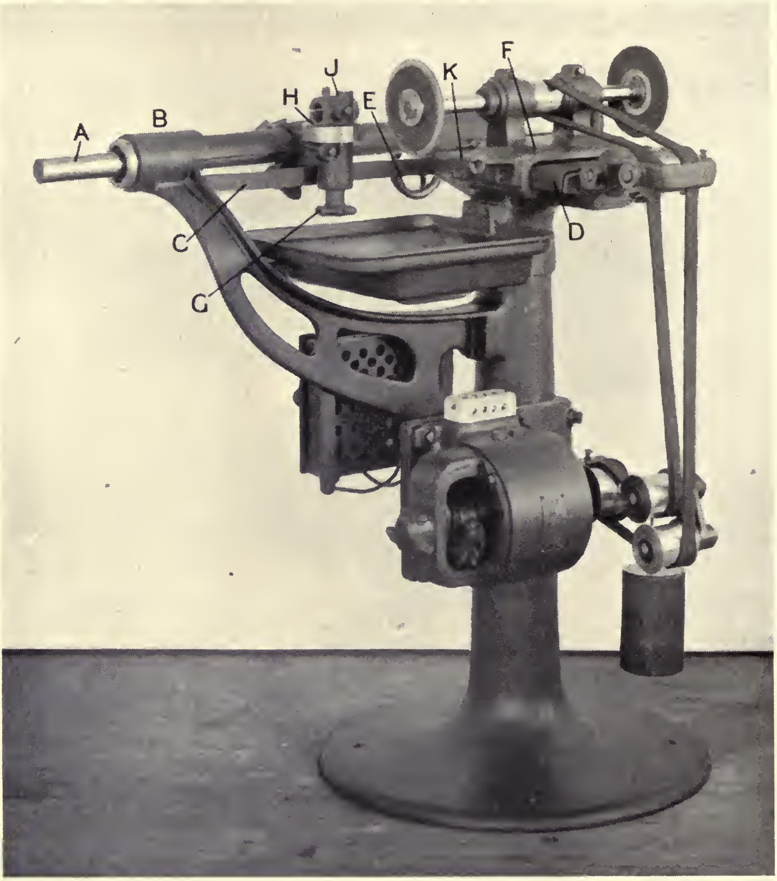


FIG. 148.—BROWN & SHARPE CUTTER GRINDER

rotating by a stop which slides in contact with the hardened steel bar C, the edge of which is set parallel to the bar A. The cross slide is seen at D and the movement is controlled by the hand wheel E, which is graduated. The wheel head F is bridged across the cross slide for purposes of dust protection and stiffness. The vertical adjustment above mentioned is provided for by the action of the knob G, but there is no swivel adjustment of the whole about a vertical axis, and hence the regular run of cutters are sharpened with a disc wheel, and a cup wheel is not used for this purpose. The

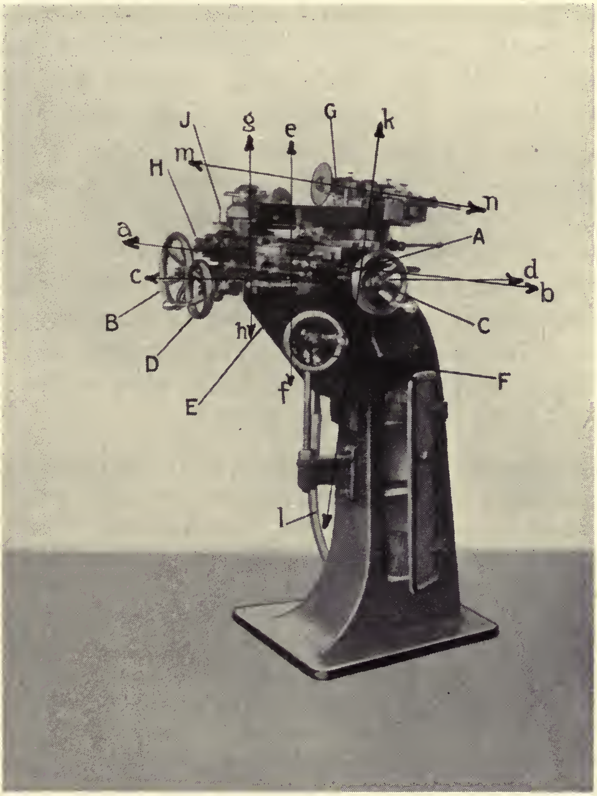


FIG. 149.—GUEST UNIVERSAL AND CUTTER GRINDER

swivel head H has an angular adjustment about a vertical axis; this corresponds to the swivel adjustment of the table on a Universal Grinder, and to both the swivels of the table Q and head R in the Cincinnati Grinder. When work has to be held between the centres, a rod carrying one fixed and one adjustable centre is gripped in the swivel head H, set to the angle of the reamer or tool, and traversed by the main slide.

At J and K are seen the grips for the tooth rests, the former on the work head and the latter on the wheel head ; on the work head a surface is formed level with the axis above the plane of rotation of the swivel head, so that the tooth rest carried on the work head can easily be set level with the centre. The machine illustrated has a self-contained drive from the motor.

For grinding parallel cutters with holes in them a bar is held in the swivel cutter head and also at the other end of the machine, and the cutters are moved along it by hand—either fitting the bar directly or indirectly by means of a collet—so that they are ground parallel by the principle described above. When the main slide is moved a small lever is attached to it for the purpose, but this is not shown in the figure. Face and end mills may be sharpened when held in the swivel cutter head, but as sometimes this is inconvenient owing to interference of the disc wheel with the next tooth to that being ground, a compound swivel head, presenting the teeth to the wheel in the method illustrated in Fig. 152, is generally used.

The Universal Cutter Grinder shown in Fig. is 149 designed for cylindrical and surface grinding as well as for cutter grinding, and is shown set up for external work. The main slide A is traversed by the hand wheel B for regular work, but for fine feeds used for facing, snap gauges, &c., a fine feed, operated by the hand wheel C, which is graduated, can be thrown in. The cross-feed is by an ordinary slide, and is operated by the graduated hand wheel D. The vertical adjustment is by means of the knee E, the elevating hand wheel is at F. The swivel adjustment to provide for the use of cup and dish wheels in sharpening ordinary cutters is here obtained by swivelling the wheel head G round, but the axis is inclined at the standard angle of clearance. The effect of this is that in the position shown the wheel spindle is inclined at the standard angle of clearance, but if the head G be turned through 90° about its axis *kl*, in either direction, so as to bring either the main spindle or the internal grinding spindle into its working position, the wheel spindles become horizontal. The table H has a swivel adjustment about the vertical axis *ef*, and the top of the work head J swivels about the vertical axis *gh*, but no extra swivel corresponding to the graduated circle W of Fig. 147 is fitted, being now unnecessary. The advantage of making the axis *kl* inclined is described later. The machine is shown fitted with self-adjusting guards for wet grinding.

Simpler cutter grinders than these are made by omitting one or more of the motions, with a corresponding reduction of the types of cutter which they are adapted to sharpen, and with an increase in the difficulties of setting. The great advantage of a vertical adjustment, accurately graduated, is that the clearance angle can be obtained by setting from a table such as No. X, and as the setting depends on the

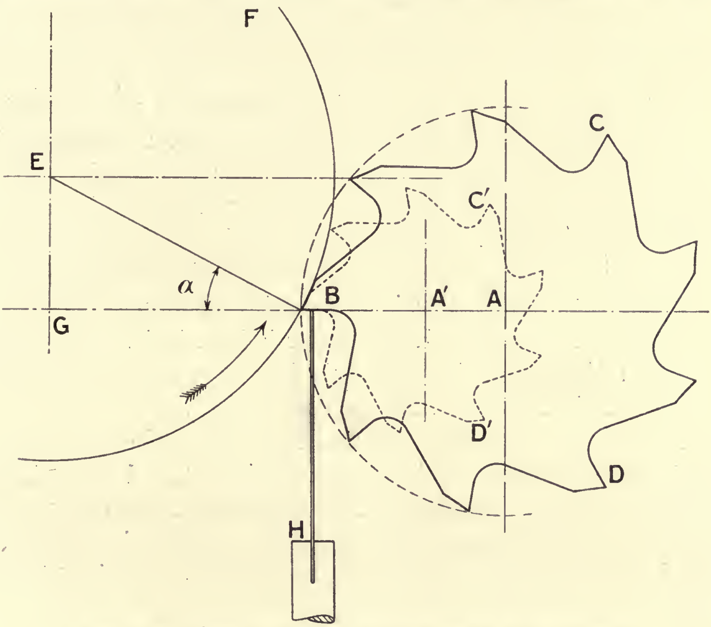


Fig. 150.—Setting for Clearance with Disc Wheel

wheel diameter (for disc wheels) only and not on the cutter diameter or angle, the setting is not changed in sharpening various cutters, but only as the wheel wears.

In Fig. 150 is shown a diagram of the usual arrangement, lettered in the same manner as Fig. 146. Here the front B of the tooth being ground (and the tooth rest) is 'level' with A, and the wheel centre E is so much higher that the angle of clearance, EBG, is obtained.

The amount EG by which the cutter axis A is set below the wheel axis E to secure the angle of clearance, a (= EBG), now depends on the diameter of the wheel only, and is not affected by the diameter of the cutter. For if A′ were the centre of a smaller cutter BC′D′ the same clearance would be ground on the tooth. Hence, if the machine table, with the headstocks and centres, is set vertically correctly for one size of cutter it is set correctly for all. The only adjustment necessary is to and from the wheel (horizontally) to accommodate the different sizes of cutters and to put the cut on, and this movement does not affect the amount of clearance produced. The alteration of EG need only be made when the wheel has worn appreciably.

Referring again to Fig. 150, since the diameter of the cutter does not affect the clearance produced, the same amount will be ground on a taper or angular cutter, as these may be considered to be built up of a large number of very thin cutters of varying diameter. To bring the whole edge of the cutter to be acted on by the wheel, the table carrying the headstocks is swivelled if the cutter is one carried between the centres, or the cutter head only if the cutter is held in it. The angle to which the cutter is ground is here the angle shown by the graduations of the table or cutter head.

Face cutters and the end teeth of end mills are a special case of angular cutters for which the angle is 90°, and accordingly the same method of setting holds good, but these cutters are more usually sharpened by the use of a cup wheel, as if a disc wheel be used it has to be of small diameter—especially if the teeth are cut close up to the centre—otherwise the next tooth is liable to be scored. The best method of sharpening them when the teeth go close to the centre is shown in Fig. 152.

In practice to set the machine for the clearance, the centre A (Fig. 150) is first set level with the wheel centre by means of a gauge ; the wheel diameter is then taken, and the amount EG corresponding to it for the angle of clearance desired is ascertained from Table X, page 434. The table (or wheel head in some machines) is then adjusted vertically through that amount by means of the graduations on the corresponding hand wheel. It then only remains to set the tooth rest B level with the centre A by means of a gauge. Not only should the vertical adjustment be easily made, but the tooth rest should also be set easily.

If the cutter have spiral teeth, the highest point of the part of the tooth rest which is opposite the wheel is the point which controls the clearance at the edge, and which should be regarded as the point of the tooth rest to be set if the clearance is wanted accurately.

When the tooth rest is carried with the work, on the table or the work head, it can be set permanently level with A.

The distance EG is easily found by drawing a large size figure to determine the ratio of EG to EB, or by looking up the value of sin a in tables, and then EG = EB sin a, where EB is the radius of the wheel in use.

As before mentioned, the terms 'vertical' and 'horizontal' are used, as almost all cutter grinders are arranged so that the adjustments are in these directions. They are, however, only relative expressions, and if the slides are tipped as a whole in any way the clearance is unaffected.

In the cutter grinder which I used to make in Birmingham these setting operations were almost eliminated. The tooth rest BHK, Fig. 151, was carried on an inclined plane LM machined on the wheel head, so that its point B moved along the line ENB, and when the blade was put just outside the wheel it was in the correct position. All that there was ('is' would be more correct, as I believe that every machine is still in use) to do in these machines was to set the table so that the centre A was level with B, which was done by adjusting it until a gauge BPQ touched the top of the tooth rest. When the wheel has worn down, say to N, the tooth rest point will then lie just outside it at N, and again the clearance ground will be a = angle EBG. The tooth rest blade was arranged so that the position of the centre of its edge was not altered by adjusting it to suit the angle of a spiral cutter; and particulars of the arrangement can be seen by reference to 'Engineering,' Dec. 1901, vol. lxii.

Limiting Diameter of Wheel.—The clearance ground by the edge of a wheel is hollow, the more so the smaller the wheel used, and it is well to use as large a wheel as possible, although the effect of this hollowness is small. A limit is soon reached, as a wheel above a certain size will encounter the cutting edge of the next tooth and spoil it. The size of wheel permissible depends on the diameter of the cutter, the number of teeth, and the angle; in the case of a face cutter or end mill it depends on the pitch of the teeth. In this case the pitch varies along the teeth, being smallest near the centre, and accordingly the sharpening of small end mills, cut near the centre, presents a difficulty, which is still further increased when it is desired to grind a larger secondary clearance (see page 320) to decrease

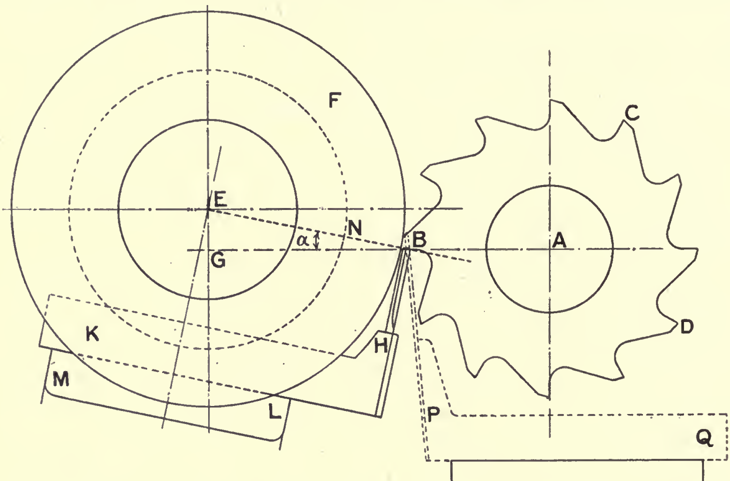


Fig. 151.—Setting for Clearance with Edge Wheel on Guest Cutter Grinder

the width of land. These cases are more easily dealt with by the use of a cup wheel, but the best method is that shown in Fig. 152, and is as follows—

Sharpening End Mills.—The cutter ABC is here shown passing by the wheel, the movement to sharpen the edge AD being as indicated by the arrow in the left-hand view, and perpendicular to the paper in the right-hand diagram. The wheel EF is set askew as shown, and looking along the cutter axis D it appears as parallel to the edge of the next tooth BD; this enables the cutter to be moved so far towards the wheel as nearly to touch the edge in the manner shown in the figure, and a stop must be used to limit the motion in this direction. It thus enables the edge to be sharpened, or the secondary clearance ground, close up to the axis. That the wheel clears the tooth opposite to B is seen in the right-hand view, which shows the way in which the wheel produces the clearance.

The tooth rest GA holds the tooth being ground, so that it is parallel to the line of motion of the slide. In small cutters the faces of the teeth pass through the axis as shown, and the tooth rest is level with the centre. In large mills they are frequently offset, and then the tooth rest must be adjusted so that the tooth edge is parallel to the line of travel.

The same arrangement is of use in the case of angular

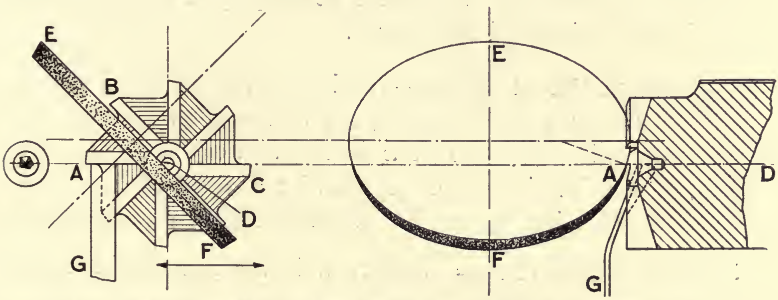


FIG. 152.—SHARPENING END MILLS AND ANGULAR CUTTERS WITH TEETH CUT CLOSE TO AXIS

cutters, in which the teeth run close together at the small end. A diamond tool is sketched on the left in the position—' level ' with the work axis—for truing the wheel properly.

In practice the wheel is not usually tipped, as shown in the diagram, Fig. 152, which is so drawn for the sake of clearness; the slide and cutter head are usually swivelled instead.

In sharpening end mills and face cutters it should be borne in mind that they should be ground slightly hollow on the face —that is, the edge of the tooth should be slightly inclined to the axis, so that the teeth cut fully on the outer corners. For this purpose $\frac{1}{4}°$ is a sufficient angle to allow. This renders sharpening small end mills with a cup wheel awkward, as when grinding on one side the opposite tooth may be touched; hence the preference to be given to the method outlined above.

Direction of Wheel Rotation.—Practice varies as to the direction in which the wheel should run—whether towards the edge of the cutter, so that the particles meet it first (as indicated by the arrow on the wheel in Fig. 150), or the reverse as indicated in Fig. 146. The former direction produces a slightly better edge, as it is free from burr, but if the cutter tooth is not held firmly against the tooth rest the action of the wheel may make the cutter turn a little, carrying the edge of the tooth into the wheel and grinding it away. In manufacturing shops where the cutter grinders are constantly in use the first method can be safely employed, but otherwise the second method is preferable. It should be employed if the cutter edge is to be oilstoned afterwards.

Maximum Size of Wheel.—The largest size of wheel which can be used on parallel cutters can be found as follows. In Fig. 153, A is the centre of a cutter, and B, D consecutive teeth, of which B is being sharpened by a wheel whose centre is C, and which just grazes D. Then if CBE $= a$ be the angle of clearance and CAB $= \frac{\pi}{n}$, where n is the number of teeth in the cutter, and the radii of the cutter and wheel be r and R respectively, then we have—

$$\frac{AB}{\sin BCA} = \frac{BC}{\sin CAB}$$

or

$$R \sin\left(a - \frac{\pi}{n}\right) r = \sin \frac{\pi}{n}$$

and hence to clear the next tooth R must be less than—

$$r \frac{\sin \frac{\pi}{n}}{\sin\left(a - \frac{\pi}{n}\right)}$$

in the case of parallel cutters. If $a = \frac{\pi}{n}$ then a wheel of any size will clear the next tooth, or a face wheel would clear right across. So that if the clearance angle be 5°, the number of teeth in the cutter may be as many as 36 for any wheel to clear ;

but if the clearance angle be $7\frac{1}{2}°$, the number can only be 24, and if $a = 10°$, 18 teeth is the maximum. A wheel of the same diameter as the cutter will just clear if—

$$\sin\left(a - \frac{\pi}{n}\right) = \sin\frac{\pi}{n} \quad \text{or} \quad a = \frac{2\pi}{n}$$

or in this case the number of teeth can be double those previously given.

Angular Cutters.—If, however, the cutter be taper or

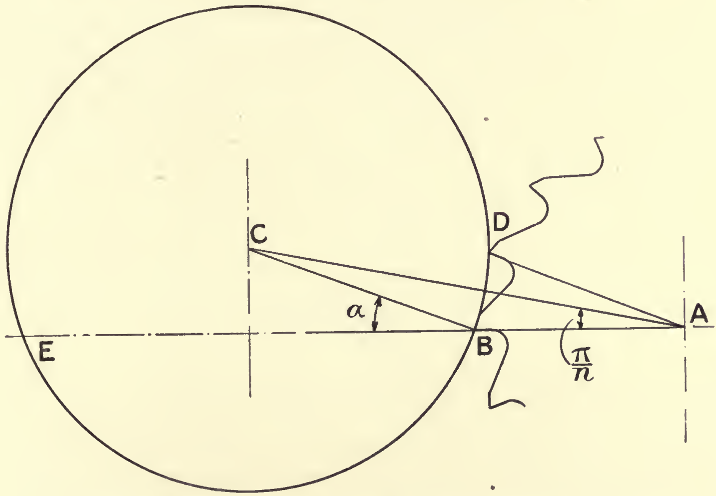


FIG. 153.—MAXIMUM SIZE OF DISC WHEEL—PARALLEL CUTTERS

angular, interference occurs with a smaller number of teeth. This can be seen from Fig. 154, in which the bottom view is a plan showing the cutter GFANB, whose axis is AH and vertical semi-angle BHA $\equiv \theta$, and the wheel CB, and on the cutter's smallest diameter BG is drawn a semicircle BDG, in which D is the next tooth point to B, so that the angle BAD is $\frac{2\pi}{n}$. The upper view is taken perpendicular to the line of movement, or to the edge B of the cutter, and the cutter section is taken close to the smallest diameter, that is close to AFG in the plan view. Here in this top view we see that for the wheel to clear CD must be > R, while from the bottom view DN $= r \sin \frac{2\pi}{n}$ and BM $=$ BN $\cos \theta = r\left(1 - \cos \frac{2\pi}{n}\right) \cos \theta$, and therefore $(\mathrm{EB} + \mathrm{BM})^2 + (\mathrm{CE} - \mathrm{DN})^2 >$ R^2 becomes—

$$\left\{\mathrm{R} \cos a + r\left(1 - \cos \frac{2\pi}{n}\right) \cos \theta\right\}^2 + \left(\mathrm{R} \sin a - r \sin \frac{2\pi}{n}\right)^2 < \mathrm{R}^2$$

and hence we obtain—

$$\mathrm{R} < r \frac{\sin \frac{\pi}{n}\left(\sin^2 \frac{\pi}{n} \cos^2 \theta + \cos^2 \frac{\pi}{n}\right)}{\sin a \cos \frac{\pi}{n} - \cos a \sin \frac{\pi}{n} \cos \theta}$$

or

$$< r \frac{1 - \sin^2 \frac{\pi}{n} \sin^2 \theta}{\sin a \cot \frac{\pi}{n} - \cos a \cos \theta}$$

and as θ increases, $\cos \theta$ decreases, and R must increase. For face cutters put $\theta = 90°$, therefore $\cos \theta = 0$, and we have—

$$\mathrm{R} < r \frac{\sin \frac{\pi}{n} \cos \frac{\pi}{n}}{\sin a} \quad \text{or} \quad < \frac{r \sin \frac{2\pi}{n}}{2 \sin a}$$

where r is the radius to the small part of the tooth.

Formerly cutters had many small teeth, but the number has been reduced, chiefly with the object of providing plenty of room for swarf; this reduction in the number of teeth has rendered sharpening much easier, for the above reasons.

Clearance with Cup or Dish Wheels.—Turning now to the use of the cup or dish wheel, it is first to be noticed that the surface produced is flat, provided that the ground part goes across the hollow of the wheel, as is correct practice, and provided that the travel of the work is at right angles to the wheel spindle. In Fig. 155 is shown the usual arrangement: the slides of the machine are set at 90° to their previous position, and the tooth to be sharpened is canted up or down to secure the desired clearance. If the grinding takes place level with the centre of the wheel, indicated by the broken lines, the slide must not be quite square with the spindle but set slightly off, so that the wheel cuts on one side only ; this is necessary in the case of reamers, as the cut must go smoothly right across,

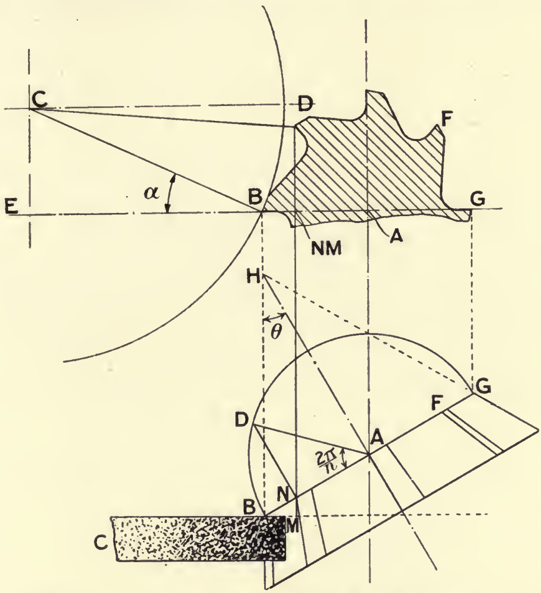


Fig. 154.—Maximum Size of Disc Wheel—Angular Cutters

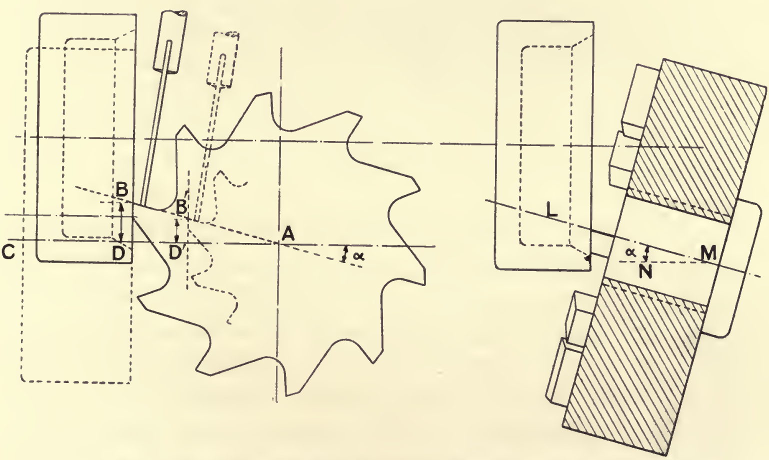


Fig. 155.—Setting for Clearance with Cup Wheel

and so only the side of the wheel nearest the reamer shank must cut. The land is practically flat. If work is set lower so as to use the bottom of the wheel, as indicated by the full lines (or up to use the top), the traverse should be square with the spindle, and the wheel must be kept hollow so close to the edge that the tooth passes within the hollow (indicated by the broken line); this gives a very smooth edge to the tooth.

By grinding at the top or bottom of the wheel, cutters with a large number of teeth or face cutters can be ground. If the tooth is set near the middle of the wheel, the wheel may interfere with the next tooth, and will do so on parallel cutters if the teeth exceed the numbers given on page 336. To clear angular cutters they must have fewer teeth. Taking the formula from page 338, we have $\sin a \cos \frac{\pi}{n} - \cos a \sin \frac{\pi}{n} \cos \theta$ equal to zero, or $\tan \frac{\pi}{n} = \tan a \sec \theta$, or the greatest number of teeth is

$$n = \frac{\pi}{\tan^{-1} (\tan a \sec \theta)}.$$

It does not matter whether the edge of the tooth points upwards or downwards; this is merely a matter of convenience in operating. In Fig. 156 is shown a tooth of a face cutter being sharpened with its edge pointing upwards; the cutter is held in a 'Universal Holder,' and the machine shown is the Le Blond Cutter Grinder. Fig. 157 shows the operation on a Herbert Cutter Grinder; the tooth, which is inclined downwards, is the inserted tooth of a face mill, and is being sharpened on the side.

In using face wheels the particular vertical position of the cutter does not affect the angle of clearance, which is regulated by the height of the point of the tooth BD, B′D′ above (or below) the centre A of the cutter, as the clearance is equal to the angle BAC, Fig. 155. Thus this height must be proportional to the diameter of the cutter. Tables of the correct heights for parallel cutters are provided by the manufacturers of cutter grinders, and such a table, No. XI, is given on page 435. To use it the tooth rest is set to the height given above the work axis, and then moved over to the tooth.

Tables of Setting and Angular Cutters.—In the case of taper or angular cutters from Fig. 155 we see that a small cutter is ground to the same clearance as a large one if the tooth rest is

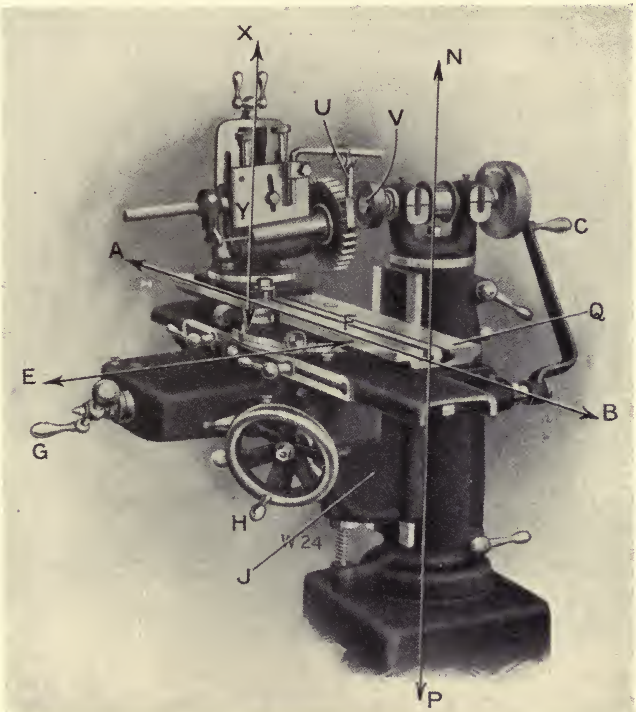


FIG. 156.—LE BLOND CUTTER GRINDER. USE OF CUP WHEEL

elevated to a proportional extent; hence, since an angular cutter may be considered as built up of a very large number of very thin cutters, such cutters can be sharpened correctly. In this connection, however, it must be noted that the tables generally given apply actually only to parallel cutters: for angular cutters the setting is different. I have calculated the settings for angles of 30°, 45°, and 60°, and given them in Table XI, page 435, in addition to the settings for parallel cutters. For face cutters the clearance must be obtained by canting the cutter head, as shown in Fig. 155 on the right, which shows the sharpening of an inserted tooth face mill. The face cutter must be tipped up through the actual angle of clearance, which is shown on the graduated circle provided on the cutter-holding head for the purpose.

For angular cutters generally, where d is the largest diameter, the height between the tooth rest and cutter axis

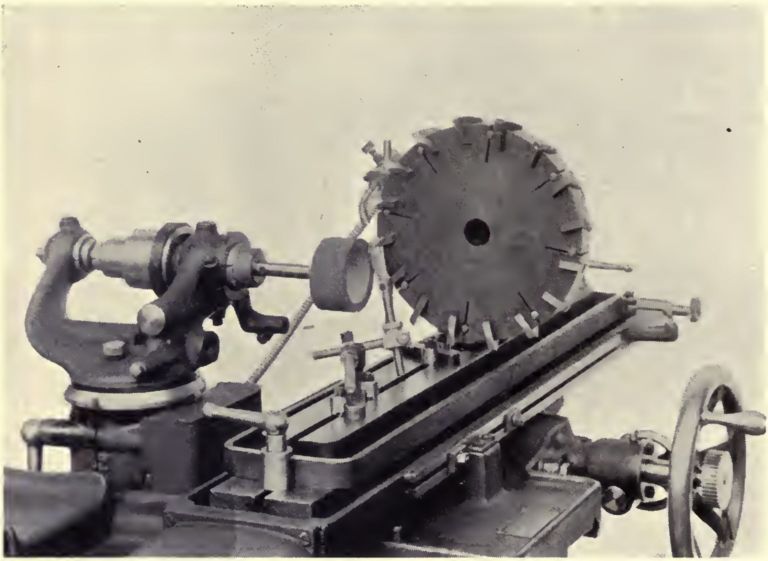


FIG. 157.—HERBERT CUTTER GRINDER. USE OF CUP WHEEL

may be got from the tables for parallel cutters, using $d \sec \theta$, where θ is the semi-vertical angle of the cutter, instead of d.

In sharpening taper and angular cutters and reamers there is no danger of getting the edge curved (as with a disc wheel), since the intersection of two planes—the radial plane of the tooth face and the ground clearance land—must be a straight line. It must be noted, however, that the angle (for example) of a taper reamer sharpened between the centres, is not the angle through which the table is set—which would be the angle of a taper gauge.

Simplified Setting for Clearance.—In the cutter grinder (referred to on page 330) which I used to make, all these difficulties were got over by the simple device of making the grinding head swivel round an inclined axis BD in Fig. 158, so that the wheel ACE when set square with the main slide was inclined to the vertical at the desired angle of clearance *a*. Apart from the advantages of turning the head round instead of the table, slides, knee, &c., the correct clearance was ground on all cutters, parallel, taper, angular, or face, without any setting—as the tooth rest had a fixed height level with the cutter axis—and so located the line from the cutter axis to the tooth that it

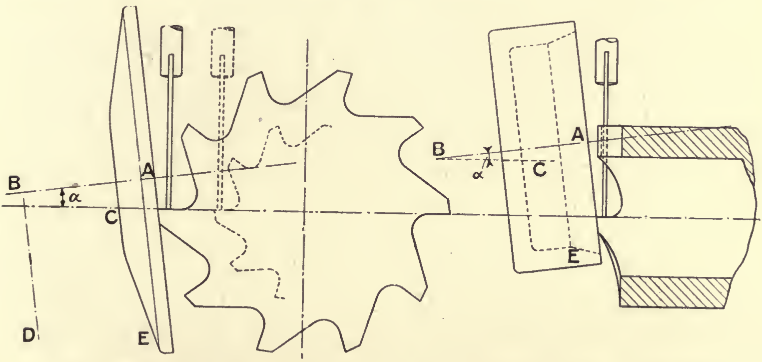


FIG. 158.—SETTING FOR CLEARANCE WITH CUP WHEEL IN GUEST CUTTER GRINDER

was inclined at *a*, the angle of clearance, to the wheel axis, whatever the size of the cutter was. On the right in Fig. 158 is shown the case of a hollow mill ground to the correct clearance in the same manner. To meet the single case of face mills with offset teeth an adjustable tooth rest was provided. This method also has the great advantage that angular and taper cutters are ground to the angle of the table setting.

Taper reamers may be sharpened on a Universal Grinder by the use of a cup wheel, setting the wheel spindle square with the main ways. The angle of the reamer will not be that shown on the taper scale of the machine. If, however, the reamer clearance be obtained by the use of an auxiliary head, such as is shown in Fig. 162, and this head canted to give the clearance to a tooth set ' level ' with the centre, the angle of the reamer will be that shown on the scale.

Broaches.—Broaches are tools which have clearance ground at the rear of the cutting edge, but they are not tools which can be made well on a cutter grinder even if fitted with attachments for circular grinding. The cross-feed of the machine on which they are made must be in good order, as the difference in the steps is so small—$\frac{1}{3}$ to $\frac{1}{2}$ of a thousandth of an inch is a usual allowance. The clearance is obtained by setting the table over to the angle of clearance, using a wheel narrower than the pitch of the teeth, and grinding each land to be a taper cone. The clearance should be very small—2° is sufficient.

Circular saws can be sharpened on cutter grinders in the same manner as regular cutters are, but owing to their large diameter and thinness they are better held on a flat horizontal plate, and in some machines provision is made in this manner for sharpening saws of considerable diameter. When such saws and band saws are much used, special machines are used for sharpening them. These present no special features from the point of view of grinding, but are interesting as examples of ingenious automatic motions. The wheel used should be a vulcanite or elastic wheel, as the cut is suddenly applied and variable.

Cutters Sharpened on the Face of Tooth.—The second class of tools—namely, those ground on the front of the cutting edge—chiefly comprise relieved cutters, and to keep the work shape correct the face ground must (usually) pass through the axis of the work, or, if the teeth are spiral, a line perpendicular to the axis must lie on the cutter face. For sharpening these a dish wheel is usually the most convenient.

Gear and Formed Cutters.—In Fig. 159 is shown a convenient mode of setting up a gear cutter to be sharpened. It is placed on a stud A, and the face of the attachment BC is set parallel to the main slide, a gauge DEF in which EF—equal to the distance of A from BC—locates the face G of the tooth so that it will be ground radially by the movement of the slide. The tooth rest HJ (which has a rigid blade, pivoted at H, and kept against the cutter by the spring K) is then adjusted to the back of the tooth, after which the gauge DEF can be removed. The wheel head should be set a little out of square as shown, so that the edge only of the wheel cuts.

If a wide formed cutter, of similar type, is to be sharpened, it is more convenient to place the cutter on a mandril between centres, in which case Fig. 159 will represent an end view of the arrangement. The wheel face is now set to pass through

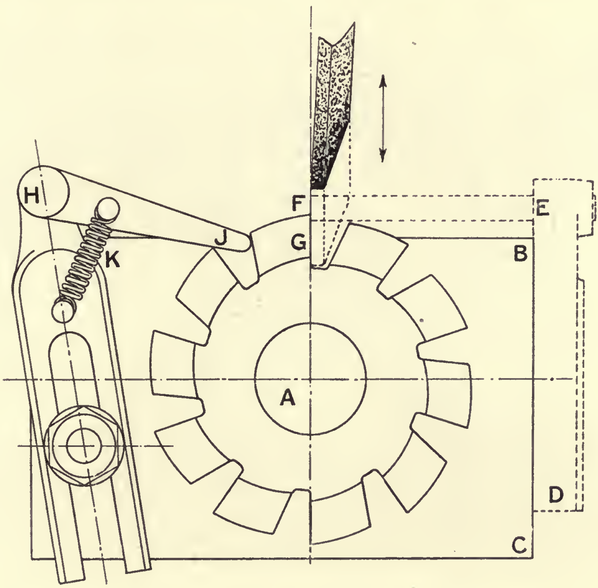


Fig. 159.—Setting Formed Cutters for Sharpening

the axis, and the movement is perpendicular to the plane of the paper.

Spirally Gashed Hobs.—Should the teeth be gashed on a spiral, the wheel must be set to the angle of the spiral, and to secure a radial cut, the wheel should be turned somewhat conical, and the grinding line in which the wheel touches the cutter should be set to pass through the axis of the hob. The tooth rest in this case must be carried by the wheel head, but the rotation is sometimes conveniently controlled by a former or by gearing from the table traverse. A Cincinnati Cutter

Grinder set up for this operation is shown in Fig. 160; the tooth rest A is carried on the wheel head since the cutter is spiral, and a master form B is used to produce the rotation. Theoretically in all these cases the cut should be put on by rotating the cutter round its axis by adjusting the tooth rest, but as it makes no practical difference, and is much more convenient, it is put on, as usual, by the use of the cross slide.

If the formed cutter has the gash not parallel, but some

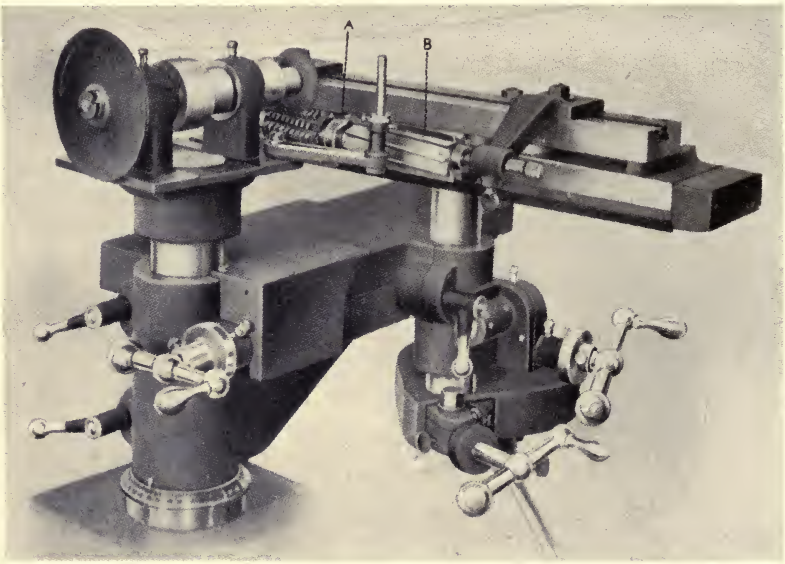


FIG. 160.—SHARPENING A SPIRAL HOB—CINCINNATI CUTTER GRINDER

parts higher than others, it is usually necessary to manipulate the vertical slide while traversing or sharpen the cutter in two operations. This trouble can be sometimes avoided by packing up the head- or tail-stock. Alternately the cutter may be made in two or more parts and the difference of diameter kept constant in the sharpening. A cutter for producing a given form may sometimes be made considerably less in diameter, or the risk in hardening may be decreased, by gashing in two or three cuts so that the bottom of the gash is irregular, and hence the cutter may be much cheaper to make thus. As the trouble of grinding is so considerable, the cutter design deserves attention.

Taps and the cutting face of reamers may be ground in the same way, and the wheel may be shaped to the groove. In these cases the holding is frequently done by use of a division plate on the head. Small taps are quite satisfactorily ground by passing them under the wheel, holding them by hand only.

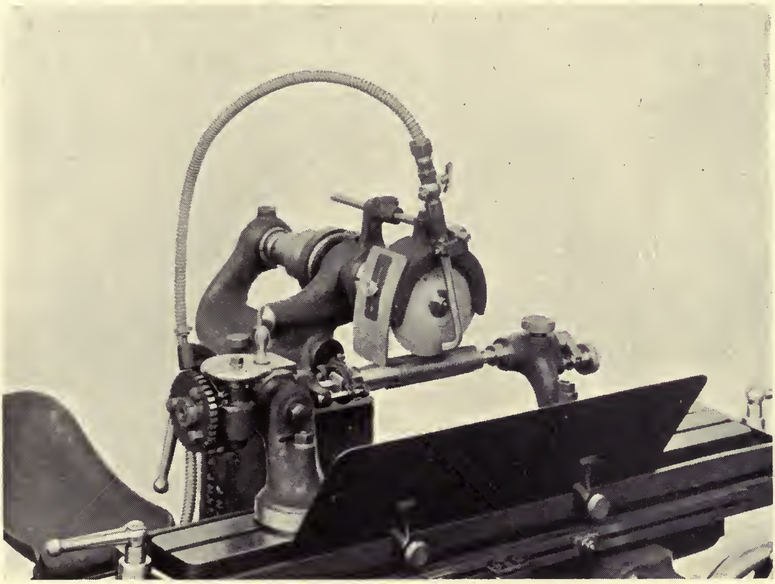


FIG. 161.—SHARPENING A TAP—HERBERT CUTTER GRINDER

Fig. 161 shows Messrs. Herberts' cutter grinder set for sharpening a tap, using a division plate.

In these illustrations the principles of the setting are shown, and as such can be easily applied to other makes of machines.

As a cutter grinding machine for general work requires more movements than a Universal Grinder, there is a tendency to extend the capabilities of the machine by adding arrangements for rotating the work, so that external circular work may be ground, and a live work spindle, chuck, and internal grinding spindle in addition to do internal grinding. A vice will equip the machine for surface grinding, so that a much more 'Universal' machine than the Universal Grinder is produced. If the parts are well enough made to be of real service the cost is not the insignificant matter it would first appear to be, but such a machine is very useful in a shop which requires accurate manufacturing tools but has no need for production grinding.

Automatic feeds are sometimes added, and as the cost

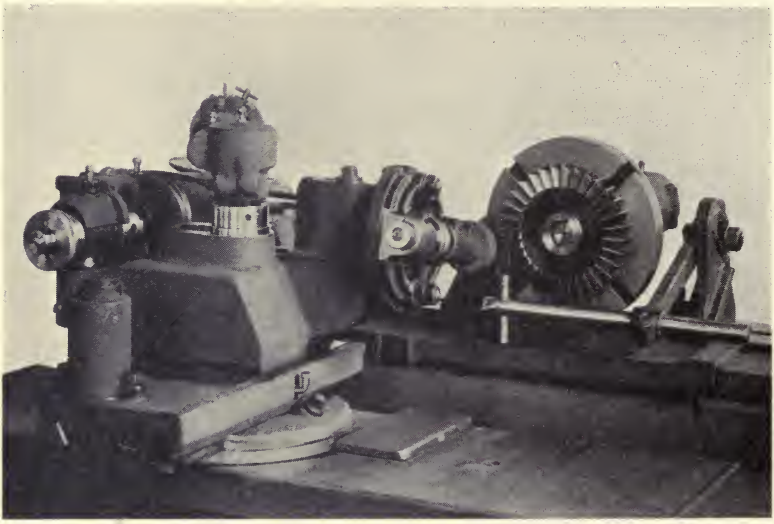


Fig. 162.—Clearance with Auxiliary Wheel Head—Landis Universal Grinder

increases the requirements are sometimes met from the other end—by adapting the more usual type of Universal Grinder to do the extra work. This involves replacing the regular wheel head by a bracket carrying a vertically adjustable (smaller) head. As this can be set with its spindle either parallel or at right angles to the main ways, the various kinds of cutter sharpening previously referred to can be dealt with. Fig. 162 shows a Landis machine so fitted up, with a small auxiliary head which takes the place of the internal grinding spindle bracket.

Universal Cutter Holding Attachments.—More recently the vertically adjustable head has been made a more important feature, and Universal machines are built so arranged. They are usually fitted also with a 'Universal' cutter holding attachment. In Fig. 163 a Universal Grinder of this type, by Messrs. The Churchill Machine Tool Co., is shown set for sharpening a face mill, using a cup wheel. The swivel platten

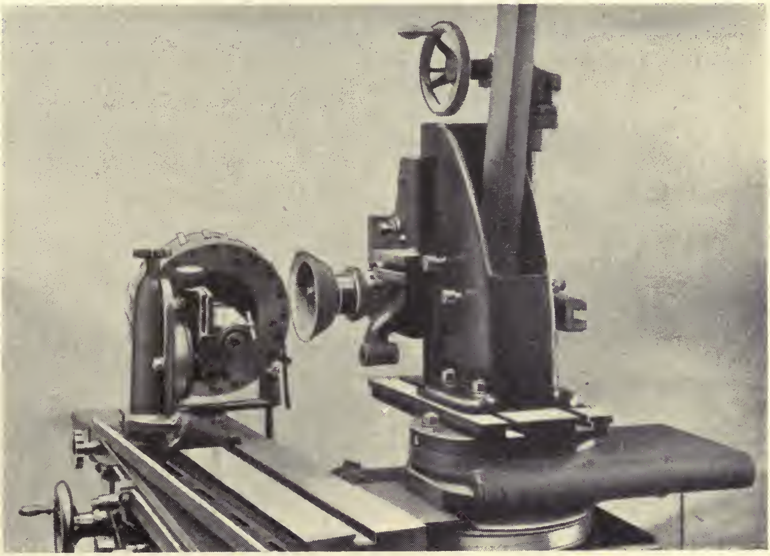


Fig. 163.—Tool Room Universal Grinder—Churchill

on the top of the cross slide here carries a bracket which carries the wheel head on a vertical slide, and the spindle is driven directly from overhead. The wheel spindle is elevated by the screws just visible on the right, operated by the hand wheel at the top through bevels: various means of holding tooth rests are seen on the wheel head. The Universal cutter head is set to cant the cutter up so that the teeth, inclined to the axis, are horizontal where sharpened.

As cutters with various types and sizes of shank are in use, collets to suit them are usually required, but several firms make a universal attachment, such as is shown in Figs. 156

and 163. Any shank, within the capacity of the attachment, can be conveniently held in the vee by aid of the swivelling piece Y, which is adjustable by means of the screw above it, and suits its position to the taper of the shank by swivelling, holding it sufficiently firmly, but permitting it to be turned by hand. The rear end of the cutter or its mandril is held up by a plate (or rod if the shank or mandril be short, as in Fig. 156) carried on a tail rod. The angular movements are for the angle and clearance of the cutter, and to compensate for the inclination of cutter due to the taper of the shank. Such attachments do not hold the cutters for grinding in the same way as they are held in the milling machine spindle, and so accidental damage to the cutter shank may affect the grinding, so that the cutter does not run quite true when in the miller.

Twist Drill Grinders. — Although twist drills can be sharpened along the cutting edge in such cutter grinders as are described above, it is afterwards needful to grind away the material behind this clearance. All that is necessary in grinding a twist drill is that the lips should be of equal length, the clearance just behind them correct throughout, and the angle at the apex approximately right, and that the part behind the clearance should be quite clear. It requires a little skill to do it by hand, and as twist drills are so universally used, machines for sharpening them are manufactured. Various devices for giving the clearance to the edge, and grinding away the metal behind it at a simple movement have been used, almost all needing to be set for the diameter of the drill. If, however, the movement consists of rocking the drill round an axis AB—as shown in Fig. 164—and grinding it by a flat surface C, while the drill is held by planes or lines all passing through the point D in which AB intersects the surface C, then all drills will be ground to the same geometrical shape on their lips when being sharpened. This is the principle upon which the twist drill grinder I formerly made was based, and it is also used in the 'Yankee' twist drill grinder shown in Fig. 164. In this, the drill is held between the two planes E and F and by the edge of the lip rest G, all of which, if continued, would pass through the point in which the axis AB intersects the surface C. The small tailstock prevents the drill from slipping back under the cut of the

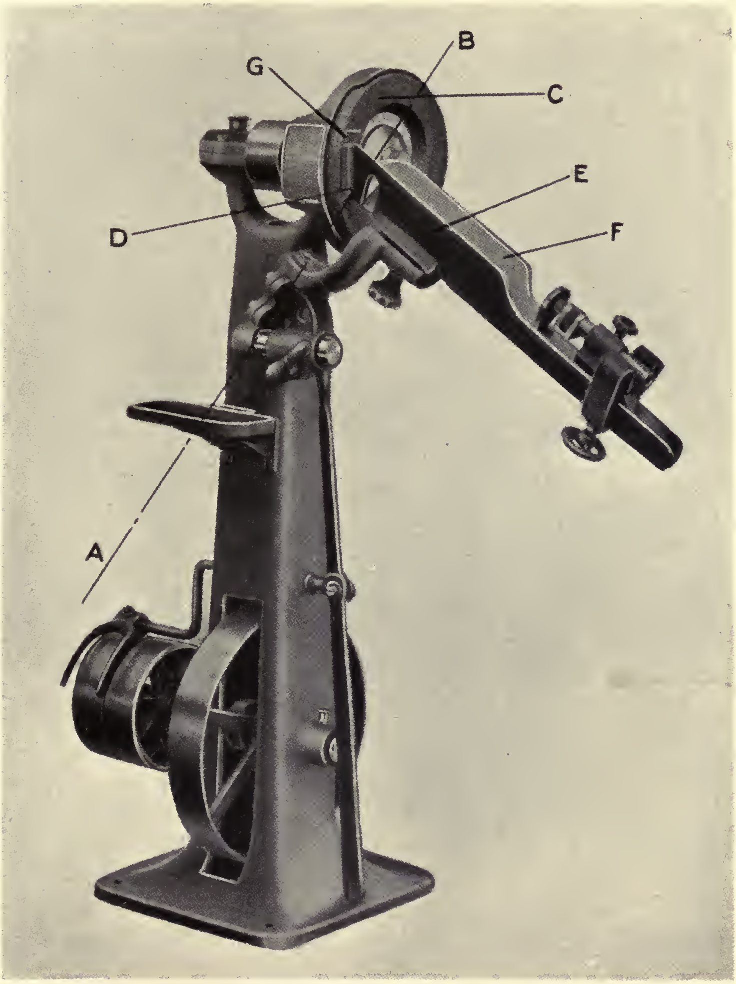


FIG. 164.—'YANKEE' TWIST DRILL GRINDER

wheel, and serves to feed it up as grinding proceeds. The surface is produced by the flat face of the wheel, as the drill holder is rocked round the axis AB. The larger drills are easy to sharpen, but the machine needs to be accurately made and free from shake to sharpen the small drills correctly. Fortunately these are easily sharpened with sufficient accuracy by hand.

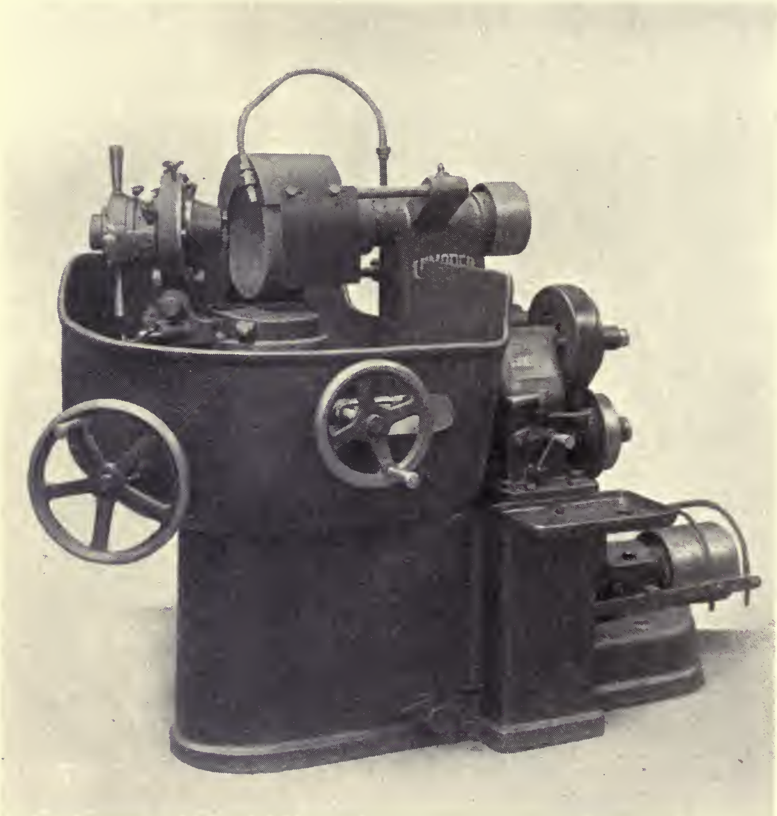


FIG. 165.—LUMSDEN TOOL GRINDER

Large drills have a considerable thickness of metal at the centre for reasons of strength, and the point therefore has difficulty in entering the metal. To make the drill cut freely the point is 'thinned' by grinding small channels up it with a thin elastic wheel. A vee to lay the drill in for this point thinning is convenient, and is fitted to some machines.

Mechanically Guided Lathe Tool Grinders. — In modern manufacturing the production of lathe tools has now been transferred to the tool room, with the exception of the smithing, and this has been reduced to a minimum. With a tool grinder such as the Lumsden, shown in Fig. 165, the forged tools or cut-off bar can be rapidly ground to the desired shapes at the points when soft, although there may be a considerable amount to be ground off, so that usually no other operations are necessary to produce a lathe tool. After hardening and use

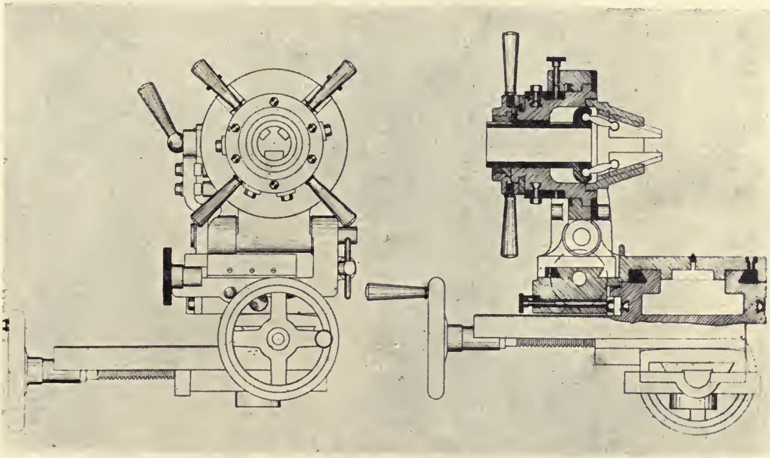


FIG. 166.—LUMSDEN TOOL GRINDER. TOOL HEADSTOCK

they can be re-sharpened to the same angles, or slightly less, so that the tools are sharpened at the edges only.

The motions necessary for grinding can be obtained in several ways, either by moving the tool or the wheel; in the machine shown the wheel oscillates about an axis (near the floor) parallel to the wheel spindle, so as to grind the facet on the tool and to keep the wheel surface true.

The tool is held in a chuck capable of presenting it to the wheel in any desirable position, and which can be swung round a vertical axis so as to grind a radius on the tool when necessary. The arrangement of the chuck and adjustments is seen in Fig. 166; the chuck has three jaws, and the bottom of the tool is placed on the wide top of the bottom jaw. The chuck swivels round a horizontal axis so that the side clearance can be ground, and stops are provided for duplicating work. The upper

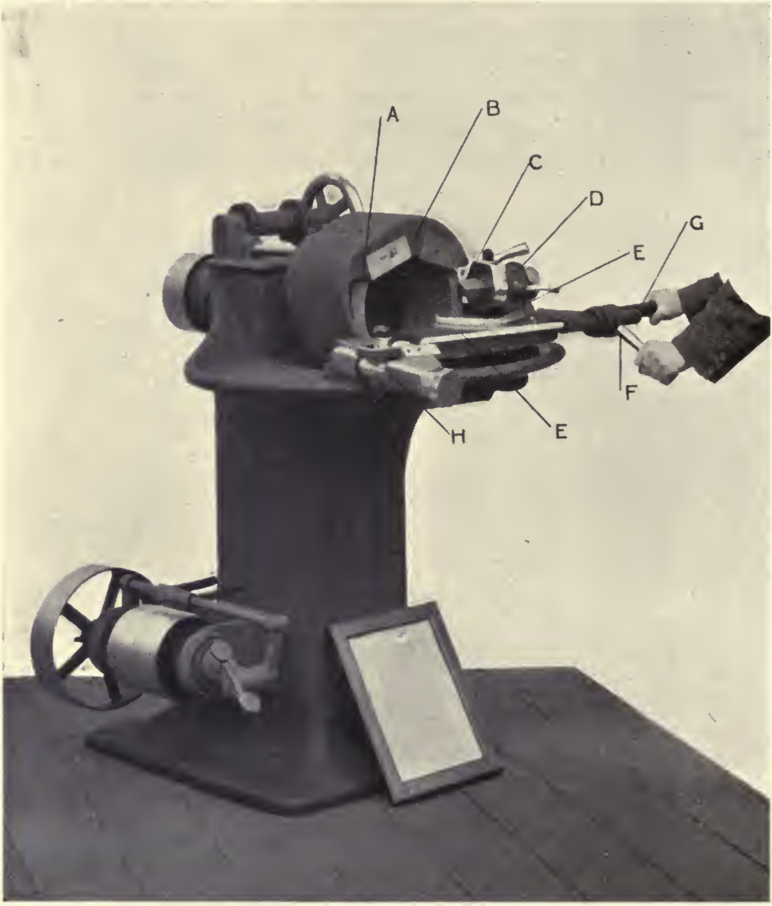


FIG. 167.—LUMSDEN COMBINATION TOOL GRINDER

horizontal slide is for the purpose of setting the tool for grinding a radius on it, which is done by swinging it round the vertical axis shown ; this movement also has adjustable stops provided. The two lower slides are for adjusting the tool to the wheel and putting the cut on.

The use of grinding for shaping lathe and planer tools, introduced by Sellars many years ago, made its way very slowly, but small shops now appreciate the advantages to be obtained, and to meet the requirements of such firms, the Lumsden Combination Tool Grinder, Fig. 167, has been designed. The wheel used is of the cup type, and is trued mechanically by a diamond tool carried in a jig at B. The tool holder C is fitted to rotate in its bracket D, and can be set at the desired angle by graduations at the rear, while the bracket itself can be set to any angle on the graduated arc E. The traversing movement is given by the lever F by means of a quick-pitch screw, and the tool is kept up to the wheel by the lever G. When not needed this mechanism can be swung up and back to the left, leaving only the lower plate, which forms a rest inclined to the wheel at the usual angle of clearance. The machine then becomes an ordinary tool grinder with a cylindrical wheel. The whole is adjusted towards the wheel by the knob at H. In this machine, ball bearings are used for both the journals and thrust of the spindle.

CHAPTER XI

FORM GRINDING AND CURVED SURFACES

Mechanically Generated Cups and Cones.—In the machines of the preceding chapters, the surfaces ground are of simple shape, such as circular tapers of straight axial section and flat surfaces, but the requirements of engineering now demand the application of the process of grinding, with the precision and quality of surface inherent in it, to the production of other surfaces. The development of machines for such purposes and for the production of simple ground work in quantities at lower cost than at present, is the care of several firms to-day. Straight shafts and tapers are produced in the Universal Grinder by a double copying process, the wheel face being first

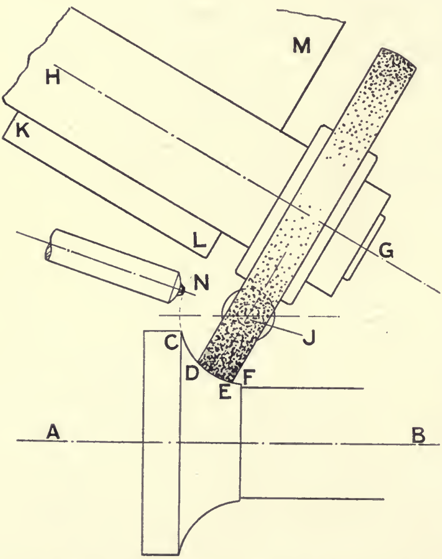


FIG. 168.—GRINDING A CONE BALL RACE. GENERATING METHOD

'trued,' and thereby made to be a copy of the ways, and then the surface produced by the wheel face being traversed along the work by the main ways. The work touches the wheel edge right across while the grinding is going on, and as the traverse takes place the 'line' of contact is maintained. Geometrically, a piece of a straight line can move along the continued line and coincide with it always. So, geometrically, a piece of a circular arc can move along a circular arc of equal radius and fit it always. Mechanically adapting this, such surfaces as 'cups' and 'cones' for ball bearings, where the axial sections are portions of circles, can be ground. Fig. 168 shows the motions for grinding a 'cone,' and Fig. 169 those for grinding a 'cup'; these are lettered in a similar manner, so that a single description will apply to both. The work, whose axis of revolution is AB, has a portion CDEF of its shape of circular axial section :

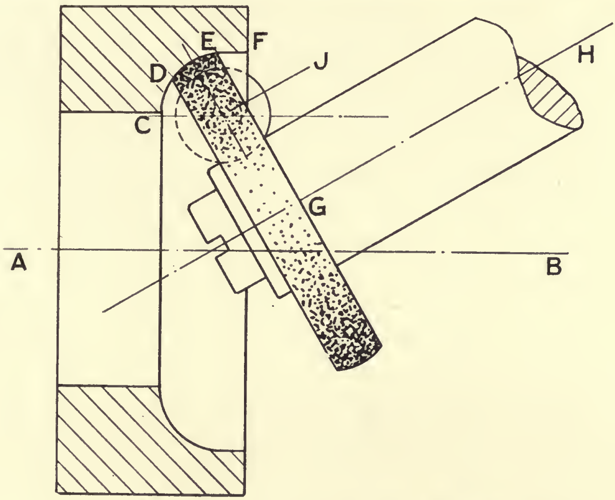


FIG. 169.—GRINDING A CUP BALL RACE. GENERATING METHOD

the wheel, whose axis is GH, touches it along the portion DE. If J be the centre of CDEF, then if the wheel head, carrying the spindle GH and wheel DE, have a movement round an axis through J perpendicular to the plane ABCDEF, the wheel edge traces out the shape CDEF as it moves, and is always in contact with it. This corresponds exactly to the grinding of a shaft of straight taper, and the contact of wheel and work is maintained throughout the movement. The truth of the surface produced is dependent on the mechanism and not on the particular shape of the wheel, initially or after wear, though these produce an effect on the quality of the surface.

To put the cut on, it is necessary to mount the wheel on a cross slide, indicated at KLM, and this slide moves the wheel spindle farther towards the work as the wheel wears. To true the wheel correctly the diamond—as in the Universal Grinder—must be supported on the work carrying part of the machine, and is shown at N. Either the wheel or the work may receive the movement round the axis at J, corresponding to those cases where the wheel or the work travel in Universal grinders. In an actual machine arrangements for properly locating the work axis and the position of the work on it with regard to J are necessary; but the essential matter here is that the truth of the surface is mechanically produced. Several machines have been brought out for grinding cups and cones upon these principles.

Taking a larger case, the point of a shell—provided, as is usually the case, that the axial section is a circular arc—can be ground in a similar manner, the wheel making contact with the work over the width of its face, and the work having the characteristics of the work from a Plain grinding machine.

If, however, the curve to be ground is other than a circular arc, the lack of continuity of the contact of the work and the wheel causes irregular wear of the wheel, spiral markings of the traverse, and other difficulties. When the part operated on is not too large the wheel may be trued to the desired sectional shape, and the result produced by simply feeding in the wheel to the necessary depth, while the work simply revolves or reciprocates in the plane of the wheel.

Form Grinding.—Such grinding may be termed form grinding; the accuracy of the product depends directly on the truth of the wheel shape, as opposed to the cases previously described, in which the accuracy depends on the mechanical guidance of the wheel relatively to the work.

Examples of the method have already occurred. The short ends of shafts on which hand wheels and gears are fitted may be instanced, and, as described in Chapter VI, page 225, the most rapid way to grind these is to feed the wheel directly in to the required depth, then traversing it off by hand.

Collars.—When considering the matter of grinding collars on shafts, it was pointed out (page 278), that there was the choice of two methods: the collar could be ground by bringing the side of the wheel, previously trued, up to it—as shown at X in Fig. 116—or the axis of the wheel spindle having been slightly inclined, the corner only of the wheel could be used as shown at Z, and the collar ground by traversing the wheel out. In the latter method the accuracy is dependent on the mechanical movement of the slide, and so is to be preferred to the former, in which errors in the wheel shape have their effect on the result.

Cups and Cones.—In a similar manner cups and cones may be ground by truing the wheel to the requisite shape, and simply feeding it into the work. The truth of the sectional shape then depends on the form of the wheel, and the surface is liable to have circumferential marks on it, owing to the prominence of some particular particles in the wheel; but in many cases the accuracy is ample, and the marks can be polished out with fine emery cloth, or they may be avoided by lightly smoothing the wheel with a piece of oilstone. The simplicity of the machine necessary is a great advantage.

In cases where form grinding is used, it is very important that the wheel should be of large diameter compared with the work; otherwise the shape turned on the wheel by the diamond soon loses its accuracy. This is not always possible, for example in the ball cups of Fig. 169. In these, however, great accuracy of curve is not needed, and as the cups have been previously machined all to the same correct curve, the wheel tends to keep it a good shape by the wear averaging the same.

Advantage is taken of this in the machine shown in Fig. 170—a Guest Hub Grinder—for such work as two-speed hubs. The work spindle is hollow and carries an expanding collet chuck operated by the hand wheel at the rear. In front of the headstock is a slide carrying a running steady, the rotating part of which is carried on balls, so that it can easily be driven frictionally by the work. The hub is placed with one race on the collet, and the slide is moved up by the lever below until the other end of the hub is held centrally in the taper hole of the steady, when the slide is locked. The collet is then expanded and the hub is held firmly. The wheel is dressed to

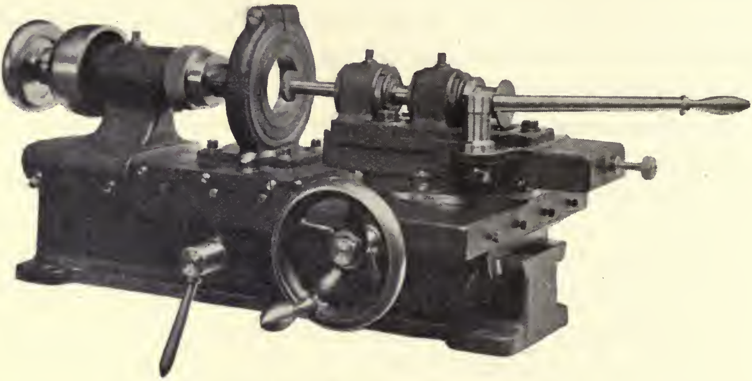


Fig. 170.—Hub Grinder—Guest

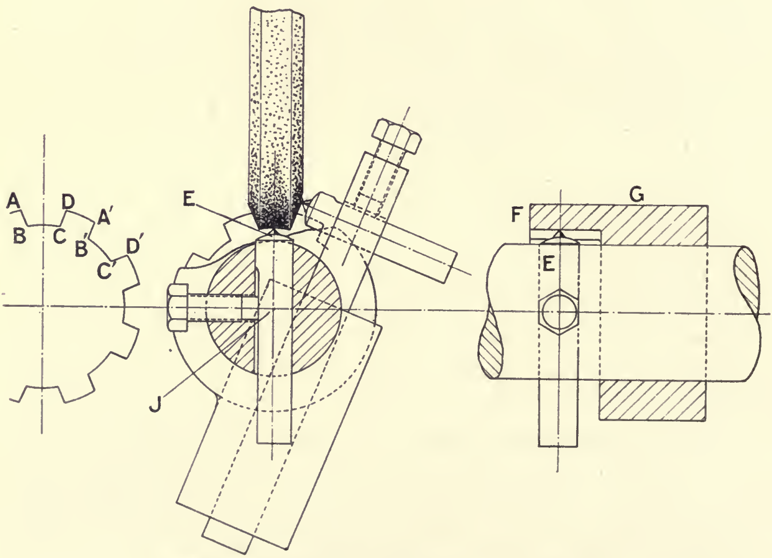


Fig. 171.—Grinding Castellated Shafts

Shape freehand, and soon wears to the form of the race as it comes from the automatic and the hardening.

The radii on crank pins (page 232) form another illustration of the method, and the size of the wheel used makes the retention of the shapes an easy matter.

In these examples the work rotates, but form grinding may take place where the form is reproduced by linear motion, as in the grinding of the bottom and sides of the grooves of shafts for castellated fits, or by helical (screw thread) motion as in the grinding of worms.

Castellated Shafts.—The former is shown in Fig. 171, in which the shape of the section of the shaft ABCD A′B′ is given on the left; the hole in the gear is ground out and the fit is on the surface BC, B′C′, which is form ground by the hollow face of the wheel, and upon the sides AB, CD, which are simultaneously ground by the sides of the wheel. To true the wheel three diamond tools should be used, one for each part, AB, BC, and CD. They should be carried in a jig supported between centres, in the same way as the shaft is carried; the diamond E, truing for BC, may be set out to the correct distance by using a gauge, as shown at FGH, and the wheel trued by rocking the jig on the machine centres. The jig is then fixed and the sides of the wheel trued by two diamonds, carried each on its slide, and set out to a gauge. The main slide should be adjusted at each truing operation, so that the diamond in use moves in a plane through the axis of the wheel spindle. The errors involved are thus reduced to a minimum. It is customary that CD and A′B′ should be parallel, but they may be radial. Only a very simple machine, consisting of a body having a main slide with a headstock (and division plate on spindle) and tailstock, and a vertical slide carrying the wheel spindle, is necessary for this work.

Gear Teeth and Worms.—To meet the requirements of high speed gearing which has been hardened (or even heat-treated only), the teeth are sometimes ground, chiefly in motor car work, and perhaps chiefly as a selling point. Machines for this purpose may follow the principle of a generating machine, or of a gear cutter using a formed cutter. In the latter case the operation corresponds to form grinding, the wheel being trued to the shape of the space between the teeth and traversed between them. The earliest machines for the purpose were designed for treating cast gears before the days of cut gearing; to-day, when practically every gear is cut, it is to the rectification of hard gears only that attention is paid. In the early machines the wheel, a hard one, was simply turned by hand

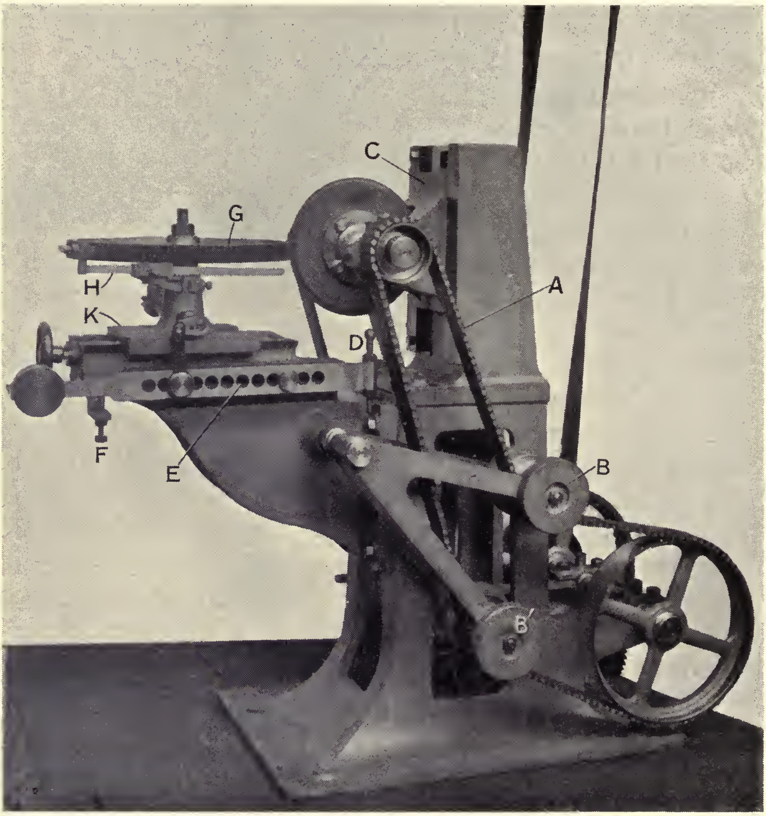


FIG. 172.—GEAR GRINDING MACHINE—L. STERNE & CO.

to the shape of a template, and it was trusted that the various irregularities of the teeth would average so that the wheel would retain its shape for some time. In Fig. 172 is shown such a gear grinding machine (by Messrs. Sterne & Co.) intended for treating cast gears. The machine works upon the form-grinding principle, the wheel, which is 8 inches in diameter, being turned by hand to the shape of the tooth space and then traversed mechanically. The wheel spindle is driven by a pair of link belts A (see page 149) running round tension idler pulleys B, B′, and the wheel head C is carried on a vertical slide, to which a reciprocating motion is given by means of a connecting-rod inside the column of the machine. Towards the lower end of the stroke a dog on the slide encounters the end of the adjustment screw D, carried on the lever E, the movement of which is limited by the screw stop F. The gear G is carried on a vertical stud on the slide K, and is indexed round (using its own teeth) by the pawl H, which receives its motion from the lever E. The cut is put on, and the position of the gear stud adjusted for gears of different sizes (up to 30 inches diameter), by means of the slide K. This machine was brought out some thirty years ago, before the days of universally cut gearing, but recently machines have been made on somewhat similar lines, but embodying the worm dividing wheel and indexing mechanism customary in gear-cutting machines, and provided with mechanical guiding apparatus for truing the wheel. As these machines are intended for correcting the distortion of gears caused by heat treatment or hardening, a high degree of accuracy is necessary if the running of the gear is to be much improved, and hence the advantage of a jig for guiding the diamond when truing the wheel. The production of the desired wheel tooth shape—whether cycloidal or involute—appears to be a problem of some difficulty. In the movement of the diamond over the wheel face it is essential that it should bring one point only of its angles into action, or at any rate that small variations of the actual working point should have little effect on the resulting shape of the wheel. In the truing jig of one machine which I examined this point had been attended to, but the total motion of the diamond was produced indirectly by the superposition of two movements (one controlled by a cam) connected through a large number of working parts. Such arrangements are very seldom adopted in machines which aim at any precision. Supposing, however, that the complete motion of the diamond tool for producing a gear shape were produced very directly and in a manner free from the errors indicated above, the accuracy of shape initially given to the wheel would be dependent on the precision of the lay-out and making of the cam, and upon the accuracy with which the actual working point of the diamond was set with

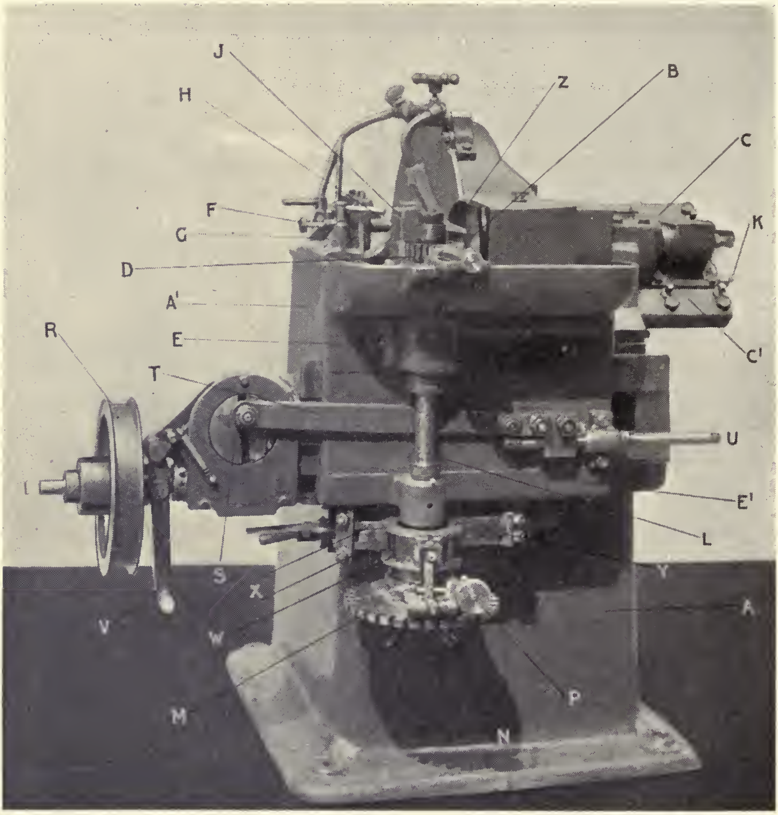


Fig. 173.—Daimler Gear Grinding Machine. Generating Principle

reference to the cam and mechanism. The difficulties will be appreciated by those familiar with the production of gear tooth shapes and used to precision work.

These troubles can be avoided by adopting the generating principle for grinding gear teeth, and this is done in the machine (Fig. 173) of the Daimler Company. In this machine the side of the wheel (near its edge) is trued flat, and the tooth shape, which is an involute, produced by rolling the gear relatively to the wheel.

The geometrical arrangement is shown in Fig. 174, where the teeth of the gear being ground are indicated in two positions. An involute is the curve traced out by a fixed point, here P, on a line AB, which rolls upon a fixed circle (centre C) without slipping; by this motion P would trace the outline of the

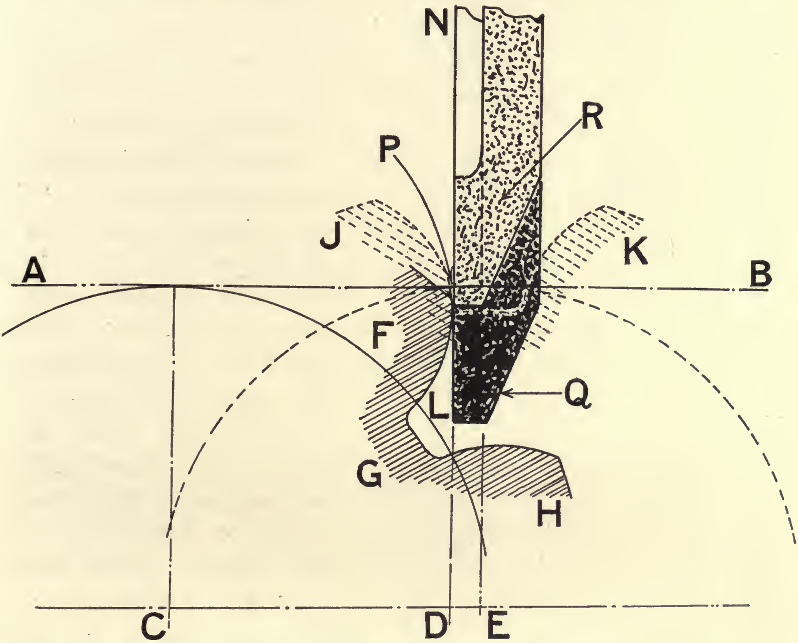


FIG. 174.—GRINDING GEAR TEETH. GENERATING PRINCIPLE

shaded tooth F. As P at any moment will be moving perpendicular to the position of AB at that instant, a line LPN, drawn perpendicular to AB at P, will always touch the involute as it is being traced out by P. Hence by using the wheel LNQ as shown, it will in its movement always touch the involute side of F, and will therefore grind the tooth correctly.

Such a movement of a high-speed spindle carrying a wheel would present practical difficulties (partly owing to gyroscopic effects), and it is better to fix the line AB, the spindle, and the wheel, and to roll the circle with its gear teeth upon AB—as is done in the Bilgram bevel gear generator. The motion, being relative, produces the same geometrical results.

When the gear centre is at C and the teeth at FGH, the wheel face DLPN is grinding the point of the tooth F at P. The gear circle then rolls along AB until its centre goes to E just beyond D. The teeth are then in the position J, K, indicated by the broken lines, and the grinding is finished at the bottom of the tooth.

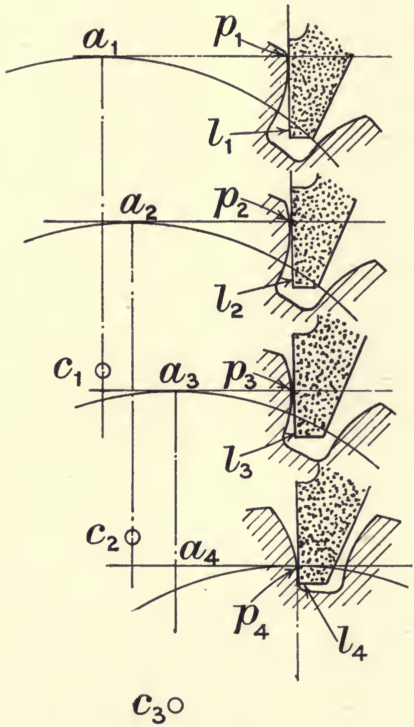


Fig. 175.—Grinding Gear Teeth Generating Principle

It will be noticed that as the gear rolls the point of contact with the wheel is always at the point P, and hence in grinding the wheel would wear at this point only. To distribute the wear of the wheel a reciprocating motion is given to the wheel head, so that the wheel face moves to and fro in its own plane. When the gear is at JK the wheel only just reaches to the bottom of the space, its position being shown at R lightly sectioned; as the gear rolls the wheel advances, until, when the gear is in the shaded position FGH, the wheel is in the heavily sectioned position Q. The wheel is of the section sketched, and by its movement the wear is thus distributed over its grinding face.

In Fig. 175 four positions of the action are shown. The point of contact of the rolling circle with the fixed line is at *a*, the centre of the circle at *c*, the point of contact of wheel and gear at p, and the wheel point at l. The suffixes refer to the different positions, and the movement of the wheel as the gear rolls is clearly seen.

No movement is given to the wheel parallel to the axis of the gear in order that it should cover the width of the tooth; the wheel used is so large in diameter that this is unnecessary, the small clearance at the bottom of the tooth space being sufficient to permit the whole working surface of the tooth to be ground up. The two faces of the teeth are ground separately, the gear being reversed on the spindle for the purpose.

No reference has been made to the pitch circle, as it is only in text books on machine design or when the axes of a pair have been definitely fixed in position, that involute gears possess pitch circles.

The action of the machine itself (Fig. 173) can now be understood. The body AA′ carries the wheel B on a wheel head C, which is arranged to slide parallel to the spindle axis for the convenience of maintaining the position of the wheel face constant; the gib of this slide is seen at C′. The whole wheel head is then carried on a double cross slide—one part adjustable to provide for gears of various sizes and for wear of the wheel as it decreases in diameter, and the other to give the oscillating movement of the wheel in synchronism with the rolling of the gear D, which is mounted on the top of a vertical spindle, and is carried to and fro by the slide EE′. The wheel face is trued by a diamond tool at F, which is set up to a fixed stop at H. When the wheel is to be trued, a small cover J in the wheel guard is lifted, and the slide carrying the diamond moved forward. The wheel head is adjusted forward a sufficient amount for the truing by the screw K, and is then dressed; thus its flat face is kept always in the same plane.

The vertical spindle L which carries the gear D has a division plate M, with the same number of teeth as the gear, operated by hand by the latch N. The pressure being always one way, the notches are made taper with one side radial, as is usual in good capstan lathe practice. An adjustment is provided at P for setting the tooth correctly in relation to the wheel. The driving pulley for the reciprocating movement of the slide EE′ is at R, the adjustment for the length of stroke at S, the connecting rod driving the slide at T, and the adjustment for the position of the slide movement at U. The gear is indexed round by hand, and for this purpose the slide movement is stopped by the lever V, which takes the clutch out of gear and applies the band brake, which can be seen immediately above the lever.

The rolling motion of the gear is produced by means of a drum W carried on the spindle L, and thus by the slide E, and forced to turn as it moves by the steel bands X and Y, of which X is made in two parts so that there is balance of force. One end of each strip is fastened to the drum W, and the other is anchored to a bracket, which is carried on the machine body, and is adjustable in position for drums of different sizes.

The mechanism for moving the head in unison with the reciprocating rolling of the gear, consists of a cam carried on the wheel head cross slide and a roller carried on the slide EE′, the wheel head slide being forced up to keep the contact by means of springs. The water piping, nozzle, wheel, and splash-guards and other details are customary grinding-machine practice.

Gears ground by the generating method naturally possess the advantages inherent in it, and these in addition to those due to the simplicity of the method of wheel truing in it, as opposed to the complications mentioned in connection with the form-grinding method. When the hardening treatment is careful, gears are little distorted, so that ground gears are a comparative luxury, the chief desire being usually an improvement in the silence of running. Machines have been made to improve gears by running them together with abrasive powder, making a manufacting method of the old crude cure for noise. Where the desire is for the best, the fact that grinding on the generating principle is the more expensive may be disregarded.

In truing the wheel for the purpose of form-grinding a worm consideration must be given to the question of interference. The worm may be finished in a lathe by a tool cutting on an axial plane, and of the shape of the section of the worm—which almost invariably consists of straight lines. It cannot, however, be ground by a wheel trued to a similar axial section, owing to interference at other points. In Fig. 176

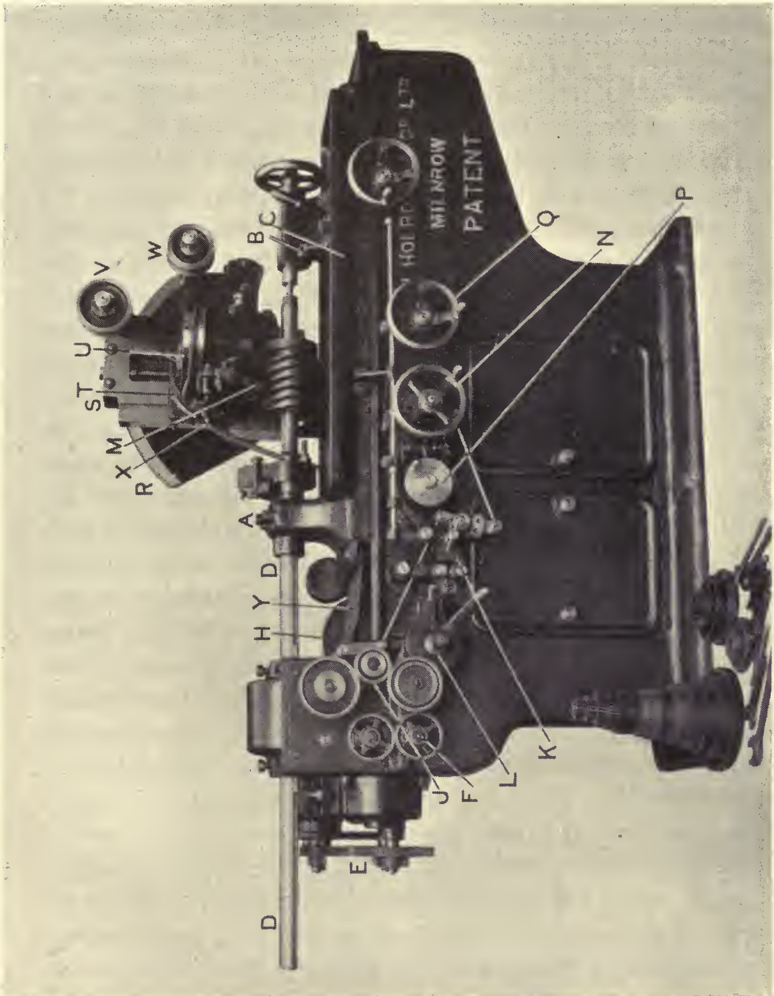


Fig. 176.—Worm Grinder—Holroyd

is shown the worm and hob grinding machine of Messrs. Holroyd, which is adapted for grinding worms either by form grinding—in which case the wheel covers the whole worm surface at each travel—or by grinding a small portion of the worm face at a time, and traversing the wheel down the tooth face at the reverse after each stroke. The latter process requires much longer time, but is necessary with worms having large teeth.

Here the work is carried between centres on the headstock A and tailstock B, the latter of which is adjustable along the main slide C, to suit various lengths of work or mandrils, and the reciprocation of the table, which is by means of a screw, carries the work to and fro under the wheel; at the same time it is rotated by the shaft D in due ratio by means of the change wheels at E. The drive for this table motion is obtained from two pairs of fast and loose pulleys (not visible) on the rear of the shaft F. These are driven by open and crossed belts, the forks of which are operated from the table by means of stops on the rod seen in front of the machine. This gives the reciprocating motion. The table can also be traversed by the hand wheel on the right. As worms and hobs frequently have several starts, a dividing mechanism, which can be set to act at either or both ends of the stroke, is inserted; the top of the driving pulley for this is seen at H, the change wheels at J, the trip mechanism at K, and the handle for hand operation at L. The action is similar to that customary in gear cutters. The vertical adjustment of the wheel M is by means of the hand wheel N, just behind which is an automatic feed for this movement, so that when the wheel grinds the worm by feeding down its side, the motion is automatic; the automatic throw-out, necessary for this motion, is controlled by the hand wheel P. The hand wheel Q traverses the horizontal wheel slide which carries the vertical swivel R, the vertical slide S, the second vertical swivel T, and the horizontal swivel U to the wheel head. This cross adjustment serves to set the wheel centre vertically over the work axis for worm grinding; for sharpening hobs the slide has to be run back some distance to bring the wheel to the correct position. The belt to the wheel spindle runs over the idler pulleys V, W. The water supply is shown at X and the spring roller protecting cover for the main slide at Y.

When the wheel is to be traversed down the side of the tooth, the line of motion of the ' vertical ' slide is first set to the angle of the tooth, and the wheel spindle then set horizontal by means of the second vertical swivel, but in form-grinding this need not be done, it being sufficient that the wheel spindle is horizontal. The horizontal swivel is then adjusted to the angle of the worm thread, taken on the pitch line (which is not, however, quite definite unless the worm wheel to be used is settled), and the wheel adjusted vertically until it is in the correct position for grinding, and it is then trued. To do this so as to form the worm face correctly the diamond point is made to traverse over the (imaginary) desired worm face. This is done by carrying the diamond tool in a jig between the centres, and using the automatic motion—previously set up as to the lead of the worm—so that the point of the tool traces out a helix, which will in grinding be reproduced on the worm. The diamond is carried in a slide which is adjusted to the angle of the worm tooth, and by slowly traversing it down this as the point of the tool reciprocates helically, the whole surface of (one side of) the worm will be traced out by the diamond, which will during this movement turn away all parts of the wheel projecting across this traced-out surface. The diamond point must be set so that the slide movement by which it is slowly traversed at the angle of the worm tooth, would, if it could be continued, make it pass through the worm axis ; the reciprocating movement need only be sufficient for the diamond to clear the wheel. Now if the actual worm be placed in position the wheel will grind it so that none of it projects across the surface traced out by the diamond tool—that is, it will form-grind it to the correct shape.

The motion traverses the worm past the wheel ; the return is rapid, and on it the wheel does not cut. If the worm has more than one start, it is automatically indexed round between the strokes, the actual stroke set being longer than the length of the worm so as to allow time for this. Before actually starting the grinding the wheel is raised a little from its ultimate position, and gradually fed up to it as the grinding proceeds. By adopting this method of truing, no great difficulty occurs in setting the diamond so as to true the wheel correctly, though the truing itself requires considerable time and care.

Complex operations on a wheel whose shape is at best temporary are difficult to enforce in a shop, and how this ingeniously conceived method of truing fares in practice I cannot say, but theoretically it deserves success.

The same machine serves to sharpen hobs in the same manner, except that here the feed is put on by giving the hob a slight extra rotation, without simultaneous axial motion, which feeds its cutting face into the wheel face, previously trued in the manner just described.

The machine illustrated grinds worms up to 12 inches diameter by 18 inches long, and takes a wheel up to 7 inches diameter. It is equipped for wet grinding, but only the delivery pipe and nozzle are visible (at X) in the view shown.

The employment of 'form' grinding as a manufacturing process will increase, as the wheels are employed efficiently and the machines are of simple construction. The chief essential is that the wheel should be large in diameter compared with the length of work surface ground; the grade of wheel should be rather harder than would be used for similar work in regular machine grinding. In some manufacturing, wheels with faces up to 12 feet in width are used, a small reciprocating motion being employed to keep the wheel face straight and to reduce scratch marks.

Some other forms containing 'generating' lines may be produced by traversing the wheel over the work and retaining a width of contact, but these forms are not useful in engineering.

Cam Grinding.—With the employment of hardened cams for high speed work, such as petrol engines, jigs and machines have been designed for grinding them so as to secure the advantages of the resulting accuracy. Small cams, whether separate or integral with the shaft, can be ground by means of swinging fixtures in a Plain or Universal Grinder. For cams ground on the camshaft, the swinging part must take the form of a small bed carrying a tailstock so as to accommodate various lengths of shaft. The swinging motion must be derived from the rotation by means of a master cam. A similar arrangement is sometimes used for grinding reamers with a convex backing off.

For larger cams special machines are desirable; one such by Messrs. The Churchill Machine Tool Co. is shown in Fig. 177. The cam spindle is here carried on a cross slide, and its movement to and from the wheel is controlled by the master cam, carried on the cam spindle close to the cam which is being ground, and which is kept in contact with a roller by means of a weight acting on it through a pinion and rack. The roller is carried on a lower cross slide, which is slowly fed towards the wheel by a mechanism similar to that of a Plain

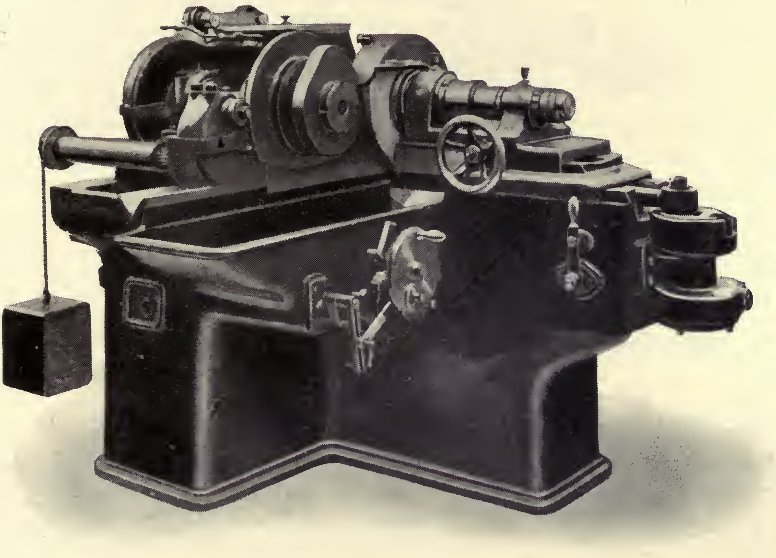


FIG. 177.—CAM GRINDER—CHURCHILL

Grinder, the feed taking place at each oscillation of the upper cross slide. The wheel has a traverse motion over the face of the cam by means of an adjustable crank motion, and has a quick hand motion for withdrawing the wheel from the work.

In thus grinding a cam by means of a disc wheel the precise shape of the cam is dependent on the size of the wheel, the cams ground by the machine having a slightly different shape as the wheel wears down. If the cam has a form such that the difference becomes important, the diameter of the wheel used should be kept between certain limits. This difficulty can be got over by using a face wheel, which is equivalent to a disc wheel of infinite radius as regards this purpose. However, as the errors involved are usually insignificant, and the surface produced by the disc wheel is superior, cams are usually ground

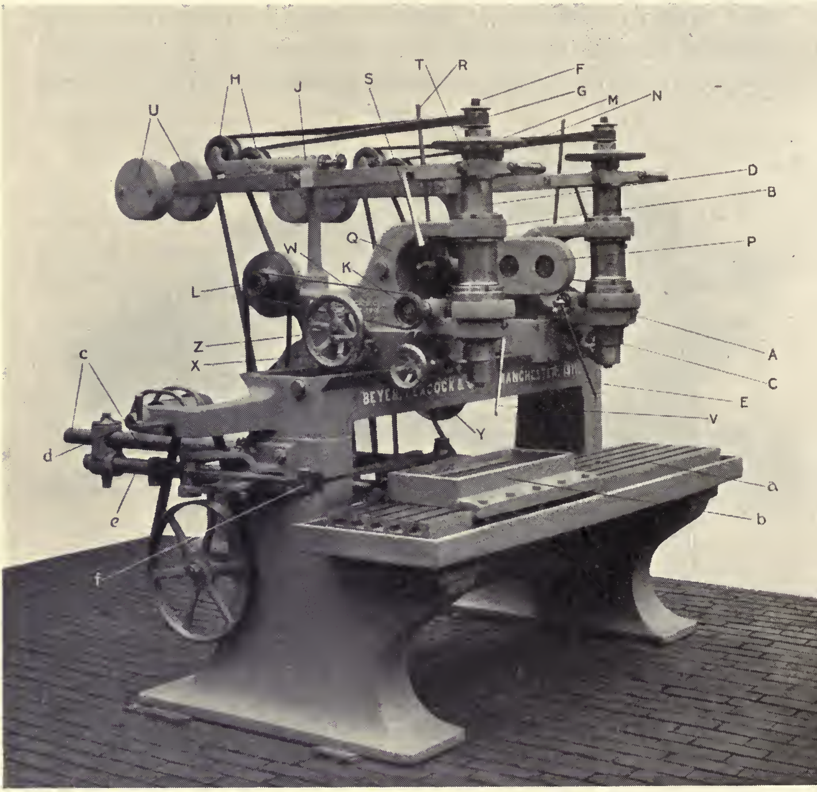


Fig. 178.—Link and Hole Grinding Machine—Beyer, Peacock & Co.

by this method. If the edge of the cam is hollow at any point, a face wheel could not be used, and a limit is at the same time set on the diameter of the disc wheel which it is possible to use.

Link Grinding.—The grinding of links for locomotives has been the regular practice for many years, and in Fig. 178 is shown a machine built by Messrs. Beyer, Peacock & Co., Ltd., for this purpose. The machine illustrated is a double headed combination link and hole grinder, and for the latter purpose the cylinder grinder method of page 247, which was first brought out—in 1887—by this firm, is employed.

Here A is the main spindle, revolving in bearings at B and C, and carries within it a sliding spindle D, the axial movement of which traverses the wheel through the work. The spindle D is bored eccentrically for the feed-adjustment spindle E, which in turn is bored eccentrically for the wheel spindle F. This is driven by a belt running over the idler pulleys H, which are forced to maintain the tension on the belt by a spring in the case J. The main spindle A is simultaneously driven by a worm and worm wheel, the worm pulley K being belt-driven from the pulley L. At M is the hand wheel for adjusting the radial position and cut of the grinding wheel, which is done while the spindles are in motion through the differential gears seen at N. The vertical reciprocating motion of the spindle is obtained through elliptical gears in the case P, which drive a slotted disc Q, from which the motion is transmitted by the connecting rod R. By means of the handle S, this can be locked to the lever T, which moves the spindle by a collar connection, and also balances it by the weights U. The lever T can also be operated by the handle at its front end. At V is the water supply. The whole of this mechanism is carried on the head W, which is fitted to slide in the base X, and can be adjusted to and fro in it by means of the wheel Y, which operates the screw through a worm and worm wheel. The whole can be adjusted on the longitudinal slide of the machine by means of the hand wheel Z, so that the two heads can be adjusted to any points of the work, which is carried on the table *a* in front of the machine. Holes are ground in the same manner as in a cylinder grinder, but for links the wheel spindle is not carried round, the link being held in and moved by the frame *b*. For straight links this slides on the table *a*, and is guided by the gibs shown in position; for curved links it is fastened to, and its motion thus controlled by the radius bar *c*, which is pivoted at an adjustable point *d* carried on a fixed bar *e* at the rear of the machine. The radius bar is removed for grinding straight, and the gibs, for curved links. The reciprocating motion is given by the linkage *f*, which is driven through elliptical gears, so that the important advantage of a nearly uniform motion is obtained.

Grinders with more than two Wheel Spindles.—It is sometimes necessary that a face should be square with a hole, and it is then convenient to be able to grind them at one setting. This can easily be done on some Universal cutter grinders which

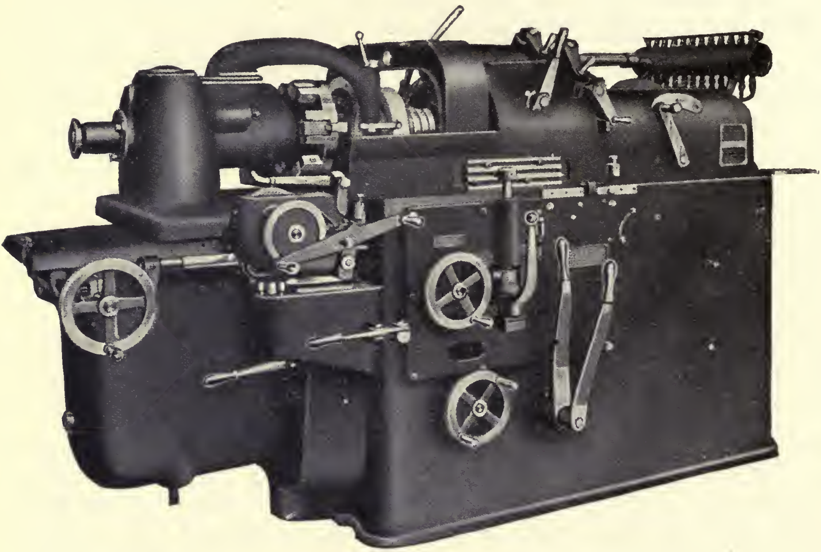


Fig. 179.—Bryant Chucking Grinder

are equipped for circular grinding, and some machines have been placed on the market specifically for the purpose. If a machine be fitted with more grinding spindles, and suitable stops or throw-outs, more complicated work can be duplicated at one setting, and the machine corresponds more or less to a capstan lathe.

In Fig. 179 is shown the Bryant Chucking Grinder, in which three parallel spindles are carried in sleeves, which can be adjusted axially to their working positions by means of the three handles seen at the right near the top of the machine; the lever seen near the handles locks the sleeves in the arranged positions. The whole head carrying these wheel sleeves traverses, the positions of the reverse being controlled by the dogs on the front. The work head is carried on a cross slide which has hand and power feed, and the whole slide is arranged to swing about a vertical shaft for taper grinding; the work spindle is driven by a belt from a drum carried in this swinging part and driven through bevels from a shaft in the main body. The spindles carry 10-inch, 6-inch cup and $3\frac{1}{2}$-inch wheels respectively, and smaller internal work can be provided for; the traverses vary from $\frac{1}{16}$ inch to $\frac{5}{8}$ inch per revolution of the work.

The Churchill Three-Spindle Grinder, shown in Fig. 180, carries three spindles on a capstan head, by the rotation of which the spindles—usually carrying wheels for external, face, and internal work—can be brought into their working positions. The capstan is mounted in the place of the wheel head of a Universal Grinder, and not only chuck work but work between the centres can be done. The spindles are driven from overhead by a belt, which is shifted from spindle to spindle as needed.

The capstan type has been employed for as many as six spindles, an idler pulley being mounted in its centre and the belt transferred on to it while the capstan is being revolved. That these machines have been placed on the market is an indication of the trend of development and trial; whether they will hold a permanent place in manufacturing establishments is an open question. It is seldom that it is necessary that a piece should be so accurate in its various surfaces as to necessitate grinding them all at one setting; parallel surfaces and holes true with them can be ground within very close limits by the aid of magnetic chucks, and as a general rule it is cheaper to do work in two operations on simpler machines.

A machine by the Norton Grinding Machine Company for grinding the outside of ball races in quantity is shown in Fig. 181; it is fitted with an automatic work head, into which the work is fed down a slide. The wheel is driven from overhead in the usual manner, and the other motions are driven from the pulley A. To the left this drives a train of gears in the case B and so the shaft C, which at the far end

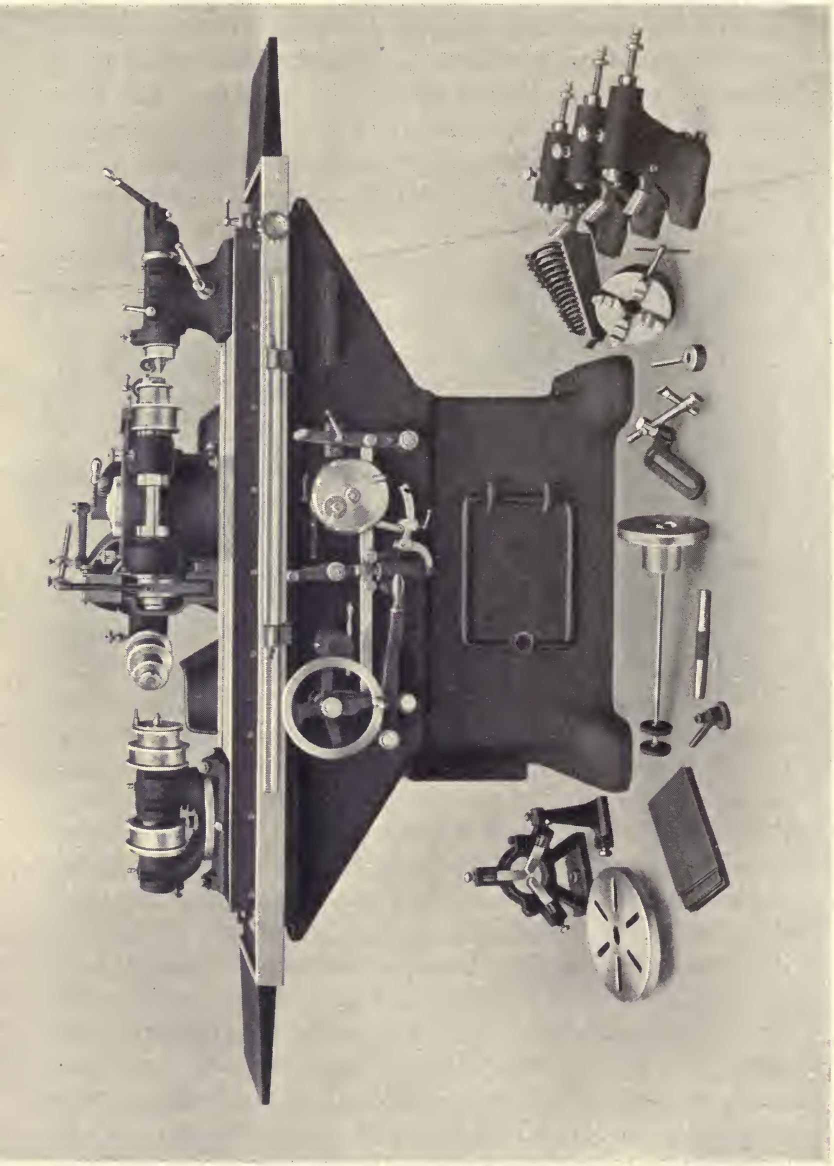


Fig. 180.—Three Spindle Manufacturing Grinder—Churchill

D drives a cross shaft connected with the traversing mechanism, and at its centre has a cam enclosed in the case E, which operates a lever pivoted at F, and so the wheel head. From A the motion is transmitted to the right through bevels to the inclined shaft GG, and so through bevels at H to the work head, the speeds of which are obtained through a small gear box, and the automatic feed motion through a cam. The

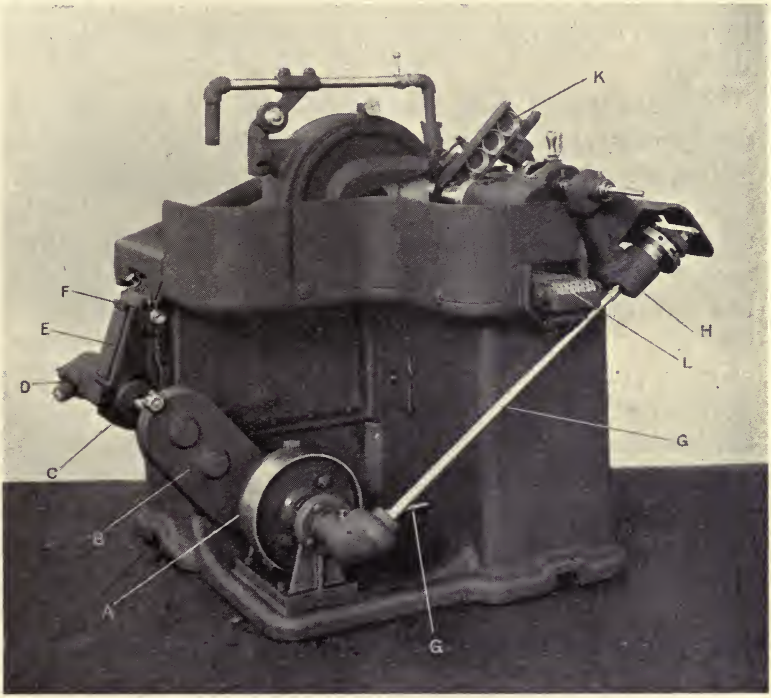


Fig. 181.—Norton Automatic Grinder

work is delivered to the machine by the slide K, and is removed after grinding by the travelling chains L. Mechanism for giving the cycle of motion to the wheel head is shown in Fig. 182, where the cam Z in the case E and the pivot F of the lever Y are lettered to correspond with Fig. 181. The wheel head P is moved by the nut Q, which is fitted with oil retaining caps R, R′. The screw S receives a reciprocating motion, giving the automatic movement of the wheel head for each piece of work, from the rod T, which is moved by the lever Y. This receives its motion from the cam Z, and its forward motion is rigorously limited by a stop screw. To compensate for the wear of the wheel, or to make other adjustments, the screw S is rotated by its tailshaft T′ in the usual way; by these means a double cross slide is avoided. The rotation of the screw is given by hand through the gears U, U′ from the handle V, and the usual fine adjustment is fitted by means of the gear W, pinion W′ with division plate and latch X.

Grinding Shafts and Rods, &c.—Ordinary shafting and slender rods, already turned or drawn fairly close to size, can be best ground by aid of a steady fixed relatively to the wheel, as described in Chapter V. A machine, suitable for rods up to $\frac{3}{4}$ inch diameter, is shown in Fig. 183. This machine was constructed by Mr. Hans Renold, and both the wheel and feeds are driven by chains. The chain to the wheel spindle is of the ‘ silent ’ type, 2 inches wide, and the chain wheel 4 inches in diameter; the wheel is 16 inches diameter and 2 inches face. The work is rotated and simultaneously fed forward by the head at the left-hand end of the machine, passes through the steady and is ground, and then is received by the head on the right-hand end of the machine, which continues to effect the rotation and traverse after the rear end of the work has left the other head. This motion is driven by the chain B, which drives a shaft in the body of the machine; from this the chains C and D run to sprockets on the work heads. The four heads E, F, G, and H are of similar construction, a worm on the sprocket shaft driving a worm wheel, upon the shaft of which a convex disc, J, is mounted. The work is frictionally driven by two opposed discs J and K, the heads carrying them being vertically adjustable so as to give a variation of the ratio of traverse to rotation. In other machines the combined rotation and traverse is given by the mechanisms used in the roller feeds of capstan lathes. The rods pass through the tube L to the central dies N, and are finally delivered from the second heads to the receiving channel M. The dies are controlled by the screws at N, and the wheel head is fed up by the hand wheel P

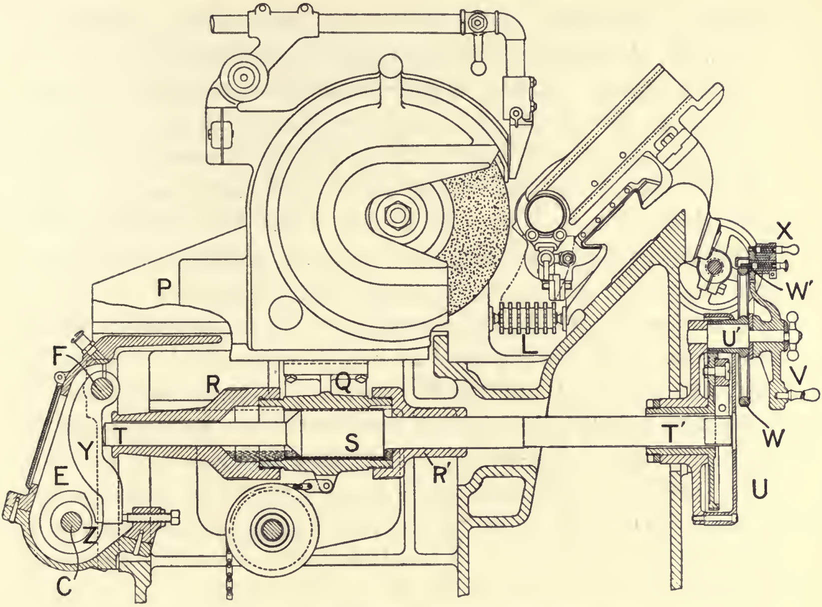


Fig. 182.—Norton Automatic Grinder

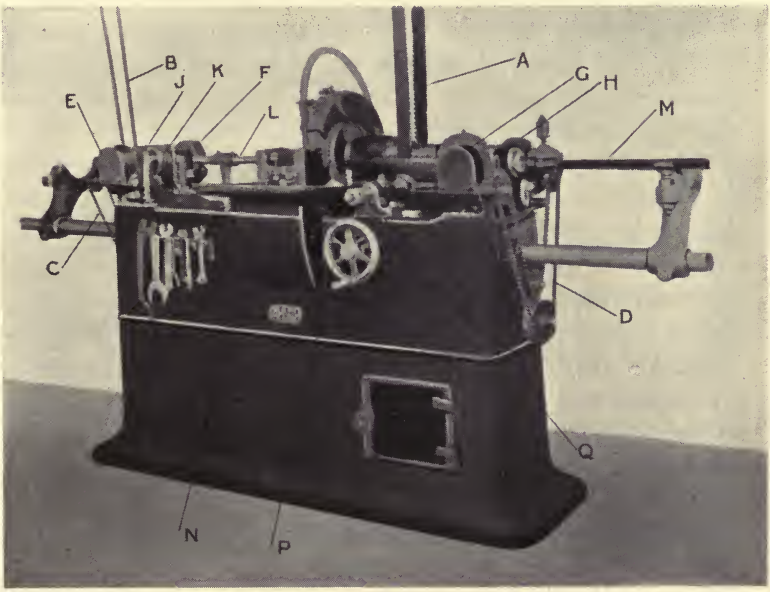


Fig. 183.—Rod Grinder—Hans Renold

until an abutment on it meets the end of the micrometer screw Q, which is adjusted as the wheel wears.

The steady bears for a considerable portion of the circumference on the work, and must be adjusted so as to support the work on both sides of the wheel without appreciable shake, receiving the unground work on the left, and passing it on the right after it is ground to size. The wheel has a coarse grit on the left hand side for roughing out, and a fine grit on the right side so as to secure a good finish.

If more than 0·002 inch has to be removed—and this is about the accuracy to be expected in bright drawn steel—the shafts have to be passed through the machine twice to secure roundness and accuracy of size. I have examined bars ground on machines of several makes (in addition to my own) and find that 0·0005 inch is a limit, both as regards roundness and gauge size, which can be obtained without difficulty, while 0·00025 inch or less can be attained. The surface produced is seldom as good as that of commercial plain grinding, but a high rate of output is aimed at. Samples of work from the machine illustrated bear no evidence that the wheel was driven by a chain.

Steel balls are ground by an adaptation of the old process for making 'marbles.' The rough pieces are placed in a vee groove in a rotating face plate and operated on by a face wheel on a parallel, but not concentric spindle. The action of this, while it grinds the top off a piece, turns it round in the groove, and so presents a fresh point to be ground, so that the nearly spherical balls twist over continually as they run round the vee groove and continually become more nearly spherical. Steel balls are nearly spherical after hardening, and in their case the face wheel and the ball face plate are co-axial; they rotate in opposite directions, and the balls are caused to twist so as to present other portions of their surface to the wheel by the action of a stationary edge bearing on them, or the groove is spiral, and after travelling along it the balls are transferred by passages within the grooved plate to the starting point, and can be examined when on the way. After grinding the balls are polished in a tumbling barrel. Rollers are finished in a similar manner.

Machines and attachments are on the market for several special purposes, such as the automatic sharpening of band and large circular saws, the truing-up of lathe centres in position, &c., but except as examples of ingenious mechanism these present no special features. The machines described above have been selected as illustrating methods of grinding, or as suggestive of development.

Jigs and Fittings.—In the design of special grinding equipment and jigs, in addition to the usual considerations, those introduced by the accuracy aimed at and by the process of grinding itself must be borne in mind. The work must not be held in a manner liable to spring it, and usually very little hold is necessary ; split and magnetic chucks are often suitable. In important work the geometrical effect of errors in the alignments and fitting should be reckoned out. All connections and movements should be as direct as possible, and backlash taken out wherever possible by springs or weights—in quickly acting mechanism the former are to be preferred on account of the lesser inertia effects. Overhangs should be reduced to a minimum, this often making the difference between a fine and a poor finish. The effect of the grit is to be considered, and protection provided to parts when necessary. All belts, electrical conductors, and switches must be located well away from the water-supply and spray. If dry grinding is adopted in a manufacturing process, dust extraction must be provided for. In most of the machines illustrated the wheel and work are brought into contact gently, and in automatic manufacturing operations this should always be aimed at, the feed being slowed at the moment ; when this is inconvenient an elastic wheel should be used, or the disc grinding method adopted.

CHAPTER XII

POLISHING AND LAPPING

Polishing.—Polishing consists of grinding with a buff, mop, or belt, charged with abrasive powder; the elasticity of the material carrying the abrasive enables it to follow any small irregularities of the surface of the work, so that a true shape is not produced, but any surface projections and roughnesses are smoothed off.

The kind of powder used varies with the material and class of work; fine emery for coarse work is followed by crocus powder, rouge, or lime as the work's surface becomes finer. The particles of rouge, rotten stone, and Vienna lime vary from a twenty-fifth to a hundredth of one-thousandth of an inch, or less, in size.

Whatever the grade of work, high spindle speed and adequate power are necessary to rapid economic production; high spindle speed is also necessary, otherwise mops wear away quickly, and the speed should be increased as the mop wears down, or the mop should be changed on to another machine having a faster-running spindle. A circumferential speed of 5000 to 8000 feet per minute is usually suitable. The cost of the power (energy) used represents a considerable item in the total cost.

Polishing Lathes.—The total energy consists in that used in actually doing the polishing, and that absorbed by the friction at the bearings, and since the spindle often runs continuously under a rather tight belt, whether it is actually being used or not, the latter portion is high. As the work is not highly accurate, and it is not necessary that the spindle should fit closely in its bearings, these are usually unduly neglected, though the cost of reasonable attention is well repaid in the power saved. The men, machines, and belts usually work under hard conditions, and it is only recently that dust extractors have come into general use; if a machine is to be run under such conditions it must be simple and cheap, and this is the reason why the bearings of most polishing spindles are not provided with such effective lubricating and dust-proofing arrangements as are really advisable and economic. The manner in which oil acts in a running bearing is well known, but it may be briefly recalled here. The diameters of the journal and bearing differ by a certain amount, and the space is occupied by a continuously replaced film of oil. If the surfaces are merely greasy the friction is many times greater than if the oil film is perfect; in fact, should the oil film be broken from any cause the friction instantly increases to a very considerable amount. Hence for such bearings a well-arranged lubricating system would soon save its cost in the power saved.

At starting the oil film is not ready, and the starting effort, or torque, in a properly lubricated bearing is considerable, especially if the fit is close; when, however, the oil film has formed, the effort necessary to keep the shaft turning immediately drops, and it decreases further as the oil gets suitably warm and so thinner. The power required to run a shaft must not be judged from the starting effort. Polishing heads are usually merely fitted with a Stauffer lubricator on each bearing, while for power economy they should have a supply of oil introduced at the right point of the bearing, and be thoroughly dust-proofed.

Since good ball bearings have become commercial articles, they have been fitted to polishing heads in order to save this power loss; they must be very perfectly dust-proofed, but have the great advantage of requiring practically no attention. The power taken is less than for a spindle with 'oil bath' lubrication, but not so much that it seriously affects the power bill; it is of course very much less than for a spindle which is merely greasy.

Small polishing spindles are often simply spindles with pointed ends, supported by wooden blocks forced against the points; for freehand grinding the same cheap construction is advantageous where wheels of different diameters must be used in succession, as the spindle with its pulley and wheel in position can easily be changed.

Belt Polishing Machines.—Where it is desired to preserve sharp corners on the work, and in some other cases, a running belt charged with abrasive is more convenient than a polishing spindle. Such a machine, by the London Emery Works Co., is shown in Fig. 184, and consists merely of an endless belt, charged with abrasive, and driven by power from the pulley A. At B is a necessary tightening pulley. The belt is usually supported at the place C where the work is applied to it. Three pulleys are usual, but not necessary—the driver and a tension pulley are sufficient; the grinding can be done at or near the latter, which should be covered with rubber to make a better cushion.

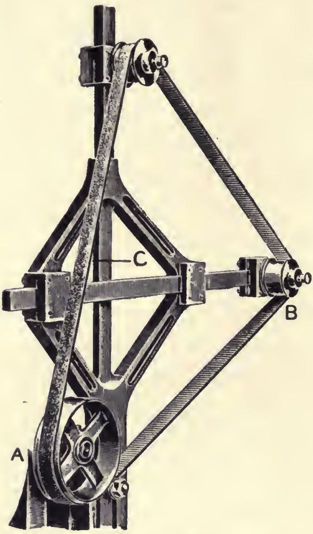


FIG. 184.—BELT POLISHING MACHINE—LONDON EMERY WORKS CO.

Belt polishing machines are also arranged with a flat support at C for polishing up flat work (such as the sides of hexagon nuts), but are not so efficient for this purpose as the disc grinders previously described. The speed of the belt cannot be so high as that of a steel disc towards its edge, and the under-side of the belt rubs along the support at C, causing friction.

Polishing is a cheap process, and can be sometimes used to displace machinery operations. Owing to the dust it can only be commercially conducted in a special department, which should be fitted with adequate means for extracting the dust as it is formed.

The Surface Produced.—The surface produced by polishing is very bright and to a high degree smooth, but very close examination shows that, where the material polished consists of parts of different hardness—such for instance as ferrite (Fe) and cementite (Fe_3C) in steel—the softer parts are rubbed away and the harder ones stand out. In some cases the softer parts are spread over the surface to a certain extent, and this helps to give the uniformly bright appearance; this action depends upon the particular polishing powder used.

Burnishing.—A very bright smooth finish is produced by burnishing, in which the small irregularities are pressed or rolled flat by a hard polished tool, usually of hardened tool steel or agate. The work surface is hardened by the process, but burnishing is seldom used in engineering work, although the effect is produced incidentally—e.g. by roller steadies.

Lapping.—In grinding the abrasive particles are carried by being cemented together; in polishing they are carried by a soft mop or leather, but they may be carried by being embedded in a piece of metal, which is termed a lap, and the process of using it is termed lapping.

The lap may be charged with abrasive powder so fine that it would be impossible to make it into an effective wheel, so that lapping is used to give a fine surface to work already ground, as, for example, the smoothing of the edge of a tool. In certain cases, by particular adaptation, it can be used also to improve the geometrical shape, as in the cases of standard gauges.

As generally the process is used on work previously ground, the abrasive powders need to be very uniform, so as not themselves to cause scratches in the work. Fine alundum, carborundum, emery, crocus, rouge, alumina, and diamond dust are most frequently used.

Grading Fine Abrasives.—The best method of separating fine particles of a substance according to their size is to mix them thoroughly with a liquid and then allow it to stand. The larger particles fall to the bottom first, and the liquid then contains in suspension no particles above a certain size. It is carefully poured off and the process repeated, so that the original powder can be separated into a number of lots of particles, each lot being nearly of the same size. They are denominated as powders of so long (e.g. ten minutes) suspension in the liquid. This is very indefinite, as the distance the particles have to fall in the fluid is a factor. Various oils and paraffin are suitable fluids. It is this very slow falling of very fine particles which keeps a cloud of fine water particles suspended in air. The rate of falling of a sphere in a particular fluid can be calculated mathematically, the theory having been worked out by Prof. Stokes, so that the size of the particles can be determined should it be desired to know them for any particular object. This principle of separation was used by M. Perrin to obtain quantities of similar very fine particles for his microscopic work on the Brownian Movement, and in this case the rate of separation of the excessively minute particles was increased by using centrifugal force in the same manner as a centrifugal separator hastens the separation of cream and milk, which takes place so slowly by gravity. It may be pointed out that the particles will separate out of the emulsion more quickly if it is placed in shallow dishes, as the particles have not so far to fall.

Charging Laps.—The lap or piece of metal carrying the powder is charged, or has the powder embedded into it, by the aid of a piece of much harder material, usually hard steel or stone, such as agate. The hard steel has the advantage that it can be formed into a very true roller. When a particle comes between the hard steel and the softer lap, it is forced into the latter and remains there, and for this reason the material of the lap must be softer than the work lapped, otherwise particles will leave the lap and become fixed in the work. The arbors of old clocks will be found to have worn by dust becoming charged into the bearing, and so cutting the steel arbor, which therefore wears although it is so much harder than the (brass) bearing.

For the best work the particles are to be embedded in the lap, and those not embedded removed before the lap is used. Quicker work is done by feeding fresh abrasive to the lap, but at the expense of quality of the result.

Lead, various white metal alloys, copper, brass, cast iron, mild steel, and glass are all used as laps. The softer the material of the lap the larger the particles of abrasive which it can be charged with, and the more rapidly it will cut. The quality of the work produced on the other hand improves with the hardness of the lap and the fineness of the powder.

Lapping Machines for Flat Work.—When a wheel lap—whether the side or face is to be used—is made, it must be got very true before being charged, as otherwise the wheel will not touch the work continuously, for the particles stand out from the surface so minute a distance. The wheel therefore must be made true upon the spindle while it is running, and charged with abrasive, and used without being removed from the spindle; otherwise the necessary truth is lost. The material employed in wheel laps is cast iron or copper. In Fig. 185 is shown a vertical spindle machine in which the flat side of the wheel is used, and by its side the roller used for charging the disc. Lapping of this nature partakes of the nature of grinding, more especially in a case such as that of the grinding of small holes by means of a mild steel lap charged with emery (see page 41), in which case the movement of the work is entirely mechanically guided. It merely consists in substituting a wheel charged with abrasive for one composed of abrasive held together by bond.

Fig. 185.—Vertical Lapping Machine—Lud. Loewe

In what is regarded as more properly lapping, as opposed to grinding, the work is in contact with the lap over a large portion of its area—such are the cases of lapping end gauges on the flat ends and plug gauges on the cylindrical surface. This area, over which the abrasion proceeds, makes this lapping much quicker than where the nearly-line-contact of a wheel edge is used to produce work of so fine a quality.

Principles of Lapping.—The object of lapping in these cases is, not only to improve the quality of the surface, but to attain a higher degree of geometrical accuracy than that possible in grinding, and the accuracy attainable stands to that of grinding much as the accuracy of grinding stands to that of turning. For example, however well a bar may be turned, if it is placed in a grinding machine and a light cut passed over it, numerous defects of surface and truth at once become apparent; in the same way, if a carefully ground part be lapped, similar defects of a much smaller amount immediately make themselves apparent. The defects of the grinding of round parts which have to slide, such as drilling machine quills and milling machine arms, are soon shown up by the rubbing action in sliding; usually a broad screw thread appears round such parts, the effect of the traverse of a very slightly rounded wheel. The depth of such a thread is hardly measurable, but in certain lights it shows up conspicuously. I have found that very striking traverse marks are lapped out when less than $\frac{1}{10000}$ inch has been removed from the work's diameter, so that the depth of such marks is less than 0·00005 inch.

Allowance for Lapping.—We hence see that in grinding work for lapping sufficient must be left on so that the following process will take out the marks of grinding—just as the lowest allowance in turning for grinding is that at which the turning marks will clean out. As lapping is a very slow process, the least possible amount should be left on, and the grinding done very carefully. The amount necessary is from one to two ten-thousandths of an inch for work up to 3 inches diameter.

Again, in lapping, successive laps may frequently profitably be used charged with finer and finer powders, so that even the worst scratches left by one will be removed by the next, and the surface continually improved.

The surfaces which are best adapted to lapping are those in which a considerable portion of the surface of the work keeps in contact with the lap, as they move relatively to one another—such as flat surfaces or screw threads.

That the results of lapping excel those of grinding as regards accuracy is due to the errors caused in the latter process by the oil films and by vibration. In lapping one surface acts directly upon another, and the effect of the oil film round the grinding-wheel spindle is eliminated; if, however, the lap does not keep contact with the work, errors (such as the ends of a plug gauge being small) creep in.

Surfaces which can be Lapped.—When two surfaces are in contact, one element (that is a small portion) of one may move upon the other in one or more directions, keeping the contact, according to the shape of the parts—that is, there are two 'degrees of freedom' possible in the movement of the surface, but these may be reduced to one, or to none, by the nature of the surfaces. The last case, where the surfaces are not able to move along one another, does not interest us; in the first case, which includes flat and spherical surfaces, and circular cylinders (plug gauges), the surfaces can move in two directions on one another, without losing the surface contact. For example, a plug gauge can turn round in a ring gauge and slide to and fro at the same time; or one flat surface can slide on another and turn on it simultaneously. These are the kind of surfaces which profit most by lapping, and their truth can be improved in both ways by the process. In the second class, to which belong conical surfaces and screw threads, the motion of one surface over the other is possible in only one way; the conical surfaces, for example, can only be turned round, but cannot be moved axially without separation. Lapping in these cases only improves the corresponding truth of the parts—that is to say, the lapping of a conical surface improves its roundness, but not the straightness or angle of its taper, and lapping a screw improves the uniformity of its pitch and its freedom from drunkenness, but it does not improve the shape of the thread—nor can it make the pitch nearer to any arbitrary standard: it merely averages the errors.

Lapping Spherical and Flat Surfaces.—Returning to our first case, the lapping of flat surfaces such as the ends of length gauges, of micrometer screws, &c. The flat surface is a special case of a spherical surface in which the curvature is zero. If a spherical bowl is placed inside another and touches it all over, the first can be turned round a vertical axis, keeping its contact complete, and also tilted sideways—that is, turned round a horizontal axis—also keeping its contact, except just at the edges. If the first bowl be the work and the second the lap, moving them together will gradually wear the first bowl down until it becomes a uniform fit in the second—that is, it will have a spherical shape. The second bowl or lap will not wear much as the abrasive is embedded in it; its shape will, however, gradually become more spherical, as the higher parts will do their work first. In ' grinding ' lenses this is the process adopted; the lenses are kept continuously in motion while pressed against a spherical lap, which is convex for the concave lenses and *vice versa,* and so the lenses are gradually lapped to the desired radius.

As the radius becomes larger and larger, the curvature of the lens or bowl becomes shallower and shallower, and finally it becomes a flat plane. Still further alteration of curvature makes the work concave, and the lap will be convex. Such lapping does not essentially make for flatness: it makes for a spherical fit, and something further is necessary to secure flatness. This is similar to what occurs in originating surface plates; two scraped together must be spherical, but the simultaneous working of a third is necessary to secure flatness. To lap a surface flat it is best to make use of previously prepared flat surfaces as a guide; one surface moving on the other will keep parallel to itself, and a body carried on it can therefore be lapped flat by the motion. A convenient jig for lapping the ends of rods flat is shown in Fig. 186. The part A to be lapped—here supposed cylindrical and a good fit in the hole for its reception—is held in the part B, which moves on the part C, which it touches over the annular area D. The central part E of the body C is charged as a lap, and by rubbing the end of A on it in the motion the end of A can be lapped flat. If the two ends of A are to be parallel, the axis of the hole in which A fits must be accurately perpendicular to the flat surface D. This can be secured by grinding the surface D when the part B is on a true mandril. If the piece A which is to be lapped is square, the hole in B must be replaced by two flat surfaces, which are each made square with the surface D.

In this case of lapping spherical and flat surfaces, there is no question of fit of lap to work; the surface of the work lies in contact with the particles embedded in the lap, and is pressed to it by a suitable force. Free particles of abrasive matter should be washed off before lapping, so as not to roll loosely about between the two surfaces. As the material of the work is removed in very minute portions it is important in all cases that the surface should be machined — usually ground —

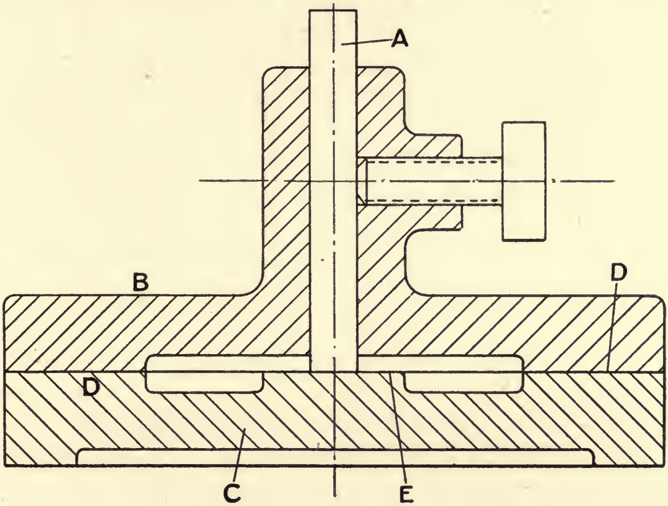


FIG. 186.—LAPPING THE ENDS OF RODS

closely to shape, with as little as possible left on to be removed by lapping, before lapping is commenced.

Plate glass is now produced so very nearly flat and parallel that it can be used, when charged, as a lap for flat surfaces. It has the advantage that its truth of flatness can be easily tested optically. If two pieces of glass are squeezed together, bands of colour are seen, formed by the interference of the reflected light at the surfaces which are placed together. Actually there is a thin film between them, so that the reflexions at the very near surfaces interfere. If the bands are uniform and wide, the surfaces fit uniformly, so that if three fit one another in this manner they are flat. Such glass plate, charged with flour abrasive, forms a convenient means of rectifying the ends of micrometer screws which are worn ; the screw is set up to the plate so as to hold it very lightly against the anvil, and the micrometer is then moved to and fro.

Lapping Cylindrical Work.—A lap suitable for parallel circular work such as bearings and plug gauges is shown in Fig. 187. It is important to make them very carefully, otherwise only a small portion of the charged surface will be actually lapping, and the time taken will be increased. The length

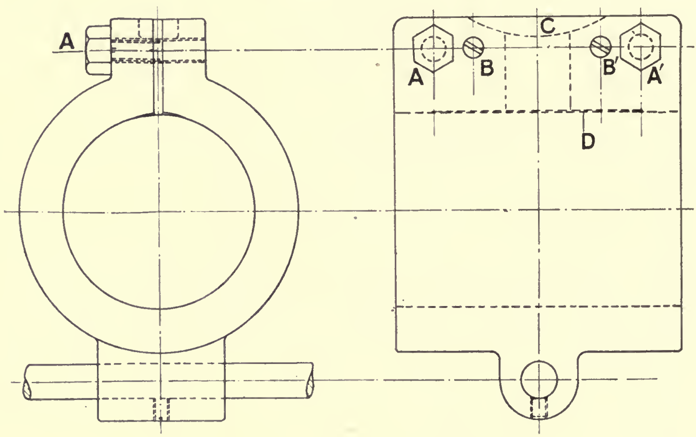


Fig. 187.—Lap for External Work

of the lap should be about equal to that of the work. In making, it should be bored, split, and fitted up ; then the lap should be compressed a little by the screws A, A′, and ground to size when so compressed, and a slight relief given at D. In use the lap must be set up to the work by means of the screws A, A′, so that there is no play, and the screws B, B′ are then used to lock the position. If there is play the lap will cant a little as it moves over the work, and tend to lap it small at the ends. Plenty of oil must be used ; a recess is provided at C to receive it, and soft wood strips at the outer part of the slot to prevent its escape there. The lap must be continually moved lengthways to and fro, as the work rotates inside it. It should at first have a longitudinal movement more than its length, and this amount should be reduced as the work progresses. At frequent intervals it should be reversed, end for end, on the work.

For purposes requiring less accuracy a half-lap is sufficient, and it can be applied very easily.

Much inside lapping is done in manufacturing—not for the perfecting of ground work, but as the cheapest way to produce the work. Small holes in hardened steel parts when contracted a little in hardening are quickly lapped to size, while grinding them is difficult on account of the small diameter. Carriage axle boxes of small diameter are also commonly lapped, as, being about 1 inch diameter by 6 inches long, grinding is slow. They are made of cast iron, chilled on the inside, which is

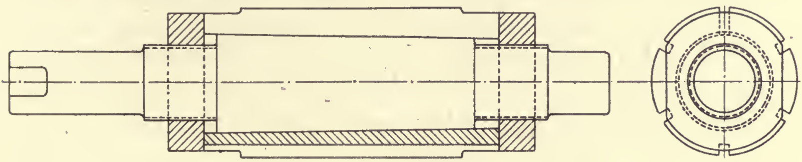


FIG. 188.—LAP FOR INTERNAL WORK

taper so that the chill can be easily knocked out. The hole needs to be cleared up and made parallel. For this and similar classes of work lead laps are the best; they are quickly made by casting the lead round a square notched bar which is centred at the ends, so that the cast lead can be turned to size, and they take a charge of rather coarse emery easily. For very accurate work they are not suitable, as they are very soft, and so do not keep their shape; neither can they be expanded so as to fit the hole closely, and so prevent bell-mouthing. A suitable lap for such work is shown in Fig. 188. The taper mandril should be ground and the split lap, which is preferably keyed, ground in position on the mandril. The mandril taper should be about one per cent.

Accuracy Attainable.—As regards the accuracy of the process when at its best, it may be noted that standard plug gauges by first-rate makers have errors of about $\frac{1}{50000}$ of an inch, while the flat gauges made by Johansson and others are generally of a higher accuracy still. These are actual standard length dimensions; the accuracy of the surface produced to itself is higher. In order to ascertain the cause of the force between flat gauges when wrung together for building up a required length (see page 406), Mr. Budgett lapped the surfaces he experimented with true within the one-millionth of an inch, as tested with optical proof planes. He proved that the adherence was almost entirely due to very fine fluid films between the surfaces of the gauges.

Internal limit gauges can be ground within $\frac{1}{10000}$ inch, but if the conveniences are at hand it is well to lap off the last one or two ten-thousandths, at any rate at the go-in end, as the life of the gauge is so much increased by it—there being more material close to the geometrical surface.

The size of a hole cannot well be measured except by the size of the plug which will go into it. A plug can be made so tight a fit in a ring that it can hardly be moved, and a reduction of a ten-thousandth of an inch makes it an easy fit. A reduction of half a thousandth of an inch makes the plug appear to be quite loose in the ring.

The object of lapping a screw is to correct errors of pitch and drunkenness by averaging them. For the finest work the same precautions must be taken as in lapping plug gauges. The lap must be collapsible and must be kept adjusted to the screw; its length should be about equal to that of the screw; it should have a movement at first of more than its length, and this should be reduced as time goes on, and it should frequently be turned end for end. This is very expensive, and can only be undertaken in particular cases; commercially, screws required to be accurate are lapped with less elaborate precautions, but with useful results. The sizing feed screws of the principal machines I used to make in Birmingham were lapped, which improved their action considerably. As regards the accuracy attainable, the screws used for ruling diffraction gratings present the most perfect results. A screw 9 inches long will rule a grating 6 inches long with lines spaced so accurately that none of them are a hundred thousandth of an inch out of position, so that all appreciable errors of pitch and drunkenness are lapped out of the screw. The mounting of such a screw introduces errors greater than those in the screw itself; and in the use of the ruled gratings, errors of a millionth of an inch in the spacing are perceptible, provided these errors are periodic. These screws are lapped in a bath of water kept at a constant temperature, and the action is arranged to be automatic, except changes such as reversing the nut.

This accuracy is far beyond what is needed in any commercial work, but it shows the capabilities of the process of lapping. In lapping for commercial work, tool-room or other, the progress made can easily be judged by the appearance of the work, the fine scratches of the grinding cut and other irregularities gradually disappearing, and the high parts becoming bright first. The lap must be kept a close fit to the work, so that there is no shake to produce inaccuracy. It is advisable to grind before lapping if it is possible, and to grind very carefully, leaving a good quality of surface, and an allowance of one to two ten-thousandths of an inch on hardened steel.

CHAPTER XIII

MEASURING AND ITS BASIS

The Basis of Measurement.—Modern grinding is essentially a process developed in response to the demand for increased precision in the manufacture of parts of machinery; its success is due to its meeting the requirements with such readiness as not to necessitate the employment of exceedingly highly skilled labour in its use. Apart from the machine, however, there is the simultaneous necessity of measuring the dimensions of the parts produced, both by the operator who produces them and by the viewer in checking them, and the fine limits necessary have led to the development and manufacture of tools and gauges specially suitable to such work.

Alternate Standards—the Yard and Metre.—The ultimate standards to which all measurements and gauges are referred are the British standard yard and the standard metre. The British standard yard is defined by Parliament to be the distance at 62°F. between the centres of the transverse lines on the gold plugs in a bronze bar 38 inches long by 1 inch square, kept in the Standards Office; and the metre is similarly defined as the distance at the melting point of ice between the ends of a platinum bar kept in the French Archives. Of each of these there are a number of very carefully made copies, and should either original be destroyed it would be replaced by means of these copies.

Both these standards are quite arbitrary; they are, however—which is essential in a standard—very definite and exact. There has always been a desire for a natural, ultimate unit of reference, as is evinced by the terms cubit (length of the forearm), foot, hand, and the familiar three barley-corns which once made an inch. These, however useful in the past, are all indefinite and variable, and hence likely to lead to disputes. The Royal Society took the matter up in the year 1742, and put forward a standard yard; a copy was made later by a Parliamentary Committee, and finally was made the legal standard in 1824 by an Act. At the passing of this Act, the question of adopting the length of a pendulum beating seconds was considered as a possible standard, but wisely rejected. The Houses of Parliament and the standard were destroyed by fire in 1834. The standard was then replaced from its copies, as was provided for in the Act.

Natural Standards.—Although the metre was intended to be a natural standard and to be the one ten-millionth part of a line (meridian) on the earth's surface, reaching from the pole to the equator, it is now, by law, the length of the bar previously mentioned. More accurate measurements of the length of the meridian have shown the former estimate to be appreciably in error, and in any case it would be a very difficult matter to compare any particular length with it practically. Sir John Herschel proposed to adopt the earth's polar axis as the fundamental unit of length, but like the meridian length this is slowly changing, and hence not suitable as a standard. Similar objections apply to the acceptance of the length of a 'seconds pendulum' as a standard; its length depends on gravity, and is very difficult to measure, and further involves another unit—that of time.

Perhaps, though it is so small, the most suitable natural standard would be the wave-length of light of a particular refrangibility (in air at a standard temperature and pressure), as this is intimately connected with ultimate molecular structure and the ether. Various measurements of the wave-length of light of different colours have been made by interference methods, and it is found that the wave-length varies from $H_2 = 3933$ to $A = 7604$ tenth metres ($\frac{1}{10^{10}}$ of a metre) from the red to the violet end of the spectrum. The light corresponding to D_1 (one of the bright yellow sodium lines) has a wave-length of 0·00005896156 inch, or rather more than $\frac{1}{20000}$ inch. It is true that there is a certain 'width' to a line in the spectrum, but the difference of wave-length corresponding to it is not one part in a million.

Comparisons of the standard metre and yard make the metre equal to 39·3709 inches, or nearly 3 feet $3\frac{3}{8}$ inches. Conversely one inch is equal to 2·539998 centimetres.

By special instruments — comparators—standard scales such as yards and metres can be compared with one another to a degree of accuracy of about the one hundred thousandth of an inch. When working to this degree of precision, the manner of support of the bar is important, and the effects of temperature variation would be very considerable if any appreciable range were allowed. The expansion of hard steel is about 0·00001045 of its length per degree centigrade, so that with even so small a temperature variation as that, a yard length of hardened steel would expand nearly four ten-thousandths of an inch. Hence comparisons of scales to the degree of accuracy desired are made in a room carefully kept at a constant temperature.

Subdivision of the Yard.—While the yard is the distance between the points on two exceedingly fine lines, workshop convenience usually calls for 'end measurements,' such as the diameter of a shaft, the thickness of a plate, or the distance between two shoulders. The production of original standard gauges of an accuracy of a few hundred thousandths of an inch is very difficult, and involves the use of measuring machines of the highest degree of accuracy. The standard yard or metre has first to be copied for the purpose and then subdivided into smaller portions. There is also involved the problem of making an accurate transference from the 'line' measurement of the standard yard—that is, the measurement of an ordinary scale—to the end measurement of the distance between the end surfaces of a flat gauge, or of the diameter of a plug gauge.

End and Line Measures.—Sir Joseph Whitworth subdivided the yard into feet and then into inches by the production of end measures which would interchange. The principle used to compare end and line measurements was to make two end measures alike, and scribe lines across them close to the centre parallel to the end surfaces. The equal end measures were placed together with a pair of ends in contact, and the distance between the lines gave a line measure; then the two end measures were placed with the other ends in contact: the distance between the lines gave a second line measure; the mean of these line measures gives the length of each of the end measures.

These end measures were square bars of hardened steel, such as is shown in the machine in Fig. 189, with the end surfaces reduced and carefully surfaced up parallel to one another. In making such gauges two sides are ground flat and at right angles; the piece is then held in a right-angled groove of a jig similar to that shown in Fig. 186, which has an end surface formed at right angles to the groove, and the gauge end is surfaced by rubbing on a charged lap whilst the motion is controlled by the end surface of the jig being on a surfaced plate. By reversing the gauge the second end is lapped parallel to the first.

The end measure gauges could be compared by the use of the Whitworth Measuring Machine, and by having a number of equal end measures which made up a known measure, then each of the smaller ones was known to be right to within the degree of accuracy of the measurements. This process is very tedious and costly.

Whitworth and other Measuring Machines.—In Fig. 189 is shown a Whitworth Measuring Machine designed for workshop use, and measuring to the ten-thousandth part of an inch. For the origination of his gauges Sir Joseph Whitworth constructed machines capable of indicating millionths of an inch; the principles involved were much the same, but the machine was more massive, and neither headstock was adjustable. Essentially machines for end measurement consist of: (1) two surfaces, A and B, Fig. 189, made very accurately parallel, and provided with mechanism for moving them to and from each other while keeping them parallel, (2) means of determining when these surfaces touch the piece to be measured, and (3) means of determining the distance they are then apart. In all regular measuring machines the two surfaces A and B are carried on bars in poppet heads C and D, one at least of which (here D) can be adjusted along the bed. For work to a ten-thousandth of an inch it is not necessary to have any special means of determining when the surfaces are in contact, but care must be taken to keep the pressure light and about the same for the different pieces measured ; beyond this a more refined method which will tend to eliminate personal error is necessary. In the Whitworth machines a 'feeler' E, which is a thin disc of metal with its sides surfaced parallel and a light cross handle, is placed between the flat A of the measuring machine and the

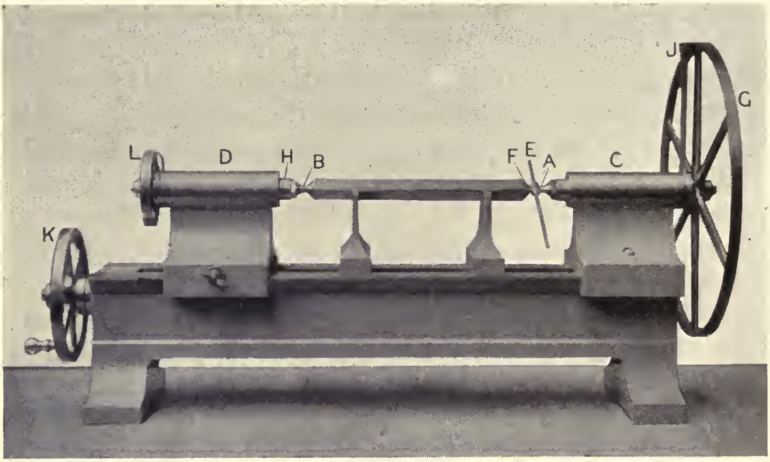


Fig. 189.—Whitworth Measuring Machine

flat surface F of the end gauge being measured. The surface A is adjusted by the wheel G until the feeler will just slide down by its own weight. This is a very sensitive arrangement, but is not easily used on cylindrical gauge work. To adapt this device for convenient use in measuring cylindrical gauges, Messrs. Pratt & Whitney carry a secondary surface on the tailstock barrel H, and place the feeler between this secondary surface and an anvil carried on the tailstock D, using a spring to force the tailstock barrel H up until the feeler is supported. A small plug gauge is used as the feeler, and is set with its handle horizontal ; when the tailstock barrel is forced back a very slight amount by the gauge being measured, the handle of the gauge falls to a vertical position, and a little more movement suffices to allow the gauge to fall out altogether. The one twenty-fifth of a thousandth of an inch is a difference which affects promptly the fall of a feeler or secondary gauge.

In the Newall Measuring Machine the tailstock barrel is forced forward by a spring, and its position in the tailstock is indicated by means of a lever multiplying gear which tilts a spirit level; when the spirit level bubble is at zero, the barrel is in a certain position, and is pressed forward by the spring with a definite force, so that the gauge being measured is under this force.

In the Rogers-Bond Comparator, used by Messrs. Pratt & Whitney in the origination of their standard gauges, the poppet barrel is also arranged to slide, and is held up to the work by a spring, and the end force on the gauge measured is arranged to be nearly constant, though the exact force makes no appreciable difference to the measurement. In a machine used at the National Physical Laboratory contact is considered to be complete when the barrel is moved so as to make an electrical contact at its rear end; this is considered to be sensitive to the ten thousandth of a millimetre ($\frac{1}{250000}$ inch). Thus there are several effective modes of standardising the contact, satisfactory to the degree of accuracy required.

The third and final function of a measuring machine is to determine the distance between the measuring faces A and B, and in this a reference, indirect, to the original standard of length is necessary.

The first operation in measuring a gauge is to set the tailstock in the correct position on the bed of the machine; and for that two very different methods are in use. The first is by the aid of standard length end gauges, and this is the method used in the Whitworth machine. The zero of the graduated wheel G is set to the fiducial mark on the arm J, and a standard gauge set up as shown in Fig. 189. The tailstock D is then moved up by the hand wheel K, operating a screw within the bed until the surface B nearly touches the end of the gauge, and then the tailstock is locked in position. The final adjustment of the surface B to contact with the end of the gauge is made by the graduated wheel L, which moves the surface B forward by means of a screw, the determination of the correct setting being effected by means of the feeler E. The surface B is then set correctly.

The second method is by the use of a scale set in the body of the instrument and observed by a microscope carried on the tailstock. This is the method in the Pratt & Whitney Measuring Machine. The scale consists of a bar in which are inserted plugs at distances, usually of one inch apart, with very fine parallel lines marked on the plugs, so that the lines are spaced at 1 inch apart. The tailstock has a fine adjustment along the bed of the machine, given to it by means of a screw carried in a small bracket which can be clamped to the bed ways. The wheel A is first set to zero; the surfaces A and B are then set together so as to release the secondary gauge previously described, and the cross-hair in the microscope set to the line on the zero plug. The tailstock and its bracket are then moved approximately to the desired position, and the bracket again clamped. The fine adjustment of the tailstock is then used to move it until the cross-hair of the microscope coincides with the fine line on the scale, and the setting is then correct, the surfaces A and B being a definite distance apart, exact to the accuracy of the scale.

The two methods of setting the tailstock are very different, the first depending on end and the second on line measurement. No wear of the scale occurs in the second, while in the first the setting is made under the same conditions as the machine is used in.

In both cases the reliance is ultimately upon the accuracy of the standard end measures or scale of the machine. For purposes involving high accuracy the errors of the end measures or scale can be ascertained and allowed for if necessary.

The poppet D and surface B having thus been set to the nearest unit (inch), the fractional measurement of the size of a part to be measured is determined by the movement of the surface A to bring it into correct contact with the piece to be measured. This movement is produced by the movement of the graduated wheel G, which is mounted on a screw which moves the part having the surface A; and the amount is recorded by the number of complete turns and the fraction of a turn necessary to give correct contact. When necessary, fractions of a division of the graduations of G are read to the next decimal place—the one hundred thousandth of an inch in the Whitworth machine—by a vernier at J. In this subdivision of the inch then, reliance for the measurement is primarily placed upon the accuracy of this screw, both the exactness of its pitch and its freedom from 'drunkenness.' For very refined work the errors of the screw can be found, and allowance made for them, either mechanically or by reference to a table.

Although this is the practice adopted in almost all cases, the Rogers-Bond Comparator, previously mentioned, employs line measurement entirely, and compares the end measurement of any gauge directly with a finely divided line measure. For gauge work a scale made of hardened steel (so that temperature may affect scale and gauge equally) is used; it is ruled by means of a diamond with fine lines spaced 2500 to the inch. It is observed by a microscope and subdivision of the graduations is made in the eye-piece. By means of the finely divided scale and with a knowledge of its errors, gauges which are fractions of the unit can be made without the making of the series of interchangeable end gauges by which such gauges were first produced by Sir Joseph Whitworth.

Small differences of length can be compared by means of the number of wave-lengths of a particular kind of light contained in this difference. This method is used in the latest Comparator; it is, however, a method of measurement not well adapted to engineering methods.

As described in the preceding chapter, the errors of drunkenness and irregularity of pitch can be lapped out of a screw, so that, provided it is of the correct pitch, it will form a reliable method of subdividing the unit of the measuring machine. It will be noticed that in the Whitworth measuring machine the anvil surface A is formed on the sliding nut and not on the rotating screw; this has the advantage that the end surface preserves its accuracy better—as it does not rotate on touching the work—and also that subsidiary measuring jaws can be attached to the barrels H and A, so that snap gauges (such as shown at C, D in Fig. 1) and cylindrical limit gauges can be easily measured.

Standard Gauges.—For the production of standard gauges to be used as references in engineering works such measuring machines are necessary, for such gauges must be very accurate—for sizes between 1 inch and 4 inches the error should not exceed 0·00005 inch. As the machines are expensive and require skill in their use it is generally advisable to obtain standard gauges from firms making a speciality of their manufacture. Sir Joseph Whitworth first placed reliable plug and ring gauges on the market; now there are several firms, the accuracy of whose products can be relied upon to be much closer than the figure given above as necessary. For small sizes—less than a tenth of an inch—cylindrical gauges are not so convenient as flat gauges, and recently the employment of flat gauges for larger measurements have come into vogue. The accuracy attained in the gauges by Johansson and one or two other makers is very high, being about the one hundred thousandth of an inch. As several gauges will adhere together when 'wrung' to one another, a large number of end sizes can be obtained with comparatively few gauges, and as the error in each individual gauge is so small the error in the compound gauge cannot be of importance. By having the smallest pieces varying in thickness by very small amounts, limit snap gauges can be easily checked.

Should any doubt arise as to the accuracy of a standard gauge, it is advisable to requisition the services of the National Physical Laboratory to report upon its precise measurement.

Gauges—plug and ring and flat end types—of such accuracy are not intended for use in the shop, but merely for reference. For actual use copies of these gauges to a lower degree of accuracy are made in the tool-room or furnished by one of the specialist firms. For such gauges an accuracy of one ten-thousandth of an inch (or 0·0025 mm.) for regular engineering work is ample; higher accuracy is unnecessary, and adds considerably to the cost.

Micrometers.—In making these workshop copies of the standard gauges, or the corresponding limit gauges, while a measuring machine is desirable, it is not necessary, as the accuracy can be attained by a good micrometer carefully handled. This tool appears to have been originated by James Watt, and although his instrument (to be seen in the Patent Museum) appears very crude to-day, it represents very high-grade workmanship for those early days. As a screw gauge to meet the requirements of instrument makers and wire drawers, it took somewhat its modern shape; several detail

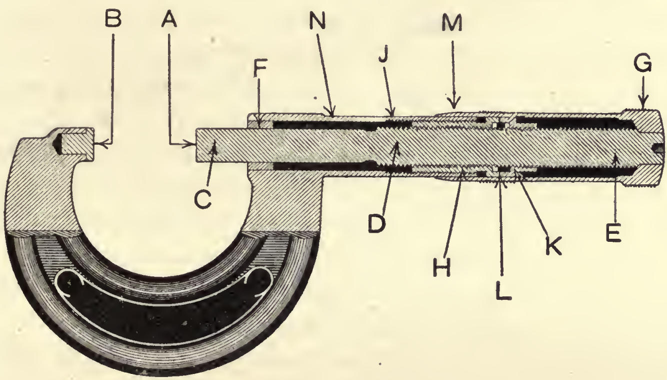


Fig. 190.—Micrometer—Slocomb

improvements in its construction have since been made, the most important being the protection of the screw thread by Messrs. Brown & Sharpe.

The details of a modern micrometer by the Slocomb Co. are shown in Fig. 190. The parallel measuring surfaces are A and B, of which B is fixed, and A is formed on the end of the measuring screw CDE. The plain parallel part C of the screw slides through the closely fitting bush F, and the thread D is never exposed, the rear part being covered by the thimble G. The nut H is held in the body of the micrometer by a screw thread J of a different pitch to the micrometer screw D, so that by turning H wear of the surfaces A and B can be differentially compensated for. A secondary nut K is forced away from the main nut H by means of a short spiral spring L, and so takes up any backlash. The thimble G is pressed tightly on the end of the screw CDE. The thimble is graduated round the bevelled edge M, so that the divisions represent thousandths of an inch, the pitch of the screw being 40 per inch. The whole turns of the screw are read by a scale marked along the barrel N, the line of the scale being the zero line for the divisions marked at M round the thimble's edge. Some micrometers are provided with a spring ratchet movement to the thimble, so that the ratchet slips when more than a certain turning force is applied to the thimble, so as to minimise the 'personal error' involved in the use of the instrument. Where the instrument is intended to be used over greater lengths than an inch, the anvil is formed on the end of an adjustable bar, and a gauge provided for setting it correctly for the longer work. A very useful fitting is a split collet, and a closing nut fitted to the bush F, so that the screw CDE can be locked in any position, and the instrument used as a snap gauge. When using it in this manner very little force should be used; it must never be forced over any cylindrical work, as a slight force tending to push it over the work produces considerable end force on the surfaces AB.

For making workshop gauges it is a convenience if the barrel N has, in addition to the zero line for the thimble graduations, a set of vernier lines marked along it; the decimal fraction of a thimble division can then be read on the vernier instead of being estimated.

The accuracy of good commercial micrometers is high, and they meet the requirements of limit work such as given in Tables I to III. Work can be duplicated within these limits with the aid of a good pair of ordinary calipers, but the measurement takes much longer, and for commercial manufacturing the micrometer is a necessity for economic reasons. If a limit snap gauge, such as at CD in Fig. 1, be used alone, it gives no indication of the amount the work is over-size, and so of what the cross-feed setting should be.

In using a micrometer work should be wiped with the hand at the points of measuring to remove grit, the anvil B slid on to the work, and the screw adjusted gently down.

Unless the screw is locked as described above, it should not be used as a snap gauge ; this is apt to depreciate the micrometer rapidly, as the end forces produced are great.

Temperature has little direct effect in measuring steel work in the shop, for the micrometer and work will be practically at the same temperature, and hence will have expanded the same amount. If the micrometer be used to compare the work size with the size of a gauge of the same nominal size—e.g. a 2-inch running size with a 2-inch standard gauge—which is the best method of working, care should be taken that the gauge should acquire practically the same temperature as the work and micrometer. If the difference of temperature be 10°F. the error on a 2-inch shaft would be about a ten-thousandth of an inch, and so would not be often of any importance.

Temperature, however, produces indirectly a much larger effect, for if the frame of the micrometer be held so that the inside of the horseshoe frame touches the hand and gets warm, while on the outside it remains cool, the frame distorts so as to close the surfaces A and B towards one another. The effect depends upon the depth of the gap, and is therefore more conspicuous in the larger sizes ; care must be taken to avoid this error by handling the instrument properly. In large instruments the body should be protected by non-conducting material.

The instrument should be checked frequently by bringing the surfaces A and B together and noting that the reading is zero, and resetting or allowing for it if it is not so, and by checking it on a standard gauge of its full capacity.

In measuring work the amount of force used in turning the thimble affects the reading, for the pitch of the screw is small ($\frac{1}{40}$ inch) that a small torque on the thimble produces considerable end force at the measuring points, and so strains the body of the micrometer a little. A slight contact force is all that is necessary, and more tends to wear the surface A, as it twists as it makes contact ; it is, however, quicker to work with a fair amount of force. If the method of comparing the work with a gauge is employed it eliminates this personal error—that is, the difference of size between the work and the gauge is made to be the same by different persons, although one will use more force than the other and the actual reading of the micrometer will be different.

Large work (say a foot in diameter) can be easily measured by taking the circumference with a thin steel tape; a thousandth of an inch on the diameter gives $\frac{1}{300}$ inch on the circumference, which can easily be appreciated by the naked eye.

Internal work above 2 inches diameter is easily measured by the use of an internal micrometer. This consists of a micrometer body A, Fig. 191, into one end of which rods B, B′ of various lengths can be inserted and clamped in definite positions. The

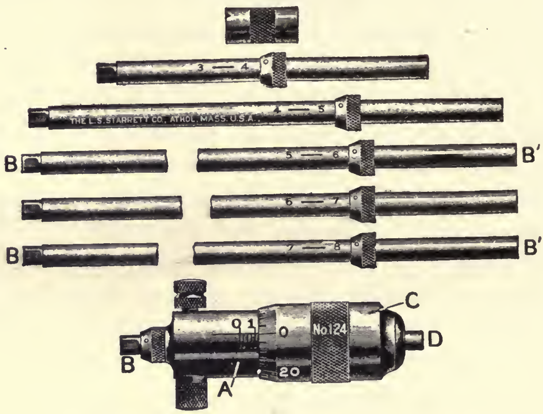


Fig. 191.—Internal Micrometer—Starrett

thimble C terminates in the other measuring point D. The points are slightly rounded. In use the point D is maintained firmly against one side of the hole, and the end of B is held and moved about to feel its way through the hole. Dimensions can be very accurately compared, to within $\frac{1}{4000}$ inch on holes up to 6 inches. There is the same kind of personal error as referred to in connection with the external micrometers—a thousandth of an inch or even more on such a 6-inch hole—but in comparison of holes this disappears. The particular design shown is that of the Starrett Company.

The sizes of holes may be taken with ordinary inside calipers, setting them to the hole and comparing them with an external micrometer or other gauge, but the time taken is so much longer that regular internal micrometers should be used. Messrs. The Newall Engineering Company make an internal micrometer with three points to touch the work at points on a circle separated at 120°; this renders one rocking motion only of the instrument necessary.

For holes smaller than 2 inches, micrometers are not available, and calipers or a series of gauges must be used. Vernier calipers may be used to take the diameter of a hole near its mouth, but these tools are not generally useful in connection with grinding.

Limit Gauges.—In manufacturing micrometers are used to give the size of the work as it approaches the limits allowed, but for the control of the final size and for checking the work, limit gauges should be used. These practically eliminate personal error, so that the work can be relied upon to be truly within the limiting sizes specified.

All limit gauges have two sizes, one which passes over or into the work, and which therefore is subject to wear, and one which will not pass over or into the work, and so does not wear. To distinguish the ends the gauge surface of the latter is made short, while that of the former is made longer to withstand the wear. This will be noticed in various types of limit gauge (Fig. 1).

External limit or snap gauges are usually made out of steel $\frac{3}{16}$ inch to $\frac{1}{4}$ inch thick, and take the shape shown at CD in Fig. 1. A hole, as shown at E, is convenient, as they can be then hung up on a board in the tool-room. Lightness is a virtue, and drop forgings can be obtained suitable for making into gauges of this type, and for the larger sizes they are desirable. Large sizes should be single ended only. They may be made out of steel rod merely bent to a horseshoe shape and the points hardened and ground to size, but a more formal gauge receives better treatment and care in the shop, and the cost of the forging is a fraction only of the total cost of the gauge.

In grinding such gauges on a Universal machine, they should be supported on the work table with the length of the gauge surfaces parallel to the main ways, so that the traverse can be used for grinding the surface and the cross-feed for putting on the cut. The flat faces of the wheel, undercut on both sides, are to be used, and the spindle set square with the main ways, and all end play should be taken up. The cross-feed in a Universal Grinder is usually graduated in thousandths of an inch on the work diameter, so that each of these divisions represents a one half-thousandth of an inch only in actual movement. The effect of a movement of one division of the cross-feed hand wheel may be made still less by swivelling the cross slide, as explained in Chapter IV.

In use no appreciable force is to be used on these gauges; the weight of the gauge itself should be sufficient to take the

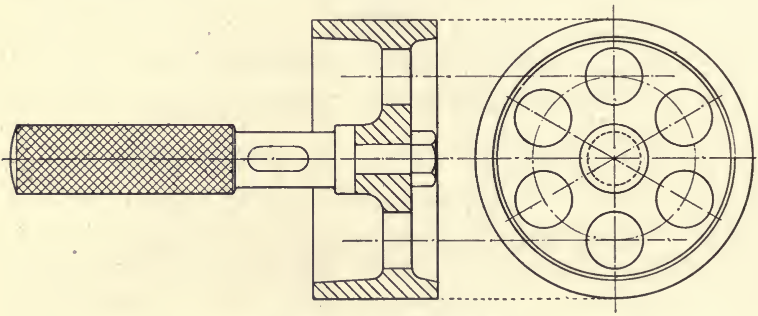


FIG. 192.—DESIGN OF GAUGE

large end over the work. A difference of size of 0·00005 inch is easily appreciable by their use.

For small quantities, where the cost of a special limit gauge is not warranted, reliance may be placed on the micrometer or on adjustable limit gauges such as are made by the Newall Machine Co. A variety of types of variable limit gauges have been brought out; in them the chief features to be looked for—after accuracy and reliability—are simplicity and lightness.

Limit gauges for holes take several forms. For the smaller holes the type shown at AB in Fig. 1 is most suitable. The 'go in' end, it will be noticed, is longer than the 'not' end, for purposes of resisting wear and so that the ends can be distinguished at a glance. In making these gauges it is well to lap off the last ten-thousandth of an inch, as it gives a longer life to the tool.

Some limit gauges of this type have been made with the end discs ground to a spherical surface. They go into the hole very easily, as there is no necessity that the gauge axis should coincide with the work axis. They are more difficult to produce and wear more rapidly, since the contact with the work is along a line and not over a surface.

As the size of these internal gauges increases, their weight increases to an inconvenient amount. They should then have the end portions recessed and holes bored through, and as

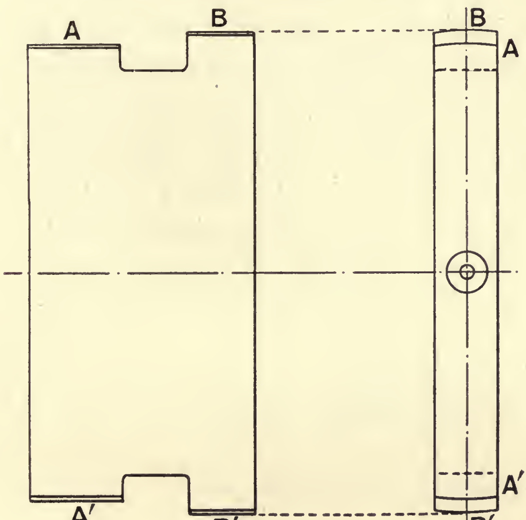


Fig. 193.—Limit Gauge for Internal Work

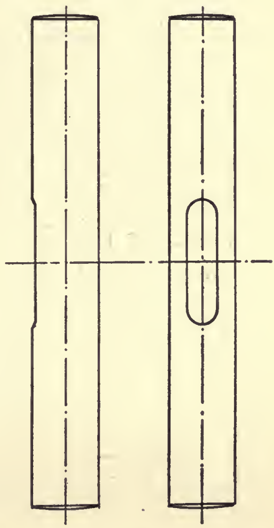


Fig. 194.—Spherical-Ended Measuring Rods

the size further increases made single ended. A sketch of such a gauge is given in Fig. 192.

A cylindrical gauge should be used in finally trying holes for size, but for the larger sizes flat gauges, such as shown in Fig. 193, with the surfaces at AA′, BB′, ground cylindrical, or spherical ended rods as in Fig. 194 are useful. The ends of the latter are ground to form portions of one spherical surface, and enter a hole very easily. Both types are very light. Some expensive jigs for grinding spherical ended gauges have been described, but all that is necessary is a simple one, such as is shown in Fig. 195. The hollow spindle AB revolves in bearings, and the pulley C is driven from the drum by a belt ; the whole can rotate about the vertical axis DE, which must intersect the axis of AB. The flat side FG of the wheel is used, and the axis AB is rocked by hand—using the lever at H—about DE as the work rotates. On turning AB round through 180° to grind the other end of the gauge the belt merely becomes crossed. The wheel spindle should be set perpendicular to the main ways, and the cross-feed used for sizing.

Fairly accurate estimation of the excess of the diameter of a hole over the length of a sharp-ended rod can be made by holding one end of the latter against one side of the hole, and noting the amount of movement of the other end necessary to bring it into contact with the sides of the hole. The amount varies with the plane in which the rod is rocked; it is least when the rod lies in a plane normal to the axis, and this is the amount to be considered. In Fig. 196 AB, AC are the two positions of the rod and AD the diameter, so that ABD is a right angle, and therefore—

$$\begin{aligned} BD^2 &= AD^2 - AB^2 \\ &= (AD + AB)(AD - AB) \end{aligned}$$

Hence—

$$\begin{aligned} \text{excess of diameter above length of rod} &= AD - AB \\ &= \frac{BD^2}{AD + AB} \\ &= \frac{(\frac{1}{2}\,BC)^2}{2\,AD} \text{ (nearly)} \\ &= \frac{BC^2}{8\,.\,AD} \end{aligned}$$

If the excess be n thousandths of an inch, and k be the length of BC in eighths of an inch, and R the radius of the hole in inches, we have—

$$n = \frac{1000\,.\,k^2}{64\,.\,8\,.\,2\,R} = \frac{1000}{1024}\,.\,\frac{k^2}{R} = \frac{k^2}{R} \text{ (nearly enough).}$$

With final reference to the standard yard (or metre), made indirectly by the use of instruments and gauges such as are

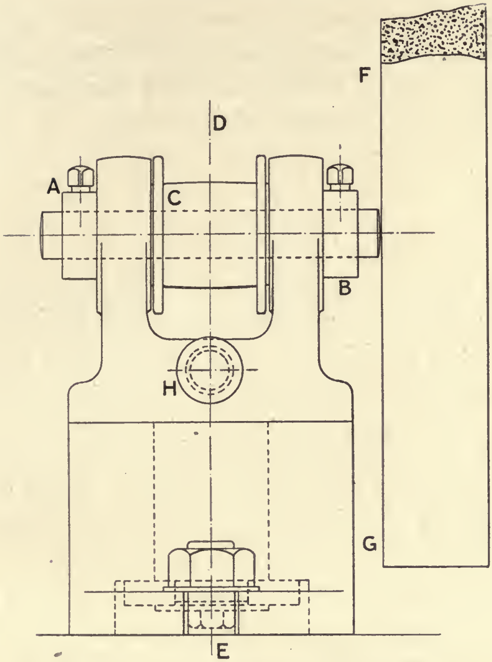


Fig. 195.—Grinding Spherical-Ended Measuring Rods

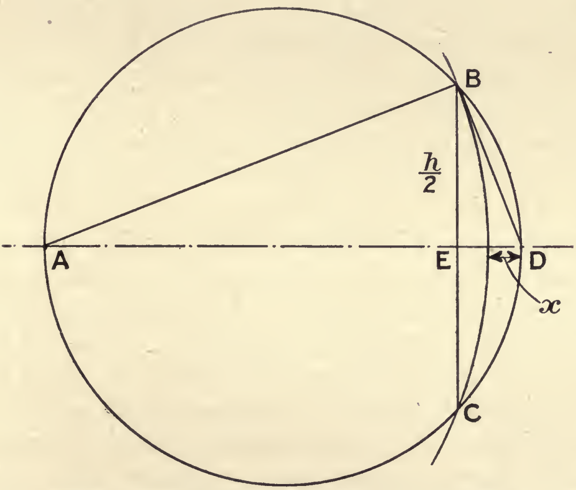


Fig. 196.—Gauging Hole with Pointed Rod

above described, parts can be produced in one factory so as to interchange with those produced elsewhere, although the variations from size permissible are those small amounts whose nature is discussed in Chapter I.

Conclusion

The development of grinding as a manufacturing method is illustrated by the series of machines described above, and it has influenced and been in turn influenced by other manufacturing processes ; it has rendered work which was previously almost impossible, easy and inexpensive, and has created the modern view as to what constitutes high-class machine work. The determination as to whether the process should be adopted in any particular case will depend not only on what can be done by its aid, but on what can be done without it.

The principal reasons for the adoption of grinding are (i) the hardness of the material of the work, (ii) the accuracy necessary, (iii) the quality of surface required, (iv) the smallness of the amount of stock to be removed, and (v) the total economy of the process. Of these (i) and (ii) may render grinding necessary apart from the matter of cost, and (iii) may leave a choice between grinding and polishing only, which is a selection easily made. As regards (iv), the process is always to be considered as a manufacturing proposition when the part to be made can be produced nearly to the required dimensions by a cheap or necessary manufacturing process, or where the part itself is slight ; it is also to be considered as a final operation to a roughing process, as in ordinary plain grinding after turning. The accuracy and cost of the product of modern capstans and automatics is well known. If the maintainable quality of their product is satisfactory, grinding is a waste of labour ; if it is not, it is almost invariably cheaper to rough out the part in a capstan and finish by grinding than to make complete in a centre lathe. The makers proclaim that wheels are cheaper than files (they are much more expensive than tool-steel, though), but this is a matter of little moment ; the controlling factor in the direct manufacturing cost (v) is almost invariably that of the labour involved, which depends greatly upon the amount of material to be removed, and hence upon the other processes in the manufacture of the part.

The correct selection of wheels is important, as the amount of labour involved depends largely thereon. The action of a wheel has been described in detail, and when the conclusions drawn thence have been grasped there should be little difficulty in arriving at the most suitable grits and grades. There is no mystery in the matter ; the statements of some wheel makers that the publication of their grades would do harm is suggestive of a Delphic utterance. The functions of the abrasive and bond are quite definite.

The selection of a machine is determined by many factors. A light machine is usually a cheap one, and such a machine may do good work if the wheel is in perfect balance, and it may be sufficient for the purpose in view. Practically it is generally necessary to do good work rapidly and with wheels having the small want of balance which is commercially unavoidable, and, as explained, this implies substantial machines. Grinding machines of a high class, however, are so well protected against grit and injury from other causes, and are built of such good material, that the depreciation is small if proper attention is paid to them. The accuracy of construction necessary to give satisfaction is such, and the alignments involved are so many, that grinding machines—however good the design—should not be purchased from any firm whose actions are not honourable.

APPENDIX

EXAMPLES OF GRINDING TIMES, TABLES, &c.

EXTERNAL GRINDING

TIMES OF GRINDING VARIOUS PARTS,

Selected from Examples furnished by Messrs. Brown & Sharpe

Production Times							
Material	Dimensions (inches)		Time. No. in 10 hrs.	Limits	Notes, Finish, &c.	Wheel	Machine
	Diam.	Length					
S. Hardened	$\frac{1}{4}$	$4\frac{3}{4}$	317	$\frac{1}{2}$	The allowances for grind-	36–4 or 5E	No. 11. Plain
M.S.	$\frac{1}{2}$	$5\frac{3}{16}$	308	Std.–$\frac{1}{4}$	ing are those given on	54 M.	,, 11. ,,
M.S.	$\frac{3}{16}$	$6\frac{5}{16}$	308	Std.–$\frac{1}{4}$	page 215.	54 M.	,, 11. ,,
M.S.	$\frac{3}{4}$	$2\frac{3}{4}$	295	$\frac{1}{2}$	The work is done in	54 M.	,, 11. ,,
S. Hard.	$\frac{3}{16}$	$6\frac{1}{4}$	148	$\frac{1}{2}$	batches of 50 or more.	36–4 or 5E	,, 11. ,,
S. Hard.	$\frac{7}{32}$	$11\frac{1}{8}$	131	$\frac{1}{2}$	Most of these parts are	36–4 or 5E	,, 11. ,,
M.S.	$\frac{3}{4}$	$8\frac{5}{16}$	123	$\frac{1}{2}$	handled twice, for rough-	54 M.	,, 11. ,,
S. Hard.	$\frac{13}{32}$	$11\frac{3}{8}$	91	$\frac{1}{2}$	ing and for finishing, &c.	36–4 or 5 E	,, 11. ,,
M.S.	$\frac{7}{8}$	$6\frac{5}{8}$	88	$\frac{1}{4}$		54 M.	,, 11. ,,
S. Hard.	$\frac{3}{8}$	$8\frac{1}{2}$	80	Std.	Very fine finish	46 K.	,, 11. ,,
M.S.	$1\frac{1}{4}$	8	62	—	Taper—to gauge	54 M.	,, 11. ,,
S. Hard.	$1\frac{1}{2}$	$2\frac{3}{8}$	60	$\frac{1}{2}$	Hollow—$1\frac{1}{2}$ in. diam.	46 K.	,, 2. Univ.
S. Hard.	3	$2\frac{7}{8}$	60	1	Hollow—$2\frac{5}{8}$ in. diam.	46 K.	,, 2. ,,
S. Hard.	$1\frac{9}{16}$	16	30	$\frac{1}{2}$	Very fine finish	46 K.	,, 14. Plain
M.S.	$3\frac{1}{2}$	47	30	Std.		54 M.	,, 18. ,,
M.S.	$4\frac{3}{4}$	$63\frac{3}{4}$	25	Std.		54 M.	,, 28. ,,
S. Hard.	$\frac{3}{4}$	24	20	$\frac{1}{4}$	Very fine finish	46 K.	,, 11. ,,
S. Hard.	$1\frac{9}{16}$	$39\frac{5}{16}$	20	1		46 K.	,, 14. ,,
C.I.	2	$1\frac{1}{4}$	120	1		46 K.	,, 11. ,,
C.I.	$2\frac{1}{2}$	$13\frac{5}{8}$	60	1		—	,, 28. ,,
C.I.	9	16	40	—		—	,, 28. ,,
Bronze	$\frac{13}{16}$	$2\frac{23}{32}$	513	Std.–$\frac{1}{4}$		54 M.	,, 11. ,,
M.S.	as fig.	3	400	as in fig.	Fig. 197. No. 1	54 M.	,, 11. ,,
M.S.	,,	$6\frac{3}{8}$	150	,,	,, ,, 2	54 M.	,, 11. ,,
M.S.	,,	$12\frac{1}{2}$	100	,,	,, ,, 3	54 M.	,, 11. ,,
M.S.	,,	$9\frac{1}{4}$	64	,,	,, ,, 4	54 M.	,, 11. ,,
Soft.	,,	$13\frac{1}{2}$	40	,,	,, ,, 5	54 M.	,, 14. ,,
M.S.	,,	$17\frac{9}{16}$	37	,,	,, ,, 6	54 M.	,, 11. ,,
M.S.	,,	$10\frac{1}{8}$	33	,,	,, ,, 7	54 M.	,, 11. ,,
M.S.	,,	$11\frac{7}{8}$	25	,,	,, ,, 8	54 M.	,, 14. ,,
M.S.	,,	$32\frac{15}{16}$	24	,,	,, ,, 9	54 M.	,, 2. Univ.
M.S.	,,	$17\frac{1}{16}$	22	,,	,, ,, 10	54 M.	,, 14. Plain
M.S.	,,	$20\frac{7}{8}$	17	,,	,, ,, 11	54 M.	,, 11. ,,
M.S.	,,	$37\frac{15}{16}$	17	,,	,, ,, 12	54 M.	,, 14. ,,
M.S.	,,	$62\frac{1}{8}$	16	,,	,, ,, 13	54 M.	,, 16. ,,
Hard.	,,	$15\frac{15}{16}$	15	,,	,, ,, 14	46 K.	,, 11. ,,
M.S.	,,	$27\frac{7}{8}$	12	,,	,, ,, 15 Lots of 25	54 M.	,, 14. ,,
M.S.	,,	$32\frac{3}{4}$	10	,,	,, ,, 16 Lots of 25	54 M.	,, 14. ,,
M.S.	,,	$36\frac{1}{16}$	10	,,	,, ,, 17	54 M.	,, 16. ,,
M.S.	,,	$70\frac{5}{16}$	10	,,	,, ,, 18	54 M.	,, 16. ,,
M.S.	,,	$9\frac{7}{8}$	22	,,	,, ,, 19	54 M.	,, 2. Univ.
C.I.	,,	$8\frac{1}{2}$	44	,,	,, ,, 20 Lots of 25	—	,, 2. ,,

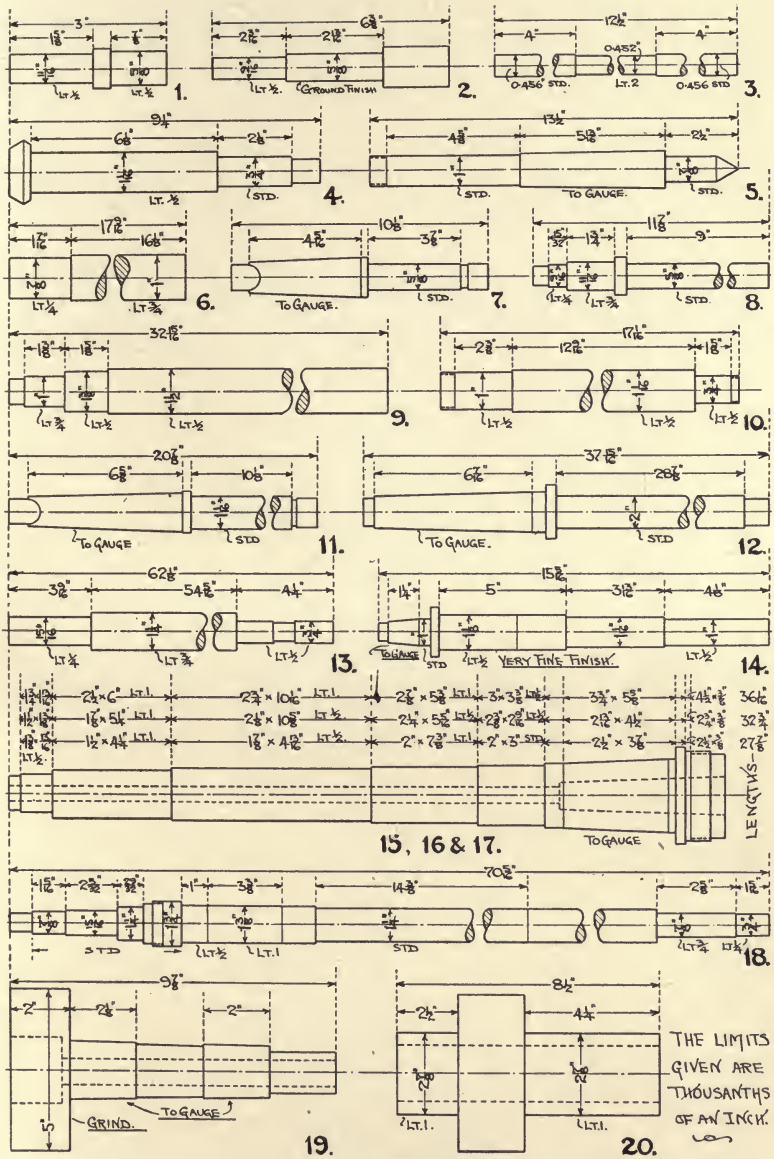

1.
2.
GROUND FINISH
3.
0·456 STD.
0·452
LT. 2
0·456 STD
4.
5.
TO GAUGE.
6.
7.
TO GAUGE.
8.
9.
10.
11.
TO GAUGE
12.
TO GAUGE.
13.
14.
TO GAUGE
VERY FINE FINISH.
15, 16 & 17.
TO GAUGE
LENGTHS
18.
19.
GRIND.
TO GAUGE
20.
THE LIMITS
GIVEN ARE
THOUSANTHS
OF AN INCH.

FIG. 197.

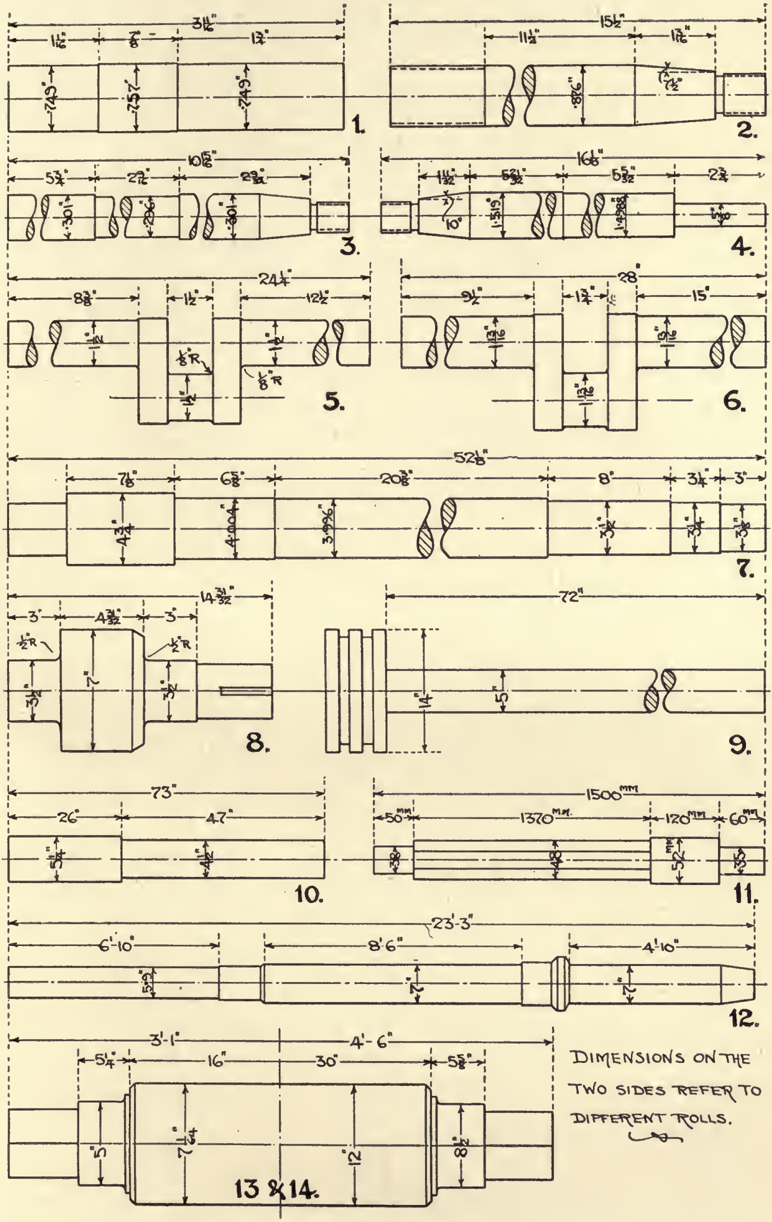
EXTERNAL GRINDING

TIMES OF GRINDING VARIOUS PARTS,

Selected from Information furnished by Messrs. The Landis Tool Co.

Grinding Time Only

Material	Dimensions (inches) Diam.	Dimensions (inches) Length	Time in Mins.	Allowances in thousandths For Grinding	Allowances in thousandths Limit	Notes, Finish, &c.	Wheel	Machine
								Inches
Ni.S.	·4375	2¾	1	15	¼	First class—valve stem	36–46 L.	10 × 20 Plain
C.H.S.	⅞	3⅞	1	15	¼	First class—gudgeon pin	36–46 L.	10 × 30 ,,
C.H.S.	⅞	4¾	1 1/10	15	¼	,, ,, ,, ,,	24 comb.L.	10 × 30 ,,
C.H.S.	1⅛	4⅜	1½	25	¼	Commercial ,, ,,	,,	10 × 30 ,,
M.S.	¾	9¼	3	6–8	¼	First class—tube ½″ hole	36–46 K.	12 × 42 Univ.
M.S.	1¼	18	8	30	1	Commercial—loco. work	36 L.	16 × 32 × 72 Plain
·4 C.S.	1·495	26⅞	8	25	¼	First class	36–46 L.	12 × 42 Plain
M.S.	8	36	18	30	2	Commercial—hollow ¼″ thick	24–36 L.	16 × 72 ,,
M.S.	3½	36	20	30	1	Commercial—piston rod	36–46 L.	16 × 72 ,,
M.S.	8	36	20	30	5	Commercial—pipe roll	24–36 K.	16 × 72 ,,
H.T.S.	8	12	20	40	—	Taper roller—to gauge	46 N.	12 × 32 ,,
M.S.	2½	36	25	25	1	First class—thin wall	36–46 K.	12 × 66 ,,
M.S.	4¾	20	40	30	½	Commercial—hollow (3¾″) sleeve	36–46 L.	12 × 66 Univ.
Ni.S.	17 23/32	96	120	30	2	First class—⅜″ thick metal	36 L.	20 × 150 Plain
C.I.	2 3/16	4⅛	3	180	—	Taper—to gauge; gas plug	24 L.	10 × 20 ,,
C.I.	3·025	3½	3	15	½	Commercial—piston	34–46 L.	10 × 30 ,,
C.I.	3·738	5	4	18	½	Commercial—piston	36 L.	12 × 42 ,,
C.I.	4½	5½	4	15	¼	Commercial—piston	36 L.	10 × 30 ,,
C.I.	3	22	10	150	10	Commercial—drum	24–36 L.	12 × 66 ,,
C.I.	6	39½	20	30	1	Commercial—Corliss valve	24–36 L.	20 × 96 ,,
C.I.	23¼	27¾	20	20	5	Commercial—press roll	46 N.	24 × 144 ,,
C.I.	5¼	28	35	30	1	Commercial—Corliss valve	24–36 L.	16 × 72 ,,
C.C.I.	6⅞	19	120	150	1	Very fine—sheet metal roll	46 L.	16 × 72 ,,
C.H.S.	as fig.	3 11/16	2	20	¼	Fig. 198, No. 1 Commercial	24 L.	10 × 20 ,,
M.S.	,,	15½	8	25	¼	Fig. 198, No. 2 First class	46 M.	10 × 20 ,,
C.H.S.	,,	10 15/16	18	20	1/10	Fig. 198, No. 3 Gloss finish	46 L.	10 × 20 Univ.
C.H.S.	,,	16⅛	35	30	as fig.	Fig. 198, No. 4 Very true point	46 L.	16 × 30 Plain
Forging	,,	24¼	25	30	½	Fig. 198, No. 5 First class. Pin ground from rough forging	46 L.	16 × 42 ,,
Forging	,,	28	35	25	½	Fig. 198, No. 6 Commercial. Pin ground from rough forging	46 M.	Crank grinder
·4 C.S.	,,	52⅛	40	30	½	Fig. 198, No. 7 First cl.	36–46 L.	12 × 72 Plain
Chilled C.I.	,,	14 31/32	50	30	1	Fig. 198, No. 8 Fine	24–36 L.	12 × 42 ,,
M.S. and C.I.	,,	6′ 0″	60	30	1	Fig. 198, No. 9 Commercial. Piston and rod both ground	24–36 L.	20 × 96 ,,
M.S.	,,	73″	60	60	—	Fig. 198, No. 10 Commercial	30 M.	16 × 72 ,,
M.S.	,,	1500 mm.	60	·3 mm.	0·02 mm.	Fig. 198, No. 11 Commercial	46 M.	16 × 66 Univ.
M.S.	,,	23′ 3″	300	60	3	Fig. 198, No. 12 First class	—	20 × 144 Plain
Chilled C.I.	,,	37″	80	30	1	Fig. 198, No. 13 First class	46 L.	16 × 72 ,,
Chilled C.I.	,,	54″	120	30	1	Fig. 198, No. 14 First class	36–46–60 L.	16 × 72 ,,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DIMENSIONS ON THE TWO SIDES REFER TO DIFFERENT ROLLS.

Fig. 198.

INTERNAL GRINDING

EXAMPLES OF TIMES FOR GRINDING VARIOUS HOLES

	Material	Dimensions (inches)		Time in Mins.	Allowances in thousandths		Notes and Wheel	Machine
		Diam.	Length		For Grinding	Limit		
By Messrs. Brown & Sharpe .	S.Hard	$1\frac{1}{2}$	$2\frac{3}{8}$	15	—	$\frac{1}{2}$	Thin—$1\frac{3}{16}$ O.D.	No. 2 Univ.
	S.Hard	$2\frac{5}{8}$	$2\frac{7}{8}$	20	—	Shrink fit	80 J. or K.	,,
	S.Hard	$1\frac{1}{2}$	$8\frac{7}{32}$	30	—	—	,,	,,
	Bronze	$3\frac{1}{4}$	7	30	—	1	54 K.	,,
	Bronze	$2\frac{7}{8}$	$5\frac{1}{2}$	37	—	$\frac{1}{2}$	54 M.	,,
By Messrs. The Churchill Machine Tool Co. Ltd. .	C.H.S.	$1\frac{3}{8}$	$2\frac{1}{8}$	5	10	1	—	10″ Internal
	C.H.S.	$1\frac{3}{8}$	7	16	10	1	—	12″ ,,
	C.H.S.	$1\frac{1}{4}$	$2\frac{3}{4}$	8	15	1	—	12″ ,,
	C.H.S.	2	$\frac{3}{4}$	15	15	$\frac{1}{2}$	—	12″ ,,
	M.S.	$1\frac{3}{4}$ $\frac{5}{8}$	$1\frac{1}{4}$ $2\frac{3}{4}$	20	12	—	To No. 3 Morse taper gauge	12″ ,,
	C.I.	$2\frac{1}{4}$	4	10	15	—	To taper gauge	12″ ,,
	Gun metal	2·125	2·385	3	12	$\frac{1}{2}$		10″ × 24″ Univ.
By the Landis Tool Co. . .	C.H.S.	$1\frac{1}{2}$	$1\frac{1}{4}$	3	10	—	To taper gauge	No. 1 Internal
	C.H.S.	$1\frac{1}{4}$	$2\frac{13}{16}$	5	15	$\frac{1}{4}$	36–46 L.	,,
	Hard T.S.	$1\frac{3}{4}$	$3\frac{1}{4}$	8	15	$\frac{1}{4}$	36–46 L.	,,
	Hard T.S.	$2\frac{1}{8}$	$3\frac{15}{16}$	9	20	$\frac{1}{4}$	,,	,,
	Ph.Br.	$2\frac{3}{8}$	$2\frac{1}{8}$	5	20	—	To gauge 46 L.	,,
	Ph.Br.	2·256	$5\frac{7}{16}$	8	20	—	,, 36–46 L.	,,

TABLE I.—LIMITS FOR CYLINDRICAL WORK.

The Newall Eng. Co.'s System — IN HUNDREDTHS OF ONE MM. — Transposed to METRIC by the Author

Nominal Diameter (mm.)	Holes				Shaft Fits													
	Class A		Class B		Forced		Drive		Push		Running					
											Class X		Class Y		Class Z	
	+	−	+	−	+	+	+	+	−	−	−	−	−	−	−	−
0–15	·7	·7	1·3	1·3	2·6	1·3	1·3	·7	·6	1·9	2·5	5·1	1·9	3·2	1·2	1·9
16–25	1·3	·7	1·9	1·3	5·1	3·8	2·6	1·9	·6	1·9	3·2	7·0	2·5	5·1	1·9	3·2
26–50	1·9	·7	2·6	1·3	10·2	7·7	3·9	2·6	·6	1·9	4·5	9·0	3·2	6·4	1·9	3·9
51–75	2·6	1·3	3·2	1·9	15·3	11·5	6·4	3·9	1·2	2·6	5·1	10·8	3·8	7·6	2·5	5·1
76–100	2·6	1·3	3·9	1·9	20·4	15·2	7·7	5·1	1·2	2·6	6·3	12·7	5·1	8·9	2·5	5·7
101–125	2·6	1·3	4·5	1·9	25·4	20·3	8·9	6·3	1·2	2·6	7·6	14·6	5·7	10·1	3·2	6·4
126–150	3·9	1·3	5·1	2·6	30·6	25·4	10·2	7·6	1·2	2·6	8·9	16·5	6·3	11·4	3·2	7·0
151–175	3·9	1·9	5·7	2·6	35·8	30·6	11·4	7·6	1·3	3·2	8·9	17·1	7·0	12·1	3·2	7·0
176–200	4·4	2·2	5·7	3·2	41·0	35·8	12·7	8·9	1·3	3·8	8·9	17·9	7·0	12·7	3·8	7·6
201–225	4·4	2·5	6·3	3·2	46·2	41·0	14·0	10·2	1·3	3·8	9·5	19·1	7·6	14·0	3·8	7·6
226–250	4·4	2·5	6·3	3·2	51·4	46·2	15·2	11·4	1·9	5·1	10·2	20·3	8·3	14·7	3·8	8·3
251–275	5·1	2·5	7·0	3·2	56·6	51·4	16·5	11·4	1·9	5·1	10·2	21·0	8·3	15·2	4·4	8·9
276–300	5·1	2·5	7·0	3·8	61·8	56·6	17·8	12·7	1·9	5·1	10·8	21·6	8·9	15·8	4·4	8·9

Two sets of limits are given for the holes to suit different grades of work.

Three sets of limits are given for running fit for similar reasons.

In the columns the first figure gives the upper limit, the second the lower. If the column is headed +, the amount is to be added to the nominal diameter; if −, it is to be subtracted.

TABLE II.—LIMITS FOR CYLINDRICAL WORK

The Newall Eng. Co.'s System — IN THOUSANDTHS OF AN INCH — Arranged by the Author

Nominal Diameter (inches)		Holes				Shaft Fits											
		Class A		Class B		Forced		Drive		Push		Running					
												Class X		Class Y		Class Z	
from	to	+	−	+	−	+	+	+	−	−	−	−	−	−	−	−	−
0	$\frac{1}{2}$	·25	·25	·50	·50	1·0	·5	·50	·25	·25	·75	1·00	2·00	·75	1·25	·50	·75
$\frac{9}{16}$	1	·50	·25	·75	·50	2·0	1·5	1·00	·75	·25	·75	1·25	2·75	1·00	2·00	·75	1·25
$1\frac{1}{16}$	2	·75	·25	1·00	·50	4·0	3·0	1·50	1·00	·25	·75	1·75	3·50	1·25	2·50	·75	1·50
$2\frac{1}{16}$	3	1·00	·50	1·25	·75	6·0	4·5	2·50	1·50	·50	1·00	2·00	4·25	1·50	3·00	1·00	2·00
$3\frac{1}{16}$	4	1·00	·50	1·50	·75	8·0	6·0	3·00	2·00	·50	1·00	2·50	5·00	2·00	3·50	1·00	2·25
$4\frac{1}{16}$	5	1·00	·50	1·75	·75	10·0	8·0	3·50	2·50	·50	1·00	3·00	5·75	2·25	4·00	1·25	2·50
$5\frac{1}{16}$	6	1·50	·50	2·00	1·00	12·0	10·0	4·00	3·00	·50	1·00	3·50	6·50	2·50	4·50	1·25	2·75
$6\frac{1}{16}$	7	1·50	·75	2·25	1·00	14·0	12·0	4·50	3·00	·50	1·25	3·50	6·75	2·75	4·75	1·25	2·75
$7\frac{1}{16}$	8	1·75	·75	2·25	1·25	16·0	14·0	5·00	3·50	·50	1·50	3·50	7·00	2·75	5·00	1·50	3·00
$8\frac{1}{16}$	9	1·75	1·00	2·50	1·25	18·0	16·0	5·50	4·00	·50	1·50	3·75	7·50	3·00	5·50	1·50	3·00
$9\frac{1}{16}$	10	1·75	1·00	2·50	1·25	20·0	18·0	6·00	4·50	·75	2·00	4·00	8·00	3·25	5·75	1·50	3·25
$10\frac{1}{16}$	11	2·00	1·00	2·75	1·25	22·0	20·0	6·50	4·50	·75	2·00	4·00	8·25	3·25	6·00	1·75	3·50
$11\frac{1}{16}$	12	2·00	1·00	2·75	1·50	24·0	22·0	7·00	5·00	·75	2·00	4·25	8·50	3·50	6·25	1·75	3·50

Two sets of limits are given for the holes to suit different grades of work.
Three sets of limits are given for running fit for similar reasons.
In the columns the first figure gives the upper limit, the second the lower. If the column is headed +, the amount is to be added to the nominal diameter; if −, it is to be subtracted.

TABLE III.—LIMITS FOR CYLINDRICAL WORK

Messrs. Brown & Sharpe's System — IN THOUSANDTHS OF AN INCH — Arranged by the Author

Nominal Diameter (inches)	Holes		Shaft Fits																	
	Ground		Standard		Running				Sliding		Drive				Forced		Shrinking			
					Ordinary Speed		High Speed Heavy Pressure Rockers				To be easily taken apart		Fast				Shells less than $\frac{3}{8}$ inch thich		Shells thicker than $\frac{3}{8}$ inch	
Up to		+		−	−	−	−	−	−	−	+	+	+	+	+	+	+	+	+	+
½	0	·5	0	·25	·25	·75	·50	1·00	·25	·50	0	·25	·50	1·00	·75	1·5	·25	·50	·50	1·00
1	0	·75	0	·5	·75	1·50	1·00	2·00	·50	1·00	·25	·50	1·00	2·00	1·50	2·50	·50	1·00	1·00	2·50
2	0	1·00	0	1·00	1·50	2·50	2·00	3·00	1·00	2·00	·50	·75	2·00	3·00	2·50	4·00	1·00	1·50	2·50	3·50
3½	0	1·50	0	1·50	2·50	3·50	3·00	4·50	2·00	3·50	·75	1·00	3·00	4·00	4·00	6·00	1·50	2·00	3·50	5·00
6	0	2·0	0	2·00	3·50	5·00	4·50	6·50	3·00	5·00	1·00	1·50	4·00	5·00	6·00	9·00	2·00	3·00	5·00	7·00

Special cases should always be considered, as it may be desirable to vary slightly from the tables.

TABLE IV.—TURNING

ALLOWANCES FOR GRINDING

Messrs. Brown & Sharpe allow 0·008 to 0·012 on the diameter for all sizes. The Landis Tool Co. recommend allowances as below :

Length in inches	Allowances in thousandths of an inch										
	3	6	9	12	15	18	24	30	36	42	48
Diam.											
up to ½	10	10	10	10	15	15	15	20	20	20	20
¾	10	10	10	10	15	15	15	20	20	20	20
1	10	10	10	15	15	15	15	20	20	20	20
1¼	10	10	15	15	15	15	15	20	20	20	20
1½	10	15	15	15	15	15	20	20	20	20	20
2	15	15	15	15	15	20	20	20	20	20	25
2¼	15	15	15	15	20	20	20	20	20	25	25
2½	15	15	15	20	20	20	20	20	25	25	25
3	15	15	20	20	20	20	20	25	25	25	25
3½	15	20	20	20	20	20	25	25	25	25	25
4	20	20	20	20	20	25	25	25	25	25	30
4½	20	20	20	20	25	25	25	25	25	30	30
5	20	20	20	25	25	25	25	25	30	30	30
6	20	20	25	25	25	25	25	30	30	30	30
7	20	25	25	25	25	25	30	30	30	30	30
8	25	25	25	25	25	30	30	30	30	30	30
9	25	25	25	25	30	30	30	30	30	30	30
10	25	25	25	30	30	30	30	30	30	30	30
11	25	25	30	30	30	30	30	30	30	30	30
12	30	30	30	30	30	30	30	30	30	30	30

GRINDING TIME-TABLE (APPROXIMATE)—LANDIS TOOL CO.

Diam. of work in inches	Length of work in inches											
	6	12	18	24	30	36	42	48	54	60	66	72
	Time in minutes											
1	2	4	6	9	12	15	20	25	30	35	40	45
2	3	5	7	10	13	16	21	26	31	36	42	50
3	4	6	8	11	14	18	22	27	32	37	45	55
4	5	7	9	12	16	20	24	28	33	38	48	60
5	6	8	10	14	18	22	26	30	34	40	51	65
6	7	9	12	16	20	24	28	32	36	42	55	70
7	8	10	14	18	22	26	30	34	38	46	60	75
8	9	12	16	20	24	28	32	36	41	50	65	80
9	10	14	18	22	26	30	34	38	45	55	70	85
10	12	16	20	24	28	32	37	42	50	60	75	90
11	14	18	22	26	31	36	41	46	55	65	80	95
12	15	20	25	30	35	40	45	50	60	70	85	100

Time has been figured on a basis of grinding $\frac{1}{32}$″ from the diameter, and the work to be ground to a first-class commercial finish. If $\frac{1}{64}$″ on the diameter is allowed for grinding, take $\frac{2}{3}$ of the time given in the table. Time is for grinding only.

For Guest formula for grinding times, see page 236.

TABLE V.—GRADES OF WHEELS

Firm	Grades (Very soft · Soft · Medium soft · Medium · Medium hard · Hard · Very hard)
American Emery Wheel Co., British Abrasive Wheel Co., Courtland Corundum Co., Norton Mfg. Co. and others.	E F G H I J K L M N O P Q R S
Carborundum Co.	U T S R Q P O N M L K J I H G F
Safety Emery Wheel Co.	C $C\frac{1}{2}$ H $H\frac{1}{2}$ A $A\frac{1}{4}$ $A\frac{1}{2}$ $A\frac{3}{4}$ M $M\frac{1}{4}$ $M\frac{1}{2}$ $M\frac{3}{4}$ P $P\frac{1}{4}$ $P\frac{1}{2}$ $P\frac{3}{4}$ I $I\frac{1}{4}$ $I\frac{1}{2}$ $I\frac{3}{4}$ O
American Emery Wheel Co., Elastic and also Silicate, British Abrasive Elastic, Norton Elastic	$\frac{1}{4}$ $\frac{1}{2}$ 1 $1\frac{1}{2}$ 2 $2\frac{1}{2}$ 3 $3\frac{1}{2}$ 4 5 6

The uppermost line is the Norton System, which is followed by a number of firms, and is used in this book when referring to the grade of wheels. The Carborundum Co.'s letters run consecutively, but in the reverse order. A number of firms adopt a lettering which can hardly be called a system—an example of which is given in the Safety Emery Wheel Co.'s grading. Gradings have been furnished to me by the Norton Mfg. Co., the American Emery Wheel Co., and others: the above table is averaged from these data and from experience. British firms, other than that above, were unfortunately unable to supply particulars of a grading system.

TABLE VI.—WHEEL SELECTION.

EXTERNAL WORK

Material of Work	Messrs. Churchills' List	The American Emery Wheel Co.'s List	Norton Co.
Steel—Soft (0·15 C) . .	46–60 L.M.N.—24 Comb. M.	46–60 L.M.N. 24 Comb. L.M.	24 M.
Harder (0·3 C) . .	46–60 L.M.—24 Comb. M.	60–80 M.N. 24 Comb. M.N. (for slender work)	
High Tension . .	46–60 K.L.—24 Comb. M.		24 L.
Nickel-Chrome . .	46–60 K.L.M.		
Hardened Steel (Tool & C.H.S.) . . .	46–60 J.K.	46–60 J.K. and 2–2½ W. and 1½ and 1–1½ E. for fine finish.	24 K.
		60–80, 2–3 W. or 2½–3 E for gauges.	24 J.
Brass	60 L.	36–54 L.M.N. and 2½–3 W.	
Bronze	60–4 E.		
Copper		46–54 K.L. and 2–2½ W.	
		100–150 2½–4 E.	
Cast Iron—Soft . . .	30–60 J.K.	46–50 J.K.	24 J.K.
Chilled . . .	36–60 I.	46–50 2–2½ W., 1½–2 E. fine finish.	

INTERNAL WORK

Steel—Hardened . . .	46–60 J.K.	46–60–100 J.K.M.N.	
Cast Iron—Soft . . .	36–46 I.J.K.	36–60 Comb. I.J.K.	
Chilled . . .	36–46 H.J.		

SURFACE WORK—CUP WHEELS

Steel—Soft	36–46 J.K.L.	24—$1\frac{1}{4}$ W.
Hardened	36–46 I.J.	30—$\frac{1}{2}$–$\frac{3}{4}$ W.
Cast Iron—Soft	24–36 H.I.	24—J.K.L.
Chilled	24–36 G.H.	24—H.I.
Aluminium and Bronze	46–2 E.	24—K. Carborundum

CUTTER SHARPENING

Carbon Steel	3846–3860 K. 46 L.M. 60 M.	46–80 J.K.M.N. and $1\frac{3}{4}$–$3\frac{1}{2}$ W. and $1\frac{1}{2}$–3 E.
High Speed Steel	3846–3860 J. and K.	

The wheels are of vitrified bond unless marked E for elastic or W for silicate.

The finer grit wheels are suitable for the smaller and the more highly finished work, and the coarser grits for large work or where output is the chief consideration, or in roughing preparatory to finishing as a different operation.

Two complete independent reliable lists (one English and one American) are tabulated alongside: and from them, bearing in mind the size and class of work to be done, satisfactory wheels for use on machines for the various purposes can be selected.

TABLE VII

EXTERNAL WORK.—Generally useful Wheels (Vitrified unless otherwise specified) J. J. Guest

Material of Work	Alundum or Corundum									Carborundum		
	24 Comb. K	24 Comb. L	24 Comb. M	36–4 Elastic	60 J	60 K	60 L	60 M	80 K	36 I	36 K	50 L
Steel—												
Soft (up to ·3C) } Nickel Chrome }	—	large diams.	generally	small diams.	—	—	finer finish	finer finish	Facing shoulders	—	—	—
Harder (over ·3C)	—	generally	—	—	—	finer finish	finer finish	—	finerfinish	—	—	—
Hardened (Tool or C.H.S.) .	generally	—	—	—	finer finish	finer finish	—	—	gauge and finer work	—	—	—
Brass . .	—	—	—	—	—	—	generally	—	—	—	—	—
Bronze . .	—	—	—	—	—	—	—	—	—	—	—	generally
Cast Iron—Soft .	—	—	—	—	—	—	—	—	—	—	generally	—
Chilled	—	—	—	—	—	—	—	—	—	generally	—	—

INTERNAL WORK.—Generally useful Wheels

	Alundum or Corundum						Carborundum	
	36 J Sil.	60 J Sil.	60 J	60 K	80 K	50–2 Elas.	36 I	60 I
Steel—Hardened (Tool or C.H.S.) .	generally	finer finish	generally	generally	fine finish	generally	—	—
Bronze	—	—	—	—	—	generally	—	—
Cast Iron	—	—	—	—	—	—	generally	finer finish

In ordering regular wheels the following seven factors are necessary:—Diameter, Face and Hole diameter, Grit and Grade, Abrasive and Bond. For example: 14″ × 2″ × 5″ 60 K, Alundum Vitrified. For special wheels dimensioned sketch of shape is advisable.

Some specially shaped wheels are stocked—see makers' lists. Wheels can be made with harder edges for work up to corners.

Carborundum is to be used on Cast Iron, Alundum on Steel and Brass, either on Aluminium or Bronze. For wheels up to I, I prefer silicate wheels, for J silicate or vitrified, K and beyond vitrified bond.

TABLE VIII

GRINDING WHEEL SPEEDS

Diam. of Wheel (inches)	Rev. per minute for a surface speed, in feet per minute, of						
	4,000	4,500	5,000	5,500	6,000	6,500	7,000
1	15,279	17,189	19,099	21,009	22,918	24,829	26,738
2	7,639	8,594	9,549	10,504	11,459	12,414	13,369
3	5,093	5,729	6,366	7,001	7,639	8,276	8,913
4	3,820	4,297	4,775	5,252	5,730	6,207	6,684
5	3,056	3,438	3,820	4,202	4,584	4,966	5,348
6	2,546	2,865	3,183	3,501	3,820	4,138	4,456
7	2,183	2,455	2,728	3,001	3,274	3,547	3,820
8	1,910	2,148	2,387	2,626	2,865	3,103	3,342
10	1,528	1,719	1,910	2,101	2,292	2,483	2,674
12	1,273	1,432	1,592	1,750	1,910	2,069	2,228
14	1,091	1,228	1,364	1,500	1,637	1,773	1,910
16	955	1,074	1,194	1,313	1,432	1,551	1,611
18	849	955	1,061	1,167	1,273	1,379	1,485
20	764	859	955	1,050	1,146	1,241	1,337
24	637	716	796	875	955	1,034	1,114
28	546	614	683	750	819	886	955
30	509	573	637	700	764	827	871
36	424	477	531	583	637	689	743
Suitable for Wheels of Grade	H	I	J K L		M	N	

J. J. Guest.

TABLE IX.—WORK SURFACE SPEEDS AND REVOLUTIONS PER MINUTE

R.P.M. FOR SURFACE SPEEDS, IN FEET PER MINUTE, OF—

Work Diameter in Inches	12	16	20	25	30	35	40	45	50	60	70	80	100	120
¼	183	244	306	382	458	535	611	688	764	917	1070	1222	1528	1833
½	92	122	153	191	222	267	306	344	382	458	535	611	764	916
¾	61	81	102	127	153	178	204	229	254	306	357	407	509	611
1	46	61	76	95	114	134	153	172	191	229	267	306	382	458
1¼	37	49	61	76	91	107	122	138	153	183	214	244	305	366
1½	30	41	51	64	76	89	102	114	127	153	178	204	254	305
1¾	26	35	44	55	65	76	87	98	109	131	153	175	218	262
2	23	30	38	48	57	67	76	86	95	114	133	153	191	229
2½	18·3	24	31	38	46	53	61	69	76	92	107	122	153	183
3	15·2	20	25	32	38	44	51	57	64	76	89	102	127	153
3½	13·1	17·4	22	27	33	38	44	49	54	65	76	87	109	131
4	11·4	15·2	19·1	24	29	33	38	43	48	57	67	76	95	114
4½	10·2	13·6	17·0	21	25	30	34	38	42	51	59	68	85	102
5	9·2	12·2	15·3	19·1	23	27	30	34	38	46	53	61	76	92
6	7·6	10·2	12·7	15·9	19·1	22	25	28	32	38	44	51	64	76
7	6·5	8·7	10·9	13·6	16·4	19·1	22	25	27	33	38	44	54	65
8	5·7	7·6	9·5	11·9	14·3	16 7	19·1	21	24	29	33	38	48	57
9	5·1	6·8	8·5	10·6	12·7	14·9	17·0	19·1	21·2	25	30	34	42	51
10	4·6	6·1	7·6	9·5	11·5	13·4	15·3	17·2	19·1	23	27	31	38	46
12	3·8	5·1	6·4	7·2	9·5	11·2	12·7	14·3	15·9	19·1	22	25	32	38

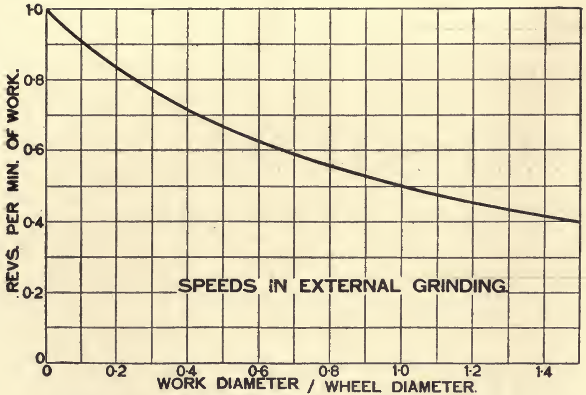

FIG. 199.—DETERMINATION OF WORK SPEEDS IN EXTERNAL GRINDING

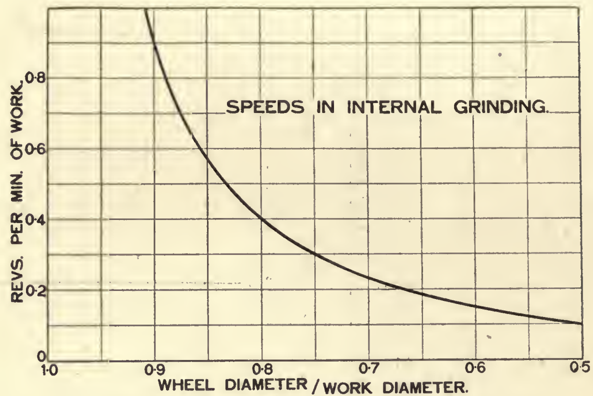

FIG. 200.—DETERMINATION OF WORK SPEEDS IN INTERNAL GRINDING

Make a trial with the machine and ascertain the best R.P.M. in any case; divide this number by the ordinate corresponding to the work diameter, thus obtaining the factor for the diagram.

To find the R.P.M. for any other work diameter, multiply the corresponding ordinate by the factor.

The R.P.M. of work depends upon the materials of the work and of the wheel, upon their diameters, and upon the particular machine used. The wheel surface speed is regarded as constant.

In the figures the R.P.M. of the work is plotted against the ratio of work and wheel diameters. For external work the ratio of work to wheel diameter is taken, as the diameter of the work coming to the machine varies considerably, and the R.P.M. of the work is changed to suit it. For internal work the ratio of wheel to work diameter is taken, since in grinding a number of holes of the same size, the wheel diameter lessens and the R.P.M. of the work is to be changed to suit it. The figure gives a rapid indication of the amount of change necessary to restore the grinding regimen as the wheel wears—see Chapter VII.

TABLE X

Cutter Grinding

SETTINGS FOR CLEARANCE WITH DISC WHEEL

Amount wheel axis is set above or belo.v cutter axis (inches)

Sin 5° = 0·087156. Sin 7° = 0·12187

Wheel Diameter (inches)	5° Clearance	7° Clearance
2	·087	·122
$2\frac{1}{4}$	·098	·137
$2\frac{1}{2}$	·109	·152
$2\frac{3}{4}$	·120	·168
3	·131	·183
$3\frac{1}{4}$	·142	·198
$3\frac{1}{2}$	·152	·213
$3\frac{3}{4}$	·163	·228
4	·174	·244
$4\frac{1}{4}$	·185	·259
$4\frac{1}{2}$	·193	·274
$4\frac{3}{4}$	·207	·289
5	·218	·304
$5\frac{1}{4}$	·229	·320
$5\frac{1}{2}$	·240	·335
$5\frac{3}{4}$	·251	·350
6	·262	·365
$6\frac{1}{2}$	·284	·395
7	·305	·426

TABLE XI

Cutter Grinding

SETTINGS FOR CLEARANCE WITH CUP WHEEL

The amount the tooth rest is to be set above or below the cutter axis—inches. The diameter of Angular Cutters is reckoned where the tooth rest touches them. For intermediate cutters interpolate by adding: thus for a $6\frac{3}{4}$ inch diameter add the amounts for a 6 inch and a $\frac{3}{4}$ inch cutter = ·261 + ·033 = ·294 inch for a parallel cutter.

J. J. Guest.

Diam. of Cutter (inches)	Parallel Cutters For 5°	For 7°	Semivertical angle, 30° For 5°	For 7°	Semivertical angle, 45° For 5°	For 7°
$\frac{1}{4}$	·011	·015	·013	·017	·016	·021
$\frac{3}{8}$	·016	·022	·018	·025	·023	·032
$\frac{1}{2}$	·022	·030	·025	·035	·031	·043
$\frac{5}{8}$	·028	·038	·032	·044	·040	·054
$\frac{3}{4}$	·033	·046	·038	·053	·047	·065
$\frac{7}{8}$	·038	·053	·044	·061	·054	·075
1	·044	·061	·051	·070	·062	·086
$1\frac{1}{4}$	·054	·076	·062	·088	·076	·107
$1\frac{1}{2}$	·065	·091	·075	·1	·092	·129
$1\frac{3}{4}$	·076	·106	·089	·122	·108	·150
2	·087	·122	·101	·141	·123	·172
$2\frac{1}{2}$	·109	·152	·126	·175	·154	·215
3	·131	·183	·151	·211	·185	·259
$3\frac{1}{2}$	·152	·213	·175	·246	·215	·302
4	·174	·244	·201	·282	·246	·345
5	·218	·304	·252	·351	·309	·430
6	·261	·365	·302	·422	·370	·517
7	·305	·426	·352	·497	·432	·603
8	·348	·487	·402	·562	·492	·690
9	·392	·548	·453	·635	·555	·775
10	·436	·609	·504	·703	·617	·860
11	·478	·670	·552	·774	·676	·948
12	·522	·731	·602	·845	·738	1·035

For 60° set the amount for a parallel cutter of twice the diameter.

ENGLISH AND METRIC CONVERSION

TABLE XII

1 in. = 25·39998 mm.

Inches	Millimetres
1 =	25·400
2 =	50·800
3 =	76·200
4 =	101·600
5 =	127·000
6 =	152·400
7 =	177·800
8 =	203·200
9 =	228·600
10 =	254·000

8ths	Inch	Millimetres
$\frac{1}{8}$ =	·125 =	3·175
$\frac{1}{4}$ =	·250 =	6·350
$\frac{3}{8}$ =	·375 =	9·525
$\frac{1}{2}$ =	·500 =	12·700
$\frac{5}{8}$ =	·625 =	15·875
$\frac{3}{4}$ =	·750 =	19·050
$\frac{7}{8}$ =	·875 =	22·225
1 =	1·000 =	25·400

16ths	Inch	Millimetres
1 =	·0625 =	1·587
3 =	·1875 =	4·762
5 =	·3125 =	7·937
7 =	·4375 =	11·113
9 =	·5625 =	14·287
11 =	·6875 =	17·462
13 =	·8125 =	20·632
15 =	·9375 =	23·812

32nds	Inch	Millimetres
1 =	·03125 =	0·794
3 =	·09375 =	2·381
5 =	·15625 =	3·969
7 =	·21875 =	5·556
9 =	·28125 =	7·144
11 =	·34375 =	8·731
13 =	·40625 =	10·319
15 =	·46875 =	11·906
17 =	·53125 =	13·494
19 =	·59375 =	15·081
21 =	·65625 =	16·669
23 =	·71875 =	18·256
25 =	·78125 =	19·844
27 =	·84375 =	21·431
29 =	·90625 =	23·019
31 =	·96875 =	24·606

TABLE XIII

1 metre = 39·37079 in. = 3 ft. $3\frac{3}{8}$ in. (nearly)

Millimetres	Inches	Millimetres	Inches
1 =	·0394	51 =	2·0079
2 =	·0787	52 =	2·0473
3 =	·1181	53 =	2·0866
4 =	·1575	54 =	2·1260
5 =	·1968	55 =	2·1654
6 =	·2362	56 =	2·2047
7 =	·2756	57 =	2·2441
8 =	·3150	58 =	2·2835
9 =	·3543	59 =	2·3228
10 =	·3937	60 =	2·3622
11 =	·4331	61 =	2·4016
12 =	·4724	62 =	2·4410
13 =	·5118	63 =	2·4803
14 =	·5512	64 =	2·5197
15 =	·5906	65 =	2·5591
16 =	·6299	66 =	2·5984
17 =	·6693	67 =	2·6378
18 =	·7087	68 =	2·6772
19 =	·7480	69 =	2·7166
20 =	·7874	70 =	2·7559
21 =	·8268	71 =	2·7953
22 =	·8661	72 =	2·8347
23 =	·9055	73 =	2·8740
24 =	·9449	74 =	2·9134
25 =	·9843	75 =	2·9528
26 =	1·0236	76 =	2·9922
27 =	1·0630	77 =	3·0315
28 =	1·1024	78 =	3·0709
29 =	1·1417	79 =	3·1103
30 =	1·1811	80 =	3·1496
31 =	1·2205	81 =	3·1890
32 =	1·2598	82 =	3·2284
33 =	1·2992	83 =	3·2677
34 =	1·3386	84 =	3·3071
35 =	1·3780	85 =	3·3465
36 =	1·4173	86 =	3·3859
37 =	1·4567	87 =	3·4252
38 =	1·4961	88 =	3·4646
39 =	1·5354	89 =	3·5040
40 =	1·5748	90 =	3·5433
41 =	1·6142	91 =	3·5827
42 =	1·6536	92 =	3·6221
43 =	1·6929	93 =	3·6614
44 =	1·7323	94 =	3·7008
45 =	1·7717	95 =	3·7402
46 =	1·8110	96 =	3·7796
47 =	1·8504	97 =	3·8189
48 =	1·8898	98 =	3·8583
49 =	1·9291	99 =	3·8977
50 =	1·9685	100 =	3·9370

(100 mm. = 1 decimetre.)

TABLE XIV

TAPERS

Taper per Foot	Included Angle	
Inches	Deg.	Min.
1/16	0	18
1/8	0	36
3/16	0	54
1/4	1	12
5/16	1	30
3/8	1	47
7/16	2	5
1/2	2	23
9/16	2	40
5/8	2	58
11/16	3	16
3/4	3	34
13/16	3	52
7/8	4	10
15/16	4	28
1	4	46
1 1/8	5	22
1 1/4	5	58
1 3/8	6	34
1 1/2	7	9
1 5/8	7	44
1 3/4	8	20
1 7/8	8	56
2	9	31

Taper per cent.	Included Angle	
	Deg.	Min.
1	0	34⅓
2	1	8⅔
3	1	43
4	2	17⅓
5	2	51⅔
6	3	26
7	4	0⅓
8	4	35
9	5	9
10	5	45½
11	6	18
12	6	52
13	7	26
14	8	0½
15	8	35
16	9	9
17	9	43
18	10	17
19	10	51
20	11	25

		Taper per Foot	Taper per cent.
Deg.	Min.	Inches	
0	20	0·069	·58
0	40	0·138	1·15
1	0	0·209	1·74
1	30	0·313	2·61
2	0	0·418	3·48
3	0	0·629	5·24
4	0	0·838	6·98
5	0	1·049	8·74
6	0	1·258	10·05
7	0	1·469	12·25
8	0	1·678	13·98
9	0	1·889	15·75
10	0	2·100	17·5

Morse Tapers. . . . . No.	1	2	3	4	5	6
Diam. of small end—inches .	·374	·574	·783	1·027	1·484	2·117
Taper per foot—inches . .	·605	·600	·605	·615	·625	·634

Brown & Sharpe Tapers. No.	1	2	3	4	5	6	7	8	9	10
Diam. of small end—inches	·20	·25	·313	·35	·45	·50	·60	·75	·90	1·05
Taper per foot—inches .	·5	·5	·5	·5	·5	·5	·5	·5	·5	·5161

No.	11	12	13	14	15	16	17	18
Diam. of small end—inches .	1·25	1·50	1·75	2	2·25	2·50	2·75	3
Taper per foot—inches .	·5	·5	·5	·5	·5	·5	·5	·5

Jarno Taper. Diam. small end $= \frac{\text{No. of Taper}}{10}$

Diam. large end $= \frac{\text{No. of Taper}}{8}$. Length $= \frac{\text{No. of Taper}}{2}$

All Tapers 0·6 inch per foot, or 1 in 20, or 2° 51′ 40″ included angle.

MISCELLANEOUS NOTES

Grinding Solutions.—

For hardened steel and cast iron—$1\frac{1}{2}$ to 2 oz. of soda (washing) to 1 gallon of water.

For unhardened steel, bronze, &c.—either the above, or soluble oil 1 part, water 20 parts.

Density of Wheels.—

Vitrified—0·09 to 0·1 lb. per cubic inch. Silicate—0·105 to 0·12.

Mohr's Scale of Hardness.—

1. Talc.	6. Orthoclone.
2. Gypsum.	7. Quartz.
3. Calcite.	8. Topaz.
4. Fluorspar.	9. Corundum.
5. Apatite.	10. Diamond.

The hardness of any substance which will scratch any one of these minerals, and can be scratched by the one next higher in the scale, is said to have a value between the numbers of the minerals.

Steel.—

The ultimate tensile strength varies from 50,000 lb. per square inch for soft steel up to 250,000 lb. per square inch for the high tension steels (nickel, chrome, vanadium).

The elongation at fracture varies from 33 per cent. in a length of 8 inches, downwards to 3 per cent. or 4 per cent., according to the quality and heat and mechanical treatment.

The elastic strength (yield-point stress) varies from 40,000 to 160,000 lb. per square inch, being from 0·6 to 0·85 of the ultimate stress.

The elastic extension is proportional to the stress producing it (**Hooke's Law**).

Ductile materials fail elastically when a certain shearing stress is reached (**Guest's Law**).

A material will break after a large number of repetitions of a lower (about half) stress than the yield point (**Wohler's Law**).

Young's Modulus, E, average 29,500,000 lb. per square inch.

The Modulus of Rigidity (or Torsion), C, average 11,000,000 lb. per sq. in.

Poisson's Ratio—the proportion of side contraction to elongation—averages 0·35.

Weight = 490 lb. per cubic foot = 0·28 lb. per cubic inch.

Sp. gr. = 7·84.

The expansion per 1° F. = 0·0000067 of the length.

The expansion per 1° C. = 0·000012 of the length.

The sp. heat is 0·10983.

Temperature for carbonising is 800°—900° C. or 1470°—1550° F.

Temperature for hardening must be above the A point (at which recalescence occurs) = 700° or more.

Temperature for tempering hardened steel tools—

Temper Colours—	Straw	Yellow	Brown	Light Purple	Purple	Dark Blue	Pale Blue
Temperature in degrees F.	440	480	510	530	550	570	600

Slightly overstrained steel can be restored by annealing at the boiling point of water.

Units, &c.—

$$\frac{\text{Circumference of Circle}}{\text{Diameter}} = \pi = 3{\cdot}141592654 \ldots \text{ or } 3{\cdot}1416 \text{ or } \tfrac{22}{7} \text{ (nearly).}$$

1 inch = 2·539998 cm.	1 cubic inch = 16·38702 cubic cm.
1 square inch = 6·451589 square cm.	1 lb. = ·45359 kilogramme.

1 electrical unit (Board of Trade unit of electrical energy) ≡ 1 kilowatt hour = $\frac{1000}{746}$ or 1·34 of 1 h.p. hour.

1 h.p. = 550 ft.-lb. per second = 33,000 ft.-lb. per minute.

1 British thermal unit (heat required to raise 1 lb. of water at 39° F. 1° F.) = 778 ft.-lb. (Joule's equivalent).

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