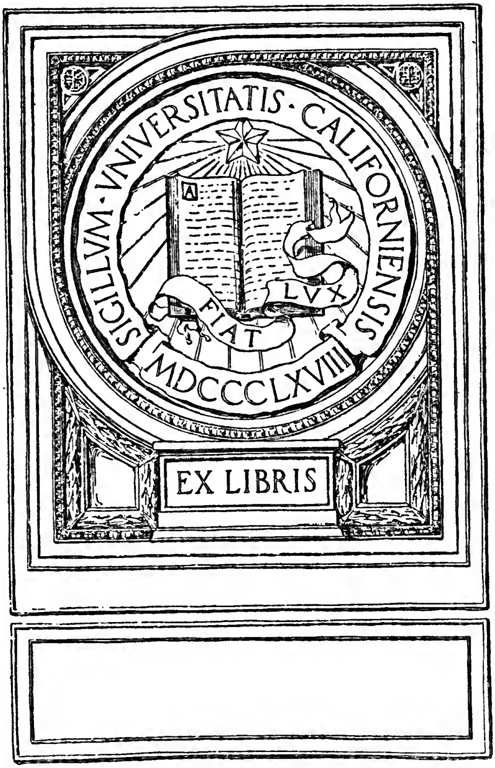
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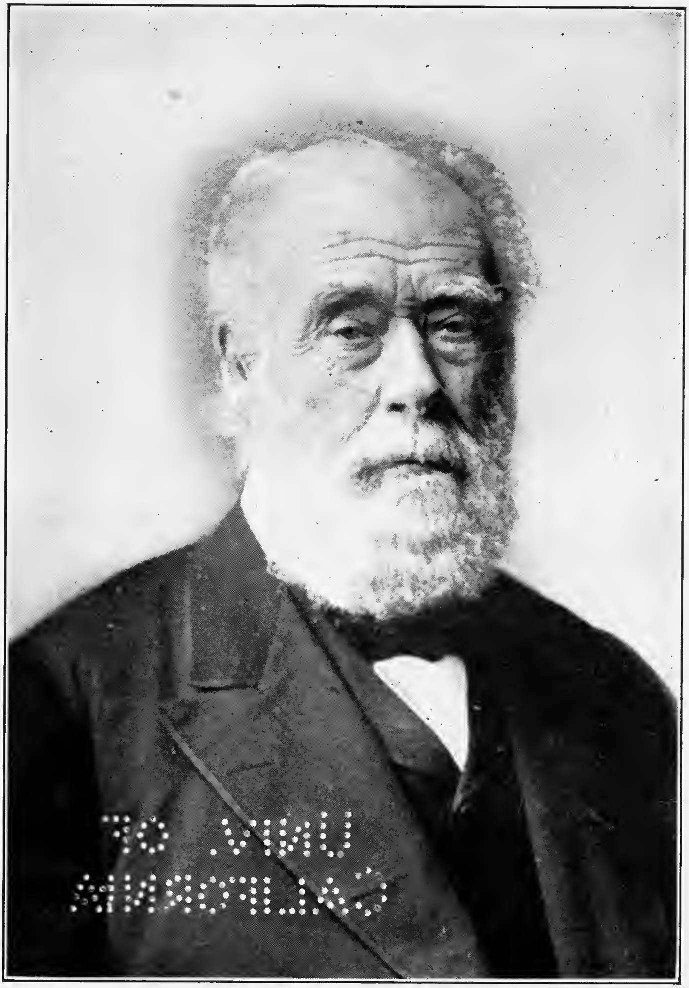
METHODS OF MACHINE SHOP WORK



Frontispiece

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SIR JOSEPH WHITWORTH

METHODS OF
MACHINE SHOP WORK

FOR APPRENTICES AND STUDENTS IN TECHNICAL AND TRADE SCHOOLS

BY

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PREFACE

While the printed page cannot take the place of personal experience, there is, nevertheless, a great fund of information regarding tools, methods and processes that can be acquired from the printed page more effectively than from any other source. Effective as the "picking up" process is as regards the things picked up, it passes by many which are equally important and it has, at best, no logical order or sequence, the information so gathered being unassorted, fragmentary and incomplete. Few machine shops make use of more than a small fraction of the methods which are herein explained and which the properly informed should know but the learning of which commonly requires half a lifetime. While many of the methods shown are the commonplaces of the experienced mechanic, they have not, heretofore, been gathered together in print, and still less have their underlying principles or their mutual relationships been explained for the use of beginners. It is to the explanation of these things that the printed page is best adapted and to which these pages are chiefly devoted.

The volume comprises the substance of the lectures which the author has presented to the students in mechanical engineering at Columbia University for the past three years. It has been prepared in the belief, which is shared by friends who have been consulted, that it would prove useful elsewhere, in trade as well as engineering schools and to apprentices.

The volume presupposes no more than a reasonable familiarity with the more common machine tools, their general construction, uses and fields of application; in other words such a degree of mechanical intelligence as should be acquired by an apprentice in serving one or, at most, two years in any modern machine shop.

The chapters relating to actual machine tools might have been expanded indefinitely. In the embarrassment due to the voluminous material available, the author, in addition to showing basic principles, has chosen to present the less obvious features, passing by many which, while equally important, are reasonably certain to be gathered in the course of everyday experience. To those manufacturers who may feel aggrieved because their own products have not been included, although in many cases as meritorious as those shown, the author would explain that his object is to show methods, not machines, the appearance of the machines being incidental to the showing of the methods. When choice has been necessary, preference has usually been given to those machines which first introduced a given method.

The reader as well as the author is under large obligations to the manufacturers who have so liberally supplied the photographs from which the half-tone illustrations have been made and the more so because, in numerous cases, the illustrations do not show things made for sale. Such photographs have been supplied in the true educational spirit—a spirit that has gone so far as to lead to the making of special exposures when suitable negatives were not available. When old negatives had been destroyed and the making of new ones was impracticable, existing engravings have been reproduced, chiefly from the pages of the *American Machinist* where, in fact, the counterparts of most of those made from new photographs first appeared.

The machine shop is the center from which all modern industries radiate. From the brickyard to the flying machine, from the sawmill to wireless telegraphy, from the stone quarry to the moving-picture camera, there is no modern industry more than twice removed from the machine shop. Of the works of man it is to the author the most interesting place on earth and in this spirit this volume is offered, not only as a source of instruction to the succeeding generation, but as a tribute to those great mechanics, living and dead, of this and other lands, whose active brains and deft fingers have created the marvels of which the attempt is here made to portray some of the inner spirit.

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INTRODUCTION

The object of this volume is to show how the problems of the shop are attacked and solved—not to show how machine tools are operated. This plan necessitates giving considerable attention to precision work which, in turn, emphasizes the intellectual character of the work—a feature which cannot fail to impress the reader and give him increased respect for those who are responsible for the methods and solutions herein set forth. These methods relate largely to the work of the tool maker, which has now reached a stage of development which almost entitles it to be called a profession. In this, tool making is unique among occupations commonly called manual. Its development to the point where manual skill alone is helpless is a matter of the past fifty or sixty years and the development is one the like of which was never seen before.

An attempt has been made to give credit for the leading inventions which mark the development of the machine shop. The author is well aware that in doing this he is treading on dangerous ground, as few things are more difficult than the apportionment of credit for these things. For this there are several reasons. Frequently the first appearance of an invention is in such shadowy form as to make the identification of its origin difficult and even impossible. Frequently great inventions are of a composite character—different elements being supplied by different men—and in many cases of this kind the various elements are useless until combined by some one who does nothing else. Frequently the original suggestion came at a time when the collateral arts were not sufficiently developed to make the use of the invention possible and it had to be reinvented at a later date. In such cases it is a subject of dispute which inventor is entitled to the greater credit. Some consider the chief credit due to him who made the effective invention, as it is certainly to him that the world is indebted for its use. In many cases this is just and proper because of the fight, at first with inertia and later with infringers, with often, in the end, defeat and despair and the passing on of the benefits to others, which too often accompany the introduction of an invention and which should not be forgotten when apportioning the credit. On the other hand, in many cases it is unjust because a later inventor is frequently merely more fortunate in time and circumstance. Even more unjustly, inventions which are perfectly applicable at their first appearance, frequently lie dormant for many years through nothing but indifference and inertia. Add to these considerations the scanty records of industrial developments that exist, and the difficulties of apportioning credit for these things become apparent, as do the reasons for the disputes between friends of rival inventors.

Prof. J. W. Roe has summed up his view of the matter in these words:

> "It is not easy to assign the credit of an invention to individuals. Mere priority of suggestion or even of experiment seems hardly sufficient. Nearly every great improvement has been invented independently by a number of men, sometimes almost simultaneously, often in widely separated times and places. Of these, the one who made it a success is usually found to have united a superior mechanical skill to the element of invention. He first has embodied the invention in such proportions and mechanical design as to make it commercially available, and from him its permanent influence spreads, and the chief credit is due the one who impressed it on the world. Some examples may illustrate this point.
>
> "Leonardo da Vinci in the fifteenth century anticipated many of the modern tools. His sketches are fascinating and show a wonderful and fertile ingenuity, but while we wonder, we smile at their proportions. Unless a later generation of mechanics had arisen to reinvent and redesign these tools, mechanical engineering would still be as unknown as when he died.
>
> "The slide-rest is clearly shown in the French Encyclopedia of 1772, and even in an edition of 1717. Bramah, Bentham and Brunel, in England, and Sylvanus Brown, in America, are all said to have invented it. David Wilkinson, of Pawtucket, R. I., was granted a patent for it in 1798. But the invention has been, and will always be, credited to Henry Maudsley, of London. It is right that it should be, for he first designed and built it properly, developed its possibilities, and made it generally useful. The modern slide-rest is a lineal descendant from his.
>
> "Blanchard was by no means the first to turn irregular forms on a lathe. The old French rose engine lathe embodied the idea, but Blanchard accomplished it in a way which was more mechanical and which is in general use to this day."

METHODS OF MACHINE SHOP WORK

CHAPTER I

THE TWO SYSTEMS OF MACHINE PRODUCTION

The making and manufacturing systems defined and contrasted—The machine tools characteristic of each, their place of origin, development and distinguishing characteristics—Early developments of accurate measurements in Great Britain and the United States—Early history of the manufacturing system—Basic features of the two systems—Effect of the measuring system on shop organization, workmanship and business policy.

THE MAKING AND MANUFACTURING SYSTEMS

There exist two sharply contrasted systems of machine production called respectively the *making* and the *manufacturing* system. Under the first term are included the methods employed when machines are produced one at a time or, at most, in such limited numbers that the methods used are not essentially affected by the number. The second term refers to the methods followed in wholesale production of interchangeable parts.

Of these terms *manufacturing* is suitable and appropriate but as much cannot be said of *making*. Properly considered, the latter term is applicable to *all* methods, but it has come to be used, and will here be regularly used, in this restricted sense. For this there is excellent warrant, as these terms were used in these senses by Charles Babbage in his Economy of Machinery and Manufactures published in 1832, in which these words were defined in a manner which might be used to-day.

While the system used is commonly determined by the number of things made, nevertheless the distinction between the systems lies in the methods employed and not in the quantities produced. Because A makes a few things of a kind and B makes many, it does not follow of necessity that A works under the making and B under the manufacturing system. If we are unwise we may make things in large numbers and so also we may manufacture things in comparatively limited numbers. The two systems are frequently used conjointly in the production of a single product. For instance, in the production of Corliss engines, the larger parts, of which each machine contains but one and which differ with each size of engine produced, are naturally made, whereas the smaller parts of the valve gear, of which each machine contains several, one size of which may be used on several sizes of engines and which, by reason of their smaller dimensions, are better adapted to manufacturing processes, may be manufactured.

MACHINE TOOLS CHARACTERISTIC OF THE SYSTEMS

For the making system and the machine tools by which it is carried on, we are indebted to England, while, for the manufacturing system and the machine tools which are characteristic of it, the United States has the chief credit. Other countries have supplied plenty of things to make—Germany gave us the gas engine, France the automobile and Sweden the steam turbine—but the methods of machine production are almost exclusively the work of the English-speaking peoples.

The machine tools employed in the making process are commonly called the *standard* tools and they comprise the lathe, the planer, the shaping machine, the slotting machine, the boring mill, drilling and gear-cutting machines, all of which originated in England and were brought to a high state of perfection there by the close of the first half of the last century. With the exception of drilling and gear-cutting machines, the characteristic feature of these machines is that the workman determines the dimensions of the work by direct measurement and by the adjustment of the cutting tools for each piece as made.

Without attempting to trace the earlier development, though without forgetting the work of Maudsley, who introduced the mechanical control of cutting tools, it may be said that "the beginning of practice that has endured" is found in the work of John G. Bodmer whose work was done about 1840. Judged by present standards, the machine tools antedating Bodmer's work were primitive, while Bodmer's were not. It may be fairly said that Bodmer started machine-tool design on lines which it has ever since followed. Bodmer's tool-building enterprise was, however, a business failure, and the effective introduction of modern designs is found in the work of Sir Joseph Whitworth who left a wider and deeper mark on machine-shop methods and practice than any one else. He built a great works which still exists.[1] For years his was a name to conjure with. No one else has, or can in future, occupy a similar position. Bodmer and Whitworth were two of a great galaxy of mechanical giants who laid the foundations of the manufacturing industries of Great Britain and of the world, some of the others being Watt of the steam engine, Murdock who was Watt's superintendent and who invented gas lighting, Trivithick who introduced high-pressured steam, Babbage of the calculating machine, Stephenson of the locomotive, Arkwright and Hargreaves of textile machinery, and Naysmith of the steam hammer.

The leading characteristics of Whitworth's work were high-class workmanship, massive construction, hollow frame members, appropriate design, proper distribution of metal, smooth surfaces, rounded corners, straight lines or long sweeping curves, and appropriate paint.

An adequate idea of the advanced character of Whitworth's work may be obtained from Fig. 1, which illustrates a Whitworth lathe (now preserved at the University of Manchester) from designs made in 1849.

While all of the machine tools which characterize the making process originated in England, in some cases their development in the United States outran that in England. This is especially true of the boring mill which, although originally designed by Bodmer, became an established and common tool in the United States several decades in advance of its general

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[1] Consolidated with the works of Sir W. G. Armstrong.

acceptance in England. Similarly, while gear-cutting machines originated in England, their development into automatic machines and the reduction of gear cutting to a manufacturing basis took place in the United States. This latter involved the general acceptance of the diametral pitch system which, although originated by Bodmer and used by some in England, was introduced into general practice by the Brown and Sharpe Manufacturing Company through their production of diametral pitch cutters as an article of manufacture.

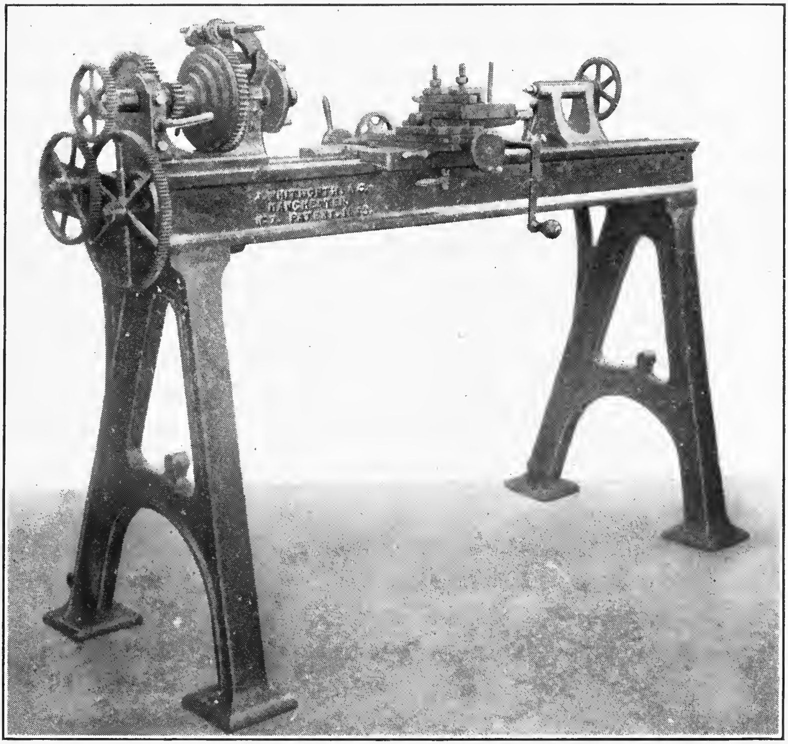

FIG. 1.—Whitworth lathe of 1849.

This adoption of the diametral pitch system was both a case and an illustration of the manufacturing spirit and of manufacturing methods. If a single pair of gears, including the cutters, is to be made, the circular pitch system is as appropriate and perhaps more appropriate than the diametral pitch system and, in fact, is still commonly used for heavy or mill gearing. For small cut gears, especially when made for interchangeable sets, and with the cutters produced as an article of manufacture by specialists, as they must be if they are to be of high grade, the diametral pitch system has every advantage, by reason of its reducing the problem of gear cutting to a manufacturing basis, and for such gears it is and has long been in universal use in the United States.

With the standard tools provided, the Englishman found himself equipped for doing almost anything required and activity in the development of machine tools practically ceased. New machine tool building shops were started, largely by ambitious young men who had learned their trade with Whitworth, but they copied Whitworth's designs—the best thing that could be said about any machine tool being that it was as good as Whitworth's. New machine tool building shops were started in the United States in much the same way, but here the product offered was usually something different from existing designs. Often, in fact, the shop was started because of a burning desire to launch a new idea. In Great Britain this would have been unsafe, because of the overshadowing authority and influence of the name of Whitworth, and in this way the same man acted at one period as a most powerful influence for progress and at a later period as an almost equally powerful influence for stagnation. This period of stagnation came to an end during the first years of the present century, when active development was resumed. In Great Britain the period of stagnation is commonly charged to the antagonism of the trade unions to more productive machines and, no doubt, that antagonism was a contributory cause.

The keynote of English machine-tool design is and always has been quality and serviceability—a fact to which it is impossible not to render ungrudging acknowledgment, and, in some fields of work, notably steam-boiler construction, British work still leads in this characteristic.

The machine tools and equipment characteristic of the manufacturing system are the milling machine, including the profiling machine and the automatic gear cutter, the turret lathe, including the automatic turret lathe, the grinding machine, the multiple spindle drilling machine and all manner of special machines, gages and fixtures or jigs. Of these the plain milling machine, although originally developed in connection with the manufacturing system, has now found large use in the making system, this extension of its field having taken place first in England.

In contrast with the standard tools the characteristic feature of these machines, the grinding machine excepted, is that the cutting tools are adjusted to a certain size which they reproduce in the work, piece after piece, until they become dull, when they are sharpened and readjusted.

While the original appearance of the principle of some of these machines was in primitive and obscure forms which cannot always be identified, it is nevertheless a fact that their chief development, their acceptance as means of production and, in most cases, their original invention took place in the United States. This was due to the combined influence of the high cost of labor and a large homogeneous home market. The former stimulated the search for methods which reduced the labor cost, while the latter justified the increased investment of capital required by these methods.

Without meaning to imply that quality has been lost sight of for machine work in the United States is, and for many decades has been, equal to that done elsewhere, it is nevertheless true, that the impelling motive of American machine-tool design has been quantity—mass production.[1]

THE BEGINNING OF ACCURATE MEASUREMENTS

It should, however, be pointed out that one essential element of the manufacturing system, without which, indeed, it would be impossible, namely, standard gages, originated in England and at the hands of Mr. Whitworth, who, moreover, recognized that "the soul of manufacture is duplication," and Charles

[1] To this the grinding machine is a conspicuous exception, as it is an exception to nearly all general statements that can be made. Its original object was the improvement of quality and it was only after it was put into use that it was discovered that along with improved quality went increased quantity.

Babbage clearly pointed out the advantages of mass production in 1832.

As with so many other things, Whitworth's gage work was foreshadowed by that of Bodmer who invented plug and ring gages and had them in use in his own shop, but it was Whitworth who first produced them with a grade of workmanship entitled to the name of precision and who made them available to others by offering them for sale. This was done about 1850, from which date down to about 1880 the Whitworth works were the world's headquarters for instruments of this character which, during all that period, could be obtained nowhere else.

Meanwhile a corresponding development was taking place in the United States in the improvement of line measures or graduated scales which Whitworth neglected because of his erroneous belief in the fundamentally superior accuracy of end measures. In 1850 D. R. Brown produced a graduating machine and about two years later Samuel Darling produced another, both of which were of such accuracy that they are still in use at the Brown and Sharpe works. As a contribution to the development of accurate measurements, the Brown and Sharpe scales have a place alongside the Whitworth gages. A recent examination of one of these scales of two feet length, made in 1868, showed no error greater than two ten-thousandths of an inch. In 1851 Mr. Brown brought out the vernier caliper, substantially in the form now used and shown in Fig. 53, which was the first American contribution to measurements of precision grade.

This was, however, more than a precision instrument. Giving as it did all sizes within its capacity, it was not only accurate but at the same time so low in cost as to be available for general use.

For reasons which are explained later, plug and ring gages are not well adapted to shop use and, for such use, they have been displaced by others, chiefly the solid caliper or snap gage which was invented by John Richards who had a set of such gages made by the Brown and Sharpe Manufacturing Company in 1865 and who patented the design in 1867. In 1877 Mr. Richards undertook the regular manufacture of these gages, relying upon an imported Whitworth measuring machine to originate the sizes, but this was found so inaccurate that it could not be used and, about two years later, he completed a measuring machine of his own design. The John M. Rogers Works is the lineal descendant of the gage-making business established by Mr. Richards, which was the pioneer in the production of solid caliper gages for sale.

Prior to the construction of Mr. Richard's measuring machine one shown in Fig. 57 was completed in 1874 by Dr. John E. Sweet at the Cornell University shop and exhibited at the Centennial Exhibition of 1876, which was the first American machine of this character. It was intended to form the basis of the manufacture of solid caliper gages, but the attempt to make such gages in any considerable number failed, because of the imperfect action of abrasive grinding wheels as then made.

The development of the subject at the Brown and Sharpe works had in the meantime made a measuring machine necessary there, and the first of the present Brown and Sharpe type was completed in 1878. In 1882 the Rogers-Bond comparator for comparing line and end measures was completed at the Pratt and Whitney works, measuring machines being offered for sale by this company in 1892. Both these companies produced gages which far surpassed those of Whitworth in accuracy, comparisons by independent parties of gages made by the two companies showing perfect agreement. The two companies had independently copied the standard yard at Washington and divided their copies, the agreement of their product being the most satisfactory proof possible of the work of both.

THE BEGINNINGS OF THE MANUFACTURING SYSTEM

It is not to be supposed that the manufacturing system is the outgrowth of the tools which have been named in the preceding pages. On the contrary, the tools are the outgrowth of the system, which originated and was practiced on a large scale at a time when the tool equipment available was of the simplest kind. The system was first developed for the manufacture of small arms which were the first mechanical devices required in large numbers, and its beginning appears to have been in France.

Thomas Jefferson, writing from Paris to John Jay under date of May 30, 1785, says:

> "An improvement is made here in the construction of muskets which it may be interesting to Congress to know, should they, at any time, propose to procure any.
>
> "It consists in making every part so exactly alike that what belongs to any one may be used for every other musket in the magazine."

In a letter to the Governor of Virginia, dated Jan. 24, 1786, Mr. Jefferson testifies that he has examined the gun locks and says: "I found them to fit interchangeably in the most perfect manner."

The most famous early example of true manufacturing methods is the production of blocks for ship's rigging by a series of forty-four special machines designed by Sir Samuel Bentham and Sir Marc Isambard Brunel and made by Henry Maudsley. The machines were put at work in 1808 and continued to supply the British navy with blocks so long as wood continued in use for the purpose.

These examples seem, however, to have been of a sporadic character and to have exerted but little influence on contemporary or subsequent industry. The effective beginning, which was followed by general adoption in not only its own but in many other industries, is found in the production of small arms for the United States army.

This beginning was due to Eli Whitney—he of the cotton gin—who in 1798 contracted to make 10,000 muskets for the United States Government. That these guns were interchangeable we again have the testimony of Jefferson who, writing to Monroe in 1801, said of Whitney:

> "He has invented molds and machines for making all the pieces of his locks so exactly equal, that take 100 locks to pieces and mingle their parts and the 100 locks may be put together by taking the pieces which come to hand."

Equally definite and more competent testimony is found in a report rendered in 1800 by Capt. Decius Wadsworth, inspector of muskets, to the Secretary of the Treasury.[1] The system then adopted for the manufacture of American small arms became and has remained the characteristic feature of their production and the U. S. Armory at Springfield, Mass., became,

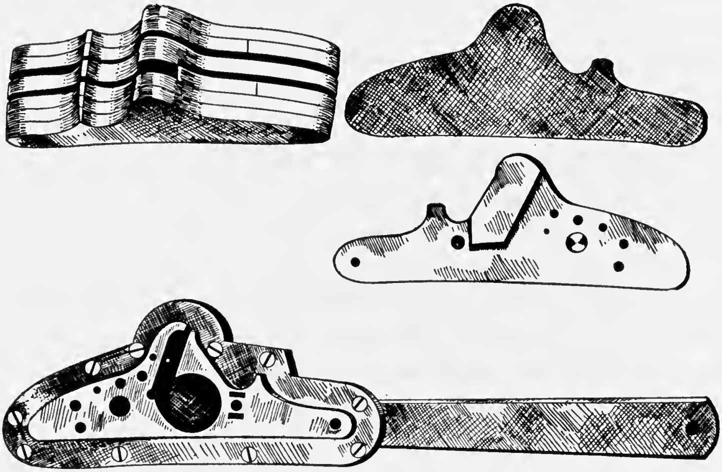

FIG. 2.—The genesis of the manufacturing system.

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[1] Almost contemporaneous with Whitney's contract was one executed with Col. Simeon North for 500 horse pistols, and, although this contract was obtained fourteen months after Whitney's, deliveries under it began earlier. In a biography of Colonel North by his descendants, priority in the use of the interchangeable system is claimed for him. That he used the system in the execution of this contract is not improbable, although the proof is less categorical than in the case of Whitney.

The first contract in which interchangeability was stipulated was awarded to North in 1813 for 20,000 pistols, the stipulation reading: "The component parts of pistols are to correspond so exactly that any limb or part of one pistol may be fitted to any other pistol of the twenty thousand." The appearance of such a requirement in a contract indicates that the system was already established, as no prudent contractor would guarantee such a feature in advance of actual experience with the system.

Just when the requirement of interchangeability became the established custom is not known, but in a contract with North for pistols, dated Nov. 16, 1826, the phrase "uniform locks and the usual uniform component parts" appears.

Both Whitney and North had, for their time, large and well equipped armories—the former at Whitneyville, now part of New Haven, and the latter at Berlin and later at Middletown, Conn. Both continued to make small arms for the government until the end of their lives—the former in 1825 and the latter in 1852. North made both muskets and pistols—the number of the latter aggregating not less than 50,000.

later, the nursery from which the system was transplanted and became the recognized American system of production.

Beyond the fact that Whitney invented and used the milling machine, almost nothing is known of his methods.[1] The earliest record of interchangeable methods of which the author has knowledge is shown in Fig. 2, which is from relics found at the Springfield Armory and which shows the methods used in making the lock plate of the Springfield musket of 1855. When this picture was originally taken other relics showing similar methods and dating as far back as 1840 were found, but in these older cases the exhibits were incomplete and did not show the entire process as does this.

THE ESSENTIAL DISTINCTION BETWEEN THE SYSTEMS

At the upper right-hand corner will be seen the forging for the lock plate as it came from the smith shop. Below is the same plate after having had its flat surfaces milled and some holes drilled through it. In the upper left-hand corner the same piece is again seen between two templets or filing jigs, the inner plates of which are of hardened steel. The jig with the forging in position as shown was placed in a vice and the workman, with a common file, reduced the outline of the lock-plate to that of the filing jig. At the bottom of the illustration the same piece is seen after additional work had been done upon it, and in process of being gaged by insertion in a receiver gage of hardened steel by which the uniformity of the various pieces was tested and determined.

The thing to be especially noted in this illustration is the gage and the fact that the gun part was made to fit this gage instead of being made to fit a mating part of the gun. There is every

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Colonel North's armory was of sufficient importance to have been included in the itinerary of General Lafayette who visited it on the occasion of his re-visit to the United States in 1824, and at this armory were made the pair of gold-mounted pistols presented to Commodore Isaac Hull by the State of Connecticut in 1820. These pistols are now preserved in the Navy Department at Washington and are beautiful specimens of the armorer's art.

The Winchester Repeating Arms Company is, by purchase, the successor of Whitney's business. That of North long since disappeared.

[1] One of Whitney's milling machines—believed to be his first—is preserved at Yale University.

testimony that these guns were interchangeable, and it is obvious from the methods followed that there is no reason why they should not have been. Interchangeability is the determining feature of the manufacturing system and we find in this case true manufacture, although the cutting tool used—a common file—was among the simplest of all.

The feature that makes this a case of true manufacture is the fact that the part was made to fit a gage and this points out the fundamental distinction between the making and the manufacturing systems, which lies not in the methods of production but in the system of measurement. In the making system we use *line measures* or graduated scales, while in the manufacturing system we use *end measures* or gages and it is here that the distinction between the two systems lies. All other differences that can be pointed out are differences of degree, while this difference is one of kind.

While these methods now seem extremely simple and even primitive, it is not to be understood that the workmanship was poor. On the contrary, many old specimens of armorers' work are beautiful examples of workmanship.[1] Simple as the methods now seem, there is ample proof of their advanced character, measured by the standards of their time, as the following extracts from the autobiography of James Naysmith will show:

> "In 1853 I was appointed a member of the Small-arms Committee for the purpose of remodelling and, in fact, reestablishing the Small-arms Factory at Enfield . . . The United States government, though possessing only a very small standing army, had established at Springfield a small-arms factory . . . The government resolved to introduce the American system . . .
>
> . . . "The committee resolved to make a personal visit to the United States factory at Springfield. My own business engagements at home prevented my accompanying the members . . . The United States government acted most liberally in allowing the committee to obtain every information on the subject . . .
>
> "The members of the mission returned home enthusiastically delighted with the results of their inquiry. The committee immediately proceeded with the entire remodelling of the Small-arms Factory at Enfield. The

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[1] The fit of mating pieces is just as apparent under one system of production as another, and the old mechanics possessed a skill of hand which, so far as making the parts fit one another was concerned, answered all requirements.

workshops were equipped with a complete series of special machine tools, chiefly obtained from the Springfield factory."

EARLY PROGRESS OF THE MANUFACTURING SYSTEM

At the beginning of the Civil War the manufacturing system was well developed as measured by its results—interchangeability. Moreover, mechanical, as distinguished from hand, methods had been applied to a number of operations. The drop hammer, the turret lathe, the milling machine, the drilling jig, the Blanchard lathe for gun stocks and other special machines were in use, most of those named being well established. When the war began, the enormous demand for small arms for the Union forces led to further great developments. These were brought about largely by the cooperation of the authorities at the Springfield Armory and the firm of Pratt and Whitney which recently had been established at Hartford. The demand for small arms could not, however, be supplied by the Armory and the Government advertised for bids from private manufacturers. Other business being prostrated by the war, manufacturers having shops adapted—or thought to be adapted—to the work, bid for contracts and, the prices being, under the circumstances, large and safe, they obtained them. They then went to Springfield to learn how the work was done and from there they went home and adopted the same general methods. The war over, the demand for guns ceased but, meanwhile, a great educational work had been done. The sewing machine was just ready to become a household appliance and to its production the same general methods were applicable and were applied. The same was true of agricultural machinery and other things were added from time to time. The application of the system to clock and watch making was made prior to the war, the former (according to Prof. J. W. Roe) by Chauncey Jerome about 1830 and the latter by A. L. Dennison at Waltham in 1848.

It was in this way that the knowledge of manufacturing methods was extended and they became characteristic American methods. The progress made at Springfield was soon recognized abroad. In the early 70's the German armories at Spandau, Erfurt and Danzig were largely reequipped with Pratt and Whitney tools and later, though on a less extensive scale, came the refitting of the armories of France, Russia, Sweden and Denmark.[1]

LINE AND END MEASURES AND THEIR USE

The names, line measure and end measure, are common and of them the former is a good, because a descriptive, name. The latter is not so good because less descriptive. It correctly describes some but not all of the instruments to which it is applied. Fig. 3 shows a group of end measures of which those in the upper left-hand corner are called *rod gages*, the dimension which they give being the distance between their ends. At the right is the *plug and ring* construction, substantially as made by Whitworth. In the lower group of views are shown *solid caliper gages*—or *snap gages* in shop vernacular—the one at the left being for external and the one in the middle for internal measurements. The external and internal gages are frequently combined in the same instrument as shown in the lower right-hand corner.

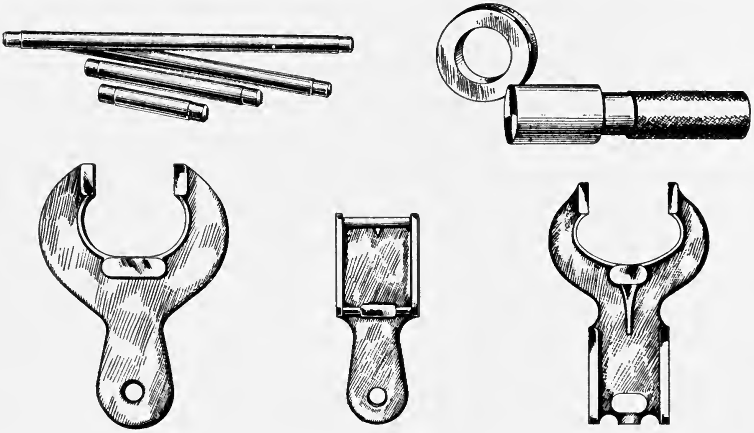

FIG. 3.—Various forms of end measures.

Of these the rod gages are typical end measures, although the solid caliper or snap gage is the most usual form. The plug and

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[1] The author repeats these facts as he heard them from the lips of F. A. Pratt.

ring gages are not adapted for direct use in gaging parts and were not intended for such use by Whitworth. His plan was to substitute a set of these gages for the customary graduated scales and then have the workman adjust his calipers to them—the size of the work being simply a repetition of the size of the gage.

It will be observed that, in the use of line measures, the sense of sight is employed, whereas, in the use of end measures, we use the sense of touch and hence these two kinds of instruments are sometimes called sight and touch measures which names are better than the customary line and end measures.

An obvious difference between these two types of measuring instruments is that, within the limits of its graduations and length, the line measure gives all sizes while the end measure gives one size only, for which reason an equipment of end measures is far more expensive than one of line measures. Another difference is that while the line measure does not lose its accuracy because of wear the end measure suffers deterioration from that cause.

When making two mating parts by the use of a line measure, say a shaft and its bearings, the procedure is to take the size from the graduated scale with a pair of calipers and proceed to make one piece. The size of the mating piece is obtained by transferring from that of the first by outside and inside calipers. If the second piece is made immediately, the same initial adjustment of the calipers may be used, but, if made later, the calipers are first adjusted to the first piece and then transferred, when the second piece is made to fit the first. There is, however, always a difference between the sizes of the two pieces in accordance with their use. If, as in the case supposed, one piece is to turn within the other, it must be smaller by an amount sufficient for lubrication. If, on the other hand, one piece is to be forced within the other, as in the case of a steam-engine shaft and its crank, the first piece must be larger than the bore of the second. Under the procedure described, these allowances for the fit are left to the judgment and skill of the workman.[1]

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[1] This statement refers to the older practice, which, however, is still in large use. In the better shops using the making system the allowances for the fits are now obtained by the micrometer.

It will be seen that the basic feature of this—the making—system is that one part is made to a line measure while the second part is made to fit the first.

On the other hand, when manufacturing parts, the procedure is to make one hundred, one thousand, or ten thousand of both mating pieces to end measure gages and then assemble them expecting that they will fit—the allowance for the fit appearing in the gages—and this is the basic feature of the manufacturing system.

THE INFLUENCE OF THE MEASURING SYSTEM ON FACTORY ORGANIZATION AND WORKMANSHIP

The effect of this difference of procedure is a profound one and it affects the entire organization of the factory.

Under the making system the responsibility for the workmanship is divided. The lathe hand determines the lathe fits, the planer hand the planer fits and the vice hand the hand-made fits. In doing this they have the large advantage of being able to compare the parts by inserting one within the other and thus bring direct judgment to bear on the suitableness of the fits. They do not need to think in thousandths of an inch nor even to have any definite idea of their value. As a matter of fact, before the days of the micrometer caliper, although making fine fits, they had no such definite knowledge and always looked upon such a dimension as the thousandth of an inch with derision, until actually shown by that instrument that they had been habitually making fits that required working well within this limit.

Under the manufacturing system, in place of this division of responsibility, we have concentration of responsibility on the gage maker for, when making the gages, he must determine the fits. He must do this for all grades of work and for parts with the direct production of which he has nothing to do and which, in fact, he seldom sees. Because of this he must possess something more than that intangible thing which we call skill. To skill he must add that very tangible thing which we call knowledge and that most tangible of all tangible knowledge which can be expressed in figures.

It will be seen that the whole gage system is simply a mechanical application of a geometrical axiom—things which are equal to the same thing are equal to each other—and, looking back at the old piece of armory work shown in Fig. 2, we realize again, and more forcibly than before, that, in spite of their laborious character, the piece shown was produced by true manufacturing methods.

To one who has been brought up under the older method of trying parts together and who knows how very, very little is required to spoil a fit, the adoption of the gage method requires courage. The mating parts are made by different men to fit gages made by other men. They are made at different times and, most likely, in widely separated parts of the factory. From the place of production they are sent to a store room to be withdrawn promiscuously as needed and sent to the assembling department, perhaps months after they were made, in the expectation that they will fit. All this requires faith—not merely faith in a geometrical axiom, but faith in tools, in men, in methods, and in the team work of the entire organization.

The story of the manufacturing system is not, however, all written on one side of the shield, for the system has its limitations and its disadvantages. To begin with, the investment is enormous. The cost of gages as compared with line measures has already been pointed out and, while the gages are but a small part of the factory equipment, their cost as compared with that of line measures may be taken as illustrative of the comparative cost of equipment for production by the two methods. The machine tools which have now become identified with the manufacturing system are far more expensive than the much simpler tools which suffice for the making system and, added to their first cost, comes a large outlay for special fixtures and jigs of all kinds. This increased cost of equipment leads to a corresponding increase in interest and depreciation charges and the more so because much of the special equipment is short-lived. In the conduct of the system a tool-making department must be installed and manned by high-priced men, and this department produces nothing that sells. There must be a higher class and an increased number of superintendents and foremen all down the line to the inspectors, all of which leads to a heavy increase of the overhead charge or burden.

The development of the manufacturing system has reached the point where, in many instances, the direct labor cost has almost reached the vanishing point, but against this the overhead charge has increased. Formerly the chief item of cost in producing machinery was the wages paid for direct labor, but to-day the direct labor and the overhead have changed places, the latter being much the larger of the two and the question is frequently and legitimately asked if, after all, the new condition is as healthy as the old.

It is easy to ask: What difference does it make? If the total cost has gone down, as it has, why should one care if the distribution of the cost between labor and overhead has been changed? The reply is that the difficulties of the new system manifest themselves in seasons of dull business. Under the older system in which the chief outgo is in wages to direct labor, the dismissal of some of the workmen in dull seasons reduces the outgo to a degree not differing largely from the reduced volume of business. Under the newer system, however, with the overhead far exceeding the direct wages, the dismissal of some of the workmen has no such effect. The overhead, in turn, is substantially fixed and can be reduced but little and, adjusted as it must be to the conditions of active trade and the chief item of the outgo under those conditions, it becomes ruinous when distributed over the smaller output of dull seasons.

The entire manufacturing system is predicated upon a large output and this compels the manufacturer to make goods of a grade for which there is a large demand. There is thus a relationship between the manufacturing system and the workmanship of the product, but this relationship is so many sided that a comprehensive summary of it is almost impossible. There are cases in which the system distinctly improves the output, a conspicuous example being the making of balls, which are now made by the million, with a degree of accuracy and uniformity surpassing any other mechanical product except gages, and one which would be an absolute impossibility under the making system. Another example is found in machine screws which are turned out in enormous quantities and with a degree of precision that would be entirely impossible under the making system.

The maintenance of a proper standard under the making system would, in many cases, involve prohibitive cost, and under these circumstances, which are illustrated by the manufacture of typewriters and adding machines, the manufacturing system not only improves the workmanship, but does more by making the production of such machines of suitable workmanship a commercial possibility. There are other cases in which there is no need of a high quality of workmanship, an example being found in agricultural machinery in which a high quality of workmanship would be absurd. In still other cases it is undoubtedly true that the general tendency of the system is toward the production of products of medium and cheap grades, examples of this tendency being seen in the enormous present day production of cheap clocks and watches. Even in such cases, however, the system improves the quality of the product which is purchasable at a given price, and even makes possible the production of products which, otherwise, could not be produced at all.

Another effect of the system is the outgrowth of the enormous investment in plant which it demands, a large part of which is for equipment designed for and adapted to the production of the particular thing produced and which must be scrapped when changes are made. The effect of this is to postpone improvements—the desire to make improvements being held in check by the knowledge that they call for large additional capital investment.

THE INFLUENCE OF WORKMANSHIP ON COST

There is no doubt that the standard of workmanship of manufactured goods is rapidly improving or, more properly, extending. This latter word is used because progress in these matters is not a matter of yesterday or the day before. In some things Whitworth set the highest standard that prevails to-day three-quarters of a century ago. Watt made a micrometer caliper over a century ago and Whitworth's crowning achievement—a measuring machine which did unquestionably indicate differences of dimensions of a millionth of an inch—was publicly exhibited in 1851. These citations will show that the conception of accuracy and, in some cases, its realization are by no means recent and that present day achievements are the outgrowth of the gradual development of the constructive arts rather than of the conception of and desire for higher standards.

The extension of accurate workmanship is largely due to the growing knowledge of the fact that up to a certain (or uncertain) point the product is made more cheaply as the workmanship is improved—a fact that grows out of the increased economy of assembling when the parts are well made. If the parts are not alike, fitting must be resorted to during the process of assembling and, in complex machines like typewriters or adding machines, the expense of this would be ruinous. On the other hand, if the parts are alike, the assembling becomes little more than placing and securing them in position.

This point up to which improved workmanship cheapens the product cannot be defined, but beyond it further improvement of quality increases the cost at a rapid rate and nothing is more important than a realization of this fact. Because of it mechanical enthusiasm must constantly be held in subjection to sound judgment. At every point the question must be asked, is not this good enough? This phrase "good enough" is subject to much unmerited criticism. As a matter of fact, no commercial product is produced of any better grade than that which the producer considers good enough. This subject is treated at greater length at the conclusion of the chapter on Fits and Limits.

CHAPTER II

PRECISION WORK AND WORKMANSHIP

Interchangeability and high accuracy not synonymous—Tendency of all machine work toward degradation of workmanship—Precision workmanship checks this tendency—The three kinds of accuracy—Originating flat surfaces—Uses of such standards—Originating squares and other angles by the scraping process—Other methods of originating squares and angles—Uses of such standards—The principle of the division of funcitons—Originating index plates—Originating index worm wheels.

THE INHERENT TENDENCY TOWARD DEGRADATION OF WORKMANSHIP

It is, no doubt, by this time clear to the reader that interchangeability and high accuracy are not synonymous, although there is a very common—almost vulgar—impression that they are synonymous. Interchangeability by itself means little more than that the holes shall be larger than the plugs—the amount by which they are larger being a matter of workmanship and not of interchangeability. A concrete example of interchangeability without accuracy is found in stove lids which never fail to interchange, but which no one ever called accurate. The remarkable thing about an interchangeable machine is not that it is interchangeable but that, being interchangeable, it is also well made. It is an easy thing to make stove lids interchangeable, but interchangeable watches are another story and between stove lids and watches the essential difference is one of workmanship.

Any discussion of manufacturing methods is thus inextricably bound up with the subject of accuracy, by which is meant not high accuracy but the degree of accuracy suitable to the product and the means by which it is obtained.

In all machine work there is an inherent tendency toward degradation of workmanship. The manufactured product is never as good as the gages to which it must conform and it is very seldom as good as the machine tools on which it is made. This tendency arises from several causes and is of such fundamental importance as to require the giving of concrete examples.

Assume the dividing head of a universal milling machine to be set up for the purpose of cutting some gears. The dividing head of the Cincinnati Milling Machine Company is shown in Fig. 4, and like all others, it contains three parts whose accuracy determines the accuracy of the spacing of the gear teeth. These are the worm wheel *a*, on the work spindle *b*, the worm *c* by which this worm wheel is driven and the index plate *d* by which the divisions are determined. If the dividing head is by a first class maker, all of these parts are of a high degree of precision but the maker would be the last man to claim them to be perfect. The spacing of the teeth of the worm wheel is not absolutely uniform, the thread of the worm is not a perfect helix and the spacing of the index plate holes is likewise not absolutely uniform. All of these parts contain errors of a magnitude such that they can be found and measured.

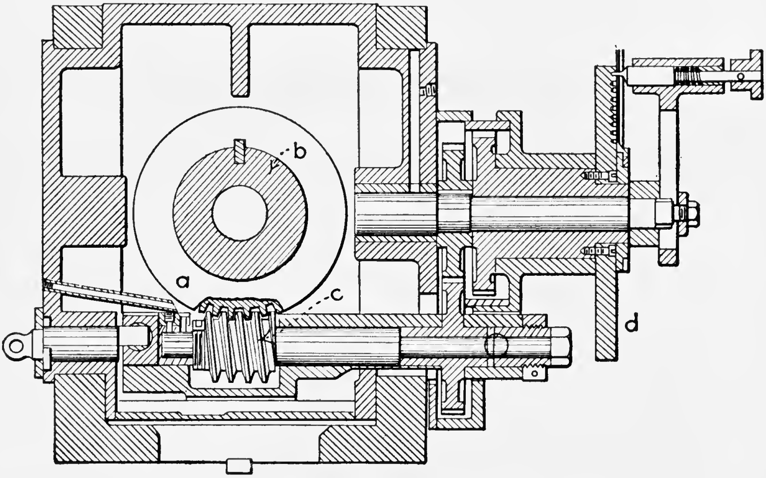

Fig. 4.—Section of milling machine dividing head.

As the gear blank is turned from tooth to tooth, these three parts assume various relative positions and the three errors, combined in various ways, reappear as errors in the spacing of the gear teeth. In some of these positions the three errors are added together and if the work is continued long enough, a position will ultimately be found in which the three maximum errors are added together. These considerations show that the errors in the product must exceed the individual errors of the dividing head parts.

Suppose next that these gears are to be the change gears of a lathe and assume them to be mounted on the lathe for the cutting of a screw. The gears are first class gears because they were made with first class appliances but, as we have seen, they contain errors. If the lathe is from a high class maker its lead screw is a high grade product, but again the maker is the last man who would claim it to be perfect. Like the dividing head parts, it contains errors that can be found and measured.[1] Under these conditions it is plain that when a screw is cut in the lathe the same combination and addition of errors takes place, the resulting screw being of an accuracy which is inferior to that of the lead screw of the lathe.

Assume next that this screw is to be the worm of the dividing head of a milling machine. Assume it to be in place and a second set of gears to be cut. Then assume these gears to be placed on the lathe and another worm to be cut which, in turn, is used to cut another set of gears, and so on indefinitely. It is clear that in every case the addition of errors takes place and that each succeeding worm and set of gears is more inaccurate than its predecessor. A vicious circle, so to speak, has been established and every time we go around it the product is worse than the time before.

The above is an illustration of the degradation of workmanship from geometrical causes. There are other causes which are more universal and all-pervading than this. If a bar be turned in a lathe and then placed in a grinding machine and a light cut be taken from it, the action of the grinding wheel will disclose high and low spots, precisely as the turning tool in a lathe will disclose high and low spots in a bar of rough iron. Now the errors thus disclosed are not in the lathe. The ways

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[1] Methods of finding and measuring some of these errors are given on later pages.

of the lathe are as straight as they can be made and the spindle is as well made and as good a fit in its bearings as can be made. The errors disclosed by the grinding wheel are due to the spring of the work under the pressure of the cut.

Other causes of similar spring are found in the pressure of chuck jaws and binding straps, while in other cases the effect of heat comes in to introduce errors. When a gear blank is mounted for cutting it is, at the beginning, of uniform temperature. The action of the cutter generates heat and, after a few spaces have been cut, there exists a region of gradually warming metal ahead of the cutter and another of gradually cooling metal behind it, leading to local distortion of the work.

It is not to be imagined that these errors are necessarily important in their first generation. Some, like the spring due to binding straps, may be unless the workman exercises care and skill, but others are not. The trouble is, however, that, like the rabbits in Australia and the gypsy moth in Massachusetts, while harmless at first, they breed.

THE FUNCTION OF PRECISION WORKMANSHIP

What is to be done about it? Obviously something must be done. We cannot go on indefinitely round and round a vicious circle repeating and multiplying old errors. Some way must be found by which to establish and maintain a suitable standard. Since the workmanship of the product is poorer than that of the machine tools on which it is made and since machine tools are themselves the product of other machine tools, and subject to the same tendency toward degradation, it is plain that, if a suitable standard is to be maintained, a way must be found to offset this tendency and to make machine tools better than the products that come from them—they must be good enough to permit some letting down of workmanship and still have the workmanship good enough for its purpose.

All this is equivalent to saying that, back of the commercial product, there must be a grade of workmanship superior to it. This grade of workmanship is called precision workmanship and it had its origin with Sir Joseph Whitworth. A definition of precision workmanship is difficult to formulate—in fact impossible if it is to be made to cover all kinds of work entitled to the name. Broadly speaking and with some exceptions, precision workmanship may be defined, in the first place, as workmanship of high accuracy, of course, and, in the second place, as done by methods of which the resulting accuracy is not dependent on the accuracy of similar work previously done.[1]

Enough has been said to show that precision workmanship is of fundamental importance and it will receive corresponding attention in these pages, the aim being to give some idea of its spirit, methods, and purposes. This can be done by examples only, as the subject is not capable of generalization. The only generalization regarding these methods that can be made is a negative one, namely: Precision work is never done by direct methods, those methods being, on the contrary, indirect and roundabout. Even this statement is purely a matter of observation which shows that one practically never goes about a piece of precision work in the manner which a novice would expect or as experience with commercial methods would suggest. Precision workmanship is, in fact, in a class by itself—a thing apart.

It is doubtless already apparent that the importance of precision workmanship is out of all proportion to its volume. Except as seen in gages, measuring machines and high-class machine tools, it is not, to any large extent, offered for sale. It is usually done at home to meet the problems in hand. So thoroughly apart from ordinary commercial workmanship is it, that one may live a life time in a mechanical atmosphere and scarcely see it. One may go as a common sightseer through great factories which are absolutely dependent upon it and not see it. The National cash register, the Burroughs adding machine and the Morse silent chain are composed chiefly of punchings which convey no impression of accuracy, and yet no finer examples of precision work exist than can be found in the tool rooms of the factories where those things are made. The way to see work of this character is to get next to the head tool maker in a factory of this kind and to ask a few questions of a

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[1] The principal exception to this definition is the work of the grinding machine.

kind to show that the enquirer is one of the elect, when the result will be to open up such a fountain of interest and enthusiasm as exists nowhere else in the factory.

THE THREE KINDS OF ACCURACY

In discussing the subject of accuracy three kinds of accuracy are to be distinguished. These are accuracy of form, of size and of position or adjustment. By accuracy of position or adjustment is not meant the kind of adjustment obtained with a knurled headed screw but the kind of adjustment that is built into a machine. For example, the head and tail spindles of a lathe must be accurately in line with one another, the movement of the cross slide must be accurately at right angles to this line and, similarly, the shaft of a steam engine must be at right angles with the center line of the cylinder, all of these cases being illustrations of what is meant by the term accuracy of position or adjustment.

Accuracy of form and of position are equally important whether machinery is made or manufactured, but accuracy of size is of importance in the manufacturing system only. For example, in making the shaft of a steam engine of which the drawing calls for a diameter of ten inches, it is obviously of no importance whether the actual size is exactly that or not and, made by the usual methods, it is certain to vary from that size by several thousandths of an inch. It is likewise of no importance whether or not the shafts of different engines are of exactly the same size. The requirements are that the shaft shall be round and straight—that is, have accuracy of form—that it shall be a suitable fit in its bearings and that, when assembled, it shall stand at right angles with the center line of the cylinder —that is, have accuracy of position.

In manufactured work, on the other hand, accuracy of size becomes important because of the necessity for interchangeability and it is because of the necessity for interchangeability in one case and the absence of it in the other that we have the different methods of measuring in the two systems.

Of accuracy of form we have no unit, gage or method of measurement. Because of this we cannot specify in any definite manner the degree of accuracy of form desired. Accuracy of this kind is determined by the method of production. If a planed surface is sufficiently accurate for the purpose we call for planing; if scraping is needed we call for it and if we want something better still we call for lapping. In the same way turning, grinding or lapping is called for in connection with round work and in accordance with the degree of accuracy required. It does not follow that all planed, scraped, turned, ground or lapped work is of the same grade, but, in the absence of any definite unit of accuracy of form, specifications of the method of production are the only recourse, the expectation being that the work will come up to the standard of the methods specified.

THE ORIGINAL PRECISION PROCESS

The first precision process to be taken up is scraping, which insures that surfaces shall be flat—that is, have accuracy of form. Not only is this process the first to be taken up here, but it was the original precision process, as it is still the most important and the most common. It is, moreover, the foundation of all others as it is a simple fact that not one thing of a precision character can be done without flat surfaces to begin with. The process was invented by Whitworth and, although now a commonplace thing in the shops it was, when new, received and published as a paper by the foremost scientific society of the world—The British Association for the Advancement of Science. The publication of this paper took place in 1840 and it marks an epoch in the history of the machine shop, as it marks the birth of the attainment of precision. Prior to that date there was no known means of making truly flat surfaces, which is equivalent to saying no known means of doing precision work of any kind.

The process is believed to have been brought to the United States by A. M. Freeland at a date which cannot be located more closely than that it took place prior to 1857.[1]

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[1] Regarding this and other features of Mr. Freeland's work, of which particulars are given later, the author's information is obtained from W. H. McFaul who was associated with him from 1857 until the end of his life.

The ordinary process of scraping, with a standard surface plate already in existence, is well known and need not be described. Whitworth's invention was of a method by which plates were made without reference to existing plates and such that the method itself supplied the proof of the accuracy of the result. In brief, the process consists of making a set of three plates and continuing the scraping until any two plates from the set of three make perfect contact throughout their surfaces. In order to insure this it is necessary that each plate have three points of support and no more. Three points determine a plane and with three points of support a plate may rest on any surface without distortion due to its own weight. With more points of support a plate, when placed on a work bench, which cannot be flat, will distort from its own weight and, placed in different positions on the bench, it will distort in different degrees and directions. Satisfactory results cannot be obtained with more than three supporting points. The ribbing also should be carefully laid out with the primary ribs connecting the three supporting points. Such ribs are sufficient for small plates, but larger ones require additional ribs.

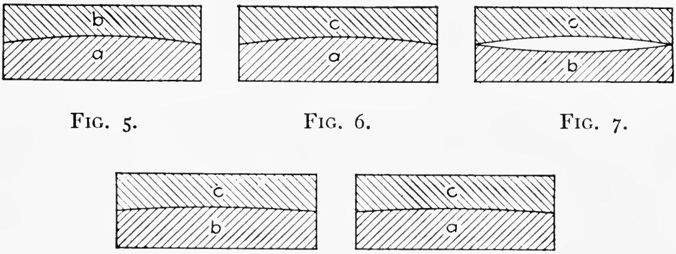

Fig. 5. Fig. 6. Fig. 7.

Fig. 8. Fig. 9.

Method of originating flat surfaces.

The process is illustrated in detail in Figs. 5–9. The plates are first planed and then one of them is smeared with paint—red lead or Prussian blue. The second plate is then rubbed upon the first, after which the high spots shown by the paint are removed with the scraper. This is repeated several times when the paint is removed from the first plate and applied to the second and the scraping process is continued on the first. The object of reversing the paint is to get rid of the tooled surfaces and their local irregularities. Eventually the plates are brought into agreement but without certainty of their being flat—the presumption being, in the ratio of infinity to one, that they are not flat but curved as in Fig. 5. When a satisfactory degree of agreement has been obtained, one of the plates, as *b*, Fig. 5, is laid to one side and *c* is scraped to agree with *a* as in Fig. 6. At this stage of the work there is no reversal of the painting and scraping, the aim being to make *b* and *c* duplicates—that is, have the same degree of untruth. When agreement between *a* and *c* has been obtained as in Fig. 6 *a* is laid to one side and *b* is brought back as in Fig. 7. The degree of untruth of both *b* and *c* which, in the illustration, is, of course, grossly magnified, is made manifest by another application of paint and the scraping process is renewed, the aim at this stage being to remove, as nearly as possible, the same amount of metal from each plate. To insure this *b* is first smeared with paint and a certain number of scrapings are made on *c*, after which the paint is applied to *c* and the *same number* of scrapings is made on *b*. The result is, obviously, a great improvement, but when *b* and *c* have been brought to agreement there is still an overwhelming probability that they will still be curved, although to a much larger radius as indicated in Fig. 8. After agreement has again been brought about, one of the plates, as *b*, is placed to one side and *a* is scraped to agree with *c*, Fig. 9. When this has been accomplished *a* and *b* have become duplicates, when they are brought together and scraped to agreement—the scraping being again divided, as nearly as possible, equally between them. This process is continued with progressive improvement until any two of the three plates show perfect agreement, when, by the very nature of the process, all three of them are flat.

It may be objected that the process is one of successive approximation to which there can be no end but, as a matter of fact, there is. The process may be compared with a rapidly converging series—meaning by this, not rapid in the sense of time, for the work is slow and tedious, but rapid in the sense that, if the work is intelligently done,[1] comparatively few passes around the circle will bring the plates to a condition in which no further error can be discovered.

It will be observed that this is a perfect illustration of the definition of precision work, as the result obtained is in no way dependent upon anything previously done. Given a scraper and a pot of paint, it might, if necessary, be done in the wilderness with just as good final results as if done in the best machine shop in the world.

There is a high degree of satisfaction in doing work of this character. When finished, one feels that he has really *made* something—made it himself and without dependence upon others or the work of others.

Plates made in this manner are called *original* plates. It is not to be understood that all plates are original and, as a matter of fact, but few of them are. With three plates originated in this manner, they may be used as standards and be copied indefinitely, provided they are occasionally tested and corrected by another application of the process by which they were made.

When long and narrow, surface plates become *straight edges* and in this form they illustrate Dr. Sweet's classical definition: "A perfect straight edge is one of three, any two of which, when placed together, coincide throughout their length." This is a mechanical definition of a straight line. It is fundamental and is at least as satisfactory as any geometrical definition that has ever been given.

APPLICATIONS OF SCRAPED STANDARDS

One application of such straight edges is to the making of the V's and cross rails of planing machines and this application is a perfect illustration of the manner in which precision workmanship establishes a standard and sets a limit to the degradation of commercial workmanship. Were the V's and cross rails of planing machines made on existing planing

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[1] There is no class of work in which good judgment on the part of the workman is more important than this.

machines and were this process repeated indefinitely, the accumulation of errors, which has been explained, would obviously be in full operation and there would be no limit to the process of degradation. By scraping the V's and cross rails, however, every planer begins its life with a certain standard of accuracy, and the work which comes from it is only once removed from precision workmanship.[1]

Figs. 10 and 11 show the application of a straight edge to the testing of the vertical parallelism of the ways of a lathe bed, as practised at the works of the Hendey Machine Company. Six blocks which are flat on their tops and have V notches to fit the V's of the lathe bed, are placed upon the V's and across them are laid three parallel strips—all these parts being accurately made so that, the lathe bed V's being individually straight, the straight edge will make contact with all three of the parallels in the position shown in Fig. 10. If, now, the lathe bed V's are not parallel vertically the tops of the parallels become three elements of a warped surface containing no straight lines except one set parallel with the parallels and another set parallel with the lathe V's. Consequently, if the straight edge is swung diagonally across the lathe bed as in Fig. 11 it will ride upon the end parallels and fail to make contact with the center one, or it will ride upon the center one and fail to make contact with the end ones and, the direction of the error being determined, the lathe bed V's may be scraped to correct it.

Another application of the same principle is shown in Fig. 12, which illustrates the process of erecting a long planer bed in the shops of the American Tool Works Company on which the work is finished but which, by reason of its length—fifty-five feet—and flexibility, must be set in its permanent position with great care. The planer V's being inverted from those of the lathe, the V blocks used in the former case are here re-

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[1] The author is well aware that some planer manufacturers succeed in making planer V's of a satisfactory degree of accuracy without scraping them, but this does not alter the fact that the work was begun with scraped V's and that the scraping process must be reverted to again from time to time if a suitable standard is to be maintained.

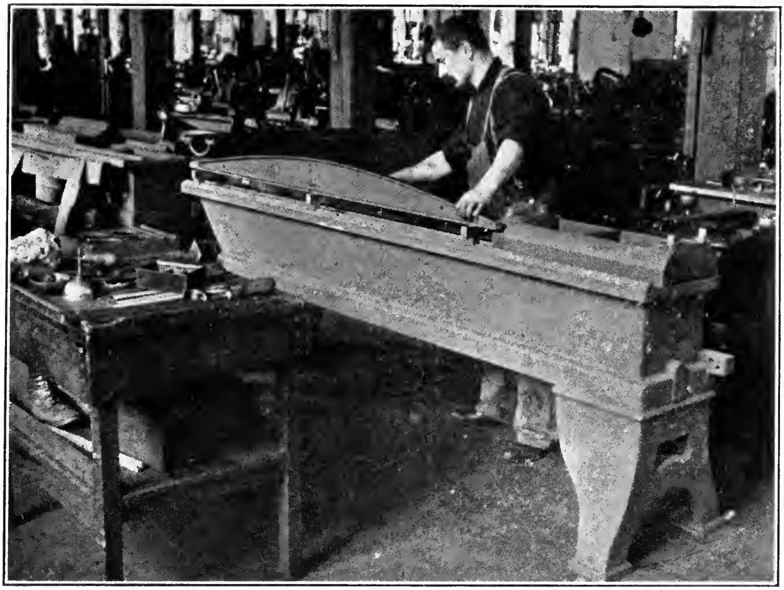


FIG. 10.—Testing a lathe bed for straightness.

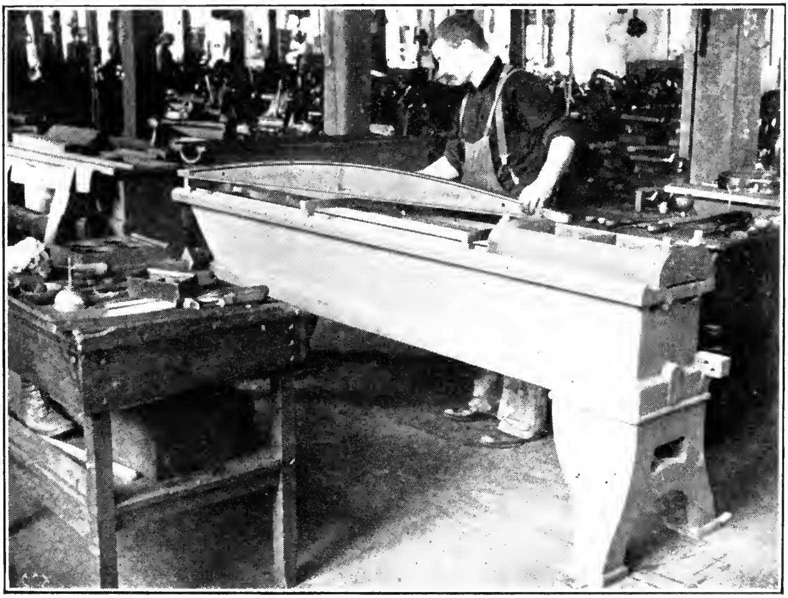


FIG. 11.—Testing a lathe bed for wind.

placed by short cylinders which may be easily made of the same diameter. Across these cylinders are laid three parallels of precisely the same thickness and to these the straight edge is applied in the manner shown in connection with the lathe bed—the straight edge in this case being eight feet long. Below the planer bed at regular intervals adjustable wedges are placed

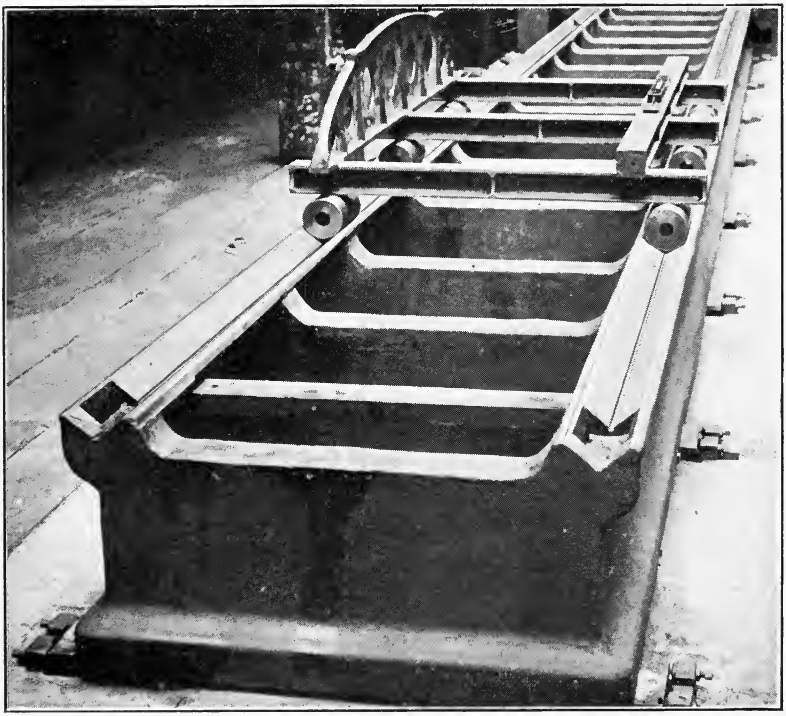


FIG. 12.—Erecting a long planer bed.

and by suitable adjustment of these in accordance with the indications of the spirit level shown and of the straight edge, the planer bed may be brought to a position in which it is level and without wind.

ORIGINATING SQUARES BY THE SCRAPING PROCESS

Other things besides surface plates and straight edges may be originated by the scraping process and among these are right angles or squares. The customary form of shop square is not satisfactory. The surface of the blade edge is inadequate and the blade is not well secured in the head. Few shop squares which have seen much use will satisfactorily stand a test for accuracy.

Figs. 13–16 show a form of square due to Dr. John E. Sweet which is far more permanent than the usual form. The hypothenuse and other braces insure that, once made correct, it will stay so, while the surfaces are large enough to endure much use without appreciable wear. The hypothenuse gives angles of thirty and sixty degrees and the short brace has raised pads near its ends by which angles of forty-five degrees may be determined. Small plates, slightly longer than the width of the faces of the square and shown each side the square in Fig.

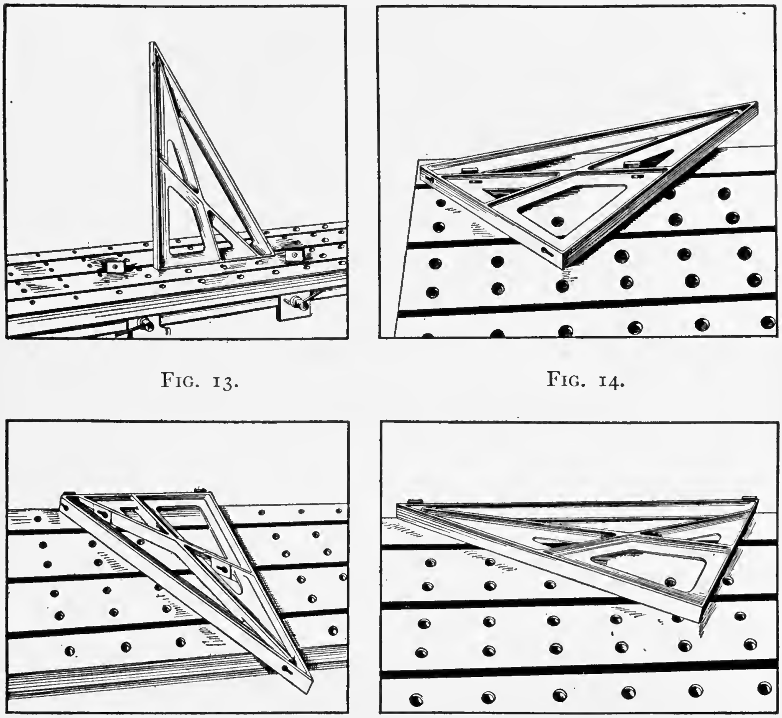


Fig. 13. Fig. 14.

Fig. 15. Fig. 16.

A superior machine shop square.

13, are fitted with small bolts and thumb nuts by which they may be attached to the square as indicated in the various figures. Fig. 15 shows the instrument in use for obtaining a right angle, Fig. 14 for obtaining angles of forty-five degrees, and Fig. 16 for obtaining angles of thirty and sixty degrees.

The method of originating these squares—which was used by Whitworth—is shown in Figs. 17–19. A straight edge is first provided and here we have an illustration of the fundamental importance of straight surfaces for, without them, the originating of the squares would be impossible. As in the case of the surface plates and straight edges the squares are made in sets of three. These are first planed as correctly as possible and, as in the case of the surface plates, two of them are first scraped to make their sum equal to two right angles but, as indicated in Fig. 17, when this has been done the probabilities are all against their being true squares, one of them being slightly over and the other slightly under ninety degrees. When agreement has been secured, one of the squares, as *b*, is removed and square *c* is substituted for it and scraped to agree with *a*—no scraping being done on *a* at this stage in order to insure that *b* and *c* shall have the same degree of untruth. When the agreement between *a* and *c* is obtained, as indicated in Fig. 18, *a* is removed and *b* and *c* are placed together as in Fig. 19, when they are scraped into agreement, the aim at this stage being, as in the case of the surface plates, to divide the scraping equally between the two squares as nearly as can be done. The result is a large improvement, but when *b* and *c* have been brought to agreement there will still be an error similar to that between *a* and *b* in Fig. 17 but smaller. The process of correcting this is exactly

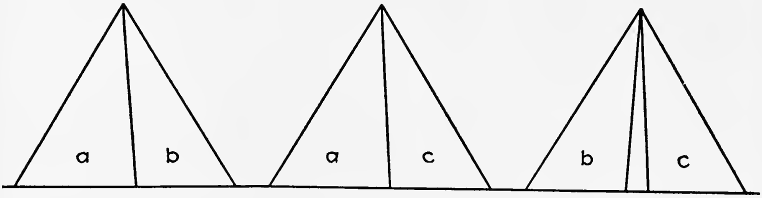


Fig. 17. Fig. 18. Fig. 19.

First method of originating squares.

parallel with that followed in the case of the surface plates and it seems unnecessary to explain it in detail at greater length. The final result is three squares which, by the nature of the process by which they were made, are known to be correct. Uses of such squares are shown in Figs. 82–85.

OTHER METHODS OF ORIGINATING SQUARES

Other methods exist for originating squares, one of which is illustrated in Fig. 20. A square—in this case having an internal angle—is first made as accurately as possible by mechanical means. A rectangular plate of sheet metal is then fitted to this square at one of its angles, as *a*, and then at *b* and *c* in order.

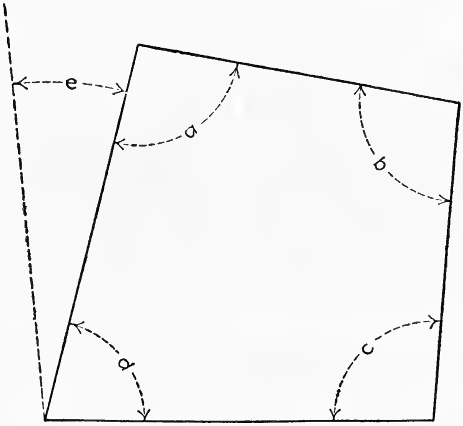


FIG. 20.—Second method of originating squares.

This done, the square is applied to the angle at *d* when the error will be shown at *e* multiplied by four—three times for the rectangular plate and once for the square. The direction of the error being now known, the square is corrected, as nearly as may be, and the angles of the plate are corrected to agreement with it. The process is continued until the error at *e* disappears when, obviously, both the square and the plate are correct. The work once done, the square may be put into use and the plate may be preserved for making future squares.

In the above cases the original squares were intended for shop use. More frequently the aim is to make a test square by which to test and correct the working squares. An example of this kind, from the works of the Ingersoll Milling Machine Company, is shown in Fig. 21. A scraped surface plate of suitable form is first made and then a skeleton cylinder is ground on a grinding machine to be truly parallel and cylindrical and to have at least one end truly square with its center line—the making of such a cylinder with a good grinding machine being an easy and simple matter. The cylinder is then placed upon the surface plate as shown when, by the nature of the work, the angle between the surface plate and the side of the cylinder is truly square. The illustration shows also the manner of test-

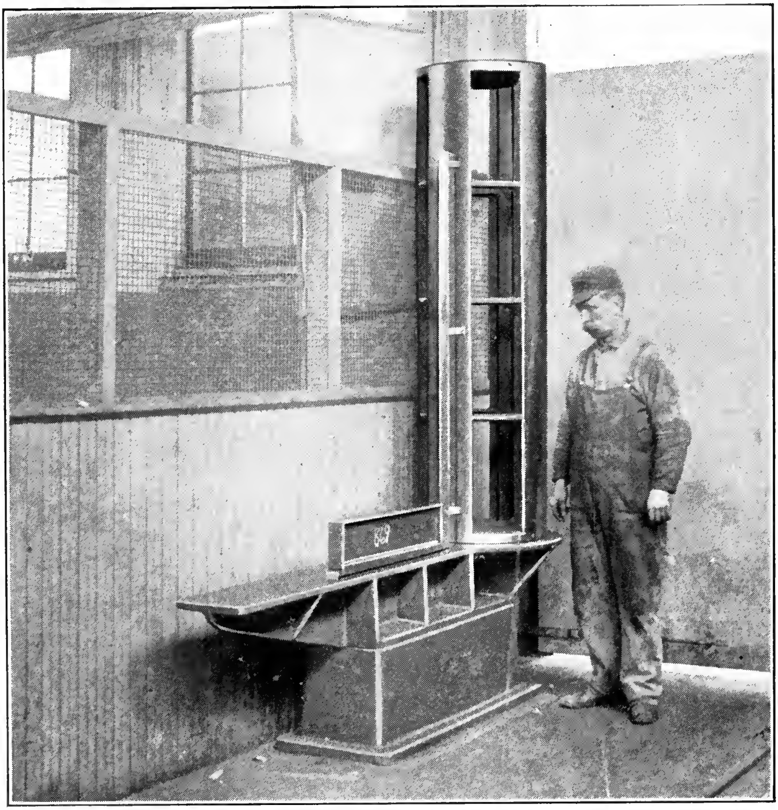
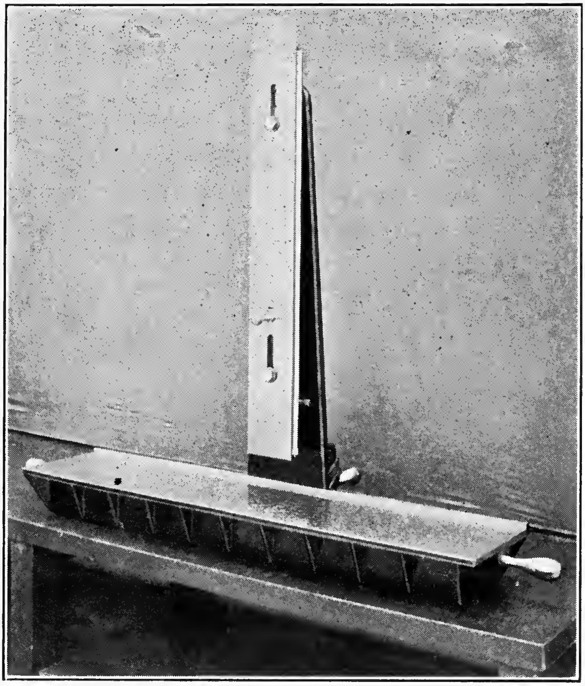
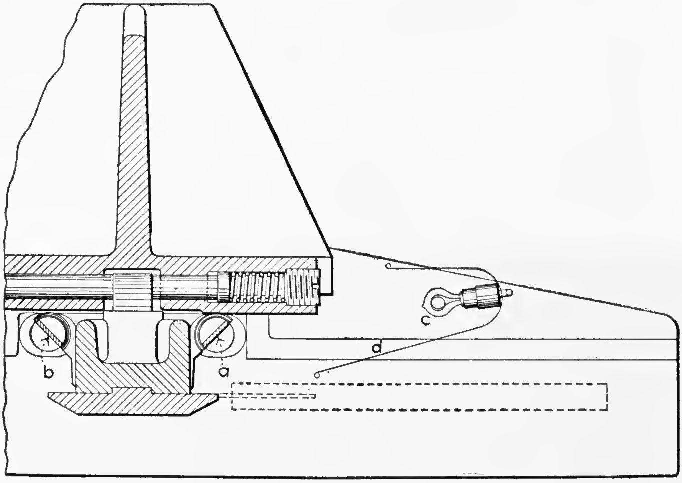


FIG. 21.—Third method of originating squares.





FIGS. 22 and 23.—Fourth method of originating squares.

ing shop squares by the test square. Placed in position as shown, small pieces of paper are placed between the cylinder and the blade of the shop square and, if the pieces of paper are all pinched alike, the truth of the shop square is proven.

Pieces of paper used in this way are commonly called *tissues*, although actual tissue paper is seldom or never used. Good printing paper is surprisingly uniform in thickness and, in use, is very sensitive and satisfactory. It has many applications.

It will be observed that this process does not conform to the definition of precision work, as the result depends on the accuracy of the grinding machine. It is the cheapest method of making a correct square and is in wide use.

Another form of test square, from the works of Ludwig Loewe and Company, is shown in Figs. 22 and 23.[1] The base of the instrument is a narrow surface plate having at its rear a vertical arm from which there is suspended a blade of hardened steel of which the two edges are truly parallel. In use, the shop square resting upon the surface plate has its blade applied to the blade of the instrument as indicated in the dotted outline of the plan view. The instrument blade is now adjusted to make contact with the blade of the shop square and the shop square is turned bodily around and applied to the opposite edge of the instrument blade. If the shop square is correct, it will, of course, make perfect contact in the second position whereas, if incorrect, the error will appear, multiplied by two, as an angle between the two blades. To facilitate the use of the instrument, long narrow mirrors *a* and *b* are placed as shown, together with a row of incandescent lights *c* and a suitable shield *d*—the instrument being used in a darkened room.

Another very satisfactory form of square for some purposes is an application of the spirit level. A false impression of the accuracy of this instrument prevails because, in the form most commonly seen—that used by masons and carpenters—it makes no pretension to accuracy. For this use, in fact, a really accurate level would be practically useless. Every surveying instrument carries precision levels and should prevent the

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[1] The two illustrations do not agree in all details because made from different instruments. They are, however, identical in all essentials.

formation of this impression. In the present use the level used is of surveying-instrument grade.

A shop square in which dependence is place upon a spirit level is shown in use in Fig. 24, the operation being that of testing the squareness of a boring mill housing with its bed. The application of the instrument is obvious and self-explanatory.

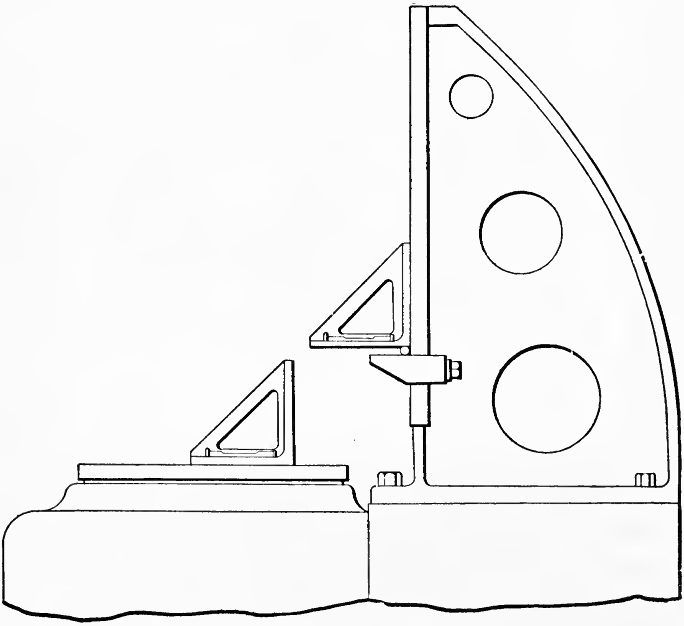

FIG. 24.—The spirit level square.

ORIGINATING ANGLES OTHER THAN RIGHT ANGLES BY THE SCRAPING PROCESS

Certain angles other than right angles may be originated by the scraping process and among these are angles of forty-five degrees for which the process is indicated in Fig. 25. As always, we begin with a surface plate to which must be added two straight edges. In order to originate angles of forty-five degrees we must first have, also, a right angle as one angle of a triangle of which the forty-five-degree angles desired are the others. The straight edges are laid upon the surface plate and adjusted to fit one of the forty-five-degree angles, *a*, of the square. The square is then removed and, without disturbing the straight edges, it is replaced with the angle *b* in the angle between the straight edges. The angle *c* being already a right angle, if the test shows angles *a* and *b* to be equal, they are necessarily of forty-five degrees and if they are unequal, the direction in which scraping must be done on the hypothenuse in order to make them equal will be shown by the tests.

Angles of thirty and sixty degrees may also be originated in sets of three. For this we require a straight edge, a square and three triangles of which the right angles are correct and of which the other angles are to be the ones required.

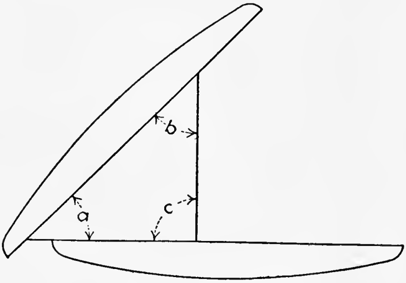

Fig. 25.—Originating angles of forty-five degrees.

With these parts provided, they are grouped in the manner shown in Fig. 26 and the triangles are scraped until the right angle between the stright edge and the square is filled by the two angles of the triangles. When doing this the scraping of each triangle is on its hypothenuse alone in order to avoid disturbing the correctness of its right angle. When the right angle between square and straight edge is completely filled, the top and bottom lines of the triangles are truly parallel because of the correctness of the right angles, and we have two parallel lines cut by a diagonal. Consequently angles *a* and *b* are equal, as are *c* and *d*. Moreover *a* and *c* are complements, as are *b* and *d*. There is, however, no certainty that *a* and *b* are truly thirty degrees or that *c* and *d* are truly sixty degrees and, without the certainty that they are correct, there is every probability that they are wrong. Triangle *A* is now removed and triangle *C* is substituted for it and scraped on its hypothenuse until the right angle is again filled—no scraping being done on triangle *B* at this stage, as the aim is to insure that the three triangles have the same degree of untruth. This process completed, we know that the three smaller angles, while in all probability not of thirty degrees, are, nevertheless, equal. They are next grouped as shown in Fig. 27 when the error, multiplied by three, is at once shown by the three angles added together failing to fill, or more than filling, the right angle. The direction of the error being shown, the three triangles are scraped by the same amount, as nearly as possible, and each upon its hypothenuse, until the right angle of Fig. 27 is perfectly filled. In spite of the care used, this scraping will, in all probability, slightly disturb the equality of the angles, and the triangles are then grouped again as in Fig. 26 and the error is corrected by a second application of the first process. This process is repeated until the triangles satisfy both tests when, the angles being equal and their sum ninety degrees, they are necessarily correct.

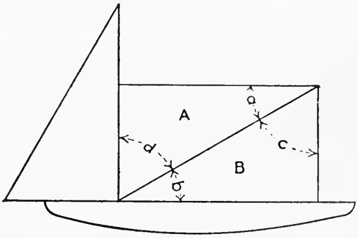

Fig. 26.

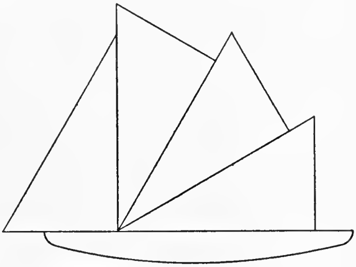

Fig. 27.

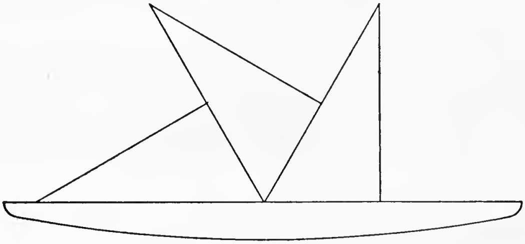

Fig. 28.
Originating angles of thirty and sixty degrees.

Two of the angles of each triangle being now known to be of ninety and thirty, it follows that the third one must be of sixty degrees but, if desired, an independent test of this fact may be made by grouping the triangles as shown in Fig. 28 and, should they satisfy the test, the correctness of the sixty-degree angles is obviously proven.

OTHER METHODS OF ORIGINATING ANGLES

There is in the machine shop a surprising lack of appliances for making pieces of which the surfaces are to have various angles with one another. Universal milling machines are, of course, supplied with protractors but these are never fitted with verniers and can only be read with accuracy for the angles which actually appear in the graduations.

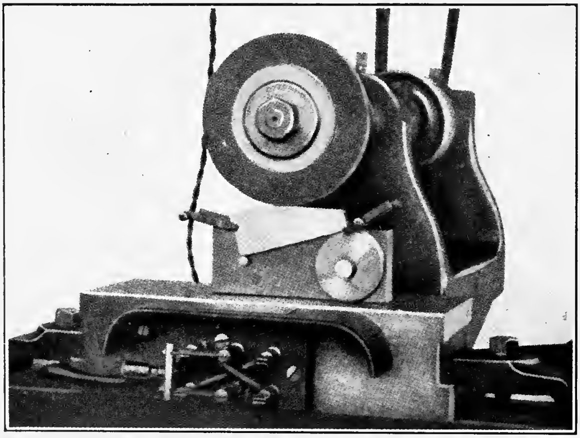

Fig. 29.—Two-disc method of originating angles.

In the absence of provisions of this sort, when correct angles are required other than those supplied by the milling machine protractors, it is necessary to resort to various expedients. One such expedient is shown in Fig. 29, which shows a surface-grinding machine fitted for producing a correct angle on the inclined piece below the grinding wheel. This piece is shown clamped to a plate which, in turn, rests upon the magnetic chuck of the grinding machine. The plate has two holes through it, the centers of which are at exactly the same distance from its bottom and which are at a known distance apart. Two discs, as shown, are made of different diameters and with short shanks which fit the holes in the plate. It is obviously a simple matter to calculate and to make the discs of such diameters that the angle between their common tangent and the center line shall be the angle required and, with the piece of work clamped in the position shown, the result of the grinding is to produce this angle upon it.

This is called the *two-disc* method and it has many applications and variations. More commonly it is so used that the angle produced is that between the two common tangents of the discs and not as in the case shown, that between one common tangent and the center line.

An application of this kind is shown in Fig. 30 in which the piece *a* is required to have an angle of 18 deg. 46 min. as shown. The body *b* of the fixture has a tongue *c* fitting the T slot of the planer or milling machine table and a ledge *d* to act as an abutment to the discs *e* and *f*, the distance between which is determined by the distance piece *g*. The piece of work is drawn snugly against the discs by the bridle *k* and the set screw *j*, a similar set screw *h* securing the larger disc in position against the displacing tendency of the pressure of the piece *a* against it.

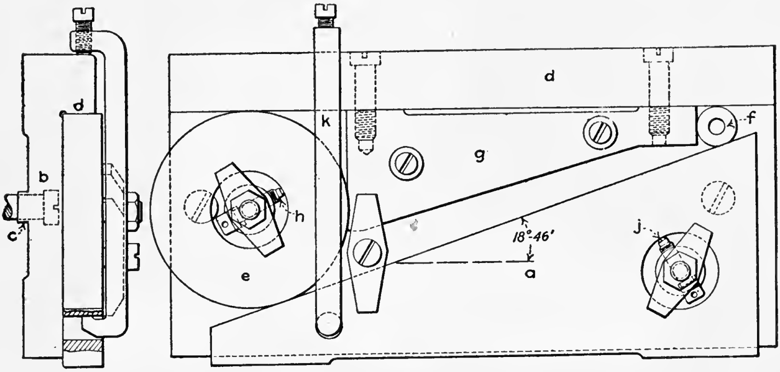

Fig. 30.—Second application of the two disc method of originating angles.

Again, as before, it is a simple matter to calculate and to make the discs of proper diameters and the distance piece of proper length for the angle required and then to produce that angle on the planer or milling machine by planing or milling the lower edge of piece *a*.

There are in the machine shop certain standard tapers. The taper shanks of twist drills and the sockets by which they are held and driven are made to the Morse taper of nominally, though not exactly, five-eighths of an inch per foot. The work ends of milling-machine spindles have each a hole for the cutter arbors made to the Brown and Sharpe taper of one-half inch per foot and in some other machine spindles the Sellers taper of three-quarters of an inch per foot will be found. It would be much better if we had but one taper, but the unfortunate diversity is too firmly established to be corrected.

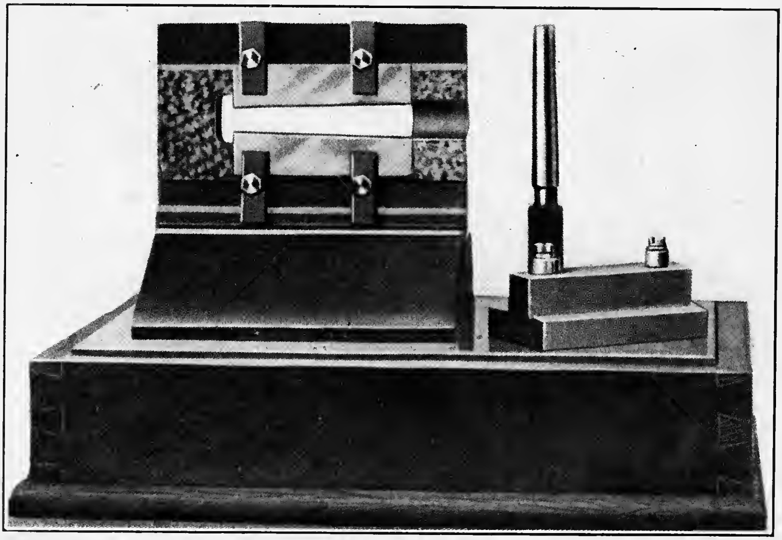

FIG. 31.—Third application of the two-disc method of originating angles.

Interchangeability of these taper pieces in imperative. Twist drills must interchange in their sockets and so with milling-machine arbors. That each milling machine should have its own complete set of arbors, for example, is unthinkable. Means for originating these tapers are therefore important, both for the original production of plug gages by which to test them and for the detection and correction of wear of the plug gages.

This may be done by another application of the two-disc

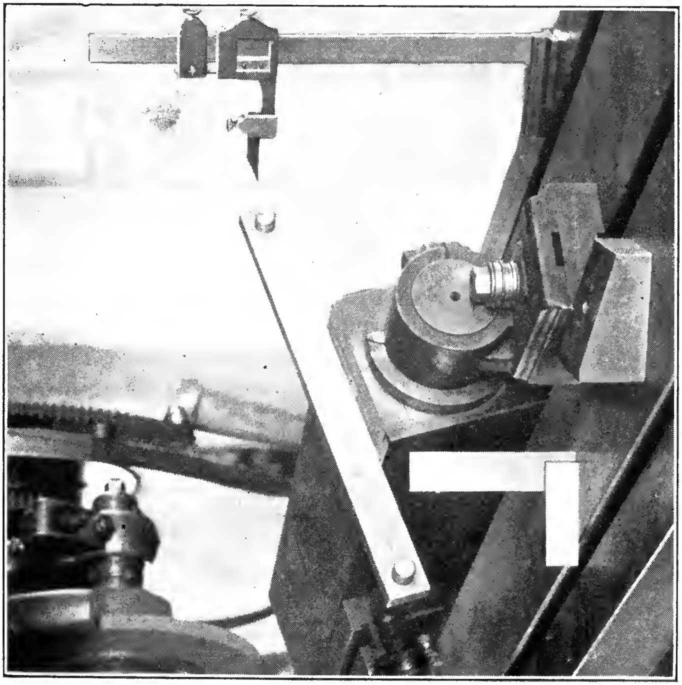

Fig. 32.—First application.

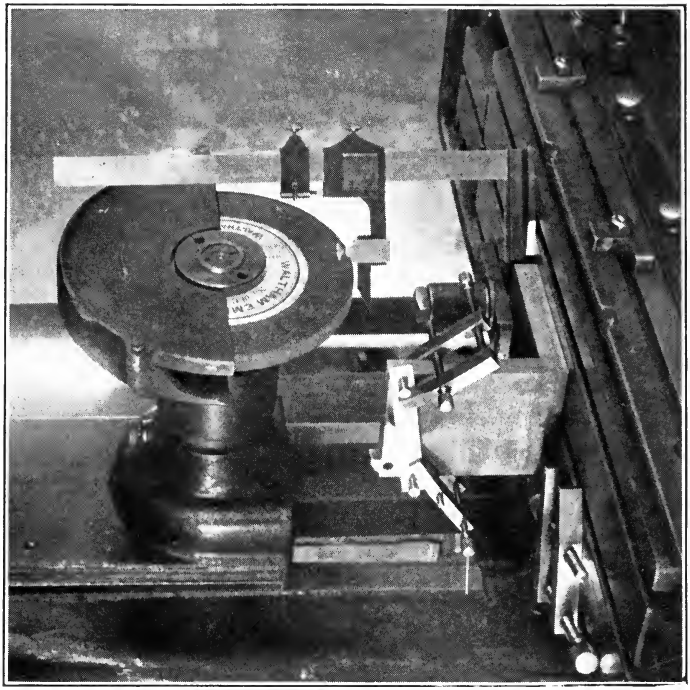

Fig. 33.—Second application.

The sine bar method of originating angles.

method shown in Fig. 31, which illustrates the originating of a taper test gage from which to make the working taper plug gage shown in the background. The stand at the left has a slot through it and suitable binding straps by which to hold the blades shown behind them, which are adjusted to correct position by means of the parts shown in the right foreground. These parts consist of a steel block to which are secured two discs of such size and distance apart that the angle between their common tangents is the angle desired. The block is placed in the opening through the stand from behind, the dimensions being such that when thus placed the discs project through the stand. With the parts thus placed, the blades are adjusted to contact with the discs, when, the block and discs being withdrawn, we have a gage with which to compare the taper plug.

Another method of originating angles is by the use of the sine bar (due to H. P. Camp) shown in Fig. 32. Here we have the work table of a surface-grinding machine on which is placed a swiveled magnetic chuck which it is desired to adjust to an angle such that the wedge shown in the foreground on the work table may be ground upon it and with a high degree of accuracy.

The sine bar shown upon the chuck is a bar of steel having its two edges accurately parallel and carrying near its ends two pins of exactly the same diameter located on a center line which is exactly parallel with the edges of the strip and which are at a known distance apart—usually ten inches between centers. At the right is seen a height gage,[1] which is an accurate instrument for measuring vertical distances from the bottom of its base to the lower side of the projecting finger. The sine of the required angle is taken from a table and multiplied by the distance between the centers of the pins, when the chuck is adjusted on its trunnions by trial until the pin at the right stands above the pin at the left by an amount equal to the sine of the angle thus multiplied—this difference in height being determined by the height gage.

The sine bar has many other applications of which two are shown in Figs. 33 and 34. In Fig. 33 the bar is applied to an

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[1] This instrument is described at greater length in the chapter on Measures of Length.

angle plate and it locates directly the piece of work to be ground to the desired angle. In Fig. 34 two sine bars and a suitable stand are so assembled as to provide a taper gage similar to the one already shown in Fig. 31—the gage being here shown in the act of gaging a taper reamer.

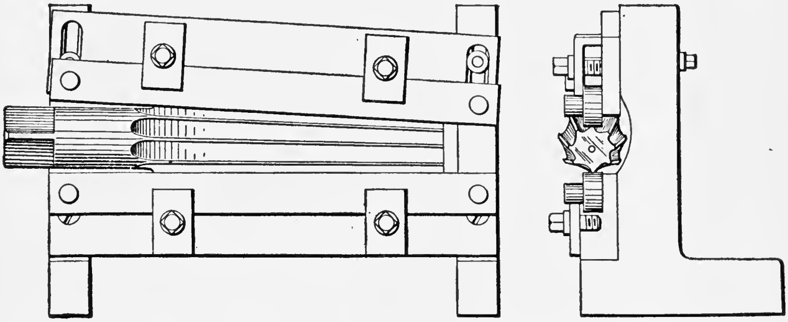

Fig. 34.—Third application of the sine bar method of originating angles.

The sine bar provides, perhaps, the most generally useful method of originating angles. It is extremely simple, quite accurate and, unlike the two-disc method, does not require special construction for each case. Against it is the fact that, in each of the repeated trials necessary to adjust it, the positions of both pins are naturally disturbed and this adds to the time

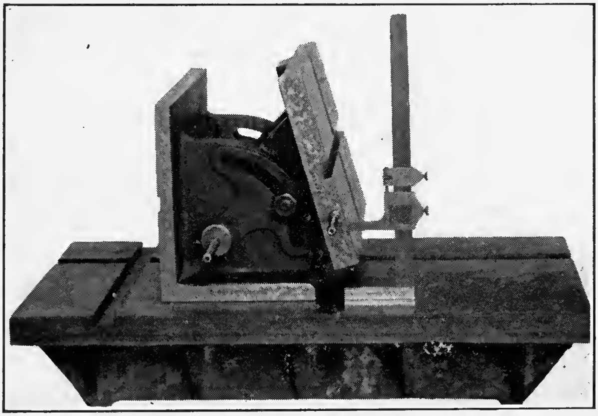

Fig. 35.—Adjustable angle plate for originating angles.

required for the adjustment. This may be avoided by the angle plate shown in Fig. 35 from the works of the United Shoe Machinery Company. In this instrument one of the pins is concentric with the axis on which the adjustable plate swivels, the result being that the height of the second pin may be adjusted, once for all, by the use of the height gage as shown.

ORIGINATING INDEX PLATES

The next method, shown in Figs. 36–38, is from the works of the Westinghouse Electric and Manufacturing Company and is for much larger work. It was developed under the following conditions:

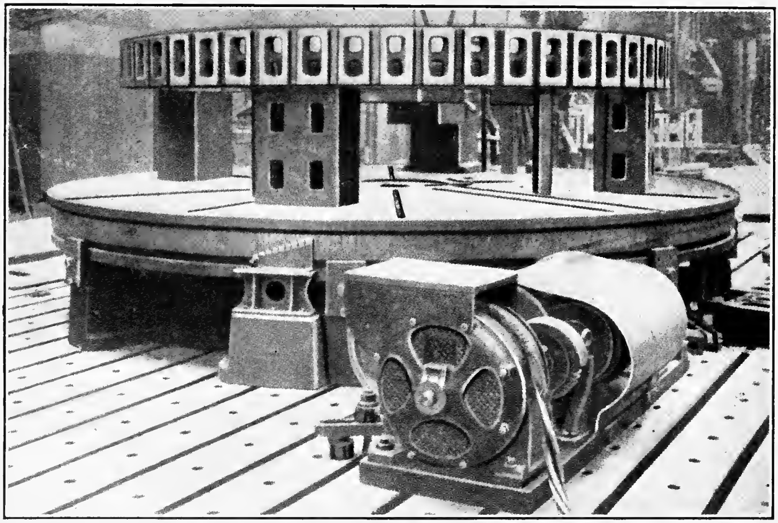

Fig. 36.—A large index plate.

The magnetic circuits of electric generators and motors are built up of punchings of sheet steel. In small machines these punchings are complete rings but, as the size increases, it soon becomes impracticable to follow this plan and the rings are made of segments. Under these circumstances it becomes necessary to anchor the punchings to the spider which carries them and this is done by dovetails which project from the inner arcs of the

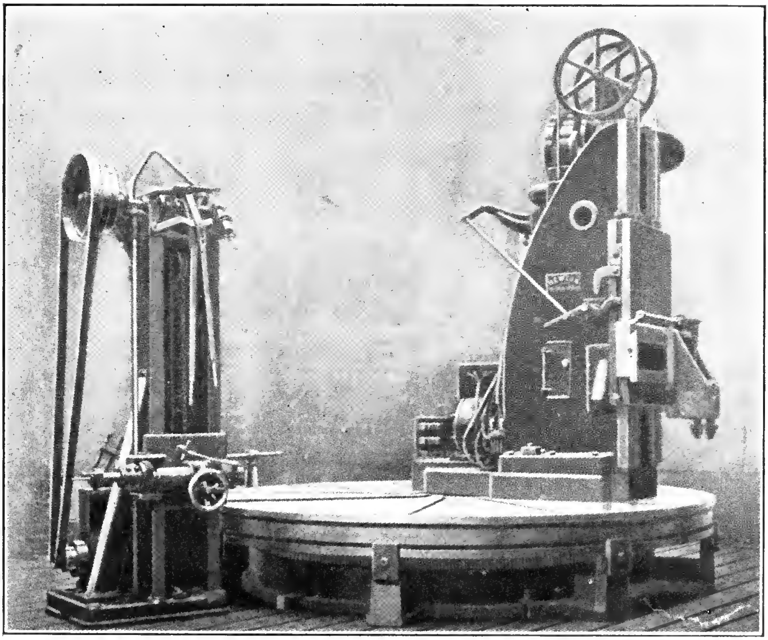

FIG. 37.—Second method of using the large index plate.

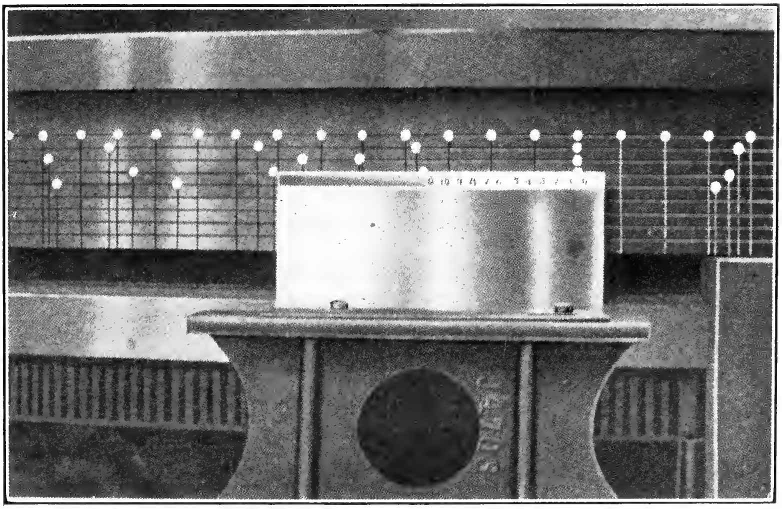

FIG. 38.—Divisions of the large index plate.

punchings and fit corresponding dovetail slots in the spider. The dovetails must really fit the slots because, not only is it necessary that the segments be anchored to prevent flying off by centrifugal force, but they must be so perfectly anchored as to prevent movement among themselves, as such movement would soon chafe and destroy the insulation of the windings.

All this requires that the spacing of the dovetails and of the dovetail slots shall be accurate, and the more so because, in order to preserve magnetic continuity, the punchings are so assembled on the spider as to break joints, the result being that in the assembling of the punchings the dovetails are placed in the slots in every possible position around the circle. It is clear that, if good fits are to be made with uneven spacing of the dovetails and slots, the assembling would be accompanied by a large amount of hand fitting. Formerly this was the case and, since a single large armature contains many thousands of punchings, the cost of this fitting became a serious item. To reduce this cost the index plate shown in Figs. 36–38 was constructed, its object being to insure accurate spacing of the slots in the spider, or of the ring frame as the case may be. The result was to reduce the time required for the assembling to one-tenth of the former figure, the case being a perfect illustration of the statement already made regarding the economy of assembling due to good workmanship.

The index plate, which is of fourteen feet diameter, is shown in Fig. 36 with an armature spider mounted upon it. The plate is mounted upon a slotted cast-iron floor plate and, as the work which it carries frequently weighs many tons, it is supported on a ball bearing and fitted with an electric motor shown in the foreground for turning it, with hand adjustment for the final setting. The slotting machine which is to machine the dovetail slots is also mounted upon the floor plate, or, in case the slots are to be on the inner circumference of a ring frame, this frame is mounted upon blocks which surround the index plate and the slotting machine is placed upon the index plate as shown in Fig. 37.

Fig. 38 shows a near view of the index plate. Several circles are turned upon it, each circle containing a number of brass plugs in accordance with the number of divisions to be made, and upon these brass plugs fine lines are engraved, the turning of the plate from line to line being determined by matching these lines against a stationary line on the curved shield in front of the plate. In the case shown, this shield is provided with a vernier for more minute divisions.[1]

This plate was divided by means of a high-class shop transit instrument which was mounted upon a cast-iron support whose concentricity with the plate was insured by a shallow recess turned in the center of the plate when the plate was made and shown in Fig. 36—a projecting hub on the bottom of the transit support fitting this recess. The graduated circle of the transit was of the highest attainable precision but, for this purpose, its divisions were not trusted because, small as its errors were, the greatly increased radius of the table over that of the instrument circle would have led to a magnification of those errors which it was desired to avoid.

At a distance of approximately a hundred feet a pair of targets was erected, consisting of a horizontal plank with an ivory marker mounted on each end. One of these markers was fixed in position while the other was adjustable by a micrometer screw. The required number of divisions in a circle having been reduced to degrees and minutes, it was easy, by swinging the instrument through this angle, so to locate the movable target that the lines upon the targets should be split by the cross hairs of the telescope at the two positions defining this angle. This done, the micrometer reading was taken, when the setting was destroyed, the table was turned to a new position, and the process repeated on a different portion of the instrument circle, in order to eliminate local errors which it might contain. At each repetition the micrometer reading was taken and when a sufficient number had accumulated, the average of all the readings was taken. The micrometer was then set to this average reading and the dividing of the table was done by the use of the targets and without again consulting the instrument circle. In doing this, the instrument was first adjusted

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[1] The lines shown upon the edge of the plate leading to the brass plugs are mere leader lines to locate the plugs. The actual division lines on the plugs are too fine to be seen.

until its cross hair split the line upon one of the targets, when table and instrument together were turned until the telescope cross hair split the line upon the other target. With the table in this position the instrument was then turned back to the first target when table and instrument together were again revolved to the second target. At the completion of each step a line was drawn on one of the brass plugs and from a fixed base, and the process was continued until the circle was completed. In order to avoid the effect of vibrations due to the work in progress in the shop, this process was carried out on Sunday.

This great index plate opens up the subject of index plates in general. The process described is, to the best of the author's knowledge, unique, in that the value of a division of the plate was reduced to degrees and minutes. The usual method of attacking this problem is to provide a means by which the equality of the divisions is insured and then, the number of divisions being correct, the work is necessarily correct. As in the case of the Westinghouse plate, precision methods are not resorted to in these matters in the cultivation of a fad or the pursuit of an ideal. Such work is done because it is necessary and this necessity sometimes arises in connection with work for which it would be least expected.

The web printing press by which newspapers are printed from continuous sheets does the poorest grade of commercial printing and, at first sight, it is the last printing press in which precision work would be looked for. Between the beginning and the end of the printing process there are, in one of these presses, about seventy-five lineal feet of paper included, this paper going over and around various cylinders and drums in its progress through the press. It is very clear that unless these cylinders revolve at uniform velocity the effect on the paper would be disastrous, and so exacting is this requirement that, for the production of the gears which drive these cylinders, the firm of R. Hoe and Company found it necessary to make an original index plate on which more money was probably spent than on any other existing index plate.

THE DIVISION OF FUNCTIONS

Before proceeding with the division of index plates, one feature of them should be noticed. This relates to the shape of the indexing notch by which the plate is located in its various positions. The correct shape of these notches and of the latch bolt which engages them is shown in Fig. 39.[1] The natural and formerly the universal form of the notches is that of a truncated V as shown in Fig. 40. In the operating of an index plate the latch bolt must be depended upon to move the plate a small distance as it enters the notch. In other words, the sides of the truncated V notch are subject to wear which in time destroys its accuracy. In the notch shown in Fig. 39, one side will be observed to be radial while the opposite side is inclined to the radius and the latch bolt is offset, one edge, prolonged, passing through the center of the ring. Under these circumstances the radial side cannot produce movement and, the turning mechanism being so adjusted as to leave the plate in a position such that the bolt will enter the notch, it is clear that the inclined side alone can do the final turning, the wear due to this work being thus confined to this side, while the accuracy of the radial side remains unimpaired for a long period. The only result of wear is that the depth by

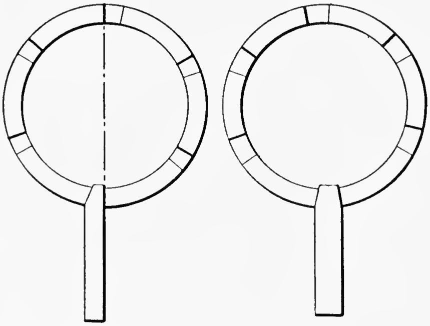

Fig. 39. Fig. 40.
Correct and incorrect constructions of index rings.

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[1] This construction was introduced into general practice by Pratt and Whitney. In a letter published in the American Machinist for Oct. 13, 1898, Mr. Pratt disclaims its invention, saying that he obtained it from Colt's Armory.

which the bolt enters the notch gradually increases but this does not affect the accuracy of the indexing. With the V notch, both sides are equally concerned in the final movement of the plate and in locating its final position whereas, with the improved notch, one side does the turning while the other side does the locating. The author calls this action the *division of functions* and it appears in various forms in connection with precision work and always with improved durability, accuracy or other advantage.

The notch under discussion has another advantage. In the truncated V notch, both sides are equally concerned with the indexing and hence both must be made with equal accuracy. In the improved notch, since one side only is concerned with the indexing, that side only need be made with high accuracy and hence the cost of the work is reduced.

A still further improvement has been made on this construction by the National Acme Manufacturing Company through an additional application of the same principle. As so far shown, the division of functions is between the *two sides* of the latch bolt, and there remains a slight sliding of the index side of the bolt on the corresponding side of the notch during the small movement in which the tightening of the bolt is effected. In the Acme construction the division is between *two separate bolts*. The indexing bolt first enters its notch to its full depth and without contact with the side of the notch, when the bolt which moves the turret enters its notch and moves the index side of the notch to contact with the index bolt and absolutely without sliding.

It should be observed that the importance of this feature is confined to working plates for continuous use, such as those by which the turrets of turret lathes are fitted. Some of the methods of precision indexing involve the use of a master plate which is used only to produce working plates by copying. Such use of the master plate is too limited to introduce appreciable wear, and the improved notch must usually be sacrificed in master plates in order to accommodate the process by which they are produced. Again, for tool room work, the use of the plate is too limited to introduce much wear, and plates for such work usually have round holes and index pins.

Many methods of producing precision index plates have been used and, of these, it is only possible to show here two which are selected in order to indicate the leading methods of attack, of which other plans are, to a large extent, variations.

THE STEP-BY-STEP METHOD OF ORIGINATING INDEX PLATES

Fig. 41 shows the method used by Professor Rogers for graduting the dividing wheel of the Cornell University dividing engine in which machine the wheel is divided by lines for visual reading and not by notches.

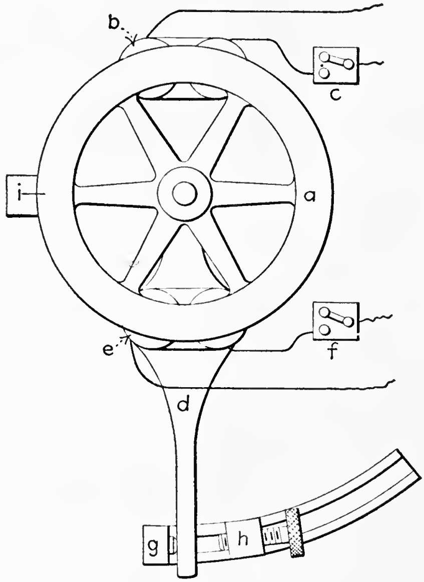

Fig. 41.—First method of originating index plates.

The wheel *a* to be divided, which must be of iron, has below it and in light rubbing contact with it, an electro magnet *b* fitted with a switch *c* by which it may be energized and de-energized. Swinging about the center of the wheel is an arm *d* carrying a second electro magnet *e* which is also provided with a switch *f*. The swinging arm *d* may be swung between two stops *g*, *h*, of which the latter is minutely adjustable. At *i* is a fixed point carrying the stationary zero for reading the graduations.

By energizing *e*, swinging arm *d* to stop *h*, then energizing *b* and deenergizing *e*, returning arm *d* to stop *g* and then repeating the process, it is clear that the wheel may be rotated step by step, the action being that of a ratchet and pawl with infinitely fine teeth. It is, moreover, clear, that by repeated trials, an adjustment of *h* may finally be obtained such that after the required number of movements the wheel *a* has made an exact revolution. When this adjustment has been found it is only necessary to repeat the step by step movement, and make a graduation mark on the wheel at the completion of each step in order to obtain a correctly divided wheel. If desired, and this was done in the case of the Cornell dividing engine, additional precision may be obtained by continuing the step by step movement during the initial adjustment until the wheel has made several revolutions—this process multiplying the residual error which might not be apparent at the completion of a single revolution. Moreover, by reading the lines through a microscope, any conceivable degree of accuracy may be reached.

This method has been a favorite one and has many variations, especially in the replacing of the magnetic action by mechanical gripping devices. It is known as the *step by step* method, the appropriateness of which is apparent.

THE DUPLICATION METHOD OF ORIGINATING INDEX PLATES

For the division of index plates which are to be used by the application of stationary latch pins or bolts and not by visual reading, the method which was developed in connection with the Thorne typesetting-machine, and which is now used in the production of the Unitype, appeals to the author as the most satisfactory of all, since, in addition to the highest degree of precision it is, compared with most other methods, of moderate cost. In principle it is as follows:

In Fig. 42 a disc, which is to become the index plate, has a ledge *a* turned upon it. A number of smaller discs *b*, equal in number to the divisions required are made—such discs being about the easiest of all things to make of a high degree of accuracy and uniformity. The diameters of the ledge *a* and of the discs *b* are so calculated that, when the discs are placed in position on the ledge, they will make contact with the ledge and with each other. It only remains to secure them in position by means of the cap screws shown, when the structure forms a correct index plate.

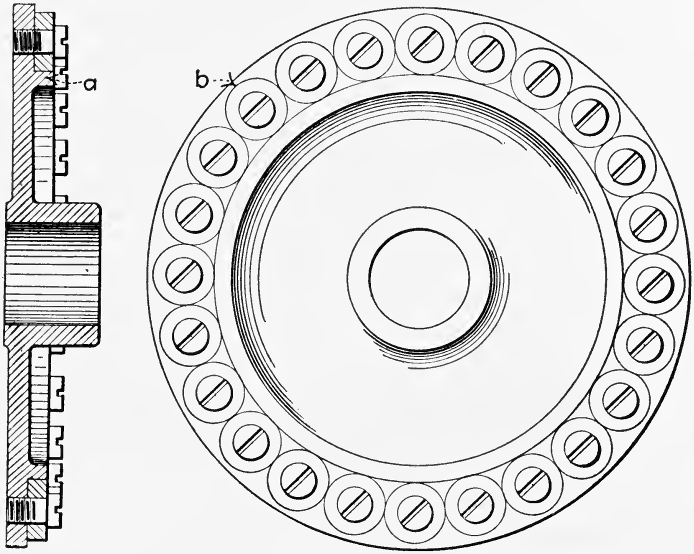

FIG. 42.—Second method of originating index plates.

ORIGINATING INDEX WORM WHEELS

In a very common form of gear cutting machine the indexing of the gear teeth is dependent upon a large worm wheel mounted upon the shaft which carries the blank operated upon, and there is the same necessity for precision workmanship in this worm wheel as in index plates. A method of constructing these worm wheels has come down to us from early times and is still in use.

The work is done upon a hobbing machine which it is first necessary to describe. Such a machine, by the Newton Machine

Tool Works, is shown in Fig. 43, a worm wheel in process of being cut appearing mounted on its spindle while behind and concealed by it and mounted on the cutter spindle is a hob which does the work. A hob is shown in Fig. 44. It is a cross

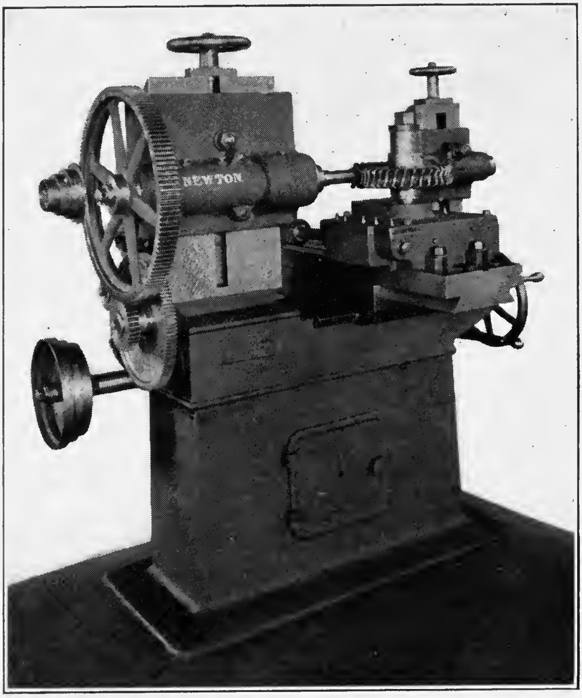

FIG. 43.—Worm wheel hobbing machine.

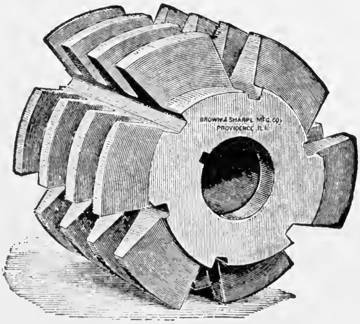

FIG. 44.—A hob.

between a milling cutter and a tap or, otherwise described, it is a worm suitably gashed and relieved to make it a cutting tool. The worm wheel and hob spindles are connected by gearing, partly shown in Fig. 43, by which the wheel blank is made to turn past the hob as the latter revolves, precisely as though the hob were a worm and the blank a finished worm wheel. With the parts in motion as described, the blank is slowly fed toward the hob which thus cuts the teeth.

Fig. 45.—Construction of precision worm wheels.

When a precision worm wheel is to be originated the blank for it is made in the manner shown in Fig. 45, the rim being in halves as shown and the two halves being secured together by taper pins of which there are at least four and sometimes more. The holes for these pins are so accurately spaced that the rings may be turned upon each other and the pins be seated in the holes in any position. The spacing of these holes so that they will meet this requirement is itself a precision job of which, however, details are not here given.

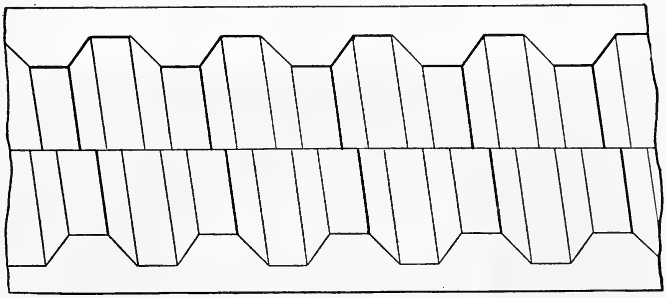

Fig. 46.—Appearance of worm wheel teeth when halves are reversed.

The worm wheel blank being placed in position on the hobbing machine the teeth are cut, following which the rings are separated, turned half way around relative to each other when the pins are again seated in their holes. In this new position of the parts the two halves of the teeth will be found not to match perfectly, most of them being offset, as shown in Fig. 46, though by varying amounts. The wheel is then replaced in the hobbing machine, the gearing which connects the hob and wheel is disconnected and the hobbing is repeated, the teeth of the wheel finding their own places in the hob. Consulting Fig. 46, it is obvious that substantially the same amount of metal will be removed from one side of one half and the other side of the other half of each tooth, the result being a great improvement in the work. When the offsets of the teeth have been removed the parts are again separated, turned one-quarter

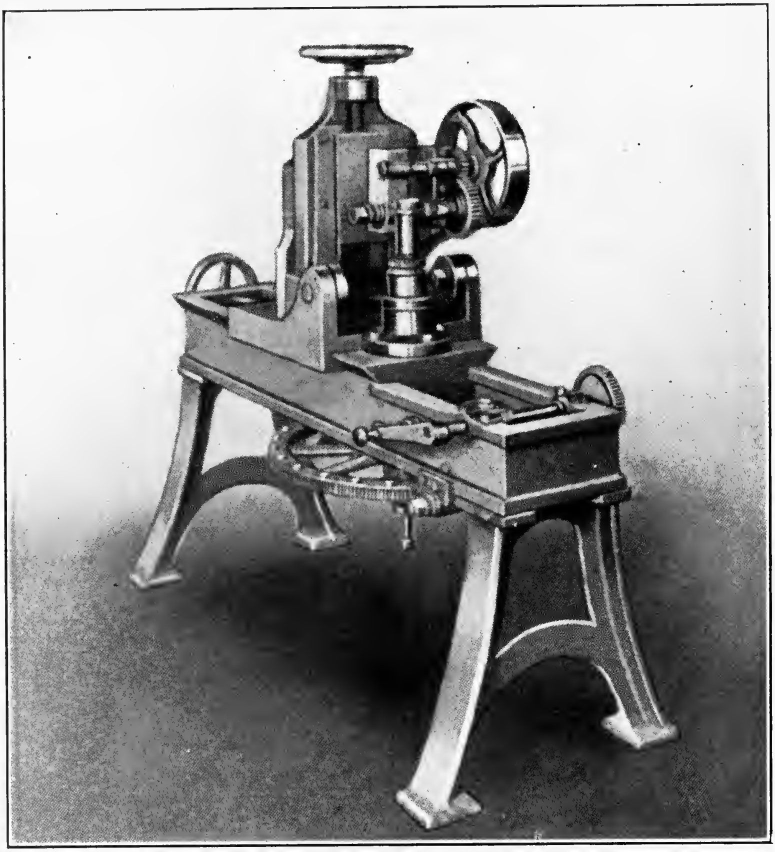

FIG. 47.—Freeland geer cutting machine known to have been in use in 1857.

of the way around and the hobbing process is repeated—again with improvement. This process is continued until the teeth of the two halves match in all positions, when the worm wheel is correct.

A striking illustration of the high ideals that prevailed in some quarters in former times is shown in Fig. 47, which illustrates a small gear-cutting machine made by Mr. Freeland and known to have been in use by him in 1857, the illustration being from a photograph made when the Freeland Tool Works were dismantled in 1896. The worm wheel is clearly shown below the bed as are the bolts by which its two halves are secured together. It was unquestionably made by this rehobbing process. Another refinement which would not be looked for in a machine of that date is found in the adjusting screw and hand wheel at the rear for adjusting the cutter to depth, which is fitted with a graduated circle reading to thousandths of an inch. This machine is one of several illustrations of advanced designs by early constructors which these pages contain. Compare this illustration with Fig. 256, which shows a modern machine which, except for its increased size and the changed location of the crank and gearing by which the worm wheel is turned, scarcely differs from the Freeland machine and, to carry the parallel still further, the worm wheel of the modern machine was made by the same process.[1] Mr. Freeland is not, however, to be regarded as a mere copyist. In planing machines, for instance, he introduced improvements for the use of which others paid him royalties during the life of his patents. Other constructors, including Sir W. G. Armstrong Whitworth and Company, continue to use the same general construction, than which, for a non-automatic machine, there is nothing better.

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[1] The Freeland machine is so very Whitworthesque in its outlines, and Mr. Freeland was such a disciple of Whitworth, that it is more than probable that the design of this machine came from the Whitworth works.

CHAPTER III

MEASURES OF LENGTH

The metric fallacy—The origin of measures of length—Relative accuracy of line and end measures—Relation of accuracy of measurement to character of surfaces—Source of error in shop use of line measures—Methods of avoiding this source of error—Early history of measuring machines—The line measure as a standard—Characteristic features of modern measuring machines—The micrometer caliper—Precision lathes for cutting precision screws.

THE METRIC FALLACY

A discussion of measures of length for the machine shop naturally includes some consideration of the metric system.

The old claims for the almost universal use of this system have been turned to ridicule. The imposing list of forty-four countries in which the system was gratuitously assumed by its advocates to be "in habitual and customary use" have dwindled under searching examination to a few in Western Europe where the use of the system is compulsory. The other countries of the list have passed laws of two general kinds, one of which merely legalizes the system—that is, makes its use permissive—while the other adopts it as an official government system but without compulsion on the people. Neither has resulted in any appreciable adoption of the system in trade and commerce, while in no country whatever have compulsory laws of the most sumptuary character succeeded in eradicating old units.

NON-DECIMAL UNITS PREFERRED BY THE PEOPLE EVERYWHERE

The people everywhere show substantially unanimous preference for their old non-decimal units, even after, in some countries, several generations of use of the new and in spite of the imposition of legal penalties. This preference can be explained in two ways and in two only: Either the old units are preferred because they have been found better for their purpose than the new, after long trial of the latter, or the change from the old to the new system is so difficult that even compulsory laws are not able to bring it about. It is for the metric party to choose between the horns of this dilemma, either of which is fatal to their case.

The broad fact stands out that in no country whatever—France included—have the people adopted the system in trade and commerce because of its supposed advantages. Whereever and to whatever extent it is used in trade and commerce, its use is due to compulsion. Were the advantages claimed for it real, compulsion would long ago have become unnecessary. The adoption of improvements is always because of their merits and were the metric system an improvement it would be adopted for that reason.

Dissipated also are the old claims for the ease of adoption of the system. In view of the continued use of old units in France after more than a century of effort to suppress them, it is only through crass ignorance or worse that the adoption of the system can longer be represented as an easy matter.

The foundation feature of the system is that it is a decimal system, the ratio of each unit to the one above it being expressed by the number ten. This feature was introduced in order to bring the system into harmony with our system of arithmetical notation, and to bring about a supposed convenience in calculations which forms the chief argument for the claimed superiority of the system, although it is purchased at the expense of all other qualities and properties which a system of weights and measures should have. The argument for simplicity of calculations has been exaggerated beyond all reason, while the disadvantages which accompany the decimal feature have been ignored.

To bolster up the claim for convenience in calculations the metric party give hypothetical problems to solve. They assume, for example, a distance of so many miles, furlongs, rods, yards, feet and inches, show the number of figures required to reduce this expression to inches and then give a corresponding problem in which distances are expressed in kilometers, hektometers, dekameters, meters, decimeters, centimeters and millimeters and show that the expression can be reduced to millimeters by the simple process of properly locating the decimal point. Similarly they show the amount of work involved in reducing an immense number of inches to miles, furlongs, rods, etc., and, alongside, they place an exhibit showing that millimeters may be reduced to kilometers etc., hektometers, etc., by merely changing the decimal point.

THE USE OF SINGLE UNITS NULLIFIES THE CLAIMS MADE

The trouble with these problems is that they are purely hypothetical. No one has them to do—no reader of these pages has occasion to solve problems that are so much as comparable with those on which the metric case is based. With the exception of feet and inches which are used in combination, although the tendency is against the practice, quantities are commonly expressed in single units.[1] Thus the flow of aqueducts and the capacity of pumping engines and of city reservoirs are given in gallons and the strength of materials in pounds per square inch. Similarly, when we buy small quantities of things at the drug store we do it by the ounce and its fractions, while, if we buy larger quantities at the grocery, we do it by the pound and its fractions—pounds and ounces being, practically, never mixed. Again, we buy milk by the quart, gasolene by the gallon, grain by the bushel, and cement by the barrel, but no American reader of these pages ever sees these units used conjointly. The civil engineer uses the mile as his long and the foot as his short unit of length—these units being divided decimally for purposes of measurement and calculation—but he never uses the two in combination. His unit of excavation is the cubic yard, but, like the others, it stands alone. Reduction, ascending or descending, among these units is among the rarest of problems and the ratios between them are about the least important things that ever produced a heated discussion.

Not only is this the method by which these units are used but it is the manner in which they were intended to be used. Units of different sizes, English and metric alike, are provided

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[1] This practice, while almost universal in the United States, is not so common in Great Britain.

in order that those suitable for various purposes may be available. The quart being suitable for the amount of milk commonly purchased, the quart is used for that purpose, while the gallon being suitable for the amount of gasolene commonly purchased, the gallon is used for that purpose. For the same reason the ounce is used for the purchase of drugs, the pound for groceries and the ton for coal. The use of a mixture of units for the same purpose is uncalled for and unnatural and its appearance in the problems referred to is simply a case of manufacturing evidence to suit the case which it is desired to prove.

Using units in this manner, the importance of the ratios between them sinks into insignificance. For purposes of calculation they may be divided decimally,[1] as they usually are, when they fall into perfect harmony with decimal arithmetic. Used in this way, no discoverable difference in the time required for calculations in the English and the metric systems has ever been shown because none exists. The engineer calculates stresses or pressures in pounds per square inch with absolutely the same simplicity of calculation that he does in kilograms per square centimeter. So, also, the dimensions of structural members are calculated in inches with the same degree of simplicity as in millimeters and hydraulic calculations in gallons are as simple as in liters.

TEN A BAD DIVISOR

From whatever other constructor's standpoint the matter is viewed, the metric system is at a disadvantage, and this because its base, ten, is awkward and inflexible. It is well known to all who have given the subject attention, that one of the misfortunes under which the human race suffers is the

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[1] The metric party labors under a strange hallucination that they possess a monopoly of decimal arithmetic and they hail every use of decimals as a concession to their claims. Decimal fractions are, of course, centuries older than the metric system, the fathers of which system adopted but did not originate them. With the English system they are used when convenient and dropped when inconvenient. With the metric system, on the contrary, they must be used whether convenient or not.

fact that our system of arithmetic is based on ten. It has been truly said that of all even numbers below twenty, ten is the worst possible choice for this purpose with the single exception of fourteen, and if ten is a bad base for a system of arithmetic, much more is it a bad one for a system of weights and measures.

In the constructive arts, the badness of the divisor ten shows itself chiefly in its inflexibility as regards the sizes which are possible under it. It is a basic feature of all manufacturing that of the many sizes which are possible but few shall be used. Thus between one and two inches we have but eight sizes of standard screw threads, while of shafting we have but four and of pipe but three. For constructive purposes the basic requirement of a system of measurement is that the choice of these sizes shall be flexible and herein division by successive halving is infinitely superior to division by ten.

THE MANUFACTURER'S CASE AGAINST THE SYSTEM

The chief objection to the adoption of the system is, however, that it involves a complete change in the established system of sizes used in manufacturing—a change so difficult that it has not been completed in any so-called metric country.

Fig. 48 shows an English and a metric scale in contact. The base units of the two systems being incommensurate, their divisions cannot agree and the two sets of lines seem to fairly play a game of hide and seek in their efforts to elude one another. The lines upon the English scale give the dimensions to which things have always been made in English-speaking countries and, reduced to its lowest terms, the proposition is that these sizes shall be abandoned and those shown on the metric scale substituted for them, and, not only are the English sizes to be abandoned, but the established mechanical standards based upon them as well.

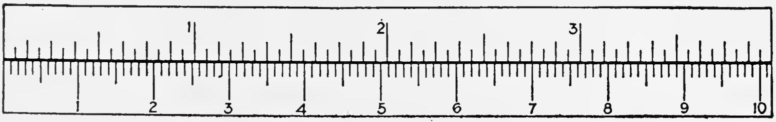

Fig. 48.—English and metric scales.

Consider the couplings with which the air brake hose ends of railroad cars are coupled together. These couplings have been standardized by the Westinghouse Air Brake Company, and, because of this and standardized draft couplers, railroad cars of all American lines interchange as a matter of course. The attempt to change them would lead to confusion worse confounded, and, the new couplings being no better than the old, it would accomplish no useful purpose. It is not a matter of willingness to change, nor of getting people to think in the new units, nor of the length of life of individual couplings, nor of the tools that make them. The obstacle to the change is physical; the simple necessity for continuity between old and new couplings requires the continuance of the present standard.

This example is selected not because the difficulty of the change here is greater than elsewhere, but because it is so plain as to be obvious after the slightest reflection.[1] "Measures of length are tied irrevocably to the past." The overwhelming difficulties of these changes growing out of the simple necessity for continuity of sizes between old and new constructions pervade every application of measures of length in the constructive arts, takes the subject from the realm of choice and makes the change in such applications impossible.

THE USE OF METRIC EQUIVALENTS OF EXISTING SIZES IMPOSSIBLE

Until recent years the metric party have ignored this difficulty.[2] Repeated insistence upon it as the prime reason for the objections of manufacturers to the change has now compelled the metricites to take notice of it and they suggest, as a means of getting around it, the continued use of existing sizes expressed in millimeters and fractions thereof, a sugges-

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[1] Other examples are screw threads, pipe and pipe fittings, shafting and pulleys, diametral pitch gears, rolled shapes and the numerous standards of the Railway Master Mechanic's Association.

[2] Because that party is composed chiefly of scientific men. The use of a defined set of sizes, which is the characteristic feature of manufacture, has no place in the scientific use of weight and measure, which consists in measuring things as they happen to be. Having no knowledge of manufacturing, scientific men naturally ignore it, and, by the same token, their opinions regarding the use of the system in manufacture have no value.

tion that is too amateurish to merit discussion were it not offered seriously and repeatedly.

In this they show a hopeless incapacity to understand the difference between *measuring* and *making*. The element of choice of dimensions is absent from the process of measuring. Things are measured as they happen to be, whereas they are made of sizes which are deliberately chosen, and the chosen sizes are those shown by the lines on the measuring scales used. Since the sets of sizes which characterize the two systems do not agree, it follows that if the sizes shown by the lines of one scale are to be expressed in units of the other, draftsmen and mechanics will be required to use a set of sizes which are not given by the lines on the scales from which they are taken. That is to say, instead of taking from the scales the sizes shown by their lines, intermediate sizes are to be taken by estimation. Worse yet, from the draftsman's standpoint, the set of sizes which, as expressed on English scales, fairly memorize themselves, become, when expressed in metric units, a series of such character that the memorizing of it is impossible, and yet this must be done if this specious scheme is to be carried out.

The impossibility of memorizing this series of equivalents will be apparent from a glance at the accompanying table.

Metric Equivalents of English Sizes

ins.	mm.	ins.	mm.
1	25.4	2	50.8
1⅛	38.57	2⅛	53.97
1¼	31.75	2¼	57.15
1⅜	34.92	2⅜	60.32
1½	38.1	2½	63.5
1⅝	41.27	2⅝	66.67
1¾	44.45	2¾	69.85
1⅞	47.62	2⅞	73.02
		3	76.2

The combinations of figures do not repeat themselves, each added inch adding a new set of combinations, which is to say that the table has no end. The metric party will tell us that this table is to be used "during the transition period only," but the transition period is not yet past in France, and it will not be past in the United States until all existing mechanical standards are abandoned.

Is it reasonable to suppose that eight threads per inch will ever be translated into eight threads per twenty-five and four-tenths millimeters, or that six diametral pitch will be thought of as meaning six teeth per twenty-five and four-tenths millimeters diameter? Will six-inch shafting ever be thought of as one hundred fifty-two and four-tenths-millimeter shafting or twelve inch I-beams as three hundred four and eight-tenths-millimeter beams?

Let the reader turn to the metric scale of Fig. 49 and by it attempt to lay down, as a draftsman would have to do, a few such sizes as $\frac{7}{16}$, $1\frac{3}{8}$, and $3\frac{1}{4}$ inches. Explanation is unnecessary. If the reader will but try it the simple childishness of the scheme will be apparent.[1] And yet it is to this pitiful thing that the metric case has been reduced.[2] The preservation of mechanical standards is admitted to be a necessity. If they are to be continued and the metric system is to be used in connection with them, this plan must be made to work, and made to work it cannot be.

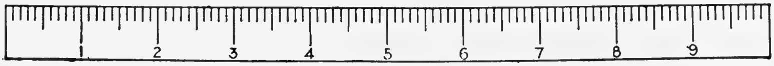

FIG. 49.—Metric scale.

Cannot the metric party see that if the plan were workable it would have been adopted years ago in metric countries? Such countries would not, as they all, in fact, do, measure screw threads, pipe and lumber in inches, were it feasible to thus express the sizes of one system in the units of another.

THE PERSISTENCE OF OLD UNITS INVERTS ALL ARGUMENTS FOR THE SYSTEM

Dismissing this scheme, nothing is more certain than that existing mechanical standards will not be changed. The only

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[1] The object of the plan is to retire the inch from men's thoughts as well as from the drafting board. The use of a table of equivalents is therefore inadmissible.

[2] See the *Value World* for March, 1913, where the plan is urged in all its bald absurdity.

effect of the adoption of the system would be to superimpose it on the existing system. In some applications the change is not difficult and in such applications it would be made, while in the applications that have been discussed the old units will be continued. The net result would be, as it uniformly has been elsewhere, the conjoint use of both systems. The incommensurate ratios between the units of the two systems are far worse than any existing ratios. In other words, at the very point at which the system is urged in order to make matters better than now, it would, in fact, make them far worse.

The ratio

3 feet make 1 yard

is held up as an example of all that is bad and as the cause of complexity in calculations, but the ratio

3.28083 feet make 1 meter

is accepted without a murmur. Moreover, while, as has been pointed out, the ratios between English units seldom enter calculations because different English units are used for different purposes, the ratios between English and metric units frequently enter calculations because corresponding units of the two systems are used for the same purposes—the uses of the inch and millimeter and of the pound and kilogram being identical. It is for this reason that every engineer's reference book contains extended tables to facilitate conversion calculations between the two systems.

All arguments for the adoption of the system rest upon the tacit assumption that the old units are to disappear. If the old units are to persist, every argument for the system inverts itself and becomes an argument against it. Thus, instead of uniformity we would have diversity of units, instead of simpler more complex ratios, instead of simplified more complex calculations, and so on to the end. In the final analysis, the effect of this conjoint use of old and new units is the chief thing to be considered. It is found in every metric country—France included—and it not only nullifies but reverses every metric argument.

THE METER SHOULD HAVE BEEN ABANDONED WHEN ITS ERROR WAS DISCOVERED

It is well known and universally acknowledged that the attempt to derive the meter from a measurement of an arc of a meridian of the earth's surface was a failure. The actual base meter is the distance between two lines ruled on a standard bar of which all other meters are, directly or indirectly, copies. With the error of the survey proven, the meter had no longer an excuse for existence. It then became an arbitrary unit like the yard and in no manner nor degree better than the yard, while the effect of its continuance was the introduction of another base unit of which the world already had too many. The discovery of the error was made before the adoption of the meter had made much progress and when it could easily have been changed, and, in view of the established position of the yard, the surveyed value should have been abandoned as the result of a well meant but abortive attempt to establish a natural unit.

After the error had been discovered and the significance of the surveyed value destroyed, Sir Joseph Whitworth, realizing the consequences of incommensurate ratios, urged that the length of the meter be changed to forty inches (an increase of about five-eighths of an inch). This small change would have made the decimeter exactly equal to four inches and twenty-five millimeters exactly equal to one inch, the incommensurate ratios disappearing. The suggestion fell upon deaf ears. The system had already become, what it now is, a sort of religion. The meter had taken on a sacrosanct character and a change in its value was looked upon as sacrilege. For no better reason than this—the simple worship of a fetich—the most sane and useful suggestion ever made in connection with the system, and one from the man of all men best able to speak with authority and best deserving a hearing, came to nothing. The incommensurate ratios were fastened upon the world, and the irony of it is that this was done in the name of simplified ratios.

The most ardent advocate of the system, as a system, if he is not purblind, cannot fail to see that the introduction of a new incommensurate base unit, having in itself no element of superiority, had no justification and was certain to lead to confusion and complexity instead of clarity and simplicity. Those who did it in the interest of a needless revolution have their reward, for they but added another obstacle to the adoption of their system.

The anti-metric case is, however, far too large a subject to be adequately treated here. For additional voluminous information the reader is referred to The Metric Fallacy by the author and The Metric Failure in the Textile Industry by S. S. Dale, to contributions by the author and others to the Transactions of the American Society of Mechanical Engineers, Vols. 24 and 28, and especially to the official confession of the French Minister of Commerce, Industry and Labor regarding the failure of compulsion to suppress old units in France, Trans. A. S. M. E., Vol. 28, p. 877.

THE ORIGIN OF THE INCH

The absolute uniformity of measures of length throughout the English-speaking world is one of the marvels of modern times. Gages may be bought from various makers located indifferently in the United States, Great Britain or Sweden, which, when compared, are found to agree to the last measure of perfection. The beginning of this uniformity dates from Magna Charta, one of whose provisions reads: "There shall be one weight and one measure throughout our realm," and while, of course, that sentence voiced an intention rather than an immediate realization, it is a fact that every step in the attainment of accuracy, except the last which came from Sweden, has been the work of the English-speaking peoples. Long after uniform measures, according to the standard of accuracy of their time, were an established fact in England, the French were in the slough of despond with numerous local standards of varying values. When the confusion became intolerable, instead of standardizing their existing units or adopting those already standardized, the French developed an uncalled-for new system, thereby increasing instead of reducing the existing confusion and disorder.

The uniformity which exists among measuring instruments obtained from different makers and different countries is due to the fact that they have a common origin, namely the standard yard which is deposited in the Standards Department of the Board of Trade at London. It is a line measure, the distance between two fine lines near its ends being, by act of the British Parliament, a yard,[1] and of this yard, suitably divided and multiplied, all measures of length of the English system are, directly or indirectly, copies. Extraordinary safeguards protect this yard from possible damage. It is preserved in a vault from which it is taken once in ten years for comparison with the working standards. A copy of this yard is preserved in Washington, of which copies were made by the Brown and Sharp Manufacturing Company and the Pratt and Whitney Company, which copies are the bases of all measuring instruments supplied by those companies, of which independent comparisons have shown an agreement that is perfect.

THE COMPARATIVE ACCURACY OF LINE AND END MEASURES

Some comparisons between line and end measures have already been made, but it is necessary to obtain a more exact idea of their relative accuracy. The only deliberate determination of the accuracy of line measures of which the author has knowledge was by F. J. Miller, who turned five plugs by the making process, these plugs being of different sizes in order to insure against the formation of habit in the setting of the calipers. The plugs were made as carefully as possible without using a magnifying glass in setting the calipers and, when finished, they were measured with a micrometer. The result was to show a maximum variation from truth of one and one-half thousandths of an inch. Some of the plugs were small and others large, the extreme variation between the smallest and the largest being two and one-half thousandths.

This is undoubtedly a smaller error than would be obtained if a greater number of plugs had been made and it is certainly smaller than would be found, if comparisons were made be-

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[1] As has already been shown the meter stands upon exactly the same footing.

tween the work of different men.[1] It was the recognition of the inevitable error due to the taking of sizes from graduated scales that led Bodmer, about 1840, to design plug and ring gages. Sizes can be taken from such gages with calipers with a far higher degree of precision than from graduated scales.

A set of Whitworth plugs and rings, now the property of The American Society of Mechanical Engineers, which were imported into the United States by Mr. Freeland prior to 1857, is shown in Fig. 50. Although the mating plugs and rings are still good fits, showing absence of wear, the gages are not of an accuracy which would now be considered sufficient for such instruments.

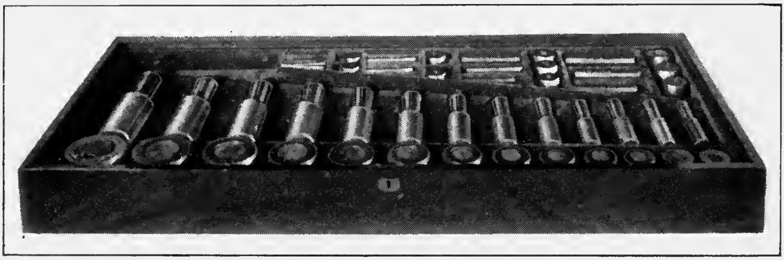

Fig. 50.—Whitworth plug and ring gages.

For many years such gages supplied the only means of introducing standard measurements of their degree of accuracy. They are still made and are listed in the catalogues of gage makers, but are going out of use. Their present use is chiefly as reference gages for detecting wear of snap gages, for which purpose they are unnecessarily expensive. For this purpose the ring gages are not really required and the plugs have an unnecessary extent of surface which adds seriously to their cost. For this use the Brown and Sharpe reference discs,[2] shown in Fig. 51, answer every purpose and are much cheaper.

[1] An investigation by the Engineering Standard's Committee of Great Britain showed the prevailing tendency to be to make plugs too small and holes too large. Of 456 plugs examined 56 per cent. were too small, 35 per cent. too large and 9 per cent. correct. Similarly of 329 holes examined 25 per cent. were too small, 62 per cent. too large and 13 per cent. correct. In both cases the direction of the largest error was the same as that of the greatest number of errors.

[2] Gages of this form and for this purpose were first made by John Richards.

The degree of accuracy to be expected from the use of line measures and calipers having been shown, so far as it has been determined, it remains to show the increased accuracy of end measures. Fig. 52 shows two Brown and Sharpe plugs which differ in diameter by a ten thousandth of an inch and between them is a snap gage. Trying this gage upon the plugs, the hand of any one, no matter how unskilled, will detect, without possibility of mistake, the larger plug. We have already seen that, using line measures and calipers, uniformity within two and one-half thousandths cannot be expected, and we have here at once a relative sensitiveness between the two methods

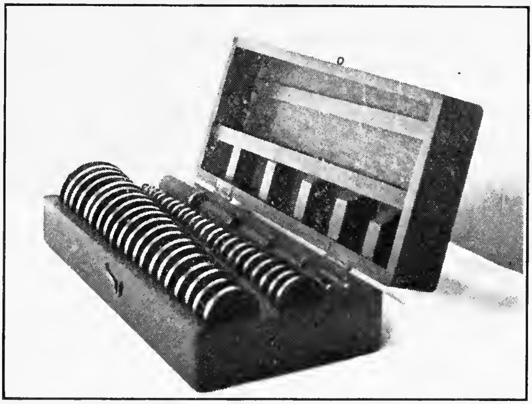

Fig. 51.—Standard reference discs.

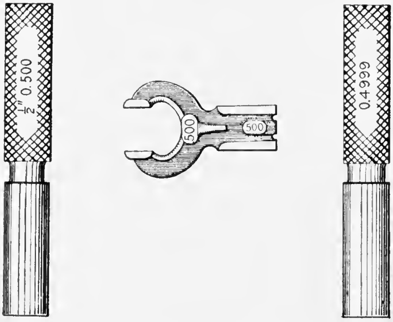

Fig. 52.—Lapped plugs and snap gage.

and under the most favorable circumstances for the line measure of twenty-five to one. As has been explained, moreover, if the results obtained by different workmen were compared, the result with line measures would be still worse while, by increasing the stiffness of the snap gage, its sensitiveness may be still further increased.

THE RELATION OF ACCURACY OF MEASUREMENT AND THE CHARACTER OF THE SURFACES MEASURED

While it is easy to speak freely of such minute quantities as the ten thousandth of an inch, and with proper grades of workmanship to show their existence, a word of caution is necessary. The easy detection of this quantity in the case of the Brown and Sharpe plugs is due to the perfection of their surfaces. We cannot measure a brick to the sixteenth of an inch because the errors of its surfaces exceed that amount and, precisely so, we cannot measure parts having surfaces made with cutting tools to the ten thousandth of an inch, and for the same reason. The ten thousandth of an inch has no place in the measurement of parts made with cutting tools, its place appearing only in the highest quality of work made by grinding or lapping. For cut surfaces the thousandth of an inch is about as small a measure as has any practial application.

THE SOURCE OF THE ERRORS WHEN USING LINE MEASURES

It is now necessary to point out the source of the error when using line measures. These measures may be of any required degree of accuracy, and the calipers used with them, while, as explained below, not equal to snap gages, are nevertheless end measures and fairly entitled to be called precision instruments. At the same time, having two instruments which are individually accurate, we find their combination to be the reverse. The errors arise in the transfer of the sizes from the scale to the calipers. The workman is expected to accurately divide the lines of the scale by the caliper legs and this he cannot do.

This line measure, however, which gives many sizes from one cheap instrument and the accuracy of which is not impaired by wear, is too serviceable a thing to be discarded and it is only necessary to devise means by which the transfer from the line to the end measure can be made with increased accuracy to make the line measure an accurate as well as a useful instrument.

For the doing of this we have four methods, namely: the vernier, the micrometer,[1] the multiplying lever and the microscope.

THE VERNIER

Fig. 53 shows the most obvious application of the first of these devices to the vernier caliper of the Brown and Sharpe Manufacturing Company. The line and end measures are here combined in one instrument, with screw adjustment for accurate setting, the adjustment being much more accurate than that of the common calipers applied to a graduated scale, by reason of the fact that the lines of the vernier may be matched against those of the scale with far greater accuracy than can the unlike ends of the caliper legs and the lines of the usual scale. The verniers of these instruments are commonly so divided as to read to thousandths of an inch—the error of their adjustment being naturally somewhat less than this. With finer division lines and a microscope the adjustment may be made still more accurately. Examples of such verniers and microscopes are seen on surveying instruments.

Figs. 54 and 55 show height and depth gages respectively. One application of the former has already been shown in Figs. 32–35 and others follow. The depth gage finds large use in die sinking and other branches of tool making. In the reading and adjustment all these instruments are line, while in use they are end measures.

It has already been pointed out that the line measure is free from deterioration due to wear and this makes such measures a necessity for ultimate standards. The official standards of the yard and of the meter are line measures.[2] In such standards

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[1] The author includes the micrometer here because, so far as the reading of its scale is concerned, it is a line measure, in which particular it is exactly parallel with the vernier and the multiplying lever.

[2] The ignorance of the fathers of the metric system of fundamental requirements is shown by the fact that the original meter—long since discarded—was an end measure. The original standard yard has always been a line measure.

the lines are so fine that they cannot be seen with the naked eye. They are read through a microscope of which the eye piece carries a spider cross hair. While these lines are extremely fine, they can be read with an error much less than their width.

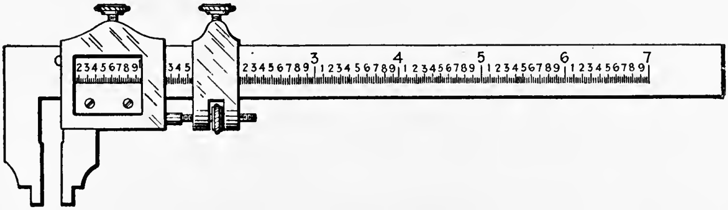

Fig. 53.—Vernier caliper.

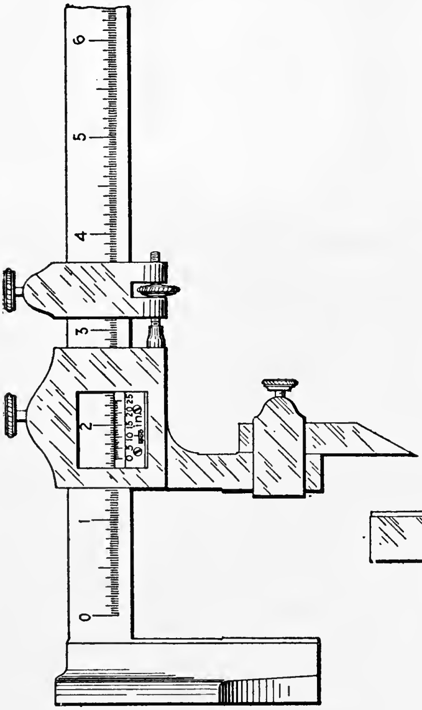

Fig. 54.—Vernier height gage.

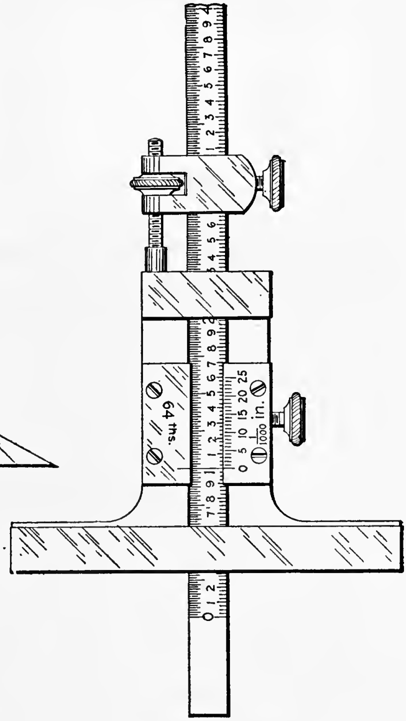

Fig. 55.—Vernier depth gage.

If the cross hair of the microscope is somewhat narrower than the line upon the standard it may obviously be centralized over it with an error much less than the width of the lines. Mr.

Bond informs the author that his practice is to match the edge of the cross hair against the edge of the line.

THE HISTORY OF MEASURING MACHINES

To the best of the author's knowledge the history of the shop micrometer begins with one made by James Watt, now in the South Kensington Museum and shown in Fig. 56.[1]

This instrument has, curiously enough, 18 threads per inch while its dial is divided into 100 parts, making the nominal value of its indications the eighteen hundredth of an inch.[2]

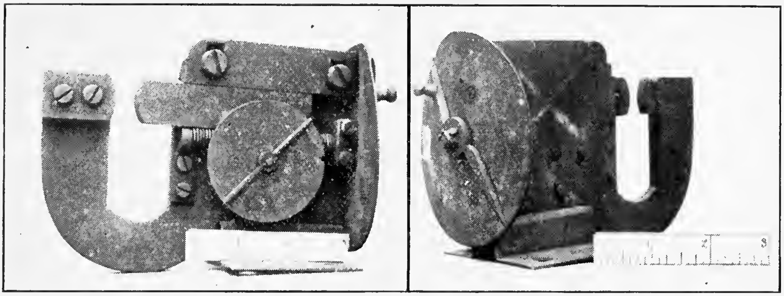

Fig. 56.—James Watt's micrometer caliper.

While this instrument shows clearly enough the conception of accuracy and a method of obtaining it, it is not to be imagined that its real was equal to its nominal accuracy. It was not possible in Watt's time to make screws sufficiently accurate for such a purpose which, alone, would defeat the object of the instrument.

The early history of accurate shop measurements has already been outlined. As regards end measures, Sir Joseph Whitworth exhibited his millionth measuring machine, which is still preserved, in 1851. While this machine is chiefly of academic interest, its construction marked an epoch in the history of accuracy of size, precisely as Whitworth's surface plates marked

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[1] The original application of the micrometer screw was to the eye pieces of telescopes. It was thus applied in 1648 and it was largely through its assistance that astronomy became an exact science.

[2] The small dial on the front side of the instrument indicates the number of whole turns of the screw.

an epoch in the history of accuracy of form. It should be said, further, that the machine would not now be called a measuring machine. Its purpose was not to determine the absolute length of pieces but to compare different pieces and determine their differences. It would now be called a *comparator* rather than a measuring machine.

It is difficult to conceive the crudity of measuring instruments prior to the dates that have been given. End measures were unknown prior to Whitworth's work, while prior to the scales of Brown and Darling, it is not too much to say that the carpenter's square of to-day is a precision instrument in comparison with any line measures then obtainable.

To those who have grown up with micrometers in their hands, so to speak, it is difficult to understand the mental attitude toward this subject which prevailed prior to the introduction of the micrometer. With their calipers mechanics had been habitually repeating sizes with an accuracy exceeding a thousandth of an inch but, without the micrometer, they had no means of determining the limits to which they were actually working and the thousandth of an inch as an actual dimension was looked upon with derision. Under such conditions Whitworth's deliberate setting out to measure minute differences that could be felt but not seen, seemed almost like attempting to weigh a shadow. Starting with this mental conception of minute quantities, Whitworth made the thousandth of an inch a common-place, the ten thousandth a tangible reality, and the hundred thousandth something more than a philosophical abstraction.

Whitworth believed, erroneously, that he had proven end measures to be more accurate than line measures, even when the latter were used with a microscope and, through his plug and ring gages, he proposed the abandonment of line and the substitution of end measures in machine construction. This is exactly what has been done in the manufacturing system and, in view of the conditions that obtained in Whitworth's time, the conception was nothing less than brilliant. In this, as in so many other things, he was decades ahead of the rest of the world.

The only limitation that can be placed upon admiration for Whitworth's work grows out of the fact that the real accuracy of his gages was far behind the claims made for it. Measurements of the Whitworth plugs shown in Fig. 50, by Mr. Bond have shown errors that are irreconcilable with the old claims. Moreover, gages imported by different parties were found, when compared, not to agree, and even gages of the same set were found to be inconsistent—two plugs placed side by side being found to overfill or to fail to fill a ring which was nominally their sum. Nothing is better established than the fact that the early Whitworth gages fell far below the claims made for them.

No explanation of this has ever been made. The critic should, however, remember that it is manifestly unfair to judge pioneer work by the standard of ultimate achievement. The only proper comparison is one that measures the progess made and, when judged by this standard, Whitworth's work is found to be revolutionary. Whatever may be said regarding the failure of his gages to meet specifications, it may at least be said that it is not to his discredit that he aimed at a mark beyond his reach, nor that he left something for others to do, even though that something was the placing of the keystone of the arch.

The beginning of accurate shop measurements in the United States, as has already been said, was by Dr. John E. Sweet at Cornell University, who completed a measuring machine, shown in Fig. 57, in 1874. The screw of this machine has 16 threads per inch and its divided circle has 625 divisions, the readings being thus to the ten thousandth of an inch. The machine has several features which are now universal in such machines: It stands upon three legs, its screw is of the ratchet section and the screw and nut are of the same length, thus eliminating local wear.

The machine was made before Whitworth's dictum regarding the superiority of end measures had been overthrown and it is thus an end-measure machine. Accompanying it were a series of end-measure rods differing by whole inches. By the use of these rods, one of which is shown in the illustration, the tail stock was adjusted for the whole inches, the fractions being determined by the turning of the screw. The necessity of nicety of adjustment of the tail stock was, however, eliminated by the adjustable zero bar which may be turned about the screw to match the position of the zero on the divided circle wherever it may happen to fall—a feature which, also, is found in more recent machines.

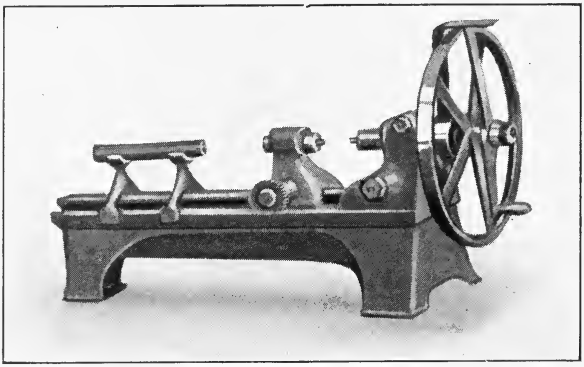

FIG. 57.—Cornell University measuring machine.

MODERN MEASURING MACHINES

In all measuring machines, next to accuracy of parts, the chief problem is the finding of means by which to secure uniform pressure of contact. The means adopted in this machine for this purpose—and it was, perhaps, the least satisfactory feature of the machine[1]—was that of friction between the cross bar in front of the divided wheel and the face of the wheel. The chief differences between various makes of measuring machines are at this point and the leading methods adopted are hence given in connection with the descriptions of the following machines.

The Brown and Sharpe Machine—due to O. J. Beale—which is a development of the original machine made in 1878, is shown in Fig. 58. Its most striking feature is the remark-

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[1] That is, for the degree of precision aimed at. For micrometers reading to thousandths the device is entirely satisfactory.

ably massive bed which is of box form and eighteen inches deep. The machine is a bold and original application of the principle of the increase of sensitiveness due to increased stiffness which is explained at the beginning of the chapter on gages. With its massive bed the sensitiveness of simple touch is so greatly increased that dependence is placed upon it alone, and by it the hundred thousandth of an inch is easily detected.

This does not eliminate the personal equation and, were the machine put into the hands of miscellaneous users, differences of measurement due to differences of pressure would arise. The machine is not, however, so used. It is not made for sale, being used only in the gage department of the Brown & Sharpe works where the machines are used by none but trained men and under these conditions the readings are entirely satisfactory. This was the first machine in which the authority of Whitworth as regards the superiority of end over line measures was disputed and the line-measure rehabilitated and placed where it belongs as the ultimate standard. While end-measure machines are still made, the line-measure machine is much more common. The line measure of this machine is engraved on the long tail stock spindle, of which the upper half is cut away in order to bring the scale at the center line of the machine, a

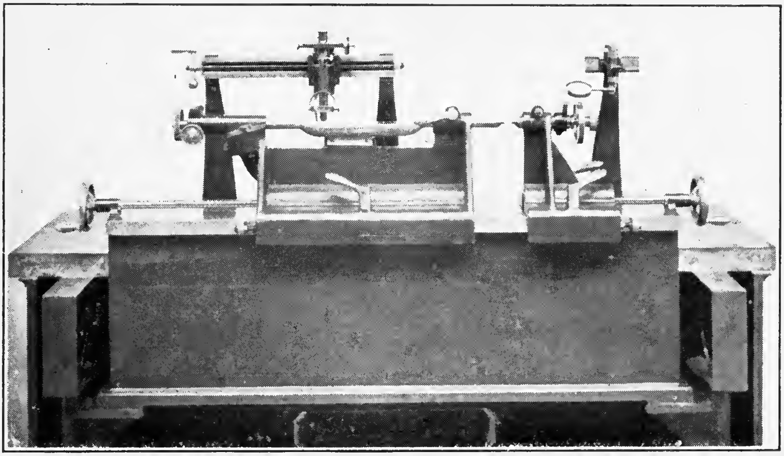

FIG. 58.—Brown and Sharpe measuring machine.

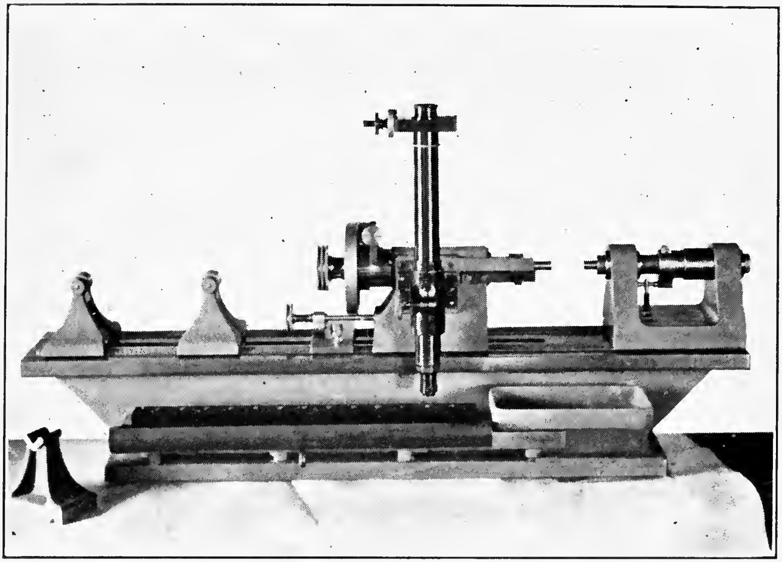

Fig. 59.—Rear side.

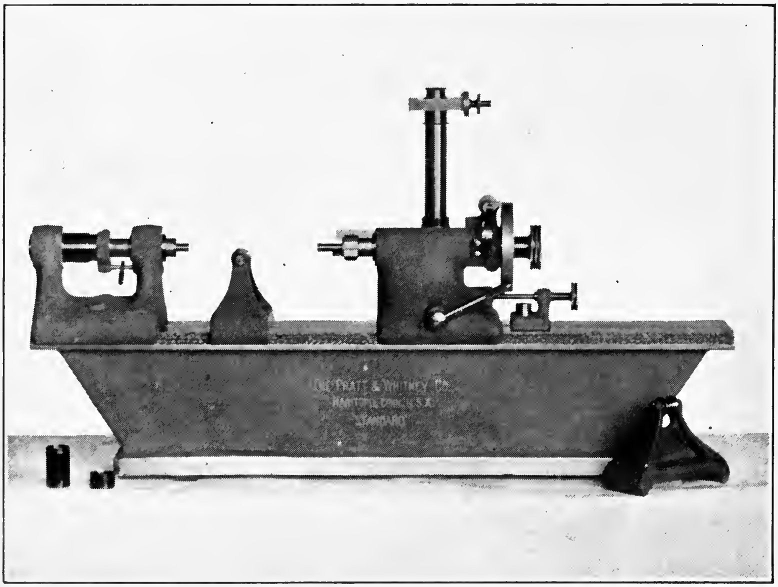

Fig. 60.—Front side.
Pratt and Whitney measuring machine.

microscope being provided for reading it. In this location of the scale the machine is unique. The lever action due to the position of the measuring fingers above the bed causes the fingers to change position with flexure of the bed and the arrangement described was adopted in order to provide for this effect.

The Pratt and Whitney machine—due to Professor Rogers and G. M. Bond—is shown in Figs. 59 and 60.[1] The line measure, which is divided into whole inches only, fractional readings being obtained from the screw, is seen lying on the bed in Fig. 59 together with the microscope for reading it attached to the moving head stock.

Uniform pressure of contact is secured by means of a gravity drop piece.[2] This device, which is clearly shown in the tail stock of Fig. 60, is a small cylinder of hardened steel, precisely like a plug gage, which is pinched between two opposing fingers. One of these fingers is attached to the frame of the tail stock and the other to an arm projecting from the spindle of the tail stock—a spring behind the spindle maintaining pressure sufficient to hold the gravity piece in a horizontal position. When making a measurement the measuring screw is turned until this gravity piece drops to a vertical position like a semaphore, but without dropping out. This machine was intended for sale and it has gone to all quarters of the globe where such machines are needed. It was, in fact, this machine which first carried means for making independent measurements of high precision into the workshops of the world.

The measuring machine of the [British] Newall Engineering Company—due to J. E. Story—is shown in Fig. 61. The method of obtaining uniform pressure of contact is by the use of a sensitive level swiveled upon the tail stock casting and having a short arm projecting from its lower side, against which the spindle of the tail stock abuts, a light spring pushing the spindle forward. The construction, which is shown more fully in Fig.

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[1] The machine shown is not in all respects of the most recent pattern. The illustrations shown are chosen because they show the desired features most clearly.

[2] This device was used by Whitworth in his millionth measuring machine.

62, multiplies the spindle movements, as read by the bubble of the level, by about four thousand. The machine shown is fitted with a line measure and microscope, but end-measure machines are also made.

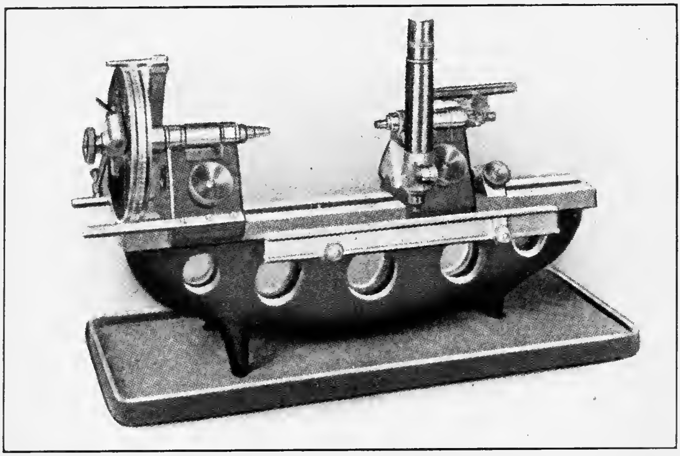

FIG. 61.—Newall measuring machine.

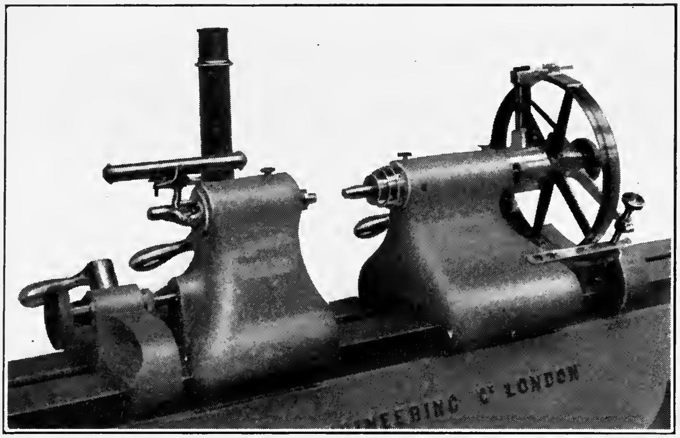

FIG. 62.—Contact feature of the Newall measuring machine.

Another refinement of this machine is found in the construction of the head stock. In previous machines the measuring screw acts not only to traverse itself but as a bearing to carry its own weight and that of the graduated wheel. In this machine the shank of the screw is extended at each end to form bearings which support the weight of the parts, relieving the screw of that duty and leaving to it the traverse function only. The arrangement will be recognized as an application of the principle of the division of functions. It is shown in Fig. 63.

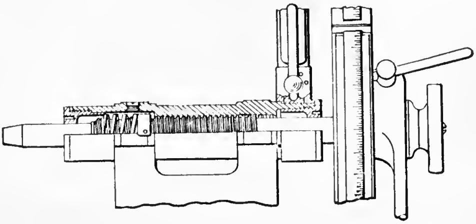

Fig. 63.—Section of headstock of the Newall measuring machine.

THE MICROMETER CALIPER

The micrometer caliper, which was first made an article of commerce by the Brown and Sharpe Manufacturing Company in 1867, is essentially a small portable measuring machine. Just as the Pratt and Whitney measuring machine has been the means of carrying precision measurements of the grade required into the tool rooms of the world, so the Brown and Sharpe micrometer caliper has performed the same office for the commercial departments of machine construction. It has also been the greatest of all educators in the matter of what really constitutes accuracy. It is made in a great variety of forms and for both inside and outside measurements.

The range of adjustment of the measuring screw is uniformly one inch. The tail spindle or anvil of large instruments is sometimes adjustable by means of end-measure rods of even inch lengths, by which the range of the instrument is made to cover several inches, and this anvil is sometimes permanent, the range in such instruments, whatever their capacity, being one inch only. A set of micrometers of the latter construction by the J. T. Slocomb Company is shown in Fig. 64. In the base of the frame which carries the micrometers is a set of end-

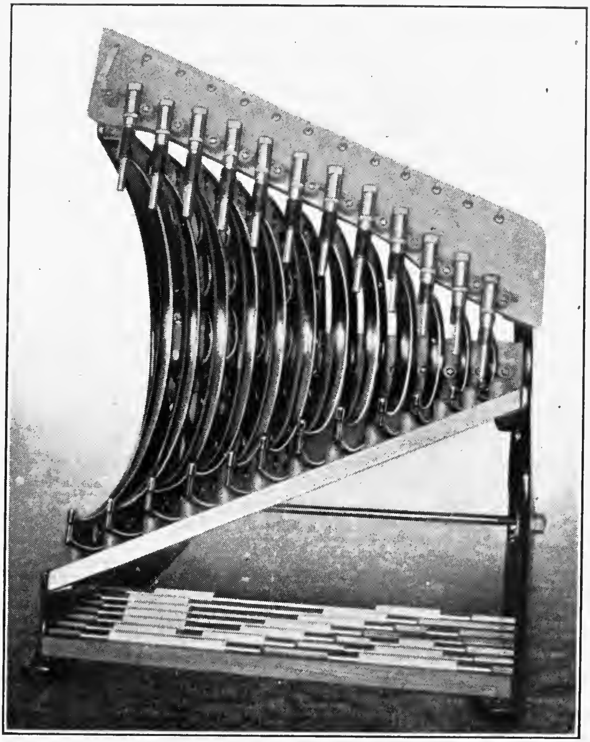

FIG. 64.—Set of Slocomb micrometer calipers.

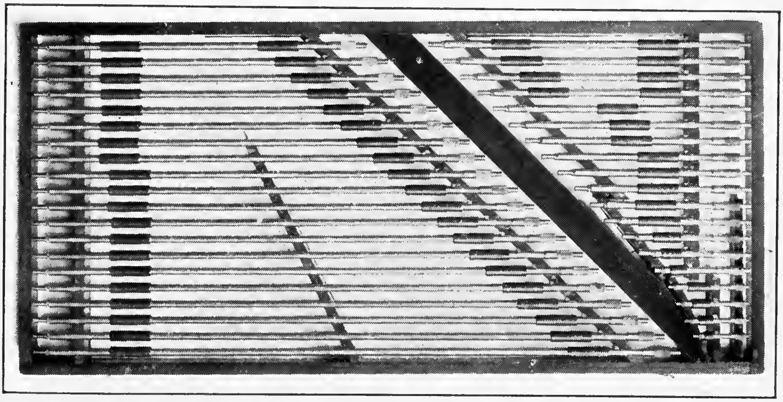

FIG. 65.—Set of Brown and Sharpe inside micrometer calipers.

measure rods by which to verify and, if necessary, correct the accuracy of the instruments, for which purpose the anvil screws are adjustable through a slight distance. Fig. 65 shows a set of inside micrometers by the Brown and Sharpe Manufacturing Company. In these, as in the outside instruments, the range of the screw is uniformly one inch. Micrometer heads without frames or other attachments are also provided and have many applications in connection with special gages of various kinds. Such micrometer heads are seen in the large Westinghouse micrometer calipers of Figs. 93 and 94 and in the machine for measuring the errors of pitch of long screws, Fig. 116.

PRECISION SCREWS AND PRECISION LATHES

All of these measuring machines depend upon a screw for their readings and it is apparent that this screw must be of precision grade and be cut on a precision lathe. The lathes with which measuring-machine screws are cut have not been published and in their stead are given two others.

While methods have been devised for that purpose, screws are seldom originated in the sense that flat surfaces are originated. In the production of precision screws the procedure is to take the best screw available as a starting point, measure its errors and then adopt means by which, although this screw is used as a lead screw, its errors do not appear in the screws cut from it.

To the best of the author's knowledge there is but one method of doing this which is shown with great clearness in the illustration, Fig. 66, of Professor Rogers's precision lathe.[1] The first thing to be observed about this lathe is its massiveness. The slabs which form the shears of the machine were two and a half inches thick and the other parts of corresponding massiveness. The liberal use of mass was, in fact, one of the cardinal points of all of Professor Rogers's work.

In order to get rid of the tendency to slew the tool carriage, due to the customary location of the lead screw in front of the

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[1] The lathe, which was made by Webber and Philbrick, was destroyed by fire shortly before the death of Professor Rogers.

machine, that screw was in this machine placed within the shears and vertically below the center line of the centers. Carried by the slide rest is a microscope which is used to read a line measure, divided into inches, which lies upon the rear side of the lathe bed. The microscope contains, of course, an eye-piece micrometer.

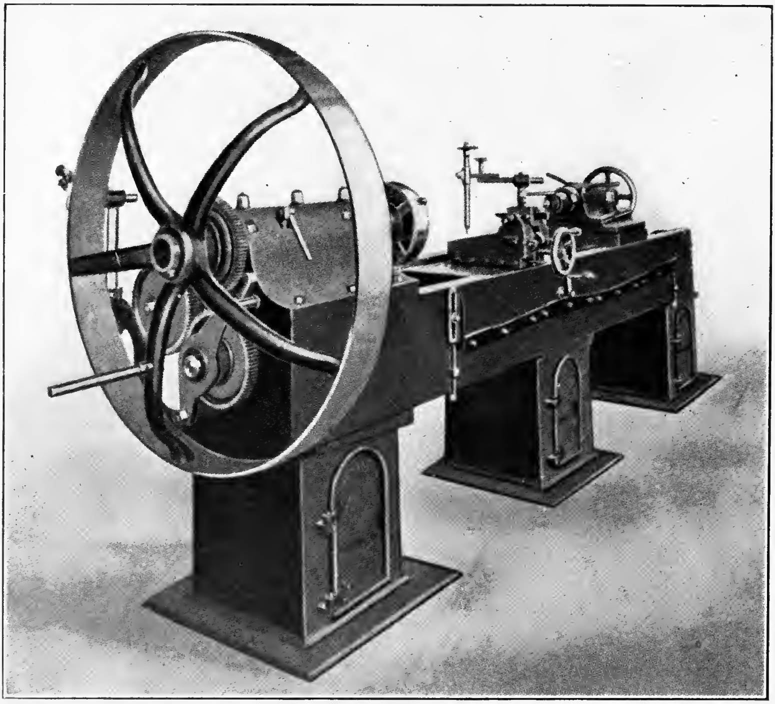

FIG. 66.—Professor Rogers's precision lathe.

A slab-shaped piece of iron will be seen upon the front side of the lathe, to which is bolted a templet of irregular outline. The center of curvature of the slab, as seen endwise, is at the center of the lead screw. The nut which engages the screw has no rigid connection with the carriage—being what Professor Rogers called a *free nut* which traverses the carriage by pushing it. The nut is also free to turn about the screw and has attached to it a curved lever which reaches over the lathe shear and carries at its outer end a roller which rides on the correction templet.

It is obvious that as the carriage advances the lever will rise and fall on this templet, turning the nut with it and thereby hastening or retarding the advance of the carriage as the case may be. It is this hastening and retarding of the action of the screw which corrects the errors of the screw, the outline of the templet being such as to accomplish this result.[1]

In the determination of this outline the divided scale was adjusted lengthwise until one of its lines was split by the cross hair of the microscope. The driving pulley was then turned such a number of turns as would, assuming the screw to be correct, advance the carriage one inch. Reading the division of the scale through the microscope, if the cross hair and division line did not agree, the lever attached to the nut was raised or lowered until the cross hair and line did agree, thereby locating a point of the templet. This process was then repeated for the next inch division of the scale and so on to the end, thus obtaining a series of points in the outline of the templet through which, a smooth curve being drawn, the outline of the templet was determined and made. This being done and the roller upon the end of the lever being placed in position, it is clear that, in the action of the lathe, the turning of the nut due to the rise and fall of the lever on the templet would compensate the errors of the screw when cutting another.

The gears at the end of the lathe are of the same size because the lathe was not intended to cut screws of other pitches than that of the lead screw. To attempt to do this would introduce errors due to the irregular spacing of the teeth of different gears which it would be impossible to compensate. With the gears shown it is obvious that the errors determined in outlining the templet are the combined errors of the screw and gears, and, once determined, it is only necessary to keep the gears on the lathe permanently or, if removed, to replace them in the same relative positions in order to insure the continued correctness of the corrections. As a matter of fact, after the errors were determined the gears were marked so as to insure their future

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[1] Professor Rogers obtained the method from M. Froment of the French firm Dumoulin and Froment, makers of optical and scientific apparatus.

replacement in the same relative positions in case it was found desirable to remove them.

Figs. 67–69 show the precision lathe of the National Physical Laboratory of Great Britain which employs the same device for correcting the error of the screw as Professor Rogers's lathe, but which is in many other respects far superior to it. Among these may be noted the support of the machine upon three points and by a suitably trussed sub-frame casting; the provision of a tubular bed which, in torsion, is enormously stiffer than any other possible section, and the provision of separate nut and tool carriages connected by massive rods in direct tension only, whereby the lead screw and the screw in process of being cut are placed in line with one another. As originally made the machine was provided with an independent driving head and an equalizing driver of which portions are shown in Fig. 67, whereby

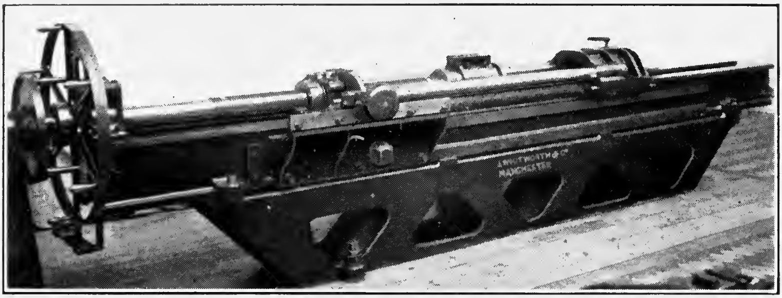


Fig. 67.—Precision lathe of the British National Physical Laboratory.

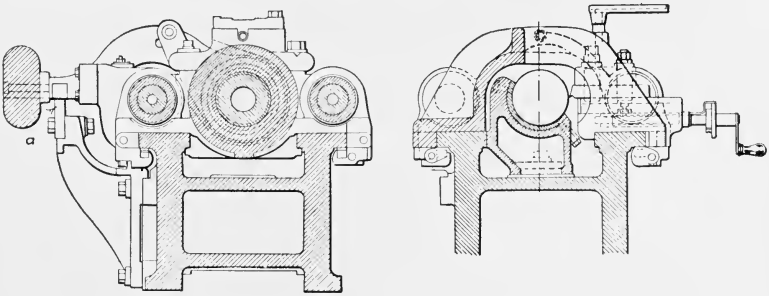


Fig. 68.—Nut carriage. Fig. 69.—Tool carriage.
Section of the precision lathe shown in Fig. 67.

the pull of the belt on the machine was eliminated. As now used, however, the lathe is driven by hand. Its only use is to finish screws which, except for the correcting cut, are made on other lathes.

The correcting bar is plainly seen in Fig. 67 while Fig. 68, which is a section through the nut carriage, shows the same bar at *a* and in addition the tubular bed. Fig. 69 is a section of the tool carriage and shows the support of the screw being cut and the fact that the cutting tool is inverted from the usual position, this arrangement being adopted because believed to be more conducive to the avoidance of chatter. Screws have been cut with this lathe of which the errors are less than the ten thousandth of an inch in twelve inches of length. It represents the culmination of the solution of the fascinating precision screw problem which has engaged the attention of many mechanics from Maudsley down, including Whitworth.

CHAPTER IV

THE MEASUREMENT OF ERRORS

Instruments for measuring errors embodying the multiplying lever—Uses of these instruments—The dial gage and its uses—The measurement of errors with extemporized apparatus.

In a large number of cases of measurement the thing measured is the error from truth. This error may be the error from truth of size, in which case the process of measurement is one of comparison with a standard, the measuring instrument giving the difference between the standard and the piece which is compared with it. In other cases the error measured is one of position or adjustment, in which, for example, the degree of parallelism or of squareness of one piece with another is determined. For both these classes of measurement instruments embodying the multiplying lever possess advantages over the micrometer because less time is required for their use and the personal equation is eliminated.

APPLICATIONS OF THE MULTIPLYING LEVER

An application of the multiplying lever to the comparison of parts with a standard is shown in Figs. 70 and 71 from the Canadian Ingersoll-Rand Company. The standard with which the comparison is made may be a gage or, as in this case, a sample piece preserved as a standard. The illustrations show an indicating beam caliper made by the Syracuse Twist Drill Company in the act of gaging a rock drill slide valve, Fig. 70 showing the instrument as it actually appears and Fig. 71 with a protecting cover removed in order to show the construction. The stationary head of the instrument carries a multiplying lever which plays over a graduated scale at the top, the graduations reading to thousandths. The short end of the lever is connected with the measuring finger, which has a

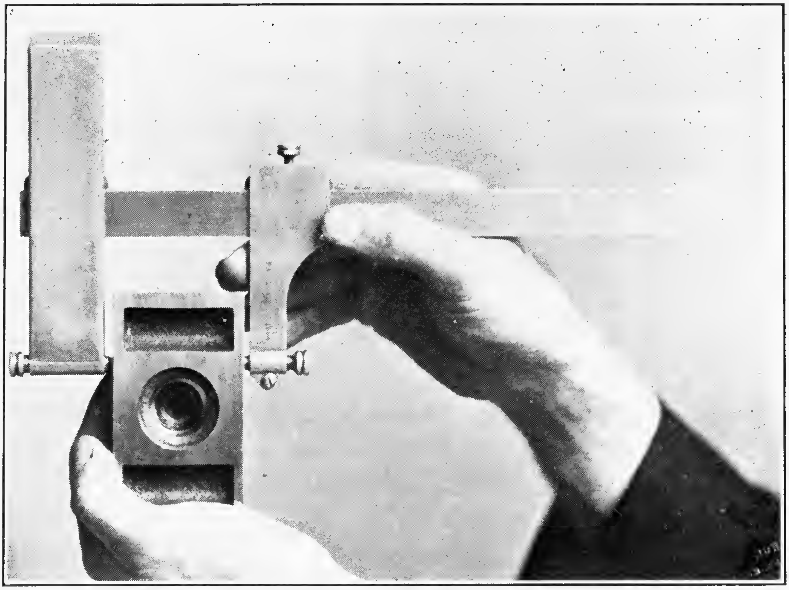


FIG. 70.—With cover plate in position.

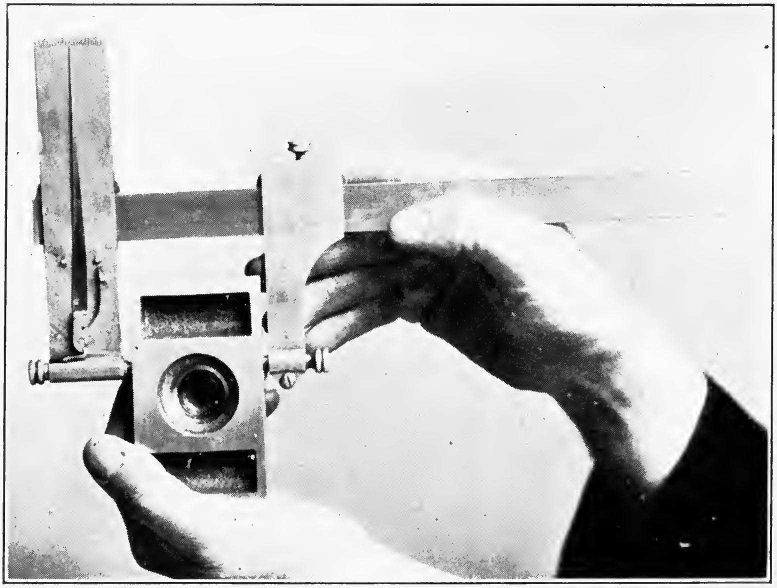


FIG. 71.—With cover plate removed.
Indicating beam caliper.

slight endwise movement. The sliding head carries a second finger which is threaded and fitted with a knurled head. The standard—an end-measure rod or a sample piece preserved as a standard, as in the present instance—is placed in position and the finger upon the moving head is adjusted until the multiplying lever stands at the zero of the scale, this zero being at the center of the scale in order to read errors in both directions. This being done, the parts as made are placed in position and their correctness or their errors are determined at once.

This is the cheapest method known to the author of introducing the limit gage system. The limits are tabulated and the inspector has only to compare them with the readings of the instrument in order to determine if the parts are within the limits. The instrument has received far less application than it deserves and this is the more strange because of the wide application of the multiplying lever to other uses. It will be observed that the instrument is in no sense a measuring instrument. It is a *comparator*, that is to say, it compares parts and determines their differences but it does not determine their absolute sizes.

THE TOOL-MAKER'S INDICATOR

The widest application of the multiplying lever is to the toolmaker's indicator, one of which, by Koch & Son, is shown in Fig. 72, of which the lower view shows the sliding cover removed and the multiplying levers exposed. Such indicators appear in a great variety of forms as they are frequently home made. The present instrument is unusual in that it is fitted with compound levers, thereby making it extremely compact. These levers are enclosed in a steel box which has at each end a projecting finger which engages with the short end of the lever system. The finger at the left slides endwise while the one at the right is a bell crank, its external movement being vertical in the position shown. Great flexibility of adjustment is thus made possible, including internal readings by entering the bell crank end into holes to be indicated.

The applications of this instrument are almost endless.

Perhaps the most common is to the centering of work in the lathe, as illustrated in Fig. 73, in which the vibration of the lever as the lathe revolves shows the amount of untruth of the piece of work. Fig. 74 shows the adjustment of a milling machine vise at right angles with the cutter arbor to which latter the indicator is clamped by a series of collars and a binding nut. By traversing the work table the indications of the instrument indicate any lack of truth of the vise jaws. Fig. 75 shows the instrument used for transferring a measurement to an otherwise inaccessible place. The height from the surface plate is taken in the indicator from the height gage, when the indicator is lifted over the jig body into which the measuring finger enters. The position of a point within the jig may then be compared with the reading of the height gage. Fig. 76 shows the application of an instrument of different pattern to the adjustment of a swiveled angle plate. The small angle plate clamped to the swiveled plate being known to be accurate, it is obvious that by sliding the indicator and its base about the horizontal surface plate, the parallelism of the small plate and the perpendicularity of the swiveled plate with the large plate are determined.

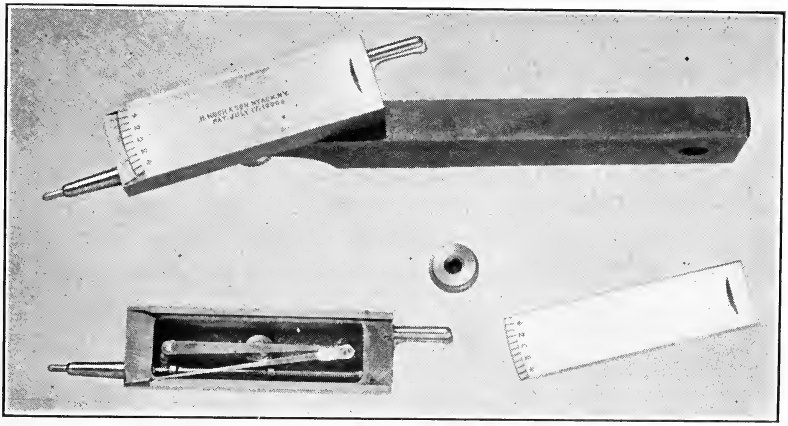


Fig. 72.—Tool-maker's indicator.

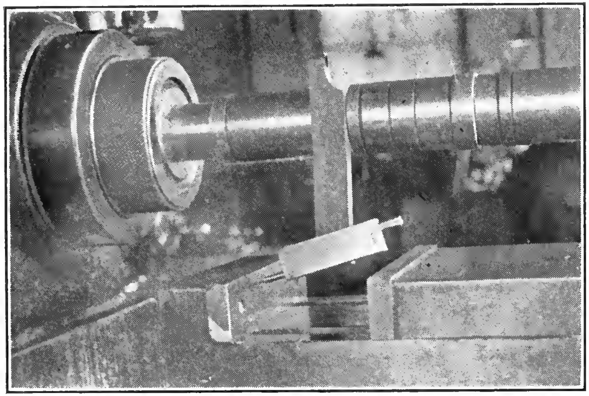


FIG. 73.—First example.

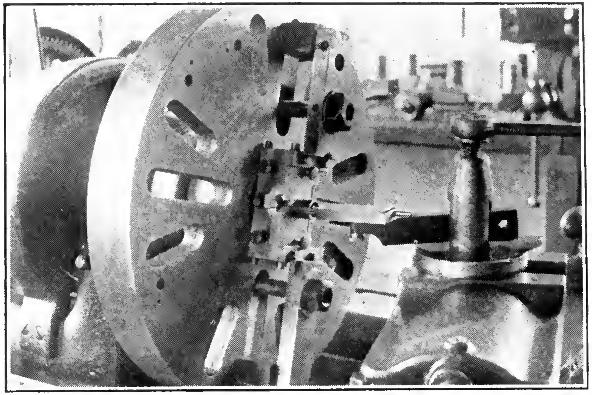


FIG. 74.—Second example.

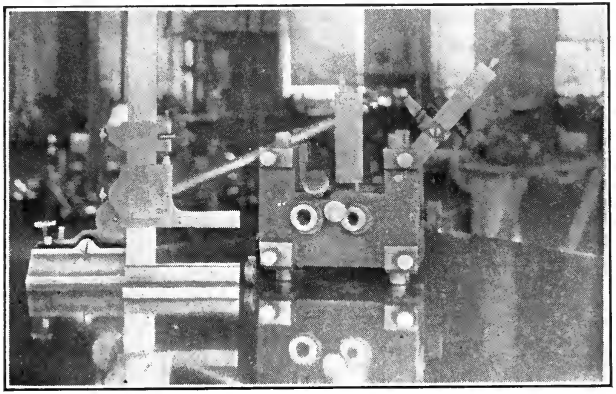


FIG. 75.—Third example.

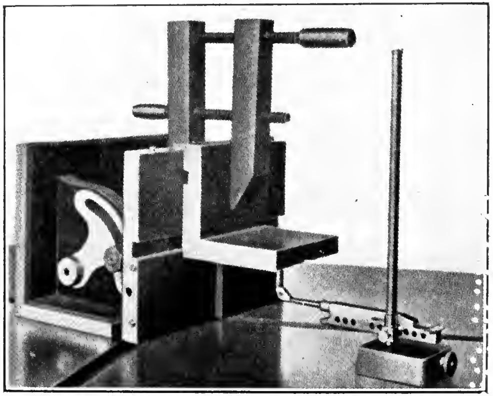


FIG. 76.—Fourth example.

Applications of the tool makers indicator.

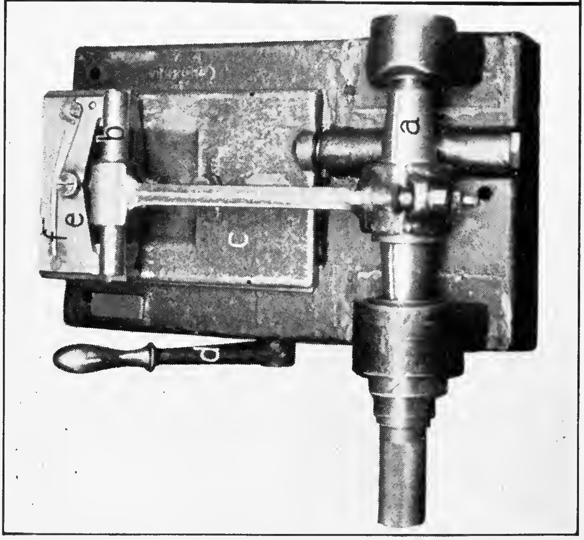


Fig. 77.—Testing parallelism of crank and piston pin holes.

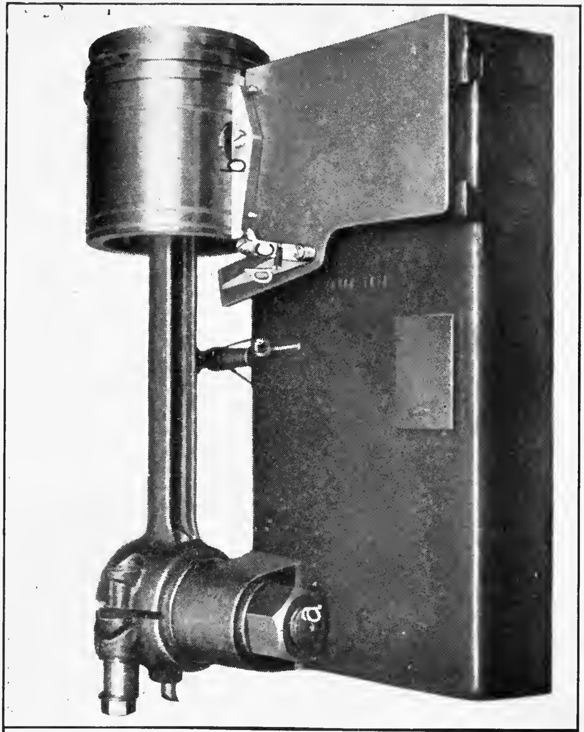


Fig. 78.—Testing squareness of piston with crank pin holes.

MEASURING ACCURACY OF POSITION

Applications of the multiplying lever to the determination of accuracy of position are shown in Figs. 77 and 78, from the Cadillac automobile works. In Fig. 77 the parallelism of the crank pin and piston pin bearings of a connecting rod is being tested. The crank pin bearing is clamped upon a true arbor *a* which is mounted in suitable supports, the piston pin end having inserted within it a similar true arbor *b*. A slide may be reciprocated a short distance by the hand lever *d* and a swiveled lever *e* carried by the slide *c* be thus brought into contact with the arbor *b*. A multiplying lever *f* plays over a graduated scale at its left-hand end and thus shows any departure from parallelism of the two arbors.

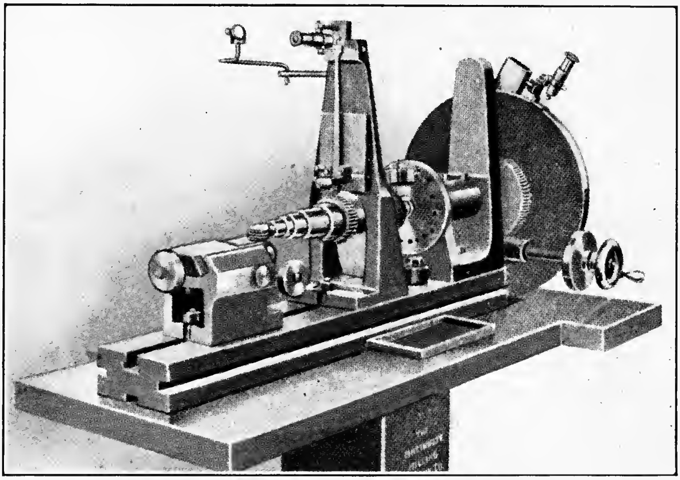


FIG. 79.—Testing accuracy of spacing of worm wheel teeth.

In Fig. 78 the squareness of the piston with the crank-pin hole is similarly tested after the parts have been assembled. The crank-pin bearing is clamped upon the pin *a* and the slide at the right is adjusted until the swiveled lever *b* makes contact with the piston. Two multiplying levers *c*, *d*, of which the latter plays over a graduated scale at its further end, show any lack of truth, suitably magnified.

Figs. 79 and 80, from the Cincinnati Milling Machine Co., show an application of the multiplying-lever principle to the determination of the accuracy of the spacing of the teeth of the worm wheel of a milling machine dividing head. The multiplying lever is forked at its lower end, as shown more clearly in Fig. 80, and at its upper end it carries a spider-web line which is read against a line upon a silver disc attached to the frame. Going back to Fig. 79, the arbor upon which the worm gear to be tested is mounted carries on its rear end an accurately divided circle by which the worm wheel may be turned through the spaces corresponding with the intended spacing between the teeth. Were this spacing correct, it is clear that the spider-web line and the line upon the silver disc would agree for every tooth and that the errors will be shown by a lack of such agreement. The degree of precision of the equipment is sufficiently indicated by the fact that both graduated circle and hair lines are read by microscopes.

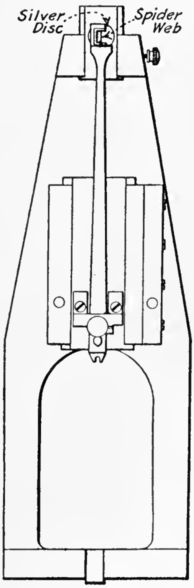


Fig. 80.—Indicator of worm wheel testing apparatus.

THE DIAL GAGE AND ITS APPLICATIONS

A modification of the multiplying-lever principle which has many applications is found in the dial gage of the B. C. Ames Company, shown in Fig. 81. In this instrument the movement of the measuring finger is shown by the turning of the index on the dial, the two being connected by multiplying internal mechanism not shown. In the instrument shown the readings are to thousandths which are numbered from 0 to 50 in each direction, as

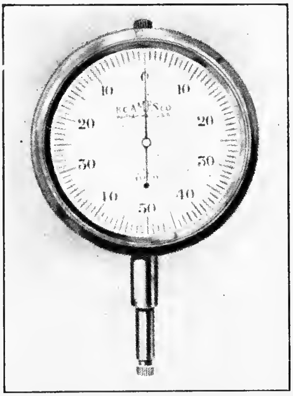
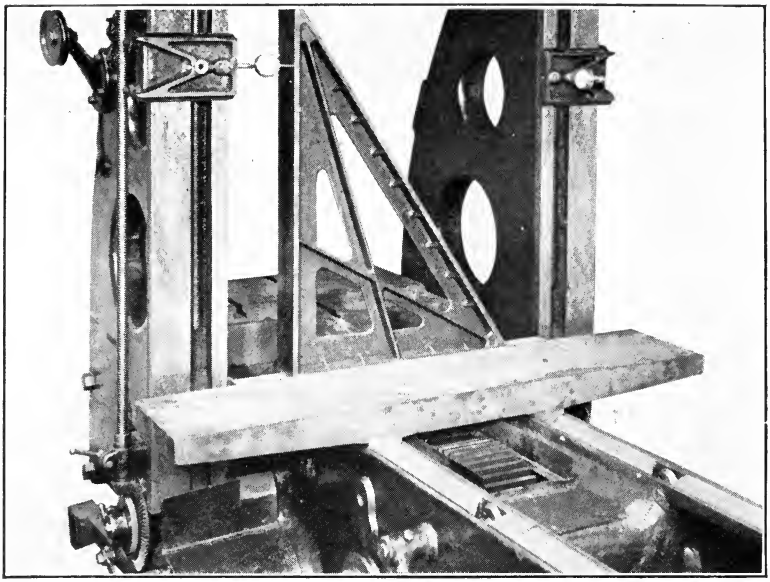
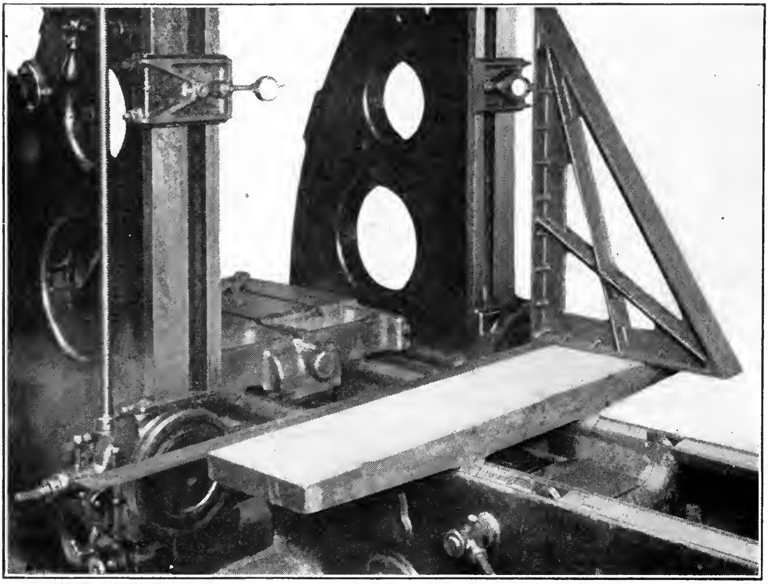
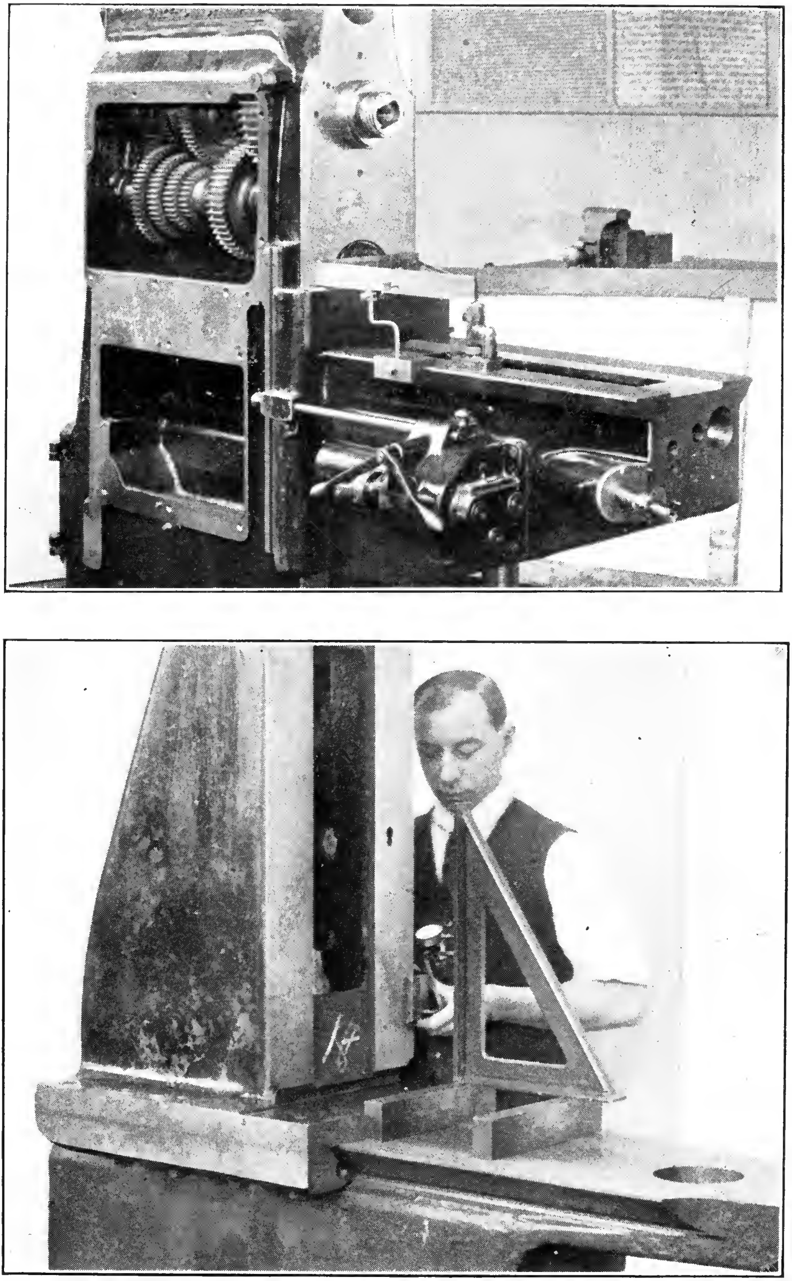


Fig. 81.—Dial test indicator.





FIGS. 82 and 83.—Testing the squareness of planer housings.



FIGS. 84 and 85.—Testing the squareness of a milling machine knee.

errors are as apt to lie in one direction as the other. The dial may be turned to bring the zero under the index wherever it may happen to lie at the first reading. This adjustment, combined with the increased range of the instrument, makes it more convenient for many purposes than the lever construction previously shown.

Figs. 82 and 83, from the American Tool Works Company, show the instrument used in combination with a square. By moving the indicator and the block to which it is attached vertically, it is obvious that the degree of squareness of the planer housings with the V's of the bed in both directions is quickly determined. Similarly Figs. 84 and 85, from the Cincinnati Milling Machine Company, show applications to milling-machine construction. In Fig. 84 the squareness of the knee with the main frame as seen in plan, and in Fig. 85 as seen in elevation, is determined. The errors found are removed by scraping.

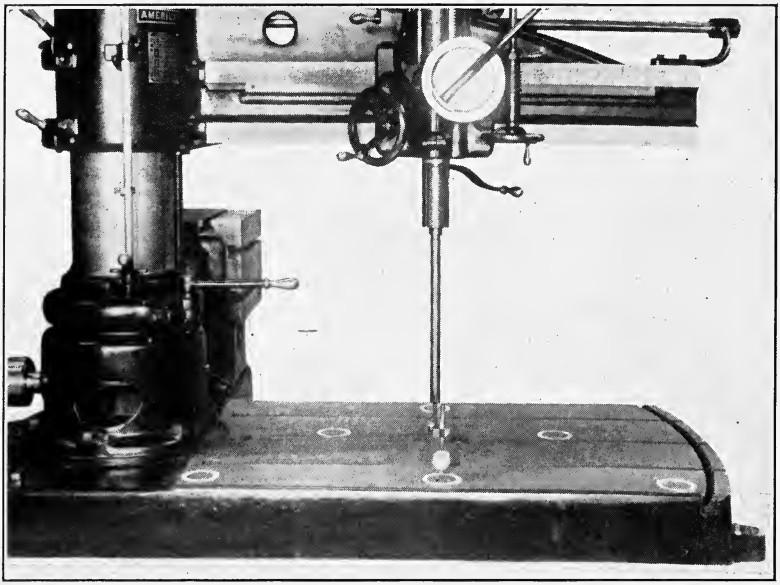


FIG. 86.—Testing the parallelism of a radial drilling machine arm and base and the squareness of the spindle with the base.

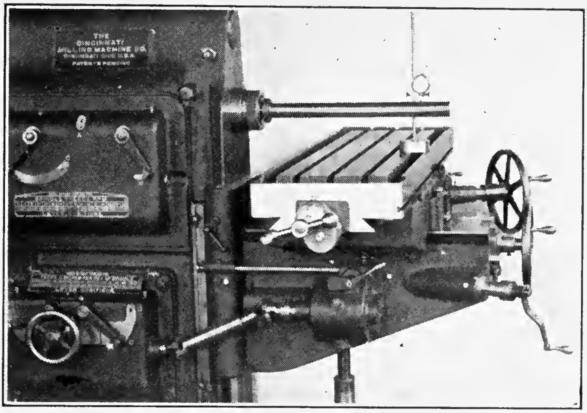


FIG. 87.—Testing the alignment of a milling machine spindle.

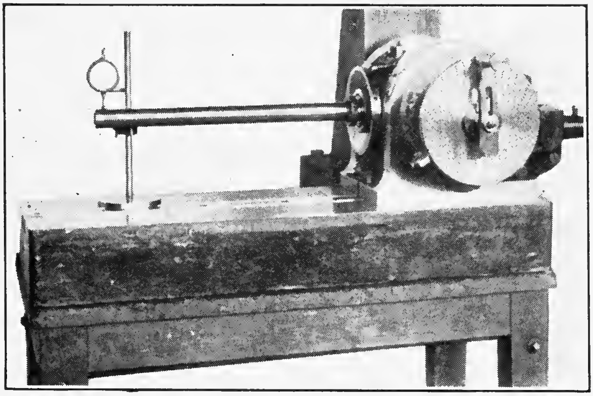


FIG. 88.—Testing the alignment of the spindle of a milling machine dividing head.

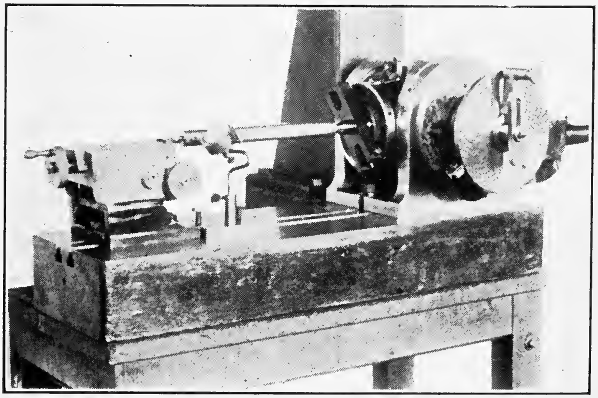


FIG. 89.—Testing the alignment of milling machine centers.

Fig. 86, also from the American Tool Works Company, shows applications that are typical of many. The indicator is attached to an arm seen endwise but extending radially from an arbor inserted in a radial drilling machine spindle. By traversing the head along the arm and taking readings at various points indicated by the three circles at the front of the base, the error in the parallelism of arm and base is determined. Similarly by revolving the spindle and taking readings at the four points indicated by the circles, the squareness of the spindle with the base is determined.

Fig. 87, from the Cincinnati Milling Machine Company, shows an application to the testing of the alignment of a milling-machine spindle and work table. The test arbor, which is inserted in the taper hole of the machine spindle, being known to be true, it is only necessary to revolve the spindle in order to show any lack of truth of the hole since such lack of truth will cause the arbor to vibrate and this vibration will appear in the movements of the indicator pointer. Similarly by moving the indicator and stand to the inner end of the arbor, any lack of parallelism of arbor and work table will be shown, and, again, by traversing the work table on the knee, lack of parallelism between the arbor and the knee will appear.

Fig. 88, from the same source as the preceding illustration, shows a similar application to the taper hole of the work spindle of a milling-machine dividing head. After the truth of the hole has been proven, the head may be adjusted on its swivel until the readings show the arbor to be parallel with the base, when the zero of the graduated arc for reading the angle of elevation may be located, or, if already located, its truth may be proven. Still another application appears in Fig. 89 in which the base of the stand for the indicator has a tongue which drops into the T-slot of the main base. The head and tail stocks have similar tongues and, the arbor being known to be true, traverse of the indicator in the slot will show the truth of the alignment of the live and dead centers.

These illustrations indicate the degree of precision that enters into the construction of modern machine tools.

TESTS WITH EXTEMPORIZED APPARATUS

A large number of entirely satisfactory tests may be made with extemporized apparatus and an ordinary micrometer caliper by measuring from the rear end of the barrel. Figs. 90–92 show such tests of the accuracy of a lathe. Putting a well-centered arbor in the lathe and mounting a micrometer upon it, as in Fig. 90, and taking readings against the face plate at the ends of the vertical and horizontal diameters, it is clear that the squareness of the plate and with it the alignment of the live spindle with the line of centers may be determined. Again by mounting the calipers as shown in Fig. 91, taking a reading with the tail spindle drawn in, then loosening the tail stock upon the bed, running out the tail spindle and repeating the reading, the horizontal alignment of the tail spindle with the line of centers may be determined. Again, mounting the caliper as in Fig. 92 and repeating the operations just described, the vertical alignment of the tail spindle may be determined.

Fig. 90.

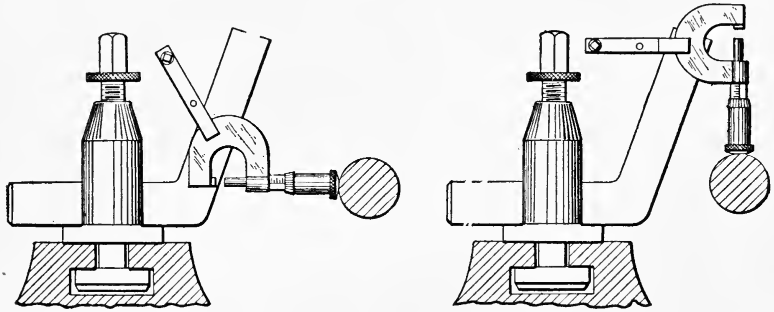


Fig. 91. Fig. 92.

Extemporized tests with micrometer calipers.

CHAPTER V

GAGES

Relation of stiffness and sensitiveness of gages—In large gages stiffness must be sacrificed to lightness—Expedients used under these conditions—Defects of snap gages—Explanation of the popularity of common calipers—Limit gages—Improved construction of snap gages—Causes which restrict the use of gages—The Johansson combination gages, their principles and properties—Uses of these gages—Screw thread gages—Independent measurements of the various elements of screw threads—Measuring the errors of pitch of long screws.

THE FUNCTION OF STIFFNESS IN GAGES

Referring again to the Brown and Sharpe plugs, Fig. 52, an important lesson may be learned by comparing them by means of a pair of common calipers. Using the gage shown with them the difference between them may be detected by any one, but using common calipers, an unskilled person will find this detection impossible. Using calipers a tool maker would detect the difference with reasonable certainty but the fact remains that while with the gage this detection is easy, with the calipers it is difficult.

This difference between the two instruments is due to the increased stiffness of the snap gage as compared with the calipers. It is clear that when either gage or calipers is passed over the larger plug the instrument must spring to accommodate the increased size. Because of the stiffness of the snap gage, the increased effort required to push it over the larger plug is sufficient to be felt by the hand while, because of the flexibility of the calipers, this increased effort is so small that, to all but the highly skilled, it is imperceptible. This shows at once the function of stiffness in gages which become more sensitive as they are made stiffer with, however, a limitation which grows out of the fact that increased stiffness is necessarily accompanied by increased weight and this increased weight, if

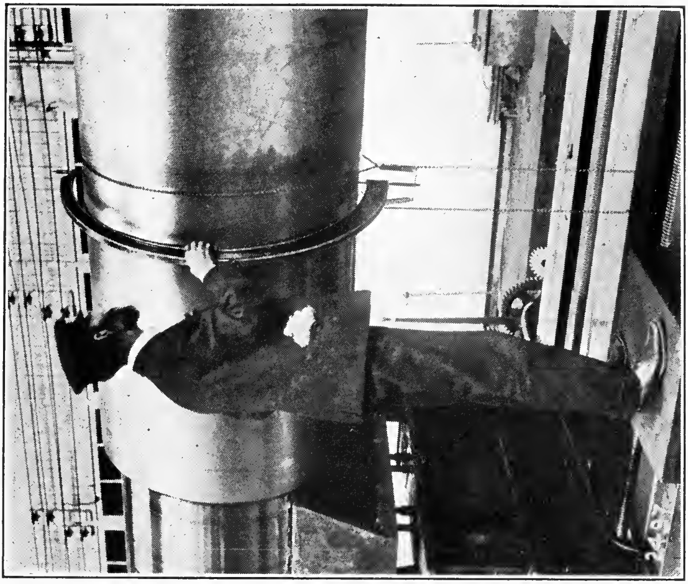


Fig. 94.—Gaging with large micrometer calipers.

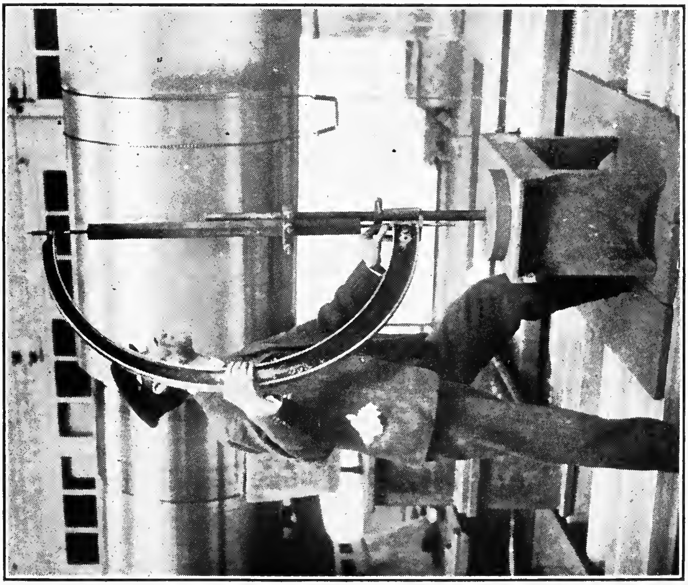


Fig. 93.—Setting large micrometer calipers.

carried too far, dulls the sense of touch. Were the snap gage of Fig. 52 to weigh ten pounds, for example, the increased effort necessary to force it over the larger plug would be lost in the weight of the gage and the hand would not feel it.

This consideration has immediate application to large gages. Were the weights of large gages made proportional to their sizes in order to maintain the stiffness, the effect would be to destroy the very object of this construction by reason of its effect in dulling the sense of touch and, moreover, such gages would be clumsy and unwieldy. It is, consequently, impracticable to make large gages of the same relative stiffness as small ones and this compels us, when using large gages, to resort to expedients. Because of their comparative flexibility large gages are subject to distortion from the effect of their own weight and, if satisfactory measurements are to be obtained, it is necessary to find means by which this distortion may be neutralized.

Figs. 93 and 94 show such an expedient used at the works of the Westinghouse Machine Company. The piece of work to be gaged—shown beyond the operator and in the lathe—is a thirty-nine inch crank shaft, in front of which is a micrometer caliper of suitable size. In order to combine lightness with stiffness as far as possible, the frame of the caliper is made of aluminum alloy. At its upper end it carries a micrometer head which has a range of adjustment of one inch. At its lower end is an adjustable anvil screw having a range of several inches in order to give the instrument a corresponding range and thus reduce the number of instruments required for a given total range.

Fig. 93 shows the instrument in process of adjustment. Supported by a suitable stand is an end measure rod of steel which is protected from the temperature of the hand by a casing of wood. This rod is of a length equal to the number of whole inches desired—the fraction being obtained from the micrometer head. At the lower end of the supporting stand is a stirrup supported in springs of a strength sufficient to carry the weight of the micrometer. When adjusting the instrument the micrometer head is first set to zero and then, with the instrument resting in the stirrup in the position of Fig. 93, the anvil screw is adjusted until the micrometer screw makes contact with the top of the rod. The fractional part of an inch desired, if any, is then obtained by turning back the micrometer when the adjustment is complete.

When gaging the shaft two light sling chains are passed around it as shown in Fig. 94, which chains carry a spring supported stirrup identical with the one on the stand for the end measure rod. The caliper is placed in the stirrup and the size of the shaft is read from the micrometer. The object of the whole arrangement will be seen to be to place the instrument in the same position as regards gravity when adjusting it and when measuring with it, by which expedient the deflection due to its own weight is obviously nullified.

GAGES CONTRASTED WITH CALIPERS

Snap gages have the defects of their virtues. The stiffness which gives rise to their extreme sensitiveness gives rise also to a property which makes them, for many purposes, an unsatisfactory substitute for spring calipers. Because of their flexibility, the calipers may be pushed over a piece of work before it has reached the final size without disturbing the adjustment or doing other damage and the skill of the workman connects the pressure required to push the calipers over the work with the amount of metal remaining to come off. This is an extremely valuable property of the calipers. Because of its stiffness, the snap gage cannot be pushed over the work until the work has reached size. If it does not go over, it tells the workman that there is more metal to come off but it gives no indication of how much more, the result being an increased number of trial cuts.

By reason of their flexibility the calipers may be used for work of various degrees of accuracy. For close work the size is made such that the feel of the contact between calipers and work is very light, while for coarser work the contact is heavier—the calipers going over the work in both cases. The stiff snap gage will not go over the work at all until—within very narrow limits—the work is as small as true gage size. To tell the workman to work to the gage means, therefore, that in many cases he will make fits that are unnecessarily good and hence unnecessarily expensive. On the other hand, to depart from this by authorizing him to use his judgment regarding the degree of correspondence between gage and work, is to lose that very control of the sizes for which the gage system is adopted and so practically abandon the system at the outset.

All this is epitomized in the expression that "gages give no warning" as the desired size is approached, and, since they give none, the size must be approached with extreme care and in constant fear that a cut may be too heavy and so spoil the work. For these reasons calipers hold, and always will hold, their own for many kinds of work, especially those in which the workman adjusts the tool for each piece produced, ordinary lathe work being a typical example.

LIMIT GAGES

These facts, combined with a recognition of the further fact that exact duplication of sizes is an impossibility, has led to the system of limit gages of which three forms are shown in Figs. 95–97.[1] Of these Figs. 95 and 96 are external and Fig. 97 internal gages. In all cases one end is larger than the other by a predetermined amount as indicated by the figures stamped on Figs. 96 and 97. In the use of these gages one end must go over or within the work, as the case may be, and the other must refuse to go over or within it. The work is thus always between the sizes of the two ends and, by a proper determination of the difference between the ends, any required grade of workmanship may be established.

It is obvious that in use these gages, like all end measures, are subject to wear and it is also obvious that this wear is confined chiefly to the end that goes over or within the work. Consequently it is customary, especially in the case of internal gages, to make the end which enters the longer of the two, thus providing increased wearing surface and also showing at a glance which is which. For purposes of distinction the two ends are

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[1] Limit gages were first advertised for sale by the Brown and Sharpe Manufacturing Company in 1875, after about ten years prior use in their own works.

distinguished as *maximum* or *minimum* and as *go* or *not-go*. The terms maximum and minimum are not satisfactory because the maximum external gage goes over the work while the maximum internal gage does not go in. The terms *go* gage and *not-go* gage avoid this ambiguity and are to be preferred.

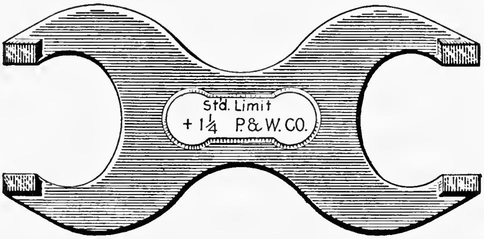

Fig. 95.

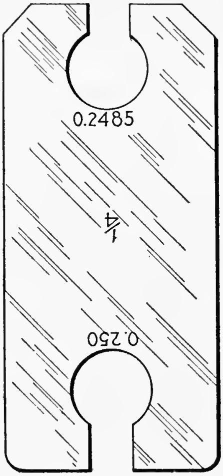

Fig. 96.

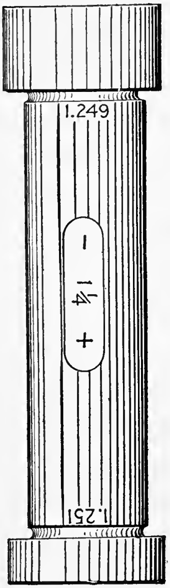

Fig. 97.

Limit gages.

Fig. 98 shows a modification of the snap gage designed to avoid the necessity for renewal after wear has taken place. This effect is accomplished by the combination of the center piece *a* and measuring jaws *b*. The original size of the gage is determined by the center piece while the effect of wear is confined to the jaws. After the jaws have worn it is only necessary to remove them, lap them flat again and then replace them in order to restore the gage to its original size and with a trifling degree of expense. This construction will be recognized as another application of the principle of the division of functions

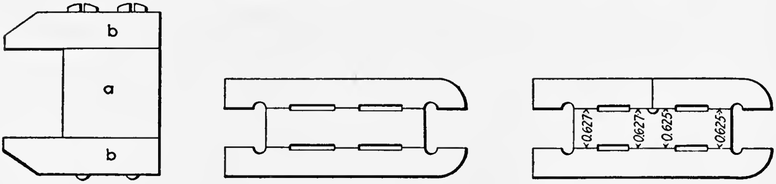

Fig. 98. Fig. 99. Fig. 100.
Modified snap and limit gages.

When limit gages are made upon this plan it is necessary that the limit be ground into the center piece as in Fig. 100 and not into the jaws as in Fig. 99. If the limit is ground into the jaws it must be repeated every time the jaws are lapped whereas, if ground into the center piece, the lapping becomes, as with the single gage, a simple process of restraightening the jaws. In some cases the go and not-go gages when made on this plan are entirely separate and then bolted together, forming

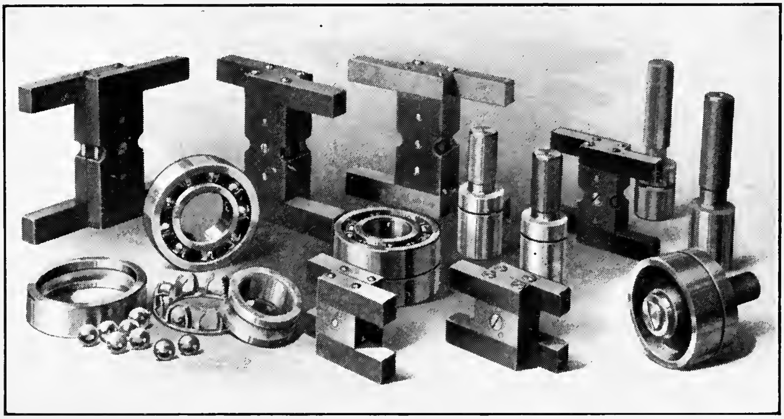

Fig. 101.—A collection of limit gages.

two gages in fact, though one as a matter of convenience. Fig. 101 shows a collection of such gages at the works of the Hess-Bright Manufacturing Company, who have many hundred such gages in use.

THE COST OF GAGES AND SUBSTITUTES FOR THEM

The use of limit gages is restricted by their high cost and their inflexibility as regards the limits. One may have two pieces of work of the same nominal size in one of which the limits may be wider than the other and, if advantage is to be taken of this, two sets of limit gages must be provided. The gages should always be in duplicate—a working set and an inspector's set—and in addition to this there should, by rights, be a third or reference set used for nothing except to check the wear on the other sets. With a pair of limit gages once made the limits are fixed and unchangeable. After limits have been set one sometimes finds it desirable or necessary to change them, in which case, with the gage described, there is nothing to do but discard the old and install new ones. The effect of wear also is ever present.

These considerations indicate the large investment involved—an investment which restricts the use of limit gages for within what their merits would justify, could those merits be considered independently of cost. Because of the cost of gages the micrometer caliper is frequently used in connection with the limit system. The indicating beam caliper, Figs. 70 and 71, is better adapted to this purpose than the micrometer and is, in fact, an almost ideal instrument for the great number of cases for which the cost of gages prevents their use. For some reason which to the author is a mystery, it has never received a tithe of the recognition that its merits deserve.

ADJUSTABLE LIMIT GAGES

Many attempts have been made to reduce the investment which fixed limit gages involve by making them adjustable through a considerable range, thereby making the same gage adaptable to pieces of different sizes and to those of the same nominal size but with different limits and also, incidentally, neutralizing the effect of wear.

The two most noteworthy results of these efforts are shown in Figs. 102 and 104. Fig. 102 shows the gage of the (British) Newall Engineering Company. The go and not-go fingers are here arranged in the same gap, as is not unusual with other constructions, the outer ones, of course, being the go and the inner ones the not-go fingers. The fingers at the left are fixed but those at the right are adjustable, the range of adjustment in the gage shown being from three to three and one-half inches. This adjustment is used to vary the size of the gage within this range and also to make the limits closer or wider according to requirements. With these gages there goes a set of fixed reference standards—such for example as the Brown and Sharpe reference discs already shown in Fig. 51—which are of true sizes without reference to limits. In use, both fingers of the gage shown in Fig. 102 are first adjusted to contact with the reference gage which is then removed and a graduated dial and zero piece are placed in position on the adjustable measuring fingers as shown in Figs. 102 and 103 but most clearly in the latter. Using the graduated dial, the outside or go finger is then adjusted by the number of thousandths by which it is to differ from the

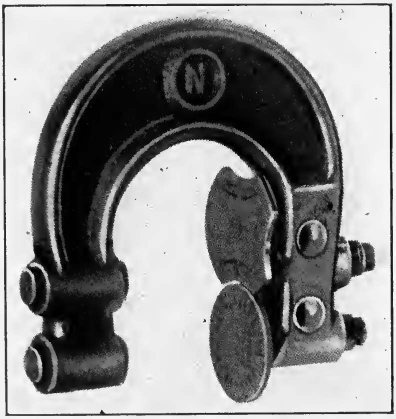

Fig. 102.—Newall limit gage.

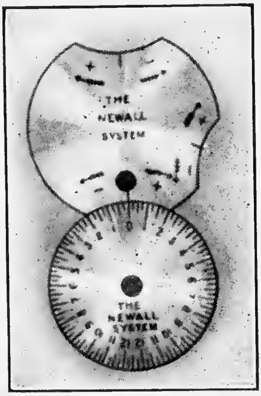

Fig. 103.—Adjusting dial and zero of the Newall gage.

true size. The index dial and zero piece are then inverted in position and the not-go finger is adjusted by the amount by which it is to differ from the true size. The index dial and zero piece are then removed and the gage is ready for use.

The large reduction of investment due to this form of gage is obvious. Because of the range of adjustment the same gage may be used for a variety of sizes and for the same nominal size but with different limits. The working gage may also be used as the inspection gage by re-examining its setting; while, the reference gages being of true size only without regard to limits, their number is largely reduced. Finally, the gage being reset repeatedly to agree with the reference gage, which is used so little that its wear may be ignored, the effect of wear is practically eliminated and the gages need never be renewed from that cause.

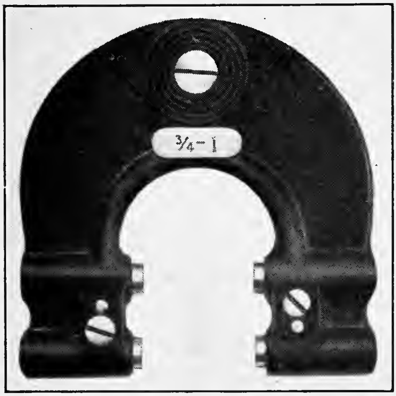

Fig. 104.—Johansson limit gage.

The second method of accomplishing this result is found in the limit gages of C. E. Johansson of Elkistuna, Sweden, shown in Fig. 104. As in the Newall gage we have here go and not-go fingers in the same jaws. The fingers are, however, simple cylindrical plugs adjusted by suitable screws in their rear which, being sunk in the yoke, do not show in the illustration. Unlike the Newall gage, these screws are adjusting screws only and do no measuring, the adjustment being determined by means of Mr. Johansson's combination gages shown in Fig. 105.

THE JOHANSSON COMBINATION GAGES

These combination gages, which made their appearance on the American market in 1907, represent the culmination of precision measurements. They have taken the mechanical world almost by storm, while their method of production is a mystery. A set of these gages was sent to the National Physical Laboratory of Great Britain for examination. The laboratory reported that of the entire set no discoverable error could be found in any except two, the error of these two being a hundred thousandth of an inch. More recently (1913) Mr. Johansson has brought out a series of gages *differing* by the hundred thousandth of an inch. In view of what he had previously accomplished, it is scarcely too much to say that no one living is competent to dispute his claim. Referring to Fig. 105, which shows a set of gages in their case, the upper row contains a series of nine gages ranging in size from $.1 + \frac{1}{10000}$ to $.1 + \frac{9}{10000}$ in. the increment between the sizes being $\frac{1}{10000}$ in.[1] The second and third rows contain a series of forty-nine gages ranging in size from $.1 + \frac{1}{1000}$ to $.1 + \frac{49}{1000}$ in. the increment between the sizes being $\frac{1}{1000}$ in. Next comes a series of nineteen gages ranging from .05 to .95 in., the increment being $\frac{5}{100}$ in. Finally, in the bottom row are a series of four gages ranging between one and four inches by increments of one inch.

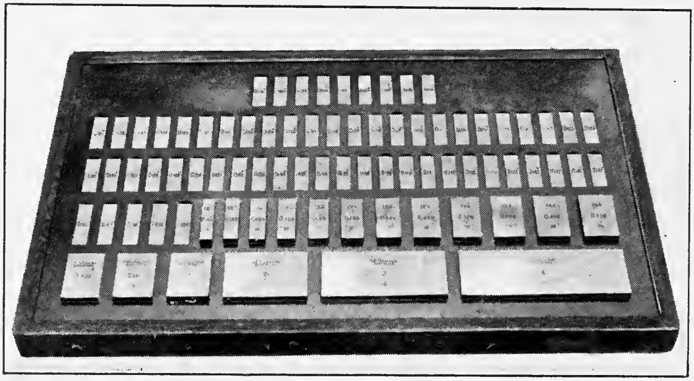

FIG. 105.—Johansson combination gages.

In addition to their remarkable accuracy these gages are also noteworthy because of the system incorporated in their sizes. The comparatively limited number of gages shown in the box is capable of giving all possible sizes within their range with increments of the ten thousandth of an inch, the total number of

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[1] Other sets are made in which the thinnest gage measures .01 inch.

sizes obtainable with the set of gages being not less than a hundred thousand and, moreover, most of the sizes may be obtained by several combinations.

The scheme of sizes and the method of combining them by which this remarkable result is accomplished are best explained by examples as follows:

Beginning with the first gages of series Nos. 1 and 2[1] and substituting the others of series No. 1 in their order we obtain, by addition, the sizes:

From series No. 1:	.1001	.1002	.1003	etc.	.1009
From series No. 2:	.101	.101	.101	up to	.101
Sum	.2011	.2012	.2013		.2019

The second gage of series No. 2 is then substituted for the first and the combinations with the gage of series No. 1 are repeated, giving:

From series No. 1:	.1[2]	.1001	.1002	etc.	.1009
From series No. 2:	.102	.102	.102	up to	.102
Sum	.1020	.1021	.1022		.1029

The third gage of series No. 2 is then substituted and the process repeated, giving:

From series No. 1:	.1[2]	.1001	.1002	etc.	.1009
From series No. 2:	.103	.103	.103	up to	.103
Sum	.2030	.2031	.2032		.2039

This process may obviously be repeated until the first inch is exhausted when, by adding the 1 inch gage, the process may be repeated up to two inches and so on.

The series obtainable includes binary as well as decimal sizes and, moreover, binary sizes plus or minus any number of

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[1] The first inch cannot, in the nature of the case, run down to zero, the smallest obtainable size being that of the smallest gage. All other inches are without gaps in the complete list of ten thousand sizes per inch.

[2] The .1 inch gage comes from the third series.

thousandths or ten thousandths that may be required in connection with the limit system. Thus, to get $1\frac{5}{8}$ in. we add:

From series No. 4	1.
From series No. 3	.5
From series No. 2	.125
Sum	1.625

Similarly to get $1\frac{7}{8}$ ins. we add:

From series No. 4	1.
From series No. 3	.75
From series No. 2	.125
Sum	1.875

To get $1\frac{5}{8} + \frac{2}{1000}$ ins. we add:

From series No. 4	1.
From series No. 3	.5
From series No. 2	.127
Sum	1.627

and to get $1\frac{5}{8} - \frac{2}{1000}$ ins. we add:

From series No. 4	1.
From series No. 3	.5
From series No. 2	.123
Sum	1.623

Similarly to get $2\frac{7}{16}$ ins. we add:

From series No. 4	1.
From series No. 3	.7
From series No. 3	.5
From series No. 2	.137
From series No. 1	.1005
Sum	2.4375

APPLICATIONS OF THE JOHANSSON GAGES

The method of using the gages in setting the adjustable limit gage, Fig. 104, will now be apparent. It is only necessary to produce the necessary size by a suitable combination of gages, insert them between the measuring fingers and adjust the latter to contact.

The setting of the limit gage is, however, but a small part of the useful applications of these combination gages which are used for a great variety of tool-making processes. Fig. 106 shows an application to the making of two holes *d* and *c* at exact distances apart represented by the gages *a* and *b* The piece of work in which the holes are to appear is bolted to the face plate of a lathe against suitable parallel strips, as in the left-hand illustration, and the first hole is bored. Gage block combinations representing the vertical and horizontal distances between the holes are then made up and inserted between the piece of work and the parallels, resulting, obviously, in a movement of the piece of work on the face plate such that if the second hole be bored the spacing between the holes will be the one required to a high degree of precision.

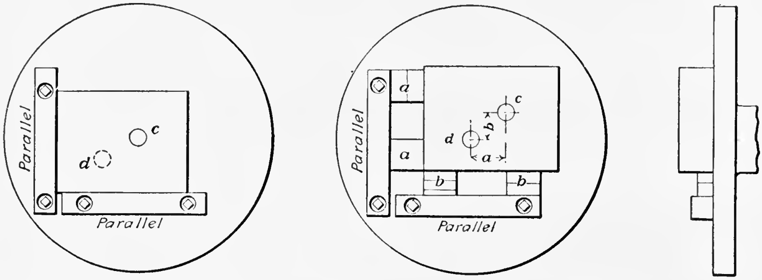

FIG. 106.—Use of Johansson gages for spacing holes.

Fig. 107 shows a frame which accompanies the gages by which they may be assembled in any convenient number and thereby produce standards by which to adjust either inside or outside calipers. In this application the gages take the place of the customary graduated scale, giving all sizes possible with the scale but with a far higher degree of accuracy. At the same time the valuable properties of the calipers already noted are retained and the workman's justifiable preference for them is respected. The uses of the gages are, in fact, almost numberless. A property which they have and which appears to most people as new although, in point of fact, surfaces sufficiently good to show this property equally well have been made for many years, is that of adhesion. If two of the measuring surfaces be wrung together after careful wiping to remove adhering dust, they will adhere to one another, as shown in Fig. 108, and with sufficient firmness to be handled and used as though one piece—a property which is extremely valuable in the every-day use of the gages. This adhesion is not to be confused with the momentary adhesion of surface plates which is commonly attributed to the pressure of the atmosphere. With the gages the adhesion is indefinite in point of time and, in fact, increases with the time they are allowed to remain in contact. So pronounced is this that the user is instructed not to leave the gages in contact indefinitely because it may lead to the ultimate necessity for violence in order to separate them. The adhesion has been measured in a testing machine without waiting for the increase

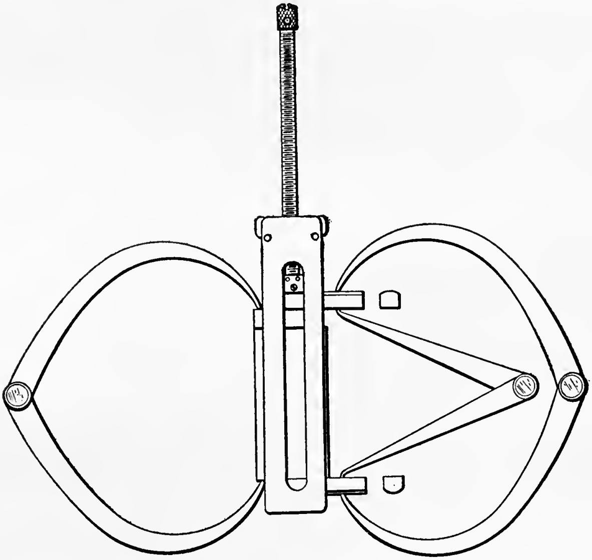

FIG. 107.—Use of Johansson gages for setting calipers.

described, and the force necessary to pull the pieces apart, figured against the area of their surfaces, has been found to run as high as the equivalent of eleven atmospheres—figures which rule out the common explanation that the adhesion is due to atmospheric pressure. The only remaining explanation seems to be that it is due to molecular attraction which is given an opportunity to act by reason of the superior closeness of contact due to the perfection of the surfaces.

In addition to gages of the types described, the micrometer caliper and the multiplying-lever caliper, as already explained, are applicable in connection with the limit system.

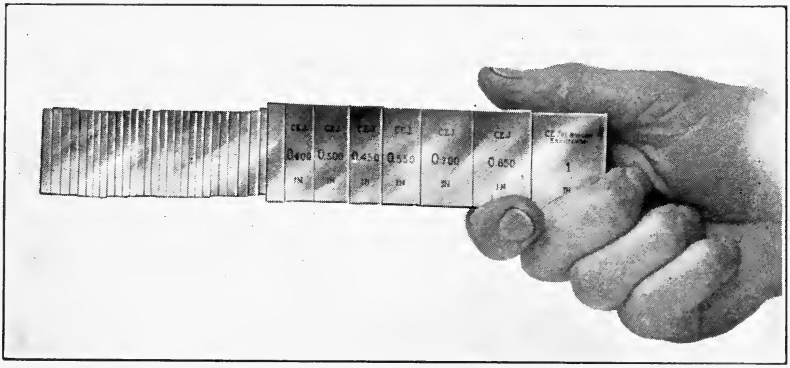

Fig. 108.—Adhesion of Johansson gages.

Both these instruments show the amount of metal remaining to come off an unfinished piece and thus have the property of giving warning in common with common calipers, and even more effectively, because they show the exact amount remaining which calipers do not.

SCREW-THREAD GAGES

An important application of the gage system is to the gaging of screw threads, a standard type of screw-thread gage by the Pratt and Whitney Company being shown in Fig. 109. The external gage is adjustable within narrow limits, two screws, one of which is a pull and the other a push screw, locking the gage in position and providing for adjustment both to compensate for wear and to provide for the character of the fit between a screw and its nut. These gages are in large use for the gaging of manufactured products, of which they insure interchangeability, but for some- classes of tool-room work some thing more is needed in order to measure independently the various elements of a screw.

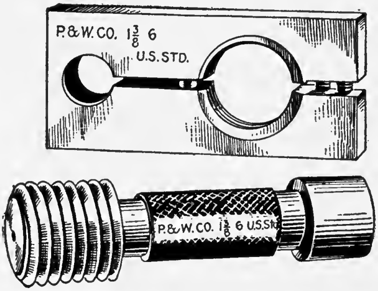

Fig. 109.—Plug and ring screw thread gages.

If a screw enters the gage that fact shows it to be interchangeable with other screws but if it refuses to enter, the gage does not show which of several elements is at fault. Thus the screw may be bodily too large as measured on the inclined surfaces which are the surfaces at which the fit should be made. On the other hand, the screw may refuse to enter because too large at the outer diameter or at the root diameter, neither of which is of importance in the action of the screw. Again the screw may refuse to enter because the pitch is too large or too small but, among these various reasons for failure to enter, the gage makes no discrimination. While satisfactory as a go gage, this construction is therefore inadequate for the detection of the source of error of incorrect screws, and for this reason other

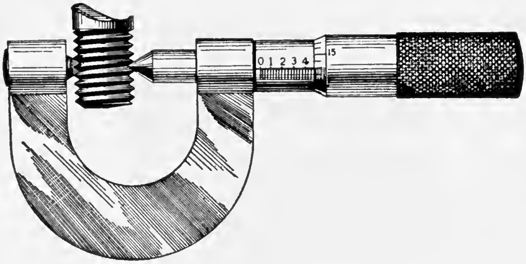

Fig. 110.—Micrometer for measuring screw threads.

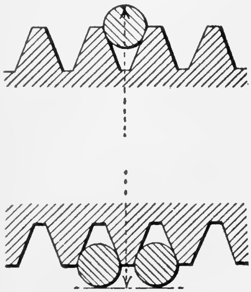

Fig. 111.—Wire method of measuring screw thread diameters.

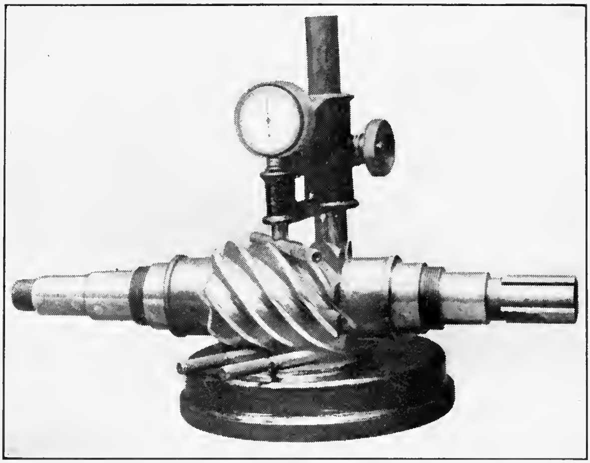

Fig. 112.—Application of the wire method to the gaging of worm threads.

methods have been devised by which to measure the elements individually.

Fig. 113.—Limit gage for screw threads.

The most important elements are the diameter as measured on the inclined surfaces of the threads, because these are the surfaces at which the fit should be made, and the pitch. A very common method of measuring the diameter is by the Brown and Sharpe screw-thread micrometer caliper shown in Fig. 110. The measuring fingers of this instrument are ground to the angle of the thread, the V's being truncated to insure they do not reach the bottom of the thread and that they make contact on the thread sides only.

Another method of measuring the thread sides is shown in Fig. 111, in which wires of known diameter are placed in the threads and the measurement is made by means of the usual micrometer over the outsides of the wires. Complete tables of readings for standard threads have been worked out for this system,[1] which is admirably adapted to the gaging of large screws and worms, an illustration of this use of it being given in Fig. 112 from the British firm, David Brown and Sons. In this case no absolute measurement is made, the worm being compared with a standard by means of the apparatus shown which, after what has been said, is self-explanatory.

Fig. 113 shows the limit gage system applied to this measurement, the instrument illustrated being by the Wells Brothers Company. As in the case of other limit gages shown, the outer fingers are of the go and the inner fingers of the not-go dimensions. For the gaging of the pitch the instrument shown in Fig. 114, also by the Wells Brothers Company, is very satisfactory. By placing a gage of this type against the threads to be gaged, very minute discrepancies between the thread and the gage are apparent.

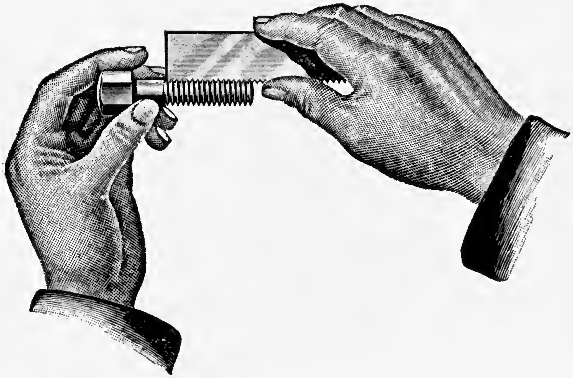

FIG. 114.—Gage for the pitch of screw threads.

Fig. 115 shows another instrument by which errors of pitch are not only shown but measured. Two stationary measuring fingers *a* and *b* are attached to the frame and a moving finger

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[1] These tables may be found in the American Machinists' Handbook by F. H. Colvin and F. A. Stanley.

c is attached to a sliding bar *d*. The moving finger abuts against the multiplying lever *e* which plays over a graduated scale at its top. With the fingers *a*, *c*, exactly one inch or the fingers *b*, *c* exactly one-half inch apart, the multiplying lever reads zero and by inserting the screw to be tested as shown the error of the pitch is read in thousandths. The right-hand measuring finger is supplied in order to measure screws of less than one inch length.

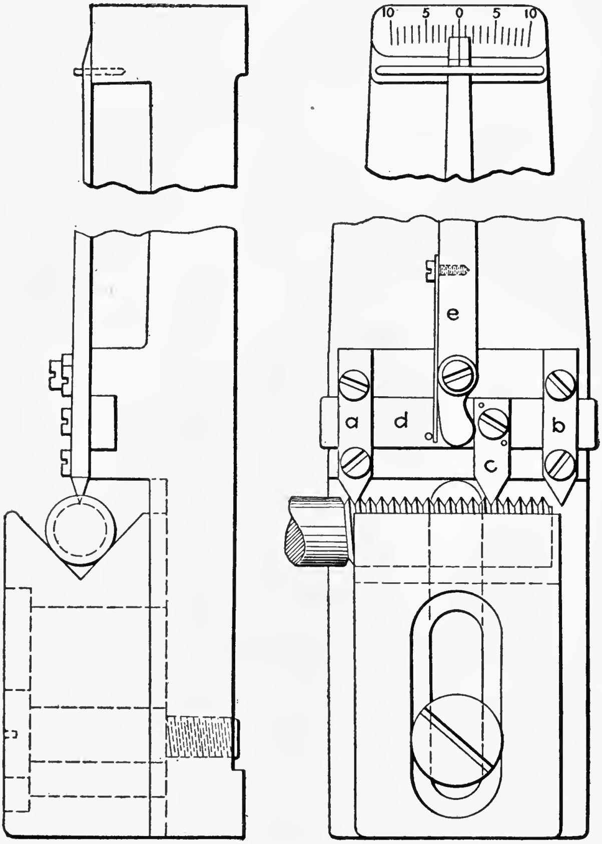


Fig. 115.—Instrument for measuring the pitch of screw threads.

All these devices are for the measurement of short screws. An equipment for measuring the errors of pitch of lead screws, from the works of the Hendey Machine Company, is shown in Fig. 116. The lead screw to be tested passes through the hollow spindle and is gripped in a chuck by which it may be turned by a covered worm gear and the crank at the left, an index wheel and stationary zero enabling the screw to be turned an exact number of revolutions. The screw traverses a carriage along the bed of the machine. Clamped to the bed in the rear of the carriage is a block carrying a micrometer head. Beginning with the micrometer head finger in contact with a second finger on the carriage, the screw is given such a number of turns as would, were the screw without error, advance the carriage an exact inch. This being done, a one-inch end-measure rod is placed between the finger points on the carriage and the micrometer, when the error of the movement for that inch of traverse is read off. Turning the screw so as to advance the carriage another inch, the reading of the micrometer is again taken with a two-inch end-measure rod and, in this way, the errors of the screw may be determined and mapped.

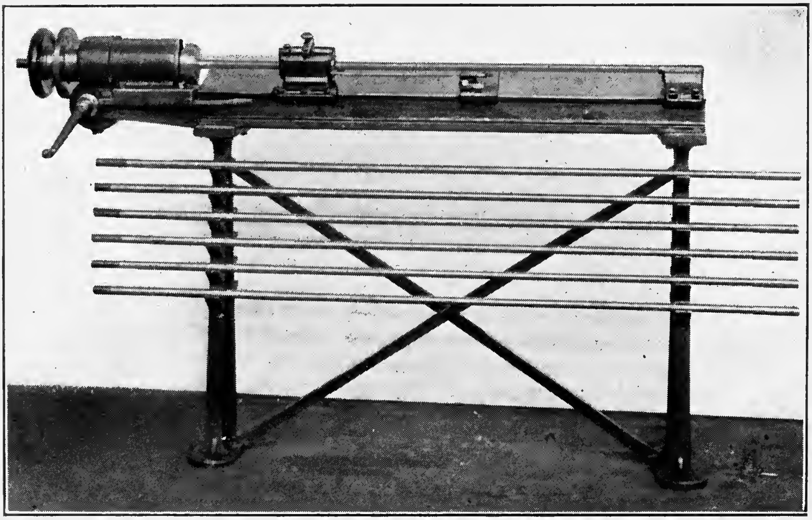


FIG. 116.—Measuring errors of pitch of lead screws.

THE STAR GAGE

For the measurement of long holes, especially those of the tubes and hoops of artillery, the gages described are not applicable and a special construction, the *star gage*, Figs. 117–120, is used. This gage is made both as a micrometer and as a vernier instrument, the former being shown in elevation and section in Fig. 117 and the latter in use in Figs. 118–120. The construction is the same in both forms except as relates to the method of reading the indications. Referring to Fig. 117 the measuring fingers will be seen to be pushed inward by springs and to abut, by their conical ends, against the similar conical end of a central push rod. At the right-hand end is a micrometer barrel, similar to those of ordinary micrometer calipers, which actuates the central push rod and by which variations of the work from a standard are determined. In order to accommodate work of varying length the central push rod and the surrounding tube are provided in various lengths suitable to the work.

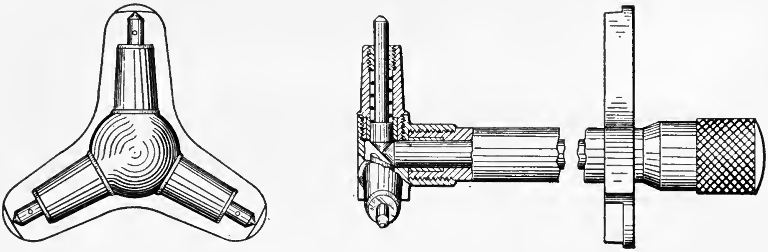
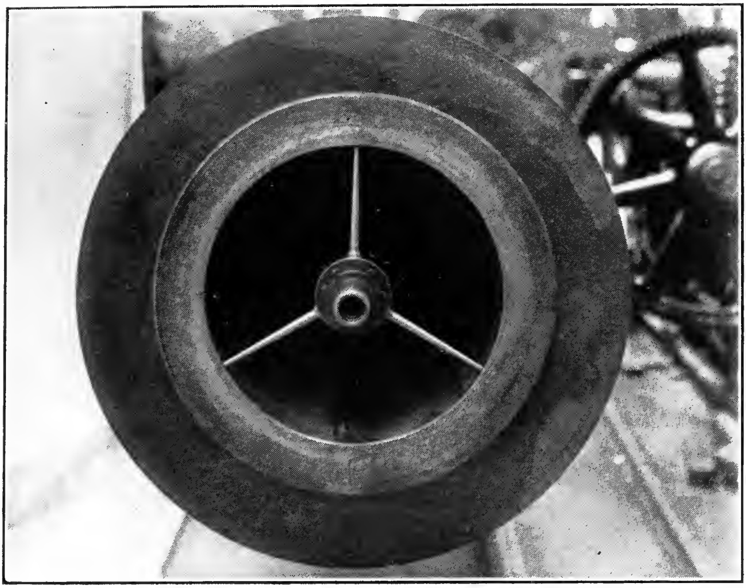
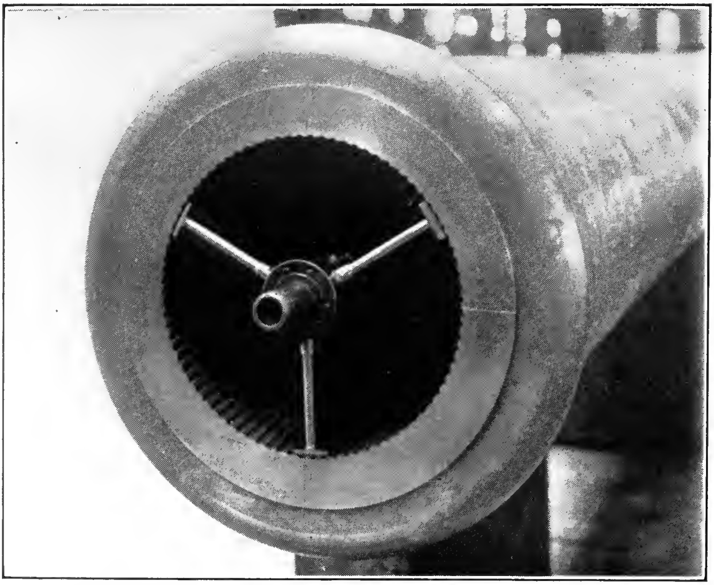


Fig. 117.—Construction of the star gage.

Figs. 118 and 119, from the Bethlehem Steel Company, show the measuring fingers in the act of gaging a gun tube, the measurement in the former case being that of a tube before the rifling has been done, while in the latter the tube has been rifled, the measuring fingers being of a form to span the grooves. Fig. 120 shows the reading end of the gage at the breech end of the gun. The central push rod is slid endwise in its tube by the hand lever shown until the measuring fingers make contact





Figs. 118 and 119.—The star gage in use.

with the bore. At the left of the lever an opening is cut through the tube disclosing the graduations on the push rod against which, and attached to the tube, is the vernier.

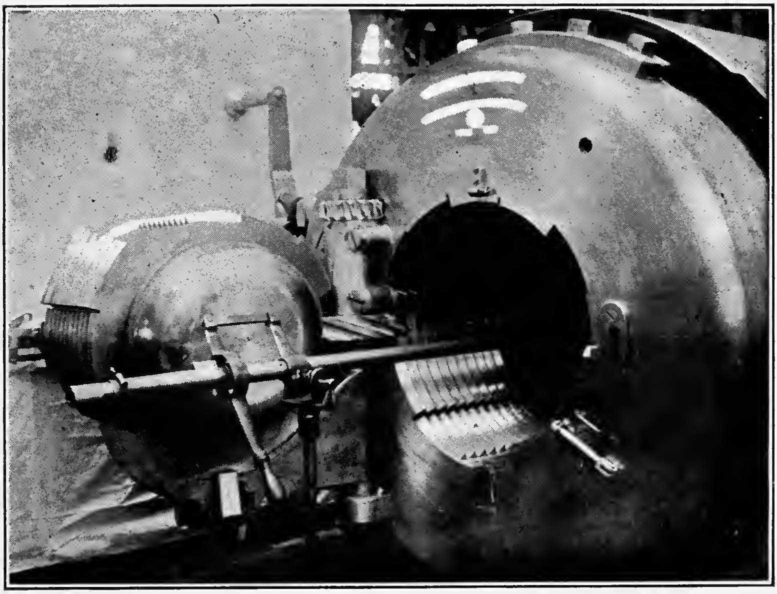


FIG. 120.—Reading end of star gage in use.

CHAPTER VI

FITS AND LIMITS

The limit system of manufacture—Definition of terms—The shaft and the hole bases for fits—Differences between American and British practice —Influence of the grinding machine—Examples of tolerances in various work—Taper fits.

THE LIMIT SYSTEM OF MANUFACTURE

The expressions limit and limit system have been freely used and it becomes necessary to say more about the system as distinguished from the gages which go with it.

The limit system is not to be looked upon as a letting down of the bars as regards workmanship but rather as a recognition and control of the inevitable. The makers of standard gages do not claim their instruments to be of exact sizes, the usual guarantee being that they are correct within the forty-thousandth of an inch, that is, they may be a forty-thousandth too large or the same amount too small. If gages are not made to absolute sizes much less is any other class of work so made. Stove lids have already been mentioned as work which is interchangeable without being accurate, and the essential difference between stove lids and gages is that the former are made between wide and the latter between narrow limits. It is simply a matter of determining what the limits shall be in order to establish any grade of workmanship desired between that of stove lids and of gages. Whatever the class of work, some variation in the size of parts which are nominally alike is inevitable and the limit system simply sets meets and bounds to this variation.

The statement, which one often hears, that a piece of work is exactly right means no more than that, *with the measuring instruments at hand*, its errors are not discoverable. If parts are made to a boxwood rule it is easy to so make them that, with that instrument, no errors can be discovered although, if measured with a micrometer, errors will at once appear. Similarly, parts may be made to a micrometer which, measured with that instrument, will show no error although, if measured with a measuring machine, they will be found to contain errors. Accuracy is a matter of degree only, absolute accuracy being unobtainable.

DEFINITION OF TERMS

In connection with the limit system three terms are used which, while not always properly used, should be defined.

An engine shaft must turn in its bearings and, in order that it may do so, the shaft must be smaller than the bearing by an amount suitable for lubrication. Similarly, if the shaft is to be forced into its crank, the diameter of the shaft must be larger than the bore of the crank in order that the parts may be securely fastened together. In both cases the parts must differ from each other, and this difference between the sizes of the two mating pieces due to the character of the fit is called the *allowance.*

As will be explained more fully presently, the allowance may be placed on either piece, but, assuming for the moment that the intended size of the hole is the nominal size, the allowance for the shaft is added to the nominal diameter for a press fit and subtracted from it for a running fit. The allowance being thus added to or subtracted from the nominal size, the result is the intended size of the shaft. From the intended size the actual size of each piece, when made, will differ, because of the fact that the exact production of any intended size is an impossibility. Moreover, not only will the pieces differ from the intended sizes but they will differ among themselves and, recognizing that some variation is inevitable, it becomes necessary to decide how much variation is permissible, this variation being small in high-class work and larger in more common work. The variation between the largest and smallest sizes which is thus decided upon as permissible is called the *tolerance.*

The allowance is an *intentional* difference between the sizes of the two mating pieces, while the tolerance is an *unavoidable* variation from the intended size. The allowance applies to one piece, the tolerance to both.

Finally the two extreme sizes are the *limits*, the tolerance being the difference between the high and the low limits. The actual sizes as made may fall anywhere between the limits.

Of the above terms, allowance is very commonly used as defined. The words tolerance and limit are, however, used somewhat loosely and even interchangeably. One will often hear the expression that the limit on a certain piece is one or more thousandths, the meaning being that the tolerance is one or more thousandths. This usage, however, is not often the cause of confusion.

VARIATIONS IN PRACTICE

In some cases the tolerance is all placed on one side of the intended size, the intended size being one of the limits—a practice that is illustrated in the diagrams, Figs. 121 and 122. In other, and probably more numerous, cases, the limits are placed each side the intended size, the variation from the intended size being one-half the total variation between the largest and the smallest pieces. When this practice is followed the variation from the intended size is sometimes called the tolerance although but one-half the total range which is tolerated. It is from this that the usage of the word tolerance was derived, and the use of the word for the total variation between the largest and smallest sizes tolerated seems to the author the more logical. For this reason the word has been thus used throughout the accompanying text.

These considerations point out a serious limitation of any system of gages which give the true sizes only. Whether we have to deal with a running or a press fit, four sizes must be considered—the two limits of the shaft and the two of the hole. Of these four sizes such a system of gages can give but one, the allowance remaining a matter of judgment and skill as when graduated scales are used, while no provision for the tolerance of either piece is made.

THE SHAFT AND THE HOLE BASES OF FITS

Since in both running and press fits the intended size of either part may be equal to the nominal size while the intended size of the other must differ from the nominal, there is liberty of choice between the pieces as relates to the one of which the intended size shall be the true size and to the one on which the allowance shall be placed, it being understood that the one of which the intended size is the true size is still made between limits, which is to say that while it does not have allowance it does have tolerance.

Growing out of this liberty of choice, two systems of construction are in use. In the first, called the *hole basis,* the hole is made, within limits, of the true size, the allowance being placed on the shaft, while in the second, called the *shaft basis,* the shaft is made, within limits, of the true size and the allowance is placed on the hole. In work of which the sizes of both pieces are determined by the adjustment of the tool, as in engine-lathe or boring-mill work, there is little choice between the systems, but in work made with tools which are set to a given size which is repeated indefinitely in the work, there is a large advantage in keeping the hole as nearly as possible to the true size and throwing the allowance on the shaft. This is due to the fact that in work of this character the holes are commonly finished with reamers and, by adopting this practice, the same reamer may be used for all classes of fits of the same nominal size, the shaft being made slightly smaller for a running and slightly larger for a press or shrink fit. Meanwhile, since this practice is most desirable for work of this character, it is natural and desirable for the sake of uniformity to adopt it for all kinds of work.

In this respect there is a difference of practice between American and British work. In the United States the hole is commonly, though not universally, kept as nearly as possible to the true size, while in Great Britain the opposite practice prevails.[1]

These terms are illustrated diagrammatically and grossly exaggerated in Figs. 121 and 122 for both hole and shaft bases, the allowances and tolerances being divided by two because in the diagram we deal with radii while the measurements are

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[1] This statement regarding the practice in Great Britain is based on the authority of the report of the British Engineering Standards Committee, rendered in 1906.

made across the diameters. The same terms apply to press fits, understanding that in such fits the shaft is larger than the hole instead of smaller as in running fits.

In this as in many other matters the growing use of the grinding machine has had large influence, especially in reducing the tolerance on the shafts. With the holes made with reamers and the shafts in an engine lathe it is easier to keep down the tolerance on the holes than on the shafts and, consequently, in work so made, the tolerance on the shafts is commonly larger than on the holes. With the grinding machine, however, the reverse is true and this machine has thus brought about an improvement not only in the character of the surfaces as respects their roundness and straightness but also in their sizes as respects the tolerance.

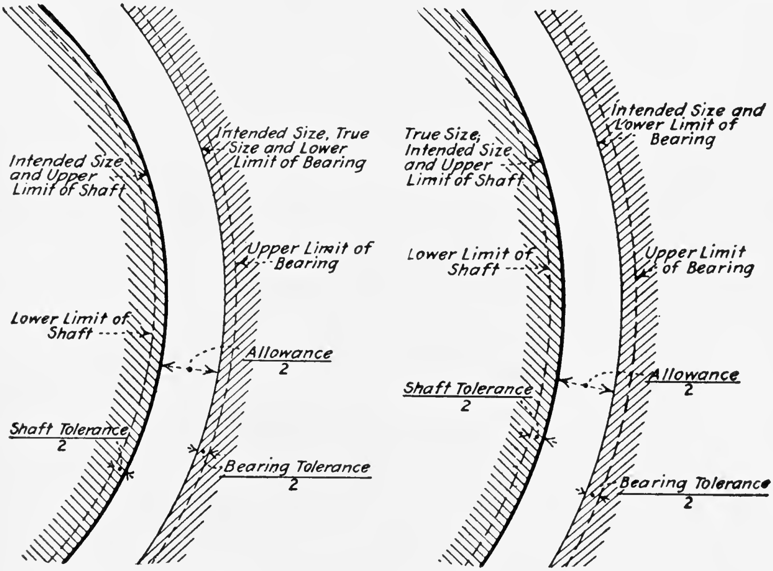

FIG. 121.—Hole basis. FIG. 122.—Shaft basis.
Allowances, tolerances and limits.

THE VALUE OF THE TOLERANCE IN PRACTICE

In an actual case the decision regarding the allowance and tolerance is a matter of large importance and, as regards lathe work, the practice of several leading constructors is available for general use. An exhaustive investigation of the practice in Great Britain as relates to running fits was made by the Engineering Standards Committee, the result being a chart in which are given recommended allowances and tolerances for running fits of three grades of workmanship and for shafts up to twelve inches in diameter. The practice of the General Electric Company for sliding, press and shrink fits, and of the Brown and Sharpe Manufacturing Company in allowances and tolerances for ground fits, may be found in the Transactions of the American Society of Mechanical Engineers, Vols. 24 and 32. The practice of the C. W. Hunt Company for all classes of fits was published in the *American Machinist* for July 16, 1903, and of the Lane and Bidley Company for press fits in the same periodical for July 30, 1899.[1]

It is neither feasible nor necessary to give all these data here but some idea of the magnitude of these variations should be given, if only to correct the impression among beginners that they are smaller than is the case. The accompanying table gives representative values of tolerances for running fits from the report of the British Engineering Standards Committee.

British Standard Tolerances for Three Grades of Running Fits

		3 ins. diam.			6 ins. diam.			12 ins. diam.		
		1st quality	2d quality	3d quality	1st quality	2d quality	3d quality	1st quality	2d quality	3d quality
Tolerance, in.	Shaft....	.0018	.0035	.0053	.0025	.005	.0075	.003	.006	.009
	Hole.....	.0017	.0035	.007	.0025	.005	.010	.003	.006	.012

Less comprehensive information is available for work of other character, but in milling-machine work of small size the tolerance is seldom less than one-thousandth of an inch, two-thousandths being much more common, the tolerances increasing

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[1] These and other data relative to fits have been collected together in the author's Handbook for Machine Designers and Draftsmen.

with the sizes dealt with as the table shows them to do in the case of lathe work.

In turret lathe work of moderate size the tolerances do not differ much from those of milling-machine work, one-thousandth tolerance being feasible for pieces which do not exceed about one inch in diameter when such workmanship is necessary, but two-thousandths being much more common. Such a reduction of the tolerance is always accompanied by increased cost. The Cleveland Automatic Machine Company find that when the tolerance on small pieces is reduced from two-thousandths to one, the output of their automatic turret lathes is reduced about twenty-five per cent. This loss is due to several causes. The cutting tools must be adjusted more carefully, be given a lighter cut to save their edges and be ground more frequently.

The attempt to reduce the tolerance below about one-thousandth increases the cost at a rapidly accelerated rate, a point being soon reached at which the cost is prohibitive and another, not far from it, which passes the ability of cutting tools and the production of the work with such tools becomes mechanically impossible. These points vary with the size of the work and a comprehensive statement regarding them is a difficult one to frame, but, for work not exceeding about one inch diameter, a single thousandth may be regarded as about the smallest feasible tolerance with cutting tools. On the other hand, a good grinding-machine operator will maintain sizes within a quarter of a thousandth without difficulty.

TAPER PRESS FITS

The most approved practice with press fits is to make them taper, the taper being so slight as not to endanger the security of the work but introducing decided advantages. One of these advantages is that the two pieces may be compared by inserting the plug within the hole when, the system being properly laid out, it is apparent from the distance by which the plug does not go home if the parts are of the intended sizes. In addition to this the lubricant is not scraped off as in the straight fit method but covers the entire surface when the pressing action begins. There is also, partly by reason of this and partly by reason of the fact that the pressing action is through a lesser length, much less tendency for the pieces to cut and score one another.

The customary taper, measured on the diameters, is one-sixteenth inch per foot of length. This taper has, however, been improved upon by the Westinghouse Machine Company who make the taper .06 instead of .0625 = one-sixteenth inch per foot. This modified taper is equivalent to .005 inch per inch of length which gives even thousandths for the diameters at each inch of length. The Westinghouse method of measuring these tapers is shown, with the taper exaggerated, in Fig. 123.

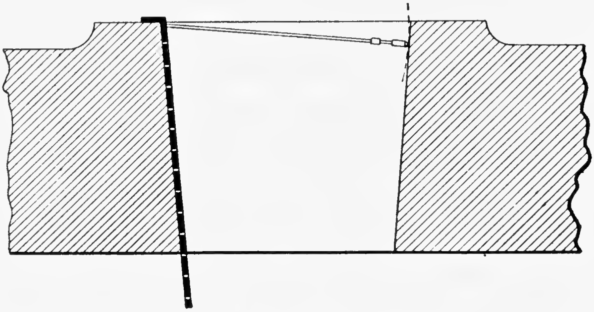

Fig. 123.—Measuring taper press fits.

A strip of steel having holes drilled through it at even inches of its length is placed within the hole when, by the inside micrometer caliper shown, the hole is readily gaged at any part of its length. The readings are not exactly equal to the diameters because of the slight inclination of the caliper, but the larger diameter as read is made equal to the diameter called for in the drawing, the difference between the two being too small to be of any importance.

CHAPTER VII

DRIVING SYSTEMS FOR MACHINE TOOLS

The three leading systems of driving and their proper fields of use—Defects of the old type of cone pulley and methods of overcoming them—Individual *vs.* group motor driving.

COMPARISON OF THE CONE PULLEY AND THE VARIABLE SPEED INDIVIDUAL MOTOR DRIVE

Machine tools are driven by the following methods:

(a) The cone pulley and back gears, power being obtained from a line shaft.

(b) The variable-speed individual electric motor and back gears.

(c) The constant-speed pulley and a set of gears arranged in a gear box and fitted with a system of hand levers whereby they are quickly shifted, power being obtained from either a line shaft or a constant-speed individual motor.

The variable-speed motor was introduced with numerous claims of superiority over the cone pulley, many of which were imaginary, but, nevertheless, when contrasted with the cone pulley as then made, it was found to have advantages which, while not inherent, were pronounced and they gave the motor drive a great vogue. No attempt had then been made to develop the possibilities of the cone pulley. To shift its belt the operator had to get a pole, which might or might not be within convenient reach, while with the motor there was supplied a controller at the operator's elbow by which the speed changes were made quickly and without effort. Consequently, while with the cone pulley the changes were often neglected, with the motor the reverse was true, the result being an increased output. A fundamentally worse defect of the cone pulley than this was the fact that the intervals between successive speeds were much too large while the intervals between the motor speeds were much smaller.

The large intervals between the cone-pulley speeds led to constant loss of output. It is not a matter of the average of gains and losses but of average losses. The cutting speed is limited by the properties of the cutting tool and, except in the few cases when the cone speed is equal or nearly equal to the correct speed for the work, the *next lower* cone speed must always be used, the result being in nearly all cases a loss from the possible output. The smaller the interval between the speeds the smaller is this loss and, since the intervals with the motor were smaller than those with the cone pulley, the loss was smaller, the result being another increase of output.[1]

Coincident with the introduction of the motor drive came the introduction of high-speed steel and the great movement for intensive production, both of which directed attention to and served to emphasize the increased output which, mistakenly, was attributed to some inherent property of the motor drive.

IMPROVED PROPORTIONS OF THE CONE PULLEY

There is, however, another serious defect of the cone pulley as commonly and, when the motor drive came in, universally made which, before it was generally understood, acted to further discredit the cone-pulley drive. Because of defective relative proportions of the steps the belt speed was unnecessarily low and the driving power inadequate.

As the belt is shifted to the large steps of the driven cone its speed—never very high—is seriously reduced until, on the larger steps, it is incapable of delivering the power required by modern requirements and this failure is just at the point where power is most needed by reason of the heavier cuts which naturally go with large work. The correction of this deficiency of the cone pulley is, however, a simple matter of its proportions.

The change required is illustrated in Figs. 124 and 125, the former of which shows the older defective and the latter the newer improved type. The change consists essentially in

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[1] The ratio between successive speeds with the older type of cone pulley is seldom less than 1.5. It frequently reaches 1.75 and occasionally goes as high as 2. According to Carl G. Barth, the ideal value for this ratio is the fourth root of 2 or 1.189. It should not be more than 1.25.

reducing the ratio between the highest and lowest cone speeds and then supplementing this reduced ratio with additional back gears in order to get the required overall range of speed, thereby increasing the belt speed on all the steps but most on the large ones where most needed. The effect of this change is greater than at first sight appears possible. The best method of demonstrating the effect is to calculate the comparative powers with the belt on the larger steps of the two pulleys shown, which are from actual machines and which are, as nearly as may be, of the same overall dimensions and are thus fairly comparable.

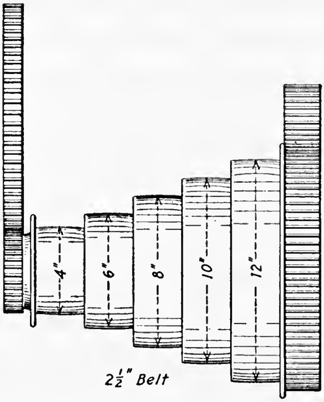

FIG. 124.—Conventional design of cone pulley.

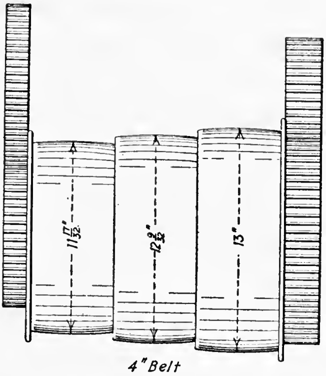

FIG. 125.—Improved design of cone pulley.

Calling the highest belt speed in Fig. 124—that obtained with the belt on the four-inch step—100, the slowest—that on the twelve-inch step—will be:[1]

$$100 \times \frac{4}{12} = 33\frac{1}{3}$$

To maintain the same driven-cone speed the highest belt speed in Fig. 125 will be:

$$100 \frac{11\frac{17}{32}}{4} = 288 +$$

and the lowest will be:

$$288 \times \frac{11\frac{17}{32}}{13} = 255 +$$

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[1] The counter-shaft cone is assumed to be, as is usual, a duplicate of the machine cone.

The smallest step of Fig. 124 is too small for a double belt, while the reverse is true of Fig. 125. To obtain the ratio of power capacities we must multiply the belt speed ratio by a suitable ratio for the double belt, say $\frac{10}{7}$, and also by the ratio of the belt widths, $\frac{4}{2\frac{1}{2}}$. Doing this we obtain:

$$\frac{\text{Power capacity of Fig. 125, small step}}{\text{Power capacity of Fig. 124, small step}} = \frac{288}{100} \times \frac{10}{7} \times \frac{4}{2\frac{1}{2}} = 6.5 +$$

$$\frac{\text{Power capacity of Fig. 125, large step}}{\text{Power capacity of Fig. 124, large step}} = \frac{255}{33\frac{1}{3}} \times \frac{10}{7} \times \frac{4}{2\frac{1}{2}} = 17.5$$

That is, the capacity of the cone shown in Fig. 125 on the small step is 6½ and on the large step, where most needed, 17½ times that of the one shown in Fig. 124.[1] In the cases shown, there is a slight increase in the diameter of the large step but, without this increase, the gain would be nearly as large, although so large a gain is seldom needed. The pulley shown in Fig. 125 gives a smaller overall range of speeds and a smaller number of speeds than does the one shown in Fig. 124. Additional back gears are needed to correct both deficiencies. It is the necessity for these gears that makes feasible the reduced number of cone steps and the increased width of belt.

There is no doubt also that the direct connection between the cone pulley and the work or tool spindle has been retained in many cases for which it should have been discarded. With small, light power machines this construction is satisfactory but, as the size of the work increases, it ultimately becomes inadequate, since with it the belt speed is too low to carry the power required. The remedy is to connect the cone pulley and spindle through gearing and thus speed up the pulley and belt. As sizes of machines increase this is always done ultimately, but the change is commonly deferred too long. High belt speed costs nothing and advantage should be taken of the increased power that goes with it. Were the speeds of machine belts two or three thousand feet per minute, instead of as many hundred, there would be no deficiency of belt power.

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[1] The first publication of the possibilities of improved cone-pulley design was by H. M. Norris.

DIFFICULTIES INTRODUCED BY THE INDIVIDUAL MOTOR

The variable-speed motor drive brought in its train many difficulties to the machine-tool maker, these difficulties being chiefly structural and due to lack of standardization of the motors. Motors from different makers differed in the ratio between their extreme speeds and, since the ratio of the supplementary back gears should have a suitable relation to the overall speed ratio of the motor, it follows that any change in the latter involved a change in the former ratio. Less fundamental, but scarcely less troublesome, was the fact that motors of different makes but of the same power were unlike in their leading dimensions. If they had the same speed ratio the heights to the shaft centers frequently varied as did the sizes of the bases and the positions of the holding-down bolt holes. These considerations interfered with the production of standard machines by requiring the adaptation of each machine to its motor. The makers found it no longer possible to make and to sell from stock standard machines, special adaptation to the specified motor being required in each case.

THE CONSTANT-SPEED PULLEY DRIVE

This was an impossible condition as the whole industry was based upon standardization, and the constant-speed pulley system was devised to meet the difficulty. In this system the first motion shaft of the machine is arranged to be driven at a constant speed which is easily obtainable from any constant-speed motor by a mere selection of pulley sizes and then, added to this, is a set of gears arranged in a gear box and fitted with a system of levers by which the change of speed is made as easily and as quickly as by the controller of the motor. The result was to again standardize the machines and to give them, from the makers' standpoint, the enormous advantage of equal adaptability to both line shaft and individual motor driving. Examples of the constant-speed pulley drive are given in Figs. 136, 163, 181, 182, 183, 216, and 217.

THE CONE-PULLEY BELT SHIFTER

For the milling machine the constant speed drive, as explained at length in the chapter on milling, has peculiar fitness and in all applications it provides a self-contained machine, whereas the cone-pulley drive includes a detached countershaft for which, in shops designed for individual motor driving, it is frequently difficult to provide. Nevertheless, the cone pulley is too simple, cheap and adaptable a thing to be discarded and manufacturers are beginning to turn their attention to it again. When proportioned in the manner that has been explained its most serious original defects—too large speed intervals and inadequate power—disappear and it only remains to devise a

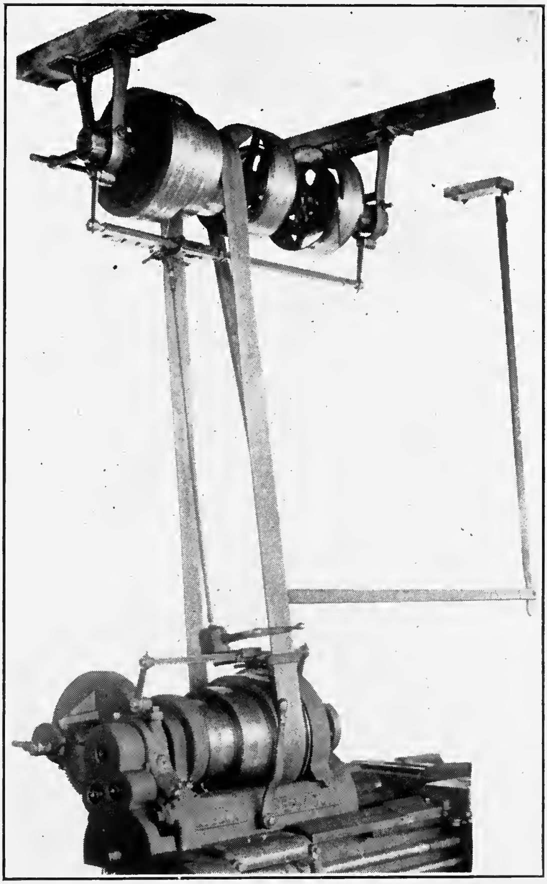

Fig. 126.—Mechanical belt shifter for cone pulley belts.

convenient mechanical belt shifter to give it all the operating qualities of either the variable-speed motor or the constant-speed pulley gear box drive, together with a lower cost than either one.

Fig. 126 shows such a belt shifter applied to a well proportioned cone pulley by the R. K. LeBlond Machine Tool Company.[1] The author ventures to predict that, through such means as this, the cone pulley will eventually be rehabilitated as a leading method of machine-tool driving.

THE FIELD OF THE INDIVIDUAL MOTOR DRIVE

All this is not to be understood as meaning that the individual motor drive has no place, for it has a large one. For portable floor plate tools it is the only practicable system. For isolated tools and for others so located that line-shaft layouts for their accommodation are inconvenient, it is the natural and proper recourse. It permits the locating of large tools under travelling cranes without interference with the runway by overhead structures, and for such tools this is a commanding advantage. In general, flexibility of location is often of large importance in connection with large tools, while, with such tools, the cost of individual motors is, relatively, a less serious item of additional cost than with small ones. For the great majority of small and medium sized tools, however, no inherent advantage has been shown to attend its use. It has, moreover, unquestioned and inherent disadvantages, chief of which is its increased cost, both of installation and of operation.

The power capacity of an individual motor must be that due to the maximum requirement of the machine to which it is attached. Unlike the group system, in which, through a line shaft, one motor drives several machines, there is no opportunity to take advantage of the average load. Of any group of machines but few work simultaneously under maximum duty, while at all times a considerable percentage is normally idle. The result is that the average requirement of such a group is but a fraction of the sum of the maximum requirements of the

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[1] Mechanical bell shifters were fitted to the cone pulleys of the Cornell University shop by Dr. Sweet nearly forty years ago.

individual tools. Under the group system advantage may be taken of this by installing a motor whose normal capacity is equal to the average requirement of the machines to be driven by it. Under the individual motor system, on the other hand, we have several much smaller motors of much greater aggregate capacity, the first result being much higher initial cost. Moreover, since the large group motor works under its normal load, or very near it, its efficiency is high, while since, at any one time, most of the individual motors work under loads much below their normal, their efficiency is low, the second result being a greater consumption of current and the necessity for a power plant of greater capacity.

In addition to the cloud under which it unjustly rests, there are serious physical difficulties in the way of the revival of cone-pulley driving. Wisely, or unwisely, many customers want individual motor-driven machines and many modern shops are laid out with its use in view. Machine-tool makers cannot be criticised for supplying machines to suit the demand, and, with the constant-speed pulley drive equally adapted, without change, to individual motor or line shaft driving, the reason for its popularity is apparent. Such influences as these are the chief determining factors, to the exclusion of considerations of the fundamental merits of the rival systems.

CHAPTER VIII

TURNING AND BORING

The primitive engine lathe—Lathes for work of large diameter and great length—The boring mill, plain and turret—The turret lathe—Special tools and their cost—The collet chuck—The pilot bar—Reamers and reaming—The automatic turret lathe—The magazine feed—The multiple spindle automatic turret lathe—The multaumatic machine—The Fay and Lo-swing lathes—The three types of boring bars and their uses—Taper and spherical boring bars—Vertical boring machines for large engine cylinders.

THE FIRST SCREW-CUTTING LATHE

The engine or screw-cutting lathe of to-day is the direct descendant of the machine shown in Fig. 127[1] which was made by Henry Maudsley about 1800 and was the first to embody principles that are now universal. Prior to Maudsley's time, lathe tools were controlled by the hand alone, after the manner of small-speed lathes of to-day. Like all great inventions, the slide rest which here appears was anticipated by the work of others but not effectively, while the connecting of the work spindle and lead screw by change gears, whereby screw cutting was made possible, appears in none of these anticipations. Maudsley is thus commonly and correctly credited with the invention of the slide rest. As the author interprets Maudsley's work, however, the invention was of wider scope than this, for he invented other machine tools embodying the same essential principle which, broadly speaking, was the mechanical control of cutting tools, in which large field his only effective anticipation was the boring bar of Wilkinson which preceded the lathe.

Maudsley was also the first to cut good screws and substantially all the screws of to-day are the lineal descendants to the *n*th generation of those made by him. He made a machine[2]

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[1] The lathe is now preserved at South Kensington Museum.

[2] Also preserved at South Kensington Museum.

for originating screws and from his time until the present day improvement in the accuracy of screws has been brought about chiefly by beginning with the best screw available as a lead screw and cutting others from it by devices which corrected its errors. Modern refined methods of doing this have already been given. True, other than Maudsley's methods of originating screws have been devised and used for precision purposes, but, measured by the number of their progeny, their influence has been small compared with that of his screws. Small screws are also still occasionally made by the use of hand chasers and such screws have no, or, at most, a remote connection with Maudsley's, but they are small in size, number and importance.

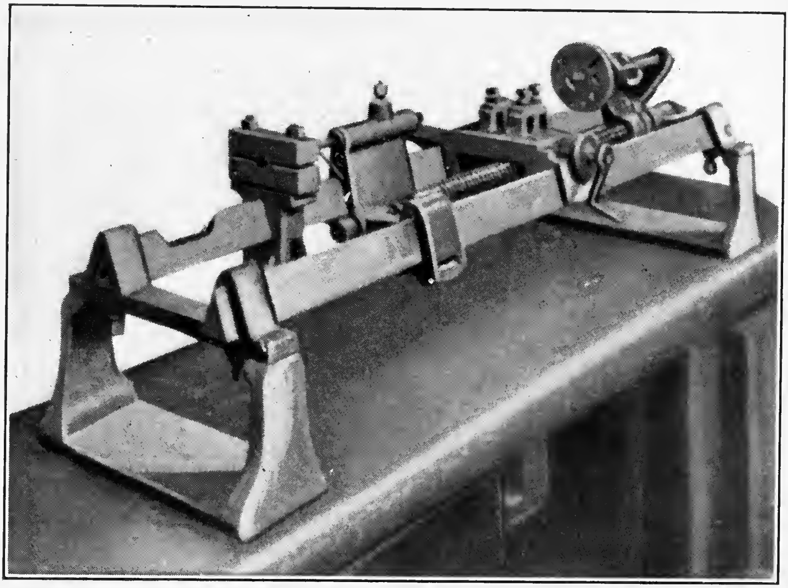

FIG. 127.—Maudsley's original screw cutting lathe.

Maudsley was the first great mechanic in the modern sense.

LARGE LATHES AND BORING MILLS

It is not the author's purpose to discuss engine lathe work in general with which the reader is presumed to be familiar.

To those accustomed to work of small and medium sizes the forms taken by lathes for large work are somewhat surprising. For work of large diameters and relatively short length the machine becomes a pit lathe of which a fine example from the works of the Mesta Machine Company is shown in Fig. 128.

When positive truth is required in turned work there is no method of mounting it equal to that of placing it on a mandrel as in the present example. Pit lathes, however, are somewhat slow and the weight of heavy pieces makes their placing in position troublesome. For work of large diameter a much more common machine is the boring mill, of which one of twenty feet swing, by the Betts Machine Company is shown in Fig. 129. Boring mills of large size are frequently made as extension mills—the housings being arranged to be drawn back on the base in order to increase the capacity. Such an extension mill, also by the Betts Machine Company, of sixteen feet swing with the housings in their forward and of twenty-four feet in their rear-

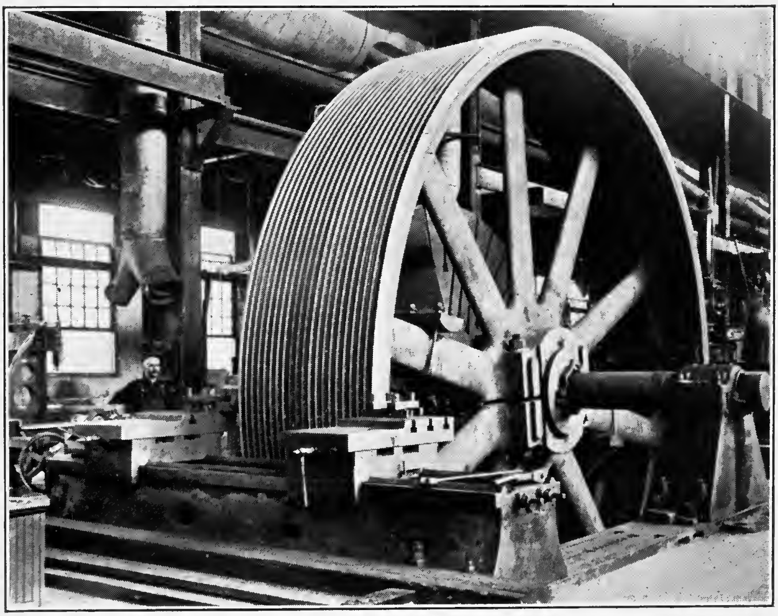

Fig. 128.—Pit lathe at work.

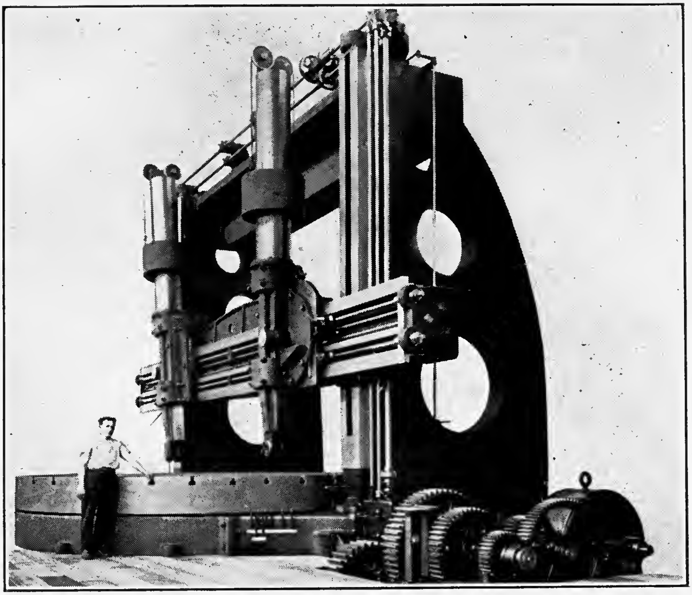

FIG. 129.—Twenty-foot boring mill.

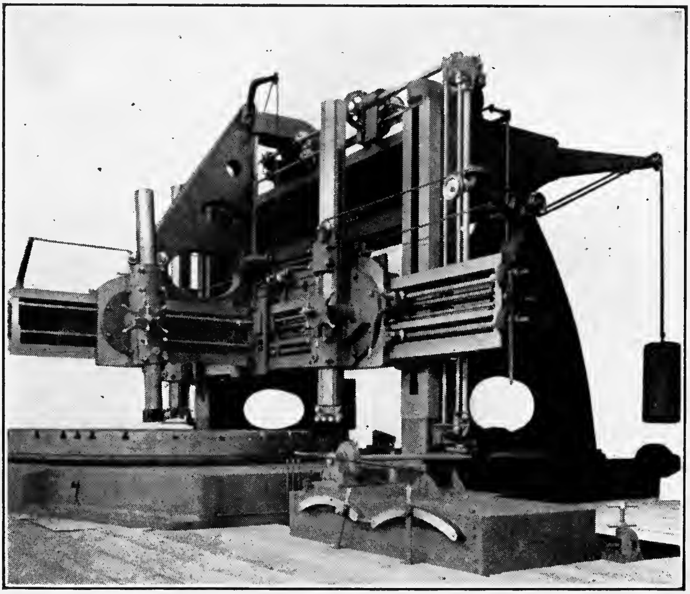

FIG. 130.—Sixteen-twenty-foot extension boring mill.

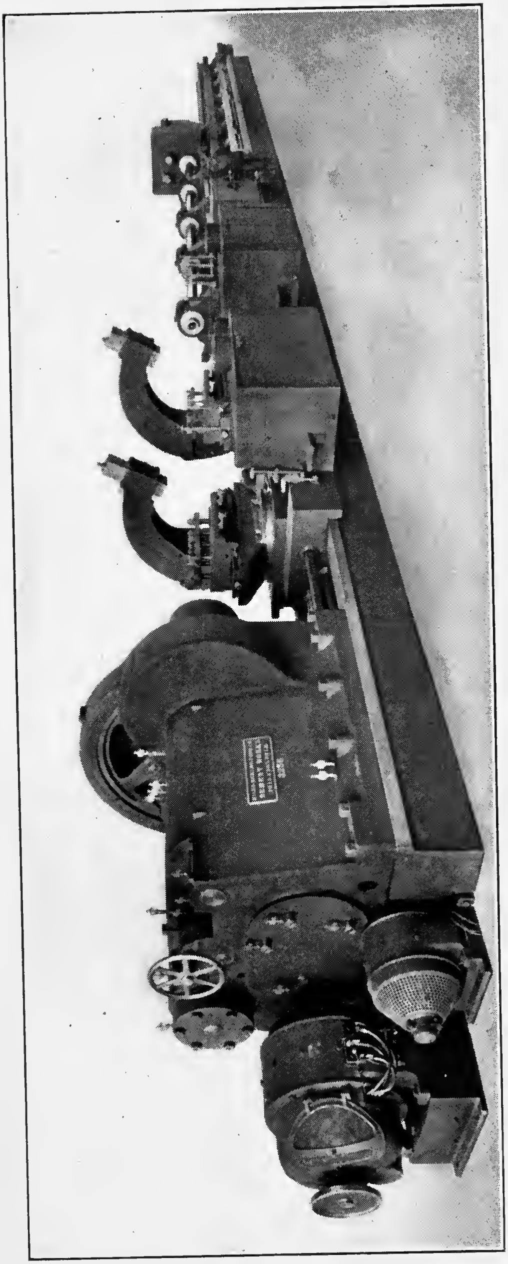

FIG. 131.—Modern gun lathe.

ward position is shown in Fig. 130. In order to reach the center of the table when the housings are run back, an auxiliary removable arm perpendicular to the cross rail is provided.

Unlike all other machine tools the boring mill developed from the top downward. Its chief advantage over the pit lathe is that the work does not have to be chucked in opposition to its own weight. Lying as it does on the face plate of the machine, a piece may be adjusted, without the difficulty that attends the adjustment of heavy work in the lathe. It was, therefore, first developed of large size for heavy work, the realization of its advantage over the lathe leading to its later production in progressively smaller and smaller sizes and, ultimately, with the addition of a turret for the production of repetition work.

For work of large size combined with great length the gun lathe shown in Fig. 131 from the Washington Navy Yard will serve as an example. This lathe, by the Niles-Bement-Pond Company, was built especially for the construction of the largest guns. The great length of the lathe is due to the necessity for accommodating the boring bar, since the lathe bores as well as turns the guns. The accommodation of this bar requires the lathe to be about twice as long as it would be were it required to take in the gun only.

THE PLAIN TURRET LATHE

The adaptation of the lathe to the manufacturing system is by the turret lathe which originated with the Jones and Lamson Machine Company in 1855.

A simple turret lathe by the Warner and Swasey Company—the principle being the more obvious because of the simplicity of the machine shown—is illustrated in Fig. 132. The basic idea of this and of all turret lathes is to preserve the setting of the tools for a succession of pieces. In the use of the engine lathe having a single tool post, each finishing tool is of necessity adjusted with great nicety as each cut is taken but, when the next cut is taken, the tool must be removed and the setting destroyed. The turret lathe preserves the setting when once made by providing a revolving turret having several holes in which are inserted suitable tool holders. After a cut is finished, the turret is revolved a step, thereby presenting the next tool to the work without destroying the adjustment of the first, which remains ready for the next piece when its turn comes. In addition to thus duplicating the diameters of the work, the lengths of the various cuts are positively determined by a series of adjustable stops which are seen projecting from the right of the turret slide. These stops form a lantern which revolves step by step with the corresponding movements of the turret, in order that they may be presented, one by one and in proper order, to a stationary stop below the turret slide.

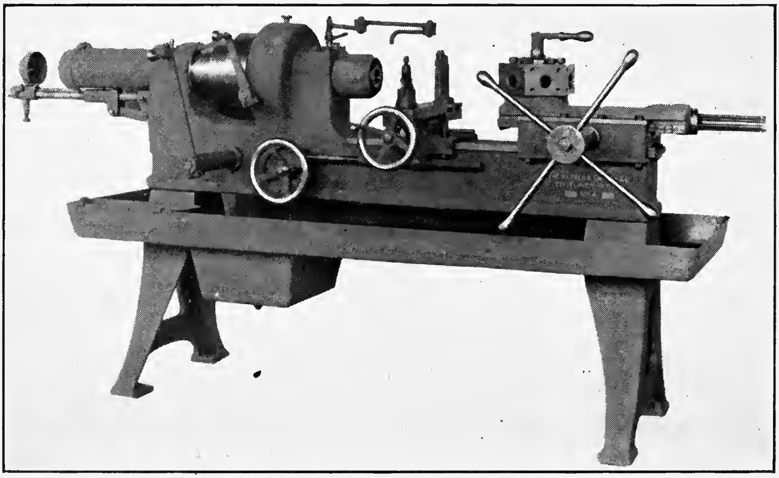

FIG. 132.—Turret lathe.

The lathe shown has a hole lengthwise through its spindle to adapt it for work *from the bar,* as the expression is—a bar of rough stock passing through the spindle and being pushed forward and then gripped in the chuck by the lever and other mechanism at the left after each piece has been finished and cut off. For this latter purpose a tool slide having a crosswise movement only, although adjustable lengthwise of the lathe, is provided. This slide is fitted with two tool posts, of which the one in the rear, fitted with an inverted tool, may be used for cutting a recess, rounding a corner, etc.

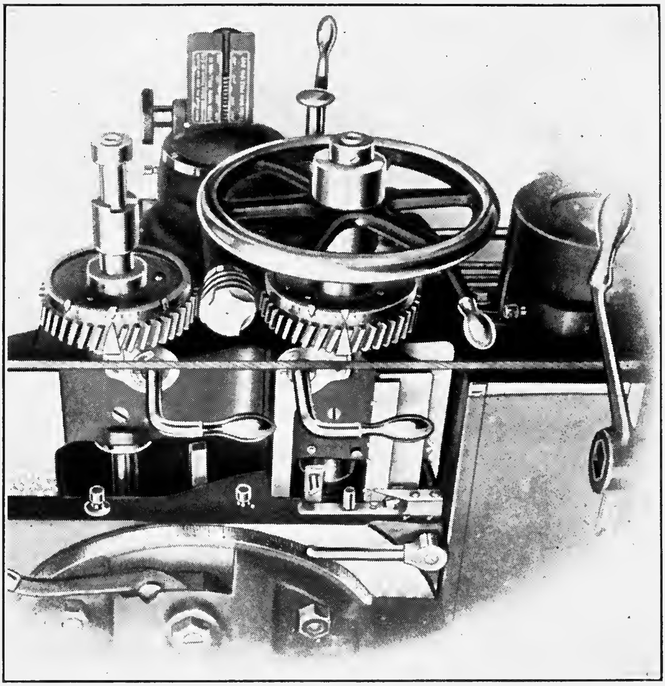

Fig. 134.—Visual stops of turret boring mill.

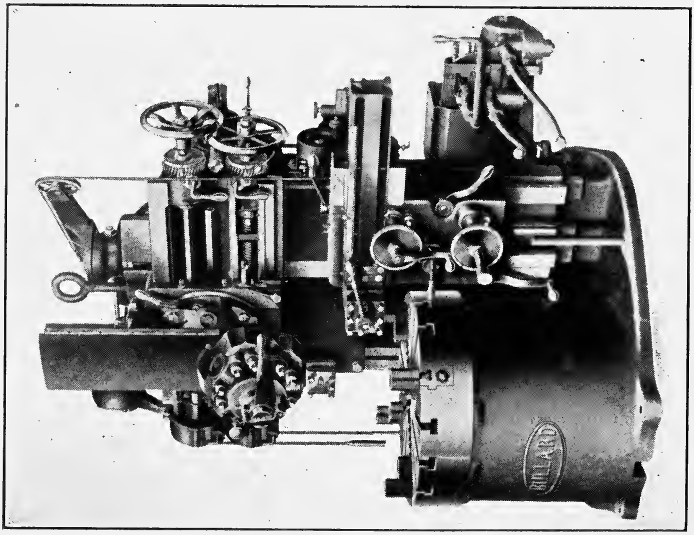

Fig. 133.—Turret boring mill.

The turret lathe was originally made for the production of small pieces—screws, studs, pins, etc., from the bar, but it has been progressively enlarged until machines are now to be made capable of taking bars of stock of eight inches diameter through their spindles. Meanwhile, another adaptation has been made by the provision of suitable work holding chucks whereby separate castings and forgings may be handled and, on top of this, both types of machines are now made to perform all their functions automatically, the work of the operator being not much more than keeping them supplied with stock.

THE TURRET BORING MILL

The turret principle is also applied to boring mills of small and medium sizes, such machines being frequently called vertical turret lathes. A machine of this type by the Bullard Machine Tool Company is shown in Fig. 133. A supplementary cross-slide turret capable of carrying four tools forms an additional feature of this machine and of others.

In this machine a departure is made from the usual construction of the stops. As was explained in connection with Fig. 132, the stops are commonly mechanical and positive—the moving stop abutting against its stationary mate. Instead of this construction, visual or observation stops are here used. Large micrometer dials carrying adjustable indexes are attached to the feed screw shafts, the sizes of the work being determined by the matching of these indexes against stationary indexes as shown in Fig. 134. To avoid confusion the faces of the turret are numbered, as are the indexes. The sizes of work dealt with make the use of the usual special tools set for the outer diameters impracticable. The tools used are therefore of the nature of those used in engine lathes, the outer diameters as well as the lengths of the pieces made being determined by the observation stops.

The general method of tooling the machine and attacking the work, combined with the use of the two turrets, is shown in Fig. 135. Except for the use of tools of the lathe type for the outer diameters, this illustration will also serve to show the application of the turret principle to small as well as large work. Two settings for the opposite sides of the fly wheel are shown, the work of the second side being shown in the two right-hand views.

A prominent example of the turret lathe is found in the flat turret lathe of the Jones & Lamson Machine Company, which is the legitimate successor of the original turret lathe. In this machine, Fig. 136, the turret is a flat turn table carrying the tool holders upon its top instead of about its periphery. These tool holders are so designed as to take simple turning and boring tools, somewhat after the manner of the tool post of an engine lathe and thus reduce the amount of tool making required and adapt the machine to the production of parts in small lots. In addition to this, long pieces may be made as, there being nothing in the way to prevent, the turret may pass under such a piece without interference. Another feature is the mounting of the head stock upon a cross slide which performs the functions of the cross slide of an engine lathe and permits facing, necking and internal undercutting to be done.

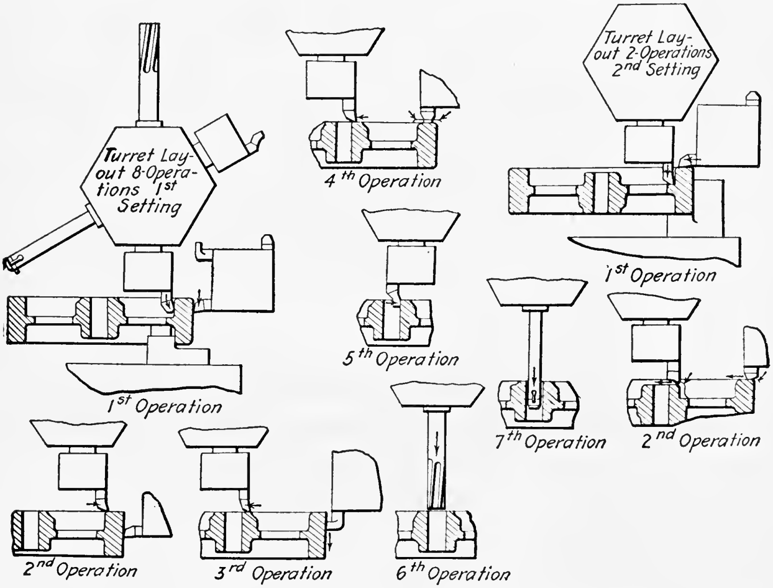

FIG. 135.—Representative arrangement of turret tools.

This machine, like others that follow, is driven by the constant-speed pulley system. The pulley is shown at the left of the head stock which forms the gear box. Within it is a system of change gears which are manipulated by the projecting hand levers.

The cutting tools and their holders for turret lathes are more or less special and made for the particular piece of work to be produced. This is true of all processes for manufacturing parts in lots.[1]

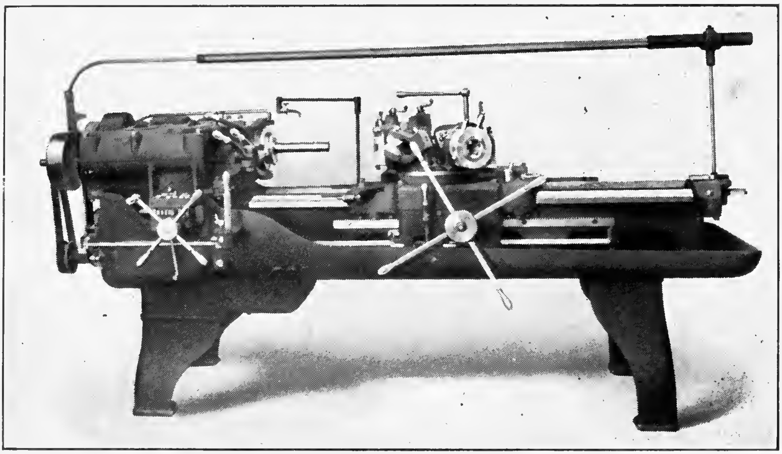

Fig. 136.—Flat turret lathe.

The cost of such tools must obviously be returned through the saving which they accomplish—this remark applying not only to the cutting tools but to other special equipment which is characteristic of the manufacturing system.

RELATION OF COST AND SAVING DUE TO SPECIAL TOOLS

Very little has been published from which the principles followed by manufacturers in determining the justifiable expense of an equipment for any particular case can be deduced and, indeed, it would appear that not many manufacturers have

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[1] In the case of the turret lathe, especially the flat turret lathe, special tools are much less required than formerly.

definite rules for this work, the common procedure being to determine the nature of the equipment by the exercise of simple judgment. In the case of pieces made in large numbers, for example in gun, sewing machine, and typewriter work, the judgment of a competent man in this connection is usually sufficient. In work of this character the saving produced by an equipment is repeated such an enormous number of times, that even a trifling saving on each piece multiplied by the number of pieces made, produces a total which justifies any equipment within reason.

The pinch comes in connection with work produced in smaller numbers in which the saving on one piece is repeated a limited number of times. In work of this kind the cost of the equipment must be considered in relation to the saving due to it and, for such work, the author adopted a rule many years ago that the estimated saving due to a given special equipment should return its estimated cost in one year's time and that if it failed to promise such a return it should not be made. This rule will impress most readers as extremely drastic and it was, indeed, made drastic for special reasons. There are, however, reasons of perfectly general application which make it necessary that such a rule should be more drastic than would at first sight appear. The rule is based upon *estimated* cost and *estimated* savings. One sometimes goes wrong in his estimates and, more often than not, the error is in the wrong direction. Moreover, one never knows when an improvement will come along which will lay a fine lot of special tools on the scrap heap. If a set of tools continues in use four years, which is longer than the average, they must earn twenty-five per cent. per annum to replace themselves and they must also earn enough to keep themselves in repair and it is not until they have done these things that profit begins. For these reasons the author is convinced that, as a general rule, subject to occasional reduction in cases where there is little probability of revolutionary improvements, special tools should return by their savings not less than fifty per cent. of their cost per annum. On the other hand, in an industry which is in process of rapid development, this percentage should be increased.

Whatever the percentage adoped, a rule in this form is of perfectly general application. It takes account not only of the size of the lots and of the lost time due to setting up and adjusting the machines, but also of idle periods between lots, regardless of their length.

THE COLLET CHUCK

An important feature of the turret lathe is the collet chuck, shown in its original form in the section of the head stock of a precision bench lathe by Hardinge, Brothers in Fig. 137 the chuck proper being shown to an enlarged scale below thela the head stock. The spindle of the lathe is bored and the end of the chuck is turned to an angle. The chuck is split by three radial slots and has a threaded portion at its rear. A tube *a* is threaded to fit the threads on the chuck and carries at its left a hand wheel. The turning of the hand wheel draws the chuck within the lathe spindle and closes its jaws upon the work.[1]

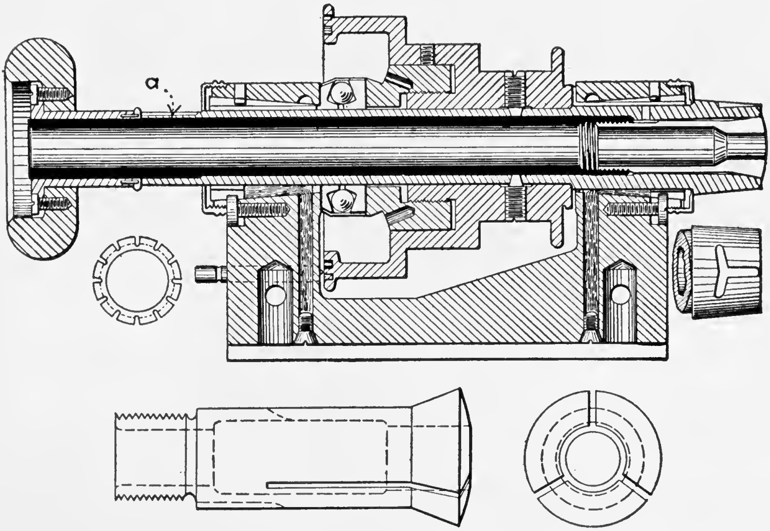

FIG. 137.—Collet chuck.

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[1] The collet chuck was originally designed for watch and watch tool work. From a capacity suitable for work of this character it has grown step by step until it has been made capable of taking in solid steel bars of eight inches diameter suitable for locomotive crank and cross-head pins.

In the adaptation of the chuck to large work a number of modifications have been made. In the form shown in Fig. 137 it is known as the draw-back collet chuck. In some cases the

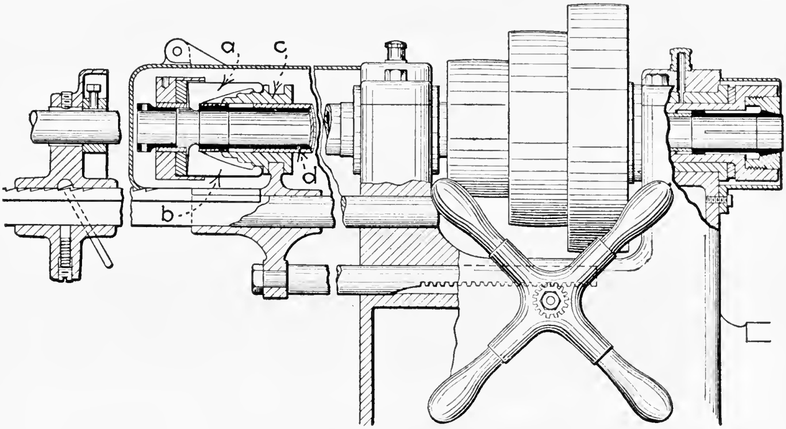

FIG. 138.—Push-out collet chuck.

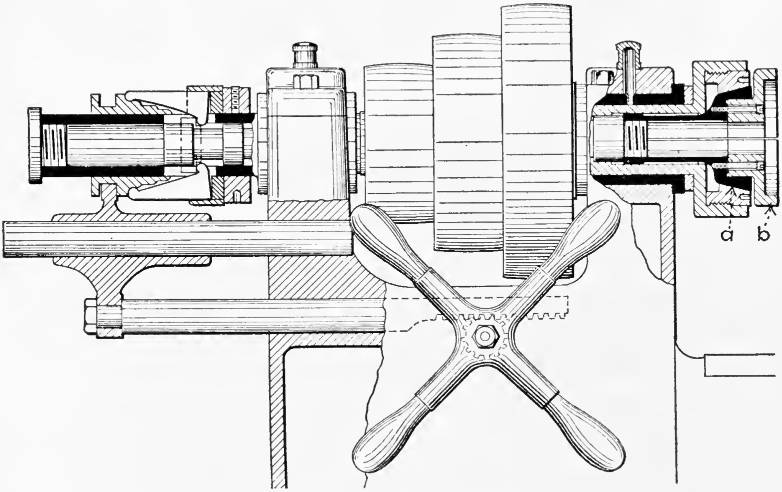

FIG. 139.—Modified collet chuck.

taper is reversed, resulting in the push-out chuck shown in Fig. 138 from a Bardons and Oliver turret lathe from which the modification will be apparent. The gripping action in this case is no longer by the hand wheel shown in Fig. 137, which is only used in connection with work of small and moderate size. The gripping is here through the bell cranks *a*, *b*, the sliding collar *c*,

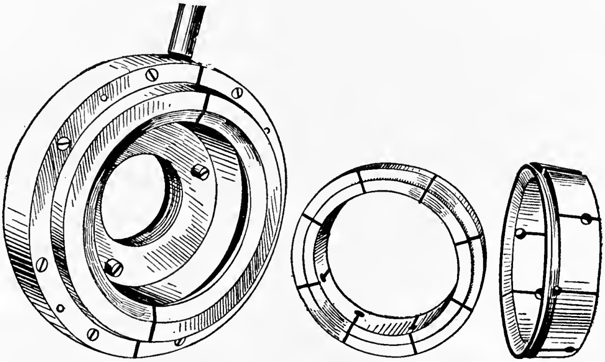

FIG. 140.—Collet chuck for work of large diameter.

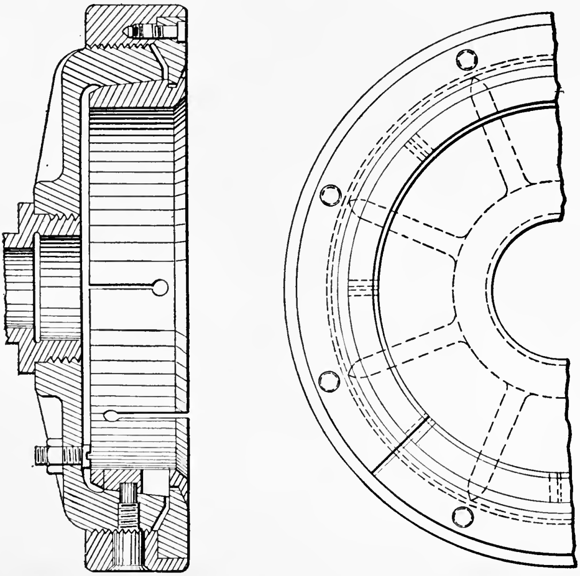

FIG. 141.—Construction of chuck shown in Fig. 140.

the tube *d*, and the connected mechanism. In the act of gripping the work the draw-back chuck draws the piece toward the head stock a slight distance. Frequently this is of no importance but in cases in which pieces are required to be of an exact length it interferes with this requirement. In turret-lathe work from the bar the length is gaged by pushing the bar through the lathe spindle until it abuts against a stop in the first hole of the turret. With the bar thus abutting, the push-out chuck cannot disturb its position and for such work it is sometimes necessary and usually to be preferred.

By a suitable modification of its construction the chuck has been adapted to the chucking of separate castings or forgings of considerable size. Fig. 139 shows such a modification of the draw-back chuck, this illustration also being from Bardons and Oliver. The collet *a* carries false jaws *b* which are adapted to the diameter of the work to be done. The closing of the jaws is accomplished by the action of a tube through the spindle of the lathe, but for still larger work this becomes impracticable and the construction of Figs. 140 and 141 is adopted. In this case the increased diameter leads to the introduction of an increased number of cuts in the collet which are made alternately from the two ends. The closing of the collet is by the action of the outer threaded ring on the body of the chuck. In this as in the last construction the work is seldom gripped directly by the collet faces. False jaws are usually inserted in the collet and are bored to suit the work to be done.

THE PILOT BAR

An important feature of turret-lathe equipment, known as the pilot bar, was introduced by the Gisholt Machine Company. The action of this appliance will be understood from Figs. 142 and 143, although these illustrations are not from a Gisholt lathe. The work in progress is the turning of the face of a bevil gear blank *a* by means of the broad-faced tool *b*, in Fig. 142 without and in Fig. 143 with the pilot bar *c*. In Fig. 142 the strain due to the pressure of the cut, starting at the arrow *d*, follows the dotted line through the tool support, the lathe bed, the spindle, and the work to the reaction arrow *e*. This roundabout course of the strain leads to spring and chatter which are largely eliminated by the use of the pilot bar as shown in Fig.

143, in which the dotted line again shows the path of the strain due to the pressure of the cut. With this construction the strain does not reach the frame of the machine at all, the more limited area which it occupies and the reduced leverage by which it acts serving to greatly reduce its effect and to increase the capacity for heavy work.

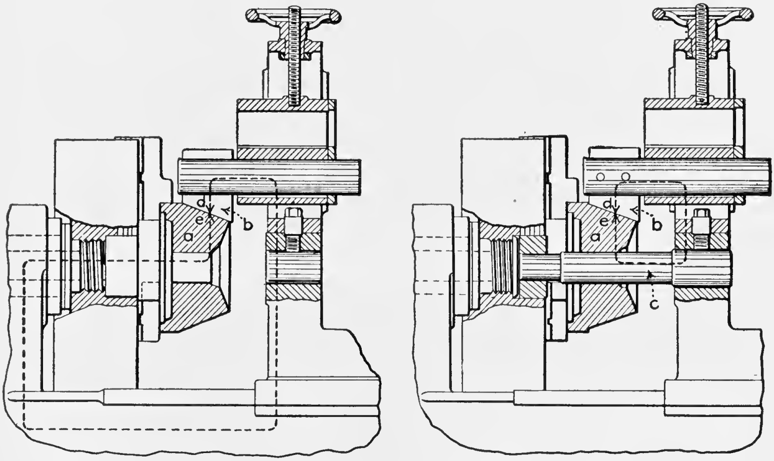

FIG. 142. FIG. 143.

Principle of the pilot bar.

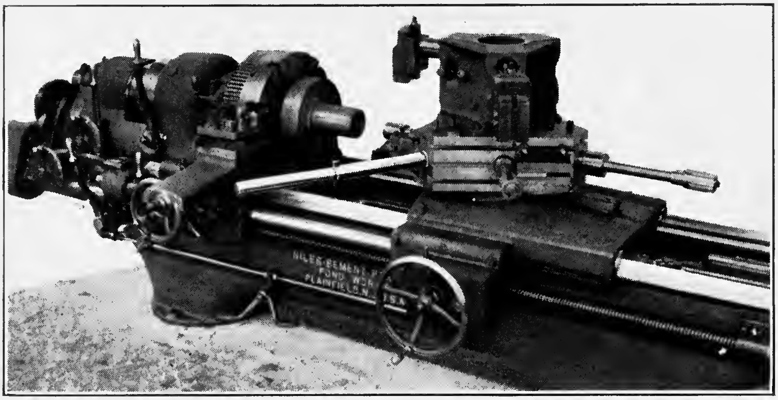

FIG. 144.—Use of the pilot bar.

The pilot bar is more frequently made to support the cutting tool, thereby, in another way, increasing the capacity for heavy cuts. Such a use of it is shown in Fig. 144 which illustrates a heavy turret lathe by the Niles-Bement-Pond Company. In this case the tool for boring a gear blank is inserted in the middle of the pilot bar which, fitting a suitable bush in the work-holding chuck, is much more favorably supported to resist the strains upon it than if the bar were cut off just beyond the tool.

REAMERS AND REAMING

An important tool in turret-lathe equipment is the reamer by which the sizes of holes are finished and maintained uniform.

Fig. 145.

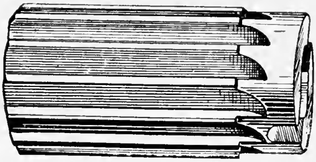

Fig. 146.

Fig. 149.

Fig. 147

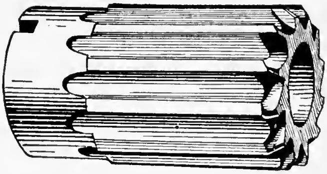

Fig. 148.

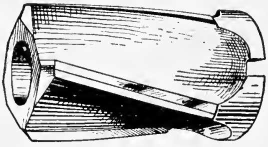

Fig. 150.

Various forms of reamers.

A collection of reamers of various types adapted to various uses and conditions is shown in Figs. 145–150. Fig. 145 shows a fluted reamer, called *chucking reamer*, in which the reamer and its shank are in one piece. The reamer is slightly tapered at its outer end, the cutting action being upon the sides. As the size increases the reamer is made with a hole through it, and its shank is made of a separate piece. Such reamers, shown in Fig. 146, are called *shell reamers.* Their action is precisely the same as that of the tool shown in Fig. 145.

A tool having somewhat the appearance of the fluted reamer but an entirely different action is shown in Figs. 147 and 148, the tools referred to being called *rose reamers.* As before, the small sizes are made integral with their shanks while larger ones are separate. The flutes of these tools, while in appearance like those of the previous reamers, are essentially different in that they do no cutting. The cutting is entirely at the end of the reamer, the flutes being provided as channels for the chips. Of these two types, the fluted reamer is commonly used for the last or sizing cut for which, if in good condition, it gives a beautifully finished as well as a true surface. The rose reamer is used as a preparatory tool, its cut being taken just previous to that of the fluted reamer. The size of the two differs enough to give a light finishing cut for the final operation.

Because of its light duty the fluted reamer will remain sharp and maintain its size a long time but, ultimately, it becomes dull and, when sharpened, its size is reduced. To meet this condition a large amount of ingenuity has been expended in devising adjustable or expansion reamers which are of two types. The first type is intended to be expanded or contracted to accommodate small changes in the diameter of the work, usually by a screw adjustment, while the second type is intended to be expanded before regrinding, then ground to its original size and used as before, precisely as though it were a solid reamer—this operation being repeated at each regrinding. While some will dispute the statement, the author believes, nevertheless, that the first type of reamer is not, in most hands, a success while the second type is a success.

An expansion reamer of the second type is shown in Fig. 149. The cutting blades are here separate from the body of the reamer and inserted in the latter in dovetailed slots. The blades and the slots are inclined to the center line on their inner surfaces in order to provide the expansion feature. When the reamer becomes dull, the blades are driven up the slots a slight distance and the reamer is then placed in a grinding machine, reground to its original size, and backed off to provide suitable clearance.

Another tool which is used in connection with reaming operations, called the *four-lip drill* or *four-lip reamer*, is shown in Fig. 150. Twist drills or, for that matter, all drills having two cutting edges, have no tendency to straighten holes which are once wrongly started and, if used to enlarge a cored hole, they will follow the eccentricity of the hole. The four-lip drill largely corrects this tendency, the action of the two additional cutting edges being to oppose a resistance to the tendency due to an untrue hole to deflect the drill sidewise. When using such a tool, if the hole is deep and the drill correspondingly long and flexible, it is necessary, when starting to enlarge a cored hole, to precede the four-lip drill with a short stiff tool in order that the eccentricity of the cored hole may be corrected by starting the hole correctly. With the hole begun in this manner, the four-lip drill may be brought into action and, unlike the two-lipped drill, it will follow the true start regardless of the deflecting action of the untrue cored hole. The hole being made straight in this manner, the four-lip drill is followed by the rose and fluted reamers in turn. The four-lip drill is used for enlarging holes only. It will not drill from the solid.

FLOATING REAMER HOLDERS AND HAND REAMING

When good results are required, the final reamer must be provided with a flexible support whereby it is free, within narrow limits, to adjust itself in line with the hole as prepared for it. Even though the alignment of the lathe may be of the highest degree of accuracy, there will be enough untruth of alignment of the lathe or of the hole to affect the finished hole if the reamer is clamped rigidly in the turret after the manner of the other tools, holes reamed in this manner being commonly somewhat larger than intended and, more likely than not, larger at one end than at the other.

Holders arranged to permit this minute adjustment of itself by the reamer are called *floating reamer holders*. They are made in a great variety of forms, one of which is shown in Fig. 151. The holder is inserted in the hole of the turret, the reamer being driven by the movable or floating feature *a*.

With the best of these devices there is always some resistance to the sidewise adjustment of the reamer due to the friction caused by the force required to hold the reamer from turning. For this reason the best results are obtained by doing the reaming operation by hand. With the reamer put through its hole by a hand-driven wrench, it is obviously perfectly free to adjust itself to the existing alignment of the hole and thus produce a hole of its own size. For this reason one often sees the specification, "hand reaming only," which is intended to and does lead to superior work.

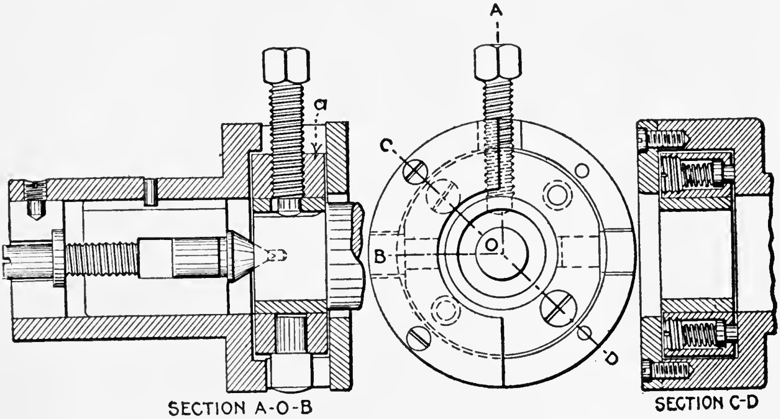

Fig. 151.—Floating reamer holder.

The author is aware of but one equipment by which reaming may be done by power and with the same accuracy as by hand. This equipment is shown in Fig. 152, from the Detroit works of the Chicago Pneumatic Tool Company. The equipment consists, first, of a cast-iron bench which is used for no other purpose than reaming and which is fitted with oil supply and drain pipes connected with the oil circulating system of the factory. The reamer is driven by a compressed air motor suspended from the ceiling by a cord, pulley and balance weight.

The reaction due to the driving effort of the motor is resisted by the two hands of the operator applied to the horizontal handles. Both driving effort and resistance are true moments without side pressure, by reason of which, and perhaps even more than with hand reaming, the reamer is at perfect liberty to follow the hole.

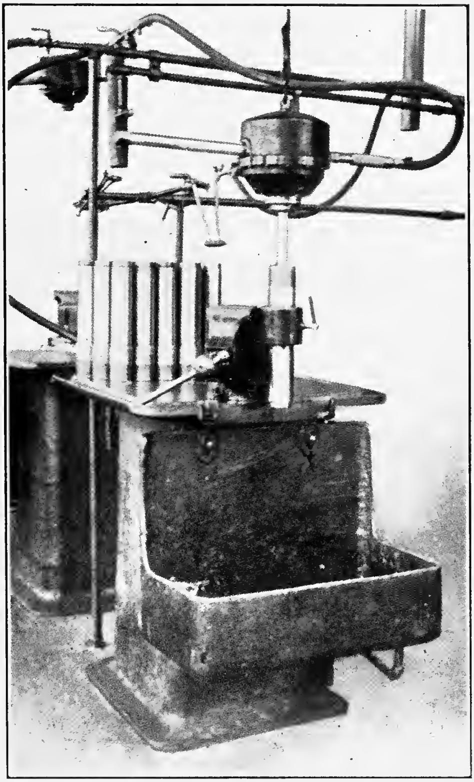

FIG. 152.—Compressed air reaming bench.

THE AUTOMATIC TURRET LATHE

The most interesting of all machine tools in the almost human intelligence which it shows is the automatic turret lathe[1] which was developed to a state of practical usefulness chiefly by Christopher M. Spencer, who made his first machine

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[1] Frequently called automatic screw machine.

about 1875. A prior patent by Francis Curtis issued in 1871 and another by L. W. Langdon issued in 1864 anticipate some features of Mr. Spencer's work. For several years the machine was not offered for sale but was used exclusively in the works of the Hartford Machine Screw Company.

An automatic turret lathe by the Pratt and Whitney Company is shown in Fig. 153, for which, like the hand-operated machine, a simple example has been chosen in order to more clearly illustrate the principle. So far as the mounting and action of the cutting tools are concerned, this machine is substantially identical with the hand-operated machine, but the reciprocation and revolution of the turret, the feeding inward and gripping of the bar of stock, and the action of the cutting-off tool are automatically performed by means of the cams

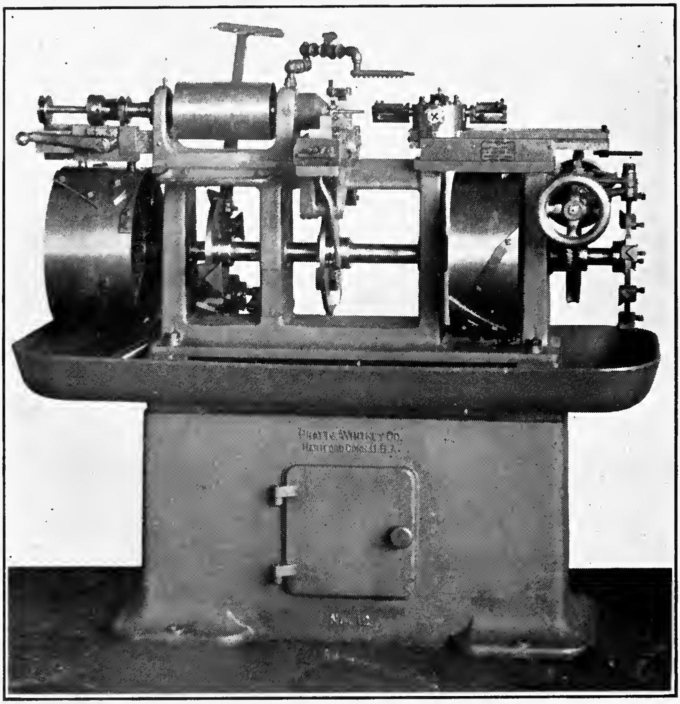

FIG. 153.—Automatic turret lathe.

attached to the drums which are mounted on a shaft extending through the base of the machine. In addition to this, the rate of feed of the various tools is changed from tool to tool in order adapt the speed to the individual cutting operation and the direction of revolution is reversed, in order to withdraw a threaded portion from the die which cuts the threads. The speed of the machine, as a whole, is changed by cone pulleys on the main and countershafts.

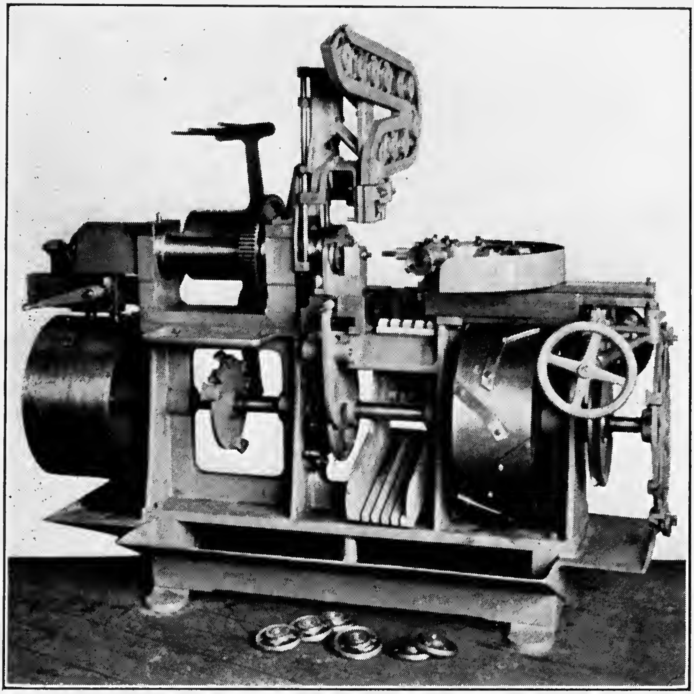

FIG. 154.—Magazine feed automatic turret lathe.

The work spindle and the drum shaft are independently driven in order that their speeds may be independently adjusted. The speed of the drum shaft has no fixed relation to the speed of the spindle, but is so adjusted that the drum shaft makes one complete turn while one piece is being made, regardless of the length of time required for its making. Starting at the left, the first drum carries a series of cams by the action of which the collet chuck is loosened and tightened and the bar of stock is pushed forward after the cutting off of each piece. The next cam manipulates the belt shipper which controls two belts. The middle pulley upon the work spindle is the driving pulley, the two outer ones being loose. One of the two belts is commonly crossed and serves to withdraw a threaded piece from its die. The cam in the middle of the machine operates the cross slide which carries a cutting-off tool and also, in a second tool post if need be, a necking or rounding tool. The next cam drum at the right actuates the turret slide. The return of the turret is much quicker than the cutting movement which latter has, if need be, a quick preliminary movement up to the point where the cutting action begins. At the extreme right is a cam drum by which the speed of rotation of the cam shaft is varied, for the slow feeding and quick return movements of the turret. The camming of these machines for various kinds of work is very much of an art.[1]

THE MAGAZINE FEED AUTOMATIC TURRET LATHE

A more recent development of the automatic turret lathe, first made by the Pratt and Whitney Company, lies in its adaptation to the machining of separate pieces by taking them one by one from a magazine, inserting them in a chuck, machining and finally rejecting them and supplying the chuck with another. So far as automatic pushing inward a bar of stock is concerned, the work does not differ except as regards the size of the bar. Individual castings and forgings are, however, of such a wide diversity of form that various kinds of magazines and as many methods of handling the pieces are required, the provision of which often requires the exercise of much ingenuity.

Fig. 154 shows the machine as arranged for the first piece of work to which it was adapted, the machining of the small belt pulleys of sewing machines. A magazine, filled with blank pulleys, is shown above the work spindle, the work of the operator being to see to it that this magazine does not get empty. By

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[1] Full particulars of the methods of laying out these cams may be found in Automatic Screw Machines and their Tools by C. L. Goodrich and F. A. Stanley.

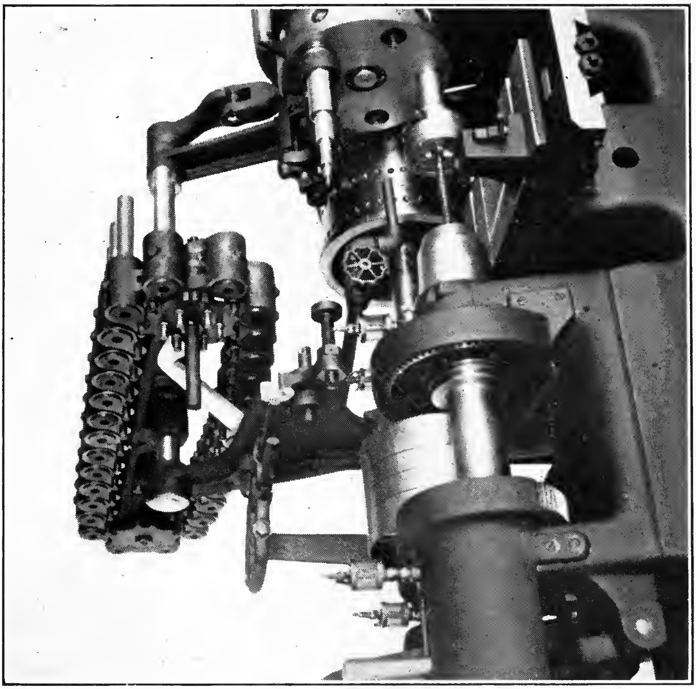


FIG. 156.

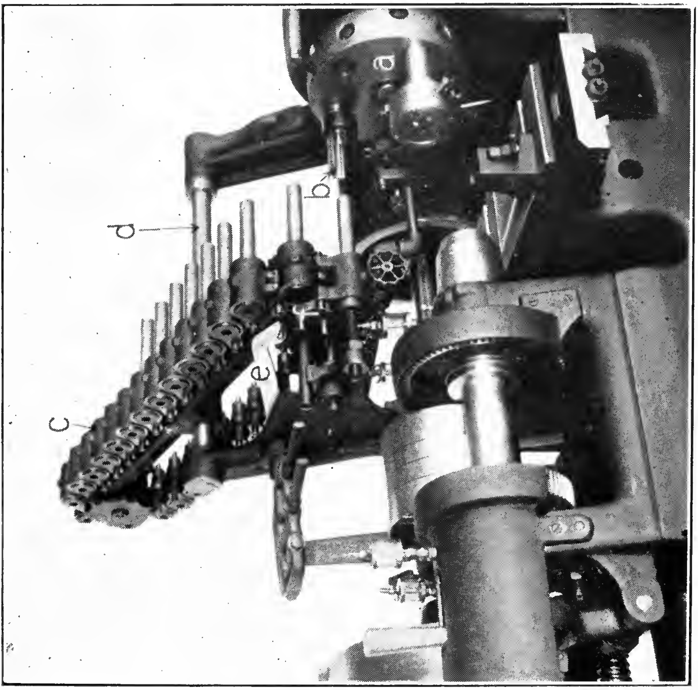


FIG. 155.

Tilting magazine feed.

reason of the inclination of the magazine, the wheel blanks roll to the outlet at the bottom, from which point a transfer carrier, operated by a special cam upon the cam shaft, takes them, one by one, and transfers them to a point in front of the spindle chuck, into which they are pushed by the first movement of the turret and then gripped by an additional cam action. When the piece is finished it is automatically released from the chuck and drops out on the floor, as shown, when its place is taken by another through the action of the transfer carrier.

It is impossible to include any considerable number of the numerous forms of magazine and of transfer mechanism which have been devised to handle pieces of various forms. One additional construction which has been designed to handle pieces of a wide diversity of forms is shown in Figs. 155 and 156. Comparison with Fig. 154 will serve to indicate the variety of constructions that have been employed to meet the numerous conditions that present themselves.

This construction is supplied with the automatic turret lathes of the Cleveland Automatic Machine Company. Unlike all others, the turrets of these machines turn upon a horizontal center line. Structurally the turret is a long drum supported by a barrel casing within which it turns and slides. The end of the turret appears at *a* in both views, projecting from its barrel support and carrying the cutting tools and the transfer carrier, *b*.

The magazine consists of a frame *c* mounted on a shaft *d* on which it is automatically oscillated between the positions shown in the two illustrations by a suitable cam. Surrounding the frame is an endless link belt, each link of which is formed into a hub. Each hub has a hole through it endwise in which is inserted a bush suitable for the pieces of work to be handled, the pieces in this instance being studs, shown projecting from the hubs. The studs are to have turning and threading operations performed on their projecting ends. With the magazine tilted to the position of Fig. 155, the turret advances, when the transfer carrier withdraws the opposing piece of work from the magazine and at the next movement of the turret transfers it to and inserts it in the chuck. Meanwhile the magazine returns to the position of Fig. 156 in order to get out of the way of the cutting tools, and remains there while the piece is being machined and until the time arrives for the next piece to be transferred to the chuck, when the magazine tilts to its downward position again. During this downward movement the long pawl *e* engages one of the pins in the sprocket wheel *f* by which the link belt is driven and thus advances the belt and its load of studs one link and presents a fresh stud to the transfer carrier. In Fig. 156 one stud is seen in the transfer carrier and another in the chuck, the latter having had the turning and threading operations upon it performed. The die with which the thread was cut occupies a hole in the turret in line with the second stud.

THE MULTIPLE-SPINDLE AUTOMATIC TURRET LATHE

Another comparatively recent development of the automatic turret lathe is found in the multiple-spindle automatic turret lathe which, although now made by several parties, was invented by E. C. Henn of the National Acme Manufacturing Company. In the automatic machine as so far shown, the various operations on a piece are successive, the time required to make a piece being the sum of the times required for the individual operations. In the multiple-spindle machine four pieces are acted upon at once and the time required to complete the piece becomes that of the longest single operation.[1]

Referring to Fig. 157 which shows the machine of the National Acme Manufacturing Company, we see at the extreme left four bars of hexigon stock which pass through the same number of hollow work spindles. The spindles are mounted and turn within a drum which is mounted within the cylindrical head stock and which, at the completion of each operation, makes a quarter turn and thus shifts the bars of stock to the successive operating positions. At the right and in line with the work spindles are four tool supports which, while stationary in position, revolve about their individual centers if need be. A more

[1] In some cases even this is reduced by dividing the longest single operation into two, thereby making the time required that of one-half the longest or the entire time of the next to the longest single operation, in case that exceeds one-half the time required for the longest.

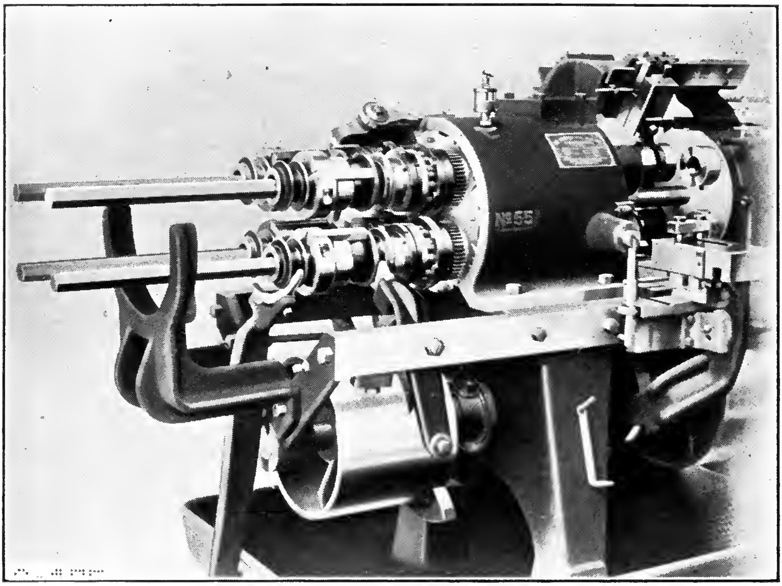


FIG. 157.—Multiple spindle automatic turret lathe.

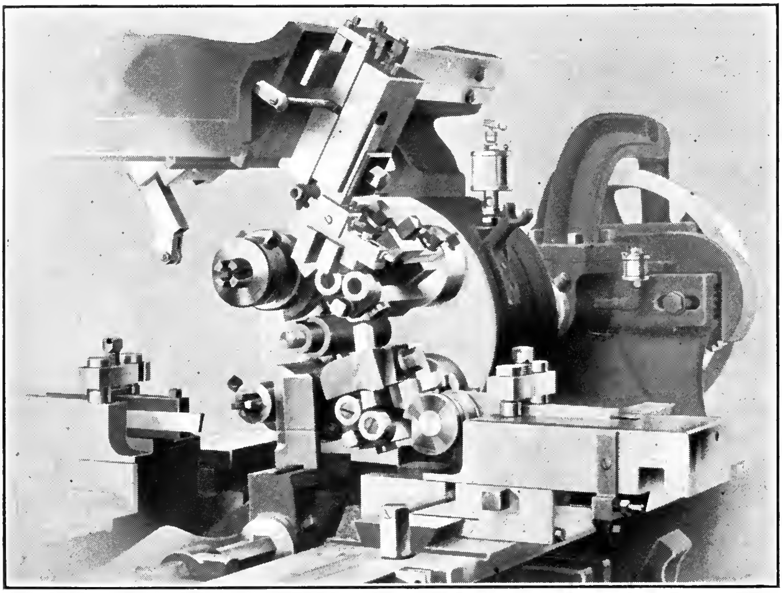


FIG. 158.—Arrangement of tools in multiple spindle automatic turret lathe.

complete view of the tool supports with various tools mounted therein is given in Fig. 158, in which are also shown surrounding tool slides carrying cutting-off, necking and forming tools which act simultaneously with the revolving tools, two operations at each station being frequently in progress.

The term turret lathe as applied to this machine is, in a sense, a misnomer. The essential feature of the turrent lathe—the mounting of the tools in a revolving turret and turning them out of and into the cutting position as required—is not found in this machine, in which the positions of the tools are fixed. On the other hand, the position of the work is changed by presenting it in succession to the various tools in their fixed positions. It would more properly be called a *station machine* to indicate that the work is shifted from station to station at each of which an operation is performed. Looked at in this way, this machine was the forerunner of a system of machines which, made at home for special purposes, have appeared from time to time, and which, as the multaumatic vertical lathe of the Bullard Machine Tool Company, has now made its appearance as a general purpose machine. The author anticipates and predicts that machines of this type will form the next large development in machine-shop productive equipment.

The Bullard Multaumatic machine is shown in Fig. 159. The work-holding chucks, of which there are six, are mounted in a revolving ring, the spindles being driven from below. Five tools are mounted on the upright column, the sixth station being the loading station. A piece of work being fixed in the chuck at this point, the first step movement of the ring brings the work below the first tool and while this tool is operating a second piece is inserted in the second chuck and so on until all the chucks are full. Thereafter, as each chuck arrives at the loading station with the work on its piece completed, it is removed and another substituted in its place, the operation thereafter being continuous with five cuts in progress at all times.

AUTOMATIC LATHES FOR WORK DONE BETWEEN CENTERS

It will be observed that all of the applications of the turret lathe shown are for work made from the bar or for pieces of a nature which can be held in a chuck. The application of the turret principle, the preservation of the adjustment of the cutting tools, to work which must be held between centers is a much more difficult problem, the solution of which came much later. The customary form of turret is entirely inapplicable because the tools, which project radially from the turret, interfere with the head and tail stocks. Two very successful machines for this purpose are the Fay and the Lo-swing automatic lathes.

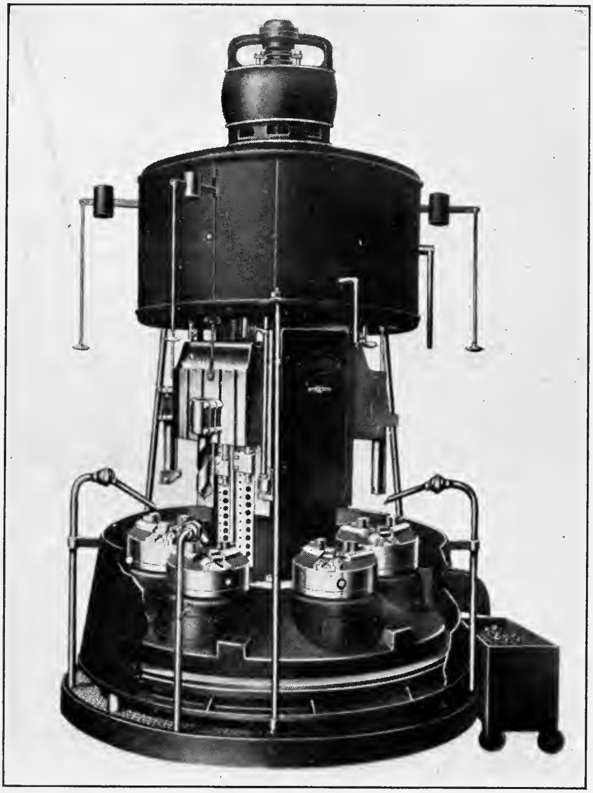
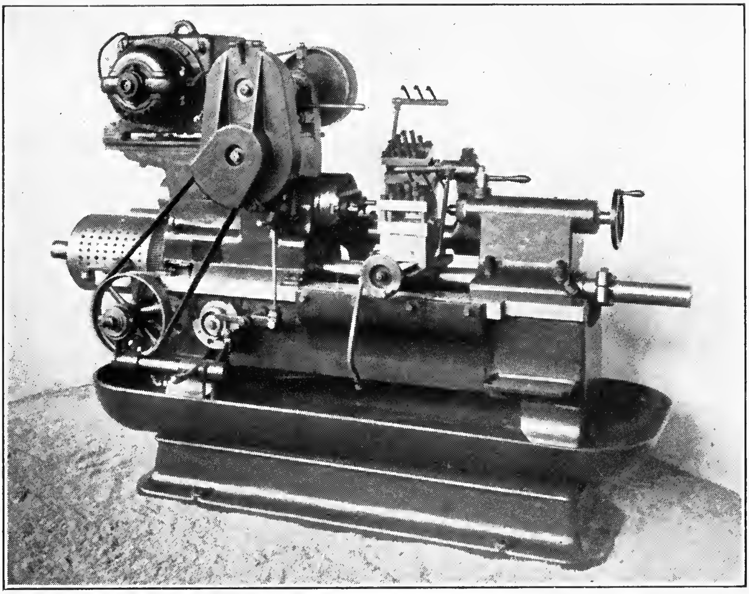
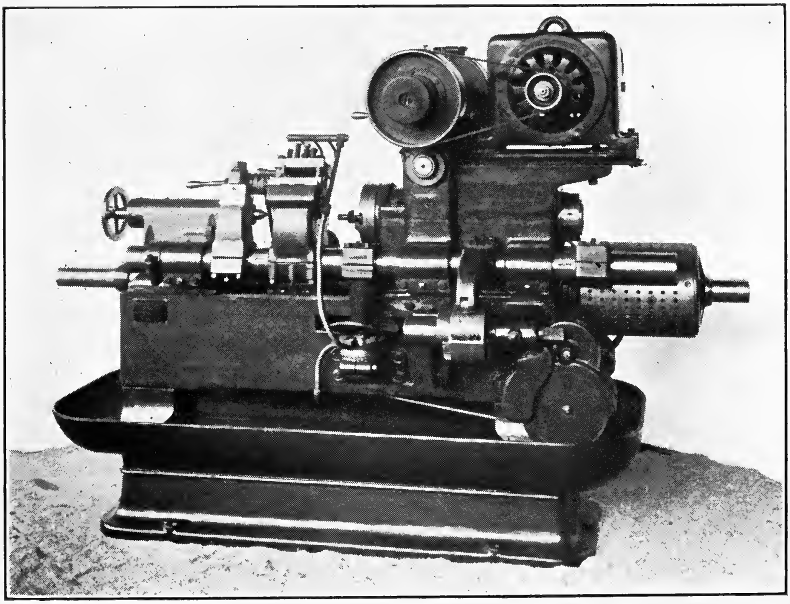


Fig. 159.—Station machine for lathe work.

The Fay lathe, Figs. 160 and 161, is intended more especially for turning pieces which are carried on mandrels while the Lo-swing lathe, Fig. 163, is for turning pieces of considerable





FIGS. 160 and 161.—Fay lathe.

length but of comparatively small diameter, the two machines thus mutually supplementing each other.

As in other automatic lathes the operations of the cutting tools of the Fay lathe are controlled by cams, a cam drum, carrying cams upon both its interior and exterior surfaces, being located at the head-stock end of the machine. The turning-tool carriage is mounted upon a sliding bar which is drawn endwise for the feed by a cam on the interior of the drum.

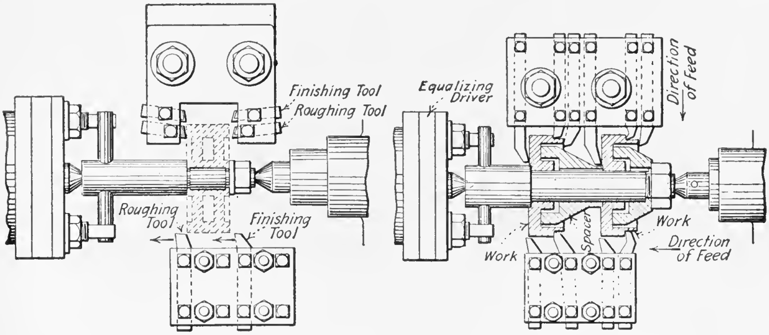


FIG. 162.—Examples of work for which the Fay lathe is adapted.

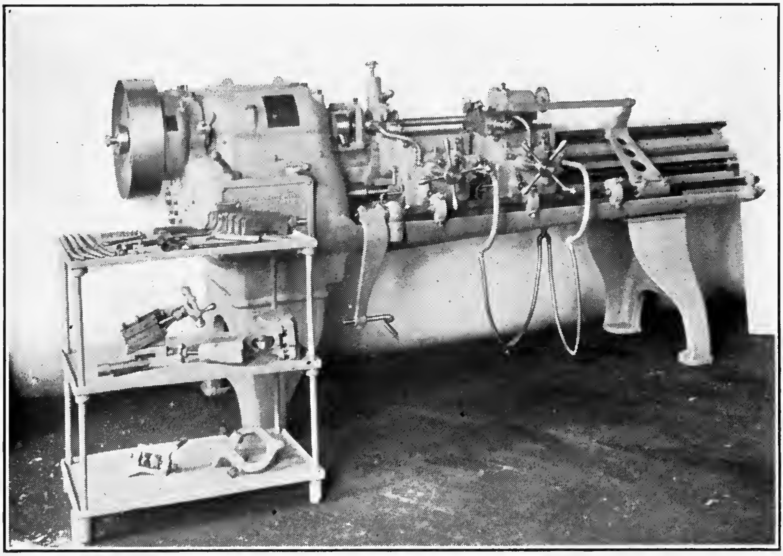


FIG. 163.—Lo-swing lathe.

The rear of the tool carriage rests upon a support which may be inclined to the horizontal or be curved if desired and thus produce both tapered and curved outlines. In the rear is a second tool support mounted, as shown in Fig. 161, on an arm also carried on a sliding and turning bar. This tool support is most used for facing cuts for which it is actuated by a heart-shaped cam within the bed. It may also be used for turning if desired. Each tool support may carry several tools if the work calls for them. The character of the work to which the lathe is adapted and the method of holding the cutting tools are indicated in Fig. 162.[1]

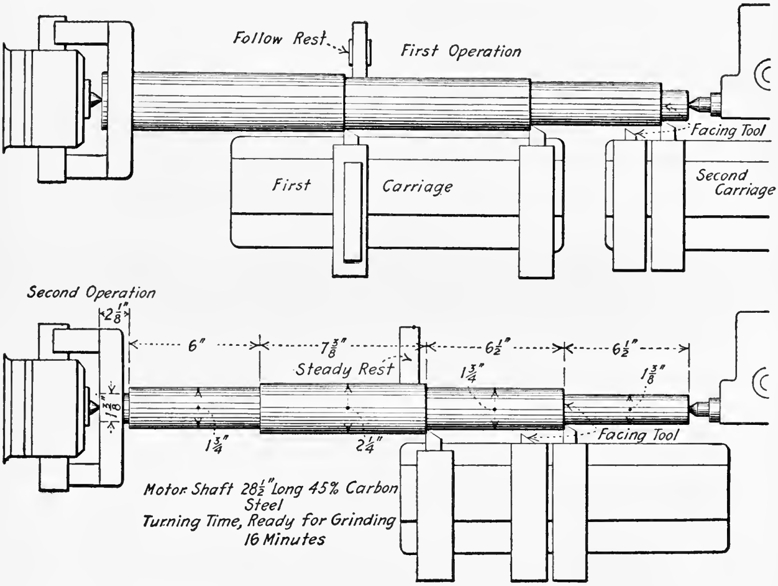


FIG. 164.—Examples of work to which the Lo-swing lathe is adapted.

The Lo-swing lathe, Fig. 163, is a single purpose machine intended for doing work on bar stock of the class that must be done between centers and nothing else. The swing is reduced to that necessary for work of three and one-half inches diameter. It has no part corresponding to a turret but the essential feature of the turret, the use of several tools, and the preservation of the adjustment of the tools is retained. Two tool carriages,

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[1] Reproduced from *Machinery*.

each capable of holding several tools, are provided, so arranged as to pass by the tail stock for starting the cuts and for short work. The general character of the work for which the lathe is adapted, together with the manner in which the successive tools act, is shown in Fig. 164. This illustration does not, however, show the operations of thread cutting nor taper turning for both of which the machine is equipped.

THE BORING BAR

For a great variety of purposes holes must be bored in pieces of a size and character such that no modification of the lathe can accommodate them. Such holes are bored by means of boring bars[1] which are of three kinds: (a) those which are fed

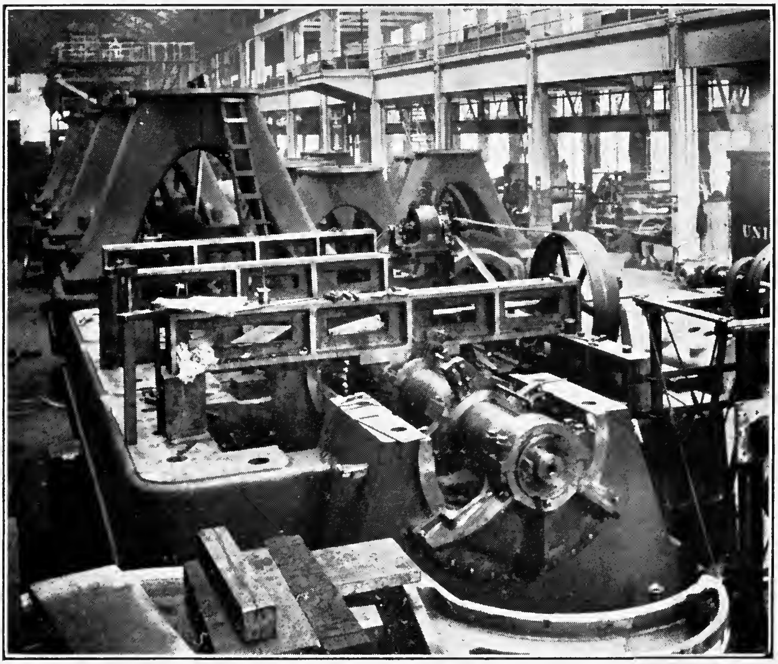

FIG. 165.—Large boring bar at work.

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[1] The boring bar was invented in 1774 by John Wilkinson for use in the boring of steam-engine cylinders for James Watt which, at the beginning, was the most troublesome and difficult construction problem with which Watt had to deal. The boring bar was of the traveling-head variety and it was the first machine tool to approximate modern standards.

through bearings with the cut, the tool being fixed in the bar; (b) those which are stationary as regards endwise motion and have tools fixed to them, the work traveling lengthwise of the bar; (*c*) those in which both work and bar are fixed as regards endwise motion, the tool being mounted in a traveling head which is fed lengthwise of the bar by means of a screw.

An application of a bar of the traveling-head variety is shown in Fig. 165 from the Westinghouse Machine Company, the work in progress being the boring of the seats for the bearing shells of a large upright vertical engine. The bar is supported in bearings, one of which is bolted to one end of the casting and the others to cross beams as clearly shown, the drive being through a worm gear and an electric motor belted to the worm shaft. Such bars and their attachments naturally take a great variety of forms in accordance with the necessities of individual cases.

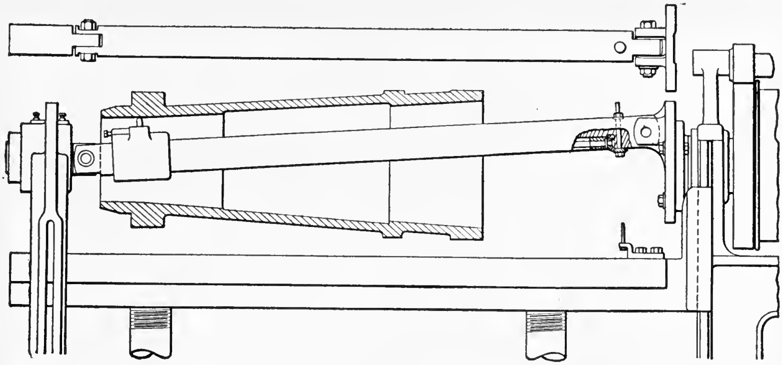


FIG. 166.—Boring bar for taper holes.

A boring bar for taper holes, from the works of the Niles-Bement-Pond Company, is shown in Fig. 166. The bar is swiveled to its supports and one end may be offset to any angle required.

BORING AND TURNING SPHERICAL SEAT

The growing use of the self-aligning ball-and-socket construction for large bearings necessitates the provision of suitable means for machining the spherical seats—external in the case of

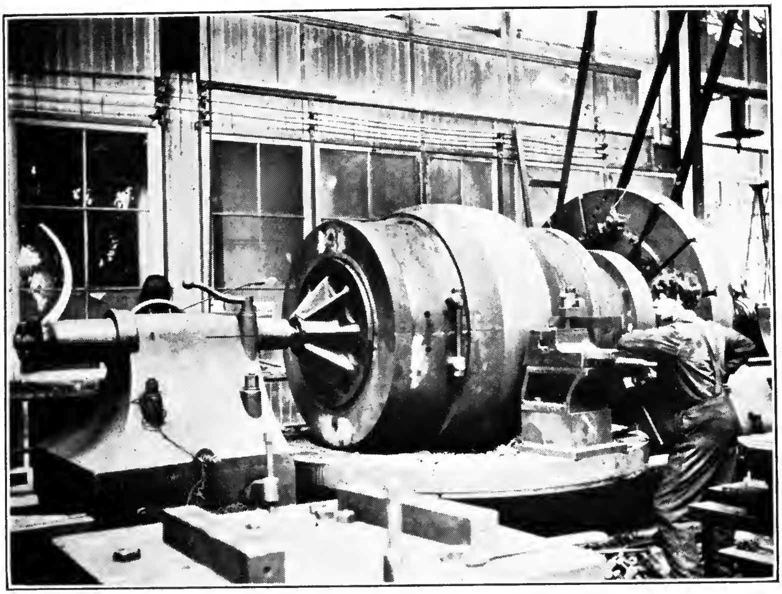
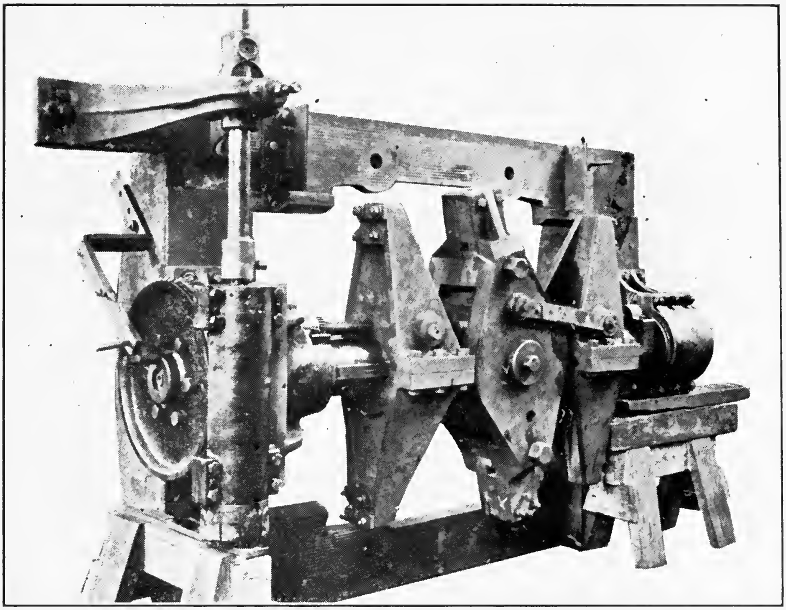
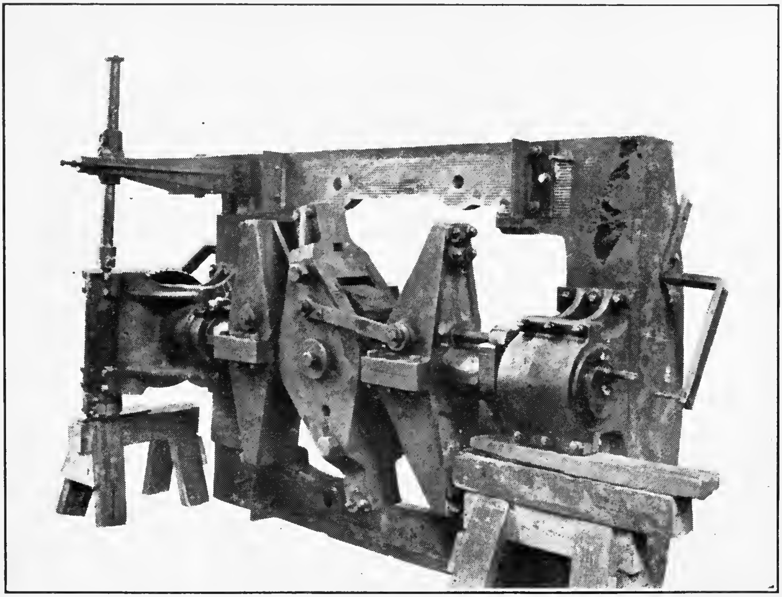


FIG. 167.—Turning spherical seats for bearings.

FIG. 168.—Boring spherical seats for bearings.





Figs. 169 and 170.—Boring bar for spherical seats.

the bearing shells and internal in the case of their supports. Fig. 167 from the works of the Westinghouse Machine Company shows such a provision for the turning of the spherical seat on a large bearing shell. The provision required is that the cutting tool, instead of traveling in a straight line as in the ordinary lathe, shall swing on the arc of a circle, the center of which is vertically below the center line of the lathe. The means by which this is obtained are sufficiently obvious from the illustration.

Figs. 168–170, from the same source as the last, show a superior equipment for boring large spherical seats. Fig. 168 shows the equipment in position boring the seat of the main bearing of a large horizontal engine. The boring bar and its driving mechanism are suspended from a frame which is bolted to the top of the bearing jaws. Figs 169 and 170 show the outfit turned up on its side and from opposite ends, the frame casting being in the background. The bar carries three tool heads of which the outer ones, which travel on the bar for the feed, bore the cylindrical ends of the engine casting. The inner head swivels on the bar and is shown connected by links to one of the traveling heads. The boring of the cylindrical ends having been accomplished with the links removed, the cutting tools are removed from the end heads and inserted in the swivel head. The links being then placed in position the result of feeding the end head along the bar is to traverse the cutting tool on the swivel head in the arc of a circle and bore the spherical seat. The feed screw by which the traverse is accomplished is shown above the bar in both Figs. 169 and 170.

CYLINDER BORING MACHINES

When boring cylinders for vertical steam engines of large size, the best practice requires that they be bored in a vertical position in order to avoid the distortion due to their own weight and Fig. 171 shows a machine for boring such cylinders at the Brooklyn Navy Yard. The boring bars, of which three appear at the left of the machine, are of the traveling-head variety and, when at work, are supported above and below by the bearings plainly shown. The driving of the bar is from above by means of gearing. In the foreground is a facing head for facing the flanges of the cylinders. When mounted upon the bar its arm

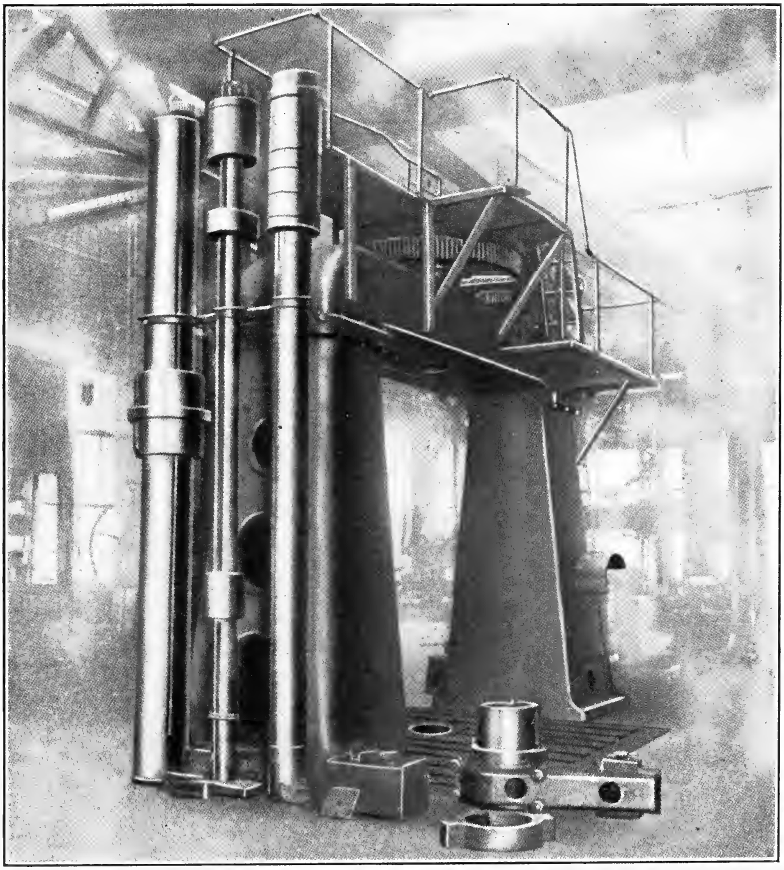


FIG. 171.—Large vertical cylinder boring machine and boring bars.

projects radially and the tool slide with which it is fitted travels radially and performs the required operation.

CHAPTER IX

FLOOR-PLATE WORK

The floor-plate system of machine tools—Such tools have no defined limit of capacity—Uses of the various tools—The floor-plate boring mill.

CHARACTERISTICS OF FLOOR-PLATE TOOLS

All of the machine tools elsewhere shown have in common the feature that the size of the work which they can normally take in is limited by the dimensions of the machine. Numerous ingenious expedients enable work to be done of dimensions which exceed those for which the machines were designed, but they are but makeshifts at best, and the growing frequency with which large work is required has led to the construction of machines of an entirely different type in which there is no designed limit of capacity. With these machines the limit to the size of parts is no longer set by the character of the machine-shop equipment but by the facilities of the railroad companies for transporting the pieces, the limiting dimensions being reached with the largest pieces that will pass through railroad tunnels and bridges.

This system of machine tools, known as *floor-plate tools*, is due to John Riddell, mechanical superintendent of the Schenectady works of the General Electric Company, from which works the system has spread to others doing large work.

The starting point of the system is the provision of a heavy cast-iron floor plate made in sections, usually ten feet square, and fitted with T slots by which both work and tools are bolted down. Large floor areas are fitted with these plates, a section of such a floor at the General Electric Company's Schenectady works being shown in Fig. 172. The machine tools themselves are of considerable variety, several being shown in Figs. 173–176, from which it will be apparent that it is the individual

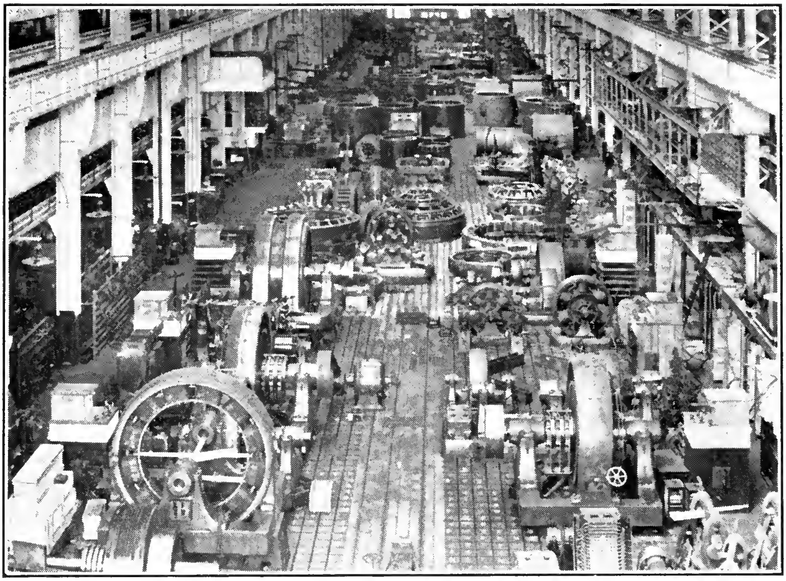


FIG. 172.—Modern floor plate.

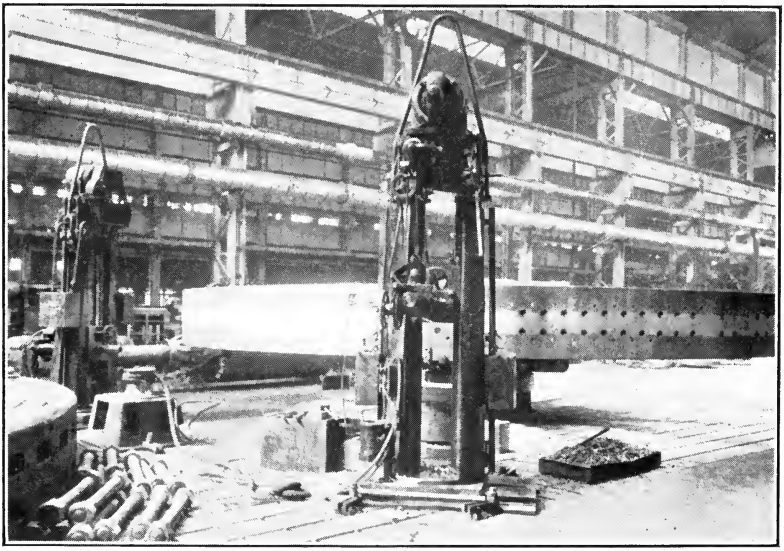


FIG. 173.—Portable floor plate drilling machine.

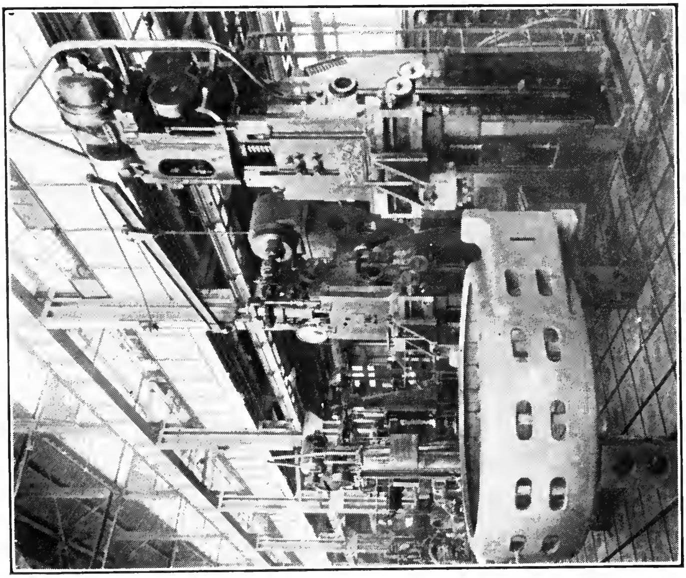


Fig. 174.—Portable floor plate slotting machines.

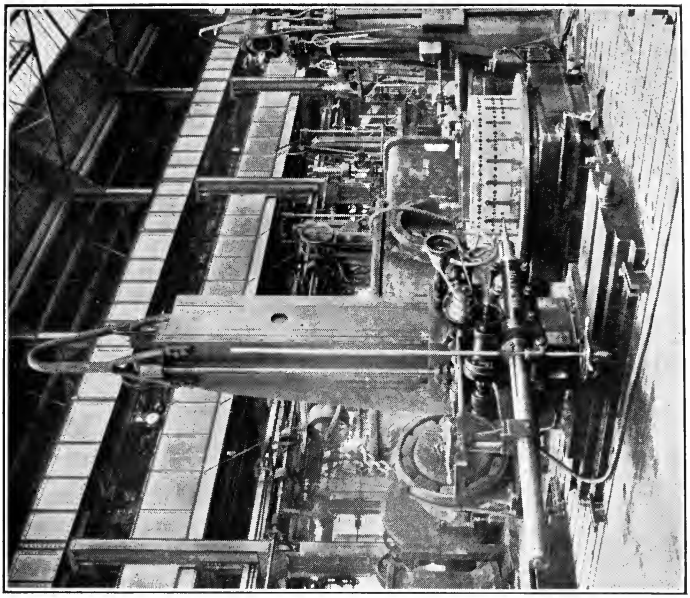


Fig. 175.—Portable floor plate drilling machine.

electric motor drive that has made the system feasible. Each machine is provided with its own motor, convenient plugs being provided for connecting at any convenient point. In each case also the machine is provided with a suitable lifting bale by which the overhead crane may transport it from place to place.

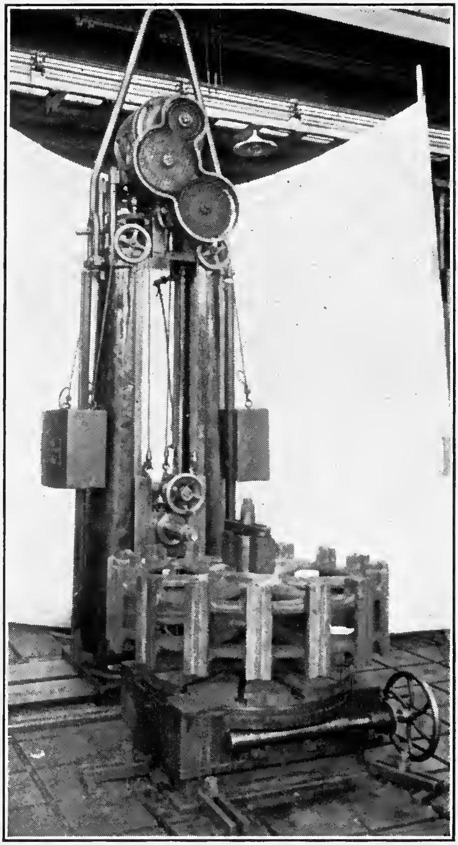


Fig 176.—Portable floor plate milling machine.

EXAMPLES OF FLOOR-PLATE TOOLS

Fig. 174 shows two portable Newton slotting machines at work planing the feed of a motor frame. Fig. 175 shows a horizontal spindle Newton drilling machine mounted on an adjustable base and Fig. 173 a drilling machine of somewhat different pattern, though by the same maker, engaged on a much larger piece of work. In both cases the piece of work is mounted on a central turn table. This last machine is also provided with a vertical feed to the spindle head and Fig. 176 shows it at work milling the dove-tail slots in an armature spider. The floor-plate system as applied to heavy milling operations is shown in Figs. 240–242 and as applied to the cutting of large gears in Fig. 270.

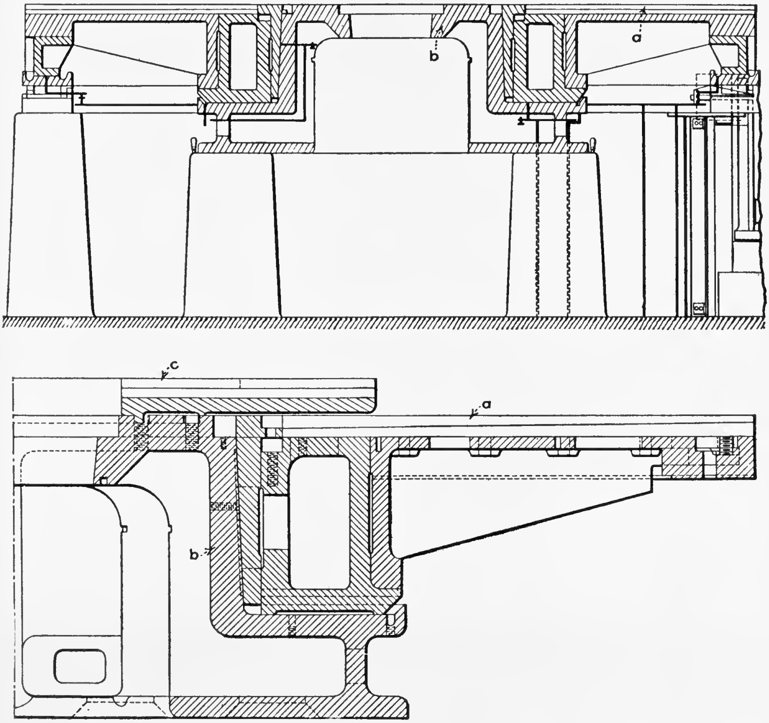


Fig. 177.—Section and half section of floor plate boring mill.

THE FLOOR-PLATE BORING MILL

One of the applications of this system is to the floor-plate boring mill. The boring mill, like all machine tools other than floor-plate tools, is limited in the capacity of the work which it will take in, whereas the floor-plate boring mill, like other floor-plate tools, has no such limitation. The floor-plate boring mill consists of a revolving table sunk in the regular floor plate which surrounds it, the work and the machine tools being mounted upon the revolving and the stationary plates in various ways and in accordance with the requirements of the piece of work in hand.

A section and half section of such a floor-plate mill at the works of the Crocker-Wheeler Company is shown in Fig. 177. The revolving table is shown at *a*, the center piece *b* being stationary and serving as a bearing for the revolving table. A supplementary, non-revolving, removable piece *c* is provided, properly fitted at its center so that it may be quickly dropped into place concentrically with the other parts. This supplementary piece is only occasionally used but it adds materially to the flexibility of the machine.[1]

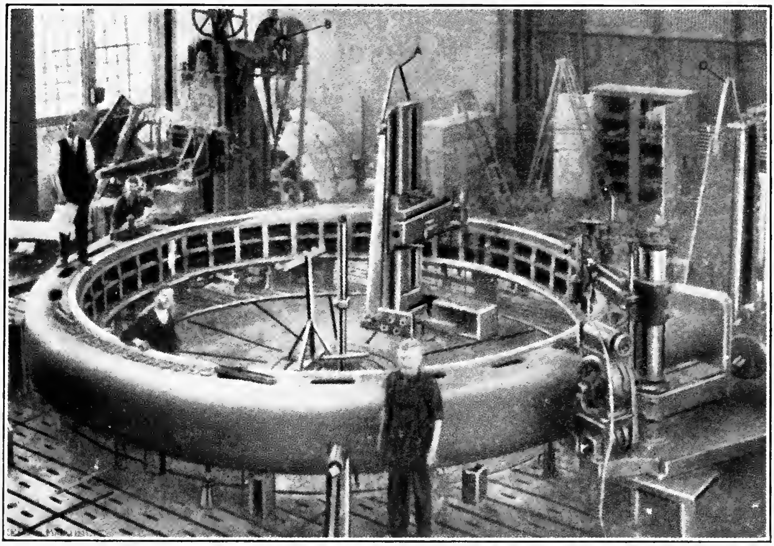


FIG. 178.—The tool revolves while the work stands still. Work of the floor-plate boring mill.

In use, the work is sometimes bolted to the surrounding floor plate, the tool being mounted upon and turning with the re-

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[1] The heavy lines of the upper view show oil supply and drain pipes.

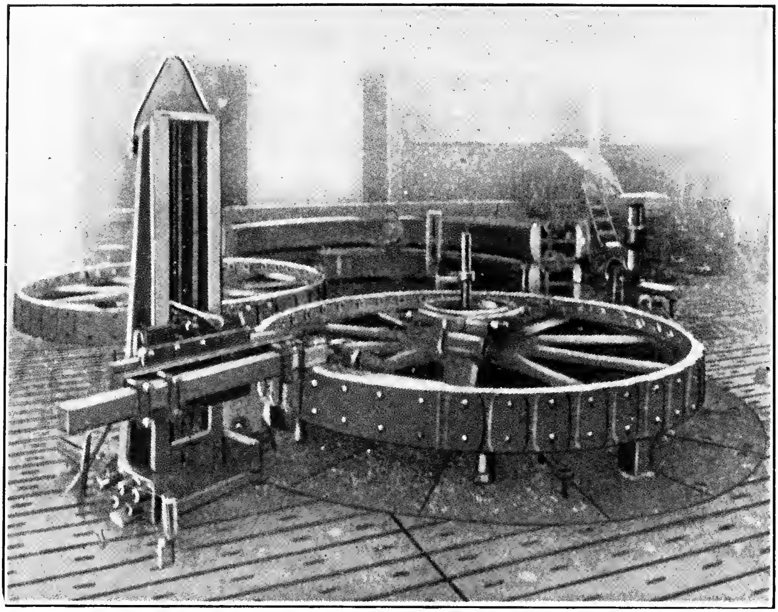

FIG. 179.—The work revolves while the tool stands still.

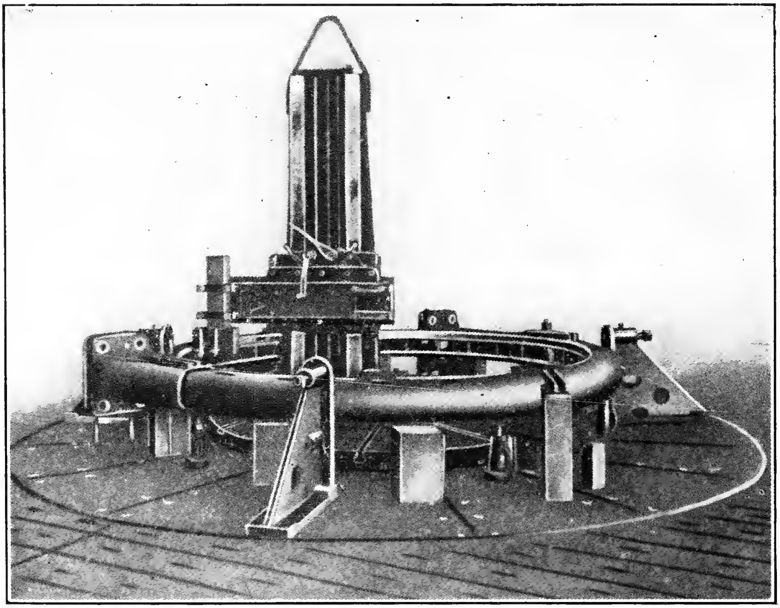

FIG. 180.—The work revolves while the tool stands still.
Work of the floor-plate boring mill.

volving table, while in other cases the reverse arrangement is used, the arrangement being determined by the size of the work. Fig. 178 shows a generator ring frame mounted upon the surrounding plate and the tool mounted upon the revolving plate, other tools performing additional operations simultaneously. Fig. 179 shows the reverse arrangement, the work being here mounted on the revolving table while the tool support is mounted on the surrounding floor plate. For still smaller work as in Fig. 180, the tool is mounted upon the inner supplementary plate, which does not revolve, while the ring frame is mounted upon the revolving table and, obviously, if required, the reverse arrangement may be used, the work being mounted upon the supplementary plate and the tool upon the revolving table.

CHAPTER X

DRILLING

Types of drilling machines—Jigs and their uses—Gang, multiple-spindle and station drilling machines—The laying-out machine for the accurate spacing of holes—The base line system of drawings—Other methods of spacing holes—The master plate.

TYPES OF DRILLING MACHINES

The drilling machine is made in a great variety of forms, of which three by the Cincinnati Bickford Tool Company are shown in Figs. 181–183. The most common form, called the *upright* drilling machine, with modern and unusual features, is shown in Fig. 181. With the two that follow, it is fitted with the popular constant-speed pulley drive.[1] By means of the two bevel gears on the upper end of the spindle and their connections, the spindle may be revolved in either direction and with the back gears and the convenient lever for manipulating them the speed may be quickly changed. Thus equipped the machine may be used for tapping as well as drilling. The tap having been driven through the work, movement of the front lever depending from the driving head reverses the tap, when movement of the rear lever accelerates the speed of withdrawal. A depth gage for the depth of drilling and an automatic trip whereby the feed is automatically stopped when the desired depth has been reached are also provided.

To accommodate work in which holes must be drilled at a considerable distance from their sides the *radial* drill, Figs. 182 and 183, has large application. In most cases these machines are made as shown in Fig. 182, the drill spindle being always vertical. Such machines are called *plain radials*. In

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[1] To the best of the author's knowledge, the first machine tool of any kind to be thus driven was a Bickford drilling machine exhibited at the Pan-American Exposition of 1900.

other cases as in Fig. 183 the arm is so made as to swivel about a horizontal line and the drill spindle about its vertical center line, whereby the spindle may be made to perform its function at any angle with the horizontal and vertical planes. Such machines are called *universal radials.* Sometimes one of these adjustments is omitted and the machine becomes a *semi-*

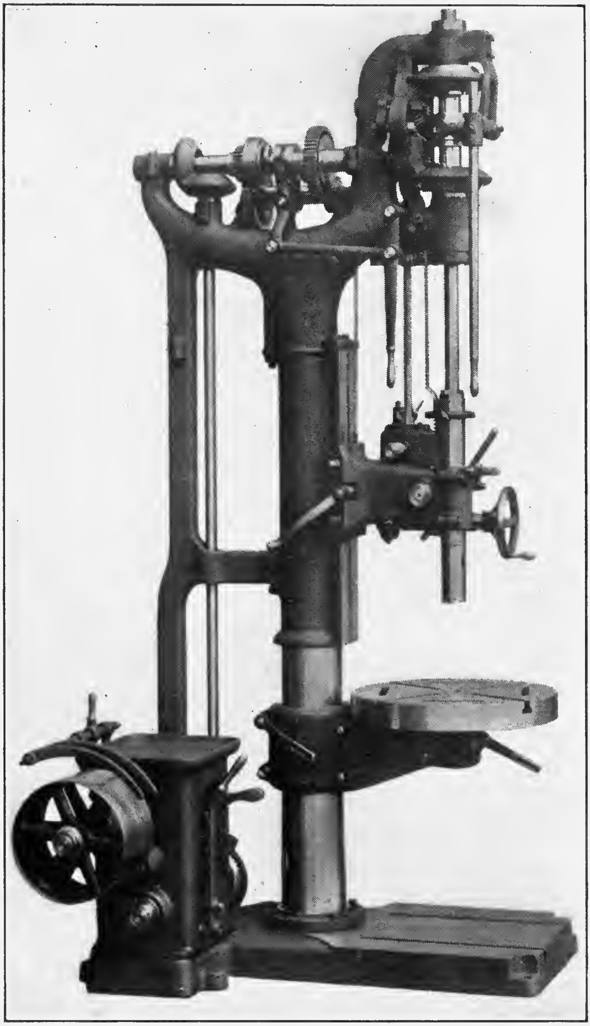
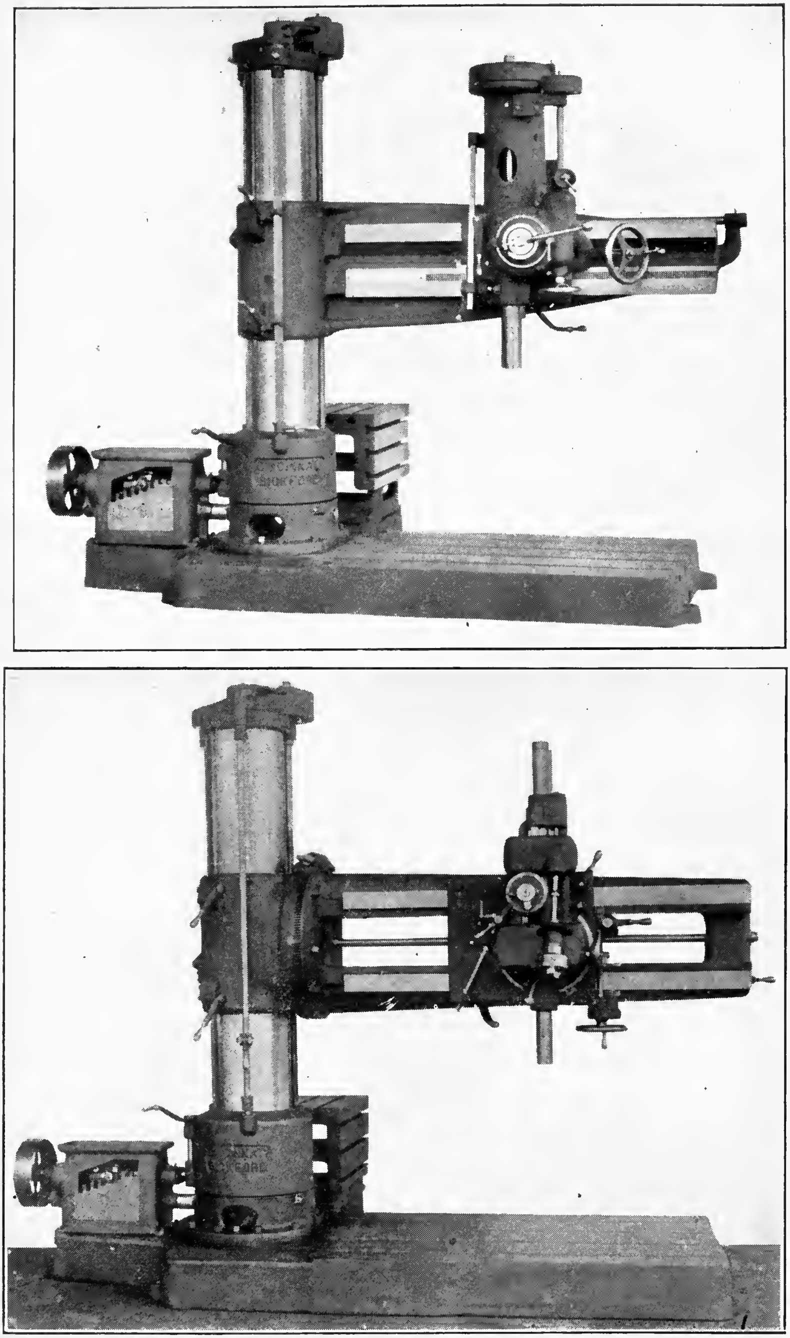


Fig. 181.—Upright drilling and tapping machine.



FIGS. 182 and 183.—Plain and universal radial drilling machines.

universal radial. The convenience of the universal and semi-universal machines adapts them to the performing of otherwise difficult operations, but the necessary joint at the base of the arm—precisely the point where stiffness is most needed—robs them of stiffness and, except as regards this convenience of adjustment, which is only occasionally required, the plain radial is much to be preferred.

DRILLING JIGS

Drilling in connection with manufacturing operations is always done in connection with drilling *jigs* which take a great variety of forms, a few of which are shown in Fig. 184. The object of a drill jig is to guide the tool, the laying-out of the holes being done once for all on the jig, uniformity of spacing

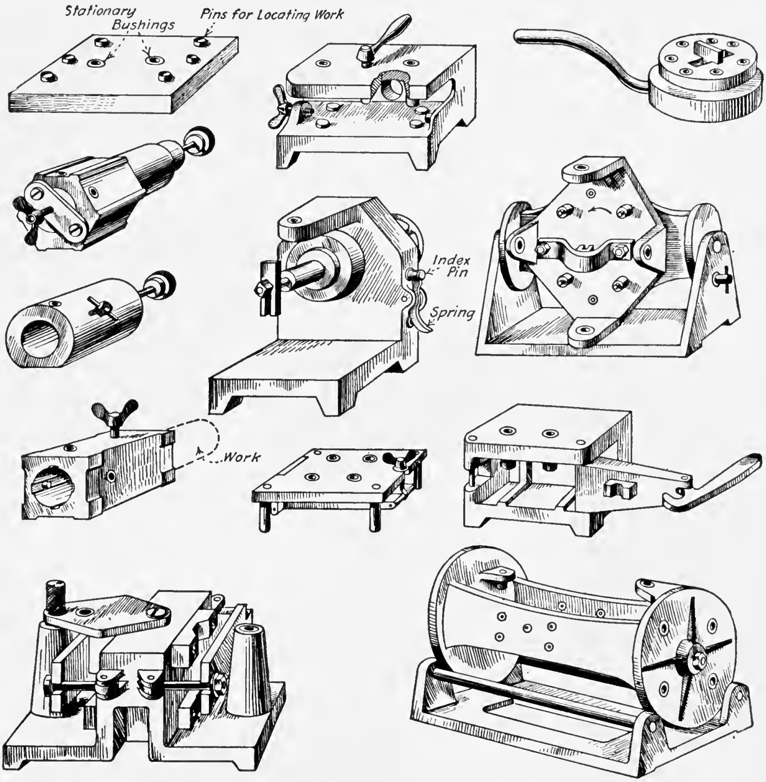


FIG. 184.—Various forms of drilling jigs.

in the work being thus assured. To insure permanence of the locations the holes are bushed with hardened steel bushes. Eventually even hardened bushes wear, but it is then a simple matter to remove the old and insert new bushes, the result being to restore the jigs to their original accuracy.

This word *jig* is properly applied to appliances which guide cutting tools. Numerous other appliances used in connection with other operations which locate the work, rather than guide the tool, are frequently called jigs but are more properly *fixtures*.

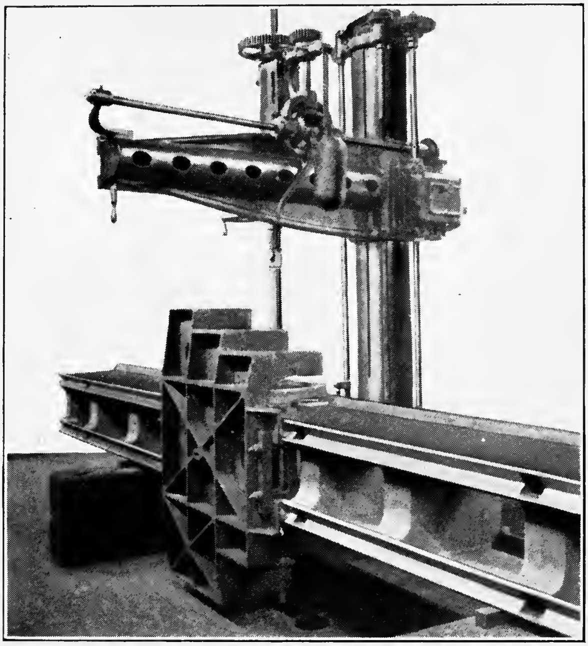


Fig. 185.—Large boring bar jig.

Jigs for large work are frequently seen, such an one from the Cincinnati Planer Company being shown in Fig. 185, which illustrates a jig for the bearings of the various shafts which extend through a planer bed. These bearings it serves to locate in proper position with respect to one another and also with respect to the V's of the planer. The jig has locating V's which enter the V's of the planer bed. The tool guided by the jig is a boring bar which is guided at both ends by bushes in the jig body, the drive being from a radial drilling machine through an adjustable knuckle joint.

GANG AND STATION DRILLING MACHINES

Drilling machines are frequently arranged in gangs, of which an example by the W. F. and John Barnes Company is shown in Fig. 186. With a piece of work in position the operator has but to trip a lever when the drill drops to the work, feeds through it and, when the hole is finished, automatically flies back to the starting point. The spindles are fitted in succession with various drills and reamers, the work being shifted from spindle to spindle and the four tools operating simultaneously on as many pieces. Arranged in this manner the equipment becomes essentially a station machine in which the shifting from station to station is by hand.

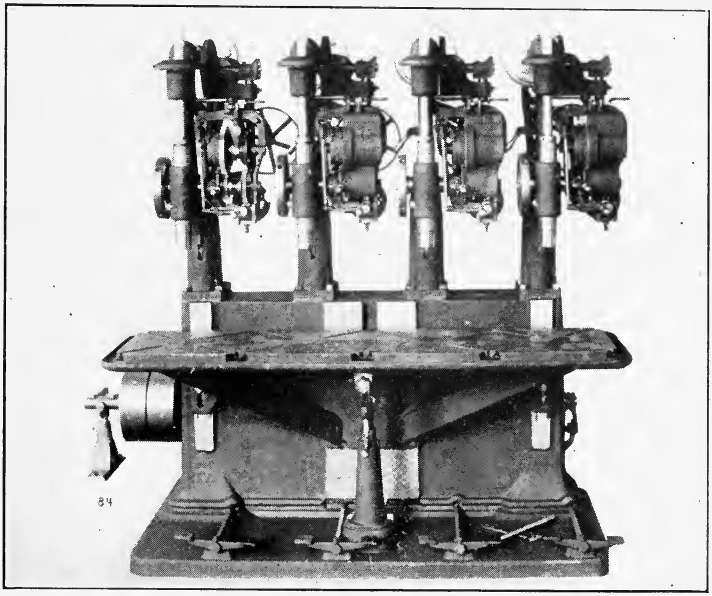


Fig. 186.—Gang drilling machine.

An automatic station drilling machine by the Windsor Machine Company is shown in Fig. 187. The work is carried on a turn table fitted with as many chucks as there are drilling spindles plus one, an extra station being required for loading and unloading the chucks. The feed is effected by the vertical movement of the turn table which revolves one step after the completion of each drilling operation. Each piece of work is finished as it passes the last operative station from which the next indexing movement carries it to the idle or loading station where the finished piece is removed and a new one is substituted, with a drilling operation in progress. The spindles are driven by universally adjustable telescopic connections permitting lateral adjustment of the cutting tool to any point on the face of the work and change gears are provided by which the speeds of the different spindles may be independently adjusted. Other operations than drilling, such as reaming, counterboring, etc., suitable for revolving tools may be carried on.[1]

MULTIPLE-SPINDLE DRILLING MACHINES

A comparatively recent development of the drilling machine is the multiple-spindle machine, if which an example, by the Baush Machine Tool Company, is shown in Fig. 188. The drills are driven from the central spindle by gearing and universal telescopic joints and are adjustable in number and to cover any layout within the limits of the machine.

Small multiple-spindle drill heads are frequently made for attachment to otherwise plain machines—such attachment being frequently homemade for the work in hand. Two such cases from the works of the General Electric Company are shown in Fig. 189 together with the jigs which go with them. The various spindles are driven by suitable gears, all connected to a central gear attached to the main spindle at the center. Other cases of multiple-spindle drill heads by the Langelier Manufacturing Company are shown in Figs. 190–192. Each of these is designed for a special piece of work and different heads are made to interchange on the same drilling machine.

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[1] The reader should compare this illustration with Fig. 159 showing a station machine in which the *work* revolves.

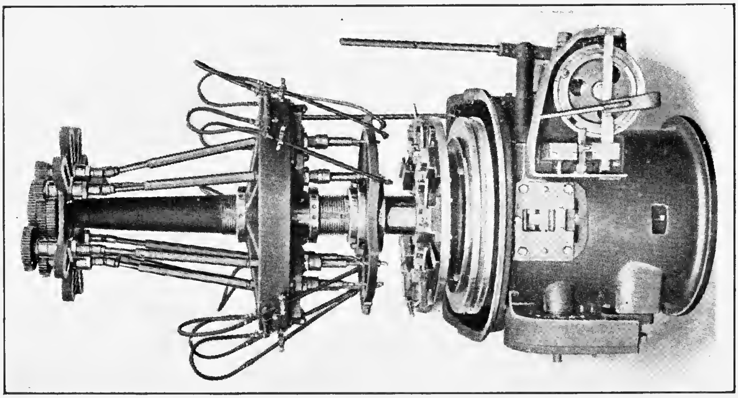


Fig. 187.—Automatic station drilling machine.

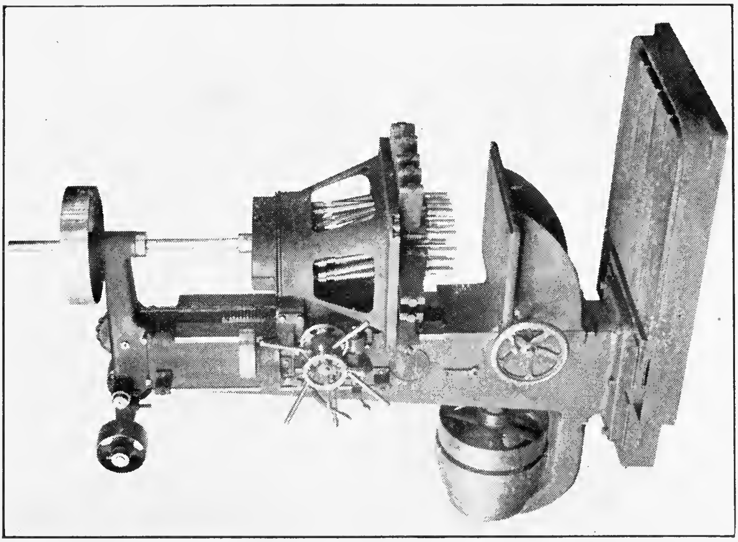


Fig. 188.—Adjustable multiple spindle drilling machine.

The driving of the spindles is by the mechanism shown in Fig. 193. Each spindle carries above its bearing an offset crank, the spindles being driven in common by a crank plate mounted eccentrically in the main spindle. This construction permits the spindles to be grouped together more closely than any other, the limiting center distance being two diameters of the drill.

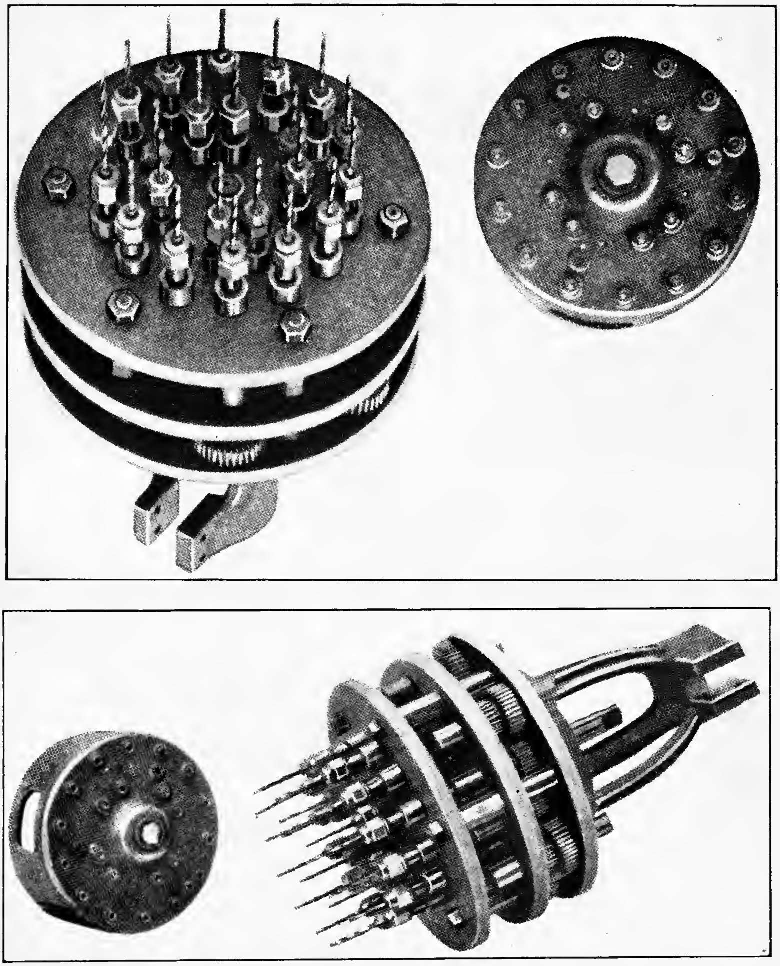


Fig. 189.—Multiple spindle drill heads.

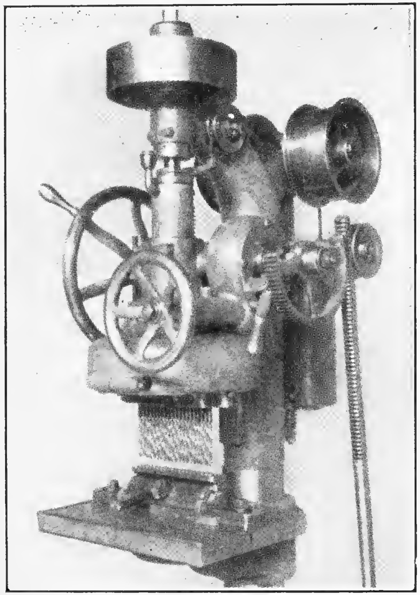


FIG. 190.—Drilling machine fitted with multiple spindle head.

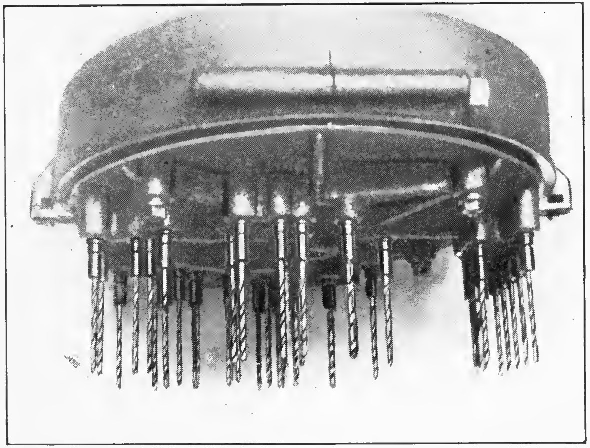


FIG. 191.—Multiple spindle drill head.

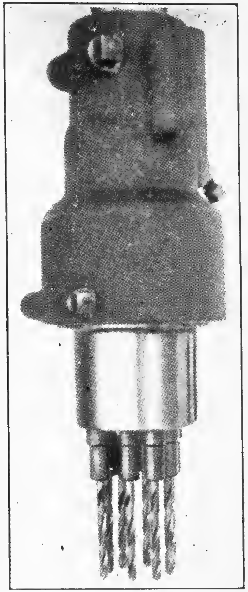


FIG. 192.—Multiple spindle drill head.

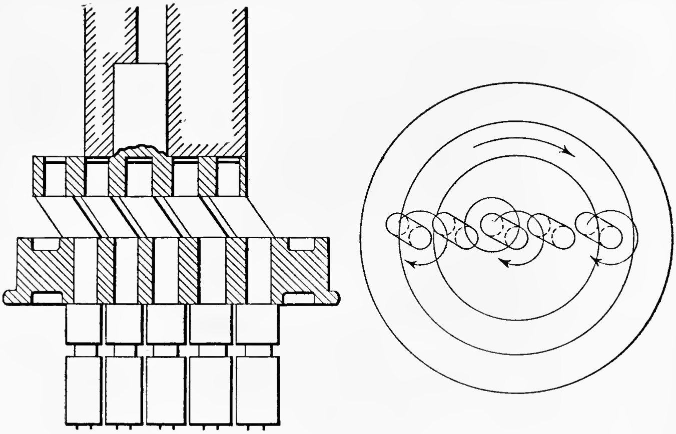


FIG. 193.—Method of driving multiple spindle drill heads.

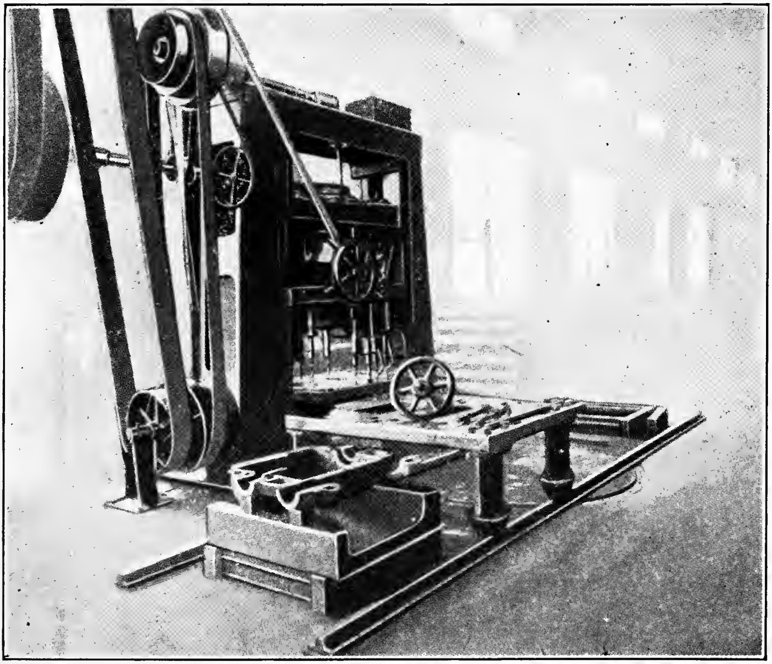


FIG. 194.—An example of highly organized multiple spindle drilling.

A highly organized piece of multiple-spindle drilling from the works of the Westinghouse Electric and Manufacturing Company is shown in Fig. 194. The work in progress is the drilling of one side of a shell of an electric railway motor. The scheme is to provide two jigs, one of which is loaded with work while the other is under the drilling machine in action, and then, in addition to this, to provide means for the quick interchange of the two jigs. A suitable track and turntable will be seen, a short piece of track, not seen, extending underneath the drilling machine and at right angles to the track shown. The jigs are fitted with wheels suitably flanged for the track. From a pile of undrilled castings in the foreground the operator loads the jig, provisions for doing which quickly are provided as shown. Meanwhile a preceding casting has been drilled under the machine. When finished it is run out on the turntable which is turned through ninety degrees and the jig and its work are run off to the rear where the jig is unloaded. The previously loaded jig is then run on the turntable and under the machine, when the other jig is run back to the loading position and loaded, this sequence of operations going on indefinitely.

LAYING OUT MACHINES FOR SPACING HOLES

The accurate laying out of holes in jigs is a subject on which a book could be written. It is, perhaps, the master operation of the tool room and a great many methods of doing it have been devised.

A superior method of doing this is by the use of a special machine, for this purpose only, from the works of the Burrough's Adding Machine Company, shown in Fig. 195. The machine is by the Sigourney Tool Company from designs by the Burrough's Company. The work table is arranged similarly to that of a knee-type milling machine with the addition that it has fitted to the work table, in such positions as to read in two directions at right angles from one another, two finely graduated scales which are provided with verniers. With this construction the adjustment of the table may be made with great accuracy and convenience, the convenience being increased by the fact that both scales and verniers are adjustable endwise in order that the

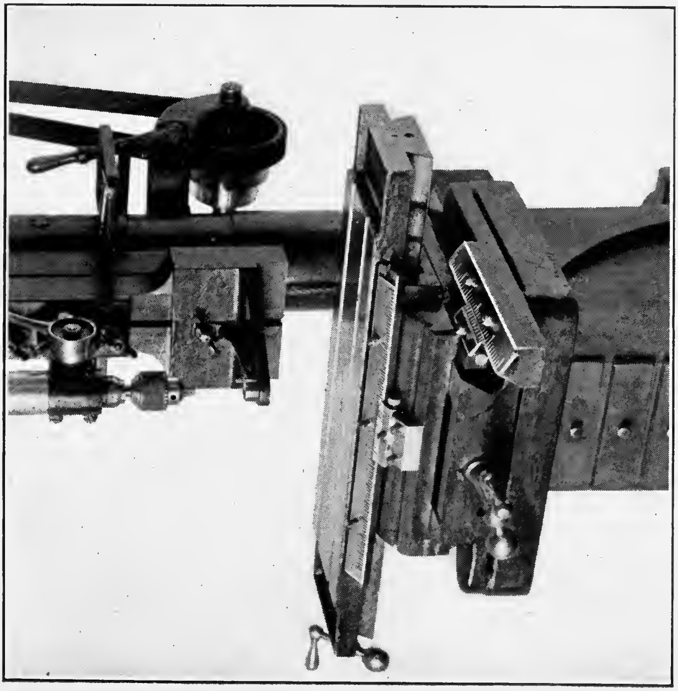


Fig. 195.—Small tool room laying out machine.

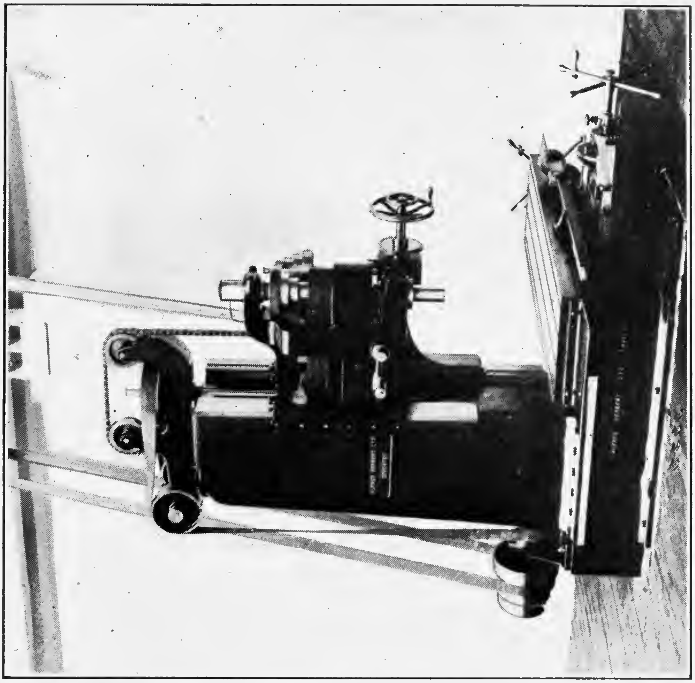
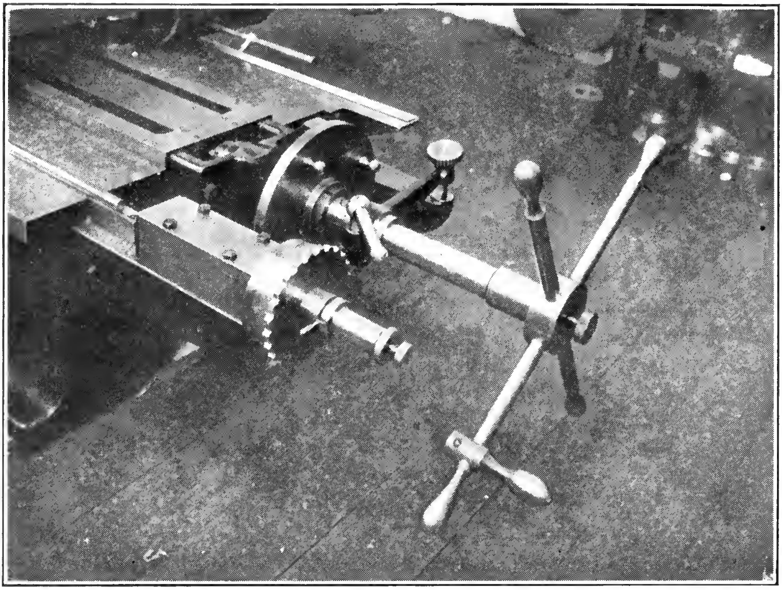


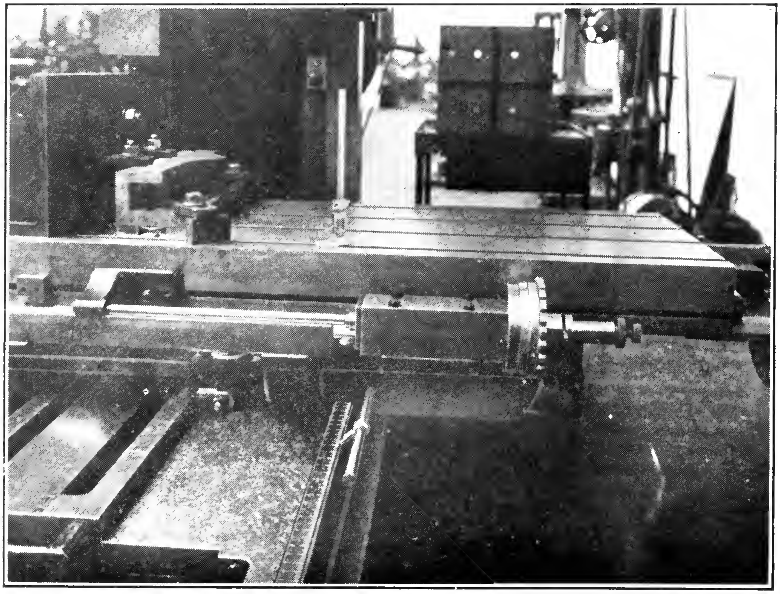
Fig. 196.—Large tool room laying out machine.

work may be begun with the first reading at the zero or, more frequently, at an even inch of the scale. To prevent the sidewise crawling tendency of the drill on the surface of the work, it is guided by a bush inserted in an arm which projects from the machine frame and since, because of the clearance with which they are provided, twist drills cannot be made to fit jig holes with precision, the hole, after being drilled, is reamed with a rose reamer having a ground shank which accurately fits a second bush in the same arm. The machine is fitted with a complete assortment of bushes and reamers which are kept in the cabinet below it.

The largest and finest example of this method of attacking the jig-making problem with which the author is acquainted is shown in Figs. 196–198, from the (British) firm Alfred Herbert, Limited. The general principle of the machine does not differ from the one just shown, although it will be seen to have much greater capacity, the longitudinal traverse being sixty and the transverse traverse thirty inches. The method of measuring the distances between holes is, however, entirely different and capable of much greater accuracy, being based on the use of end measure rods, micrometer screws and gravity drop pieces, these last being similar to the drop piece described in connection with the Pratt and Whitney measuring machine. These features are used for the fine adjustment only. While the traverse screws are not depended upon for final settings, they are fitted with graduated dials for the coarse adjustments and, to save the counting of their revolutions, graduated scales are provided for both longitudinal and transverse movements.

Referring to Fig. 197, the pilot wheel by which the transverse adjusting screw is manipulated is plainly seen. Beyond it, near the base, is its graduated dial, beyond which, on the bed, is the scale. In the foreground is the micrometer dial and in front of it the gravity drop piece, while beyond it on the base is the end-measure rod. The corresponding parts for the longitudinal adjustment are shown in Fig. 198. As the moving parts are heavy a more sensitive adjustment than that of the pilot wheels is necessary, the provision for this being most clearly shown in Fig. 197. It consists of a lever which, while





FIGS. 197 and 198.—Details of large tool room laying out machine.

usually free from, may be clamped to the traverse screw. The lever is provided with an adjusting screw at its end which bears on a fixed abutment. With the lever clamped to the main screw, the adjusting screw will obviously give very fine adjustments.

The table feed and adjusting screws of high-class milling machines are made to a high degree of precision and are fitted with micrometer dials whereby readings to thousandths are obtained. With the work clamped to the work table and a boring tool placed in the spindle, the lengthwise, transverse and elevating screws provide means for measuring the spaces between holes in a manner analogous to those used with these laying-out machines. This plan is often used but is not to be recommended unless the milling machine is new. Accurate screws are provided in these machines because customers expect them and not because it is a suitable place for such screws, for it is not. Their use as feed screws under the pressure due to the cut leads to wear which is greatest where the screws are most used, that is near their centers of length. Consequently, whatever their accuracy when new they do not long retain it.

The appropriate construction would embody the division of functions which appears in these laying-out machines, in both of which the moving of the parts and the measurement of the movements are entirely distinct and hence wear of the screws has no effect on the accuracy of the readings. The Herbert machine is unnecessarily refined for commercial milling machines but there seems to be no reason why the Burroughs construction is not applicable to such machines.

BASE LINE DRAWINGS

Drawings for work to be made on machines of this type are laid out on the base line plan. Were the dimensions between holes given as is common on construction drawings, the practice would necessitate a large amount of addition and subtraction of fractional dimensions in order to obtain the readings of the scales, a process which would not only consume time but would be productive of errors. These objections are overcome by the base line drawings in which the locations of all the holes are laid out as coordinates from base lines. An example of this kind of drawing is shown in Fig. 199. The locations of the holes are always the true readings of the scales so far as the fractions are concerned, although the whole inches frequently differ in accordance with the location of the zeros of the scales. In some cases the base lines are external to the piece of work while in others, as in the present case, the base lines pass through the center of one of the principal holes. This hole being made first and the scale and vernier adjusted to read zero or an even inch, the locating of the other holes becomes a simple matter.

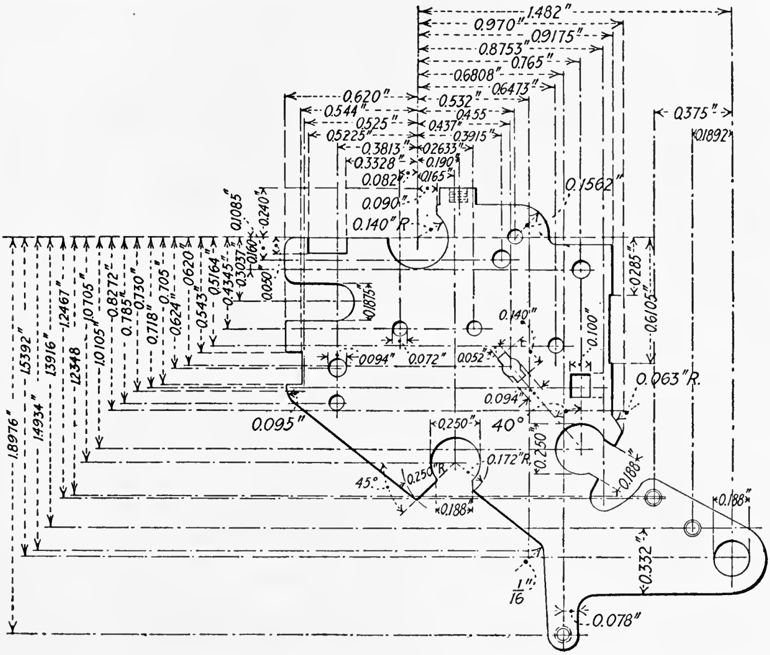


FIG. 199.—Base line drawing for use with laying out machines.

OTHER METHODS OF SPACING HOLES

These machines provide the most obvious and the quickest method of locating holes with accuracy and their cost would be justified in a large number of shops. Nevertheless they are seldom found and other methods, of which many have been developed by the tool makers, must be resorted to. An extremely accurate and satisfactory method has already been shown in connection with the Johansson gages, Fig. 106, and the same plan is obviously applicable and is frequently used with plug and other forms of gages as indicated in Fig. 200, in which the discs are of such diameters as to shift the piece of work by such amounts as will bring the centers of the desired holes in line with the lathe spindle. In these cases, as, indeed, in most others, the holes are finished with a single pointed lathe boring tool which assures perfect alignment of the holes with the lathe spindle. By this plan, the work being swung in the lathe, the size of the pieces which can be treated is limited by the capacity of the lathe.

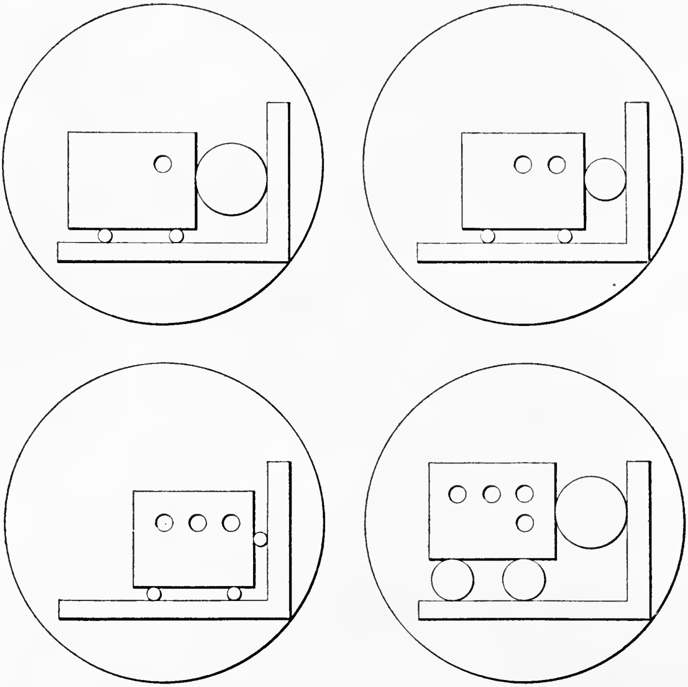


Fig. 200.—Gage method of accurately spacing holes.

A method which, for the highest class of work, has, perhaps, found larger use than any other, is the New England button method which, while slow, is capable of results of the highest degree of accuracy. This method is shown in Figs. 201–203.

The process involves the preliminary positioning of a series of *buttons* at the exact locations where the jig holes are required. The buttons are small cylinders of hardened steel of exactly the same diameter with holes through them endwise and with them go small cap screws of a diameter somewhat less than that of the holes through the buttons.

The jig having been planed, the tool maker lays out the holes as accurately as may be with scale and dividers and drills and taps holes for the button holding cap screws. The buttons are then lightly secured in their approximate positions as shown in Fig. 201 and, using a parallel strip and micrometer as in Fig. 202, they are adjusted to the exact position desired. The jig is then strapped to a lathe face plate as in Fig. 203 and carefully positioned until the tool maker's indicator stands still as the lathe revolves, showing the button to be exactly in line with the lathe spindle. The button is then removed and the hole is enlarged to the required size by a boring tool held in the tool post. The jig is then shifted on the face plate to bring the other buttons successively in line with the spindle when, the holes being bored, they are obviously accurately spaced.

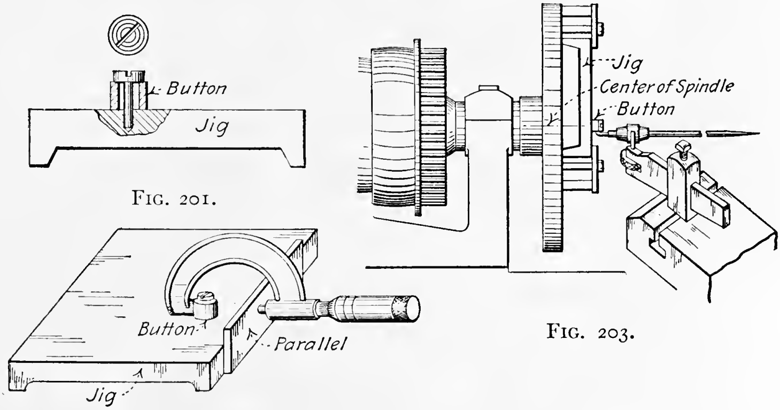


FIG. 201.

FIG. 203.

FIG. 202.

The button method of spacing holes.

As with the gage method the pieces which can be handled in this way are limited in size by the capacity of the lathe and in such cases the button method may be applied to the milling machine as indicated in Fig. 204. The indicator is here mounted in the spindle of the milling machine and the jig plate is adjusted by means of the milling machine table screws until the indicator index stands still when the spindle is revolved. This button is then removed, a boring tool is substituted for the indicator and the hole is bored—the process being repeated in succession for the remaining buttons.

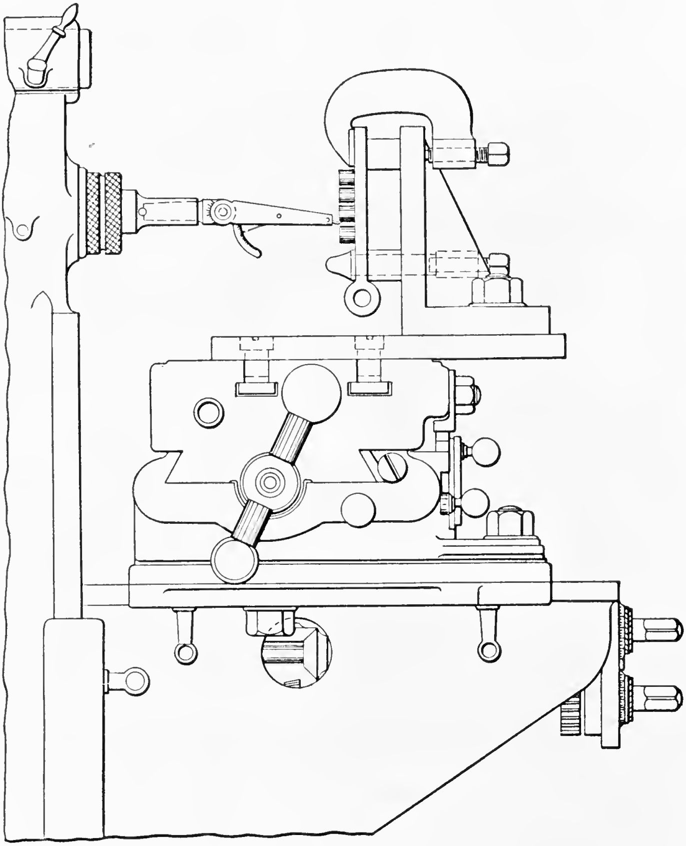


Fig. 204.—Use of the button method on milling machines.

Twist drills cannot be depended upon for making the holes, because milling machines have no provision for preventing their crawling sidewise, which they have a tendency to do. A hole is therefore drilled somewhat smaller than the final size and is then enlarged by a boring tool constructed on the principle of Fig. 205. The action is precisely the same as that of a lathe boring tool except that the tool, instead of the work, revolves, and a hole in true alignment with the machine spindle is the result. Set screws *a*, *b* serve to adjust the tool to the cut.

Another method, commonly called the disc method, is shown in one application in Figs. 206–208. Holes are required spaced as in Fig. 206. It is easy to calculate and to make three discs of diameters such that, located concentrically with the desired holes, they will be mutually tangent to one another as shown in Fig. 207. The discs are made with a recess at their centers and are lightly secured to the jig plate, using shellac for light work and solder for heavier work. The jig plate with the attached discs is swung in the lathe and adjusted in position until, when the lathe spindle is turned, the center of one of the discs stands still as shown by the indicator of Fig. 208. The disc is then removed with a light tap of the hammer, the hole is bored as in the button method and the process is

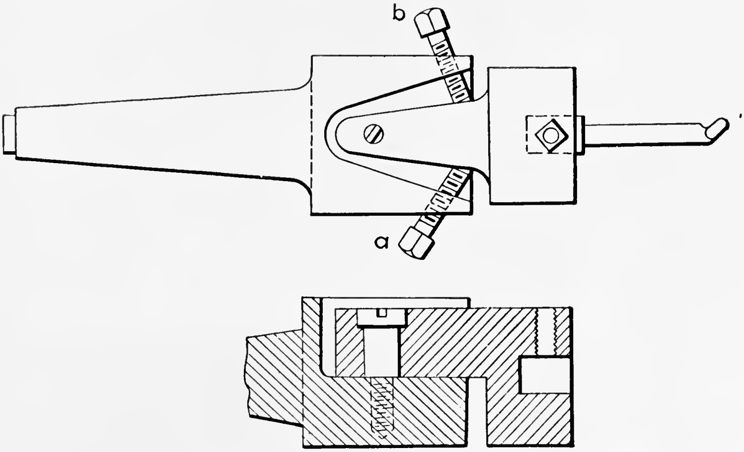


Fig. 205.—Revolving boring tool.

repeated with the other discs. This method is modified according to circumstances. Usually the holes are not grouped in convenient sets of three and in such cases they can only be partially located by the discs. Cases of this sort occur in connection with groups of gears. In such a case the diameters of the discs are made equal to the pitch diameters of the gears and, when placed in contact, they insure the proper distances between centers, but, usually, the other elements of their locations must be determined in some other manner.

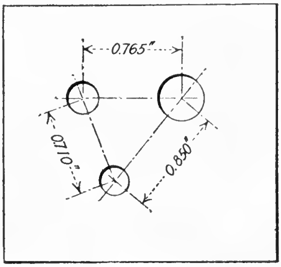


FIG. 206

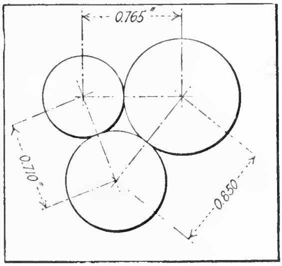


FIG. 207.

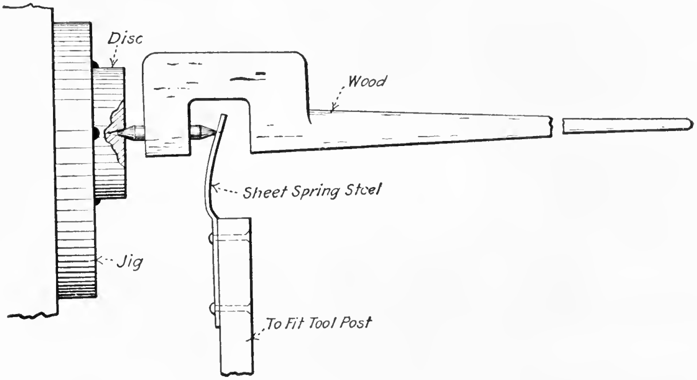


FIG. 208.
Disc method of accurately spacing holes.

THE MASTER PLATE

A feature of jig work which comes in as an industry grows in magnitude is the master plate, which is a sort of reference gage for the jig-hole locations. The necessity for the master plate arises from several causes, one of which is the necessity for duplicate jigs in cases where the required number of parts cannot be made with a single jig. Such duplicate jigs are, frequently, not made at the same time—duplicate and triplicate jigs being made later than the first one as the necessity for them arises. Under the master-plate method the careful laying out of the holes is done on the plate once for all and exact identity of the different jigs is insured.

Another condition that sometimes makes the master plate desirable will be understood by considering the front and back plates of a clock or watch. Obviously the locations of the bearings for the two ends of the shafts must correspond and, both being made from the same master plate, this is assured. The side frames of printing presses illustrate the same conditions on a much larger scale and these conditions are not infrequent.

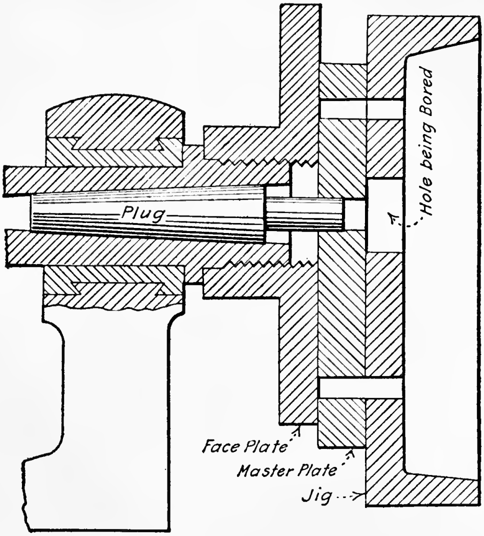


FIG. 209.—Transferring hole locations from a master plate to a jig.

The master plate is a simple flat plate of cast iron with holes located as in the jig to which it belongs. Unlike the jig holes, however, those in the master plate are of a diameter having no relation to those in the work and, moreover, in the same plate they are all of the same diameter. As they are subject to but little wear they are frequently not bushed.

With the holes properly located in the master plate, the boring of the jig holes becomes a simple matter of transfer from the master plate. The method of doing this is indicated in the sketch, Fig. 209. A plug with its shank turned to fit the taper hole in the lathe spindle has a projecting end of the same diameter as the holes in the master plate. The master plate and jig plate being dowelled together, they are mounted in the lathe with the projecting end of the plug entering one of the holes in the master plate. The jig hole is then bored to its required size and both plates are shifted to another position on the lathe face plate—the plug entering another hole in the master plate.

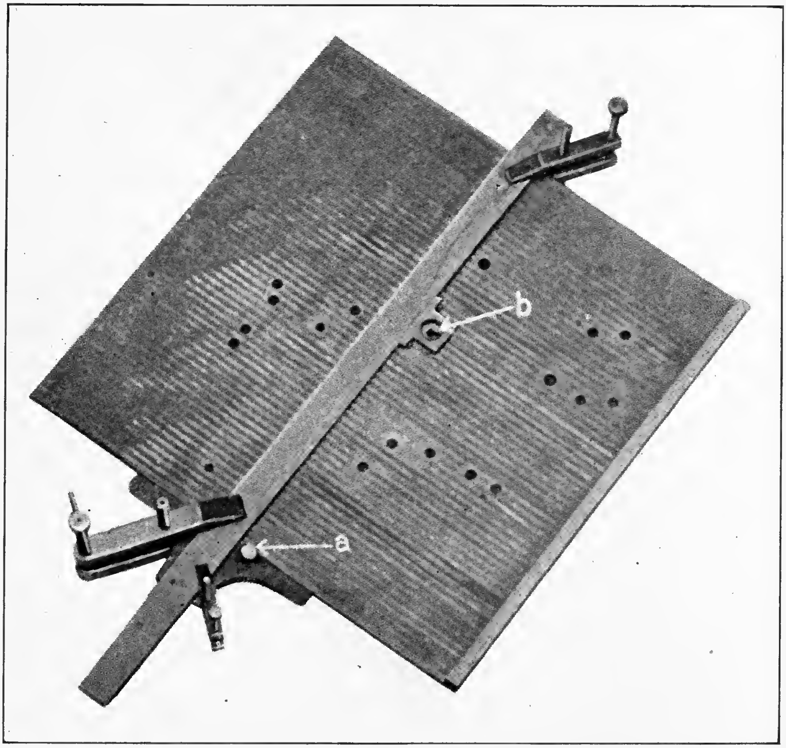


Fig. 210.—Locating holes in a master plate.

The corresponding jig hole is then bored and so on for the others. As many jigs of a kind as needed may obviously be made in this way with positive uniformity in the locations of their holes.

The locations of the master-plate holes may obviously be determined by the methods already shown for locating jig holes when master plates are not used. The simple forms of master plates, however, permit other methods to be used, one of which, from the factory of the National Cash Register Company, is shown in Fig. 210. Clamped to the master plate is a steel T square which, however, differs from an ordinary T square in that the blade is not attached to the head but may be adjusted lengthwise of itself and clamped in any location, squareness being assured by a raised ledge on the head against which the blade rests. The head of the square carries a pin *a* of known diameter and at known distances from the edges of the head and blade. The lower side of the blade carries a socket *b* with a hole through it, the center of the hole being at precisely the same distance below the edge of the blade as that of the pin *a*. A plug, not shown, is provided of two diameters, one end fitting the hole in the socket *b* and the other equal in diameter to the pin *a*. With this plug placed in the socket, the blade may be adjusted by means of a micrometer spanning the two pins until the center of the socket is at the required distance from the pin *a* when the blade is clamped to the head. Next the entire square is adjusted on the plate until the center of the hole in the socket is at the required distance from the lower edge of the plate—allowance being made in both measurements for the radii of the plugs. The square being located, it is clamped to the plate, the plug is removed and replaced by a bush suitable for guiding a drill which drills the hole. A second slightly larger bush is then substituted for the first and the hole is finished with a rose reamer fitting the second bush.

CHAPTER XI

MILLING

Early development of the milling machine—Advantages of the constant-speed drive as applied to milling machines—Vertical-spindle milling machines—Types of milling cutters—Uses of the milling machine—The rotary planer—The profiling machine—The cam-cutting machine—The screw-thread milling machine—The milling cutter grinder.

THE LINCOLN MILLING MACHINE

As already mentioned, the milling machine was invented by Eli Whitney. It appeared in a variety of forms during the succeeding years but "the beginning of practice it has endured" is found in the Lincoln milling machine designed by F. A. Pratt, when a foreman at the Phoenix Iron Works of Hartford, Conn., during the early fifties of the last century. These works were then owned by G. S. Lincoln and Company, from whom the machine takes its name.

This machine is one of the most striking early examples of advanced design, as no machine tool has suffered so little change during the succeeding years. This is shown by Figs. 211 and 212 of which the former is reproduced from an old advertising circular and represents one of Mr. Whitney's earliest machines while the latter, from the Pratt and Whitney Company, shows the machine as made to-day. Except that the latter is heavier and provided with an oil pan, it is scarcely changed from the original. No form of milling machine has been made in such large numbers. It is suited to plain work only and it lacks the facility of adjustment of other types but for work produced in large lots, in which the adjustment, once made, is retained for a long period, it is excellently adapted, while its simplicity and low cost give it a large field of application.

The most recent development in connection with this general type of machine is found in the semi-automatic machine of

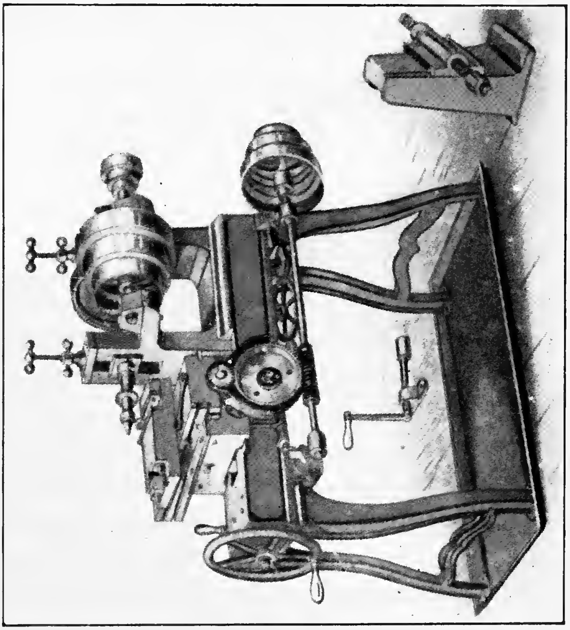


Fig. 211.—The original Lincoln milling machine.

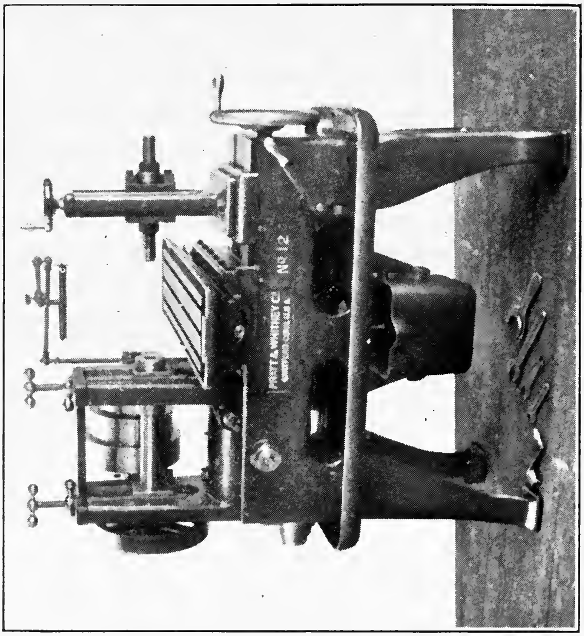


Fig. 212.—Modern Lincoln milling machine.

the Cincinnati Milling Machine Company, Fig. 213. The machine shown has two milling heads for simultaneous operations on both sides of the work, although single-head machines are also made. The distinguishing characteristic of the machine is the provision of an automatic quick return to the work table and also an automatic increase in the forward movement for the numerous cases in which the surface to be machined is not continuous.

A double set of dogs for controlling the feed mechanism is attached to the side of the work table as shown. The work being properly chucked and one of the hand levers tripped, the table goes quickly forward at a rate of one hundred inches per minute until the first surface to be machined reaches the cutter, when the motion automatically slows down to whatever feed has been selected, and this continues until one of the faces is milled. As soon as the cutter has passed this first face, the table automatically speeds up again to one hundred

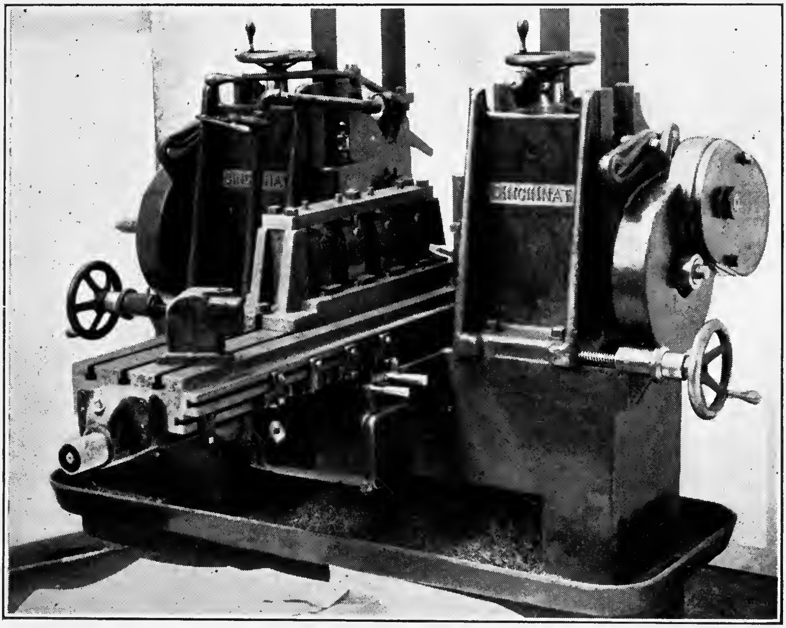


Fig. 213.—Semi-automatic plain milling machine.

inches per minute, until the second face of the work reaches the cutter. Again the work proceeds at the feed selected, and passing the second face, speeds up again, then slows down again when the third face is reached, feeds along the third face, and when this is completed, the table automatically returns at a rate of one hundred inches per minute to the starting point.

As many dogs as may be necessary for the work may be placed on the table. All the dogs in the upper slot serve to slow down from the quick forward motion, bringing the table movement to the proper feed rate. The left-hand dog in the lower T-slot serves to trip for the table return, and the right-hand dog in the lower T-slot to trip for the stopping of the table, while the other dogs in the lower T-slot are so arranged as to speed the table up from the feed rate to the quick traverse rate.

Because of these movements these machines are semi-automatic, that is, the movements of the table are entirely automatic, but the chucking of the work and the starting and stopping of the machine are normally controlled by the operator.

As these pages are in process of preparation for publication information arrives regarding a remarkable increase of output by the Cincinnati Milling Machine Company. By increasing the quantity of cooling liquid far beyond what is customary, it has been found possible to increase cutter speeds and feeds to from eight to twelve times the prevailing figures. Test cuts in mild machinery steel have been made at peripheral cutting speeds of 800 feet and under feeds of 112 inches per minute.

THE UNIVERSAL MILLING MACHINE

The first radical departure from the Lincoln machine was the invention of the Universal milling machine by J. R. Brown (he of Brown and Sharpe) in 1862. The object of the swiveled table and the spiral feeding mechanism which gives the machine its universal feature, was originally the making of twist drills which supplied the impelling motive of the design. The first universal milling machine has been recovered and is preserved by the Brown and Sharpe Manufacturing Com-

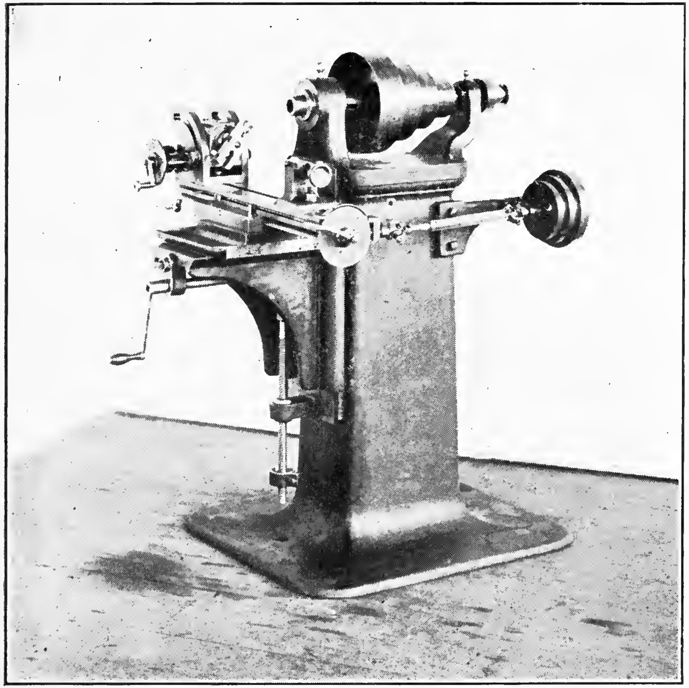


FIG. 214.—The original universal milling machine.

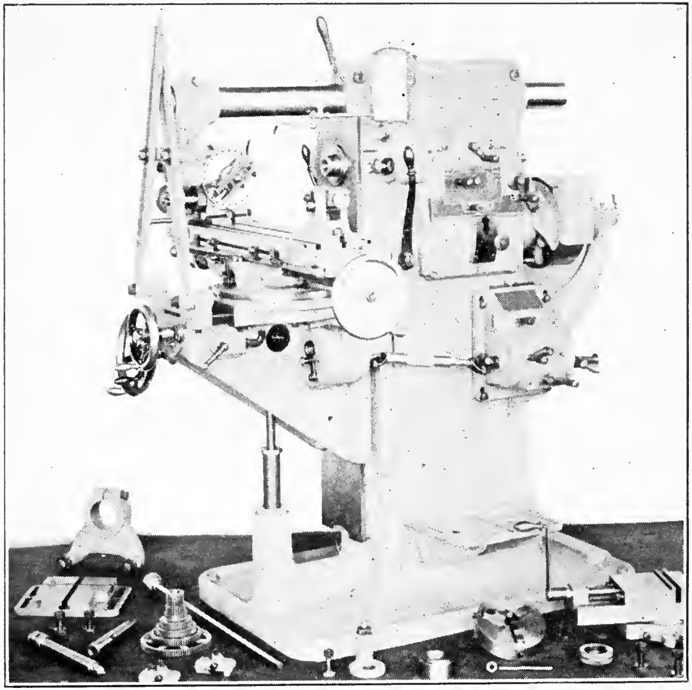


FIG. 215.—Modern universal milling machine.

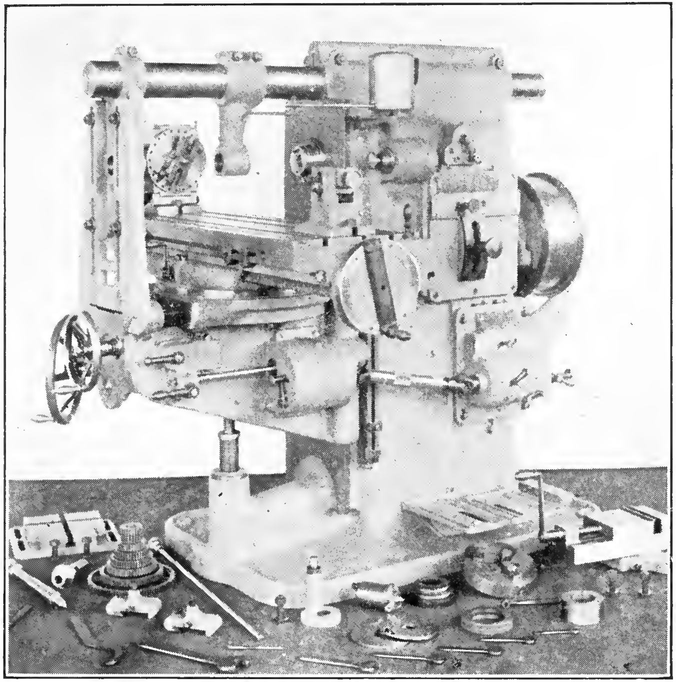


FIG. 216.—Large universal milling machine.

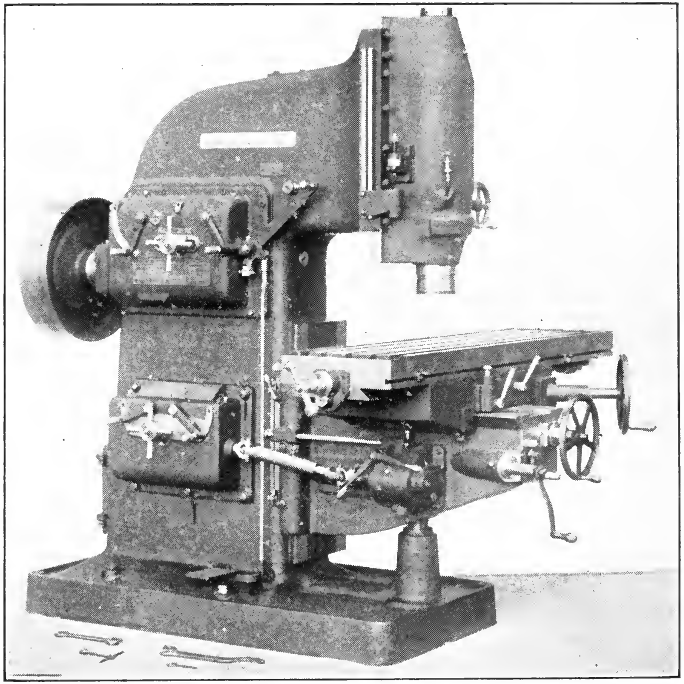


FIG. 217.—Vertical spindle milling machine.

pany, and of it Fig. 214 is an illustration from a photograph, while Fig. 215 is a small modern machine by the same makers and serves to show the long look into the future taken by Mr. Brown in the original design. The new machine has a constant-speed pulley in place of the cone-pulley drive and a geared instead of a belt feed. Nevertheless, in the essentials, which make it a universal milling machine, it is scarcely changed and this is equally true of similar machines by other makers.

The cone-pulley drive has not disappeared from the milling machine, but for heavy manufacturing the constant-speed pulley has largely displaced it. A second Brown and Sharpe machine of much larger size is shown in Fig. 216.

In this, as with other constant-speed drive machines, the different speeds are obtained by a nest of gears within the machine which are thrown into various combinations by the projecting hand levers.

THE CONSTANT-SPEED PULLEY DRIVE AS APPLIED TO MILLING MACHINES

In its application to the milling machine the constant-speed pulley drive has an advantage that does not appear in other applications. The fact that the first motion shaft runs at a constant speed makes it possible to lay out a series of feeds having definite values in inches per minute and to mark such values on the index plate which gives the positions of the hand levers which control the acting combinations of the feed gears. With the cone-pulley drive this is impossible, since the rates of feed change with each change in the speed of the first motion shaft as determined by the position of the cone-pulley belt. With the cone-pulley drive, the rates of feed can only be given in thousandths of an inch per revolution of the spindle—a far less convenient arrangement than the former one.

Increased convenience is, however, but a small part of the advantage. With the thousandths per revolution feed, a rate of feed suitable for a large cutter at a suitable low speed is increased in proportion to the cutter speed when a small cutter is substituted for the large one, this increase being so great that the feed becomes useless for small cutters. Again, a rate suitable for a small cutter is reduced in proportion to the cutter speed when a large cutter is substituted for the small one, this reduction being so great that this feed, in turn, becomes useless for large cutters. Whatever the size of the cutter, only a small part of the entire feed range is applicable to it. With the inches per minute feed, on the contrary, the entire range is applicable to large cutters and, except for their inadequate strength for heavy cuts, to the small ones also. In order to provide the same number of feeds which are available for cutters of different sizes a much greater total number of feeds must therefore be provided with the thousandths per revolution than with the inches per minute plan. As a matter of fact, so great a number is never provided, the result, whatever the size of the cutter, being a restricted choice of feeds.

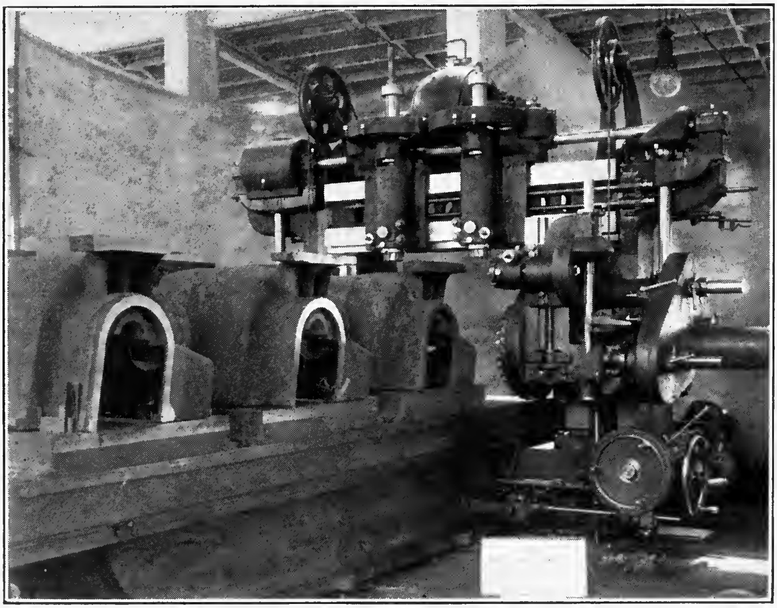


Fig. 218.—Multiple spindle planer type milling machine.

The case is essentially different from that of a lathe, boring or drilling machine. In these latter the number of cutting tools or points does not, usually, increase with the diameter of the work and a feed in fractions of an inch per turn expresses the duty imposed on the cutting points. With the milling cutter, on the other hand, the number of teeth increases with the diameter and a feed per turn tells nothing about the duty on the teeth until divided by their number, nor about the rate at which the work is being done until multiplied by the revolutions of the cutter per minute. A feed expressed in inches per minute, on the other hand, expresses reasonably well the duty on the teeth and, at the same time, the exact rate at which the work is being done.

For certain classes of milling-machine work the vertical spindle has advantages over the horizontal and a rugged vertical-spindle machine by the Cincinnati Milling Machine Company is shown in Fig. 217. Machines of the planer type have also reached large development, such a machine by the Ingersoll Milling Machine Company being shown in Fig. 218.

CUTTERS OF MILLING MACHINES

The cutters used on milling machines are of a great variety of types, of which a few are shown in Figs. 219–230. Of these the most common is the slabbing cutter, Fig. 219, the illustration showing a cutter with nicked teeth, which construction is advantageous by reason of its action in breaking up the chips. Fig. 220 shows a side or face cutter with which the chief cutting action is on the side and Fig. 221 a pair of interlocking side cutters intended for cutting grooves or slots. The object of the construction is to preserve the width of the slot after the cutter is ground, in which case the cutters are packed apart by paper washers placed between them—the interlocking teeth still giving a satisfactory cutting action. Fig. 222 shows a face cutter with inserted teeth. There are many methods of securing teeth in position of which but one is shown. The object of the construction is to save cost by the use of cheaper material on the body of large cutters. With such a construction new teeth may be inserted when the old ones are worn out and the use of the body be continued indefinitely. Fig. 223 shows an end mill and Fig. 224 a T slot cutter, the two being used in succession and in the order named for the production of the

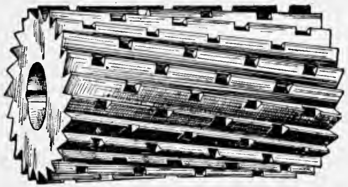


FIG. 219.

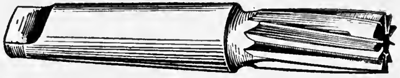


FIG. 223.

FIG. 224.

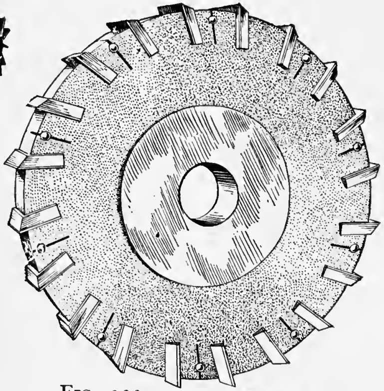


FIG. 222

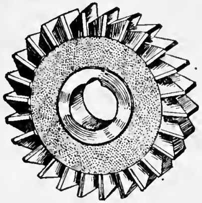


FIG. 220.

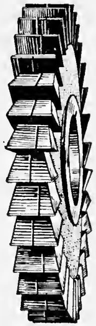


FIG. 221.

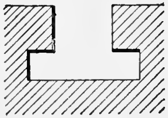


FIG. 225.

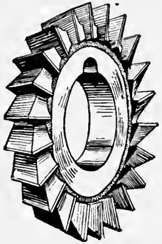


FIG. 226.

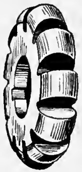


FIG. 228.

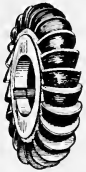


FIG. 227.

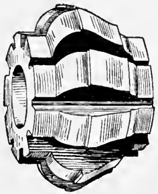


FIG 229.

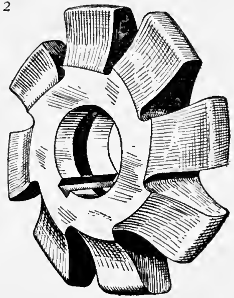


FIG. 230.

Types of milling cutters.

numerous T slots which appear in machine tools of which a section is shown in Fig. 225. Fig. 226 is an angle cutter.

Fig. 227 is a shape cutter and Figs. 228–230 are formed cutters, these two types being quite distinct. The shape cutter, like all the others previously shown, is sharpened when dull by grinding the edges of the teeth—a process which is obviously applicable to simple forms only. The formed cutter[1] on the other hand is ground on the faces of the teeth radial with the cutter. The cutter being made of proper outline this outline is not changed in the act of grinding which may be repeated until the cutter is worn out. These formed cutters are frequently made for the production of pieces of complex outline as shown in Fig. 229, for which purpose they are very suitable. Their largest use and the use for which, judging by the illustration of the patent, they were originally invented by Mr. Brown, was the production of cut gears, a cutter for this purpose being shown in Fig. 230.

TYPICAL MILLING-MACHINE OPERATIONS

The operations of which the milling machine is capable are so numerous as to almost defy enumeration. A few of them are shown in Figs. 231–239, from the Cincinnati Milling Machine Company. Simple surfacing by cylindrical or slabbing cutters is too common an operation to need illustrating. Surfacing by a face cutter on a vertical-spindle machine is shown in Fig. 231, while Fig. 232 shows a development by which the work of the cutter is made continuous. A supplementary rotary work table is mounted on the regular table and carries a number of special chucks for holding the work—in this case domestic sad irons. The operator removes the finished pieces and substitutes rough castings for them without stopping the movement of the rotary table. A case of gang milling with a combination of slabbing and face mills is shown in Fig. 233, while Fig. 234 shows the production of a curved outline by a formed cutter. A costly outfit for the wholesale production of racks is shown in Fig. 235—costly not only because of the number of cutters involved but also because the pitch of

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[1] The formed cutter was invented by J. R. Brown.

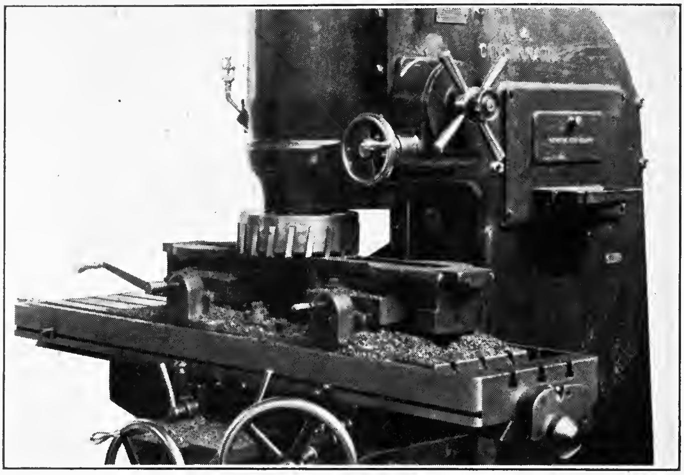


FIG. 231.—Face milling on a vertical spindle machine.

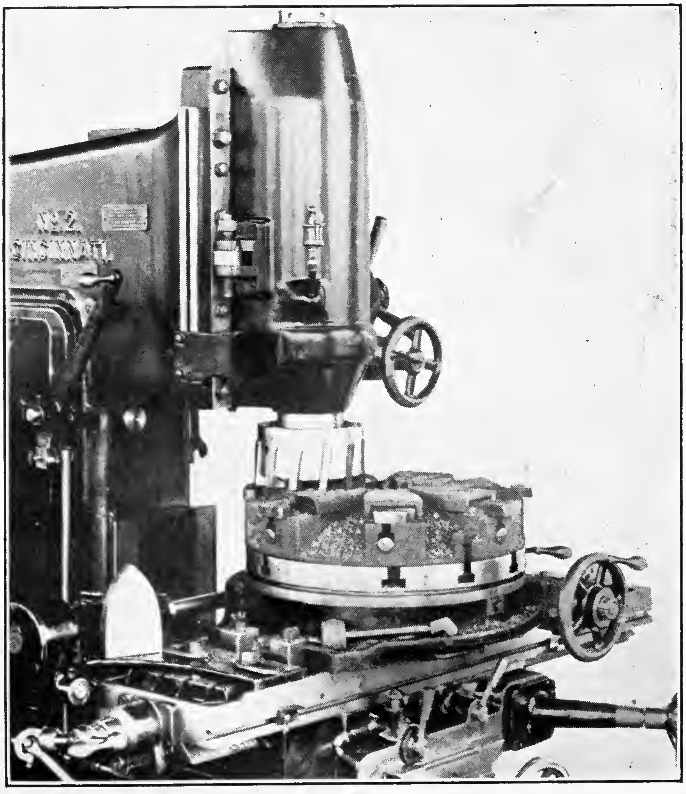


FIG. 232.—Continuous face milling.

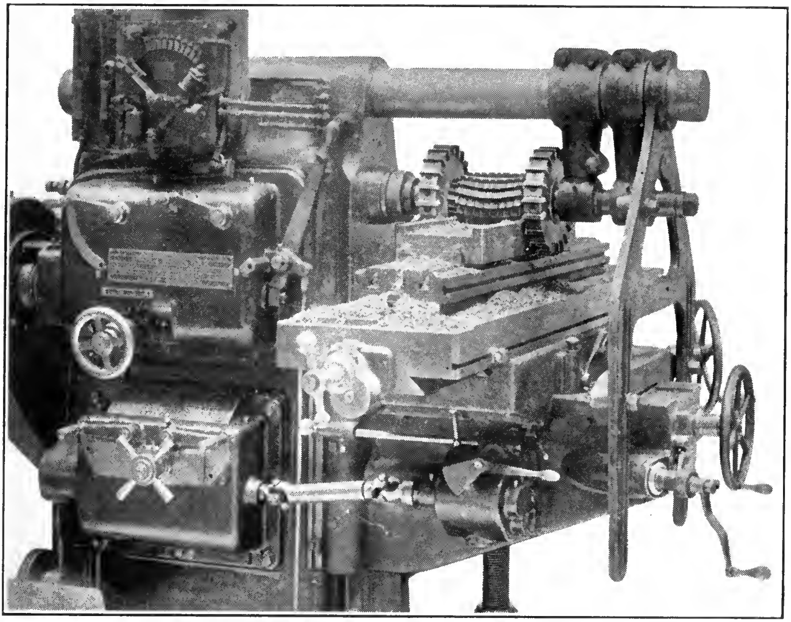


FIG. 233.—Gang milling.

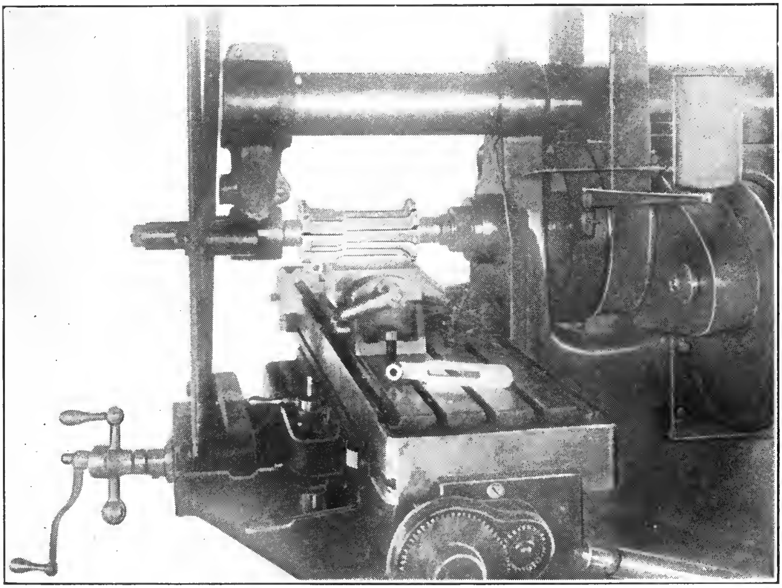


FIG. 234.—Formed cutter milling.

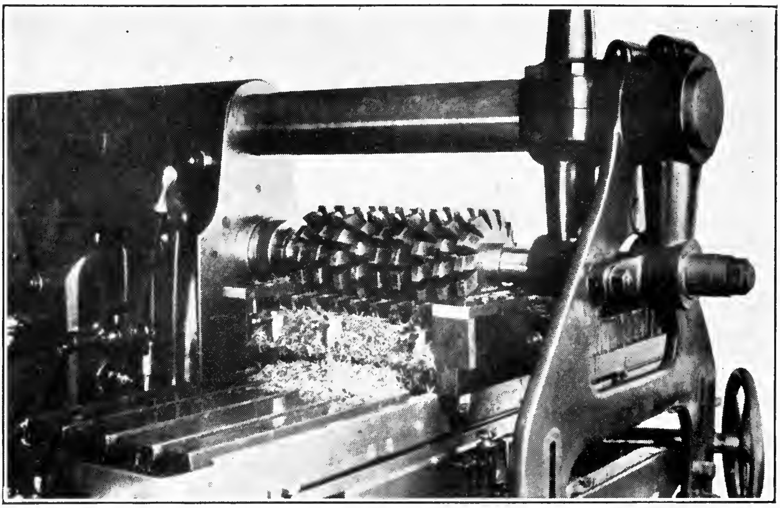


FIG. 235.—Rack cutting by a gang of cutters.

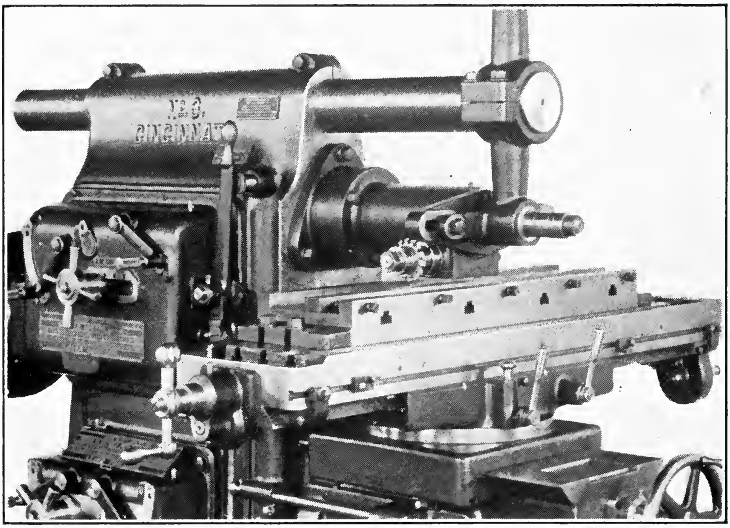


FIG. 236.—Rack cutting by a single cutter.

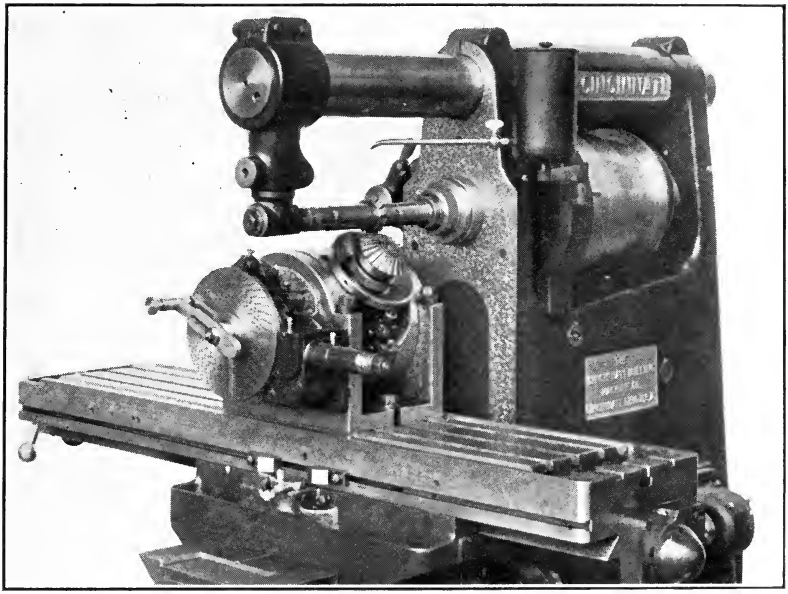


FIG. 237.—Cutting bevel gears.

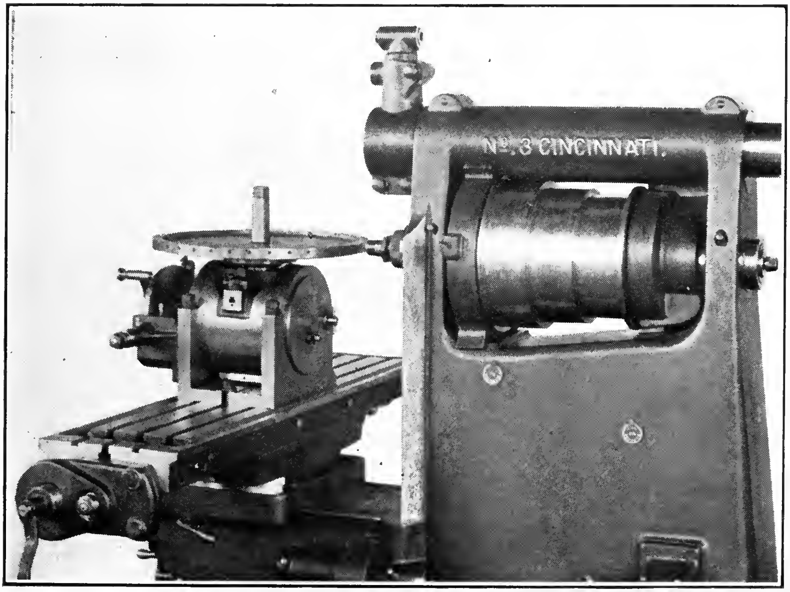


FIG. 238.—Drilling an index plate.

the rack teeth is determined by the spacing of the cutters, which must be of high accuracy. A more common method of cutting racks is shown in Fig. 236, in which, by a right-angle fixture, the cutter spindle is located in line with the longitudinal movement of the work table. The spacing of the teeth is effected by suitably indexing the movement of the table. Fig. 237 shows the dividing head as set up for cutting bevel gears, the spacing of the teeth being by the index plate, while another use of the dividing head and index plate for the production of a drilled index plate is shown in Fig. 238. Finally, the universal function of the machine in the production of a helical-toothed slabbing cutter is shown in Fig. 239. The work table is swiveled to the angle of the cutter while, by the change gears shown, the work revolves as the work is fed forward. The spacing of the teeth is by the index plate.

THE ROTARY PLANER

The inserted tooth face mill frequently assumes large diameters and is used for producing large flat surfaces by means of machines which, although true milling machines, are commonly called rotary planers. A striking development of this machine is seen in Fig. 240 from the works of the Allis Chalmers Company. The machines, of which there are two, by the Niles-Bement-Pond Company, are identical except that they are of opposite hand. They are mounted upon a cast-iron floor plate with adjusting screws connecting them at each end, one of which, with the threads covered, appears in the immediate foreground. The object of these screws is to adjust the distance between the machines and maintain them parallel. The cutter heads are of ten feet diameter and are driven by motors of forty horse power, giving a capacity for cuts in cast iron one and one-quarter inches deep with one and one-half inches per minute feed for roughing cuts. For finishing cuts feeds as high as four inches per minute are used. The work in progress is the simultaneous surfacing of the top and bottom faces of a large Corliss engine cylinder.

Another application of rotary planers, in this case by the Newton Machine Tool Works, and from the same works as

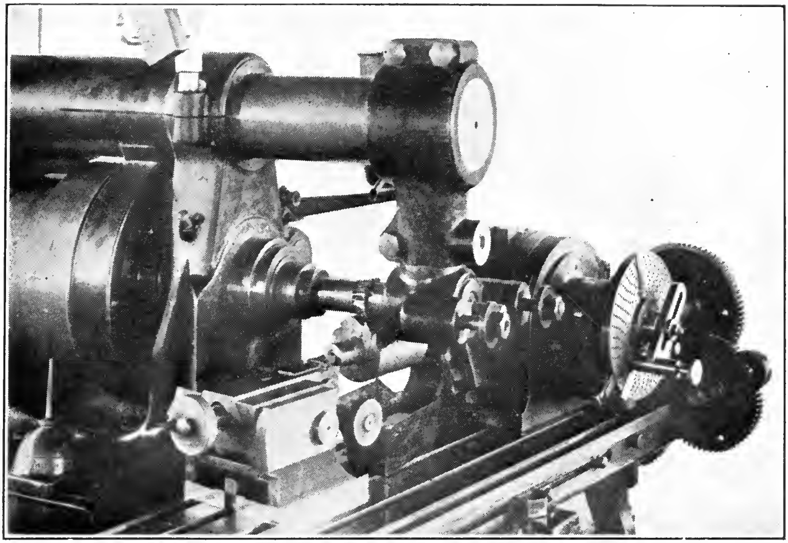


FIG. 239.—Helical milling.

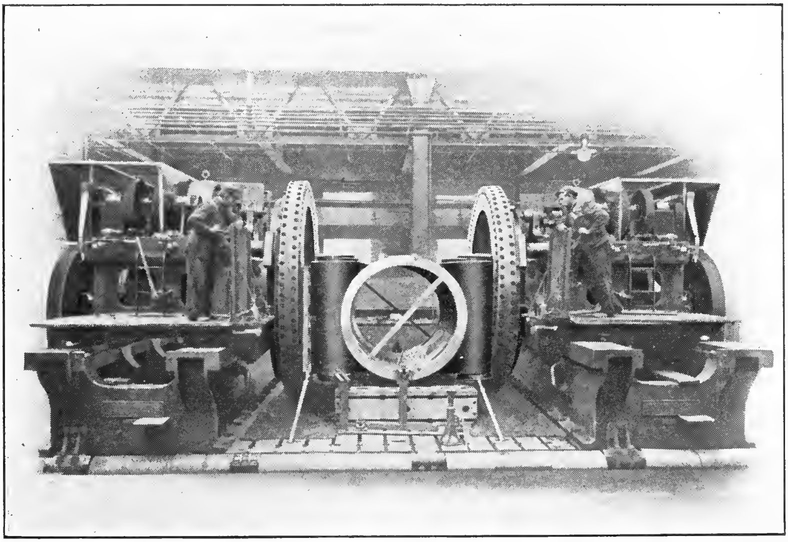
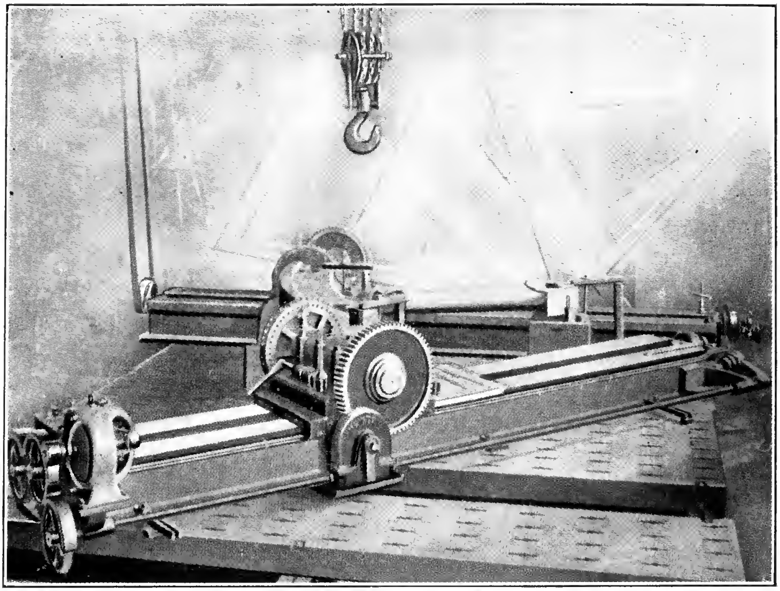
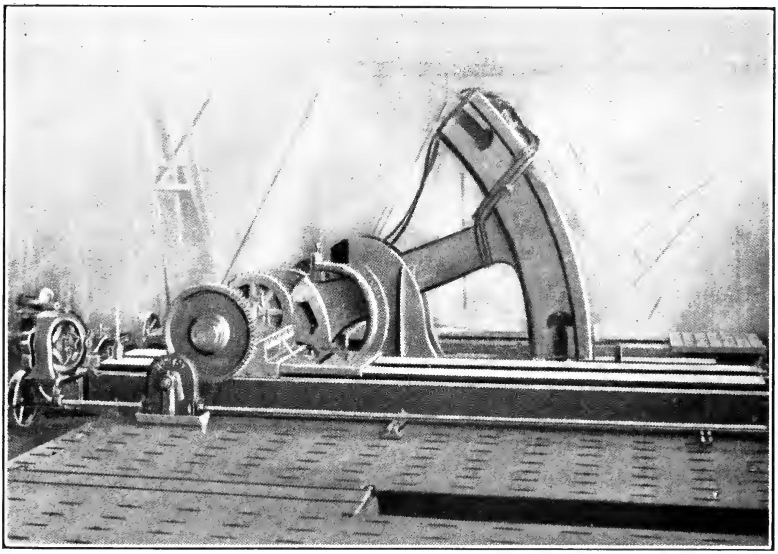


FIG. 240.—Twin rotary planers.





FIGS. 241 and 242.—Machining fly wheel segments.

the last one, is shown in Figs. 241 and 242. The work here in progress is the machining of the segments of large fly wheels, the operations being of a character which fairly entitles them to be called manufacturing methods. Two rotary planers are employed which, as before, are mounted on a cast-iron floor plate. In Fig. 241 the two machines are so located as to machine the ends of the segments to the angle required. Various angles are scribed upon the floor plate by means of which the adjustable machine may be quickly located for wheels with any number of segments. With the radial joints complete, the machines are adjusted parallel with one another and at suitable distances apart to machine the two sides of the hub ends of the segments as shown in Fig. 242.

THE PROFILING MACHINE

A modification of the milling machine which was developed at Hartford and Springfield during the Civil War period is the profiling machine which is best introduced by showing the work to which it is adapted. This work is still chiefly the parts of small arms as shown in Fig. 243, the curved outlines of the pieces shown being made by the profiling machine. The work done will be seen to be that which, in former days, was done with the filing jig shown in Fig. 2.

A profiling machine by the Pratt and Whitney Company is shown in Fig. 244. The milling head is fitted to slide on the overhead cross rail on which its movements are controlled by the hand crank at the right through the gearing shown. A second hand crank at the left gives movement to the work table at right angles to the movement of the cutter spindle. In use, the blank piece of work is secured to the work table and alongside of it a model or former, shaped to the exact outline of the desired piece. At each side of the cutter spindle, at its lower end, is a clamp socket. In one or the other of these, according to convenience, a pin of the exact diameter of the milling cutter is inserted. When at work the operator, by suitable manipulation of the cranks, brings the pin into contact with the former and then traverses it around the former, follow-

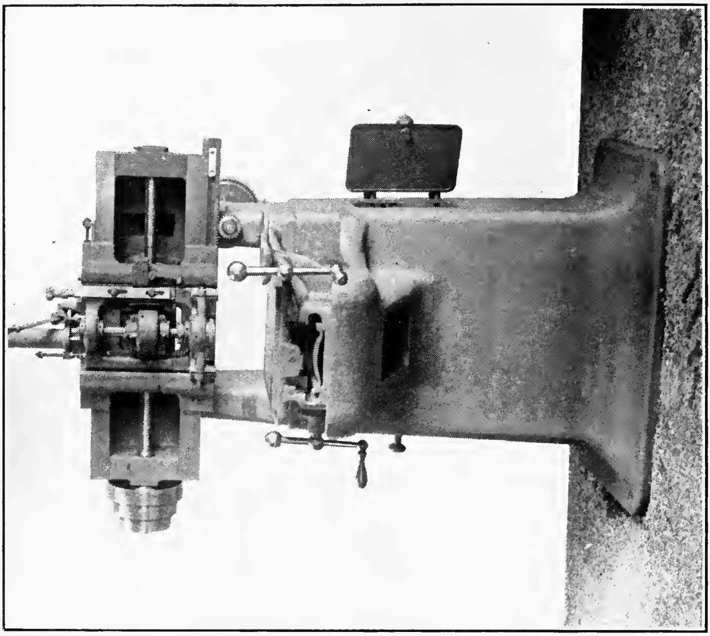


FIG. 244.—Profiling machine.

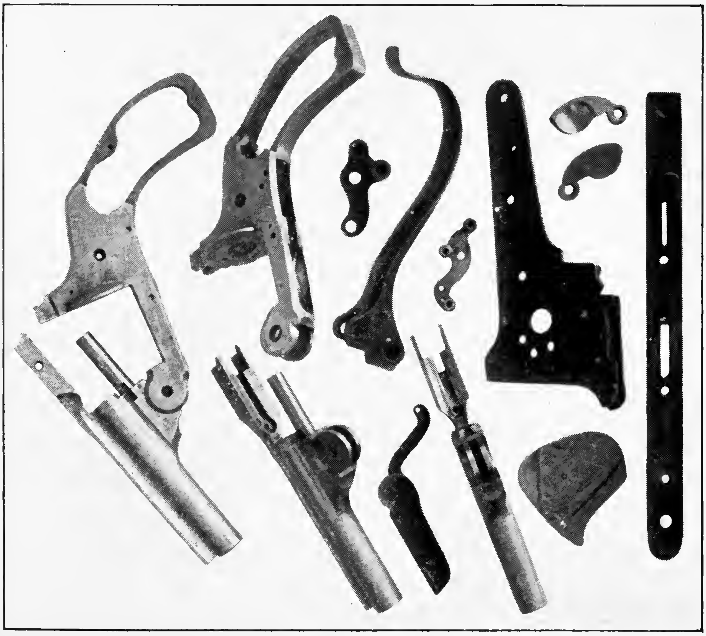


FIG. 243.—Work of the profiling machine.

ing its profile exactly, the result being to reproduce the same profile in the piece of work

THE CAM-CUTTING MACHINE

Another important modification of the milling machine is found in the cam-cutting machine of which an example, by the Garvin Machine Company, is shown in Figs. 245 and 246. Cams are of two chief varieties, called respectively *face* and *drum* cams. The face cam is a disc with an irregular shaped groove in its face for the production of a movement radial to itself. The drum cam, on the other hand, is a cylinder with a groove in its periphery for producing a movement parallel with its center line. The machine is shown as set up for the production of both kinds of cams. As in the profiling machine, the milling cutter which produces the groove in the cam is guided by a former having the exact outlined desired but, unlike the profiling machine, the feed is by power and not by hand.

Referring to Fig. 245, which shows the machine in the act of producing a face cam, two worm-driven turntables will be seen mounted on the work table. The turntables revolve slowly and in unison, the one in the background carrying the hand-made former[1] while the one in the foreground carries the cam blank in process of being cut. A long ribbed head slides upon the cross rail and carries, depending from it, a pin at its farther and a milling cutter at its nearer end—the pin and cutter being of the same diameter. The pin is held in contact with the former by a weight suspended from a chain which, passing over a sheave, is attached to the sliding head. As the cam and former revolve under the action of the feed, the action of the former is to reciprocate the sliding head in accordance with its own profile, and this movement being transmitted to the milling cutter, the latter reproduces in the cam blank the outline of the former.

Fig. 246 shows the machine as arranged for the production of drum cams. The cam-holding turntable of the previous illustration has been removed and in its place is a suitable drum-

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[1] The methods by which cams are laid out, including the making of the formers, may be found in the author's Handbook for Machine Designers and Draftsmen.

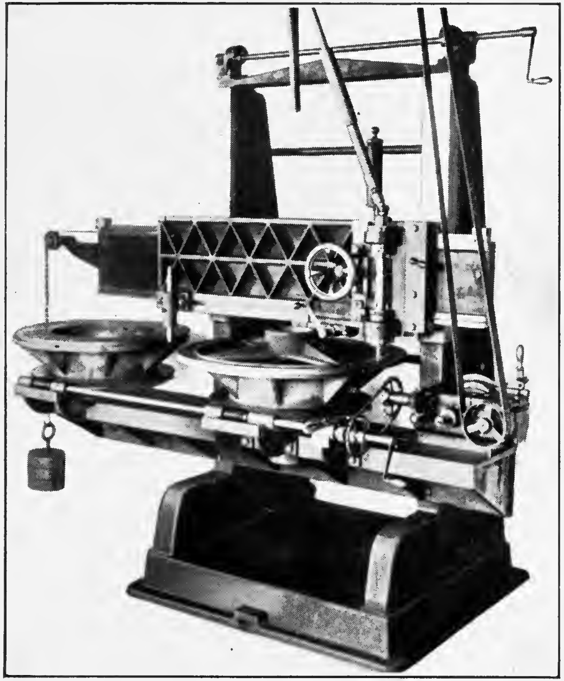

FIG. 245.—Milling a face cam.

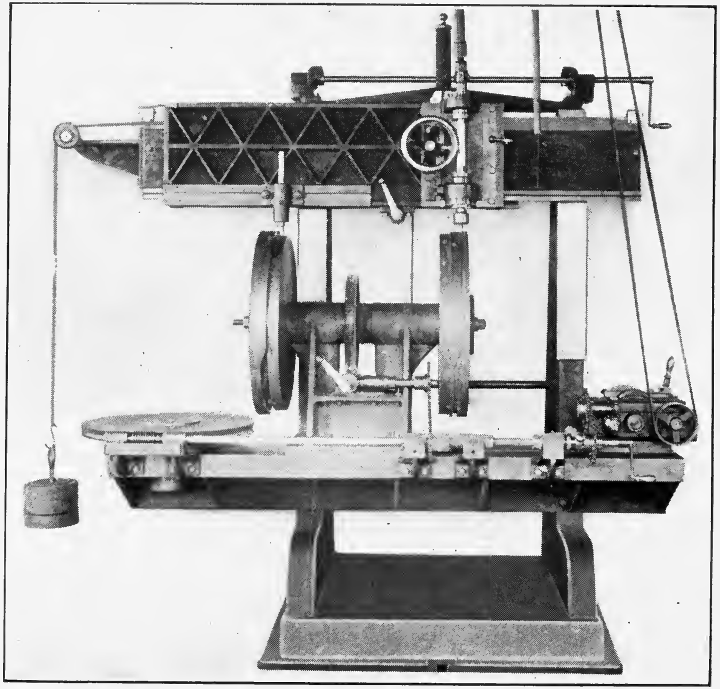

FIG. 246.—Milling a drum cam.

cam fixture. As before, the former is at the left and the cam blank at the right. The two being mounted on the same arbor, the action as this arbor revolves is to reproduce the outline of the former in the cam blank essentially as in the previous illustration.

THE SCREW-THREAD MILLING MACHINE

Another modification of the milling machine is found in the thread or screw milling machine, originally developed by the Pratt and Whitney Company, one of whose machines is shown in Fig. 247. This machine may be regarded as a combination of the lathe and the milling machine. Combined with the general form of a lathe, with the construction of a lathe so far as the means for determining the pitch of the screw are concerned, is a milling machine head carrying a milling cutter in place of the usual lathe tool. The cutter head is provided with the necessary adjustment for adapting the angle at which the cutter lies to the helix angle of the thread to be cut.

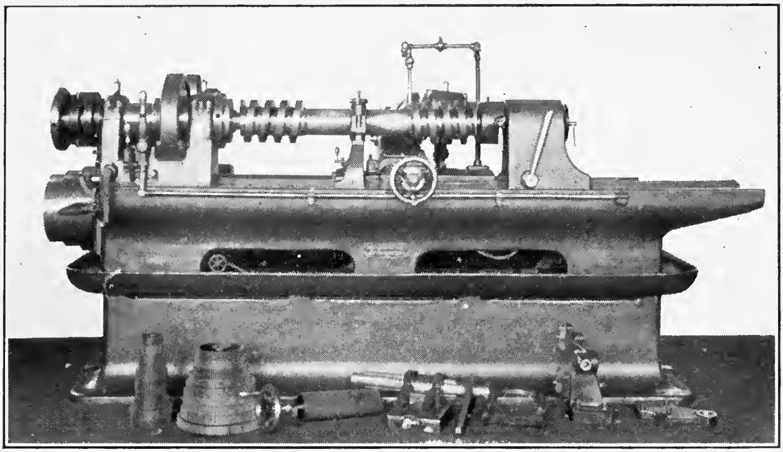

Fig. 247.—Screw thread milling machine.

Still another modification is the hobbing machine of which an example, by the Newton Machine Tool Works, has already been shown in Fig. 43.

Both hobbing and cam cutting are frequently done by extemporized apparatus, the former frequently mounted on a lathe and the latter on a milling machine, but no examples of such equipments are here shown.

THE MILLING CUTTER GRINDER

An essential adjunct of the milling machine is the cutter grinder of which one, by the Brown and Sharpe Manufacturing Company, is shown in Fig. 248. This particular machine is also adapted to the doing of small tool-room work of the character done on the universal grinding machine, but the features which here engage us are those by which milling cutters and similar tools are sharpened. To accommodate the various types of cutters, extreme flexibility of adjustment in a cutter grinder is essential. Without the exception of even the universal milling machine, the center grinder is capable of doing a greater variety of work than any other machine tool and of these it is only possible to show a few of the more representative examples.

Fig. 248 gives a comprehensive view of the working parts of the machine and also shows it adjusted for sharpening an angle cutter, the angle being obtained by the swivel of the work table. The angle is read from the divided arc on the front of the table. Fig. 249 shows the grinding of the most common of all milling cutters—the slabbing cutter. A cupped grinding wheel is used, thereby grinding flat faces to the teeth instead of concave faces which would be the result of grinding with a common disc wheel. A feature of the machine which is less clearly shown in some of the views than others, but which is always present, is the spring tooth rest shown clearly in Fig. 249, which projects up from below and against which the tooth being ground rests. The cutter is slid endwise on its supporting arbor by the hand, contact with the rest being maintained by gentle pressure and, as each tooth is finished, the cutter is turned to present the next one to the wheel, the spring of the rest enabling it to give way and snap past the teeth.

Figs. 250 and 251 show the adjustments for grinding a face cutter, in one case that for the periphery and in the other for the side, the latter showing also an adjustment of the tool-carrying head which is frequently required for other pieces of

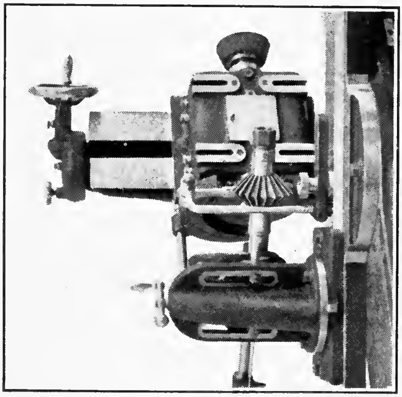

FIG. 248.

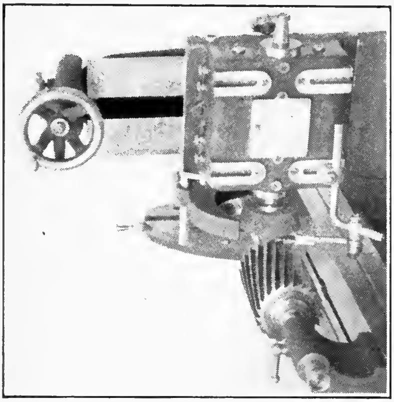

FIG. 249.

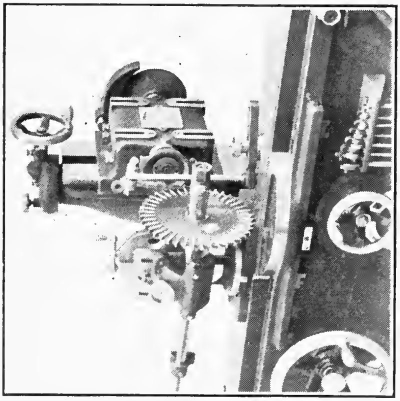

FIG. 250.

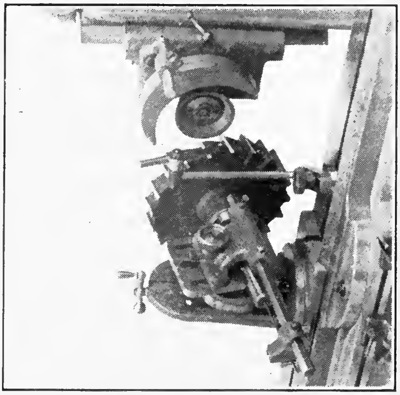

FIG. 251.

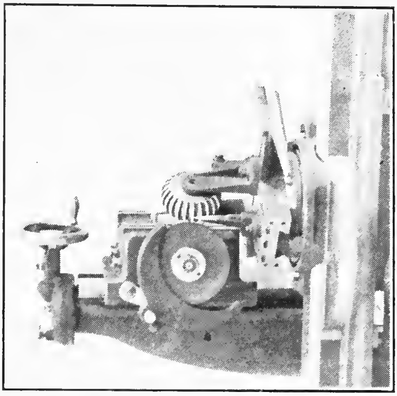

FIG. 252.

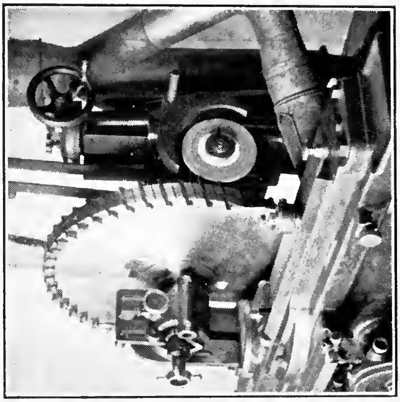

FIG. 253.

work. The tooth rest is also clearly shown in this view. Fig. 252 shows the grinding of a convex shape cutter to a circular profile by means of a swivel attachment provided for that purpose, and Fig. 253 shows the adjustment for grinding large inserted tooth cutters.

CHAPTER XII

GEAR CUTTING

Multiplicity of forms of gear-cutting machines—The advantages of the diametrical pitch system—The three basic systems of gear cutting—Machines embodying these systems—Bevel gear-cutting machines—The octoid system of bevel gear teeth—Gear-molding machines.

VARIETY OF GEAR-CUTTING MACHINES

There is no feature of machine work of greater interest than gear cutting, as there is none to which so great a degree of attention has been directed and with correspondingy fruitful results. There is no other example of a single purpose machine that has been produced in such a bewilderng diversity of forms. It is impossible to give here more than an outline of the leading methods of attacking the gear-cutting problem with sufficient illustrations to show how these methods are embodied in commercial machines. For additional information the reader is referred to the excellent treatise, Gear Cutting Machinery, by Ralph E. Flanders, wherein will be found, with but one or two exceptions, all the machines now made, both American and European.[1]

ADVANTAGES OF THE DIAMETRAL PITCH SYSTEM OF GEARS

The diametral pitch system is at the base of all modern cut gears of moderate size. This system, as already stated, was invented by Bodmer but introduced as a general commercial system by the Brown and Sharpe Manufacturing Company. Coincident, or nearly coincident with this introduction, the Brown and Sharpe Company developed and published in their catalogue a set of simple formulas for the calculation of gears, singly and in pairs. These formulas, which have been copied

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[1] Figs. 254, 257, 259 and 267 are, by permission, reproduced from Mr. Flander's treatise.

into all American mechanical engineer's pocket books, have influenced beyond measure the introduction of the diametral pitch system.

The superior convenience of the diametral pitch system is largely due to the simplicity of these formulas and of the resulting calculations. A series of standard pitches is selected, analogous to the series of pitches of standard screw threads, an indefinite number of intermediate pitches which might be used being discarded, thus making systematized cutter manufacture possible. By thus giving up complete liberty of choice in the matter of the pitch, corresponding liberty of choice of diameters is sacrificed. So far as the pitches themselves are concerned, this gives rise to just as little inconvenience in the case of the gears as in that of screw threads. It does, however, lead to an occasional slight inconvenience in connection with the diameters and center distances. Since a gear must contain a whole number of teeth, it follows that, for any given pitch, only such diameters are possible as will contain an exact whole number of teeth, the diameters for any one pitch varying by a series of steps precisely as the pitches vary. This series of diameters differs, of course, with the pitch.

Thus considering eight pitch—that is a pitch such that the gear contains eight teeth for each inch of its pitch diameter—a gear of sixteen teeth will be of two inches pitch diameter. Similarly, a gear of seventeen teeth will be of two and one-eighth and one of eighteen teeth of two and one-quarter inches pitch diameter, no diameter between these values being possible if gears of eight pitch are to be used. This feature requires attention in the design by giving the gear centers such locations as will provide for the necessary diameters.

Another essential and valuable feature of the diametral pitch system is that the diameters of the gears and the distances between centers are always expressed in even fractions and are never incommensurate. In the circumferential pitch system, since the pitch is commensurate, the circumference is also commensurate, while the diameters and center distances are incommensurate. With the diametral pitch system the reverse is true. The circumferential pitch of gears made on this system is incommensurate as is the circumference, but the diameters and center distances are always commensurate and, while commensurate circumferences have no particular value, commensurate diameters and center distances are sources of many conveniences.

THE SYSTEMS OF GEAR CUTTING

There are three basic systems of gear cutting: (a) the formed tool system; (b) the generating system, of which the hobbing system is a development and, (c) the templet system.

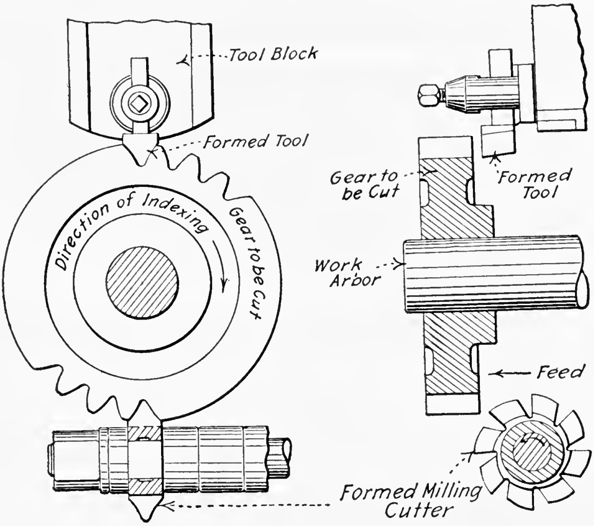

Fig. 254.—Principle of the formed tool system of gear cutting.

Of these the oldest and most widely used is the formed-tool system, of which the principle is illustrated in Fig. 254. The tool, which might be, and sometimes is, a planing tool as shown at the top of the illustration but which, in the vast majority of cases, is a rotary milling cutter as shown at the bottom of the illustration, is accurately formed to the desired profile which it reproduces in the gear. It was for this purpose that the formed cutter which may be sharpened by grinding without changing its form was originally invented.

Machines embodying this principle were first made in England.

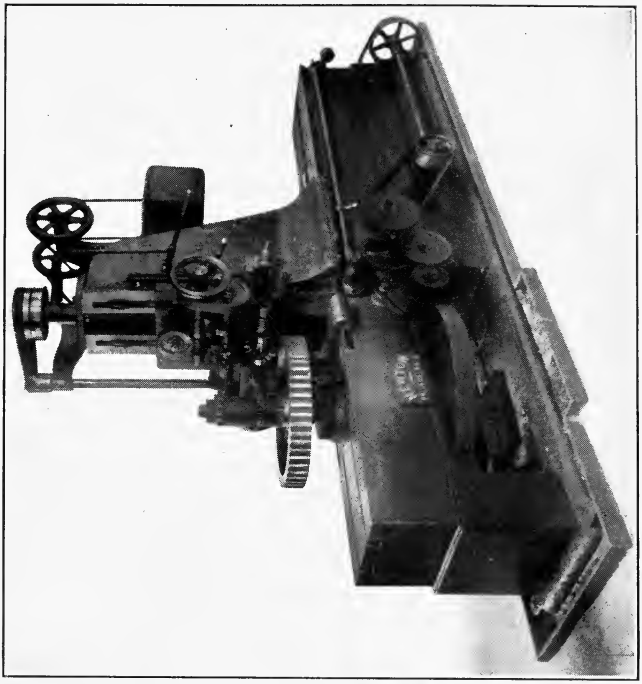

Fig. 256.—Medium size gear cutting machine, formed tool system.

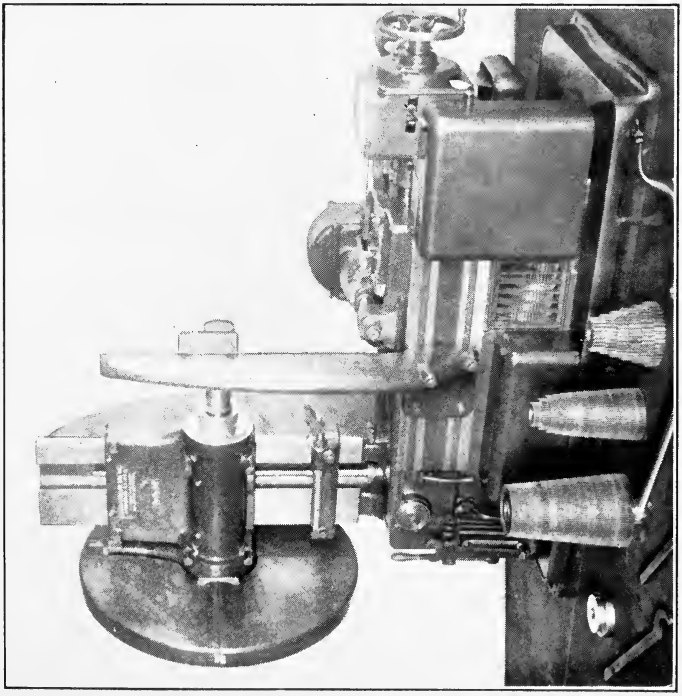

Fig. 255.—Automatic gear cutting machine, formed tool system.

The first to perform their functions automatically, requiring no attention on the part of the operator except to remove a completed gear and supply its place with a fresh blank were made by William Sellers and Company in 1866, some of the machines then made being still in use at the Sellers works. The Sellers machine was ahead of its time and, while some were sold, they were not placed on the general market, the first commercial automatic machine being produced by the Brown and Sharpe Manufacturing Company in 1877. This machine, which has supplied the model for many others, is shown, as now made, in Fig. 255, and were the original machine placed beside it even fewer changes would be found than in the universal milling machine. It is not the author's purpose to go into detailed description of the operation of this or other complex machines, the intention being to point out the principles of the work and the general methods by which the various problems are attacked.

The action is entirely automatic, the feed and return of the cutter and the indexing of the blank from tooth to tooth requiring no attention on the part of the operator who has but to remove the completed gears and supply their place with fresh blanks. For larger work convenience of handling leads to the horizontal instead of the vertical position for the gear in process of being cut. Automatic machines have been made for cutting gears of large size but, usually, such machines are non-automatic, an example, by the Newton Machine Tool Works, being shown in Fig. 256.

For the largest work, gear-cutting machines operate more frequently on the templet principle, an example of this construction appearing on a later page.

THE GENERATING SYSTEM OF GEAR CUTTING

The generating system was invented by Hugo Bilgram who produced his first machine in 1885. This machine was invented for the production of bevel gears for which at that time no satisfactory method of production was available.[1] The system

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[1] A machine for the production of correct bevel gears was exhibited at the Centennial Exposition of 1876 by George H. Corliss. The machine was of large size suitable for the production of mill gearing. It was constructed especially

has now been adapted to the production of spur and spiral gears and the principle is best described in connection with spur gears. At the top in Fig. 257 is a gear of metal while below it is a blank of some plastic material. If the two shafts be connected by gears having their speed ratio equal to that between the pitch diameters of the forming gear and the plastic blank and the two be revolved together, the forming gear will impress into the plastic blank tooth forms which are conjugate

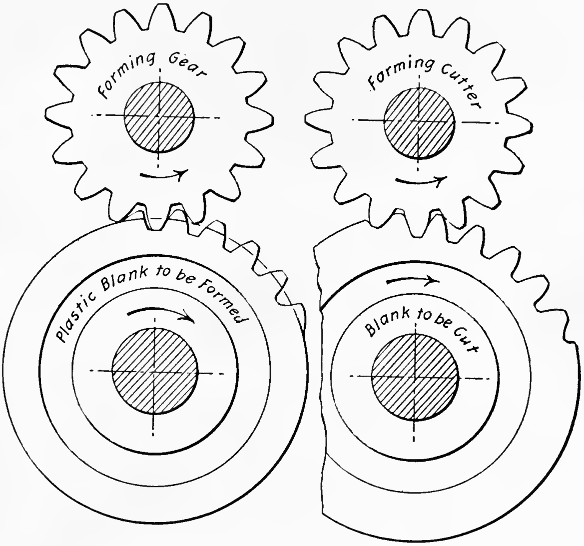

Fig. 257.—Principle of the generating system of gear cutting.

to those of the forming gear and which, if in metal, would form suitable teeth for a gear to mate with the forming gear.

If the forming gear be made of hardened steel with suitable rake and clearance to the teeth, and if it be then reciprocated on its center line as the rotation proceeds, the plastic blank may be replaced by a metallic blank, the teeth of the forming gear acting as cutting tools to generate correct mating gear

to cut the transmission gears of the monumental Corliss engine which supplied power for Machinery Hall of the Exposition and, among engineers, it attracted almost as much attention as the engine. It operated on the templet principle which was subsequently made commercial by the Gleason works, who produced a machine that came into large use.

teeth. It is exactly upon this principle that the Fellows gear shaper operates.

In this system the forming gear cutter might be a rack which would then produce in blanks of various sizes, teeth which are conjugate to those of the rack and to each other. In the involute system the sides of rack teeth are straight, whereas the sides of all gear teeth are curved. A straight-sided tool is an easy thing to originate with a high degree of accuracy and hence, in all applications of the generating system, the straight-sided rack tooth forms at least the starting point. In its original appearance on the Bilgram bevel gear machine the straight-sided rack tooth forms the cutting tool. This is not to be understood as meaning that an actual rack is used in the machine but a cutting tool which represents a single tooth of the rack or, more properly, one side of that tooth because, the spaces between bevel gear teeth being tapered, but one side can be formed at a time.

THE BILGRAM BEVEL GEAR GENERATING MACHINE

Mr. Bilgram's original bevel gear-cutting machine, as it appeared in the *American Machinest* for May 9, 1885, is shown in Fig. 258. The machines now made are fully automatic in their action which the machine shown was not. It is here used in preference to the modern machines, partly because of its historic interest and partly because its comparative simplicity makes its principle of action more apparent.

The straight-sided tool which represents one side of a rack tooth—in the case of bevel gears more properly a crown gear tooth—is mounted upon a ram driven precisely like a shaping machine ram. The gear blank is mounted below the tool upon a suitable arbor supported at its rear end by a conical segment which rolls upon a plane surface below it. The conical segment is a portion of the pitch surface of the gear to be cut, extended to the opposite nappe of the cone, while the plane surface is a portion of the pitch surface of the imaginary crown gear of which the cutting tool represents one side of a tooth. Integrity of the rolling motion without slip is maintained by a pair of steel ribbons, one end of each of which is clamped to the end of the rolling segment and the other end to the opposite end of the stationary plate.

If the segment be rolled upon the plate the gear blank will roll past the cutting tool precisely as though the latter were a crown gear and, with the tool in reciprocating motion, it will cut upon the gear blank a suitably formed tooth side when, the gear blank being indexed for the next tooth and the action repeated, the side of that tooth is formed and so on indefinitely.

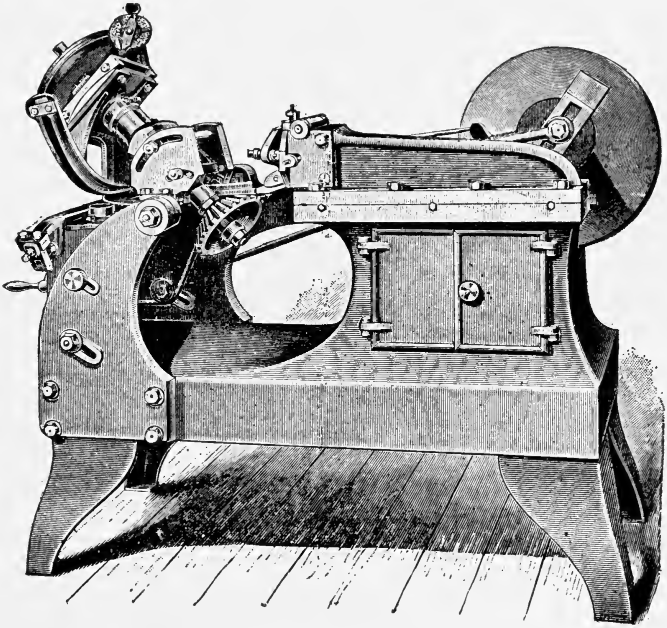

Fig. 258.—The original Bilgram bevel gear cutter, generating system.

The action is, perhaps, more clearly shown in Fig. 259. Were the gear being cut a spur, a complete rack tooth could be used as at *a*, but when cutting a bevel gear the taper of the space between the teeth makes it necessary to use a single-sided tool as at *b*—a second tool symmetrical with the first planing the second side after the first is completed. The teeth are roughed out in a preparatory machine before the generating machine is brought into action.

THE GLEASON BEVEL GEAR GENERATING MACHINE

Consideration of Fig. 259 will show two modifications of the plan of attack. The imaginary rack may be fixed as regards endwise motion, the blank rolling past it as a gear might be rolled in a rack, this being the plan incorporated in the Bilgram machine. On the other hand, the rack may travel endwise with the feed, the gear blank turning upon its center which does not change its position. This latter plan of attack is incorporated in the Gleason machine shown in Figs. 260 and 261.

The gear in process of being cut appears in both views mounted on the horizontal main spindle. Both sides of the ideal crown gear tooth are represented by tools of which there are two, by which construction both sides of a tooth are shaped simultaneously. These tools are mounted and reciprocate in guides on an arm which oscillates about the cone center of the gear blank being cut, this oscillation being obtained by the horizontal yoke and vertical connecting rod shown in Fig. 261. The yoke is secured to the main spindle as shown in Fig. 261 and carries a segment gear shown in the same view, the pitch cone of this segment being identical with that of the gear blank being cut. Mounted on the tool-carrying arm is a second segment gear in mesh with the first, also shown in Fig. 261. The second segment is a segment of a crown gear, its pitch plane (pitch cone having a cone angle of ninety degrees) being identical with that of the ideal crown gear tooth represented by the cutting tools. As the yoke oscillates it turns the gear blank with it while the meshing of the segments compels the tool arm to oscillate and to carry the cutting tools past the blank in the same relation as a crown gear tooth in mesh with a tooth on the blank. The action of the machine is fully automatic.

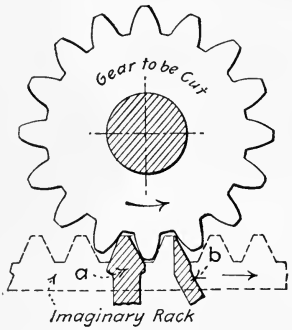

Fig. 259.—Generating gear teeth from a rack tooth.

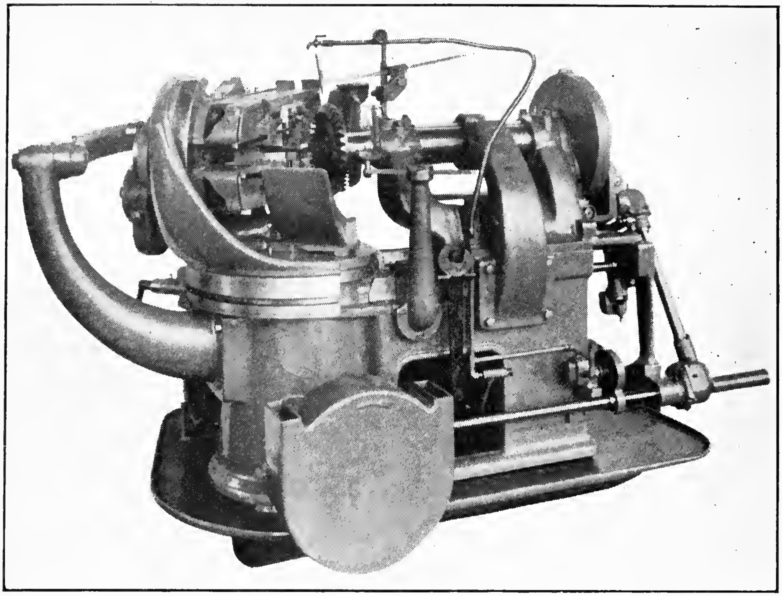

Fig. 260.

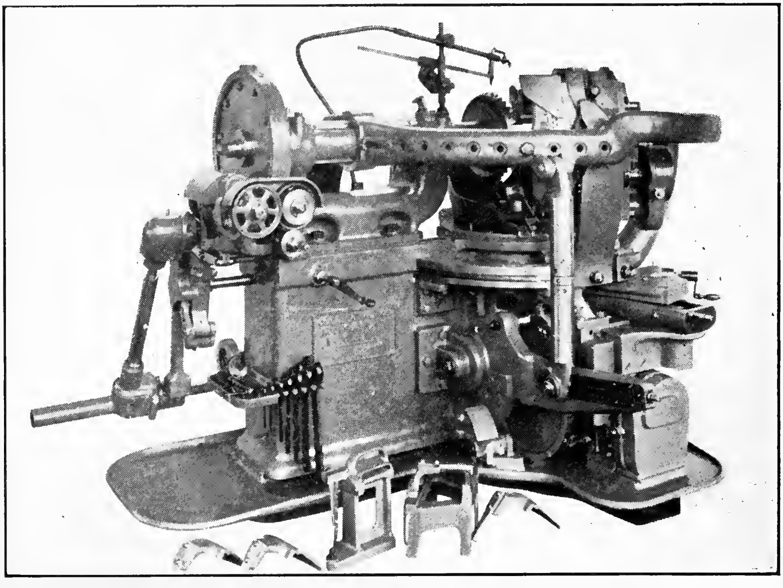

Fig. 261.
Gleason bevel gear cutting machine, generating system.

THE OCTOID SYSTEM OF BEVEL GEAR TEETH

When inventing his machine, Mr. Bilgram also invented, incidentally, an entirely new tooth form system which is neither involute nor epicycloidal. This system appears in all generated bevel gears, there being no spur gear tooth form analogous to it.

The starting point of the system is the straight-sided crown gear tooth which determines the outlines of all gears cut by it. It so happens that while the crown gear among bevel gears is analogous to the rack among spur gears its teeth do not have a straight side as do rack teeth.

The involute rack tooth has a straight side because, as a limiting construction, its center of curvature goes off to infinity. In a crown gear, however, the center of curvature does not go off to infinity, the curve being that described by a point *a* of Fig. 263 in the meridian circle *bc* when rolling upon the base circle *cd*. The center of curvature is always upon the surface of the sphere and never at an infinite distance and the involute crown gear tooth side has, in consequence, the curved form indicated.[1]

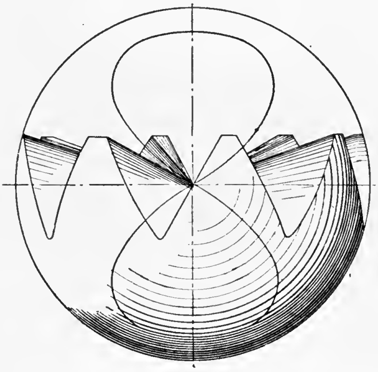

FIG. 262.—The octoïd crown gear tooth.

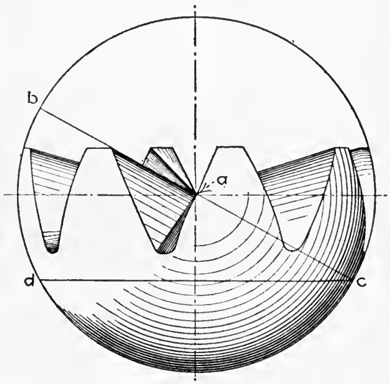

FIG. 263.—The spherical involute crown gear tooth.

The introduction of the straight-sided crown gear tooth as in Fig. 262 produced, therefore, an entirely new set of curves in

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[1] The rack is a limiting case of the crown gear. As the diameter of the crown gear increases, the base sphere also increases. When the diameter of the gear becomes infinite the gear becomes a rack. Simultaneously the sphere becomes of infinite diameter and with it the radius of curvature of the tooth profile.

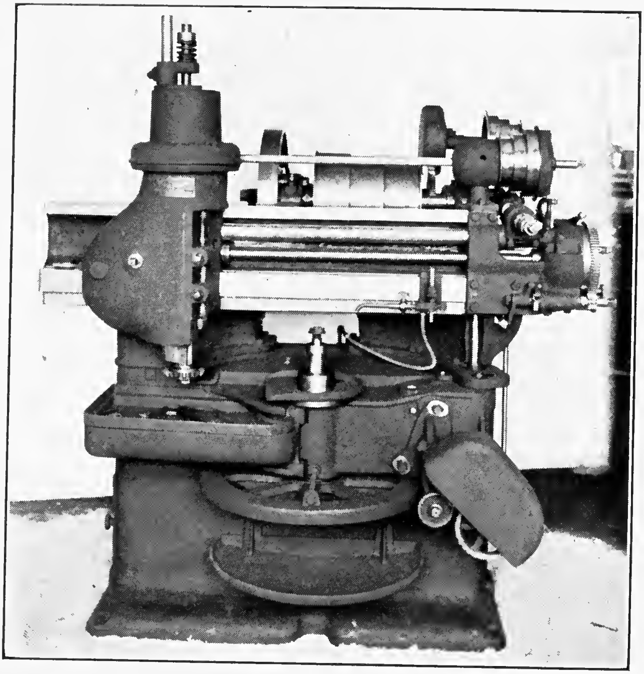

FIG. 264.—Fellows gear shaper, generating system.

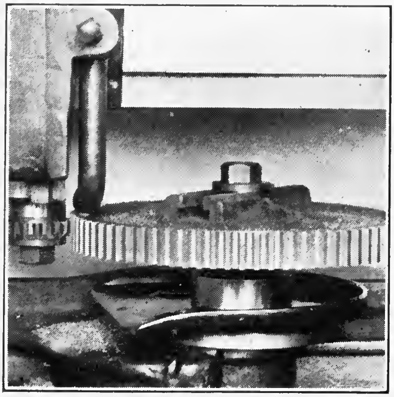

FIG. 265.—Action of the Fellows gear shaper.

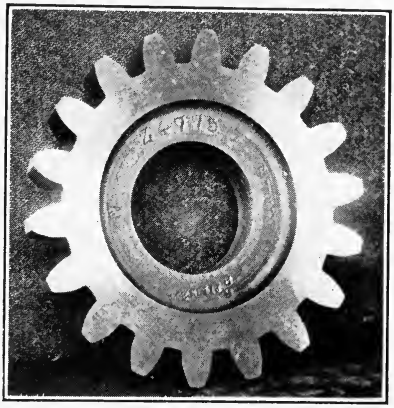

FIG. 266.—Cutter of the Fellows gear shaper.

the bevel gear teeth. To this system of tooth forms the name *octoid* has been given by George B. Grant because the outline of the path of contact between two complete gear tooth forms is a curve having a shape somewhat like the figure eight as shown in Fig. 262.

THE FELLOWS GEAR SHAPER

The leading representative of the generating process for spur gears is the Fellows gear shaper shown in Figs. 264 and 265, the principle of the action having been shown in Fig. 257. Fig. 264 shows the complete machine with the cutter in position. The gear blank arbor is shown at the right, the action of the cutter on the blank appearing more clearly in Fig. 265. Cutter and blank revolve slowly as the cutter reciprocates vertically. The appearance of the cutter is shown in Fig. 266. It also is generated from an ideal or imaginary rack tooth represented by the side of an abrasive grinding wheel, the final generation being done after the cutter is hardened. The machine for doing this which, of course, is found at the works of the makers only, is of the highest degree of precision.

THE HOBBING PROCESS OF GEAR CUTTING

The hobbing process is a modification of the generating process and was originally developed to a commercial basis by the production of machines for sale in Germany. The principle of this method of attack is shown in Fig. 267, in which the hob is represented by a worm, the two differing from one another by the fact that in the hob the threads are gashed to form cutting teeth as already shown in Fig. 44. The dotted outline indicates the imaginary rack which, in axial section, is represented by the worm.

The pitch of a hob as used in Fig. 43 for cutting worms has its pitch, measured parallel with its axis, equal to that of the worm which it is to cut, but the hob for cutting spurs has its axial pitch so modified that the pitch measured on the normal to its helix is equal to that of the gear to be cut. In action, the hob is adjusted at an angle, as shown in the plan view of Fig. 267, such that the tangent to the helix is parallel with the teeth to be cut. At the beginning of the cut the hob is presented to the side of the blank. The feed is double—that is, the gear blank revolves and as it does so the hob is fed slowly across it. The cut is continuous, the gear being completed as the hob leaves its further edge. The axial section of the hob being that of a rack, the result is to produce conjugate forms in the gear just as the reciprocating tool of the same profile produces conjugate forms.

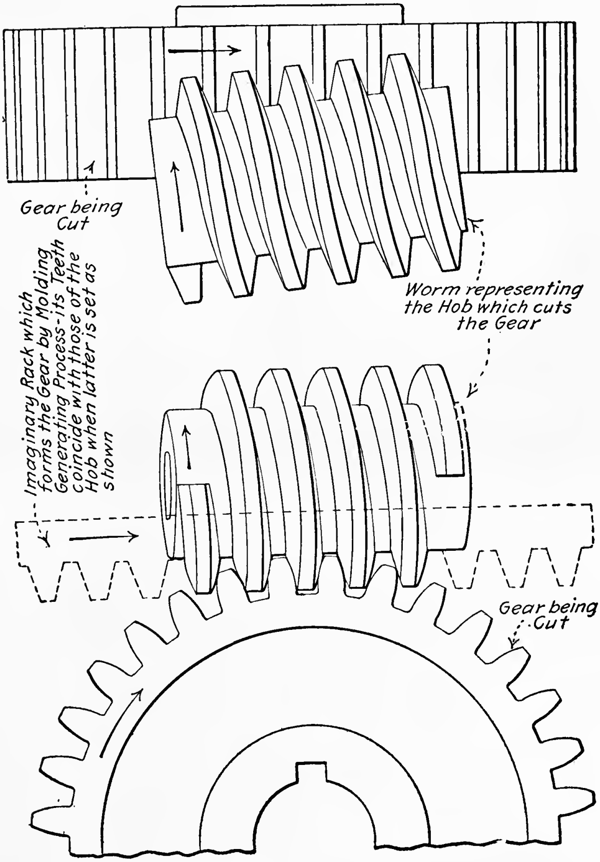

FIG. 267.—Principle of the hobbing process of gear cutting.

By suitable adjustments, with means for which the machines are provided, helical gears may be cut with the same facility as spurs. Except for a few special machines which have not been placed on the market, this is not true of other spur gear-cutting machines. There is no doubt that the use of helical gears, the merits of which are unquestioned, has been held in check by the lack of facilities for making them, and the hobbing machine, by providing these facilities, has already had a decided influence in increasing the use of this type of gear.

THE GOULD AND EBERHARDT GEAR-HOBBING MACHINE

A gear-hobbing machine by Gould and Eberhardt is shown in Figs. 268 and 269, the former showing the machine as set up for cutting spur gears, the blank, not shown, being mounted on the vertical arbor and the hob on the arbor of the swivel head on the column. Fig. 269 shows, more in detail, the adjustment and the action when cutting helical gears.

THE TEMPLET SYSTEM OF GEAR CUTTING

For large cut mill gears the templet system is most commonly resorted to. For such gears the cost of special cutters becomes prohibitive while a templet, which is the only special feature required for cutting any gear by the templet system, costs but little and may be easily made for special cases as they arise—and mill gears are usually special cases. A representative of the templet system is found in the Newton floor-plate machine shown in Fig. 270. Any diameter of gear may be accommodated by adjusting the distance between the cutting tool and the center of the blank, this machine sharing with other floor-plate tools the feature that it prescribes no limit to the size of the work which it can accommodate. The indexing mechanism is under the floor and hence out of sight.

Fig. 271 gives an outline plan view of the action of the templet which is here divided in halves—one for each side of the tooth spaces. By suitable feeding mechanism, into the details of which it is not necessary to go, the tool is guided by the rollers *a b* which ride on the templets *c d*. In actual use but one of the templets is in position at a time, thus avoiding their

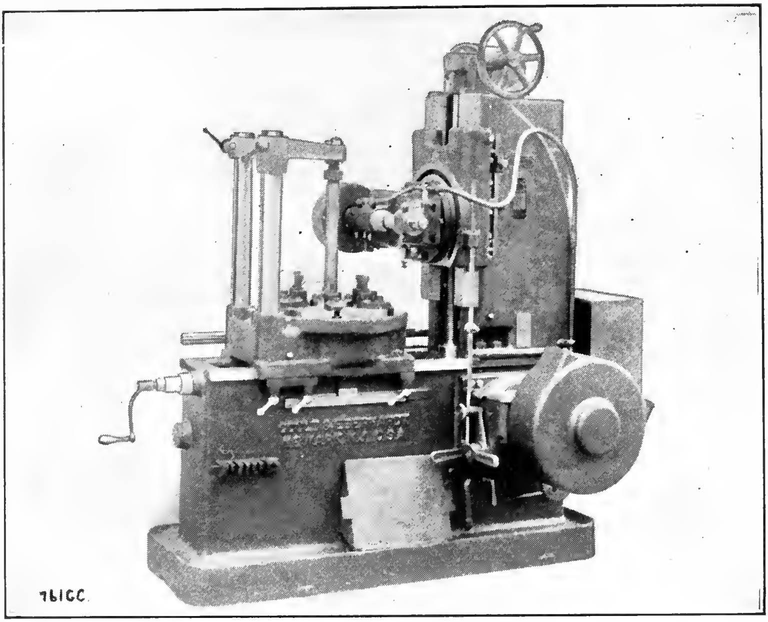

Fig. 268.—Gear hobbing machine set for spur gears.

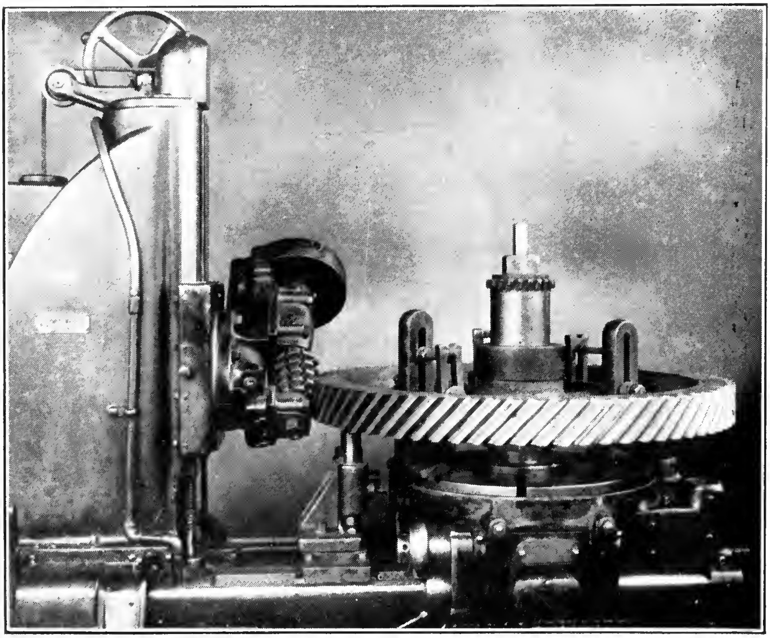

Fig. 269.—Gear hobbing machine set for helical gears.

interference with one another which, from the illustration, might be inferred to take place.

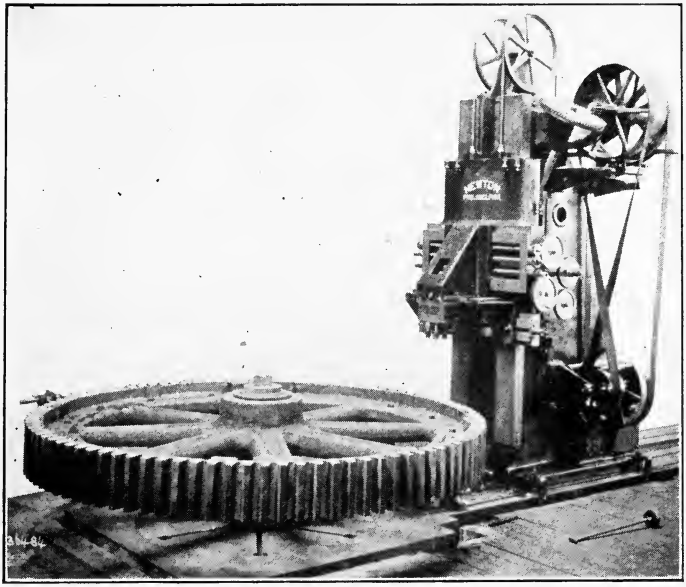

FIG. 270.—Floor plate gear cutting machine, templet system.

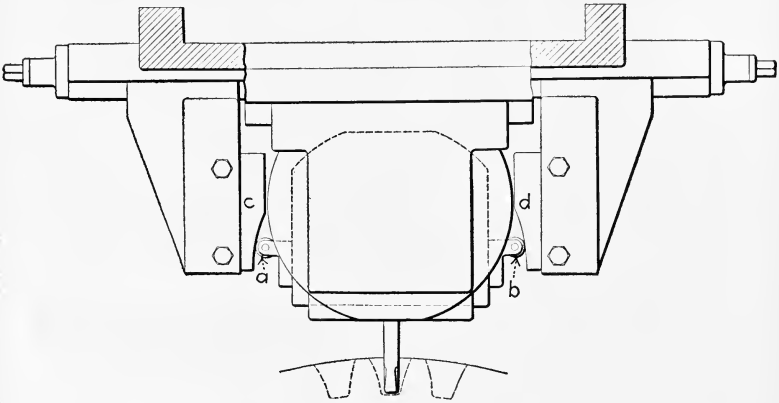

FIG. 271.—Principle of the templet system of gear cutting.

The application of the templet system to the cutting of bevel gears is shown in Fig. 272 from the Gleason Works. The arm—seen endwise—which carries the planing tool moves about the cone center of the gear to be cut, and in its movement is guided by the templet *a* on which a roller attached to the arm rides. The templet has the outline of the desired tooth profile suitably enlarged to provide for its increased distance from the cone center.

Contrasting the generating and the templet systems as applied to bevel gears, the former is limited to the smaller pitches because, in comparison with their capacity, generating machines must be much heavier than templet machines. The former is essentially a manufacturing while the latter is a making machine.

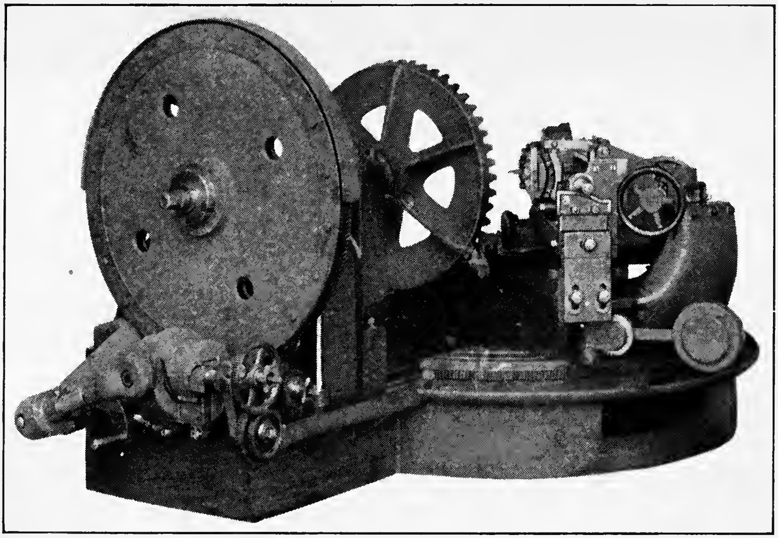

Fig. 272.—Gleason bevel gear cutting machine, templet system.

THE GEAR-MOLDING MACHINE

Heavy gears are frequently made with cast teeth. The earliest method of doing this, which is still much used, though not to be recommended, was to mold them from complete patterns. Such patterns are expensive and, moreover, it is not practicable to make and space so many pattern teeth with a satisfactory degree of accuracy. Added to this, the patterns being of wood soon warp and shrink and so lose what approach to accuracy they may have when new. Gears which are at once better and cheaper than those molded from patterns are molded on gear-molding machines[1] of which an excellent example at the works of the Mesta Machine Company is shown in Fig. 273. The machine has somewhat the appearance of a boring mill. The (iron) flask is placed upon the table which, by suitable indexing mechanism, is turned by hand from time to time to give the spaces between the teeth. The pattern is for one tooth only and hence may be made with all the accuracy possible in hand work and at small cost. It is mounted on a support depending from the cross rail. When in position the workman rams the sand around it, then withdraws it radially, indexes the table for the next tooth and repeats the process. The molding of the arms and hub being foreign to the subjects here discussed are omitted.

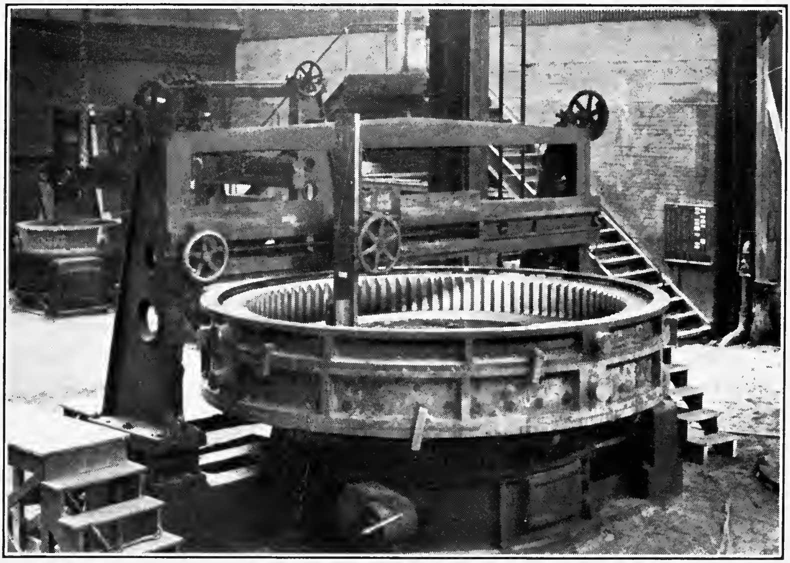

FIG. 273.—Gear molding machine.

The method is equally well adapted to the production of spur, bevel and helical, including double helical or herringbone teeth

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[1] Invented in England about 1860 by Messrs. Jackson.

which last find large use in the severe work of rolling mills. The resulting gears are entirely satisfactory for many purposes. They are, however, apt to be slightly out of round because of uneven shrinkage of the arms. This may be obviated by casting the rim and the center or spider separately, when, the rim being bored and the spider turned to fit, excellent results are obtained.

CHAPTER XIII

GRINDING

Early development of the grinding machine—Rough turning and finish grinding—Uses of the grinding machine—The planetary grinding machine—The surface grinding machine.

FUNDAMENTAL IMPORTANCE OF THE GRINDING MACHINE

The grinding machine is the most recent fundamental improvement. Until its appearance turned work was on the same basis that planed work was on prior to Whitworth's invention of the method of originating flat surfaces by scraping. The work of the grinding machine is an exception to the otherwise universal tendency toward deterioration of workmanship, the grinding machine being the one machine tool which produces work of the same quality as its own parts. It is also an exception to the general rule behind American machine-tool design in that the impelling motive which led to its original production was improvement of quality and not increased output.

Like all mechanical developments of large importance it had its germs in the work of long ago. Mr. Freeland is known to have built a lathe in 1852 of which the main spindle was hardened and ground—the bearing surfaces being made by welding strips of tool steel to a wrought-iron body. The grinding was done by a fixture secured in the tool post of the lathe on which the work was done, which fixture carried a grinding wheel driven from an overhead drum. Solid emery wheels were not then made, the grinding wheel being a disc of iron with a lead periphery which was charged with emery.

Grinding attachments of this kind came into considerable use after the appearance of the solid emery wheel and as early as 1864 special grinding machines of the lathe type were made by the Brown and Sharpe Manufacturing Company. The universal grinding machine of the present type was designed by Mr.

Brown in 1868 and the first machine was made in 1874. This machine was the prototype of many others and was, in fact, quite as remarkable a production as the universal milling machine and perhaps even more so, if judged by absence of subsequent changes which have been found desirable.

The original purpose of the grinding machine was the grinding of hardened steel shafts, thus permitting their use where unhardened shafts had previously been used because of the impossibility of truing shafts after hardening. It was not long, however, before the machine was tried on unhardened work and found to do its work more cheaply than the lathe—that is to say, the work could be semi-finished in the lathe and finally finished in the grinding machine in less time than it could be done in the lathe alone, the workmanship being, at the same time, materially improved.

The practice of semi-finishing in the lathe, leaving but a few thousandths of an inch for the grinding machine to remove, prevailed for many years, but has now largely disappeared through the efforts of the Norton Grinding Company, who in 1890 produced a grinding machine of unexampled weight and power. The wheels of this machine were much larger and were mounted on spindles and driven by belts of corresponding dimensions, the idea being to rough turn the work in the lathe only, the grinding machine being given much more metal to remove than under former practice. Coincident, or nearly so, with this development of the grinding machine the new abrasives carborundum and alundum made their appearance. These abrasives are far superior in cutting qualities to emery or corundum and, combined with renewed attention to the entire subject of grinding wheel making and grading by the Norton Company, they did much to make the new practice of rough turning feasible and it has come into large use. The Norton plain grinding machine is shown in Fig. 274.

GRINDING-MACHINE ADJUSTMENTS

Fig. 275 shows a Brown and Sharpe universal grinding machine and Figs. 276–279 show in outline a variety of set ups for different classes of work from which it will be seen that the name universal is well justified.

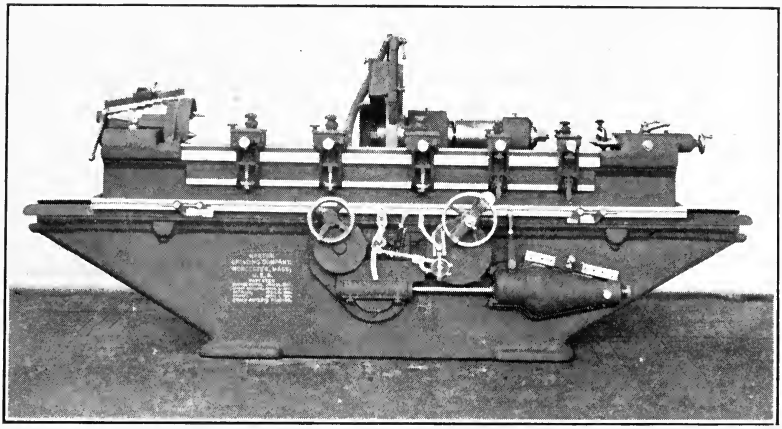


FIG. 274.—Plain grinding machine.

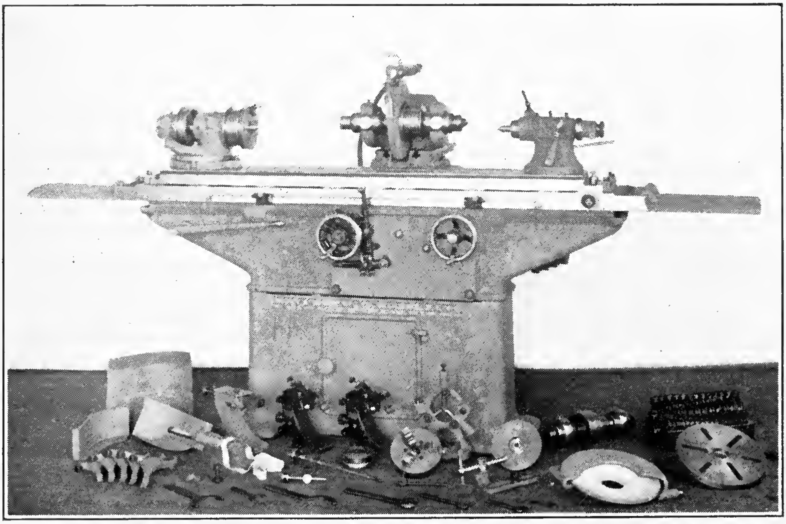


FIG. 275.—Universal grinding machine.

Three methods of making adjustments for angular grinding are provided. Tapers of small angle are most frequently obtained by the swivel adjustment of the work table on the main slide as shown in Fig. 276. More abrupt tapers are obtained by the swivel adjustment of the grinding wheel stand as shown in Fig. 277. If a piece contains two tapers these adjustments are used in combination as in Fig. 278, one taper

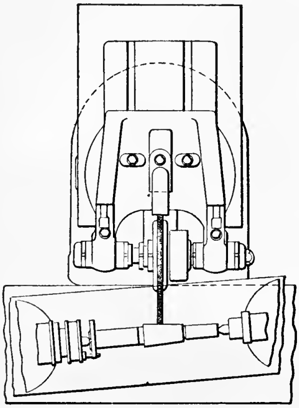


Fig. 276.

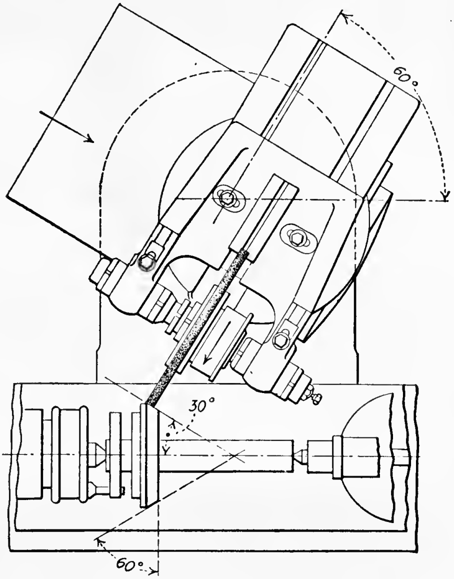


Fig. 277.

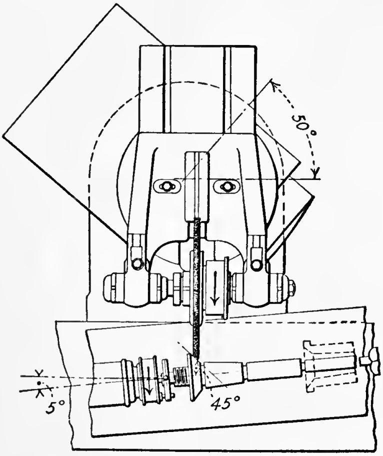


Fig. 278.

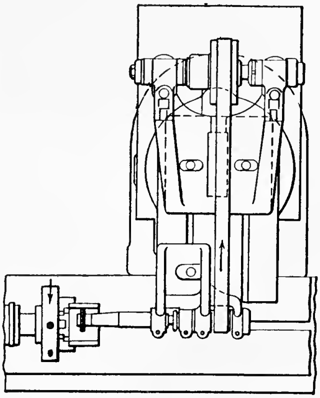
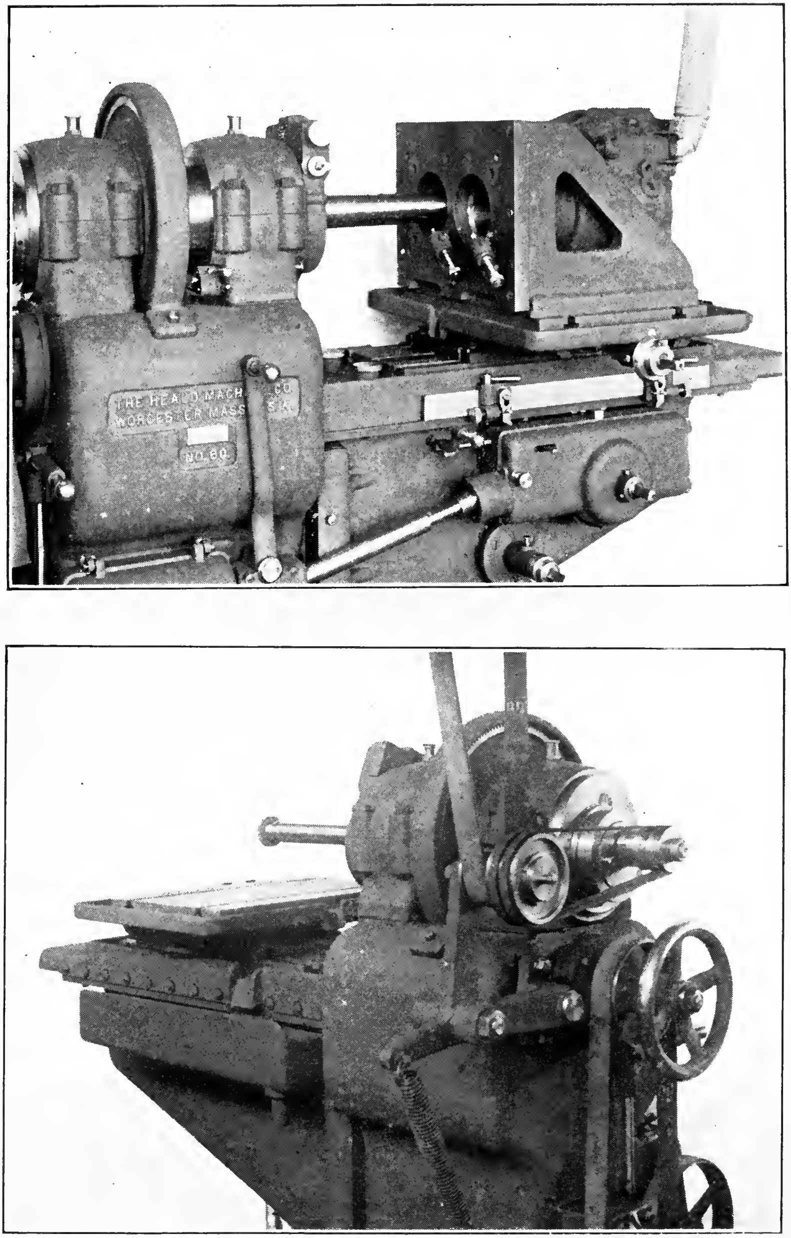


Fig. 279.

Various set ups of the universal grinding machine.



Figs. 280 and 281.—Planetary grinding machine.

being obtained from the table and the other from the wheel stand adjustment. For internal grinding the usual grinding wheel is removed and a belt pulley is substituted for it. The wheel stand is turned bodily around through an angle of 180 degrees and the internal grinding attachment and a connecting belt are put in place all as shown in Fig. 279, the work being carried in a chuck. For internal taper grinding the head stock is provided with a swivel adjustment of which no special view is shown.

THE PLANETARY GRINDING MACHINE

In the grinding machine as so far described the arrangement is always such that the work revolves. There are many cases, especially in internal grinding, in which the outside dimensions of the work are such as to make it impracticable to revolve it and for work of this type the planetary grinder was developed by the Heald Machine Company. A machine of this type, arranged for the grinding of the internal surface of automobile cylinders, is shown in Figs. 280–281.

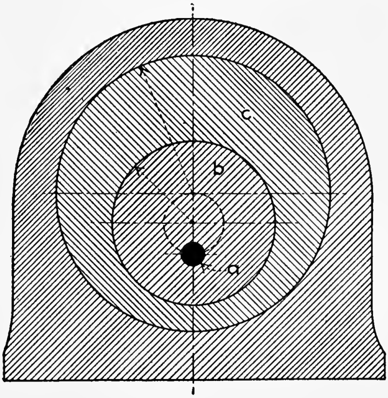


Fig. 282.—Principle of the planetary grinder.

The diagram, Fig. 282, shows the mounting of the grinding wheel spindle *a* eccentrically within the bush *b* which, in turn, is mounted eccentrically within the greatly enlarged main spindle *c*. The bush *b* may be adjusted circumferentially, the eccentricities being so proportioned that when the bush is turned half around from the position shown the centers of *a* and of *c* coincide, in which position of the parts if *c* be revolved the position of *a* will be stationary. By adjusting *b* the center of *a* may be made to travel in a circle of any diameter desired up to the one shown in dotted lines as a maximum and by this adjustment the size of the work to be ground is accommodated, the range of the adjustment being supplemented and increased by varying the diameter of the grinding wheel. The appearance of the rear end of the grinding spindle and of the eccentric bush with the method of driving the spindle are shown in Fig. 281, in which also the gear for driving the large main spindle is shown.

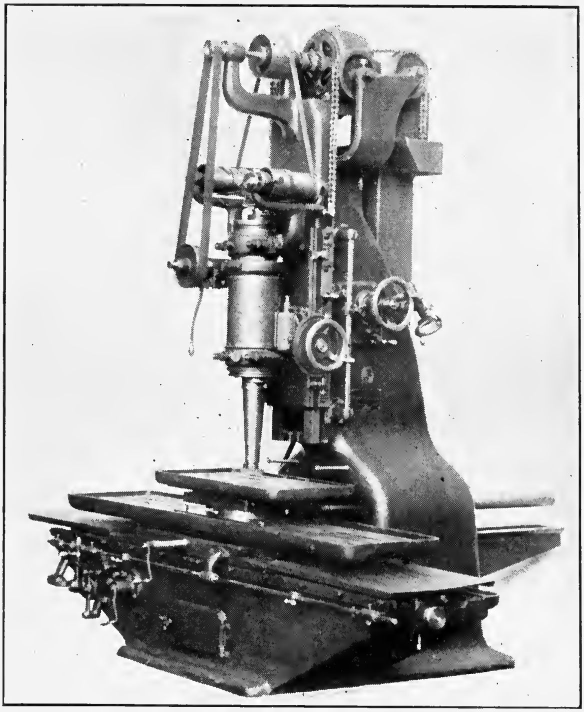


FIG. 283.—Vertical planetary grinding machine.

The planetary principle has been applied in Germany to classes of work to which grinding has not been adapted in United States. Fig. 283 shows a vertical planetary grinding machine by Friedrich Schmaltz. The mechanism of the vertical head stock by which the planetary action is obtained does not differ in principle from that already shown in connection with the Heald machine. The work table is, however, of an entirely different character and to it work of large size and of a great variety of forms may be secured, the machine being used for external as well as internal grinding. Thus a locomotive link with its eccentric rod pins in place may be strapped to the work table and the pins be ground in position by the planetary traverse of the grinding wheel around them. Likewise the holes in the links may be similarly ground, neither of which operations is possible with the usual type of machine because the dimensions of the link are such that the usual machine will not swing it.

The illustration shows the machine fitted with a supplementary work table having a radius arm projecting from its rear through the frame of the machine. By locating a center at a point on this arm such as to provide the desired radius, a locomotive link may be strapped to the supplementary table and the link arc be ground. To accomplish this it is, of course, necessary that suitable connection be made between the main and the supplementary tables so that the straight line feed traverse of the main table is transmitted to the supplementary table in the direction of the arc of a circle.

It is clear from what has been said that a hardened link may be bolted to the table and its link arc and eccentric rod pin holes be ground at the same setting—the planetary action of the wheel being brought into play when grinding the holes but suspended when grinding the link arc.

An even more ambitious German planetary grinder by the same maker is shown in Fig. 284. This machine is intended to grind locomotive crank pins after they have been forced into place. While the machine is somewhat complex in appearance its action is simple. The grinding wheel is mounted upon a frame carried by a cross arm which in turn is carried by the main spindle of the machine. The action of the spindle is to carry the wheel in planetary fashion around the pin. The driving wheels with their shaft are mounted on offset V's so located as to give the desired radius to the crank arm.

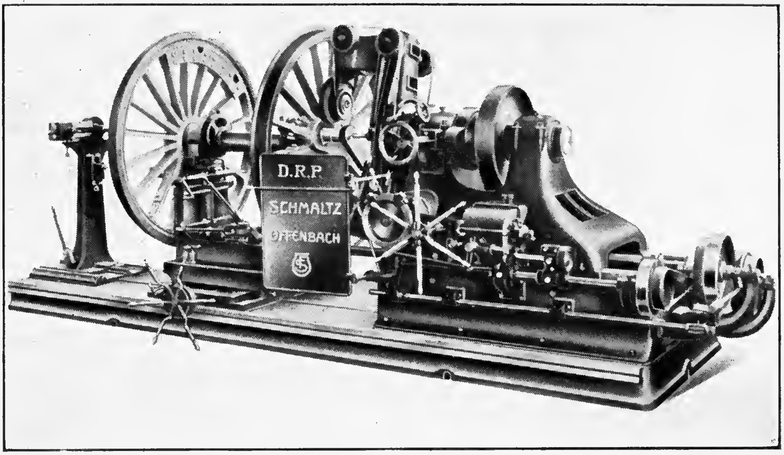


FIG. 284.—Planetary grinding machine for grinding locomotive crank pins.

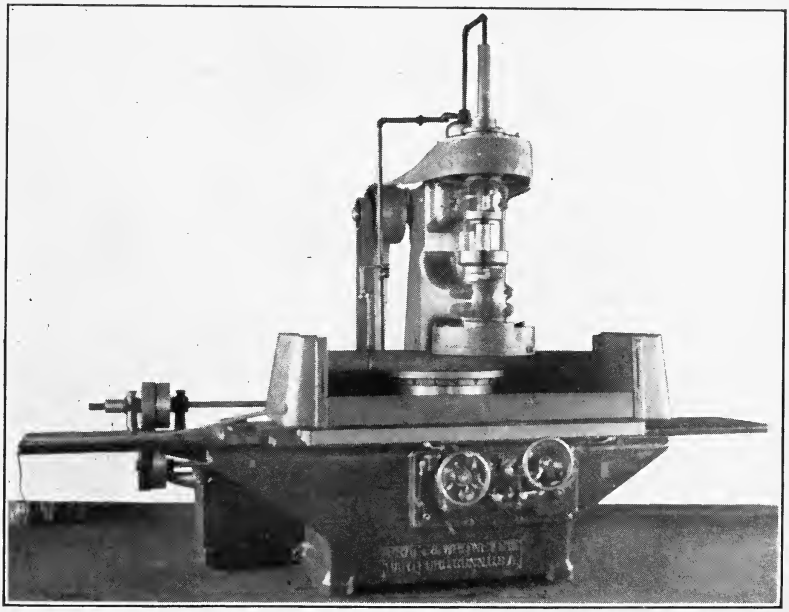


FIG. 285.—Surface grinding machine.

THE SURFACE-GRINDING MACHINE

An adaptation of the grinding process to the production of flat surfaces is shown in the Pratt and Whitney surface grinder of Fig. 285. The grinding wheel is of cup form and past it the work reciprocates after the manner of cylindrical grinding machines. A guard, partly removed in the illustration, prevents the flying of the water with which the work is flooded to absorb the generated heat.

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