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STEEL THERMAL TREATMENT

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BY

JOHN W. URQUHART

WITH NUMEROUS PHOTO-MICROGRAPHS
AND OTHER ILLUSTRATIONS

Capio Lumen

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"If Alloy Steels and Heat Treatment were taken out of the world, many of our modern advances would collapse like a pack of cards."

Sir Robert A. Hadfield, Bart., F.R.S.,
address to the Members of the Engineering Societies of the United States, London,
June 29, 1921.

PREFACE

Having been engaged in the production of machinery and various steel components and tools at my workshops in Leicester for many years, I have had opportunities, and indeed have been under the necessity, of putting into practical use all the recently introduced processes employed in the heat treatment of steel.

The remarkable changes that have taken effect in reference to the treatment of steel and iron, and the revolution thereby produced in the engine and machine-building trades within the past few years, are only realized by those actually engaged in those trades.

The time has gone when steel, as received from its maker, was forthwith worked into machines without any preliminary treatment, and when it was not realized that a thermal process could add enormously to its physical strength and effectiveness.

Great improvements have been introduced into the management of even the old-established old-type steels within a recent period, and these have been followed by an unexpected development in the evolution of a long series of alloy steels, possessing the most startling characteristics, only to be fully attained to by the aid of heat treatment.

These advances have been followed by more exact systems of applying heat, under strict methods of time and thermal measurement. Then succeeded the electric furnace, with its exactitude of performance, rendering standardization of product no longer a problem. Our American friends did not wait to argue over the rather higher cost of running these furnaces, but went ahead, and soon found that the superiority in results fully justified the means employed to secure them.

To some extent the present work is an attempt to coordinate the work of the laboratory with that of an engineer's hardening department, and with that end in view there is here presented a series of photo-micrographs, depicting the actual condition of the steel at various stages of heat treatment, chilling, and tempering, a study of which forms in itself a liberal education in steel working methods.

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CHAPTER I

RECENT DEVELOPMENTS

A brief period of the past twenty years may be said to cover the history of the development and heat treatment of the high-tensile steels as we know them. During this short time a great part of the discoveries in the field of alloy steels has been evolved, coincident with the elaboration of the processes aiming at the utmost dynamic strength of the material.

While the steel of the past consisted of soft iron, with which was incorporated a percentage of carbon, the leading steels of the present day are composed of alloys in which nickel, chromium, vanadium, manganese, silicon, tungsten and molybdenum play a leading part.

The most highly developed of the simple carbon steels, even after undergoing the most skilful thermal treatment, have been far surpassed in tensile strength and endurance by the later heat-treated alloy steels. It is recognized that the rapid progress in the fields of automobilism, aviation, electricity generation and steam turbines owe their success mainly to the superiority of alloy steels, and these, in their turn, owe their qualities to heat treatment after leaving the rolling mills in which they were made.

The Carbon Group.—The nature, thermal treatment and ultimate strength of the carbon steels, if briefly reviewed at the outset, will form a useful introduction to the subject-matter dealt with in the following pages.

Certain terms are used by steel men, descriptive of particular steels or their condition. It will be useful, at the outset, if we attempt to define the meaning of the more generally used of these, the more so because even good technical dictionaries are dumb upon the application and meaning of many of them.

Soft Iron.—This is ferrite. It is soft ductile, and possesses relatively little tensile strength. It has a high magnetic permeability, and is a good conductor of electricity. It is almost free from carbon and therefore incapable of being hardened. Sulphur phosphorus and silicon generally accompany it as impurities.

Steel is the above substance in alloy with carbon. A curious and instructive experiment was once made by enclosing a modicum of diamond, which is pure carbon, within pure iron, and subjecting the whole to heat. The diamond disappeared in the process, but the soft iron in its vicinity was found to be transformed into steel. Steel is known as *mild* when the percentage of carbon incorporated with the pure iron is as low as 0·10 %. It is known as *high carbon* steel when the percentage of carbon is 0·90 % or over. There is a very wide range of carbon steels between these two figures.

Raw Steel is untreated steel, as it is produced by the maker. The term does not imply that the steel is unfit for use—it is simply a useful word, conveying, in this case, its own meaning.

Straight Carbon Steel and **Straight Hardening Steel** are simple carbon steels, the latter having a sufficient percentage of carbon to ensure its hardening upon being heated and rapidly cooled.

Burnt Steel, as the name implies, has been so far over-heated that (to use a common expression) the carbon has departed from it, and its " grain " has become coarsely crystalline, ready to crumble under stress.

Quenching or **Cooling** is the act of chilling red-hot steel to ensure its becoming hard. The cooling medium, whether it be water or oil, is sometimes referred to as " the quench."

Annealing (also known as **Normalizing**) is the art of rendering steel as *soft* and ductile as possible to enable it to be machined—that is, turned, planed or drilled. Annealing is also carried out for purposes of relieving internal strains set up by forging or rolling. Annealing is also in extensive use in the thermal treatment with the ultimate object of developing the utmost strength of the steel.

Tempering is the art of graduating the hardness of steel for any specific purpose. Thus, steel intended for cutting hard metals will have a hard temper and steel intended for cutting wood, as a saw, will be given a softer temper.

Temper is used by steel-makers to indicate, chiefly, the carbon percentage in the metal, and in this respect has no direct reference to degree of hardness given for cutting tools; it merely means *grade*, *brand* or quality in raw steel.

Case-hardening.—The art of compelling carbon to penetrate the surface of mild steel or iron to a certain depth, thus transforming a low carbon metal that cannot be hardened into a high carbon steel that can be hardened.

Cementation.—The art of transforming iron into steel by heating it in contact with the "cement" or carbon-evolving materials such as charcoal. In this case the cementation is carried on so long that the penetrated zone from either side meets in the core, and there is no soft core felt.

Carburize, sometimes called Carbonize. A mild steel or iron is carburized when it is case-hardened. A steel may be carburized to any extent and not super-hardened—this is case-carburizing as distinguished from case-hardening.

Impurities—These are inseparable, or appear to be so, from steel. The most common are sulphur and phosphorus, which tend to increase brittleness; the sulphur combining with the iron and manganese content to form sulphides of these metals.

Grain of the steel. This is a very common word, and its meaning can scarcely be mistaken, although it is not, from a chemical point of view, correct. A piece of steel broken across exhibits to the eye a fractured surface, and a certain appearance of a crystalline nature. When this is "fine" the steel is considered to be in good condition; when it is coarse the steel cannot be made into cutting tools, or stand up to stress. The microstructure, under the lens, exposes to the experienced steel man the nature and quality of the steel. A steel that has been case-hardened to a certain depth will exhibit a very fine grain throughout the carburized zone and a coarser grain in the uncarburized area.

Saturation.—This term is used to indicate a carbon content amounting to 0·90 %, being about the limit that is usually forced into the steel by cementation or carburization as carried out in the hardening room.

Super-saturation.—A carbon content exceeding 0·90 % is generally regarded as a super-saturation. It is to be met with in all high carbon steels over this percentage. The steel-maker can accomplish this super-saturation in the manufacture of the material. It is generally called for in steel intended for the manufacture of fine cutting tools, and may be regarded as out of place in steel to be subjected to stress.

Cementite.—This is a condition brought about by the combination of ferrite and carbon forming carbide of iron (chemically Fe_3C). It consists of 6·6 % carbon and 93·4 % iron. This condition is shown in steel subjected to heat and allowed to cool slowly.

Pearlite.—Pearlite can be identified under the microscope as consisting of interstratified bands of ferrite and cementite. Cementite will form a mixture under heat, but not an emulsion, with ferrite. This is pearlite, which forms a steel with a carbon content of 0·9 %. The 0·9 % of carbon forms what is known as the saturation ratio, or the

Eutectoid steel ratio. This percentage of carbon (0·9 %) is a standard, and a eutectoid steel is known as a material that can not only be used for hard cutting tools, but is adapted also for positions and service under stress. Steels *super*-saturated are distinguished by the prefix hyper, or

Hyper-Eutectoid steel, in which, the ferrite being already, in its entirety, absorbed to form the pearlite (as in the above example), the balance of the cementite will be in the free state in the form of grains of intensely hard carbon—this is the super-saturated condition, making for hardness at the expense of strength and ductility.

On the other hand, if the carbon content fall below the eutectoid ratio, as it does in all mild steels, we have a

Hypo-Eutectoid product, in which it is obvious that, there being insufficient carbon to absorb the whole of the ferrite, there will be an excess of the latter and the eutectoid condition will not have been reached.

Austenite, Martensite, Troostite, Sorbite.—All of these substances in steel may be regarded as conditions of the materials—iron and carbon—composing it at different

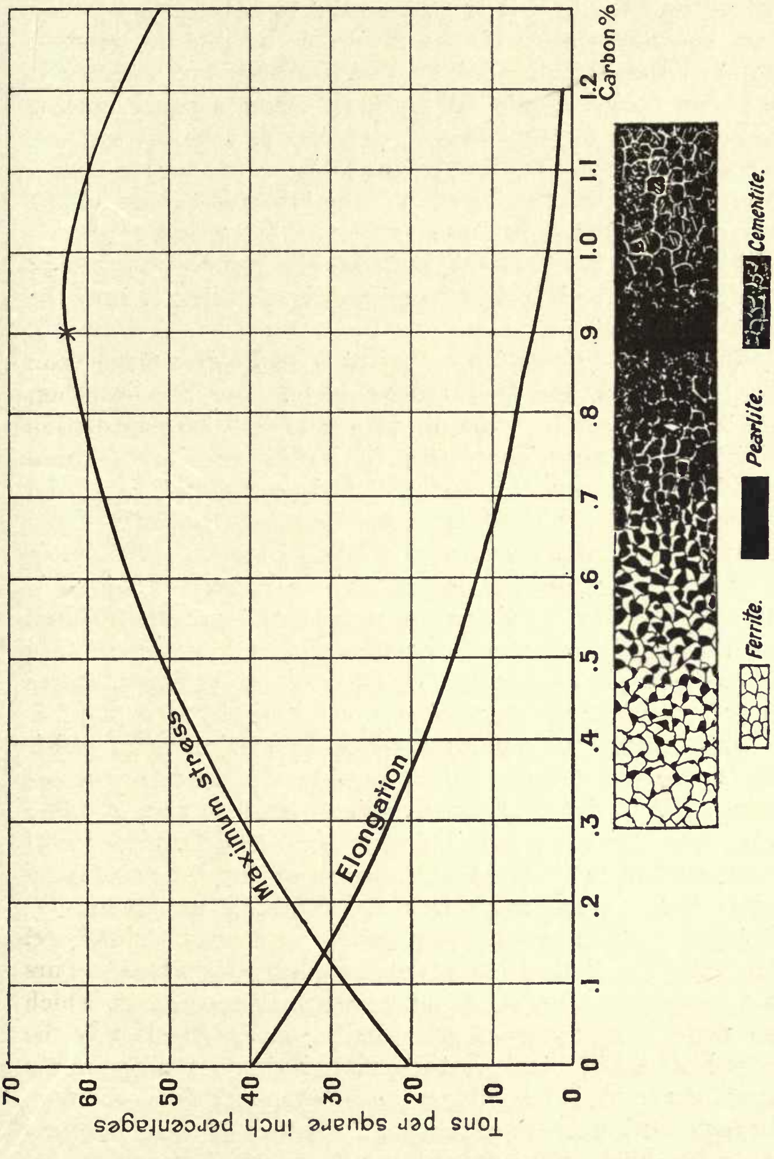

Fig. 1.—Chart showing relationship between Carbon Content and Physical Strength.

stages of heating, hardening and hardness. They are names given to distinguish the stages of change taking place in the substance of steel during the whole process of heating, slow or fast cooling and hardening. Thus a *Martensite Condition* follows rapid cooling of red-hot steel. Thus, under the microscope, and even generally by the unaided eye, it is practicable to determine at once from the appearance of the grain of a fracture whether the steel has been heated to a given heat and whether it has been cooled slowly or rapidly. After a rapid cooling the martensite appears as a fine, uniform, granular surface. A troostitic condition follows a partial or slower cooling—a partial hardening. Thus, a steel treatment man might say, upon seeing a fracture surface, "I can see that this steel is only in the troostitic state and is only half hardened; heat it higher and cool it more rapidly to bring it into the martensitic state."

The *Sorbitic Condition* occurs at a still softer stage than the troostitic; the two indeed blend into one another, and it is difficult to bring about a complete transformation of the chilled zone into either by itself. Sorbite has been considered by several distinguished metallurgists to be identified with the amorphous substance which fills the space between the crystals of hardened steel.

A graphic representation of the foregoing conditions is presented in Fig. 1, where the results of test stressing and test elongation are given, together with a diagram showing the microscopic appearance of the steel at different stages of carbon absorption beginning at 0·3 % up to 1·15 %.

The Critical Temperatures.—The foundation upon which the thermal treatment of steel has been built up is a knowledge of the effects of temperature. Steel is one of these substances that, by manipulation and temperature treatment, may be so modified or transformed that the substances composing it can no longer be regarded as chemically identical with its composition in the raw state. Moreover, the evolution of those substances, each one by itself, occurs at a particular known temperature-transformation in which the time element is of first importance. Steel may be heated to a high temperature, and during its progress its constituents will be subject to thermo-chemical changes, through a wide range of heating. Certain of those changes are associated with conditions that are favourable for strength, ductibility or hardness. But those phases may be transient, for if we permit the steel to again return to its cool state, by slow degrees, the process of evolution will be reversed, and the raw steel will still be raw steel. This is not heat treatment.

Fixation.—Complete or partial fixation is the secret of utilizing the progressive changes in steel. Arrest of the progress of transformation, by sudden cooling, is one means employed in fixing the condition of the steel at a known given point, but this given point, and the reason for it, must be known.

The microstructure of steel can be so modified by heat and cooling that its value in practical application can be enormously increased, and only by operating upon it at certain temperatures can this advantage be secured. An exact knowledge of what these temperatures are, as applicable to steel of varying carbon content, can only be acquired by a review of what are known as the *critical points* of heat, associated with the phenomena of "decalescence" and "recalescence."

Without entering upon the complex subject of the chemistry of steel, which is outside the scope of the present work, some explanation of the practical meaning of the phenomena of the critical points must here be given; for without this knowledge the working of steel would become a haphazard occupation, unworthy of present-day developments, and no reliance could be placed upon the products.

The first thing to be understood is that steel, while in its solid condition, and without in the least changing its shape, can be so operated upon by heat that its molecules behave as if it were in a state of solution, known as the "solid solution." There is an *emulsifying* of the atoms of ferrite and carbon, and upon slow cooling there is a reversal; both of which changes are accompanied by a complex series of molecular transformations.

These changes are not strictly progressive with the rise of the heat, but occur at certain "critical points," or within critical ranges of temperatures. They are changes of structure that entirely alter the nature and strength of the material, and knowing beforehand the carbon content of the steel, we can, at any of the favourable points, bring about fixation and so prevent entirely the reverse process, which, lacking fixation, must ensue.

"Decalescence" is the point at which, as before observed, the pearlite structure becomes transformed into *Cementite*, which may be regarded as carbon in the hardening state.

If at the decalescence point, or preferably rather above it, fixation is carried out by rapid cooling, the product is steel of maximum hardness.

Recalescence is the temperature at which, upon slow cooling, the cementite begins its backward transformation to the final pearlite state, passing through the troostitic and sorbitic stages of transformation.

In order to distinguish these stages metallurgists have agreed to use certain symbols. Thus the letter A, followed by a smaller letter to distinguish between the rising and falling heats, covers the decalescence and recalescence points. Thus, Ac (*chauffage*, heating) and Ar (*refroidessement*, cooling). These symbols were suggested by the metallurgists of France, whose researches in this field have been so fruitful. Further, in order to indicate more exactly the beginning, middle stage and consummation of the molecular transformation in both the rising and falling temperatures, the symbols Ac and Ar have added to them a number, or numbers—thus Ac1 indicates the rising heat at the first stage of chemical transformation upwards, and Ar 1 the first stages in reverse transformation upon cooling, Ac 1, 2, 3 and Ar 1, 2, 3 covering the three stages.

Further experiment proves that, in steels low in carbon content, the three stages of transformation are wide apart, drawing closer together as the carbon percentage increases. Thus, in a low carbon steel the Ac1 stage may be 130° F. below the final or Ac 3 stage, but in a high carbon steel the transformations are very closely placed, only a few degrees separating them.

Observation of the Critical Ranges.—To an observer experienced in the treatment of steel the critical ranges can actually be visualized. Taking the case of a mass of steel of 1·0 % carbon placed in a clean muffle furnace, after the first red heat has been attained, and when the critical stage is being approached, at about 1,450° F. there will be observed a distinct pause in the upwards tread of the heating. While the furnace continues its work the steel does not appear to become hotter. This well-marked pause is due to the fact that the temperature of the steel does not increase; but it continues to absorb heat, which is known to be expended upon the transformations occurring in the mass. This goes on for an appreciable time, about three minutes, when suddenly the heat rushes up and the comparatively dull red becomes a bright red. This is the apex of the Ac range, symbolized as Ac 3. What is really happening is that at the critical temperature the steel is *storing* *up heat* in its molecules—an absorption required to bring about the chemical change from pearlite to cementite, and other molecular movements.

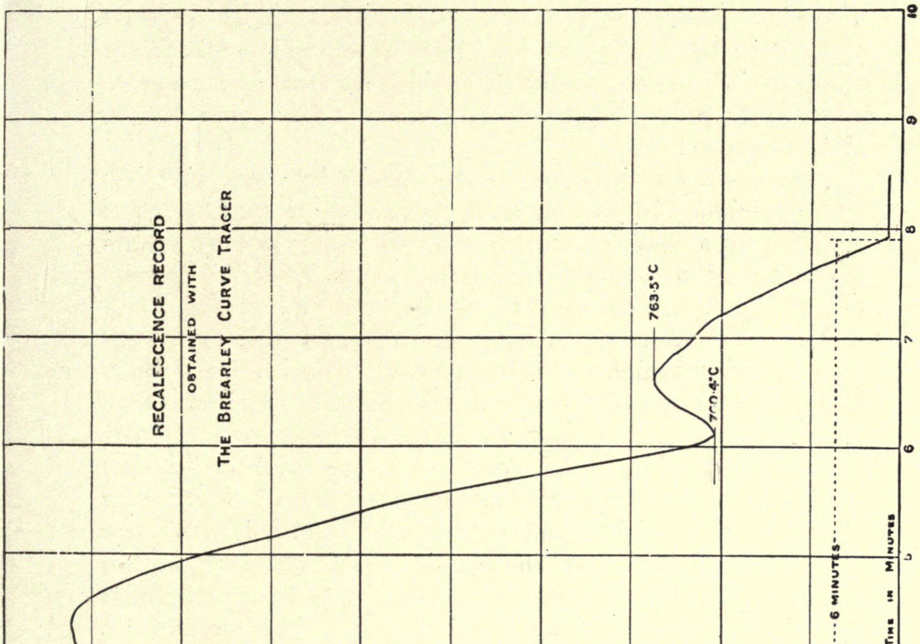

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FIG. 2.—Chart showing Decalescence and Recalescence of Steel.

If at this point (Ac 3) the furnace be shut off, and the steel permitted to cool slowly, observation will witness the *reverse* phenomenon through the Ar range, that of recalescence. At a temperature of about 1,250° F. will be observed a *sudden increase in the red-hot appearance,* or at the least a pause in the cooling of the steel, which will continue for an appreciable time—about three minutes (the Ar 3 point)—when there will be resumed the gradual cooling and dulling of the redness.

These observations are easily made by one who has had experience in the thermal treatment of steel, even if unaided by a thermometer, but an average observer should make use of a reliable pyrometer, a blind hole or pocket being drilled in the steel to receive the end of the pyrometer; or, better still, a recording instrument of this class, by employing which he will not only witness a most interesting application of heat, but will be able to check, with great accuracy, the qualities for heat treatment of any particular sample of steel, and this is the information that matters. A recording pyrometer will produce a chart or diagram of the rising and falling heat, and afford a clear view of the *pauses* at the decalescence and recalescence points, as in Fig. 2, where, at the temperature of about 780° C. on the rising heat, there begins the well-known absorption-pause in the increase of temperature of the steel, and during which the pearlitic carbon is transformed into hardening carbon. Heating is continued in this case up to 796° C. in order to consolidate the transformation. Upon shutting off the heat a falling gradient is observed, which, at a temperature of 760° C., is again arrested. A rise in the temperature of the steel here begins, during the change back of the hardening carbon into the pearlitic condition. When this re-transformation is in turn completed, the steel resumes its cooling off and the curve rapidly droops. In a suitable testing furnace the whole process can be carried out, as shown, in the space of six minutes.

A chart of this kind can, however, be plotted by the aid of a magnetic needle, as well as by the indications of the pyrometer. This fact is due to the destruction of magnetic attraction in steel or iron at a higher temperature than that of the recalescence point. Thus, in the specimen under review, which may be of 1·0 % carbon, the steel will attract a compass needle until it reaches a temperature of about 1,400° F. Having passed above this point, no magnetic properties remain, and no trace of attraction can be found, until the recalescence point is nearly reached on the cooling grade.

Test Magnet.—This is merely a magnetized needle, composed of a few inches of hard and magnetized steel, poised or pivoted upon a point. This point is fastened vertically at the extremity of a long brass rod, furnished with a wooden handle, so that the needle may be brought near to the red-hot steel within the furnace. While the decalescence point (Ac 2) can be very closely determined by the aid of the needle, the lower critical range—recalescence—cannot be so easily determined. In other words, red-hot steel will not influence the magnet, and it will continue to remain inert to it as long as it remains appreciably above the change point in cooling. As, however, the high critical range Ac 3 is only some 100° F. above the A 2 range, a fair estimate can, after experience, be made by the appearance of the steel, after it has begun to regain its magnetic properties —in fact, the full magnetic " pull " is not in evidence until the cooling critical point (Ar 3) is being passed.

Non-magnetic Manganese Steel.—There is a notable exception, however, to be borne in mind in respect to magnetic attraction in steel. This has reference to manganese steel, of which its inventor says, " this fascinating material has the peculiar quality of being non-magnetic when it should be magnetic."

It may be asserted, with considerable confidence, that the point at which the steel entirely loses its magnetic attractive power is, with sufficient practical accuracy, the Ac 3 point of heat at which the carbon and its correlated atoms have arrived at the possible *hardening* stage. But unless in the case of thin sections of steel, no measures should be taken to bring about fixation until the steel has attained from 100° to 150° F. *above* this critical point. This is done to stabilize the temperature by sufficient soaking to complete the change and so ensure its permeation of the mass.

Energy Absorption.—From the foregoing considerations we have seen that thermal energy has been expended in the steel in *two* directions—in raising its temperature and in the molecular work of transforming the carbon and ferrite. We have seen that, as the temperature has risen, its progress has been progressive, without a pause through the Ac 1 and Ac 2 stages, up to the confines of the Ac 3 critical point. We have seen that, upon approaching this point, the steel has *ceased to rise in temperature ;* there has been a pause of minutes, during which the temperature has not moved upwards, and may be proved to have sensibly *fallen.* The thermal energy being absorbed during this pause can be shown to have been stored up in the *work* of molecular transformation. Until this *work* is accomplished, the steel is in no condition for hardening, or the fixation of the cementite.

That this thermal energy is imprisoned in the cold steel, after chilling, there can be no doubt. That it is returned in the quenching, as a superficial consideration of the subject might suggest, is not accepted by the best authorities.

Energy Returned.—From the foregoing simple experiments, it has been clear that if fixation or quenching be not carried out, if the steel be permitted to slowly cool, *after having reached the Ac* 3 *point,* we enter upon the Ar range (cooling). The loss of temperature is uniform downwards through the Ar 1 and 2 stages until the Ar 3 stage is reached, which will generally be found about 150° F. under the Ac 3 critical point. Now, at this Ar 3 stage, we have ample evidence, visual and thermometric, that the thermal energy stored in the mass of the steel, *and not visible until this moment* is being given up, by a *pause* (of minutes) in the cooling, and an actual increase of temperature until the Ar 3 critical point is passed.

While it is not suggested that the foregoing procedure is necessary in the treatment of steel as a general practice, it will be recognized that a full knowledge of what changes take place, as they affect finished products, is absolutely necessary if even moderate success be expected in treating steel. Thus, hardening of the steel can be carried out from any point just beyond the decalescence (Ac 3) stage, down to the confines of the recalescence (Ar 3) stage, while the carbon is in such condition that it will still harden. But no *full hardening or refinement* of grain must be expected upon the cooling (A 2) range. Here we have a confirmation of the old steel rule-of-thumb, which directs: "Never harden upon a falling temperature."

Carbon Content and Temperature.—It is necessary, at this stage, to consider the effect of varying the percentage of carbon upon the temperature required to bring about the hardening of steel.

Steel of the eutectoid ratio, that is, having a carbon content of 0·9 %, will be found a valuable standard of comparison in the determination of temperature of the decalescence point (Ac 3), since it must be clearly understood that a low carbon steel demands a high temperature to attain decalescence and that the temperature for hardening purposes and refinement of grain varies as the carbon content. Thus, if we take a steel, as considered to be just far enough beyond the " mild " steel grade (which will not straight harden) and capable of being hardened, for example, a 0·30 % carbon steel, it will be found that it attains its decalescence at about 1,378° F., and a *thin* sample of it will harden completely, with a maximum of grain refinement, at this temperature. This is a hypo-eutectoid steel, and it will be found that all of this steel series will call for comparatively high temperatures to attain the decalescence (Ac 3) point. The steels that may be regarded as included in the above group range from 0·1 to 0·85 % in carbon content. The degree of heat to reach the critical point will vary from about 1,650° F. down to 1,175° F. When saturation point is attained with carbon content of 0·90 % we reach the eutectoid stage, and the temperature as low as from 1,050° to 1,100° F. will suffice to touch the highest point of decalescence (Ac 3). At this heat the steel will harden well, but it will not generally be in its most favourable condition of refinement. For this development it is found advisable to raise the temperature some 100° to 150° F. above the Ac 3 point. This precaution is taken on account of molecular inertia in the mass, so that there is a sensible lag in completing the full transformation. Hence it is generally conceded that the temperature of apparent decalescence is always slightly below the true Ac 3 point.

It should be noted that the overplus of heat recommended above (100° to 150° F.) has reference to subsequent quenching for hardening only. If the heat treatment be aimed at for annealing and toughening, an overheat of 50° F. only is considered sufficient.

Effects of Excess Heat.—If the steel be heated much over the critical point as above, an adverse change begins to develop in its microstructure. The " grain " will begin to coarsen and this will go on in ratio with the rising temperature until the steel is said to be "burned." It will be coarsely crystalline and it may have parted with most of its carbon.

Now this effect is not a function of the heat alone There are two factors at work—heat and time. Steel heated by inadvertence and caught at once will not suffer much. But as we have before shown, it is bad practice to allow this overheated steel to cool down to the critical point for hardening. Since no steel should be quenched upon a *falling* temperature, the preferable course to pursue is to permit cooling below the recalescence point, and reheat to the proper temperature for hardening.

Maximum versus Modified Hardness.—Up to this point our review of the modern conception of the relation of ferrite and carbon to heat has had reference to the production of a metal of maximum hardness. This is largely owing to the fact that, for practical purposes, nature produces *one* degree of hardness only. It might be reasonably supposed that a half-hardness might be produced, but a consideration of the foregoing review of what takes place in steel under heat discloses the fact that no half-measures are acceptable to the law of chemical change—it shall be pearlite, or it shall be wholly cementite. It is true that, by interstratification, we may find these substances in a fracture of steel, but the half-hardness produced when this material is suddenly cooled is not the hardness that will "stand up" to stress in actual work. This desirable half-hardness has been sought for by numerous experimenters during centuries, with no practical result; and it seems quite certain that to arrive at a modified hardness as a first intention in any quenching is impossible. Both the troostitic and sorbitic conditions must be passed over in attaining real hardness.

Modified Hardness.—A second operation has to be undertaken in order that the *whole mass* of the steel shall participate in the change, and not stratified, or mixed network sections only.

This art is known as *tempering.* The prelude to tempering in the case of tool steel must be "dead" hardening, which means maximum hardness (not to be cut by a file), of suddenly chilled carbon in the cementite condition. There is no advantage, but the reverse, in modifying this dead hardening upon its first production, but there is every advantage to be gained in its subsequent modification, and steel would be practically useless if it could not be effected.

Leaving to a subsequent chapter the development of the art of hardening, it will be useful at this stage to review the essential conditions under which it must be carried out, and the reasons underlying them.

Reverting to the subject of what constitutes a hardening steel, it should be pointed out that *all* steel cannot be hardened. There are many grades of it, yet under the designation of steel, that do not contain the substances necessary to the hardening operation, or rather, the proportion of those substances is so small as to render hardening either very difficult or even impossible.

Hardening Limit.—From extensive experience of low carbon steel working, the author has found that when the carbon content is as low as 0·20 % hardening is possible but difficult. The difficulty lies in the necessity to subject the steel to a very high temperature to reach the upper critical point, Ac 3. No temperature less than 1,500° F. is of any service. The result, even then, is more of a stiffening than a thorough hardening. Carbon percentage of 0·25 brings a great improvement, and the presence of manganese, in proportion as small as 1·0 %, is productive of a great increase of hardness. Manganese is reputed to cause a liability to cracking, but when the percentage is not overdone, and in skilful hands, it is a great source of strength in low carbon steels. It should be remembered, however, that in purchasing steel, the specification, if it includes manganese, the percentage of this metal must be in proportion inversely to the carbon content. Thus if a percentage of manganese of 1·0 % be permitted in the case of a 0·20 % carbon steel, it must be progressively reduced to as low as 0·20 % in a high carbon (over 0·90 %) steel.

Low Carbon Content Bar to Hardening.—It is reasonable to seek an explanation of the bar to hardening presented by the necessarily high temperature called for in the case of low-carbon steel. In reply it should be stated that high heat is destructive of the strength of steel, even in cases when the highest temperature attained is only slightly in excess of the high critical point. As the percentage of carbon rises, there is a marked fall in the degree of heat required to harden it. While decalescence at the highest point (Ac 3 does not occur below 1,600° F. in the case of the lowest carbon steel, it may easily develop at 1,050° F. in high carbon steel, with a corresponding advantage to the tensile strength and general stability of the material.

The act of hardening is well known and extremely simple, since it consists merely in the rapid cooling of steel that has been heated to or above the upper critical point. It is an operation of arrest, or fixation of the particular condition of the atoms composing the mass at that moment. That the network of materials composing the steel is held *under enormous tension* while the full hardness obtains we have every proof. That this condition of tension can be so great as to rend masses of steel asunder, with the force of thousands of tons, we have too much sad experience to prove. In a small way we have it in the cracking of tools after hardening. In extensive engineering work it is frequently manifested in the splitting asunder of heavy shafts, accompanied by a tremendous report.

Since hardening consists in the rapid dissipation of the heat absorbed by the steel, it follows that there are several different media employed as quenches as well as cold water. The chief of these is oil, heavy or light according to the speed required in cooling. The limit of hardness is obtained by quenching in brine. There is considerable modification of it by a quench in oil ; there is a tendency to toughness introduced, and the molecular strain is not so great. Many high carbon steels that will not harden in water without the risk of splitting will withstand the cooling of oil easily. It is at the same time worthy of note that oil hardening is never so effective as water hardening, although it may serve the purpose in view even better.

To relieve to some extent the great strain of complete hardening we have the practice of tempering, which is brought about by the application of carefully regulated heat. The heat of boiling water is extensively used for this purpose, the steel being immersed for several hours. Immersion in hot oil is also largely employed, and in this case, since oil of high flash-point can be heated to several hundred degrees, a great range of work can be treated.

In the case of high carbon steel tools, direct furnace heat is generally employed as well as hot oil, a bath of hot sand, or any source of heat that can be conveniently measured by a thermometer.

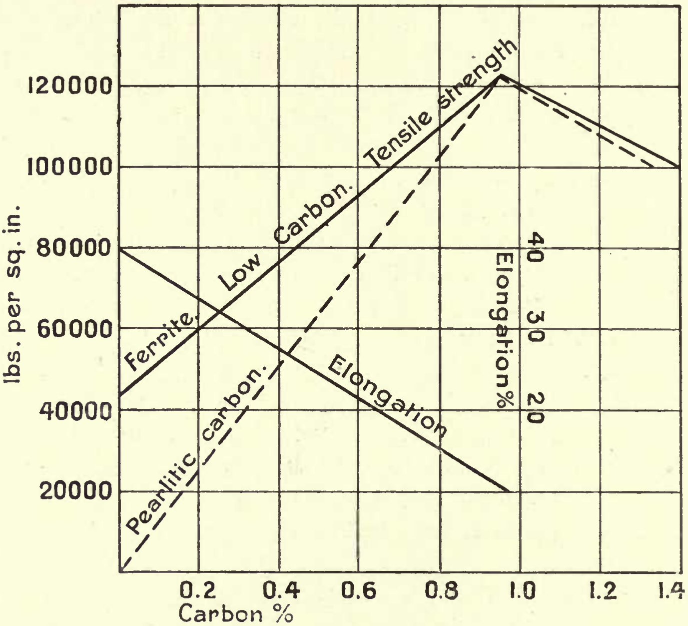
"Back heat" tempering must not be lost sight of, since it is of all methods the most readily available. Here we have the tool hardened at its cutting end only, by immersion, generally in water. As soon as the point has been cooled, the heat remaining in the rear part of the tool is permitted to creep back towards the point, and in doing so relieves the strain there, producing a slight degree of softening.

This would indeed be a haphazard manner of modifying the hardness had we not a means of showing just to what extent the softening had been carried. The ready means is at hand owing to a very simple fact: If a piece of bright steel be heated it will speedily change colour from a pale gold to a brown, followed by a deep blue. These colours, due to the formation of oxide of iron, always manifest themselves at well-known and given temperatures. Conditions of softening of the steel are associated with given temperatures and are closely indicative of them. Thus, if a piece of steel is intended to act as a spring, it will be given "spring" temperature, the colour of which is blue, 600° F. upon the oxidized steel scale. A turning tool, or a fine knife, would be given a light straw colour, 460° F., and a dark straw colour, 480° F., respectively, and so on. In the case of the supposed tool still hot in rear of the point, the colour can be seen to creep towards its extremity if the operator takes the precaution to rapidly polish a portion of it for observation purposes. The application of these principles is fully described in the chapter devoted to steel tools, accompanied by colour and temperature scales.

The kind of tool and spring tempering briefly touched upon above is only available in the case of these articles. It is a "drawing" or "letting down" of the maximum hardness intended to obviate breaking of the steel; in the case of a tool at the cutting edge. In the case of a spring it has a much greater signification in reference to the heat treatment of steel in general, in situations where resistance to stress or impact is mandatory.

Tempering applicable to masses of steel used in constructional work, in engine building, in wheels, shafts, springs and frames in automobile manufacture, is conducted in a different way, but the principle is the same. In the case of high carbon steel we have the extreme limit of hardness, incidental to carbon, developed, followed by a modifying treatment.

In the case of general machine building steel, on the other hand, we have a degree of hardness developed which is best adapted to lead to toughness and stiffness. The exception to this may be said to be the parts subject to abrasive wear, a good example of which is the bevel gear upon the differential shaft of the automobile. The actual wearing surface of the teeth of this wheel is generally desired to be in the dead hard condition, while the mass of the wheel itself should be in a comparatively flexible and even ductile condition.



Tensile strength and ductility as related to Carbon.

FIG. 3.

Automobile Steel Temper.—A frame member of an automobile, before treatment as it leaves the hydraulic press, if subjected to bending stress would "double up" and remain in that condition after removal of the stress. After the second application of heating and quenching, the same member will be harder in substance, and will offer considerable resistance to cutting. It will be tough, and it will be resilient. It will not double up under bend stress, but will give to it, ready to spring back to its original form. Lastly, its tensile strength will be enormously increased.

Physical Strength.—Dealing with carbon percentages, from 0·2 to 1·4 in the different grades of plain steel, the diagram, Fig. 3, exhibits average results obtained under test.

Tensile Strength.—The tensile test is the most informative of all tests. Figures relating to it give us the force in tons or pounds per square inch of section that have to be exerted to tear it asunder. A tensile strength declaration with guaranteed figures is the best certificate that can be obtained when purchasing steel for all purposes except those falling under the head of high carbon and high speed steel.

Elastic Limit.—Taking, as in the above example, a frame member of an automobile, an elastic limit test should clearly define the *minimum pressure required in order to cause the steel to retain a permanent set or bend.* The value of this test will be at once recognized.

It would appear that the term "elastic limit" applied to a test of this kind is a singular misuse of words, since elasticity is associated in most minds with the word "stretch." Nevertheless, many of these bending tests are still so named. Deformation or bend test would appear to be much more explicit. Many testing authorities use the words "elastic limit" in their true sense, which may be taken to mean the utmost pull that can be exerted upon the steel before it exhibits signs of stretch. This test is carried out upon a bar of moderate dimensions, frequently eight inches long and a fourth of an inch square. This test-piece is furnished with enlarged ends. Minute centre-punch marks are made upon it at exact intervals to receive the points of a Ewing extensiometer; a means of marking which has lately been condemned because rupture usually occurs at one of these marks, leaving the true point of rupture in doubt.

This means of taking an elastic limit test is really the same as that carried out for the *Elongation* test. Within the test is also that for *Reduction of Area*, where the original area has deducted from it the area of the smallest section. Many other debatable points can be determined by this test, such as the nature of the steel as a ductile material.

Torsion Test.—This is perhaps the most informative of all tests for materials to be used in automobile engine and transmission gear, for the reason that it declares the resistance to twisting of a particular brand of steel. From the crank-shaft to the road wheels there is torsion and sudden wrenching of a nature seldom met with in any other kind of mechanism. A steel of great resistance to any kind of deformation is demanded here. It is to be found among the new alloy steels, in the chromium-nickel and chromium-vanadium groups, and even, by the aid of skilful treatment, in carbon steel itself.

Impact.—The test by means of a blow delivered to the steel is much more drastic than a gradual bending test. It is carried out in the testing establishment by dropping a given weight, from a given height, upon a bar supported at either end upon a heavy anvil—Frémont's drop-test apparatus. The general object aimed at is the breaking of the sample if it is not of a predetermined resistance. Where the piece is fractured valuable data can be obtained from the figures governing the extent of the blow and the appearance of the ruptured ends. The detection of brittleness is the chief use to which a test of this kind can be put.

General Conclusions.—Speaking only of carbon steels, the strongest material must be regarded as one that possesses the salient qualities of resistance to deformation; and, when this resistance has been overcome, will show non-liability to cracking or fracture. These conditions must leave out of account the higher carbon steels that are, for various reasons, subjected to extreme hardening process. An extremely tough steel that calls for much force to bend it and that exhibits no sign of coming rupture in the result is the ideal material sought after for general purposes. To obtain this the ductility of pure iron must be associated with a due proportion of carbon.

Impurities, sulphur and phosphorus which cannot be got rid of entirely, should be as low as 0·02 %; carbon should not exceed 0·40 %, although a very tough steel can be produced with a smaller content, even as low as 0·20 %. Between these limits should be sought the carbon steels adapted even for automobile frame building, and for all purposes where wrenching is apt to produce deformation.

With the higher carbon limit there will be useful resilience. But it should be clearly understood that, as the carbon content is increased the liability to breakage under a springing test is unavoidable.

The full dynamic strength of the above steels cannot be expected in their raw state. Under heat treatment this quality can be greatly increased, as will be shown in subsequent chapters. In another chapter will be found full details of the hardness tests, carried out by means of the Brinell and Shore systems.

The value of these systems lies in two directions: the test numbers possess a real value, as giving close approximation of the actual tensile strength, and the means of carrying it out can be installed in every workroom. These two conditions being granted, it follows that the elaborate appliances of a testing laboratory can be dispensed with in the general work of an engineer's shop. Testing can be conducted continuously, piece by piece, without risk of injury to the steel. Thus, from time to time the more drastic tests of a testing institution may, and indeed must, be resorted to by way of confirmation of the work carried out by the Brinell and Shore methods.

We cannot in this chapter do more than mention either of the above three systems of testing steel. While the Brinell and Shore systems are directly associated with the daily output of the workshop, and form part of the labour expended there, it follows that these methods of the workshop tests should find appropriate treatment in the present volume. But with regard to the testing laboratory methods, the art so greatly developed in these institutions now forms a skilled pursuit by itself. Any work attempting to deal with it usefully would have to be devoted entirely thereto.

Mild Carbon Steels.—We have seen that steel is an alloy composed of pure iron and carbon. The fact that it is difficult to eliminate from this alloy certain small percentages of impurities does not alter the broad fact. Of late, certain percentages of manganese, a white hard metal, have been extensively used, chiefly with the object of stiffening the more simple alloy. But leaving this material out of consideration for the present we may regard the *Mild Steels*, all within the hypo-eutectoid carbon ratio, as that group having a carbon content so low that they will not harden if quenched at a red heat, or the heat of decalescence, Ac 3. There is a certain tendency to stiffening, but not true hardness in this group of steels.

It is difficult to set a limit to the exact percentage of carbon that will ensure hardness at the upper critical point of heat, but steels having carbon below 0·30 % may be regarded as included in this group.

These are known as *Basic Open Hearth Steels.* The *Soft* variety has commonly a carbon content of 0·10 % It is extremely ductile. It will withstand being pressed into automobile frames, or drawn into tubes, after which operations it is found to be greatly stiffened, and is generally under stress, which can be released by annealing.

This grade of steel is really too soft for turning or screwing operations. In the turning lathe it will rip and tear. Holes drilled in it are difficult to reamer cleanly, so that it is not suitable for making machinery parts demanding cutting operations.

It can be case carburized and hardened afterwards, but is not so satisfactory for this purpose as a slightly higher carbon steel.

Machinery Steel.—The next grade may be given as 0·20 % carbon steel, also within the hypo-eutectoid ratio. This is a most useful material, and with it may be included 0·25 % carbon steel. Here we have a grade of steel that may be turned, planed, screwed and reamered. But for really clean screwing, a still higher grade is better adapted. Case carburizing and hardening is at its best in steel of this class. Parts made from the 0·25 % grade may be stiffened and toughened by heating just above the Ac 3 point, about 1,400° F., quenched in oil, reheated to just above the Ar 3 point—1,250° F.—and finally quenched. This is a perfectly safe treatment, the application of which is elaborated in a subsequent chapter.

High Grade Structural Steel of the hypo-eutectoid ratio 0·40 %. This steel will straight-harden, and, being almost of " mild " grade, forms a material of great tensile strength. It is adopted for making crank-shafts, levers, connecting rods, gudgeon pins, steering gear, transmission shafts and screws and bolts. The Ac 3 heat point of this steel may be as low as 1,350° F. This may be certified, if desired, by means of the magnetic needle already mentioned, if not by a pyrometer.

A very simple means of working this steel is to take a test-piece of a size about an average of the articles to be heat treated, and to put this piece through the hardening process, using either the pyrometer or the magnetic method, *noting carefully the red appearance of the steel* just prior to quenching. If under these conditions the steel be found hard throughout a zone extending across the fourth of the diameter of the piece, a repetition of the same degree of heat should bring the same result, without resort to magnetic or pyrometer assistance. An operator used to working steel will have no difficulty in memorizing the red-hot appearance of the material at the critical point. As already stated, this quenching fixation should not be effected until the temperature has risen somewhat above the Ac 3 point, in order to stabilize the molecular condition of change and to ensure uniformity of heat penetration.

Visualizing the Heat.—While by no means advocating the practice of depending upon the eye in estimating the degree of temperature, we feel that it is useless to ignore the very great convenience of this method, when compared with the procedure in the use of either the pyrometer or magnetic test. In the case of only a few pieces under treatment it is absurd to suppose that the hardener can be induced to employ a pyrometer. And he may be justified if he can depend upon his eyes. This is all the more certain when we know that men become so expert in this respect that they can, if used to the employment of pyrometers, judge of the temperature within as close a limit as twenty-five degrees. Everything depends upon the nature of the diffused daylight around. Hardening should always be conducted in a room where the light is fairly uniform, on the dull side, and free from all direct sunlight. An ideal hardening room, if the quality of the product is to depend upon the eye of the operator, should be lighted only by electric lamps at constant voltage.

As a matter of course, if a furnace be heavily charged, and therefore contains parts of great value, pyrometer working should be mandatory. It should never be permitted to abandon the heat-measuring methods and rely upon the eye only. Further on in this work will be found instructions for frequently certifying the correctness of thermo-electric pyrometers—a very necessary procedure, as experience with these instruments has shown ; and also optical aids to the eye, which are so exact that it is questionable whether they are not more to be relied upon than thermo-couples. There need be no excuse at the present day for the empirical working of steel ; the scientific aids are available and easy to understand. One error of judgment in empirical working may eventuate in the spoiling of a whole furnace charge of valuable steel parts or, much more likely, compel the whole process to be gone through a second time through over-estimating the heat, certainly to the partial detriment of the goods.

Steel may certainly be hardened throughout a *wide* range of temperatures ; this applies with greater force to high carbon steels. Here it is that the risk of poor results creeps in. There is a very great difference between the quality of a steel hardened at the *correct* temperature and a steel hardened at *any chance* temperature. Let it be clearly understood that carbon steel can be made hard at a heat so great that its grain or microstructure is of the gingerbread order, and when it is ready to crumble into burnt steel dust under impact or stress. And steel may be hardened at so low a heat that, while a file may not cut it, its microstructure has not the dynamic strength or resilience required. It will probably be deficient in rigidity. The file-resisting cementite will be interstratified with soft pearlite ; the emulsifying effect of the heat attained has not been sufficient to complete the change. The stage reached may have been Ac 2 instead of Ac 3.

Range Temperatures for 0·40 % Steel.—The Ac 3 or high critical point should be attained at 1,425° F. It is probable that the Ac 2 point will have been touched at 1,330° F. *where magnetism will have been lost.*

Carbon, 0·60 %.—This falls also within the hypo-eutectoid ratio. We have here a machinery steel which should only be used where great stiffness and hardness is required. It is more difficult and expensive to work than the steel considered above. It is not so safe in positions liable to sudden bending stresses. It will harden easily, reaching its decalescence (Ac 3) at about 1,375° F. and the Ac 2 point (magnetic) at about 100° F. lower.

Carbon, 0·85 % to 0·90 %.—Here we reach the eutectoid stage, and that of carbon saturation. The steel is hard, difficult to machine, of high specific gravity, and will harden easily at a low heat. The Ac 3 critical point will be reached at about 1,330° F. and the Ac 2 stage (magnetic) 100° F. lower. This is a tool steel suitable for tools intended for cutting all but the hard metals, although it will make a very good showing even upon these, when suitably hardened and tempered.

Carbon, 1·0 %.—Here we enter the hypo-eutectoid field of steels, distinguished by their characteristic of super-saturation carbon ratio. And it is when the percentage carbon has reached this point that even casual observation cannot fail to notice the steady fall in the degrees of heat at which the critical stages occur as carbon is increased. Carbon and nickel have both the property of lowering the allotropic transformation of ferrite, and as will be made clear later, nickel leads markedly in this respect. Since this class of steel is of a dense, hard, non-resilient nature, its application is comparatively limited in any class of constructional work. Hence it is chiefly employed in the manufacture of cutting and percussive tools.

In its heat treatment the most striking characteristic is the lowness of its decalescence temperature (Ac 3 point).

A steel of 1·10 % carbon will be found to reach the critical point at approximately 1,330° F. Its recalescent stage (Ar) may be taken as fully 100° F. below this figure.

The American Differential Pyrometer method has shown itself as singularly accurate in securing records of the correct decalescence of these high carbon steels.

According to this system, a sample of the steel to be tested is attached to the hot end of one recorder; and a similar piece of pure soft iron (by preference) is similarly attached to the hot end of another recorder, both instruments being in correct reading condition. If the two samples in the furnace are situated close together, there will be a certification of the furnace heat—that is, the uniform heat to which the iron sample is exposed—and a reading of the changes of temperature undergone by the steel involved in its absorption and liberation of heat at the decalescence and recalescence points.

Hyper-Eutectoid Steels versus High Speed Steels.—For various reasons the rivalry between super-carbon steel and tungsten high speed steel really commences at the hyper-eutectoid stage of carbon. Below this point the carbon steel tool holds its own against all comers. Above this point it depends upon the work demanded of a tool whether carbon or high speed steel shall prove the better. From practical experience the author holds that, for execution and endurance, the high speed steels are not approached by the carbon steels, even of the highest eutectoid ratio. But in the holding of a superfine edge, resulting in a superfine finish upon the work of a turning lathe, the high carbon steels—but not the very highest—are not to be equalled. Further comparison of these qualities are given in the section of this work devoted to tool steels.

Nickel Steels.—As an introduction to the chapter devoted to the nickel group of steels, it would appear advisable to mention at this stage some of the more striking characteristics of this remarkable material, with the object of reviewing the elemental side of the subject.

The incorporation of nickel with carbon steel may be taken as the starting-point of the introduction of the alloy steels, and the results were so significant that they have doubtless led to the ceaseless search for further and yet more alloys of a useful nature. Much work remains to be done in discoveries in this field. Nickel is a metal of great hardness, of a uniform texture, and of a colour between silver and tin, difficult to purify and possessing certain magnetic properties of a peculiar kind. It is malleable, both in the hot and cold state. When cast, its specific gravity is 8·279; when compressed by forging, this may rise to 8·665. So long as it possesses a small percentage of arsenic it will remain non-magnetic. Until recently, nickel has been obtained from its sulphuret—the Kerfernickel of Germany. Its extraction, in the pure state, has always been a long and difficult process; hence its high cost.

Dynamic Strength.—The strength of nickel steel is enormous. It has displaced carbon steel in most applications where cost is considered a secondary consideration. If 1 % of nickel be added to carbon steel the tensile strength of the latter will be increased approximately 5,000 lb. per square inch of section, and this holds good for each 1 % addition up to 5 % of nickel. There is no decrease of ductility. Moreover, if this be true of a mild carbon steel of 0·2, it is still more marked in a carbon steel of 0·25 %, and so on.

A good quality of nickel steel will contain 3·50 % of nickel, 0·25 % of carbon, various percentages of manganese, and of impurities a small proportion—perhaps 0·02 % of sulphur and phosphorus. A nickel steel of this grade will exhibit a tensile strength equal to that of a straight carbon steel with 0·45 % carbon, with much greater ductility and an enhanced elastic limit.

Manganese, mentioned above in association with iron and carbon (one of the earliest alloys), is peculiarly affected thereby. A hard, brittle, whitish metal itself, it yet becomes comparatively ductile when alloyed with iron. It has great stiffening properties when alloyed with steel and nickel.

Low Critical Range.—One of the most remarkable effects of alloying nickel with mild steel is the lowering of the temperature of the Ac range, an effect which in itself makes for increased ductility, toughness and resilience in the finished product. And not only is this true of a specific nickel percentage, but the fall of the critical point is to a great extent proportionate to the nickel content. Thus, it is found that for each 1 % nickel up to about 6 % nickel the critical temperature is lowered approximately 18° F.

A straight carbon steel, which does not attain its decalesence below 1,350° F. will, if it be alloyed with 1 % nickel, reach that point of change at 1,330° F. A progressive drop is observed for each 1 % of nickel, so that when the nickel content reaches 5 % the temperature of decalescence will have fallen to 1,250° F. Here we have a drop of 100° F., which means diminished cost of working nickel steel as well as a greater margin of safety against overheating. This condition alone would give a preference in favour of nickel steel.

Carbon Saturation-point Lowered.—We have seen that the point of carbon saturation in a straight carbon steel is 0·90 %. The alloy with nickel progressively reduces this eutectoid point. From numerous experiments made by leading metallurgists it would appear that the point of carbon saturation can be reduced from 0·9 % to from 0·50 % to 0·60 % with a nickel percentage as low as 7. A ready proof of this fact can be obtained by the carburization of nickel steel of low carbon content (fully dealt with in "Case Carburization," Chapter VIII), when it will be found that the period under heat may be greatly reduced to obtain maximum results, the temperature itself being also subject to reduction in accord with the lower Ac point of nickel steel.

Long Heating not Detrimental.—Without attempting in this chapter to deal with the thermic treatment of nickel steel for the development of maximum strength, note should be made of still another point of difference between this material and straight carbon steel.

It is well known that if a carbon steel be exposed to a high temperature it is liable to embrittlement approximately in proportion to the length of exposure. It is, of course, of the first importance to know what is meant by a high temperature. This is a relative matter, and depends greatly upon carbon content. In low carbon, or mild steels, with less than 0·20 % carbon a high temperature may mean anything above the Ac 3 point, or full decalescence, which will be about 1,475° F. An excess of this heat is always recommended, in order to fully stabilize the emulsive effect upon the microstructure. This excess, in most cases, will be at least 25° F. At 1,500° F., therefore, the mild steel should be ready for quenching or slow cooling. It should not be permitted to remain many minutes exposed to the high temperature, at the risk of "opening the grain," or embrittlement. Nickel steel is found not to be injuriously affected by exposure, even for an hour or more to a much higher temperature.

It is open to question whether high heat or long exposure to it is beneficial to the ultimate finished steel. Experience points to the safer course of quenching as soon as the highest point of heat has been attained. But there can be no question as to the great practical advantage of being able to treat nickel steel with less care than usual when heating either for annealing or quenching for hardening or toughening.

The distinguished metallurgist, M. L. Guillet,[1] states that a sample of mild carbon steel, exposed for a short period to a temperature of 1,830° F. and cooled, broke under a shock-blow of 20 kg.; and after exposure to this heat for four hours gave way under 4·5 kg.; while a sample of 2 % nickel steel, exposed to the same long heating for four hours, withstood successfully a shock of 60 kg.

It may be here remarked that the above temperature exceeds anything usual in treating mild steel, except for forging purposes, and that it is far above a necessary heat for nickel steel for almost any kind of treatment. This makes the test the more remarkable, since the normal critical range of mild carbon is so far above that of nickel steel.

The Quenching Temperature.—In all heat treatments

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[1] *Traitements Thermiques des Aciers.*

aiming at toughness and dynamic strength, and not at mere hardness, the quenching may be conducted at a point between the Ac 3 and the Ar stages. The latter is usually 100° F. or more under the former. This precaution is a safeguard against deformation as well as over-hardness. Deformation and embrittlement are very apt to be caused in all steels at temperatures much above the higher critical point, and are simply fixed by the hardening or toughening quench. No advantage in the way of toughening can be secured if the quenching takes place below that Ar stage. Annealing or refining of the structure of the steel is all that can be expected.

Effect of Mass.—Whether we deal with carbon or with alloy steels, and whether the object aimed at be annealing, toughening or hardening, the most important point to keep in view is, after temperature, the diffusion of the heat throughout the mass of the steel. The behaviour of thin sections is very different from the heat progress of heavy parts such as solid locomotive and car axles. The permeation of the mass demands time ; resolution of the microstructure requires more time. The thorough soaking of the mass must be the end in view. No heed must be paid to the exterior red-hot appearance in reference to this matter. Numerous failures in heat treatment can be traced to want of knowledge upon this point.

It is a common practice to raise the furnace temperature so as to rush the heat into the core. This is bad practice. It only overheats the exterior, and tends to embrittle that portion of the mass. If mass is to be handled at all, time must be allowed for proper heat-uniformity throughout.

The Higher Nickel Steels.—While any of the grades of nickel steel can be case hardened, or simply carburized, this process is usually carried out with the object of producing a steel of super-strength internally and a hard exterior. For this purpose a nickel content of 5 % is to be recommended. As this steel is hard and difficult to machine, before carburizing, annealing has generally to be resorted to in order that the cost of turning and planing may be reduced. This may be carried out preferably by packing in iron tubes with closed ends, in lime or lime and charcoal, sand or fine ash, exposure to a heat of about 1,400° F. for one hour after thorough saturation, and followed by slow cooling.

There is one point relative to the carburization of nickel steels of from 5 % to 7 % which should be noted; very seldom is it necessary to carry the carburization far into the steel. In the case of a mild carbon steel, carburized zones of $\frac{1}{16}$ of an inch in depth are not unusual, although for some purposes, such as gears, this excess depth might lead to breakage. But in the case of high nickel steel a depth of from $\frac{1}{64}$ to $\frac{1}{32}$ of an inch is considered ample and is indeed more efficacious than a greater depth.

In order to obtain maximum results carburization should be effected at a moderate temperature (1,500° F.) in a *mild* carburent, such as ground wood charcoal, perhaps with an admixture of lime. The object aimed at is to produce a carburized zone well under the eutectoid ratio, and possibly not over 5 % carbon. When this is well carried out, followed by *oil* quenching, there will result a toothed gear glass hard on the surface, but of a superlative toughness, so that chipping or flaking cannot possibly take place. The core will be of unquestionable strength.

The latest practice points to double quenching as being still more effective. In this case the articles are left to cool slowly in the carburizing material, reheated in the open to a temperature between 1,500° and 1,600° F., plunged into oil until the colour leaves the surface; reheated to 1,350° F. and cooled out in cold oil. The first heating is the regenerative heat, aimed at bringing the molecules into the strongest dynamic relationship. The second is the hardening heat. While this process is lengthy, it cannot be equalled by any of the simpler methods in bringing out all the tensile strength of the steel. Fuller details of these treatments are given in a subsequent chapter.

Highest Nickel Steels.—These steels are so little affected by oxidation or corrosion that they are used for a variety of purposes other than machine parts, such as cutlery and instruments of precision. The carbon content will vary from 3 % to 5 %; the nickel content from 25 % to 35 %. They are hard and difficult to machine, the high speed steels being the most effective in the tools used. So little affected is this nickel steel by heat that it is used extensively for making exhaust valves of internal combustion engines.

NICKEL-CHROMIUM STEELS.

From a thermal point of view the most salient characteristic of a steel in which chromium is in alloy with nickel is the higher temperature at which the Ac range is developed. The distinguished French metallurgist, M. Guillet, gives the highest figure of 4° F. rise for each 0·1 % chromium added to the nickel steel. Taking a nickel-chromium steel of 0·50 % chromium, he found the first stage of critical range Ac 1 commenced at 1,375° F., rising steadily until it reaches 1,425° F. with a chromium content of 4·0 %.

This figure would appear to raise the Ac 2 stage to over 1,500° F. and the culminating point (Ac 3) to 1,625° F. It will at once be apparent that a maximum hardening effect upon the hardening cementite will be assured at this high temperature ; but a considerable influence upon the cementite constituent is exerted by the presence of the double carbides of chromium and iron, which modify, to some extent, the extreme brittleness of the carbides of iron.

Guillet found that the presence of carbon is necessary in chromium-iron steel to form a hardening material—that chromium was not a hardening agent in association with iron.

Chromium is found to be a valuable material in the production of steels that resist corrosion, the degree of resistance rising with the percentage of chromium.[1]

THE THREE GRADES.

Starting with a carbon percentage of 0·25 % and a chromium percentage of 0·50 %, there are in general use three types of nickel-chromium steel, reaching as high as 0·50 % carbon and 0·50 % chromium.[1]

The most successful commercial steels are graded from 1·5 % nickel to 0·5 % chromium up to 3·5 % nickel to 1·5 % chromium. An intermediate grade is the most generally useful. If chromium is in excess there will be difficulty in heat treatment.

The higher the chromium content, the harder and denser becomes the steel, with increasing difficulty in both forging and machining. With regard to the forging heats, a plastic condition must be maintained while it is under the hammer. With regard to the turning and shaping operations, the

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[1] See " Stainless Steel," Chapter XIV

effect of annealing is very marked, so that with high speed steel tools there is no difficulty in manufacturing parts in nickel-chromium steel.

The Automobile Grades.—In the manufacture of automobile parts at the present time, the nickel-chromium alloy is in high repute. The following four kinds of this material, viewed from the standpoint of their carbon content are representative. Taking an ordinary steel containing 2·50 % nickel, 0·50 % chromium, we have the carbon constituent as follows :—

0·25 % carbon. Used for all parts that should be case-hardened, or merely case carburized, making transmission systems, cams and cam rollers, steering worms and worm-wheels.

0·3 % carbon. Parts not usually case hardened, but in many instances case carburized : axles, steering shafts and rods, knuckles, untempered hardened gears, steering pivots.

0·40 % carbon. This steel is not generally hardened unless for subsequent grinding, for the following parts : crank-shaft, driving shaft, line axle, counter or cam shaft.

0·50 % carbon may be used for all of the last foregoing parts and not generally subjected to heat treatment in the *finished* condition, unless for finish grinding.

It should be remembered that heat treatment of any kind for finished parts that are intended to run true in bearings should seldom or never be attempted unless the part treated is hardened with the intention of securing its return to truth of running through the agency of grinding. Any heat treatment is apt to cause a part intended to run true to lose its " truth."

For High Duty Gears.—Under appropriate treatment there is probably no material as efficient as nickel-chrome steel for the production of heavy duty gears. It is in extensive use for the bevel and worm drives of automobiles. While it is a disputed point whether it is necessary to go to the expense of producing large gear wheels in this material, seeing that even mild steel case-hardened gears give such good service, and higher grades do better still, it is unquestionable that, where cost is a secondary consideration, a nickel-chrome steel of moderate percentage will withstand treatment that no other material hitherto tested can endure. This has as much reference to the body and boss, or bore section, of the wheel as to the teeth themselves. Indeed, from instances given in a subsequent chapter it will be seen that a perfectly case-hardened and toughened mild steel gear can be produced commercially that, as far as the resistance of the teeth to abrasive wear is concerned, cannot be surpassed. And such a wheel, barring shock that might break a tooth or deform the boss, might last as long as may be desired. The great point in favour of the strong alloy steels, such as nickel-chrome, lies in their ability to resist shock, and the same may be said to apply to the numberless parts of engines and machines made at the present time from this material.

A characteristic of the gears and parts made from nickel chrome steel is their dynamic strength *throughout*. There can be no doubt that this condition leads to endurance in a general sense. With moderately skilful treatment the extra cost of the finished part, as compared with that of parts made from any grade of carbon steel, is not great. The first cost—that is, of the raw steel—does not often exceed the basic price of a fine grade of carbon steel by 10 %.

Fatigue Effects.—Considerations of the deductions of Guillet, in his work *Les Aciers Speciaux*, appear to confirm the claim that a good nickel-chrome steel is not affected by fatigue to the extent of crystallization.

This, to some extent, appears to be a feature of most of the high resistance alloy steels of recent development.

CHROMIUM STEEL.*

The combination of iron, carbon and chromium results in a steel having certain advantageous characteristics. It can be made into undrillable plate for safes.

It may be of interest to state that chromium is generally obtained from the native chromate of iron. It is a greyish white metal, intermediate between tin and steel. Its specific gravity is given as 5·9. It is feebly magnetic, and resists all acids except nitromuriatic at a high heat.

Chromium steel is usually composed of iron, carbon, chromium, manganese and a little sulphur, phosphorus and silicon. When the chromium content is about 1·50 % and the carbon 1·0 %, a material results of a high resisting nature suitable for ball bearings, impenetrable plate, rock

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* See also "Stainless Steel," Chapter XIV.

crushing jaws, cold swaging dies, rock drills and all positions demanding a very hard surface, with an almost unyielding backing.

It should be understood, however, that the hardening agent is carbon, for if this be withdrawn, resistance to impact ceases.

This steel has a limited use, but its employment is extending. It should be forged at a good red heat only. It may be annealed in the usual way, and can then be machined. The Ac 3 critical point of this steel, to which it must be brought for hardening, is about 1,425° F. Quenching should occur before the heat falls below 1,400° F.

VANADIUM STEEL.

Although there are instances where vanadium steel—that is, carbon steel with a percentage of vanadium only—is in use, it cannot be said that this combination has proved successful for many purposes. It is probably because vanadium gives to carbon steel a fine texture on fracture, and also adds to this material an increased dynamic strength, that it has come into use at all.

But while this can be said of vanadium itself, it should be understood that it is seldom that there is not a percentage of chromium in so-called vanadium steel, since the addition of chromium appears to bring out latent qualities not otherwise developed in simple vanadium steel.

This steel is now used in France, Germany and the United States for heavy work such as locomotive crank axles, dynamo shafts and turbine shafts, as well as for lesser applications.

Heat Treatment.—The only notable result of hardening chrome-vanadium steel is that it is characterized by a somewhat greater depth than is the case with any of the foregoing steels. This is in itself a valuable feature. The higher critical point will be found to be high, at least 1,500° F., and the quenching temperature correspondingly higher. It will be understood that this feature in itself makes for an increased depth of hardened zone.

HIGH SPEED STEELS.

The hackneyed term "high speed steel" conveys no true meaning to the early student; for it is not the steel that is speedy, but the work or material upon which it is employed as a cutting tool. It is simply a super-hard steel containing with its adamantine qualities a super-toughness. Hardness is generally allied with brittleness ; here we have, as is the case with chrome-nickel-vanadium steels also, a super-toughness. It is true that, chiefly owing to its tungsten content, high speed steel *is not easily softened*, and it is this faculty that makes it a super-cutting steel.

It may be advisable to explain to those not conversant with the subject that in the cutting of iron and steels, as they are shaped in the turning lathe, or in drilling holes through them, the friction of the work being done gives rise to considerable heat. So great is this heat that running at a surface rate of, say, fifty feet per minute past the point of the ordinary cutting tool, the shavings being cut away will be red-hot. This heat is taken up by the cutting tool itself, and with the result that it becomes hot enough to become softened—or it loses its temper, as it is called. It then ceases to cut, and its edge is speedily rubbed away. In the early days of alloy steels, Mushet discovered that the addition of a proportion of the then rare metal tungsten to ordinary carbon steel conferred upon it the quality of *retaining its hardness* even at a red heat. This was a great discovery. At that time the hard alloy steels of to-day had not been thought of, but we now know that if tungsten had never been used in this connection we could have produced steels nearly as effective in this particular respect from other materials.

Tungsten itself is a very hard and brittle metal of an iron colour, but having a brilliant surface. Its specific gravity is about 17·22. It is unaffected by acids. It burns in chlorine gas with a *deep red* flame. Hence tungsten can be recognized when a tool containing it is pressed upon a grindstone as the sparks given off are of *a deep red colour.* This is a standard test, in experienced hands, as to the nature of high speed steel as distinguished from ordinary steel, from which the spark is bright, white and explosive.

The high speed steels of to-day all claim to have this property of "red-hardness," that is, great hardness at a red heat. The practical advantage of this will be at once apparent when we consider that, so long as a cutting tool will retain its hard edge, we can continue to increase the cutting or surface speed of the material operated upon ; hence arose the term high speed steel. By its use the production of a given machine tool can easily be doubled, and much more than doubled if, as is usual, the depth of cut be increased also.

Self-hardening.—The very high temperature required, to result in hardness after cooling, has made it possible to "quench" tungsten steel in the air only. But it should be noted that the difference between the quenching heat of carbon steel and water is no greater.

Composition.—The materials composing the high speed steels of to-day are those associated with a carbon steel of moderate carbon content and in addition, a percentage of tungsten chromium, and manganese. Vanadium is also included, either in place of, or in addition to, chromium.

Specifications of various makes of high speed steels are given in the chapter upon "Tool Steels," accompanied by details of forging and hardening temperatures.

The use of tungsten has of late been extended into other fields. A low tungsten steel, containing 0·60 % of tungsten, makes excellent springs. Tungsten steel is also used extensively for the making of permanent magnets and for compass needles. Since this class of steel has at present to be made by the crucible process, its production is limited, and its cost too great to permit of its use for structural purposes.

Molybdenum Steel.—We have in molybdenum an intensely hard material, difficult of fusion. Its alloy with carbon steel, to the extent of from 2% to 4 %, results in an extremely tough steel, used chiefly for rifle barrels. Its cost precludes its general use, and it is questionable whether it offers any advantages over a combination of tungsten and chromium. The heat treatment of molybdenum steel is similar to that of a high carbon steel, except that it is usually quenched in oil at about 1,500° F. and reheated to 1,025° F.

CHAPTER II

PHYSICAL CHARACTERISTICS OF STEEL

THE common term "raw steel," while more expressive than scientific, is roughly descriptive of the steel bars or plates just as they have left the rolling mill of the steel works.

Steel is manufactured under rigid specification. Its proportions of ferrite (simple iron), pearlite (carbon in partial combination with ferrite), certain impurities, such as sulphur and phosphorus, and usually silicon and manganese, form a whole which is known as Carbon Steel. This is a material which, in spite of the remarkable developments of recent years in the evolution of alloy steels, may be said to hold a high position at the present time, as it forms the basis of comparison for all subsequent advances along this line.

It should be understood that steel is a combination of the best grades of simple iron (which cannot be hardened, and are therefore useless where cutting qualities are required) with certain substances which enable us to harden the whole mass.

Influence of Ores Used.—It does not come within the scope of this book to discuss at full length the influence of the iron ore used as a basis in making carbon steel. This matter will be found reviewed in works on iron- and steel-making; but we may say here that the origin of the ores used is the determining factor in the good or indifferent quality of the product as steel for tools. The ores known as Swedish are pre-eminent in this respect. No process in the manufacture can attain to the highest qualities when the ores used are not of the requisite grade. When seeking for steel for, say, razors, make sure of the origin of the *Iron Ore,* and this preferably from the Central Ironstone Belt which lies across Sweden.

The substances referred to above are for common carbon steel only, and for alloy steels we may include Nickel, Chromium, Vanadium, Manganese, Tungsten, and Molybdenum. But all of these alloys are associated with carbon itself in certain proportion.

Nickel steels hold a high position, although the nickel content may be regarded as a toughener, rather than as a hardening agent. Nickel-iron combinations are regarded as dynamically "strong" steels and not as hard steels. The range of alloy steels aiming at a combination of hardness and toughness is now very large, and of the greatest importance. It may be taken for granted that in the matter of dynamic strength, endurance and dependability the original carbon steel has been quite surpassed by almost any of the "strong" alloy steels of recent developments.

The evolution of high speed machinery, embracing automobiles, and aero power units, during the past fifteen years gave a great stimulus to the development of those alloy steels. It is generally recognized that failing the production of these steels the automobile as we know it would have been an impossibility. Its weight would have been very much greater, and its powers of endurance a mere fraction of its present-day efficiency. The necessity has produced the material, and the possession of the material has opened up a vast field of enterprise in the history of our time.

But, given those "hard steels," and those "strong" varieties, we know that in their raw state their possibilities are but entered upon, and here we come to the important subject of after heat treatment.

Importance of Testing.—The selection of the material for any constructional or manufacturing proposition must not be left to mere specification. Actual testing, therefore, reproducing as nearly as practicable the ultimate duty of the steel is mandatory. The correlation of the chemical composition of the steel and its subsequent heat treatment must not be lost sight of in our search after the highest dynamic qualities in the product. We have already discussed certain of these problems, and others remain to be referred to in a subsequent chapter as they effect the qualities of the steel for specific performances. The use to which the steel is to be put is the question that matters, and before proceeding it will be well to briefly review both the effect of varying the composition of the steel and the means at hand of reproducing, as tests, most of the stresses and strains found under actual working conditions, or as near thereto as practicable.

Carbon and Tensile Strength.—Taking the simple Carbon steel first, let us test the tensile strength of pure iron only, and call it 100. Let us now take the same quality or purity of material with a carbon content of 0·10 %. Under test we find the tensile strength increased at once to 125. Let us continue to add to the carbon content, and our tests will show an increase in tensile strength of approximately 2·5 % for each increase of 0·01 % of carbon. There is, however, a well defined limit which should be well understood. Each of the samples of steel for our supposed tests will be known by the steel-makers as of a certain "temper." This particular application of the word temper of the steel should be distinguished from the tempering, or drawing down after hardening, of tools. The temper of a raw steel is to a great extent synonymous with its carbon content.

Formulæ to determine Tensile Strength.—Taking the commercial acid and basic open-hearth steels in their untreated condition, Campbell gives the following formulæ by the aid of which the tensile strength of such steels may be determined within the ordinary limits :—

Acid open-hearth steel—

$$\text{Tensile strength} = 40{,}000 + 1{,}000\,\mathrm{C} + 1{,}000\,\mathrm{P} + x\,\mathrm{Mn}$$

Basic open-hearth steel—

$$\text{Tensile strength} = 41{,}500 + 770\,\mathrm{C} + 1{,}000\,\mathrm{P} + y\,\mathrm{Mn}$$

In which C stands for one point (0·01 %) carbon, P for each 0·01 % of phosphorus, Mn each 0·01 % of manganese. The value of x and y is given in the table on page 40.

The Elastic Limit.—A term generally covering elongation tests, and also used to determine the point at which a permanent deformation of the bar test results. In other words, a steel bar supported at each end will, under central pressure, spring under the weight. The *minimum* pressure that serves to give a permanent set of the bar after the removal of the pressure reveals the elastic limit, or resistance to bending of the sample. Various terms have been used to express this stress test. Perhaps the term "yield point" is the least ambiguous of these.

It will have been seen from the figures given that raising the carbon content of a steel from 0·05 % to as high as 0·60 % has an enormous influence on the simple static strength of a steel, showing a four-fold augmentation, as the carbon is increased, between the lowest and the highest.

Static Strength Test.—Of the great number of steel-testing machines now at the service of the engineering trade, perhaps the most generally used are those adapted for bending tests and tension tests, both showing the results upon easily read dials.

Percentage of Carbon.	On Acid Steel, *x*. Lb. per sq. in.	On Basic Steel, *y*. Lb. per sq. in.
0·05	—	110†
0·10	80*	130
0·15	120	150
0·20	160	170
0·25	200	190
0·30	240	210
0·35	280	230
0·40	320	250
0·45	360	—
0·50	400	—
0·55	440	—
0·60	480	—

* Beginning only with 0·4 % manganese.
† Beginning only with 0·3 % manganese.

In the tensile test, a standard test-piece of the steel is held at either extremity by a vice, the vices being slowly separated until the test-piece is either pulled asunder or subjected to the maximum pull just before rupture. From calculation upon the area of the test-piece, and the maximum pull, the strength of the steel per square inch is determined. In order to arrive at exact figures in using the test machines, the greatest care is necessary, otherwise the tests may be misleading. In fact, the testing of steel, in order to arrive at correct results, is an art in itself by no means quickly acquired. This is especially true of such tests as those for tensile strength, where the time element is of the greatest importance—a piece of steel pulled asunder suddenly, and another similar sample ruptured by the slowest action of the testing machine will show different results. The accuracy of the tests is more apt to be questionable as the real strength of the material selected for trial becomes greater. The higher the tensile strength in carbon steels, the more brittleness there will be in the sample, due to a greater carbon content, and the possibility of error is much increased for these reasons. Testing has become greatly a business by itself, testing institutes and firms interested with the work being exclusively engaged therewith.

The Elongation Test.—This follows, as a matter of course, the progress of the tensile testing. It would appear that all the information required as to the amount of strength or Elongation the sample will withstand until it is ruptured can in most cases be included in the elastic limit test. Here also we have a ready means of determining the ductility of the steel, and it is generally unnecessary to conduct a separate ductility test.

The Torque Test.—We have here a most informative test. Take the case of a sample of square steel bar. Placed in the testing machine, and subjected to a twisting power, what strain will it stand without distortion of the square section ? Drawing a line lengthwise along a cylindrical sample, how much twisting force can be applied before the straight line begins to become crooked ?

Taking a steel plate as a sample, how much will it stand before it loses its flat shape ? We have also the means in these tests of determining the amount of *permanent* deflection left after the test has been carried, in each case, beyond the limit of the strength of the sample.

Impact and Drop Tests.—The International Society for Testing Materials recommends the use of a standard notched test-bar of the material 30 × 30 × 160 mm., or, alternatively, a bar of 10 × 10 mm. cross-section in the making of impact and drop tests. Here we have a specific weight dropped upon the test-piece, the force of impact, the shape of the striking point, the position of impact, etc., being matters of greatest importance, as well as the force of the calculated blow sustained by the test-piece.

Exhaustive Testing.—The foregoing examples of the more important tests will suffice for our present purposes, reference being made in the chapter on heat treatment of high tensile steels to several other tests carried out on treated steels. We may here summarize the numerous tests now used to determine all the wear-resisting qualities of the steel used in high speed and automobile constructions, namely, for endurance, fatigue, sudden stresses, ductility, compression, rotary deflection.

HARDNESS.

Resistance to penetration is a very important point in the selection of steel. In all papers and treatises on steel the term "Brinell hardness" is constantly referred to. This important test was introduced by Mr. J. A. Brinell, chief engineer of the Fagersta iron and steel works in Sweden, who read a paper thereon before the Society of Swedish Engineers at Stockholm. The Brinell testing method has received the approval of the International Congress for Testing Materials, and received the *Grand Prix* at the Paris Exposition.

It was at first thought that the resistance to abrasion, or running wear as in a machine bearing, would be somewhere about or in direct proportion to the highest of the Brinell figures. This view was long held, irrespective of the nature of the steel, or as to whether it was a straight carbon steel or a complex alloy steel; extended experience, however, has shown that this is by no means true in practical work. Wearing properties are, it has been found, not dependent entirely upon a hardness test alone. But a high Brinell number is a good starting-point for any section of steel intended to withstand abrasion and wearing.

When hardness is spoken of by the engineer, it may imply any one of a variety of hardnesses; abrasive hardness may be assumed to refer to a shaft running in a bearing, in which the hardness may be anything from steel made "dead" hard and afterwards drawn, or let down, to a pale yellow, at a temperature of 430° F. Or to any one of the six stages of partial softening, reaching a blue tint at 600° F. It may refer merely to tensile hardness, elastic hardness, or to cutting hardness.

The Brinell hardness test is carried out by forcing a hardened steel ball of a specified size into the surface to be tested. An impression is thereby secured. The diameter of this indentation forms a basis for calculation of the hardness. It will be well here to point out that the impression secured may or may not be a true test of the state of the steel immediately beneath the surface. To illustrate this, let us take the case of a piece of fine high carbon steel, water hardened. Let us suppose that the sample is of moderate depth and therefore equally hard throughout. Under test a light indentation only will probably result. Let us now suppose that a test is to be taken of a case-hardened sample of considerable thickness. The sample may fairly be described as case hardened if the carburizing has penetrated to a depth of one-thirty-second part of an inch. Applying the Brinell steel ball under pressure to this surface, it will be found that a deep indentation will be easily secured, due to the giving or yielding of the hard crust, sinking into the softer body of the sample. It will thus be apparent that the condition of the sample under test must be known before accepting the figure denoting Brinell hardness.

Brinell Test for Untreated Steel.—It cannot, however, be supposed that a test of this kind was ever intended for case-hardened steel. As a matter of fact, Brinell testing is largely confined to determining the condition of untreated steel, direct from the maker. In taking the test, the number of kilogrammes expressing the load is divided by the spherical area of the impression in square millimetres: a number is obtained expressing the pressure per square millimetre of ball impression. This is known as the Brinell hardness numeral. A standardization of the conditions of test being necessary, a standard ball of 10 mm. (0·3937 in.) under a load of 3,000 kg. (6,614 lb.) is used for all Brinell tests. The diameter of the impression secured is measured by the aid of a microscope supplied for this purpose with the instrument. The hardness number may then be obtained directly from the Brinell system table, given herewith, employing the following formulæ for this purpose:—

$$y = 2\pi r(r - \sqrt{r^2 - R^2}) \quad . \; . \; . \; . \; . \; . \quad (1)$$

$$H = \frac{k}{y} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

where r = radius of ball in millimetres,
R = radius of depression in mm.,
y = superficial area of depression in mm.,
K = pressure of ball in kilogrammes,
H = hardness numeral.

BRINELL TESTING SYSTEM.

HARD STEEL BALL 10 mm. DIAMETER.

Diameter of Impression, Millimetres.	Hardness Numeral and Pressure in Kilogrammes.		Diameter of Impression, Millimetres.	Hardness Numeral and Pressure in Kilogrammes.		Diameter of Impression, Millimetres.	Hardness Numeral and Pressure in Kilogrammes.		Diameter of Impression, Millimetres.	Hardness Numeral and Pressure in Kilogrammes.		Diameter of Impression, Millimetres.	Hardness Numeral and Pressure in Kilogrammes.	
	3,000	500		3,000	500		3,000	500		3,000	500		3,000	500
2·00	946	158	3·00	418	70	4·00	228	38·0	5·00	143	23·8	6·00	95	15·9
2·05	898	150	3·05	402	67	4·05	223	37·0	5·05	140	23·3	6·05	94	15·6
2·10	857	143	3·10	387	65	4·10	217	36·0	5·10	137	22·8	6·10	92	15·3
2·15	817	136	3·15	375	63	4·15	212	35·0	5·15	134	21·8	6·15	90	15·1
2·20	782	130	3·20	364	61	4·20	207	34·5	5·20	131	21·5	6·20	89	14·8
2·25	744	124	3·25	351	59	4·25	202	33·6	5·25	128	21·0	6·25	87	14·5
2·30	713	119	3·30	340	57	4·30	196	32·6	5·30	126	20·6	6·30	86	14·3
2·35	683	114	3·35	332	55	4·35	187	32·0	5·35	124	20·1	6·35	84	14·0
2·40	652	109	3·40	321	54	4·40	183	31·2	5·40	121	19·7	6·40	82	13·8
2·45	627	105	3·45	311	52	4·45	179	30·4	5·45	118	19·3	6·45	81	13·5
2·50	600	100	3·50	302	50	4·50	174	29·7	5·50	116	19·0	6·50	80	13·3
2·55	578	96	3·55	293	49	4·55	170	29·1	5·55	114	18·6	6·55	79	13·1
2·60	555	93	3·60	286	48	4·60	166	28·4	5·60	112	18·2	6·60	77	12·8
2·65	532	89	3·65	277	46	4·65	163	27·8	5·65	109	17·8	6·65	76	12·6
2·70	512	86	3·70	269	45	4·70	159	27·2	5·70	107	17·5	6·70	74	12·4
2·75	495	83	3·75	262	44	4·75	156	26·5	5·75	105	17·2	6·75	73	12·2
2·80	477	80	3·80	255	43	4·80	153	25·9	5·80	103	16·9	6·80	71	11·9
2·85	460	77	3·85	248	41	4·85	149	25·4	5·85	101	16·6	6·85	70	11·7
2·90	444	74	3·90	241	40	4·90	146	24·9	5·90	99	16·2	6·90	69	11·5
2·95	430	73	3·95	235	39	4·95	143	24·4	5·95	97	15·9	6·95	68	11·3

Tensile Strength and Brinell Test.—The general physical condition of the steel throughout its mass has been found to agree very closely with the Brinell numeral. Indeed, so frequently do the figures obtained in general tensile testing agree with the hardness number that a regular system of working out the ultimate strength of iron and steel is now in general use—once the Brinell test is taken, it is a matter of calculation to arrive at a very close approximation to the tensile strength of a particular sample. The Technical Institute at Stockholm publish a series of experiments carried out with great care bearing upon this subject. By means of a series of tests upon tensile testing machines, the figures from which were compared with the hardness numbers, it was a simple matter to establish a basis for ascertaining a constant coefficient or transference number. The Brinell number is multiplied by this constant to obtain a figure of the ultimate strength of the sample.

The Institute figures for a hardness impression taken transversely of the rolling direction gives a coefficient of 0·366, and when the impression is taken in the rolling direction a coefficient of 0·354; and for hardness numbers above 175, 0·344 and 0·324 respectively. These Brinell numbers being multiplied by the coefficient give the ultimate tensile strength of the material in kilos per square millimetre.

A Brinell Testing Machine.—The original machines for this work being of a costly nature, a Stockholm firm, Aktiebolaget Alpha, have placed upon the market a comparatively simple and inexpensive apparatus, which should enable a great number of engineering concerns to carry out the ball tests in their own works. It consists of a small hydraulic press, exerting its force downwards. At a convenient height is situated the anvil, the position of which is adjustable. The two chief parts are mounted upon a substantial cast-iron frame. The lower end of the ram carries the 10 mm. hard steel ball, before alluded to. Pressure is applied by means of a small hand pump, and the kilogrammes are shown upon a dial, directly above the ram. By means of an ingenious preloaded attachment, the machine can be set for the exact pressure required to be exerted upon the ball, and this amount cannot be exceeded.

The surface of the specimen to be tested is made quite flat, and is polished. A few strokes of the pump suffices to bring about the requisite pressure upon the sample of steel or iron. As soon as the predetermined pressure is reached, the machine automatically ceases to *increase* its force, maintaining, however, the pressure already set. Now, in using ball machines, it has been found that the time-under-stress factor is a most important one. The time permissible upon this machine is taken as two minutes for iron and steel. Five minutes is allowed in the case of softer and more elastic specimens. The miniature pit thus secured, the specimen is placed under the special microscope, which is so furnished that the diameter of the circle formed by the pit is ascertained within an error of less than 0·05 mm. For extra heavy work up to a required pressure of 50 tons a special type of apparatus is supplied by the same makers.

There being, at the present time, quite a number of different system Brinell testing machines upon the market, it is proposed here to limit our consideration of machines for this particular system to the sample already briefly described, and to the equally important instrument known as the scleroscope.

Following the work of the Hardness Test Research Committee (*Proceedings of the Institute of Mechanical Engineers of England*, 1916), Sir Robert A. Hadfield, 1917, invited Mr. Albert F. Shore to submit reports showing the most correct relation of the scleroscope values with those of the Brinell ball test.

Among numerous experiments which followed, the pressures developed by both machines per square inch on different metals were determined together with the accompanying hardness. It was thus found, for example, that annealed low carbon tool steel, 28 hard, possessed an elastic limit or plane surface resistance to indentation of 102,000 pounds per square inch. This means that at this pressure, permanent indentation just began to the slightest degree. The scleroscope drop hammer exerted a pressure of 160,000 pounds per square inch, or 57 % in excess of the elastic limit, causing a slight spherical indentation.

The Brinell test, on the other hand, using the standard pressure of 3,000 kilograms on a 10 millimeters ball, exerted a pressure of 258,000 pounds per square inch, or 153 % in excess of that required to exceed the elastic limit.

Subsequent experiments prove that by considerably reducing the Brinell pressure quite a consistent agreement between the scleroscope and ball test could be obtained.

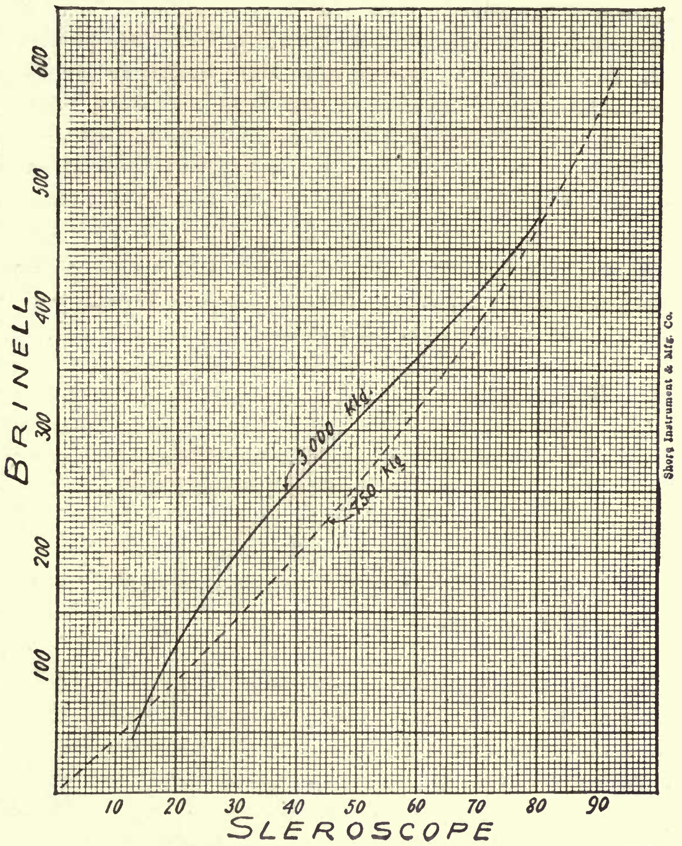

FIG. 4.

Fig. 4 indicates, by the heavy line curve, the approximate relation between the scleroscope and ball test, using a pressure of 3,000 kg. The dotted line, by the use of only 750 kg., shows a more consistent relation.

It was shown that the best results followed, using from 500 to 750 kilograms on metals over 10 hard scleroscope.

It will be seen that the heavy line curve, chart Fig. 4, is regular and therefore not a scientific relation with the scleroscope, while the dotted line curve is regular, and therefore a scientific relation. This fact was well recognized by the authorities present at the meeting of the Iron and Steel Institute, England (September 12, 1918), before which Mr. Shore's paper was read. It is further recognized and admitted that the light dotted curve, Fig. 4, had the most promise in measuring the true physical hardness by the ball indentation method.

The Scleroscope Methods of Testing.*—Invented in 1907 by Mr. A. J. Shore, we have the instrument known as the scleroscope (meaning a measurer of *hard* surface), which, with Mr. Brinell's ball-pressure device, is concerned in the bulk of commercial and engineering testing of the surface of steel at the present time. In several respects Mr. Shore's instrument differs from that of Mr. Brinell. With the scleroscope we are enabled to obtain practical and scientifically accurate information relating to the following qualities of iron and steel:

Hardness.
Elasticity.
Relation of cutting tool to work.
Tensile strength (up to elastic limit).
Resistance of cold bending.
Resistance of frictional wear.
Resistance of machining operations.
Carbon content.

The test is accomplished by noting upon a scale the amount of rebound made by a little diamond pointed hammer after it has fallen, point downwards, through a fixed vertical distance upon the surface of the metal to be tested. The rebound is measured by noting the *highest level attained by the top of the hammer.* The height of the fall, weight of hammer and area of impact are mutually so adjusted that the blow delivered exceeds, for the minute area involved, the elastic limit of the metal. There results, accordingly, a tiny permanent deformation in the form of a very small but well-defined depression. *The rebound is naturally less than the fall.* This results mainly from the loss of energy of motion in the act of

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* Views of the testing apparatus, etc., by courtesy of Coats Machine Tool Co., Ltd., Westminster, S.W., on behalf of Shore Instrument and Manufacturing Co., of Jamaica, N.Y., U.S.A.

doing work as in penetrating and displacing the metal under test.

The Scleroscope Scale.—The vertical scale against which the rebounds are measured consists of units which are determined by dividing the average rebound for certain high carbon steels into 100 equal parts. This average rebound is 6·5 in., or 16·51 cm.; so that one unit on the scleroscope scale is 0·065 in., or 1·651 mm. The scale is continued higher than 100 just as thermometer scales are carried higher than the boiling-point of water, although that point may have been used in the determination of a scale unit. On the scleroscope the upper limit is 140 and the lower one 0.

The Scleroscope Hammer.—The little hammer is furnished with a diamond tip, whose striking surface is convexed. Above the diamond, the point consists of an inverted frustum of a cone. When used with a very hard steel, the diamond tip is, apparently, the only part that actually comes into contact with the steel surface, the indentation produced being very shallow. The rebound will often amount to 65 % of the drop. As we test metal bodies that are softer, the penetration will become deeper and deeper. The whole of a diamond tip will become involved, and then more and more of the tapered body of the point. Naturally, the metallic masses tested will vary in hardness and therefore elasticity, and there will also be variations in the total area of contact as well as the depth of penetration. The result is that the amount of energy dissipated will vary. In consequence, the rebound is an ever-changing distance. The increased area of contact with the softer metals is needed to reduce the force of the blow per square inch of surface struck.

INTERPRETATION OF THE REBOUND.

The little hammer is about $\frac{3}{4}$ in. long, has a diameter of a little less than $\frac{1}{4}$ in. and a weight of about $\frac{1}{12}$ oz. The diameter of the diamond tip measured about 0·020 in. If this hammer is dropped the standard distance of 10 in. upon quenched steel 100 hard, the blow is estimated to have an intensity of 470 short tons per square inch. With softer steel, the area of contact will be greater, although naturally the total energy of the blow will be the same as before. And similarly with brass, copper, lead and the like, the softer the metal the greater the area of resistance encountered by the point. Generally speaking, the penetration is deeper as well as broader with the softer metals. There is more work performed, other things being equal, in making a wider and deeper hole, and likewise more work is performed in making the hole than is the case with steel. Naturally, the performance of this work will develop a certain amount of heat, which will dissipate itself through the mass. The reaction against the blow will for this reason not manifest itself mechanically to the point of equality with the mechanical energy of the blow. Action and reaction are equal. However, in the present case the whole of the action is mechanical, but not the whole of the reaction. The balance goes into heat, and perhaps other non-mechanical forms of energy. The rebound even from ultra-hard steel falls short, accordingly, of the drop. But an average rebound from such steel is taken as a measuring rod and with this the rebounds are compared. The hardness numbers may be regarded as expressive of the percentage which state the relation of all rebounds to the standard adopted. Thus a piece of cast brass may produce a rebound of 25 on the scale. This is its hardness number. It means that the rebound is 25 % of the standard average rebound for highly hardened steel. Cast copper will give rebounds varying from 6 to 8 on the scale. The meaning of the numbers is that the rebounds vary from 6 % to 8 % of the standard rebound.

In Fig. 5 is represented the indentation caused by the diamond hammer in different hardnesses of steel.

HARDNESS—WHAT IS IT ?

What is hardness ? Perhaps one cannot give a definition that will reconcile all the applications of the term made by technical men. At the same time we may state tentatively that hardness is that property of a solid in virtue of which it resists penetration. It is, perhaps, unnecessary that for practical shop work we trouble ourselves much to determine a definition of hardness that is sufficiently perfect to isolate this property from all other. The mechanic probably never has to do with pure hardness by itself, but only with hardness in association with other properties whose precise relations to it are unknown.

The Scleroscope and Carbon Tool Steels.

There are so many different kinds of tool steel nowadays that judicious selection has become a factor almost as important as the quality of an individual kind.

The first question to arise in tool making is the state of the annealed hardness. Is this suitable to facilitate economic machining ? Is it low enough to permit certain embossing operations, drawing or spinning, bending or upsetting ?

A plain carbon tool steel intended for cutting tools is not considered as such unless it contains at least 0·90 carbon or what is known as the saturation or eutectoid point. Those that are below (hypo-eutectoid) are often used for tools where cutting qualities are sacrificed for toughness in the unhardened parts. Those having a higher carbon (hyper-eutectoid) are more brittle in the unhardened part, but become more and more efficient for cutting purposes because of their increasing power to hold a keen edge by resisting abrasive wear at a given hardness. In making selections, thus, the peculiarity of the steel which varies with the carbon content should be well understood, for it is this knowledge alone which will enable the successful estimation of its suitability for certain purposes.

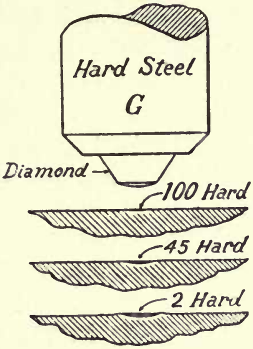


Fig. 5.—Magnified drawing of hammer point and depressions made in hard and soft metals.

The lowest annealed hardness that may be expected in a steel suitable for cold working, other than cutting, is 25, but then a higher hardness than 80 in quenching can rarely be obtained. The lowest annealed hardness normal for carbon tool steel is 30. This may make a fine cutting tool. As the carbon increases above 0·90, the annealed hardness will also rise up to 35 or 38.

A cutting die steel thus may be questioned when its annealed hardness falls below 30, yet it does not necessarily indicate that its quality will increase directly with its annealed hardness, for when this is too high it may indicate an excess of manganese. This will prevent annealed high hardening and often cause cracking.

In selecting steel of the proper carbon content for a given purpose the following facts should be borne in mind:

Low carbon steels which harden but to a comparatively slight depth are weakest in the hardened parts and strongest in the unhardened parts.

High carbon steels, if properly treated, are harder and comparatively brittle in the unhardened parts and eminently more powerful in the hardened parts.

Steel which is very pure hardens as high at 0·90 carbon, as it will with any higher carbon content, but since commercial steels are not perfectly pure, considerable higher carbon content (1·10 to 1·25) must be asked for to get the highest hardness.

For dies subjected to great pressure without great tension or transverse stress, high carbon or chrome tool steel must be selected, for particularly the latter hardens outright deepest and is harder in the core all through, so that sinking in of the surface will be best avoided. Where dies are exposed to pressure and tension, as in some cold heading operations, the lower carbon class of steels must be used, although it may be better to use special alloy steels intended for this purpose. Parts subjected to great shock and vibration as rock drills, chisels, etc., are usually made of lower carbon tool steel because of its superior toughness in the unhardened parts.

ALLOY TOOL STEELS.

The alloy carbon tool steels have each a certain advantage on the one hand, and sometimes disadvantages on the other, over plain carbon tool steel. For instance, chrome tool steel has the remarkable property of hardening very deep and to a certain extent resisting temper drawing when exposed to heat after hardening. The disadvantage of this or any other deep hardening steel is the increased tendency to warp and therefore also to crack.

In Fig. 6 we have steel fractures showing the difference between a plain carbon variety and the effect of alloying for the purpose of sensitizing to heat treatment to facilitate deep hardening.

In Fig. 7 we have a fracture of a high speed steel almost hardened equally throughout.

Vanadium tool steel does not harden so deep as chrome tool steel, but has the advantage like plain carbon steel of warping less and having in addition the maximum of toughness, and its temper need therefore be drawn comparatively less.

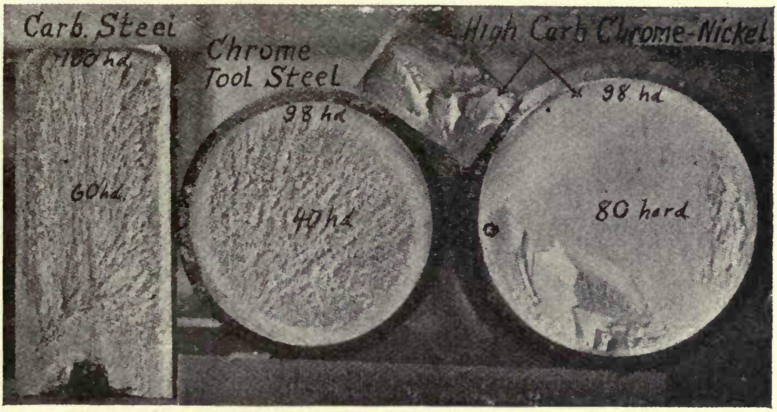


FIG. 6.—Hardened steel fractures.

For some alloy steels no special claim is made except that they do not warp in the hardening. In other words, they will be the same size after hardening as they were in the annealed state.

The common tendency, especially in ordinary carbon steel, is for it to decrease in density during the hardening process, meaning, of course, that it increases in size.

The shrinking of the hole in a die, for example, is not due to general shrinkage of the surrounding mass, but the solid portions swell equally in all directions, both outward and inward. Such expansion is due to the formation of hardening crystals, just the same as freezing or crystallizing water decreases in density with a corresponding increase in volume.

INFLUENCE OF CARBON CONTENT.

Changing gradually with the increase of carbon content, the following may also be of importance to note :—

Resistance to wear increases with carbon.
Resistance to temper drawing increases.
Deterioration by overheating increases.
Cutting endurance increases.
Fracture becomes finer.
Hardening of a large area becomes more uniform.
Warping and cracking become less.
Resistance to machining increases.
Resistance to filing as proper annealing decreases.
Ductility decreases.
Quenching temperature is lower.

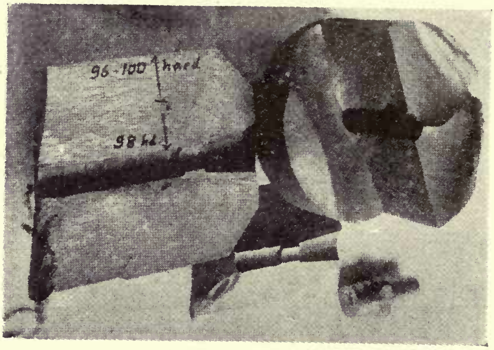


FIG. 7.—Hardened steel fracture.

HEAT TREATMENT OF CARBON STEELS.

Annealing.—The most important step in annealing is to raise the heat up to the critical (Ac 3) or non-magnetic point. Any hardness or any other ordinary condition that may have pre-existed will here become obliterated. In other words, steel will pass from a state of an aggregated ferrite and cementite to that of a homogeneous solution.

Whether the steel has been moderately crystallized due to previous overheating or whether it has been hard or tempered, forged too hard to work, heated too high in the previous annealing or superhardened by cold working and even strains set up by these various treatments, all will be eliminated as soon as the said critical point is reached and the steel will be restored to its lowest hardness by cooling slowly enough.

THEORY OF ANNEALING.

The most plausible concept of the annealing of steel is as follows: On heating above the critical point (Ac 3) and thus forming a homogeneous solution of carbon and iron, a definite body called austenite is formed. This is then normal to steel at that temperature. As this temperature is then gradually lowered, austenite is broken down and a succession of other bodies is formed, each normal to certain stages until almost cool. These are then respectively austenite, martensite, troostite, sorbite and pearlite. Pearlite, which is again composed of ferrite (iron) and cementite (carbide of iron) in a state of the widest separation, is then the ultimate body always to be reached in annealing.

Conditions of Practice. — In annealing high carbon steels the heat must never be carried more than 50° to 75° F. above the critical point. In regular works practice a suitable optical pyrometer used in conjunction with a magnet will best indicate this superheat. When pieces are large, sufficient time must be allowed for the heat to penetrate. One hour is said to be enough for a mass 12 in. thick. When the heat is raised more than 50° F. above the non-magnetic point, hardenite is formed, which consists of crystals suspended in a softer medium which are hard enough to destroy the edge of the cutting tools. By continuing the annealing heat, the crystals become coarser in proportion to the time of exposure, and an abnormally long exposure, especially at the maximum heat, may cause injury by converting useful carbon into useless graphite.

The temperatures most suitable for different carbon contents recommended in a report of the Committee on Heat Treatment of the Society for Testing Materials are as follows:—

Less than 0·12 %	.. ..	1607°–1697° F.
0·12–0·23 %	.. ..	1544°–1598° F.
0·30–0·49 %	.. ..	1499°–1544° F.
0·50–1·00 %	.. ..	1454°–1499° F.

QUENCHING TO HARDEN.

The principal factors which enter into this process are: (1) The observation of the critical or non-magnetic point. (2) The degree of superheat used, particularly in hardening the larger pieces. (3) Freedom from decarburized surfaces, either before entering the furnace or causation during the heating period. (4) Freedom from impurities on the hot steel at the moment of quenching which will cause a protective coating and therefore defeating the formation of martensite or outright hardening. (5) The condition of the quenching bath. Impurities such as soap or potash will form a film, preventing outright hardening. Air bubbles due to a falling hydrant stream will cause soft spots, while too high a temperature in the quenching water will cause irregular hardening. (6) Maintenance of a certain amount of superheat in the oven furnace, particularly for the larger pieces, to avoid undue oxidation or decarburization due to over-exposure. Seventy-five degrees Fahr. works well on masses of one pound, and more as the mass increases. (7) The chemistry of the flame. A weak air blast exerts a carburizing effect; a strong one, or acid flame, a decarburizing effect.

CRITICAL RANGE FOR CARBON STEELS.

Carbon.	Temperature Fahr.
0·60–0·70 %	1350°–1380° F.
0·70–0·80 %	1350°–1375° F.
0·80–0·90 %	1350°–1365° F.
0·90–1·40 %	1350°–1365° F.

The Effect of Quenching Heat on Hardness and Grain.—Steel does not harden directly in proportion to the amount of heat it is given preparatory to quenching. Although raised to a red heat a few degrees below the critical or non-magnetic point and then quenched, a partial hardness is not forthcoming. There will, in fact, be no hardening response at all. The critical point (Ac 3) must be reached and slightly passed. The resulting hardness will then suddenly be the maximum, the strength maximum, and the grain the finest.

If the heat is carried more than 50° F. higher than the transformation or critical point, crystallization of course begins to form, and if carried very high, will result in hardening, which while resistent to the file will read comparatively low under the scleroscope. The size of these "overheat" crystals will correspond to the highest heat given to the steel, whether quenched at such heat or if first allowed to cool down to the normal quenching temperature.

Theory of Hardening of Steel.

The most plausible concept of the hardening of steel by quenching or chilling is as follows:—

In annealing we have noted that if steel is heated a little above the critical point, it changes from one or another of a series of conditions always into one of a perfect solution of iron and carbon or austenite, a state or body normal to such a heat. Upon allowing the heat to fall we can, by allowing time enough, cause all of the changes which end in pearlite in annealing, but by denying the necessary time, as in chilling, only a very limited change can occur. Thus if the quenching heat were normal for austenite and the carbon were high enough, that state could be fixed and recovered in the cold state. But since austenite is very unstable and the succeeding state (martensite) comparatively stable, in ordinary steels as well as practice, we get the following: (1) Austenitic martensite. (2) Martensite and no further transformation. Hence we have frozen in or fixed permanently for the cold state a chemical body normal only to a hot state. This is hardened steel.

Chemical Condition: How Detected.

Martensite always means steel that is hardened outright or glass hard, and can be best retained by water quenching under favourable conditions. Detection: Must resist the file and show a high scleroscope hardness (75 to 110 hard). Troostite is formed when the cooling is too slow for the retention of martensite. Detection: High but irregular scleroscope hardness, but can be filed. Can be produced also by reheating or tempering martensite steel to not exceeding 750° F. The hardness thus extends from 60 to 95. Sorbite: Austenite, martensite and troostite lost by still slower cooling, as in an air blast, or even oil, sorbite is retained. It may also be formed by tempering hardened steel beyond 750° F., but not over

1,295° F. Hardness from 40 to 60 at an average carbon content. Detection : By the hardness, i.e. 40 to 60. Files easily.

DECARBURIZED STEEL.

Decarburization, of course, occurs at the surface only, and since it must be reckoned with in hardening, its detection is of much importance. In the annealed state it is detected by abnormal low scleroscope reading (20 to 25) against the hardness of the interior of, say, 30 to 35. In the hardened state, to distinguish from troostite and sorbite formed by delayed quenching, filability and low hardness reading in conjunction with the grinding or spark test, use a small tool grinder emery wheel. If the sparks are simple, like mild steel, there is certain proof of decarburization. If they are characteristic of tool steel, then the trouble reverts to the quenching method and troostite is revealed.

TEMPERING AND INSPECTING.

Compared to the results obtainable in hardening steel, the process of reheating to temper is under better control and therefore less critical. High hardness in steel is the most difficult thing to obtain, both in its manufacture and heat treatment, and while the more modern alloy steels are stronger, none compare favourably with carbon steel for intensity of such hardness. Hence, since in temper drawing we subtract from this precious property and add but little of the strength so common in alloy steels, it is obvious that unless the hardness were tolerably high, there may be little to spare at times, and when too much discretion cannot be urged on the part of the inspector. The first step thus in testing the initial hardness of quenched steel is to determine beyond any question of doubt whether such really is the initial hardness, whether the hardening was outright, true martensite, or glass hard, all, of course, meaning the same thing. The file alone can determine *how* the hardness was caused.

If martensite, then the file will be resisted perfectly, and when then the scleroscope is applied, it will not only show just how high the hardness is, but the figures are final in representing the true value of that steel, assuming that it had not been overheated or oversoaked. Whenever the file bites, the inspector must first determine the cause of this condition, whether due to poor quenching or decarburized surface (see previous paragraphs).

Filable steel showing a high hardness reading quite certainly indicates a troostite condition. If the hardness (usually in spots) is as low as 55 to 60, it is either due to decarburization or formation of sorbite (which see). This latter is most commonly caused by loose scale on the quenched steel.

How Hard (Martensite) Steel responds to Reheating.—(1) Shrinks in the hardened sections if expansion occurred in the hardening. (2) Quickly loses absolute resistance to the file, but not the physical hardness. (3) Gain in toughness is not in direct proportion to loss of hardness. At 480° F. some brittleness returns, and it is most complete at 510° F., and again quickly disappears at 525° F. (4) Physical hardness may decrease or increase. If a steel has been quenched at a temperature favouring the highest hardening, let us say, for example, 100, and then reheated to 500° F., it will be noted that the hardness starts to fall at about 400° F. and then continues until at 500° F. it has dropped to, say, 90.

If now, as in high carbon steels, this same bar had been overheated so that only 90 initial hardness is obtained, then you would have to heat to 500° F. before any further drop in hardness is to be expected. In other words, in the latter instance, temper drawing is not started until after 500° F. reheating.

More curiously does it follow that if the same bar is still more overheated, yielding an initial hardness of, say, 80, then at 400° F. the hardness will start to increase so that at 500° F. reheat it will closely approach 90 hard again. Further overheating will cause less and less recovery of lost hardness, showing that the steel has been damaged. Chromium in tool steel causes increased resistance to, and delays temper drawing. Detection: Moderately tempered steel is in a troostite condition, and it can be distinguished from martensite or untempered steel by its tendency to yield to the file at even very high measured hardness (90–95).

INSPECTION FOR CARBON CONTENT.

Sometimes the carbon content in plain tool steel is of considerable importance. It is so important that if, on the one hand, a razor blade were made of 0·80 carbon steel and another of 1·35 carbon steel both showing the same hardness, the low carbon blade would fail to act as a razor. So in other instances. A tool for cutting brass at high speed made of, say, 1·50–1·65 carbon steel properly hardened will not only show a surprising efficiency over a lower carbon steel of the same hardness, but it may be superior to any alloy steel including high speed steel for this or other peculiar purpose.

The proper way to determine carbon content is by chemical analysis, but since this would be out of the question in regular shop practice any quick method showing preferably the physical properties direct would be of value, and is used where ordinarily limited time would cause the most serious inconvenience.

As we have noted before, carbon steel is susceptible to crystallization directly with the increase of carbon beginning at 0·90. So we have here a method which can be readily utilized as follows :—

Heat a sample of steel to about 1,900° F. or the point where white scales begin to detach themselves and quench in cold water. Try with a file to prove that the hardening is outright. Clean well and test with scleroscope. Compare with the high hardness it is possible to obtain under normally correct heat treatment. If the hardness falls considerably as the result of overheating it shows a high carbon content. A 1·00 carbon steel will drop less than 10 points in hardness while a 1·50 carbon steel may drop as much as 35 deg. of hardness.

SELECTIVE HARDENING OF TOOL STEELS.

This process has been carried on successfully for a number of years, principally by the use of a compound known as "localcase," which comes in the form of a powder and is then mixed in boiling water. Wherever it is applied, the steel remains comparatively soft after going through the regular hardening process. After application, the paste is allowed to dry under a moderate heat. It is then put into the furnace, where it fuses to a limited extent, similar to enamel used on metals. Upon quenching this coating, even though under the water, by remaining in a plastic condition nearest the steel, adheres to it firmly until the steel has been fully quenched, and then at the proper moment it breaks up, leaving the exposed parts hardened and the protected parts in a sorbite condition, usually from 40 to 60 hard. No warping whatever occurs in the soft sections.

Dies.—In very accurate dies, perfect preservation of the configurated edge depends upon a "struggle" between the larger unhardened mass and the smaller hardened mass, for the latter usually swells in the hardening. If the hardening edge is of comparatively small area, it is not strong enough to gain its way and therefore remains true to the unhardened areas.

High Speed Steel.—This steel differs from ordinary carbon steel principally because after proper hardening heat treatment, great resistance to temper drawing is developed in it. It is this resistance to the softening action of heat that is at the bottom of its wonderful cutting powers under high speed. It is substantially a low carbon steel, running between 0·25 and 0·60 carbon.

Chromium and tungsten apparently contribute little if any to the hardening, except when in the annealed state. Carbon alone seems to possess this property. If anything, the former two retard the hardening action of carbon so that when high speed steel is heated just above the critical point and quenched practically no hardening will result. On the contrary, it must be heated up some 500° to 700° F. above the critical point before the full hardness is obtained.

Conversely, upon reheating to draw the temper, chromium and tungsten will again retard the action of carbon, this time breaking down from austenite and martensite to troostite. In good steel, this second retardation is quite equal to the first. Unlike carbon steel, high speed steel may harden according to the amount of heat it receives up to a certain point, where the hardness again begins to drop.

While the hardness thus is on the increase, temper can be drawn as in carbon steel; where the heat, however, had been high enough to arrest further increase of hardening, in fact to cause it to drop, the greatest red hardness will result.

As a tool steel, high speed steel has not a microscopic structure so favourable as that of carbon steel, and upon which the keenest edge and the greatest amount of hardness depends. It thus fails to harden as high as carbon steel. Its resistance to cold wear is also less, thus showing what a far-reaching factor its red hardness is and how impossible it is to heat treat along the lines that will ensure the retention of this property.

Annealing. — Several methods have been recommended from time to time for annealing high speed steel with a view to saving time, comparative to the one used by the steel makers. This latter is indeed prolonged, but evidently worth the trouble. The bars are packed with charcoal in iron pipes, which are sealed with fire-clay on the ends. These are then heated slowly to 1,500° F. and allowed to remain so for about ten hours, until about 1,000° F. is reached. This completes the process, and the steel may then be removed and allowed to cool more rapidly. Since these long treatments render the steel often so copper-like plastic that ripping occurs in finish machining, there is no reason why for many purposes a heating of an hour or two would not give satisfactory results. The principal point in annealing is of course the slowest cooling, particularly throughout the critical range (1,300° to 1,400° F.).

Hardening. — It is rather difficult to prescribe any definite manner for the hardening of high speed steel, for two reasons: (1) The critical point is no guide for the hardening temperature. (2) It is an alloy, the constituents of which differ with the various makers, who prescribe their own peculiar method. It is generally agreed upon, however, that the first step be one of preheating to from 1,500° to 1,800° F. in a furnace of a heat of not much higher than this, the idea of which is to avoid those strains and oversoaking of the thinner sections due to their heating first in a furnace hot enough for the final hardening heat. The latter usually runs in the neighbourhood of 2,100° F., although a higher heat approaching the melting point is recommended. In addition to the heat varying somewhat for different steels other factors enter.

Most tools which are made for the open market, with a fine finish and also must come out straight, cannot be given that high heat which would impart the highest red hardness. It also follows that since the highest red hardness is accompanied by brittleness, it would have to be rather limited in such tools as drills, one-piece reamers, taps, etc., which are subject to torsion or transverse strains.

Critical Point No Guide Here.—Since the critical point is no guide for the hardening heat for high speed steel, temperature such as will give the desired result best adapted to the class of cutting to be done with it, must be the guide. This will mean a little experimentation. Results by varying these temperatures may be divided into two kinds: (1) Martensitic, or file hard effect. (2) Troostitic or non-file hard effect.

These conditions must then show a scleroscope hardness high enough to properly meet that of the material to be cut, but will not necessarily indicate the amount of red hardness. Red hardness can only be measured by the scleroscope after reheating the steel to about 600° to 1,000° F. What is then left is the red hardness.

Further Factors to be Noted.—Unlike carbon steel, it has a range of hardening heat of several hundred degrees Fahr. The lowest heat yielding a high scleroscope hardness lacks resistance to the file and red hardness, but is strong and will toughen readily by tempering.

The highest heat will not increase scleroscope hardness, but if the steel is suitable will develop resistance to the file, and also red hardness, but at a loss of toughness, while the response to temper drawing is delayed. The highest heat maintained longer than necessary to heat up the steel, called soaking, will cause rapid loss of scleroscope hardness but not that of resistance to the file or red hardness. Coarse grain and brittleness also develop, and the drop in hardness indicates this.

Selective hardening is only possible by selective heating instead of selective cooling, as in carbon steel.

Tempering.—Martensitic and troostitic conditions: Important factors at a given hardness. As in carbon steels, high speed steel may be either in a martensitic or troostitic condition. The principal difference is that in the hardening troostite may sometimes appropriately be produced direct so that no tempering will be necessary. Martensite (file hard) high speed steel can be broken down to troostite (non-file hard) by reheating, and the heat required would depend on the amount of red hardness or resistance to temper drawing. For working in ductile tough metals and cutting on the slicing order, as in lathe and planer operations, drilling, etc., troostite tools of a high scleroscope hardness have most commonly given the best results. For all cutting of a scraping nature, particularly on the hard metals, as cast iron, steel and some brass castings, especially if gritty—tools notably such as milling cutters hobs, reamers, hack saws, and drills—must be in the martensitic condition, and no temper drawing should be attempted.

It may be argued that martensitic high speed steel is too brittle, for indeed many costly hobs and other tools have been crushed in service. But this is usually due to unreasonable overloading and the over-use of the modern positive feed systems.

As before stated, hard and the more brittle metals must be scraped more than sliced, hence we presuppose a rather light cut, which would naturally make for a long preservation of the edges. Under these reasonable conditions a hob, for example, 80 hard, martensitic, is better than one 95 hard, troostitic, or several of the latter if only 80 hard.

Microscopic Structure.—Why this is so, is best explained by the microscopic structure. Martensitic steel is like a diamond-faced drill, for it consists of a mixture of mineral hard crystals (nearly as hard as quartz), suspended in a softer matrix. This formation not only is favourable to high rigidity or physical hardness but resembles emery held embedded in the face of a lead or iron lap. So effective are these crystals that martensitic steel, carbon or high speed, will cut or scratch other steel in a troostitic condition, considerably harder than itself. How effective, then, this steel would be against machinable metals can be well imagined.

Limitations of Martensitic Structure.—Martensitic steel unfortunately, however, has serious limitations. For instance, in the above experiments when a martensitic steel cuts another one harder than itself of a troostitic character, that cutting was not a function of its physical hardness, but rather one of its intensely hard individual crystals, which are not only extremely minute and brittle, but very unstable under the action of heat. Consequently it is not difficult to understand that the cutting must needs be of a scraping nature, the chip not heavier than the microscopic crystals could carry, while the speed was such as not to burn them. Had excessive pressure been applied to the cutting edge, it would quickly lose its keenness, first by crushing individual crystals, then by crushing or upsetting the whole edge. The friction then developed generates enough heat to convert all martensite into troostite, and no further cutting would be possible on such a hard object.

In metals which are machinable, although rather hard, the same rule continues to hold good. It explains why when high speed steel does heavy cutting it rarely holds a keen edge, and why sometimes it fails to compete with carbon steel for finishing cuts. The latter, when martensitic, has not only greater physical hardness but more mineral-hard crystals.

Hardness in Cutting.—Recent advances in metallurgy reveal that materials are made up of two elements, the granules and the cement, and further that the physical hardness resulting may be more or less independent of the hardness of the individual grains, that of the cement and also that of the cement's cohesive power.

Now, that is because of the manner in which the physical hardness test is required to be made, i.e. by slight penetration of the plane surface. It will here be noted that by merely causing a slight depression or bending in of the plane surface under perpendicular pressure, no sliding friction is caused or entered. Were it to enter, however, as in scraping or cutting, also under pressure, then the hardness of the hardest individual granules would more readily become deciding factors, for the apparent hardness disclosed by tool wear would now be almost directly dependent on them. The lesser hardness and also cohesive power of the cement would only enter effectively here in so far as it may resist dislodgment of the harder granules and which would necessarily serve to cause a corresponding acceleration of tool wear.

Relation of Physical Properties of Tool and Material to be Cut.—Not alone, however, is this complex resistance to sliding or sheer displacement manifest in materials to be cut. The substance of the cutting tool itself must share this characteristic, only differing mainly in its superior hardness. Since the influence of the microscopic harder granules is largely one of abrasive wear if allowed time enough, and the feasibility of cutting at all is one of physical hardness relations, the importance of the test in prescribing or maintaining the proper relations in manufacturing operations can readily be seen.

In minerals, we have in Moh's scale the series of ten specimens in which one just barely cuts another, until the diamond is reached. In metals in the thermal or non-thermal worked state, we have but to select series, using one as a cutter against the other, until the physical limit is reached. Starting with soft lead 2 hard will barely be cut by a lead alloy 4 hard, 4 hard will just as readily yield to 8 hard, etc., until at last it requires a steel 100 hard to cut another 50 hard. At 60 hard, unless extremely brittle and of imperfect density, we can no longer cut with the same facility, and that therefore would mark the beginning of the end of cutting in metals.

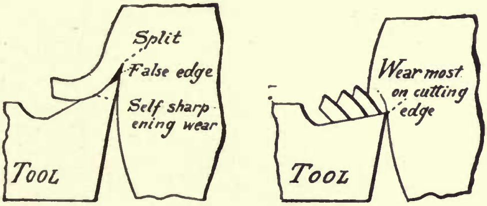
Now it follows that while the relation of 2 to 1 just permit a little cutting without instant loss of edge, at least 2½ to 1 is necessary to preserve a keen edge for a short time, while in order to preserve the edge long enough to warrant classification as a standard tool, the minimum of 3 to 1 is essential.

According to this rule the limit of free cutting by steel tools is greatly reduced, and if thus the average high grade tool had a hardness of 98 or 100, a hardness of 32 to 34 would represent the highest for stock that could be cut up without recourse to special compensating methods of edge preservation.

Cutting Under Difficulties.—When the hardness relation of 3 to 1 cannot be obtained in the tool, then by observing and meeting those compensating requirements which constitute some of the elements of the science of cutting, the feasible limit cannot only be greatly extended in over-hard materials, but the saving of time also in those well within the hardness limit. Compensation No. 1: Any method serving to avoid overheating of the tool edge, whether by reduced rate by feed, or speed, or by fluid lubrication or cooling. Compensation No. 2: Most adaptable shape and clearance of the tool edge. Compensation No. 3: Similarity of microscopic structural condition between tool and the stock.

No. 1 requires no special comment, except that an edge may easily be burnt off by friction without the mass of the tool heating.

No. 2.—The edge would be so fashioned as to obtain a continuous slice (see Fig. 8). These are more frequently split off rather than cut, and thus give rise to the well-known effect of the self-sharpening edge. Here a tool steel of great toughness is essential to resist the strain on the steep edge. Tempering will not alone impart this toughness, but fortunately the troostite or non-file-hard condition so produced is favourable to the development of the self-sharpening edge. Tempered steel thus has been deprived of its superhard brittle crystals, and it works best therefore in metals nearest to that condition, those having a minimum of superhard grains with a maximum physical hardness and ductility or toughness. Cold working increases both hardness and toughness but not the value of the hardest superhard grains. The following then in order of their relation are: cold worked metals, annealed forgings, ductile castings, unannealed forgings.



Edge too acute. Edge too obtuse.

Fig. 8.

No. 3.—We necessarily would have here to deal with metals having a maximum of superhard crystals with a minimum of hardness and toughness. Untempered steel both of the high speed and carbon varieties possesses this peculiarity. Hence steel must be in this condition to be used to the greatest advantage against such metals; these latter either in the form of the more brittle castings or unannealed or heat-treated forgings, and least in annealed forgings and cold worked metals.

As we have seen in the foregoing, the hardness of the individual superhard crystals cannot be successfully measured independently of the physical hardness. Hence we must rely upon our knowledge and experience of their presence. It is sufficient to know that if they do exist in machinable stock, they can be best dealt with by similar superhard crystals in the tool itself, viz. the martensitic or file-hard condition.

The effectiveness of this method of compensation is most surprising, so much, in fact, that if utilized judiciously, materials having a physical hardness and toughness greater than the tool can be cut slightly, those as hard as the tool to a notable extent, and those nearly as hard as the tool to such an extent as would make the operation practicable in many instances of extreme practice.

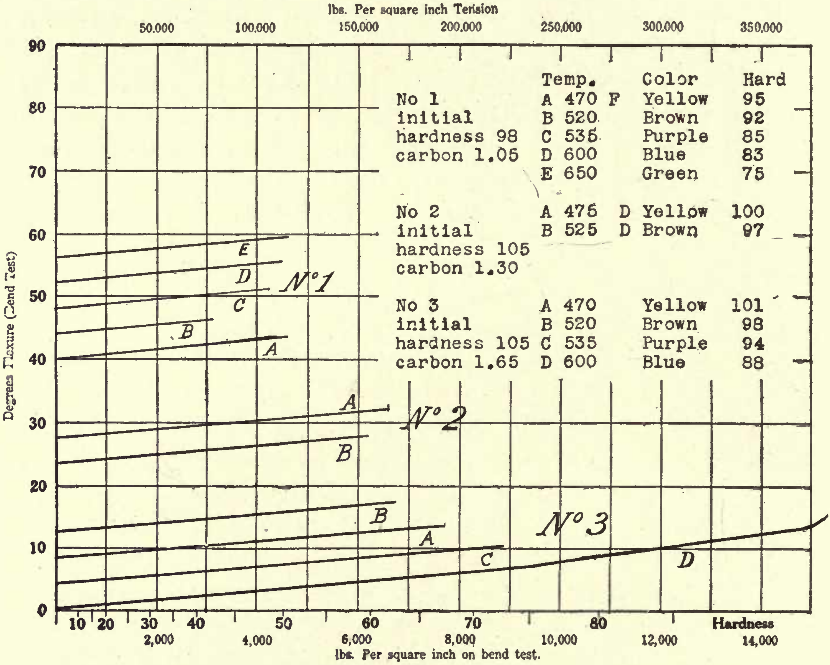
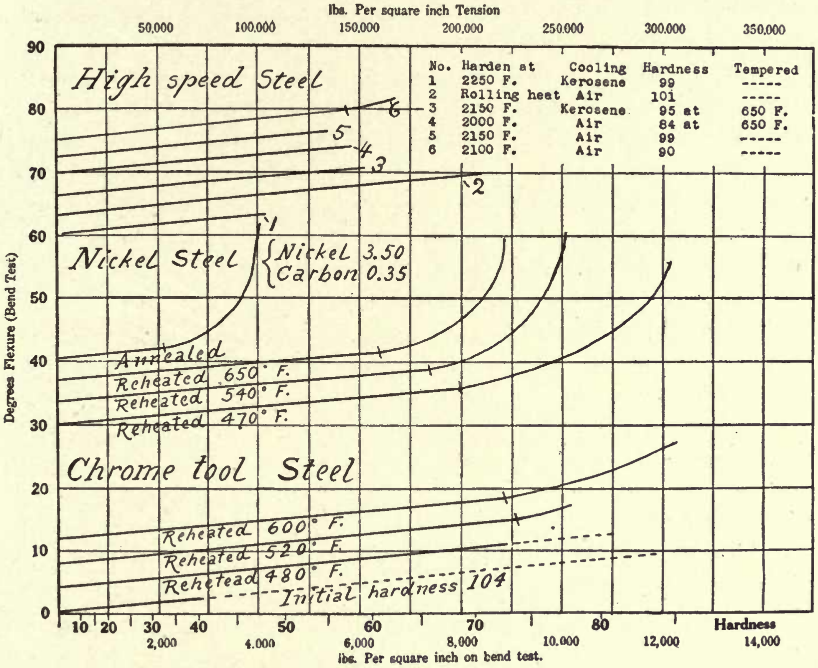


FIG. 9.

Chart showing effect of carbon on strength of hardened and tempered steel, also the characteristic lack of elongation in any of the samples.

A Remarkable Experiment in Heat Treatment.—For illustration, the following experiment may be made: Harden a high carbon steel at, say, 1,800° F. so that it may crystallize and not show more than 70 hard on the scleroscope. Harden another piece of the same bar at the lowest hardening heat so that it will show about 100 hard. Then draw the temper down to about 85 hard. The piece of 70 hard untempered will readily scratch the harder piece. In this instance it is obvious that since we are attempting to cut by the aid of microscopic superhard crystals just the same as emery in a soft metal lap, the cuts must necessarily be light and of a scraping nature. The result then would be quite independent of the physical hardness ratio between the tool and the material cut. Should, however, the attempt be made to cut heavier than the microscopic crystals can carry, then the 3 to 1 rule would again become operative, and if the hardness ratio is not great enough, the tool will be either dulled or crushed.



No.	Harden at	Cooling	Hardness	Tempered
1	2250 F.	Kerosene	99	-----
2	Rolling heat	Air	101	-----
3	2150 F.	Kerosene	95 at	650 F.
4	2000 F.	Air	84 at	650 F.
5	2150 F.	Air	99	-----
6	2100 F.	Air	90	-----

FIG. 10.

Typical bend stress curves of chrome tool steel, nickel steel and high speed steel.

The Hardness of Materials while Hot.—High speed steel is often referred to as being available for cutting although the edge is red-hot. This would necessarily imply that it must also be considerably softer in contrast to the old condition. As a matter of fact, all materials upon becoming heated show a decided drop in hardness. Consequently the chips upon becoming heated play an important part in the reduction of resistance of cutting under high speed. It is thus found, contrary to opinion, that high speed suffers as much as or more than under the same heat, let us, say, 500° F. than carbon steel. Therefore its only advantage is that ultimately where the temper of carbon steel would be drawn almost absolutely, that of high speed only partly. Therefore it wins out in the end, and it must necessarily compete with carbon steel only under these higher temperatures either on the tool or on the extreme edge. It is a strange fact that all steels rapidly lose hardness while hot up to 500° F., and thereafter scarcely any until at a bright red heat. Some steels very low in carbon show a drop of from 22 hard to 11 hard. Hence if the chips are removed at this temperature they must necessarily cut far easier than if removed in a practically cold state. Some of the non-ferrous alloys resist softening under heat more than steel.

Carbon the Determining Factor.—In the steels, carbon appears to be the determining factor, and the loss of hardness under heat is less with the increase of carbon content. Chrome and also high nickel percentages appear to increase this loss of hardness, while tungsten and very high manganese do not seem to alter the influence of carbon in the matter.

The loss of hardness in a carbon steel tool under 500° F. is about 4 to 6 deg., while on the high speed it is about 7 deg. A notable instance in which the softening of the chips due to their heat is taken due advantage of in cutting operations is the cold steel cutting buzz saw. While the chips removed perhaps depend more upon friction than that of the true cutting edge of the teeth and they are therefore very small, the fact remains that they are heated to the melting-point of the steel, and thus appear as sparks from an emery wheel.

The two charts, Figs. 9 and 10, clearly indicate the effects of hardening and tempering on different grades of carbon steel and on three of the most recent alloy steels.

The Relation of Hardness to the Elastic Limit.—Since by the stress test for elastic limit we mean the extent of load a given material will carry before it begins to take permanent set, it would necessarily follow that if this state of material failure could be indicated by the hardness test, it would be of estimable importance. It so happens that the hardness so indicated by the scleroscope does show the elastic limit very faithfully, although it must be stated that the same hardness number is not a symbol for exactly the same strength in all the metals. This is again due to the microscopic structure ; the hardness test essentially is one of pressure on a plane surface to which all materials respond alike.

Now in stressing a bar of metal, for example, tension or transverse tension stresses are developed in each instance, and it follows that where metals respond quite the same to pressure they respond somewhat differently to tension. The difference of response is due to the fact that the cohesion varies between the crystals of different metals or in different states of a single specimen. Under pressure, the cohesion between the crystals is at once improved so that they can better offer a united resistance. Under tension, in the outset, instead of improving this cohesion it is at first decreased so that early permanent set follows.

Ductility.—In metals ductility is usually estimated by the amount of elongation and reduction of area in tension tests and the degrees of bend in transverse tests, independent of the hardness.

All metals upon being stressed show no change of hardness so long as there is no permanent change of form. If this elastic limit is exceeded there is a steady increase of hardness and strength up to a point where increase of hardness and therefore increase of strength stops. If the metal continues to elongate further it is called flow. This flow becomes less and less with the increase of the initial hardness of the specimen.

Toughness.—Toughness can be described in the same manner as ductility, with the exception that the hardness number is taken into consideration when it is not feasible to make regular physical tests in the strength testing machine. In the latter instance, the difference between the elastic limit of 160,000 lb. per square inch with an ultimate strength of 200,000 lb. is tougher than another having the same elastic limit with, say, only 180,000 lb. ultimate strength.

Likewise a metal will withstand a bend of 90 deg. around a sharp angle of 50 hard twice as tough as another metal doing the same at 25 hard. Hence sharp bends or high elongations when viewed from the standpoint of toughness are not significant unless at least the hardness value is also given.

Compression.—Resistance to compression in metals is most closely related to the hardness test, for this is also one of compression. Where there is no strength testing machine available compression tests can be made on polished cones, which become roughened as soon as the elastic limit is exceeded. Cones are used because the line of roughening also indicated the exact area upset at the given pressure.

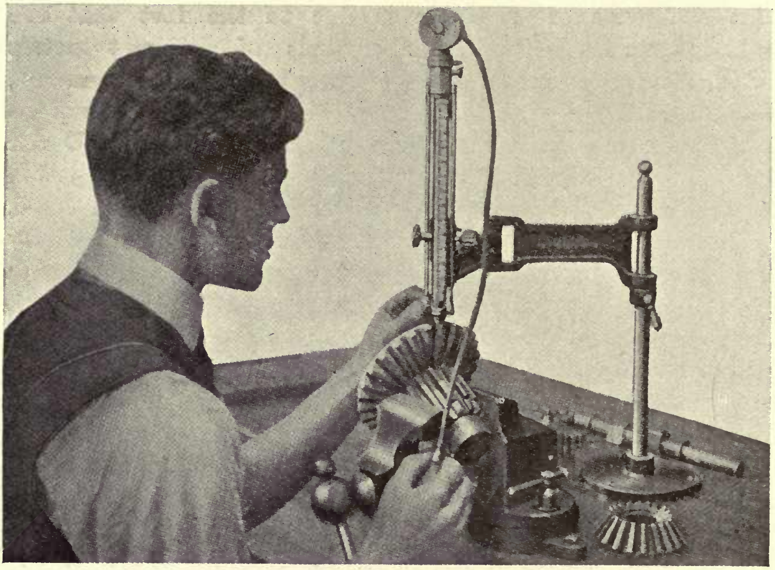


FIG. 11.—Testing gears with the aid of the swing arm.

Alloy Steels.—In the substitution of alloy steels for carbon steels, the heat treatment of which latter itself has scarcely yet been generally mastered, it is to be expected that the proper selection and heat treatment on the whole must necessarily require added care.

Since these steels are extremely tough, and usually have a comparatively high annealed hardness, it is obvious that from the standpoint of economical cutting the hardness measure would be indispensable, particularly when form cutters making many duplicate parts have to be used. The hardness measure is still more important as a guide in hardening, for then the values vary much more than in plain carbon steels.

The principal objects of alloy steels are (1) increase of toughness, (2) increase of depth of hardness.

If carbon steel could be perfectly deoxidized it would have unexampled toughness. Vanadium steel is thus highly deoxidized, but since the element after which it is named plays no part beyond one of better cohesion of the composing particles, it cannot cause deeper hardening.

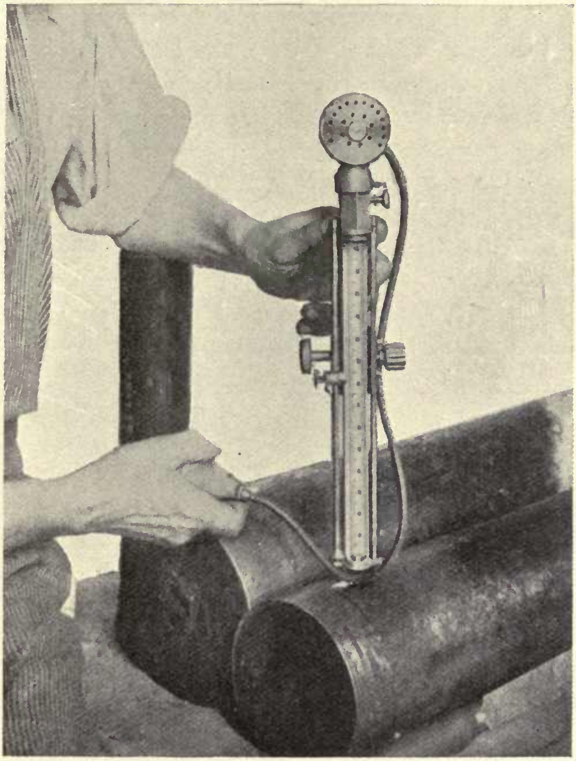


FIG. 12.—Hardness testing upon the larger masses.

To attain this important end, elements have to be added which have the property of imparting supersensitiveness to heat treatment. These elements are principally nickel and chromium used either singly or together. Besides causing great depth of hardening, chromium has the effect of making the grain finer although tungsten also has this property.

Figs. 11, 12 and 13 are self-explanatory.

HARDNESS STANDARDS ADOPTED BY AUTOMOBILE ENGINEERS.

The hardness standards which were finally adopted and are given here, as may be expected, do not apply to all kinds of steel, particularly plain carbon steel, which so rapidly loses its toughness with the increase of hardness.

Frames.—If chrome-nickel steel, 40–45 hard. Plain carbon steel, 35–40 hard.

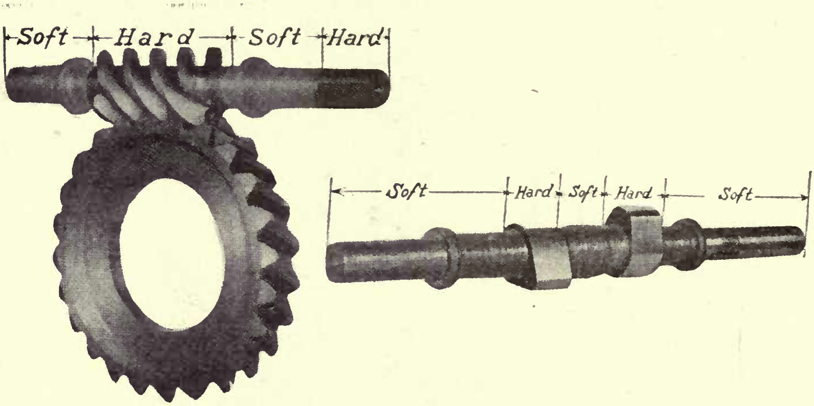


FIG. 13.—Automobile worm gear and cam shaft showing where hardness is required.

Axles.—If chrome-nickel steel (0·35 carbon), 40–45 hard.

Springs.—Very elastic and superior. Of vanadium steel, 65–80 hard; of plain carbon steel, 60–75 hard.

Crank Shafts.—Chrome nickel (0·35 carbon) heat treated 45–55 hard. When the hardness is as low as 40, as experience proves, the elastic limit is much too low, and the rate of wearing is very fast.

Transmission Shafts (Square).—50–55 hard of chrome nickel or vanadium steel. Of carbon steel, same hardness, heavier.

Transmission Gears.—The hardness allowed for these parts runs from 60 to as high as 90, depending on the character of the steel used as well as that of the work and the strains imposed. The standard strictly adhered to by the manufacturers of guaranteed cars is 80–85, when 0·45 carbon chrome-nickel steel of good quality is used. These gears when properly proportioned are light in weight, but amply powerful, and are suitable for clash or change service. Some allow a hardness of 88 or 90 to eliminate all possibility of battering. When plain steel is used, much extra weight must be allowed and the most rigid care in cementation and hardening; 3½ % nickel steel hardens well, but unless the hardness is kept down to 70–80, at which there is risk of battering and deformation of corners, the weight must be increased as against the superior and tough alloys. Continuous mesh gears may either have a higher or lower hardness than the shift gears. In high-grade machines chrome-nickel steel 80–90 hard is used for two reasons: (1) the extreme lightness, (2) high resistance to wear. Sometimes a 6 % to 7 % nickel steel is used because of its extreme toughness, when the hardness may be as low as 50 when quenched in oil, but which, like manganese steel, has a high attrition resistance. Gears of this material must be made heavier than those of chrome-nickel steel.

Starting crank shaft: 60 hard.
Pump shaft: 78–80 hard.
Piston pins: of cold-drawn steel tubing 95–100 hard (case hardened).
Steering arms: 90 hard.
Steering balls: 55–75 hard.
Spring seats: 60–70 hard.
Main countershaft washer: 80 hard.
Valve lifter roller pin: 60–65 hard.
Clutch shaft gear: 70–80 hard.
Exhaust cams: 85 hard.
Valve lifter roller: 85–100 hard.
Inlet cams: 85 hard.
Clutch shafts: 80 hard.
Ball rings: 85 hard.
Valves: 50–60 hard.
Cam shafts: 80–90 hard.
Steering worms: 70–80 hard.
Thrust and ball bearing rings: 80–90 hard. The lower hardness is confined to tough alloy steels, while the higher applies to plain steel after drawing the temper.

Engine valve plungers : 90–100 hard.
Cones : 70–80 hard.
Keys (hardened) : 75–80 hard.
Nuts (special hardened) : 90–100 hard.
Dowel pins (heat-treated) : 50–75 hard.
Screws and bolts : all 40–50 hard.

No Complete Hardening of Large Masses.—By the term "complete hardening" let it be understood that this implies hardening throughout, or as nearly so as circumstances permit. Practically, a very high carbon steel would have to be used, and a very thorough soaking in the furnace, followed by rapid cooling, preferably in running water, to attain any trace of hardening effect (in the case of thick sections) in the *core* of the *mass.* This is really difficult to *carry out.* Fortunately, it is rarely required and not always desirable. In constructional steel, and particularly in work such as crank shafts and axles, thorough hardening introduces several elements of danger. Even in the quenching for refinement of grain, followed by the reheating for toughening, there is always a risk, although it increases the static strength, of starting incipient cracks. Therefore, the latest practice is to greatly modify the violent cooling part of the procedure, where a hard surface is really required, and to avoid any attempt at core hardening. It must not be supposed that the incipient crack is due, in any case, to the *heating* part of the process. It is manifestly due to the enormous molecular strains set up in the cooling. Rapid cooling must be avoided in dealing with heavy masses of steel.

Fine and Tool Steels.

The High Carbon Group.—Commencing with a carbon content of 0·5 %, we find a range of steel adapted to a great variety of uses. Commencing with the smaller parts of machinery, such as necessitate the use of a high grade steel, we have to consider the effect of raising the percentage of carbon in its relation to the heat treatment. Equally important is the relation of bulk, or size, or mass, in the same relation, and we will consider the latter first.

Mass and Its Effect.—Let us, for illustration, take fairly large sections of steel bars (say 6 in. round) in the raw, or rolling mill condition, and gradually heat up to 1,400° F., and slowly cool. We have here a simple annealed steel, which should test out at :—

Tensile strength	85,000 lb. per sq. in.
Elastic limit	45,000 lb. per sq. in.
Elongation	22 %
Reduction of area	35 %

Taking, now, bars from the same melt of steel, and the same mill treatment, but of 1 in. diameter, and subject test-pieces to the same heating and annealing as the large masses mentioned above, testing should give us :—

Tensile strength	90,000 lb. per sq. in.
Elastic limit	40,000 lb. per sq. in.
Elongation	20–30 %
Reduction of area	35–40 %

It may reasonably be supposed that these improved results must be due to more effective "working" or manipulation in the smaller section, as compared with the large, more effective penetration of the heat to the core, and the difference in the cooling effect, which has always a powerful influence, on the quality of the steel.

We must also not overlook the relation of mass to the size of the furnace, the subsequent annealing changes, and other causes such as the time factor. It will now be apparent that so much depends upon the conditions of working, *all of which are controllable in the heat treatment shop.* Tests should in every case be taken at the outset of working of all steel intended for mass production. The heat conditions, especially of these test annealings and hardening, should be exactly noted, and continued, as far as practicable, throughout the mass production.

Test Effects of Hardening and Tempering.—So far, we have only considered the tensile strength effect of annealing. Let us proceed, followed by tempering, to attain to the higher figures always associated with hardened steel. The class of steel under consideration should harden well if brought within the critical range, 1,400° to 1,460° F. (a full blood red), and quenched in water not below 60° F. There should result a file test hardness throughout if the section be small.

To illustrate. Full hardness to the core should be secured in a ½-in. round bar, and full hardness at least three-quarters of the distance to the centre in a bar ¾ in.

diameter. A test for this hardness must not be taken at the hardened end, but upon a fracture higher up, and still within the hardened zone. If we increase the heat, before chilling, of the $\frac{3}{4}$-in. bar to some distance beyond the critical stage, we will find the bar hard to the core. If we go beyond the necessary heat the bar will still be hard throughout, but we introduce here a new danger factor, *brittleness*, accompanied by risks and some diminution in the tensile strength. Hence, all hardening should be conducted with due regard to mass. Heavy masses compel the use of higher degrees of heating, a condition which must be kept under strict control if the inherent strength of the steel be of any importance in the finished product.

Carbon Content and Hardening Temperature.—At this stage it will be well to review the effect of increasing the percentage of carbon upon the necessary hardening temperature. Selecting a particular steel, the carbon content of which has been specified by the maker, we may expect hardening to occur at the following temperatures :—

Percentage Carbon.	Hardening Temperature, °F.	Critical Range, °F.
0·05	1,400–1,450	1,320–1,360
0·07	1,400–1,425	1,320–1,350
0·08	1,375–1,420	1,320–1,350
0·09	1,375–1,420	1,320–1,340
1·00	1,350–1,410	1,320–1,330
1·11	1,350–1,410	1,320–1,330
1·20	1,340–1,400	1,320–1,325
1·30	1,335–1,375	1,320–1,325
1·50	1,330–1,375	1,300–1,320

M. Fàbry's Annealing Tests.—Dealing with the same classes of steel as the above, a series of careful tests, made by M. Fàbry,* provides the annealing operator with much useful data ; the most interesting section of the tables being, to many conversant with the appearance of steel fractures, the microscopic appearances, which are, as a rule, patent to the unaided eye.

Emulsifying Effect of the Heat.—We have seen that

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* *Variation in the Mechanical Properties and Structures of Carbon Tool Steels* (Int. Soc. Test. Mat., 1912).

TABLE A.

0·58 % CARBON STEEL—ANNEALED.

TREATMENT.	TESTS.				HARDNESS.	MICROSCOPIC.	
Annealed, Deg. Fahr.	Tensile Strength, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation, per cent. in 3·15 in.	Reduction of Area, per cent.	Brinell No.	Structure.	Notes.
1,110	99,540	—	15·8	43·4	196	Free ferrite and pearlite	Ferrite reticules, meshes filled with grainy pearlite
1,200	98,420	45,510	17·7	49·0	183	Free ferrite and pearlite	Ferrite begins to change into pearlite
1,290	84,200	39,820	20·7	59·2	174	Smaller ferrite crystals and pearlite	Structure essentially differing from other specimens, because the ferrite is uniformly distributed
1,380	93,860	36,980	18·6	43·4	176		
1,470	96,860	39,820	19·1	36·8	187	—	Ferrite forms a network; pearlite partly grainy, partly lamellar
1,560	96,710	39,820	17·9	35·6	183	—	
1,650	98,130	39,820	18·6	36·8	185	Free ferrite and pearlite	Network of large ferrite crystals filled with predominantly grainy pearlite
1,740	93,860	36,980	16·7	33·6	187		
1,830	100,700	39,820	13·1	25·2	196		

Critical range Ac commences at 1,337° F., maximum at 1,355° F.

TABLE B.

0·81 % Carbon Steel—Annealed.

Treatment.	Tests.				Hardness.	Microscopic.	
Annealed, Deg. Fahr.	Tensile Strength, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation per cent. in 3·15 in.	Reduction of Area per cent.	Brinell No.	Structure.	Notes.
1,110	102,950	—	13·1	37·6	212		
1,200	106,400	42,670	14·0	35·6	207		
1,290	99,540	39,820	17·8	43·4	187		
1,380	100,700	31,290	14·6	29·4	183		
1,470	102,840	31,290	12·5	14·8	196		
1,560	105,250	36,980	13·1	23·0	187		
1,650	100,400	31,290	13·1	19·4	203		
1,740	98,980	31,290	10·2	14·0	207		

Critical range Ac commences at 1,328° F., maximum at 1,337° F.

TABLE C

0·92 % CARBON STEEL—ANNEALED.

TREATMENT.	TESTS.				HARDNESS.	MICROSCOPIC.	
Annealed, Deg. Fahr.	Tensile Strength, lb. per sq. in.	Elastic Limit lb. per sq. in.	Elongation, per cent. in 3·15 in.	Reduction of Area, per cent.	Brinell No.	Structure.	Notes.
1,110	122,900	—	12·0	23·0	228	—	Grainy pearlite with larger grains
1,200	120,600	42,670	13·0	25·2	217	—	
1,290	98,420	36,980	11·5	33·6	163	—	Structure perfectly homogeneous and essentially differing from those of other specimens
1,380	91,030	34,130	17·8	43·4	174	—	
1,470	113,500	31,290	10·5	14·8	212	Eutectic	Grainy pearlite
1,560	112,100	—	9·1	14·0	207	—	Lamellar pearlite
1,650	112,500	31,290	8·7	14·8	216	—	
1,740	105,800	31,290	9·0	11·6	214	—	
1,830	123,450	36,980	6·8	9·2	228	—	Indications of overheated structure

Critical range Ac begins at 1,346° F., maximum at 1,355° F.

TABLE D.

1·11 % CARBON STEEL—ANNEALED.

TREATMENT.	TESTS.				HARDNESS.	MICROSCOPIC.	
Annealed. Deg. Fahr.	Tensile Strength, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation, per cent. in 3·15 in.	Reduction of Area, per cent.	Brinell No.	Structure.	Notes.
1,110	128,550	—	9·7	20·8	248		
1,200	126,300	51,200	12·6	23·0	235		
1,290	108,650	54,040	10·3	23·0	185		
1,380	88,180	39,820	19·6	49·0	170		
1,470	91,590	36,980	16·7	36·8	178		
1,560	96,700	25,600	10·3	18·6	196		
1,650	105,100	29,580	6·1	10·0	207		
1,740	100,700	25,600	6·6	9·2	202		
1,830	116,050	36,980	6·0	6·8	228		

Critical range Ac begins at 1,337° F., maximum at 1,346° F.

TABLE E.

1·36 % CARBON STEEL—ANNEALED.

TREATMENT.	TESTS.				HARDNESS.	MICROSCOPIC.	
Annealed, Deg. Fahr.	Tensile Strength, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation per cent. in 3·15 in.	Reduction of Area, per cent.	Brinell No.	Structure.	Notes.
1,110	132,550	—	6·2	11·6	262	Free cementite and pearlite	Cementite reticulated, meshes filled, partly with lamellar, partly with grainy pearlite
1,200	129,700	67,980	8·5	14·0	255		Free cementite begins to change into pearlite
1,290	123,450	48,355	9·6	16·2	288	Fine grained cementite	Structure appears uniform
1,380	93,300	45,510	14·6	37·6	192		As before, grains finer
1,470	90,310	47,500	17·3	36·8	187	Free cementite and grainy pearlite	Cementite concentrated again into smaller crystals
1,560	93,300	42,670	13·7	27·4	187		
1,650	102,100	32,710	4·5	5·0	209	Free cementite, grainy and lamellar pearlite	Cementite crystals larger, pearlite partly in lamellæ
1,740	95,580	28,446	4·6	6·8	196	Free cementite and lamellar pearlite	Structure essentially altered. Cementite forms a network with large meshes. Steel is overheated
1,830	101,830	—	2·6	4·4	223		

Critical range Ac begins at 1,345° F., maximum at 1,355° F.

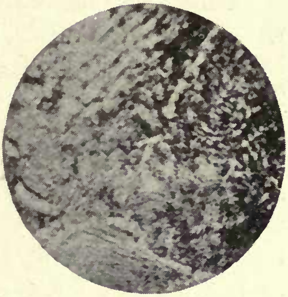
annealed steel holds its carbon in the non-hardening or cementite form. After the hardening the carbon is in the hardening or martensite form. What had happened when the temperatures had reached the critical point was a combining or emulsifying of the carbon with the ferrite. But this combination does not hold, as far as yet known, until the instant of rapid cooling fixes, as it were, the emulsion. We do know that we can bring the steel to the critical or fixing point, and by slow cooling permit of the cementite resuming to some extent its normalized form—the steel is merely annealed. But at the instant of reheating to the hardening point it is all ready to flash into the martensite condition. It is difficult to determine the exact condition of the constituents at the critical point; if emulsification has really taken place, it is clear that a separation occurs upon the slow dying away of the heat. We do know, however, that the whole molecular structure of the steel is changed by the heat and is fixed by rapid cooling. This structural change is at once apparent upon examining a piece of the steel fracture before and after the chilling process has taken effect. This is a first knowledge of a positive nature that a hardener requires.

Microphotos Figs. 14 to 18 give a graphic view of some of these transformations.

The Magnetic Test of Critical Points.—If a piece of hard steel be magnetized, it will retain its magnetism for years. If the steel be heated, it will still retain its attractive power, or at least part of it, until the heat reaches the critical stage before referred to. All trace of magnetism then passes out of the bar, *and at this hardening heat it will not attract a magnetic needle presented to it.* This well-known fact is taken advantage of in the "magnetic detector," consisting of a light magnetized bar hung upon a pivot at the extremity of a long brass bar. If there is any question whether the steel to be hardened is being brought to the correct hardening point, the needle will settle the point by showing an attraction if the critical stage has not been reached, but will remain indifferent if that stage has been attained and passed. It will be at once apparent that there is some danger here of over-heating the steel, and this can only be perfectly guarded against by offering to it the needle at various stages after the steel has passed the dull red stage.

× 100.

FIG. 14.—Massive pearlite
Van Tassel & Price.

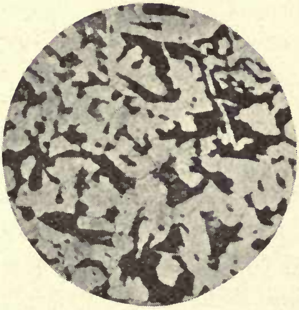


× 500.

FIG. 15.—Lamellar pearlite.

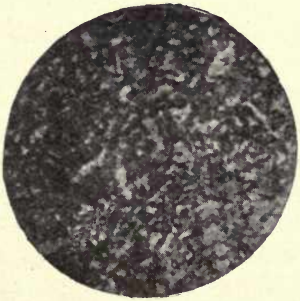
× 500

FIG. 16.—0·83% carbon steel, pearlite.



× 75.

FIG. 17.—0·30% carbon steel.
Ferrite (white), pearlite (dark).



× 100.

FIG. 18.—Low carbon steel,
quenched below Ac 2.

This test is extremely useful in determining many things respecting, say, the quality of a fresh batch of hardening steel. If the lighting of the hardening room is uniform, as it should be throughout the day, a test taken from a bar will prove the hardening property at the proper stage. Hence the operator, by taking careful note of the red-hot *appearance* of the heated end, just at the point of magnetic failure, will have a fair guide as to the future working of that batch of steel, by the eye test alone, without resort to the magnetic detector for every operation.

The Magnetic Quality Test.—Now, since it is understood that a high quality of carbon steel can be hardened at a low heat, and that a poor quality requires a higher temperature, we have, in the magnetic test, a means of checking the physical properties, as far as high or low critical point is concerned. It will be clear that, while the magnetic test is of great value, it could not, in practice, be used upon every piece of hardened steel if only for the drawback that, while the needle was being brought to the heated steel the latter would be cooling off, and possibly would have passed below the hardening point before quenching. Again, in using the magnet, care must be taken to keep all steel or iron, other than the test-piece, well out of reach of the magnetic lines of force. For example, the tongs used in holding the tested piece, and so forth.

Lowest Hardening Temperature is the Best if regard is had to the usefulness of a tool as a cutting implement, or otherwise to the strength and safety of a hardened machine part.

Dimensional Change on Hardening.—We may here touch upon a matter of the greatest interest and practical importance to the constructional mechanism. By a series of careful experiments conducted by Mr. Shipley N. Brayshaw, it has been long known that steel either lengthens or shortens during the hardening process. A machine part that will exactly fit into a position will frequently be found either too long or too short. The experiments mentioned were aimed at discovering the law, if any, controlling this change of size. It was long thought that the results were so elastic that the hardener had no control over these changes. Mr. Brayshaw has shown, however, that the change follows a uniform law; that steel heated and quenched below the critical or hardening temperature will tend to shorten.

That steel heated to or above the critical point and quenched will tend to lengthen. Experiments were then made by the aid of a preparatory furnace, in which the steel was brought up to a certain point, the heating being completed in a finishing furnace. By exact treatment it was shown that the pieces treated neither lengthened nor shortened upon quenching. The obvious inference here is that the dimensional change is due to defective heat treatment.

The experiments were conducted exclusively with two kinds of carbon tool steel that only differed materially in that one of them contained about 0·5 % of tungsten. Both samples contain 1·116 % of carbon, 0·15 % of silicon, 0·36 % manganese, 0·018 % sulphur, and 0·013 % phosphorus; these impurities (other than tungsten) being an almost invariable accompaniment of commercial carbon tool steel.

It is shown that the hardening point of both low tungsten and carbon steel may be located with great accuracy, and the complete change from soft to hard is accomplished *within a short range of* 10 *deg.* When the temperature has been raised from 35° to 55° F. above the hardening point the resultant hardness falls off. The change point was found to be about 1,615° F. in low tungsten steel and at a somewhat higher temperature in carbon steel. One of the several indications of this change point is the shortening of bars (when water quenched) below that point, whereas the bar lengthened when this temperature is exceeded at the time of quenching. Prolonged heating at a temperature of 1,400° F. has an undoubtedly injurious effect upon the nature of the steel, but does not materially influence the hardness attained. Prolonged soaking for hardness at a temperature of about 1,615° F. has a serious effect upon the steel, and almost destroys its best cutting qualities. It is notable, however, that these high temperatures do not appear to impair, to any great extent, the quality of a tool provided that the heat is rapidly raised, from the preliminary heating up, and that it does not endure for longer than about three minutes. Confirming Mr. Brayshaw in the matter, we have only to refer to the common knowledge that high speed steel (chromium, etc.) must in every case be slowly pre-heated, and then, as quickly as possible, brought up to the highest point required before air or oil quenching.

To sum up: from the steel hardener's point of view, the conclusions arrived at from the above experiments are that steel of the quality treated may be hardened within a temperature range of about 215° F.; that the lower end of this range is very sharply defined; that the highest temperature permissible is difficult to determine; that there is little evidence of overheating as far as the appearance of the fracture alone is concerned until the overheating has reached an excess of 270° F. So wide, concludes the experimenter, is the allowable variation for hardening, that when the hardness is decided by the appearance of the fracture alone, any workman of average skill can easily keep within the limits and judge the temperature by the sight alone. And, as a matter of fact, this is being done all the time on the manufacture of such articles as pocket knives, files, etc., which are hardened by the thousands with practically no waste. But, of course, it must not be understood that articles so produced reach anything like their maximum efficiency, because even small variations in the heat treatment previous to the quenching have a pronounced effect upon the condition of the steel; and even the previous treatment, such as the annealing to which the steel has been subjected, may influence the result. While it is thus easy to harden so as to obtain fairly good results, the production of the *best* results demands a much higher degree of accuracy, which can never be attained by sight alone. It must not be forgotten that the difference between good hardening and the best hardening is very pronounced. A common example may be cited—the hardening of razor blades. It is sometimes said that, whatever price one pays for a razor, the buying is a game of chance. Occasionally one hears of a remarkable razor that holds its edge as if by magic, while others, of the same make and type, may not be anywhere near as good. All of them would show to the eye practically the same fracture, and apparently seem to have been treated in the same way. The Brayshaw experiments, however, indicate that there must have been a slight difference in the hardening temperature and its duration, and consequently in the subsequent condition of the steel;

and also, that it should be possible to harden every blade in a gross so that each one would be a duplicate of the best.

It is therefore quite clear that while the appearance of the grain after fracture is to some extent a rough guide, it is not to be depended upon as a guarantee of the subsequent performance of the cutting qualities or endurance of the finished edge of the tool. And yet, until fairly recently, it was the only guide in general use—a condition of things which has now given way to incomparably more scientific and exact methods of working, taken advantage of by a superior and better educated class of workmen.

CHAPTER III

ELEMENTARY THERMAL PROCESSES

The processes developed within a recent period and generally known as the Heat Treatment of Steel are all aimed at bringing out the maximum strength of the material. Taking a steel as it leaves the rolling mill and subjecting it to certain known changes of heat and cooling has been found to confer upon it dynamic properties, brought about by the regeneration of its microstructure.

We are not dealing here with the old-established processes of softening, hardening, and tempering of tool steel intended for the making of cutting or punching tools, but rather with the requirements of constructional steel, of which the parts of locomotives and automobiles are good examples.

The term "heat treatment" has a significance far too wide to carry in itself any clear notion of the several processes to which the material must be subjected to arrive at the greatest physical strength of the steel. The procedure may conveniently be divided into the following sections:—

Normalizing.—Here we have uniform heating of the steel to a temperature exceeding its upper critical point (Ac 3) by at least 50 deg., followed by cooling in the air only. The excess of temperature beyond the critical range may vary between 50 and 100 deg. without appreciably influencing the result.

Softening or Annealing.—A steel that has already undergone normalizing should be still further improved by annealing, the main objects of which are the entire elimination of internal strains and the removal of hard areas with a view to subsequent cutting, turning, and drilling.

Hardening or Stiffening, with Toughening.—This kind of hardening is not identical with the processes of the tool maker, but may be regarded as a modification of them upon a different material. It consists of uniform heating to about 100 deg. above the critical point (Ac 3), to be immediately followed by quenching in (1) water at from 80 to 100 deg., or (2) in oil, from 60 to 80 deg.; a light-bodied oil may be used at 80 deg., or a heavier oil at 50 to 60 deg.

Tempering.—When the steel is reheated after stiffening or hardening the degree of heat to which it is subjected should be just above the critical range of the particular material; that is, the Ac 1 point must not be passed if the maximum hardness or toughness is to be retained. This point is about 100 deg. below the Ac 3 limit, in steel of 0·2 to 0·4 % carbon.

Intensified Treatment.—Experience has shown that repetition of the first favourable treatment, up to the point of heating for hardening, confers increased tensile strength upon the steel. This is known as multiple quench treatment; it is followed by drawing or tempering as before.

Metcalf's Experiment.—The benefits derived from the heat treatment of steel have been clearly demonstrated by what is known as Metcalf's experiment. Metcalf took a small bar of high carbon steel, as this steel clearly shows the effect of heat treatment, and nicked it at short intervals from the end. He then heated the end slowly until it had been burned, the rest of the bar being heated by conduction only. The bar was then withdrawn and allowed to cool slowly. Upon breaking it at the points of the various nicks a series of fractures were obtained, which corresponded to the various temperatures attained by the steel at these points. When these fractures were examined under the microscope they showed that at the burned end the grain was very coarse and bright, while that of the fractures of the nicks further removed from the fire became successively finer and duller, until the fracture on the point of the bar that had been heated by conduction to just above the critical point was reached, which showed the best structure, the greatest grain refinement. After passing this point the grain became coarser again, corresponding to that obtained by the temperature at which the bar was originally finished.

Guide to the Critical Range.—Since the whole art of thermally treating steel hinges upon the critical range, the nature of which has already been discussed, it will be obvious that, having grasped the fact of this transformation period, the next point of information desired refers to the actual degree of heat called for to touch the three stages of the Ac 1, 2, and 3 range, from which the Ar range can be deduced. For a 1 % carbon steel it occurs at 150 deg. below the Ac 3 point. It is obviously impossible to heat-treat steel unless we are able to either certify, or at least fairly judge, the degrees of heat necessary at the different stages.

The three leading methods in use at present are: (1) The use of the pyrometer, which, *when correct*, will indicate the degrees of heat only, or, if it is making a graphic record upon a sheet of paper, will show by the *pause* at the decalescence point when the upper critical range is reached. It must be remembered, however, that thermo-electric pyrometers require to be kept in a calibrated condition, otherwise they are useless.

(2) The use of the magnetic test, which can be relied upon to at least indicate the *beginning* of the critical range (Ac 1), but cannot be depended upon to indicate the upper critical point Ac 3, at which the molecular transformation of the steel is consummated.

(3) **The Visual or Optical Method.**—This divides itself into two branches, first, the use of the eye only, which under favourable conditions of experience and uniform lighting of the hardening room produces surprisingly uniform results, and is, of course, by far the most easy of application; and the optical instrument method, with which may for the moment be classed the radiation instrument method. There can be no doubt that the optical or colour instrument puts into the hands of the hardener means of accuracy impossible by any observation with the unaided eye, and this method appears therefore to have a large field of usefulness before it. There is one point, however, touching any colour-detection method which should not be lost sight of. This is the desirability of a colour-blindness test of the operator's sight. Given a perfect colour vision on the hardener's part, the colour method appears very suitable to the average hardening shop. The radiation method yields a graphic representation of the rising heat.

Carbon Content and Critical Range.—With special reference to the colour method of detection an approximate set of temperatures covering the upper critical point (Ac 3) of various carbon steels used in constructional work and the production of parts will at this stage prove useful; but while a scale of this kind may form a guide, the difference in the appearance of red-hot steel at 1,300° F. from that at 1,500° F. is scarcely sufficiently marked to enable any but an experienced hardener to pick out any temperatures between these two points. Until the eye becomes familiar with the appearance of heated steel some kind of instrumental aid should be at hand; and for constancy and a fair degree of accuracy the optical instruments furnish a degree scale that probably cannot be surpassed.

TABLE OF COLOUR TEMPERATURES.

Carbon, %.	Degrees F., Ac 3.	Appearance of the Steel.	Degrees F., Ar 3.	Degrees F., Tempering.
0·25	1,500	Very bright red	1,360	1,300
0·28	1,500	Very bright red	1,360	1,300
0·30	1,425	Bright red	1,285	1,235
0·35	1,425	Bright red	1,285	1,235
0·40	1,400	Red	1,260	1,200
0·50	1,375	Duller red	1,235	1,175
0·60	1,340	Blood red	1,200	1,140
0·70	1,340	Duller red	1,200	1,140
0·80	1,330	Duller red	1,190	1,130

Speed of Cooling Determines Hardness.—Hardness is a relative term. As applied to a low carbon steel it might more appropriately be termed stiffness or toughness. Strictly speaking, the hardness which can be gauged by the file test does not make itself manifest until the percentage of carbon exceeds 0·30 %. At a given quenching temperature hardness rapidly increases as the percentage of carbon rises. As the carbon content increases, so does the necessary hardening temperature fall. To illustrate: a carbon content of 0·4 % will necessitate a minimum quenching temperature of over 1,300 deg., while a steel of the eutectoid ratio (0·9 %) will harden, but will not be fully refined, at 1,100 deg., or less. These figures relate to quenching in cold water. As the coldness or heat-conductivity of the quench is diminished the degree of hardness developed falls also.

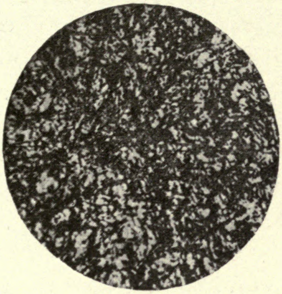
But it must not be supposed that any particular degree of hardness can be secured by preparing a bath quench of any specific temperature. Water quenching up to about 80° F. is rapid and effective. At 100 deg. or over it may fail entirely to harden steel of any carbon content, even if the quenching heat be in excess. From about 80 deg. downwards the quench in water is effective in the case of carbon percentage over 0·4 % upon temperatures 50 deg. over the Ac 3 point; and to a *slight extent* there is an increase of hardness as the temperature is increased or the quench is reduced; but it is by no means proportional thereto. Steel will either harden or it will not harden—there is no half-way house.

Toughening or Stiffening of the steel depends also upon the rate of cooling from the upper critical point down to the Ar point. Included in this range of hardening we may consider tensile hardness, abrasive hardness, elastic hardness. Cutting hardness is in a different category, and is either allied to high carbon or to carbon-tungsten-chromium alloys, with which are sometimes associated percentages of manganese.

Quenching for this toughening process is frequently done in water over 100° F. or in oil over 90° F. In such cases the quenching heat developed is usually much higher than the Ac 3 point. While 50 deg. above it is regarded as sufficient for a cold quench, 100 deg. or more is considered an advantage for a warm quench, especially in oil.

The Sorbitic Range.—What is known as fully hardened (or "dead hard") steel is in the martensitic condition. The microscope reveals a needle-like structure of extreme hardness closely allied to brittleness. Steel in this condition is not adapted for constructional purposes, or for any situation where stress has to be resisted. The martensite state is obtained by rapid cooling from something approaching 50 deg. above the higher critical point. An intermediate condition of the micro-structure, known as troosite, can be produced by delaying the act of cooling, or more correctly, cooling more slowly, as in heated water or in oil. The maximum dynamic strength of a steel is secured by the third stage of change, in which the troostitic condition changes to the sorbitic. Many of those transformations are shown in Figs. 19 to 23.

Sorbitic steel is not easily obtained by quenching, however it be delayed. It may occur, but it is more likely to



× 75.

Fig. 19.—Martensite (hard).

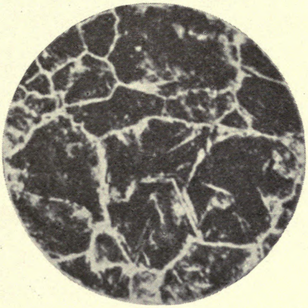


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Fig. 20.—Pearlite (dark), cementite (white).

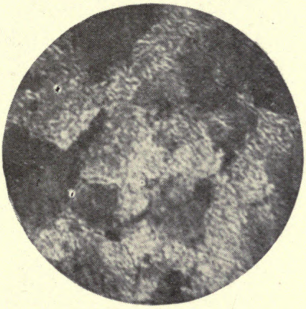

Fig. 21.—Pearlite, and appearance of excess cementite (as veins).

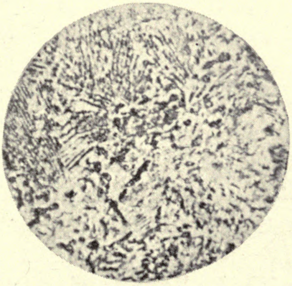

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Fig. 22.—Sorbite-pearlite transition into normal pearlite.

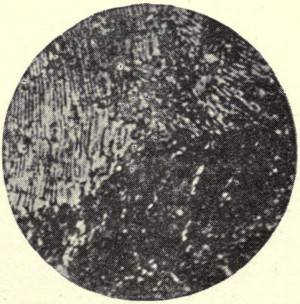

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Fig. 23.—Sorbitic pearlite (bottom), laminated pearlite (top).

be a combination of troostite and sorbite, not favourable to the development of maximum strength.

Granted, then, that the desired condition cannot commercially be brought about by merely quenching, there remains only the roundabout process of full quenching, to be followed by tempering up to a limit short of the Ar range. The range of heating throughout which the desired sorbitic condition is developed varies between 800 and 1,200 deg., according to the carbon content and the composition of the steel. Beyond 1,200 deg. the softer condition, known as the pearlitic, begins to develop, with the accompaniment of greater ductility and a gradual loss of tensile strength, and this proceeds, under increase of temperature, until complete anneal is attained.

Typical Process for Carbon Steel of 0·30 %.—After forging, anneal by heating to 1,500° F., and cool slowly. Heat to 1,500° F., quench in water at 60° to 80° F., or oil at 60° F. While still warm, reheat to from 600° F. (hard), or 1,000° F. (soft), and cool slowly. The steel is improved by a second quench at 1,400° F., tempering as before.

The Double Quench.—Two quenchings are more effective than one in raising the elastic limit (bending load) and tensile strength of all mild steels, and also alloy steels.

It is questionable whether steels with a carbon content over 0·5 % should be subjected to double quenching. Certain it is, however, that high carbon steels are not benefited by this treatment. Two conditions appear to be aimed at in heat-treatment processes. In the case of a " hard " steel, as far as low carbon steels can be hardened, we have a partial or complete transformation to the troostitic condition, and in the softer or drawn (tempered) condition a similar transformation into the sorbitic. It would appear that the single heat quenching fails to complete the transformation, the reheating and final cooling being required to bring the steel as nearly as possible to the desired stage. It should be remembered that the sorbitic condition is so effective in developing strength that " sorbitic " steel has become a commercial product under this name, or that of toughened steel.

The Nickel Steels.—Each 1 % of nickel alloyed with a given carbon steel up to 5 % will cause an increase in the tensile strength of the material of some 5,000 to 7,000 lb. per square inch.

This advantage, being obtained with no loss of ductility, has placed nickel steel in the front rank of the "strong" steels. This steel, perhaps more notably than any other, is amenable to thermal treatment. It is particularly well adapted to surface carburization, or case hardening.

The 3·50 % nickel steel, with 0·20 % to 0·50 % carbon, is a commercial product of very wide use. If a hard variety of the same characteristics is desired, it can be obtained with an alloy of from 0·5 to 0·9 % of manganese. A rather higher carbon percentage adapts the steel for the making of crank shafts and parts subject to impact. A low percentage of carbon (0·2 %) renders the steel suitable for carburization simply, or surface hardening, as may be required. In the latter condition there is probably no better material obtainable for the production of bevel gears as those upon the live axle of automobiles. We have here a tenaciously tough body and a hard surfaced tooth.

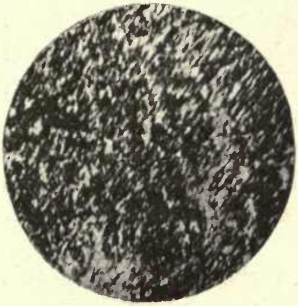


FIG. 24.—Nickel 10%, carbon 0·25%.

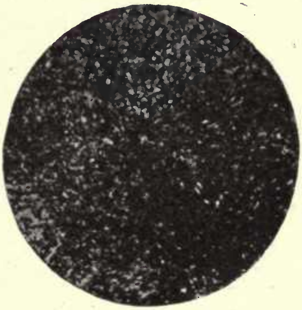


FIG. 25.—Nickel-chromium safe steel, surface hardened.

Figs. 24 and 25 are representative of these grades of steel before and after treatment.

Thermal Treatment.—Nickel steels, in common with most alloy steels, do not develop their superiority (in tensile strength) to carbon steels while in the raw or untreated state. Their potential qualities are easily developed by heat treatment, when the contrast becomes very great.

Typical Process: Nickel, 3·25 %.—After forging, heat to 1,500° F. and cool slowly in ash to relieve all strains. After machining, heat to 1,500° F. and quench in water at 80 deg. for hardness, or in oil for moderate hardness. While still warm, reheat to 1,300° to 1,400° F., and quench as before. Temper by reheating to from 600° to 1,000° F., and cool in warm oil. The different quenching temperatures for one operation refer to the degree of hardness the part will permit the development of. A part to be left hard, and yet resilient, should be withdrawn from tempering at 600° F. The double quenching treatments here recommended will be found of the greatest advantage.

If the steel is required with a high carbon, and therefore hard surface, which, however, can be drawn down to a spring temper (600° F.), or lower, carburize as directed in Chapter VIII at a temperature of 1,650° F., and allow to cool slowly in the box. Reheat to 1,500° F., and quench as before. While warm reheat to 1,350° F., and quench. Temper at from 300° to 600° F., and cool slowly. If the surface is desired very hard, omit the tempering. The nature of the quenching should depend upon the hardness permissible. If the part is not subject to stress it will probably be required hard, in which case water-quenching, either cold or at 70 deg., should be used. The temperature of the steel upon quenching should be high or low to accord with the degrees of hardness aimed at. Maximum hardness of nickel steels is produced under conditions of *high* temperature and rapid cooling.

Nickel Steels on the Anvil.—Since the expensive steels are seldom used unless they have to withstand great stress, it is important to take precautions against either weakening the steel by unsuitable treatment in the furnace or under the hammer. There are two leading risks: overheating and forging in too low a temperature.

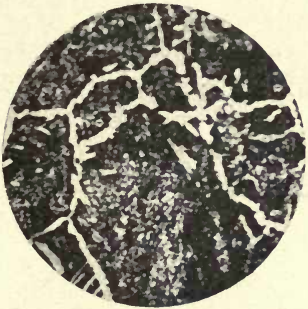
A steel may very easily be made to appear good. At the same time its microstructure may be in a burned condition, or suffering from the crushing effect of hammer work at too low a heat. If there should be any doubt about the condition of steel being worked and paid for upon a tonnage basis, efficient oversight should be secured. Failing this, frequent test fractures should be taken and compared under the microscope with standard pieces of the same grade of steel. The Shore and Brinell tests are of the greatest assistance in this connection.

Critical Range of Nickel Steels.—The incorporation of nickel with carbon steel produces a marked effect upon the critical temperatures both Ac and Ar. For each 1 % of nickel the Ac range is lowered to the extent of from

15 to 18 deg., so that a 3·5 % nickel steel will attain decalescence at from about 52 to 63 deg. below the corresponding figures for plain carbon steel. This at once raises the question whether the low figure of decalescence develops the full hardness of the carbon constituent.

The same phenomenon is of course observed when we increase the carbon percentage in a straight carbon steel, reference to the table on page 93 showing a drop of 170 deg. when the percentage of carbon falls from 0·80 to 0·25.

Below is given a list of the observed critical ranges of different percentages of nickel steels, but it should be carefully noted that the usual experience with straight carbon steels where quenching is called for at 50 deg. above the decalescence point does not hold in the case of nickel steels under thermal treatment for maximum tensile strength.



× 500.

FIG. 26.—0·45 % carbon steel badly overheated.

Nickel, %.	Ac 3, ° F.	Carbon, %.	Manganese, %.	Quench at ° F.	Reheat and Quench, ° F.
2·0	1,360	0·20	0·65	1,500	1,400
2·50	1,350	0·25	0·65	1,500	1,400
3·0	1,340	0·30	0·65	1,500	1,400
3·50	1,330	0·35	0·65	1,475	1,350
4·0	1,320	0·40	0·65	1,475	1,350
4·50	1,310	0·45	0·65	1,465	1,350
5·0	1,300	0·50	0·65	1,460	1,300
6·0	1,280	0·50	0·65	1,460	1,300

The disastrous effect of overheating is well exhibited in Fig. 26.

Instability of the Ar Range.—Both the rising and falling critical points of the carbon steels show considerable stability for given carbon percentages; but this cannot be said of the alloy steels, and particularly of the falling point of the nickel steels. While the Ac 3 point may be within 25 deg. of the above observed figures, the Ar may vary as much as 35 deg.

Steel Less Sensitive to Prolonged Heat.—In the case of carbon steels prolongation of the higher points of heating beyond the period required to ensure thorough soaking is undoubtedly injurious. But this rule is not found to apply—at least not to the same extent—to the nickel or alloy steels. While carbon steels under prolonged heating always tend to develop a coarse grain structure, and should therefore be brought to the quenching tank without delay, nickel steels can not only bear comparatively prolonged

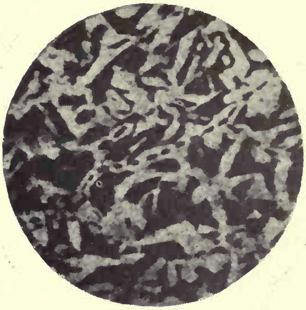

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FIG. 27.—0·40% carbon steel heated beyond Ac 3 (2,192° F.), furnace-cooled.

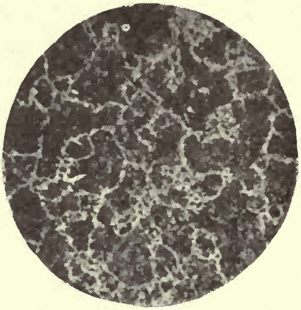
× 40.

FIG. 28.—0·40% carbon steel soaked at 1,652° F. and air-cooled.

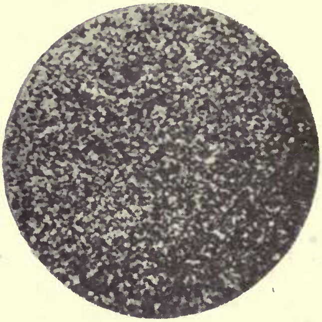
× 100

FIG. 29.—Heated to 1,472° F. and air-cooled.

heating, but are not liable to serious deterioration under excess heat. These two characteristics put into the hardener's hands a ready and safe means of ensuring the development of the utmost tensile strength and elastic limit of these steels, without the risks inseparable from the heat treatment of the carbon group of steels.

Time Limit Must be Extended.—Again, while in dealing with carbon steels the high temperature point necessary to ensure the solution and equalization of the "ferrite" and cementite must not be prolonged, because there is a risk of grain coarsening commencing, it is found that a nickel percentage necessitated more prolonged heating. In other words, carbon steel rapidly assumes the equalization condition ; nickel steel calls for a more prolonged period at or above the higher critical temperature, otherwise equalization is not completed. It is indeed incomplete equalization that necessitates double or treble quenching.

These equalization effects are shown (taking extreme instances) in Figs. 27 to 29.

CHAPTER IV

THE FURNACE

If we except the invention and manufacture of gas and oil furnaces, the production of means of heating steel has been almost entirely left to chance. Except in the case of tools, and masses of steel of moderate size and weight, the furnace maker has left the steel-treatment man to work out his own design, or rely upon someone who is already possessed of a tried and proved design. It is true that in the United States, where fuel oil is plentiful, or natural gas procurable, extensive heating plants have been developed. These improvements, however, are an outcome of the recent "boom" in the employment of alloy steels, and may even yet be regarded as being in the embryonic stage, and are largely experimental, development having been retarded by threatened shortage of fuel oil.

Fuel conditions being the governing factor as to the kind of furnace to use, these vary so enormously that to attempt any classification of a useful kind appears hopeless. There are, however, certain things required in a useful furnace, whether it be fired by coal, coke, oil, or gas, and these may be briefly specified :—

The furnace must be of sufficient size to receive the work to be treated, not only in superficial area, but in quantity, or "charge" at one loading.

It must be capable of heating the charge uniformly to the required highest temperature.

It should produce a gaseous atmosphere in the steel chamber with the object of excluding the attack of oxygen from the outside air. This is known as a reducing atmosphere. Except where an absolutely closed muffle is used, this is the best known means of ensuring that the steel charge shall not become oxidized, and to some extent decarburized. In order to effect this, the products of combustion are permitted, or forced, to pass through the operating chamber and surround the steel being treated.

While every furnace, to be efficient, must conform to the two first conditions, the third need only be met in the case of open furnace working. There is no need for a reducing atmosphere, for example, where the steel to be treated is enclosed in sealed iron boxes.

We have left out of account several other desirable conditions, not the least of which is economical working. A mere saving of fuel, however, does not necessarily mean an economical product. The final cost of heat treatment is the thing that matters, viewed from the standpoint of the finished product.

After uniformity of heat throughout the chamber, the most obvious requirement is efficient control. Following this, and largely correlated with it, is rapidity of heating.

In these countries where fuel oil, or the more volatile kerosene, is plentiful, as in the United States, the provision of well-designed furnaces for large masses of steel has developed into a profitable business, carried out by well capitalized firms, like the American Furnace Co., and the steel treatment man has the advantage of the help of people used to mass production.

On the other hand, we have in this country surpassed all nations in the invention and development of gas furnaces, which are in most cases available also for crude oil burning.

If we have not yet developed mass production to a great extent, we have available the most scientific systems of thermal steel treatment.

Solid Fuel Furnaces.—Fuel, such as coke and coal, and in special cases charcoal, are generally reserved for the largest class of furnaces, handling charges of steel running up from one hundredweight to several tons.

There are three varieties of the solid fuel furnace: (1) *Under fired*, (2) *Over fired*, and (3) *Central fired*.

In the under-fired type an attempt is usually made to compel the products of combustion to pass through the heating chamber on their way to the vent. In many cases those hot gases impart all the heat required to the inside of the chamber only; the firebrick walls being merely heat insulators. In others, the gases circulate also through a flue surrounding the walls, and so part with most of their heat before they discharge into the flue.

In the over-fired type the hot gases flow through the chamber from above, through openings in the fireclay lining. This type of furnace is known to be very inefficient, if by faulty design it leaves the floor cooler than the walls and roof. Preferential heating should be provided for the floor, at least for the first hour of operation.

In the central or side-fired furnace the fuel is burned on a level with the floor of the chamber, and the hot gases are permitted to surround the chamber on all sides, top and bottom.

The Vent.—There are great objections to venting through the roof of the chamber, directly over the charge. No matter where it is placed in the roof, its influence is to draw cold air in at the door and so tend to cool or oxidize the top of the charge. It is a standing problem with the best furnace designers how best to provide a vent where it can do least harm. This fact is illustrated by the case of several of our best gas-heated furnaces, *where there is no formal vent at all,* the products of combustion being permitted to flow slowly out by the partially open doorway. In some of the later types of gas furnaces the flues are arranged just over the entrance, and are equipped with baffles to prevent a rushing draught. The difficulty encountered by the tendency of the heat set up by the burners to make a direct track for the flue or vent has been largely overcome by so arranging the burners that their pressure is distributed preferentially at the back of the heating chamber. When this is properly managed it is impossible, even with the vent fully open, for the hot gases to make a bee-line for the flue—the bane of many gas furnaces. In Fletcher's oven furnace there are two or more flues over the crown of the chamber, but they are fitted with dampers, and can be kept almost entirely closed while the entrance door is open.

Solid Fuel Furnaces and Erratic Control.—While coal and coke furnaces are used here, and successfully, they demand the services of experienced men to run them in steel treatment. For this reason we propose to confine our further observations to the case of gas-fuel furnaces, having the merit of simple and certain control.

Producer Gas.—The high cost of town's gas has greatly restricted the use of suitable furnace equipment within the past few years. Heat unit for unit, the cost of gas is much greater than that of coal or coke. But while continuous working in the thermal treatment of steel under scientific and exact conditions by employing gas is an easy matter, the same cannot be said of any solid fuel. It has been long well known that a worker in steel carrying out operations forming the subject-matter of this book must employ gas only, in some form, in the accomplishment of the greater part of them. Adequate control of the heat and other conditions may, at great cost and trouble, be possible by using solid fuel, but the ultimate cost of the heat treatment of the finished product will then exceed that of gas. Curious as it may seem, therefore, viewed from this standpoint, gas is actually the more economical of the two.

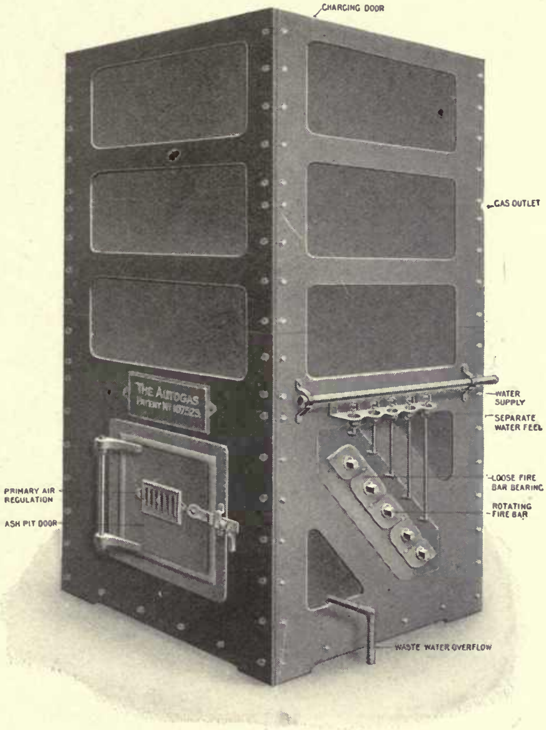

FIG. 30.—Producer-gas apparatus.

The necessity of using gas furnaces, even for the largest operations, has led to the utilization of producer or home-made gas, which is a very economical form of fuel far surpassing in ultimate advantage any form of solid fuel in any form of furnace. So impressed are the Brayshaw furnace company by this fact that they have introduced an excellent form of gas producer, intended entirely for steel treatment in its latest development.

This "Autogas" producer, on account of its simplicity, convenience of working, and economy in fuel and maintenance, permits the application of gas fuel to the largest furnaces, and opens up new possibilities in annealing, reheating, hardening, bar and plate furnaces of any required dimensions. The principle of working of this producer, while it is similar in the main to that of the usual apparatus for generating gas for gas engines, embodies many features of simplicity and convenience quite new to this class of gas plant. A general view of the apparatus is given in Fig. 30.

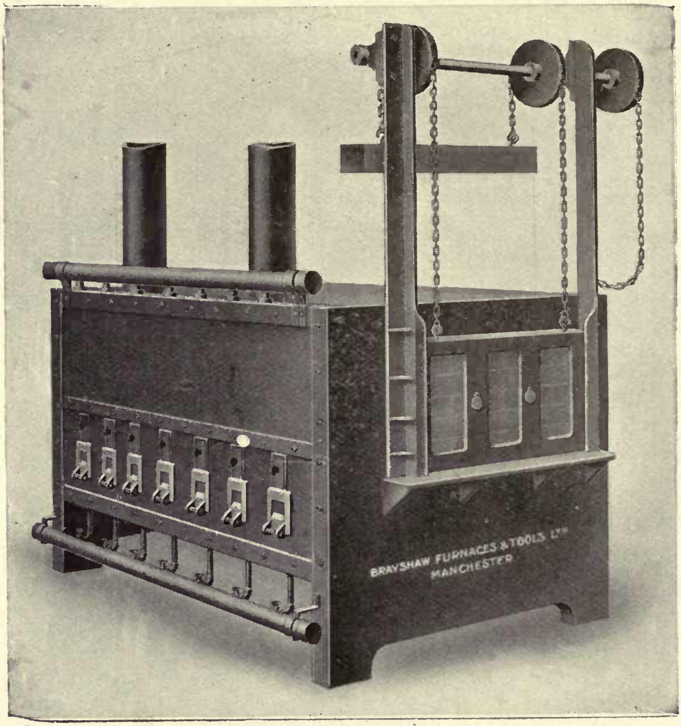

FIG. 31.—Furnace for producer gas.

Ordinary gas coke is the usual fuel. Any non-bituminous fuel of suitable grade can be used. The gas generated is of specially good quality owing to the highly efficient water evaporation. The production of a maximum quantity of gas per ton of fuel is ensured, and the rate of production

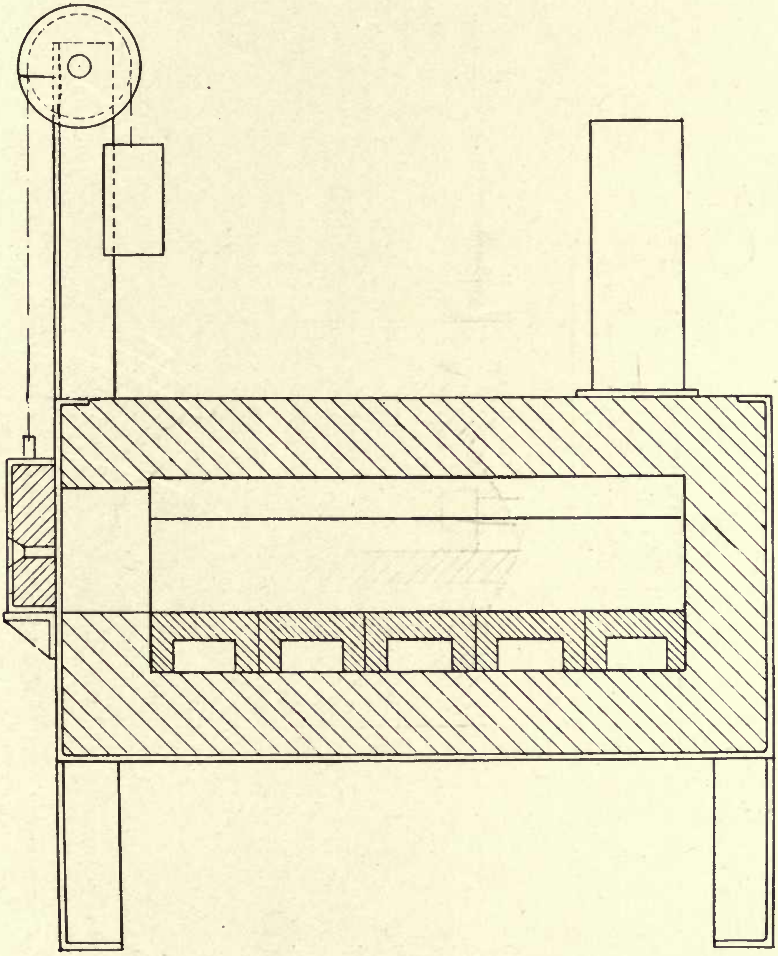

Fig. 32.—Sectional view.

is easily regulated by adjustment of the primary air inlet. The fuel is completely gasified. The gas leaving the producer is of constant value, according to the quality of the fuel used. This is ensured by means of a bed of fuel of a certain thickness always being above the gas outlet ports, preventing the suction of cold air into the flues during charging, and also reduction of temperature of the incandescent zone by dumping a quantity of cold fuel on the hot fuel bed.

The fire-bars are of X-section, having circular ends which fit into bearings, and one end terminates in a square to which a hand lever can be applied to revolve the bars. The channel which is uppermost for the time being forms a reservoir for water, keeping the fuel in direct contact with it, and maintaining the temperature of the bar at less than

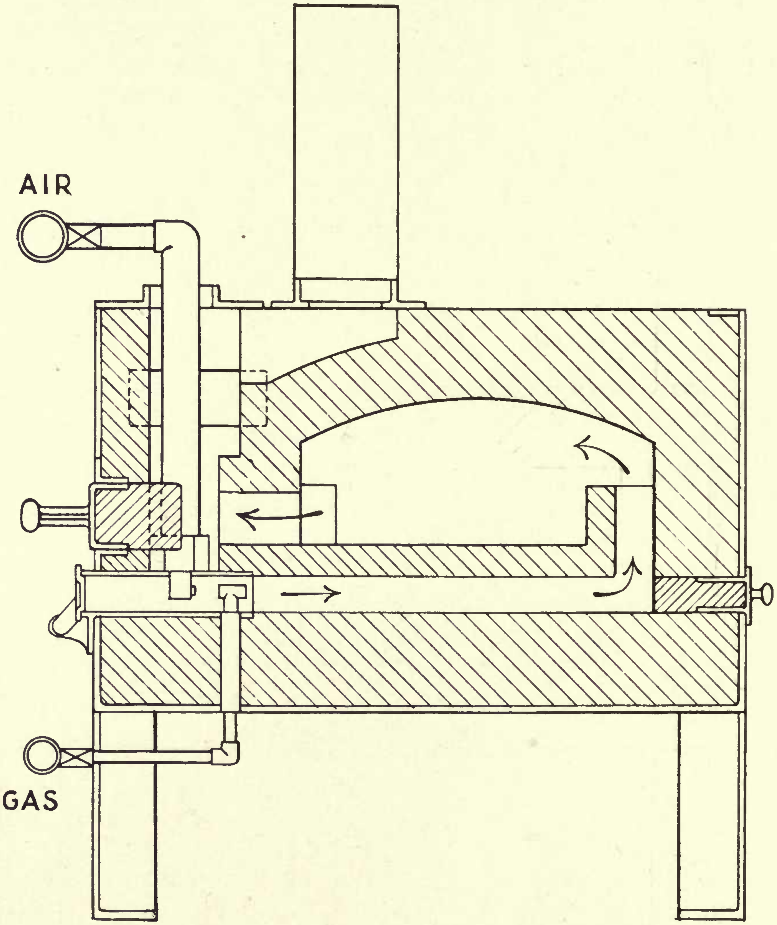

Fig. 33.—Sectional view.

the boiling-point of water; hence the long life of the bars. The fire-bars are accessible by means of a large door in front of the apparatus. The distribution of air evenly over the whole of the large grate area effects the most speedy and perfect combustion.

Judging from considerable experience of the use of gas producers in steel treatment, it is considered better practice to duplicate or multiply the number of producers rather than increase the size—a battery of them being more convenient to handle than one very large apparatus. The smallest size recommended gasifies 56 lb. of fuel per hour. This consumption suffices to feed several of the ordinary small heat treatment furnaces.

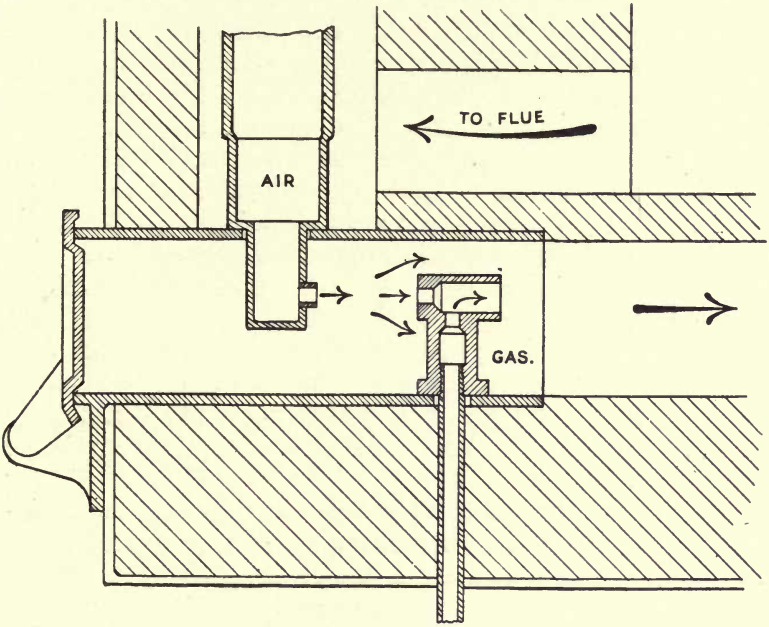

Fig. 34.—Sectional view.

Lowpress Recuperation Furnaces.—This system, which marks a new epoch in the construction of gas apparatus for annealing, heat treatment, and carburizing, was primarily designed to eliminate the oxidization and scaling of work. This has been successfully accomplished by the Brayshaw furnace company in the Lowpress series. A general view of this furnace is given in Fig. 31, and

Figs. 32 to 34 are from sectional views, which are self-explanatory. The furnace is supplied in a large number of sizes, ranging from a working depth of 2 ft. 3 in., width of 1 ft. 6 in., and height of 1 ft. 3 in., up to a depth of 12 ft. 0 in., a width of 4 ft. 6 in., and a height of 2 ft. 0 in. The flame passes under the floor into the working chamber, and the products of combustion go through a recuperation chamber to the flue. The furnace is fitted with patent burners, shown enlarged in a separate view, to permit of great flexibility of working. The gas consumption may be varied to any extent, with a very long or a very short flame ; and the furnace itself may have a " clean dry " heat, or may be filled with smoke at will. The recuperation is good, because the cold air does not chill the furnace, but is heated by the products of combustion after they have been under, and through the chamber. The special features of the furnace are the strength of the floor, the accessibility of all the flues and passages, and the uniformity of heating. Apart from this they possess great advantages over the usual types of blast-heated furnaces requiring air at from 4 in. to 8 in. pressure only. In consequence the noise due to combustion is less, and the initial working cost of a fan is much less than that of a blower. Compared with natural draught furnaces, the length of time required for heating up and the gas consumption are enormously reduced, in actual cases as much as 50 % saving being effected.

The burner apparatus embodies some entirely new principles. Explosion due to lighting back is impossible, and the handling and control of gas and air supplies are simplicity itself. In a well-known works, where twelve large furnaces of this type were installed, none but women new to this work were employed in the handling of them, and in twelve months' time no repair requiring stoppage of work was necessary. The air supply is subjected to true " recuperative " action, as distinguished from mere preheating by a cold-air jacketing arrangement. Further, a " reducing," " neutral," or " oxidizing " atmosphere can be secured at will. The smoky or " greasy " flame so essential for such annealing work, and hitherto so difficult to obtain with gas, may be readily secured.

The floor of the furnace is of solid construction, capable of withstanding heavy weights without damage.

The following letter received from a user of one of these furnaces speaks for itself :—

"I am obliged by your letter of the 1st inst., and would first like to mention that I have just concluded observations, lasting over the month of November, of the working of the 'Lowpress' Gas Furnace you recently installed here.

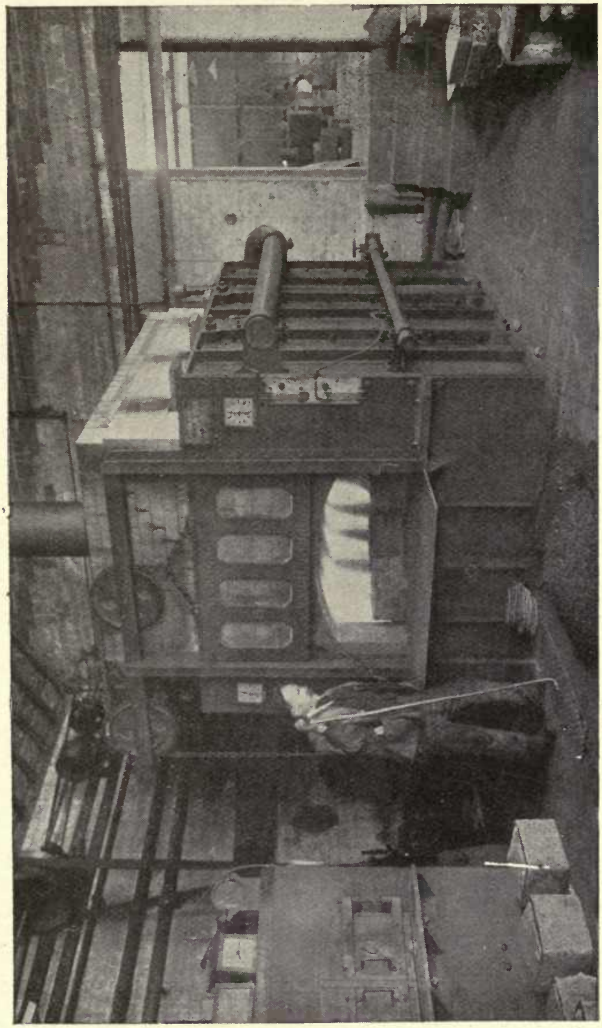

Fig. 35.—Oven furnace.

"I can only say that I am more than satisfied with the furnace in every respect. The gas consumption for the month averaged only two thousand five hundred cubic feet per ton of steel ingots annealed. This is far less than the figure you guaranteed, which, as you may remember, the present writer heard was on the low side."

Twelve Hundredweight Charge Furnace.—Taking the case of large sections and areas of steel, a good example of a heavy-charge furnace of the latest British type is the L.P.G.A. low-pressure gas and air solid floor type, which is used for every kind of heat treatment of steel (Figs. 35–36).

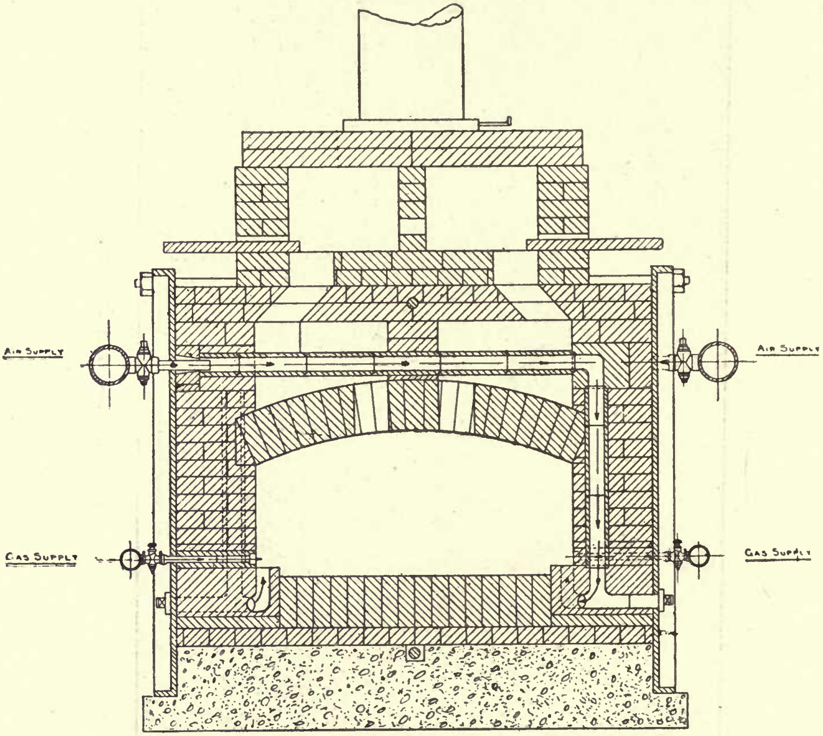

Fig. 36.—Section of furnace for producer gas.

The heating chamber of one specimen in regular use measures 5 ft. 3 in. back to front, 4 ft. wide, and 1 ft. 9 in. high. Over half a ton of charge can be handled easily in this space. This furnace was recently subjected to a severe test under the ordinary conditions prevailing in a workshop, when it was found that with a heavy load of work the furnace maintained a dead even temperature of 1,742° F. (950° C.), consuming under 900 cubic feet of town's gas per hour.

The total consumption required to reach the temperature, starting from cold, being 1,800 cubic feet, and the time taken one hour.

Accurate Temperature Control.—Any temperature within the range of this furnace is rapidly attained and accurately held for any length of time, the adjustment of one valve on the main gas supply and a similar valve on the main air supply regulates the intensity of the heat. Provision is made for local dampering along the length of the oven, and a further damper is also fitted on the main flue at the top of the furnace. An even, well-balanced heat is thereby maintained throughout the whole of the working chamber with a minimum of manipulation.

The sections shown in Fig. 37 exhibit various positions of the pyrometer (A to H), the locations A to C being the most usual.

Solid Floor and Efficiency.—It will be readily understood that for the heavy work for which this type of furnace is designed, a solid firebrick floor is a great advantage. In the present case the overfiring in no way retards efficiency. This advantage is largely due to the provision of both gas and air supply being arranged as shown in the section, to combine and enflame practically upon the floor itself in addition to the main heat distribution from overhead. Cold base and hot roof are thus avoided.

The air supply is delivered by a fan only, at a low pressure, so that the operation of the furnace is noiseless. An installation of the size given has been in constant use for nine months, and no renewals were required. These furnaces are made in any required size, but various dimensions, from the size quoted up to 15 ft. 9 in. deep by 4 ft. wide and 2 ft. high in chamber, which are stock sizes. They are manufactured by Richmond Furnaces, Ltd., London and Warrington.

Down-blast Furnace.—A well-tried Brayshaw gas furnace is known as the down-blast type. The largest listed size is 5 ft. 6 in. deep from front to back, 2 ft. 6 in. wide, and 1 ft. 9 in. high in the chamber. The same type is produced in various sizes down to 10 in. deep. The mixture of gas and air is blown into the chamber downwards at the side walls of the chamber from a series of nozzles. By these means the heating of both walls and floor is assured. This furnace can be heated up to 1,832° F. (1,000° C. in one hour

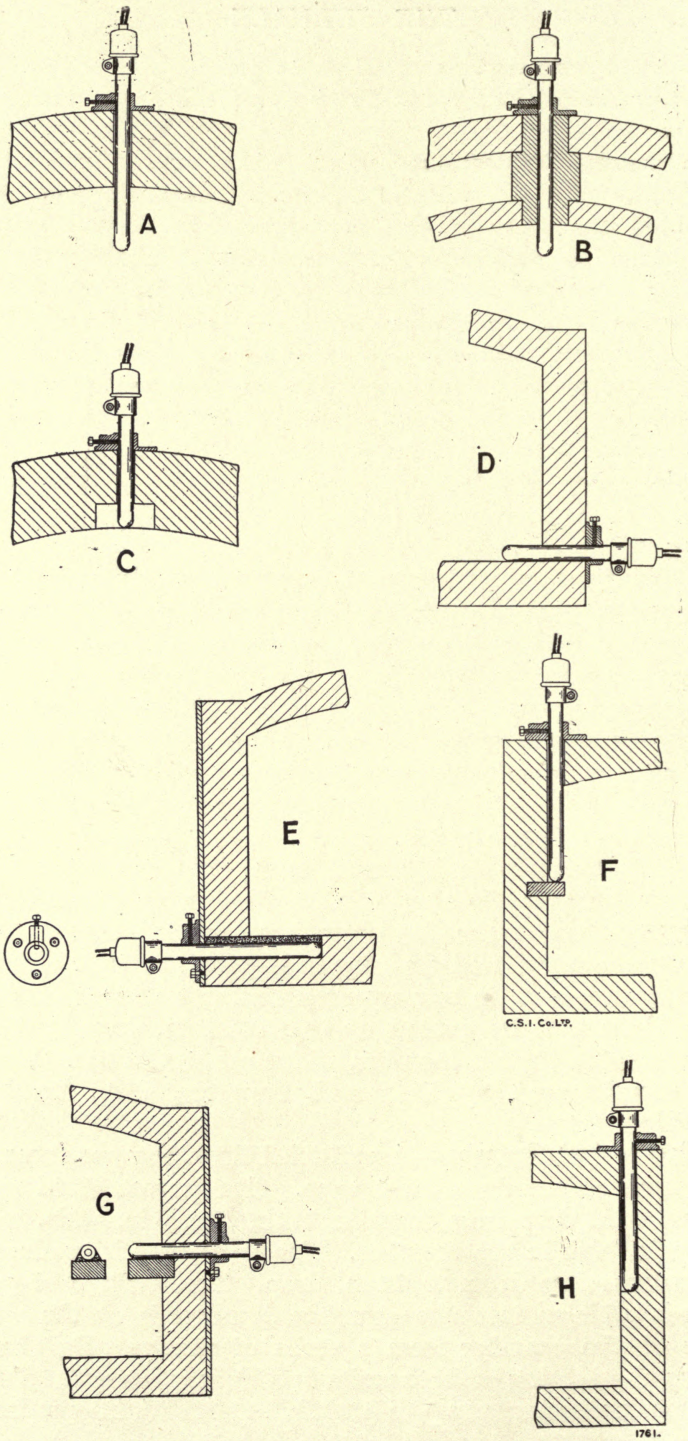

FIG 37.—Sections showing positions for thermo-couples in furnace.

and a half, after which an enormous output of work can be drawn from it in a day). The full consumption of coal gas is 700 cubic feet per hour; producer gas, 2,800 cubic feet. Air required at a pressure of 1 lb. per sq. in., 5,500 C.F. per hour.

Concerning Muffles.—A muffle is a case or box of suitable shape and material enclosing the steel to be treated, the whole being placed within the furnace. Its real function is to isolate the steel from any contact with the products of combustion other than the pure heat. An example of a fairly effective muffle would consist of a crucible having a close-fitting cover, and surrounded by the heat.

The interior of the muffle is supposed to be *free of all gases of combustion* and proof against the *intrusion of oxidizing air*, and it is just here that most muffles fail dismally.

An ordinary muffle, as furnished with a gas furnace, consists of a D-shaped vessel of fireclay, with an open end coinciding with the door of the furnace. In order that the heat may penetrate easily the walls of the fireclay muffle are of thin section, seldom exceeding three-eighths of an inch. There is seldom an end stopper, the mouth being supposed to be closed by the furnace door itself. It will at once be seen that this arrangement forms no muffle if its function be tc form a gas insulator. It is therefore in most cases a practically useless addition to the furnace for steel treatment, because while it may be effective in cutting off the direct flame of the furnace, it remains practically open to the external air. The contents of the muffle are not protected from scaling, which is a real object in view in using a muffle. Apart from these considerations, a fireclay muffle is a porous vessel, obviously easily penetrated by the gases of the furnace.

The only thing to be said in favour of the common fireclay muffle is that it affords a means of keeping smoke and soot away from the steel—a very doubtful advantage, since the hazy atmosphere is well known to exclude the risks of oxidation.

A practically effective muffling can be assured by sealing up the mouth of a fireclay vessel by means of plastic clay, and for some purposes this will answer very well, but the prevention of oxidation, which precedes scaling in the working of steel, cannot be perfectly assured by any such arrangement.

An Effective Muffle.—This must consist of a metal case, effectively sealed by fireclay. The air within must be de-oxidized by placing along with the steel charge a proportion of wood charcoal. Even under these conditions an overheat will ruin the quality of the steel, or at least destroy its superficial finish. The practical steel worker uses muffles every day, but he calls the process pack-heating or pack-hardening.

The foolish directions so frequently given : " Heat in a muffle and quench," without specifying the nature and object of the muffling, have led to many failures. Far better heat the steel in the open fire, if it consists of smoking flame, or on the open gas furnace floor, out of actual contact with the flame of the gas jets. If the object aimed at in muffling is the protection of surface from excessive oxidation, there is no kind of muffle so effective as the iron-lidded box, with a packing of ground charcoal. In particular cases the cover should be sealed down by the plastic fireclay, and transference of the steel from box to quench must be rapid.

Oven-type Furnace.—The oven natural draught town's gas class of furnaces is suitable for a great variety of work, and are very strongly constructed. The interior, including doors, is lined with good quality firebrick throughout. The base of the furnace is formed of fireclay tiles made in sections for convenience in removal. A cast-iron shelf is fitted at the bottom level of the door opening in front of the casing to facilitate the handling of material.

The doors are provided with inspection holes and shutters. The flue opening at the top is equipped with a damper, and can be used or not as required—that is, the products of combustion can be forced to flue out at the partially open door when this kind of atmosphere is required for the treatment of the steel.

In the present-day type, very efficient and powerful burners are fitted along the whole length of the furnace (the largest listed is twelve feet deep). Each burner is separately controlled by an independent gas tap and air adjuster, so that the heat can be properly regulated. When precision is required a gas pressure regulator is fitted upon the supply pipe.

Secondary Air Supply.—A valuable feature of this make of furnace is the arrangement for pre-heating and controlling the free air supply beneath the jets, which in the older furnaces was simply an open space, permitting the entrance of unlimited cold air—obviously a wasteful arrangement. Here we have dampers for the perfect regulation of the supply when it is required.

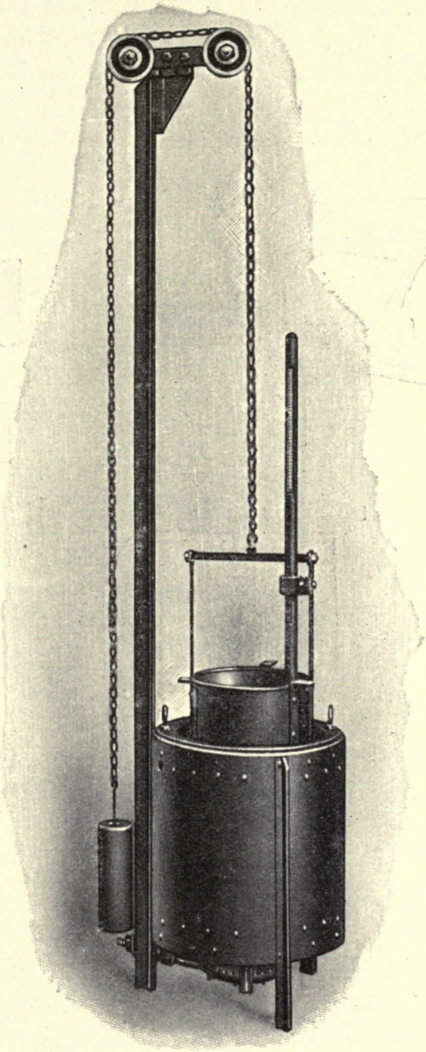

Fig. 38.—Salt bath furnace.

This particular type of furnace is made in a variety of sizes, ranging from a depth of 18 in. and a width of 12 in. up to a depth of 12 ft. and a width of 4 ft. 6 in.; commodious enough to receive a very heavy charge of steel for treatment.

Salt Bath Furnace.—In Fig. 38 is given a general view of a Brayshaw furnace designed for salt bath work. The furnace consists of a metal pot containing fusible salt. Suspended above this pot is a rising and falling counterweighted tray, which holds the work and also acts as a stirrer when in the molten liquid. Provision is made for a pyrometer to be inserted in the liquid, and for protecting it against mechanical damage.

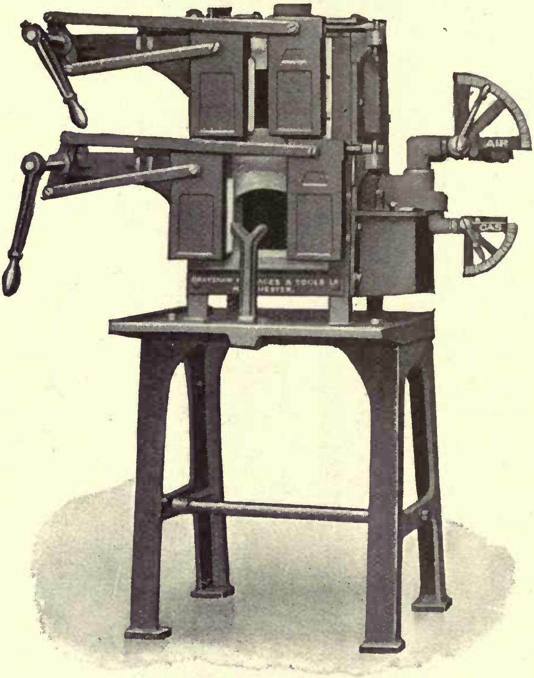

Fig. 39.—Small tool furnace.

This furnace is suitable for heating up to 1,652° F. (900° C.), but at this high temperature the life of the pots is uncertain. It may be pointed out that this temperature is never necessary for hardening carbon steels. But up to the above degree the heat is under perfect control, and any required treatment may be repeated with mechanical precision. A fusible salt of great purity is obtainable for use with the furnace. The pot and burner are arranged to avoid scaling, and at the same time to heat up as rapidly as possible. The furnaces heated by coal gas are provided with low pressure as supplied by a fan. The furnaces heated by producer gas are of similar construction, but necessary modifications are made to suit any special product of the producer to be used. The furnaces heated by oil are fitted with one or more burners, according to size. Either crude or refined oil may be used with air pressure, by blower of 1 to 2 lb. per sq. in.

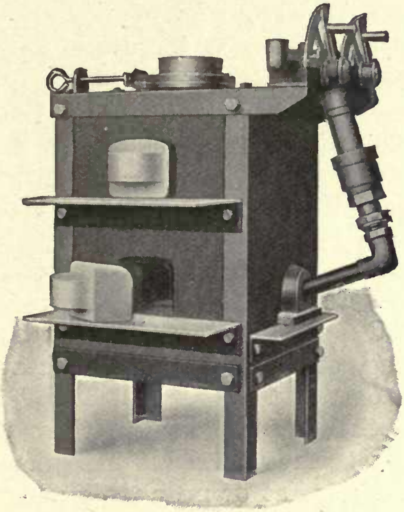

Fig. 40.—High speed steel furnace.

This extremely useful type of furnace, adapted for treatment of all steels other than high speed, is procurable with pots from 10 to 24 in. deep and from 7 to 24 in. in diameter.

Small Tool Furnace.—In Fig. 39 is depicted one of the best of the small tool furnaces, with pre-heating chamber which can be used for producing a hazy atmosphere. Being mounted upon a firm pedestal, it can be shifted about the shop as required. A moderate air pressure is used with this type; and this feature ensures rapid and intense heat, the air and gas being under perfect control.

High Speed Steel Tool Furnace.—In Fig. 40 is shown a small size of twin furnace for the hardening of high speed steel. In all of the recently designed furnaces for this purpose two chambers are provided—a pre-heating and a finishing chamber. The heating agent employed is town's gas or fuel oil. In the case of gas, air at a pressure of 8 to 10 in. by water gauge is required. In all sizes of this type of furnaces the heat is first directed into the lower chamber. It is then let into the upper chamber. The latter is used for the pre-heating of the high speed steel tools up to about 1,600° F., when they are quickly transferred to the lower chamber, with its temperature of about 2,000° F.

It should not be assumed that these temperatures are a necessary accompaniment of the use of the furnace, which can be operated at any required heat for carbon steel, as well as high speed steel.

In the models depicted the small size is equipped with fireclay door stoppers, quite detachable. The second size furnace is furnished with a one-motion sliding door. In either furnace the top vent can be dispensed with, and the products of combustion allowed to flue out of the nearly closed doorway. In the Richmond furnace of this type there is provided a special upward directed air blast across the door opening, carrying the escaped heat upwards and away from the operator.

A very effective way to operate these furnaces, when steel tools with a surface finish are being heated, is to heat up until the walls are at or near their maximum temperature, and then to turn on an increased flow of gas into the lower chamber. This will fill it with partially consumed gas, thereby excluding the presence of air. The partially consumed products are led into the chamber above, where combustion is completed.

But while the above method of working is very effective in preventing the decarburization of the steel, it must not be depended upon to preserve a bright surface on highly finished tools.

It is manifestly impossible to raise the temperature of a brightly polished steel to a high degree and expect it to emerge and harden without change, whether the atmosphere be a reducing one or not. This desirable requirement can only be met by heating in a salt or lead bath as directed in Chapter XI. But, notwithstanding this, a very satisfactory, clean, non-scale surface follows the judicious employment of an oxygen-reducing atmosphere, in whatever way it is carried out. This is especially marked if a handful of charcoal is placed in the chamber first before the full heat of the steel is attained. In the case of bright steel being brought up to the hardening heat of an open furnace chamber, even if oxygen be rigidly excluded, there is always the necessity to transfer the steel through the air to the quenching medium, whether it be a blast or oil. We have in this short interval an oxidizing influence which, while it cannot well act as an injurious decarburizer, does most decidedly, and almost instantaneously, produce a film of oxide changing a bright surface to a quite different appearance.

When steel is hardened in a salt bath, a film of the melt adheres to it on withdrawal, protecting it entirely from oxidization until it is quenched.

The working of this type of high speed steel furnace is so closely identified with the requirements of every engineer's shop that it will be quite in order to give here a table (see page 122) of the gas consumption and other data.

The Quenching Bath.—As correlated with the hardening furnaces of the different types, we may refer back to Fig. 38 which is a good model of a quenching bath, adapted for tool treatment, especially fine high speed tools. For this purpose there is employed a salt composed of equal parts of sodium nitrate and potassium nitrate, which can be kept in a fluid condition at a temperature as low as 420° F., or it can be raised to over 1,000° F. if required. If a stirring rod is occasionally used it will be found effective. There is also a special proprietary mixture sold for this purpose known under the name of "feusalt," which is quite satisfactory.

It should be understood that the partial cooling of high speed steel in this bath is not a necessary part of the procedure; but that it tends to toughen the steel, and is also less likely to produce strains or cracking than cool oil cooling, there can be no doubt. The use of the intermediate salt bath, prior to allowing the steel to cool of itself in the air, is really the process advocated by Taylor and known as the Taylor-White process, in which, however, a bath of molten lead was recommended.

The tools are carried quickly from the high-temperature

Size, No.	1.	2.	2a.	3.	4.	5.
Inside dimensions of chamber in inches—						
Width	7	9	9	12	12	15
Depth back to front ..	5	8	16	12	24	16
Height	4	8	8	12	12	15
Doorways—						
Width	4	7	7	9	9	12
Height	3	6	6	9	9	12
Time required to heat from cold in minutes	15	30	45	45	60	60
If heated by coal gas, size of supply pipe, inches	¾	1¼	1½	2	2	2
Size of pipe, air supply ..	1¼	2	2½	2½	3	3
Consumption of gas per hour for rapid heating, cubic feet ..	110	300	600	600	1,200	1,200
Consumption of gas per hour for working, cubic feet	90	250	500	500	1,000	1,000
Consumption of air per hour, cubic feet ..	550	1,500	3,000	3,000	6,000	6,000
If heated by oil, size of supply pipe, inches ..	not supplied	1	1	1	1	1
If heated by oil, size of air pipe		1½	2	2	2½	2½
Consumption of oil per hour for rapid heating, gallons ..		1½	2½	2½	4½	4½
Consumption of oil per hour for working, gallons		1¼	2	2	4	4
Consumption of air per hour ½ lb. pressure, cubic feet		2,600	4,400	4,400	7,900	7,900

chamber of the twin furnace and immersed in the melt until they are of the same temperature as the salt itself. The melt is considered to be swifter in action than oil, and cools the steel more rapidly. The quench bath consists of a steel or wrought-iron pot, provided with a cover and enclosed in a substantial iron casing lined with asbestos. The pot is heated by means of a high-power burner attached to the framework of the casing, thereby ensuring that the burner and the pot always retain their correct relationship; no air pressure is required.

Gas Consumption for Day's Run.—When there is a considerable quantity of hardening to be done, the gas consumed is considerably reduced per pound of steel, because in practice the frequent quenching of hot tools is sufficient of itself to prevent the melt from solidifying, and therefore the gas can be turned off as soon as the melt is fused.

Thermal Tempering Bath.—A similar bath to the foregoing is that known as Brayshaw's tempering bath, similar to Fig. 38, in which there is provided a counterbalanced strainer carrying a protected thermometer. This tempering bath is used with a high flash-point oil, mostly for the drawing or tempering of carbon steel tools, such as milling cutters, drills and taps. The special oil supplied to work with it has a flashpoint as high as 572° F. (300° C.). The temperature of the oil in work is kept at about 482° F., which is equivalent to a full straw colour of oxidation, as explained elsewhere.

For some classes of high-speed steel work it is much more convenient to quench the white-hot tools by dropping them with the strainer than by holding them in the melt with tongs or hooks. In this case a salt bath is used in the pot; oil being more suitable for tempering carbon steel articles. This form of bath vessel is so generally useful that we give a table of dimensions and gas consumption for the series.

COMBINED TEMPERING AND QUENCH FURNACES.

Size No.	**21.**	**22.**	**23.**	**24.**	**25.**	**26.**
Inside dimensions of pot—						
Diameter in inches ..	7	9	11	14	18	24
Depth	8	10	12	15	19	25
Inside dimensions of strainer—						
Diameter in inches ..	5¾	7½	9	12	16	21½
Depth	7½	9½	11¼	14	18	23½
Time required to heat from cold, hours ..	½	1	1½	2	2½	3
Heated by coal gas. Size of supply pipe in inches	½	½	¾	¾	1	1
Gas consumption per hour for heating up, cubic feet	30	60	90	120	150	220
Heated by producer gas, size of pipe, inches ..	1	1	1½	1½	2	2
Gas consumption per hour for heating up, cubic feet	120	240	360	480	600	900
Quantity of oil required for tempering, gallons	1	2	4	8	16	32
Quantity of melt, gallons	¼	½	1	2	4	8

Cyanide Furnace.—Potassium cyanide is used in its fused and fluid state for superficial case hardening. This kind and degree of hardening is exactly adapted to work of a small size not subjected to much stress or abrasive action. Screws and nuts, engraver's rolls and plates, and every kind of small part made of mild steel, the surface only of which it is desired to have hard, are really better treated in a cyanide bath than in any other way. The case hardening by standard pack methods is too thorough for such work as screw threads and the like. The cyanide carburizes the surface to a slight extent only, and there need be no breakage of screws if treated in this way.

FIG. 41.—Cyanide furnace.

A cyanide furnace is depicted in Fig. 41. The iron pot in this furnace is 12 in. long, 4 in. back to front, and 8 in. deep. There is a powerful burner for gas fitted, and arranged to surround the pot with flame. Air pressure of $\frac{3}{4}$ lb. per sq. in. is sufficient to run it at full heat. The noxious fumes, which must not be inhaled, are carried away by a flue, which should have a good draught.

The work done in such furnaces is usually put into an iron-wire basket with a suitable handle, immersed in the fused salt at about 1,300° F., allowed to remain a few minutes for thorough heat soaking, and then withdrawn and at once plunged into water or oil. The front of the furnace should be kept closed as much as possible. The basket and parts must be quite dry before immersion.

Furnace Working Hints.—The life of a furnace chamber, whether it be in the form of a rectangular firebrick chamber, or a crucible or an iron pot, will depend upon the intensity of the heat developed, and to other factors, as the rapidity of bringing up the full temperature, rapid changes, mechanical treatment, and so on. A fireclay paint should be kept close at hand, with which the chamber should be coated frequently, whether it shows cracks or not. A good paint of this kind can generally be procured from the furnace maker. In its absence, a mixture of fine fireclay and water can be employed. Surfaces to which repairing fireclay is applied should be wetted and the clay allowed to dry, or nearly so.

Back-firing.—Lighting-back is the bane of many furnace users. Modifications of the original Bunsen gas burner as fitted to gas furnaces are frequently faulty. A jet of gas is projected into the open end of a pipe having an area perhaps fifty times as great as the jet opening. The jet is not pushed into the pipe, but may be placed perhaps half an inch away from it. The object aimed at is, of course, the setting up of a current of carburetted air, at first of a non-inflammable nature in the pipe, which leads it into the furnace chamber.

By the time the mixture reaches the point of flaming it is sufficiently attenuated in richness to burn fiercely. *Now, lighting-back is caused by too little gas entering by the jet.* In an ordinary burner this can be shown by lighting up and then gradually reducing the gas at the jet. As soon as the mixture in the pipe becomes attenuated to the explosion point, the flame in the furnace will flash back through the whole length of the conducting pipe, and the pure gas will light at the jet. This defect is not only very common in well-designed furnaces, but it is frequently the cause of explosions and fire.

Back-firing or lighting-back can be avoided by the use of a proper rush of gas at the jet, and a means of proportioning the air inlet to its volume. In other words, if the pressure at the jet is reduced, the air space at the entrance to the pipe should be correspondingly diminished, so that the richness of the mixture in the pipe will be too great to permit a back-fire.

A great preventative of lighting-back is the use of fine nickel wire gauze at the burner end of the pipe. If this gauze be sufficiently fine, no flame can fire back through it, on the principle of the miner's lamp. Nickel gauze lasts longest when used for this purpose, as it is not easily oxidized or burned.

In the case of a troublesome furnace, which cannot be set going through lighting-back repeatedly, one remedy is to close the air inlet almost entirely, turn on at the jet, let the flow continue to fill the pipe, and then light at the burning end, finally gradually opening the air entrance nearly as far as possible, short of bringing on a back-firing. If, now, *the pressure of gas from the main be maintained*, this setting of the air opening will permit of lighting the furnace without the possibility of a back-fire. But if the gas pressure at the jet should fall, lighting-back will be inevitable. Here we see one advantage of employing a gas regulator, ensuring a constant pressure at the jet. Now, the words *pressure at the jet* imply velocity at the jet. If this is not sufficiently high, the velocity of the entering air will also be deficient, because one depends upon the other. In other words, a jet should be a *small*, cone-shaped orifice for the issue of the gas ; *not a large ragged hole*, as is frequently the case. Most troublesome back-firing burners in furnaces can be cured at once by fitting a finer, properly shaped jet. Back-firing can also be avoided in some cases by withholding the lighting match until the leading pipe is properly filled with gas. As hinted above, all trouble of this kind can be overcome at once, and with certainty, by nearly closing the air entering at the jet until the burner is at work, and then reopening it to a predetermined degree.

All gas burners should be furnished with a ready and efficient means of controlling the amount of air drawn in by the velocity of the gas at the jet, but in any specific case the remedy is simple.

Transferring our attention to the burner itself, this assumes various forms according to the shape of flame required to distribute the heat or direct it upon the work in the furnace. There are numerous forms and complexities of burners, as the flame end of the pipe is called. Some of them consist of gridded outlets; others are wire meshed; very many are made by perforating the end of the pipe with numerous holes; others are simply open, with no grid or gauze. Provided that the flame reaches its objective, the particular kind of "burner" fitted at the end of the mixture pipe is of very little consequence. The advantage lies with the simplest possible form, which is obviously the open variety, which may be so designed as to act in directing the flame where it can do most useful work. Gauze burners, even when the gauze is of nickel, are apt to be troublesome by becoming clogged, and then permitting the flame to burn behind the gauze, ensuring its early destruction. Perforated burners are useful so long as they can be kept clear. Grid burners last a long time, but there is little in them to destroy. No kind of burner that will prevent lighting-back will permit of as free an outlet for the mixture of air and gas as an ordinary open type. The lighting-back defect should be remedied at the mixing point at the jet itself. All of the foregoing suggestions must be understood to refer to simple atmospheric burners, as distinguished from air-pressure burners.

Pressure Burners.—The best type of burner or flame-end is doubtless the concentric class. Here we have a small pipe within a large pipe, with their extremities coinciding. The small pipe carries pure gas, while the larger one surrounding it carries the air under pressure. If these gas and air outlets are of such shape that we may visualize a parallel shaft of gas in the centre surrounded by a tube of compressed air, a mixture will not take place for some distance beyond the orifice. The air tube, however, is terminated in an inward curving lip, which serves to direct the air from a straight line and to force it to mix with the shaft of gas.

A very powerful flame is produced by a light air pressure. The action of this flame has a drastic cutting effect; it adversely affects the surface of the steel upon which it is directed, hence the jet should never be projected directly upon the steel. Nor should it be directed upon one spot of the fireclay lining of a furnace. The most effective way to employ the flame is to let it strike the furnace wall at an acute angle, and so set up a whirling, expanded heat. A crucible placed in a cylindrical furnace lining can in this way be surrounded by the flame projected from a single burner, provided that the burner be directed tangentially.

The ordinary burner, as used in gas cooking stoves, working at atmospheric pressure, exerts a mild, but effective, heating effect. On the other hand, a pressure burner is very much more rapid and fierce. Thus in the oven type of furnaces already spoken of, the atmospheric burners are used in any advantageous position with regard to heat, greatly because such a flame does not tend to destroy what it strikes. Greater care has to be taken in arranging the position of the pressure burners.

CHAPTER V

ELECTRICAL EQUIPMENT

Small, Medium, and Large Electric Furnaces.

In many respects the production of the necessary heat for the treatment of steel would appear to be a specially useful function of the electric current. And, as might have been expected, it has been used for this purpose in the laboratory for years. Here it offers numerous advantages, not the least of which being its adaptability to operations demanding exact temperatures, maintained for any required period of time. Its cost can be exactly ascertained. It is clean, and quite free from all of the objectionable by-products of coal, coke, oil, or gas. The destruction of the firebrick and clay work of furnaces is less in the case of electrical heat than it is with any of the fuels above mentioned, chiefly because the actual distributing point of heat can be brought into close contact with the work to be treated.

All of these advantages can be secured, and are in almost every case assured, in laboratories. But the work of the laboratory is very different from the work of the engineers' hardening department. It consists, as we know, largely of miniature reproduction of the actual work of the shop. There need be no haste in the laboratory, neither need the operator trouble about the cost of this or that.

As is well known, the Electric Arc Furnace is well established in the steel-making industry. But the induction type of furnace which is required for heat treatment is not so well developed. Its use in the United States, in France and Sweden, is, however, gradually being taken up, and numerous successful installations are open to inspection.

A brief review of some of these instances is given in this chapter, following a description of some of the miniature electric furnaces for tool treatment.

There is a field for electrical heating—a field where *its* *higher cost is*, comparatively, of no account. The question of competition between electricity and fuels does not arise at all when the employment of electricity will lead to a result which gas or oil cannot produce. And there is much of this work in connection with steel treatment.

Externally Heated Electrical Crucible.—When a current of electricity is passed through a thin wire, the wire will become hot; given a long enough wire, of a material that will not burn away, we have here a means of heating up a crucible by simply lapping a wire around its exterior. The turns of the wire spiral may be kept apart by a similar winding of asbestos string. The whole may be wrapped in asbestos "wool," surrounded by asbestos sheeting, and mounted in a suitable fireclay container. Here we have a simple form of electrical crucible useful for numerous operations where gas is at present the only source of heat.

Its chief defect is, of course, that the heat energy has to be passed through a fireclay crucible wall before it can be used within the vessel. Time is consumed in bringing the interior of the crucible up to the high temperatures generally called for. The necessity to pass the heat through the fireclay in addition to the evolution of a high degree of heat within leads to a very white-hot condition of the conducting wire. No wire yet discovered will withstand a very high degree of heat indefinitely. Hence the early destruction of the heating coil. We have here the chief cause of weakness in the usual externally heated furnace. These crucibles are obtainable commercially.

Internally Heated Crucible.—A far better arrangement for certain classes of work is the internally heated crucible, a very useful form of which is produced by the General Electric Company, who use iron electrodes, and other makers, who use both iron and carbon plates. The principle of the furnace is the maintaining of a bath of fused salts at a sufficiently high temperature by passing the electric current directly into the crucible, and through the fused salt. The resistance offered by the salt leads to the evolution of heat.

The Electrodes.—These are of pure Swedish charcoal iron, almost or quite free from carbon, the fusing point of which is said to be as high as 2,900° F. This is sufficiently high for most ordinary operations. A plate of this iron is fixed at each of opposite sides of the crucible, which is of fireclay, well heat-insulated in asbestos and fireclay case, fixed into a wrought-iron frame. The usual copper conductors, of ample size, lead the current to the iron plates.

Electrical Pressure.—In all of the most successful types of furnace, the resistance to be overcome being small, a very low voltage only is required. This generally means from 5 to 20 volts, according to the resistance of the bath. Since the usual voltage of lighting and power circuits is many times higher than these figures, the supply cannot be taken direct off the mains, but must pass through a transformer in order to reduce the voltage. In the case of an alternating supply a fixed and simple form of transformer is all that is required. If direct current is the nature of the supply, this will have to be changed to alternating of about 50 cycles or higher. The temperature is determined by two factors: the resistance of the bath and the voltage or pressure of current in circuit. This can be regulated when a transformer is used by varying the voltage, or otherwise working through a resistance in the usual way.

It will readily be understood that direct current cannot be used in this form of electric crucible. Electrolysis is set up in the bath either by direct (uni-direction) current or by alternating current of less than 25 cycles. Single-phase current only should be used.

The supply for electric crucibles should, if possible, come from a dynamo specially set apart for the purpose in the works. It should be an alternating, 50-cycle, single-phase, 100-volt, 100-kilowatt machine, adapted for small or fairly large output, and furnished with a regulating resistance, so that a small or a large current can be passed into the crucible.

The "melt" bath to be used in the crucible may be any of the fusible salts, and barium chloride will be found as suitable as any. Sodium chloride (common salt) is also a common melt.

If either of these salts be packed into the crucible, nothing will happen, although the current be switched on because the salt is practically non-conducting until it is in a fused condition. The initial fusing is the most troublesome. It is done by using a length of arc-lamp half-inch carbon rod to slowly lead the current across the top of the melt. The carbon rod is connected to one of the iron plates. As soon as it touches the opposite plate the point of the carbon rod will start an arc, and the salt around the arc will melt. By slowly moving the point of the rod away from the plate a melted trail of salt will follow it, conducting the current across. This continues until the opposite plate is connected to the canal of melted salt. A short continuance of the passage of current now suffices to entirely fuse the salt, which will begin to settle down, and its bulk will have to be added to until there is sufficient of the " melt."

A pyrometer should now be put into the crucible in order to check the temperature. Common salt fuses at 1,418° F., and barium chloride at 1,580° F. For most operations the melt will have to be maintained at a still higher figure because of the cooling effect of work introduced. Very light articles may be placed directly in the melt, but heavier parts should be well heated up before being immersed.

It will be seen that steel being treated in the crucible must not be permitted to touch either of the two iron electrodes. If metallic connection were to be made, there would, of course, be a short-circuiting which would blow the fuses, and the current would be cut off for the time being. In order to prevent this happening, the iron plates are protected against contact by a layer of perforated fireclay separator, or a strong mica screen.

Difficulty of Regulation.—In all electric furnaces of the fused bath type, carrying electrodes actually within the crucible, the conductivity of the bath is always being changed by withdrawing and placing masses of steel for treatment therein. To a certain extent this makes the crucible and its contents automatically heat-regulating; because if there is a mass of metal between the electrodes the resistance falls, and a larger current flows through the melt. But the same cannot be said of the chilling effect of immersing fresh steel. It would appear to be an advantage to arrange for pre-heating all steel to be treated to a suitable degree. It is also clear that if sufficient cold steel be immersed in the melt the salt will partially freeze, and so impede the flow of current between the electrodes.

Mixed Melts.—While, as has been pointed out, barium chloride is the most generally useful simple bath for electric crucibles, it cannot be claimed that it is suitable for universal application. But it is probably the best for high temperatures. For the lower temperatures, up to 1,700° F., a mixture of 60 % potassium chloride with 40 % of the barium salt is less troublesome. As a good deal of time may be lost by the tendency of the barium chloride bath to freeze if allowed to fall below 1,580° F., a 50 % mixture of potassium nitrate and sodium nitrate is very handy to work with for tempering, as it does not tend to freeze at 450° F.

Tool-point Heating.—A variety of other classes of work can be carried out in the electric crucible. For example, suppose it is desired to heat up the point of a high-speed steel tool to the nearly fusing temperature generally required; it is only necessary to so connect it with the wires from the dynamo that it takes the place of one of the iron plates in the crucible, or, in other words, becomes one of the electrodes. Current can be turned on and the point of the tool plunged into the salt, being kept there until the desired temperature is attained. It is then withdrawn and chilled in an air blast, or cooled in oil, as may be required.

Or if it is preferred to heat up the tool point by means of an electric arc, the salt is dispensed with, and an arc started by means of a carbon rod held close to the tool. This produces a fierce *local* heat, which may not extend, even to redness, through the thickness of the tool, and it may be successful in some cases. But the local nature of the heat is very apt to crack the tool point, while the burning, destructive nature of the arc may lead to the necessity to reforge the tool to restore its shape. These makeshifts are much more troublesome than merely heating up the tool in the forge or Bunsen burner.

Merely maintaining the barium chloride bath at the required temperature by means of the current is by far the best way to utilize electricity for small operations. Small articles are placed in iron-wire baskets for placing in the melt, in the usual way.

Resister Wire and Ribbon.—A nickel–chromium alloy, known as nichrome, is extensively used in most of the conductor types of heat-treatment furnaces. This material exhibits a surprising endurance under heat, and when not abused by passing fusing currents has a long "life" of usefulness.

In the case of small apparatus, where the current is of moderate volume, wire is generally used. For heavier currents ribbon is found more effective. In the following description of a typical heat treatment system, as used in the United States, and described by George P. Mills in a paper read before the Association of Iron and Steel Electrical Engineers of Philadelphia, some remarkable results of using nichrome ribbon resisters are given. Figures are also given showing that the use of heat-treatment furnaces in the United States is making most satisfactory progress in both medium and large scale operations.

Electric Furnace Design.—The electric furnace of the nichrome ribbon resister type, as shown in Fig. 42 (Electric Furnace Construction Co., Philadelphia), consists essentially of a strongly fabricated steel shell, with a heavy thickness of high-grade heat-insulating brick, laid in three or four courses, with all joints broken. The firebrick lining of the furnace is bonded to the heat-insulating brick so as to produce a solid rugged furnace wall of from 13 to 20 in. thick. The heating element consists of nichrome ribbon, which is exceptionally heavy. These ribbon elements are distributed over the inside walls, and in some cases the roof of the furnace, on insulating hanger bricks, which are built into the firebrick lining.

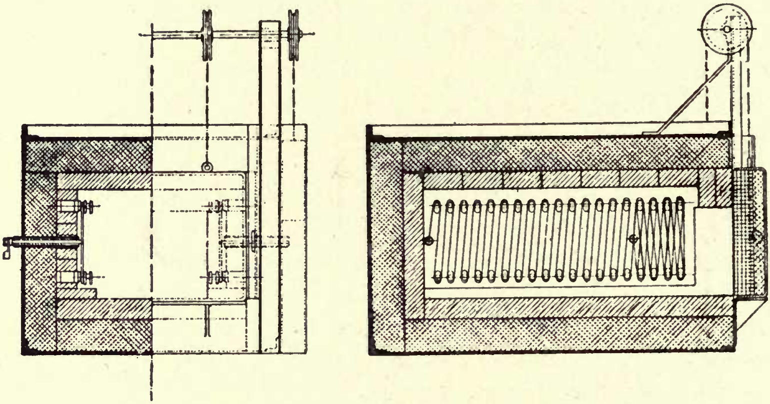

FIG. 42.—Heat-treating nichrome electric furnace.

Heating Elements.—A single length of ribbon constitutes each phase. Where splicing is necessary the joint is heavily reinforced and welded. The phase terminals are brought through the furnace walls in close-fitting insulating bushings to connection blocks on the outside of the furnace. The phases may be connected either delta or Y to the power circuit, through the control panel. This type of heating unit was developed some four years ago by engineers of the General

Electric Company at Schenectady. As to the life of the ribbon, there are furnaces which have been operating for over two years, day in and day out, and the ribbon shows no deterioration. An interesting example of the lasting qualities of the nichrome heating element is cited in the gun-treating furnaces which were installed by the Government at the plant of the Tioga Steel and Iron Company, Philadelphia, early in the war. After operating a year, shortly after the Armistice these furnaces were dismantled, ribbons straightened, shipped to Charleston, W.Va., reformed and built into new furnaces of a different size, at the Naval Ordnance Plant, and are now in operation. This is a positive proof that not only is there no reduction in area of the cross-section of the ribbon due to erosion, but there is also no deterioration or crystallizing of the structure of the ribbon.

Maintenance and Repairs.—In fact, the maintenance and repair charges on the ribbon resister type of furnaces installed have been negligible. This is the logical result of the working out of the principle and design of this type of furnace. It is the simplest of all types of furnace from a construction standpoint. No combustion chambers, flues, port holes, false bottoms, or double arches whatever are involved. The hearth, walls, and roof all being solidly constructed, can be insulated to the best advantage to prevent loss of heat. At the temperatures involved, the maximum never going higher than 1,800° F., the firebrick used, as well as the hanger brick, have a coefficient of expansion very nearly zero. The result is a tight furnace, in which all mechanical strains are reduced to a minimum. The lining does not crack, spall, or run. These facts are important, of course, not only from the standpoint of small maintenance costs, but there is no lost production due to shut-downs for repairs. Due to the fact that the ribbon resister may be formed in any reasonable shape and distributed over the interior of the furnace, remarkably uniform temperatures are obtained throughout the furnace.

Heat Distribution.—The ribbons are distributed so that extra heat energy is dissipated inside the furnace at the points requiring the most heat, in order to maintain uniform temperatures.

Large Installation.—An example of this is shown by the gun-treating furnace now being installed by the Electric Furnace Construction Company, which has inside dimensions of 36 ft. deep × 6 ft. in diameter, has a capacity of four

6-in. naval gun forgings weighing 50,000 lb. per charge. The furnace is divided into six heating zones, each controlled by an individual automatic panel. The radiation losses on the bottom and top zones are greater than on the intermediate zones, also the amount of metal to be heated is greater in the top and bottom zones than the intermediate zones. For this reason 138 kilowatts is installed in each end zone, and 110 kilowatts in each of the intermediate zones, the total installed capacity being 716 kilowatts. This arrangement insures uniform temperatures in the gun forgings throughout their entire length at all times, both during the period required for coming up to temperature and during the soaking period.

In the smaller furnaces where a single control is used, additional heat is generated near the doors by doubling the heat element back for a short distance, thus developing twice the B.Th.U.'s in this portion of the furnace where the radiation losses are greatest.

Temperature Control.—The temperature control, which is the most important feature of the electric furnace, is operated by the " on and off " principle, that is, power is cut off when the temperature of the furnace reaches a predetermined setting, and is cut on again when it falls to a predetermined setting. This operation is accomplished by means of a thermo-couple, which is placed on the surface of the charge, actuating a recording controller. The sensitivity of the control instrument is plus or minus $\frac{1}{4}$ of 1 % of the range of the chart; that is, if the chart of the instrument has a scale of from 200° to 1,800° F. the chart range would be 1,600°, and the sensitivity of the instrument would be $\frac{1}{4}$ of 1 % of this range, or 4 deg.

The " on and off " principle of temperature control has a number of advantages over the variable voltage control, in that the heating elements are designed for operation on standard power voltages—110, 220, 440, or 550 on either single-, two-, or three-phase, 25- or 60 cycle, or direct current. Often excess capacity in the existing power transformers can be used to advantage in the electric furnace. In cases where additional transformers have to be installed to take the furnace load these transformers are of standard type, and may be purchased to line up with existing power transformers.

The fact that the load is thrown on and off suddenly will produce no disturbances in line. On large furnaces, as in the case of the gun furnace just cited, the power is controlled in sections, so that only a small part of it is actually thrown on or off at any given instant. The usual maximum of a single zone is somewhat less than 250 kilowatts. The chief advantage of this method of control, however, is that it is entirely automatic, and eliminates the manual operation which is necessary in rheostatic or transformer tap control.

Two-point Controller—This instrument has the particular advantage of indicating the moment when the charge in the furnace is completely soaked, and is used in all cases where this indication is of importance. There are two thermo-couples in each heating zone, one placed adjacent to the heating element and one placed on the surface of the charge. The ribbon giving up its heat rapidly to the cold charge, its temperature is quickly reduced and that of the charge increased. As the temperature increases the two temperature curves become closer together, indicating a very low temperature gradient, the power, of course, being on all the time. As soon as the surface of the charge reaches the predetermined temperature, in this case 1,500° F., the power is cut off.

The surface of the charge only, however, is up to temperature, and the inner masses rapidly absorbing heat from the surface, the temperature is quickly decreased to a point where the power is again thrown on the furnace. The surface of the charge is again heated up to 1,500° F., when the power is again cut off. This cycle is repeated until the whole mass of the charge is up to temperature. In the case of a normal charge the time is about thirty minutes. From the moment the charge is soaked the two temperature lines become parallel. The distances between them indicate the temperature gradient, which is necessary to provide the radiation losses of the furnace, amounting to about 500° F.

Single-point Controller.—The temperature of the surface drops rapidly, making a steep curve (when a chart is taken) to a point where the power is thrown on again. It requires some little time for the temperature to come back to the predetermined value, and the curve has a slow rise to a point where power is turned off. This cycle, of course, is repeated continuously, and after a short period it will be seen that the saw-tooth effect of the curve is reversed;

that is, the heating-up curve while the power is on is very steep, and the cooling down curve while the power is off is not so steep, indicating that heat is going into radiation losses only, and not being taken up by the charge.

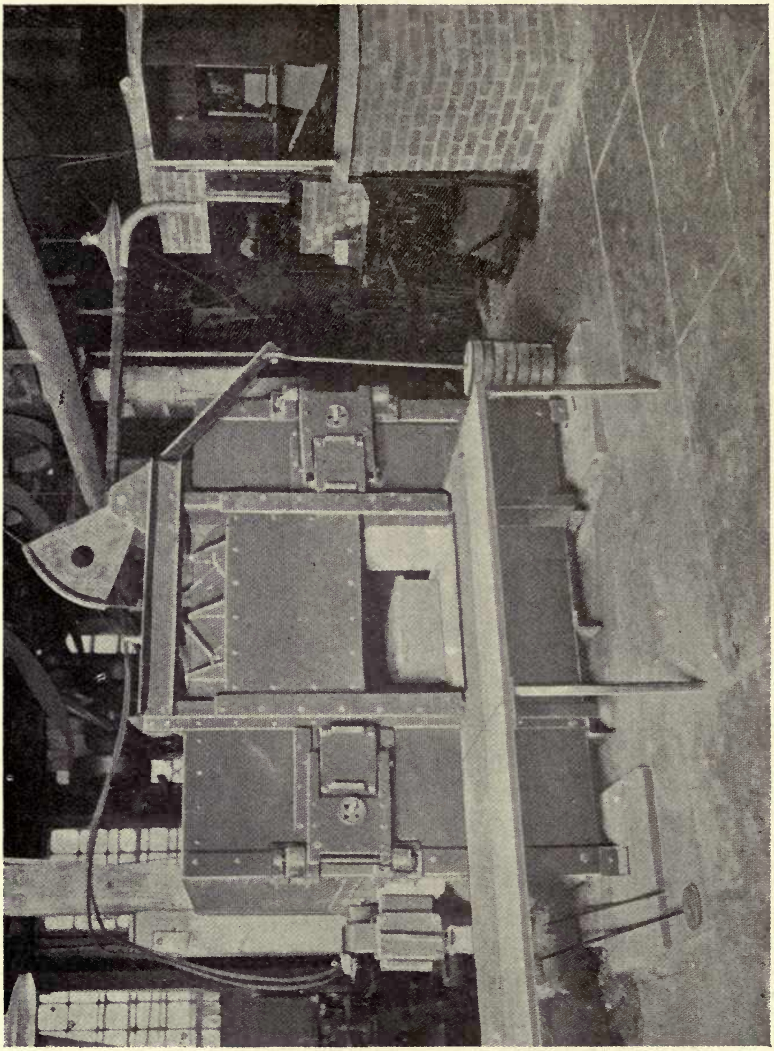

Fig. 43.—Carbon Resister (Baily) electric furnace.

Carbon Resister System.

The most generally used of the carbon resister type of heat-treatment electric furnaces are those of the Electric Furnace Company, of Alliance, Ohio, specialists who have had a long experience in producing electric melting furnaces for the non-ferrous metals and alloys. So well adapted to the work of thermal treatment have the steel-treatment type of furnace been, that many of the leading automobile

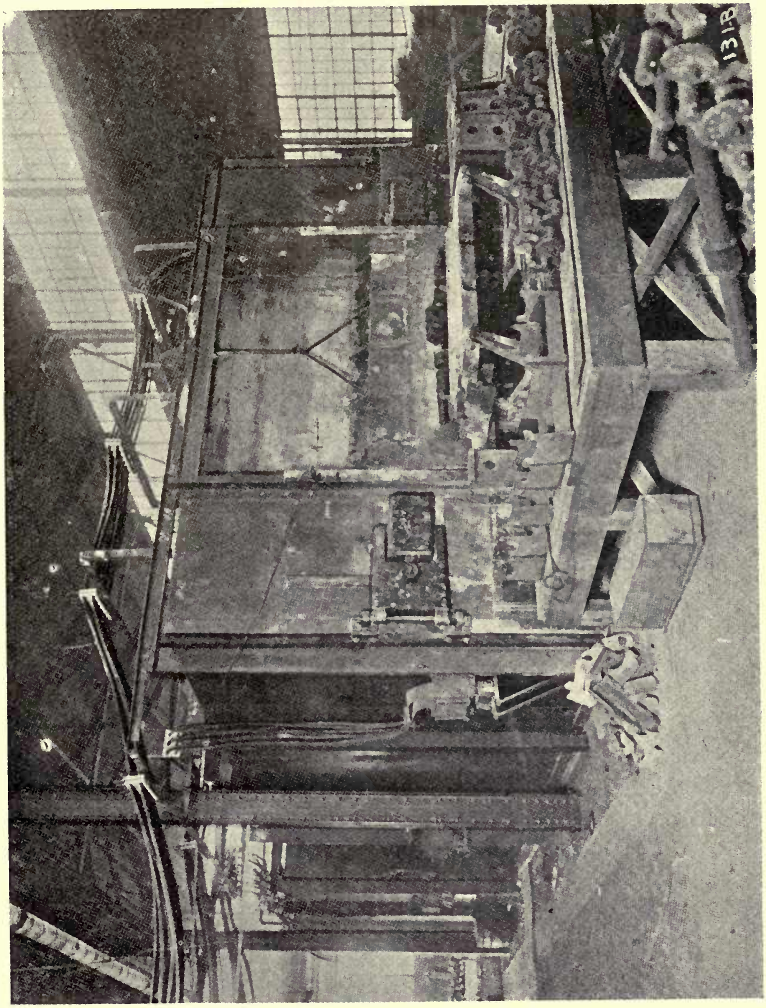

FIG. 43A.

concerns are at the present time treating their work without the aid of oil or gaseous fuel, and securing a uniformity of tensile strength probably impossible with either. There are five distinct classes of these electric furnaces in use, as follows :—

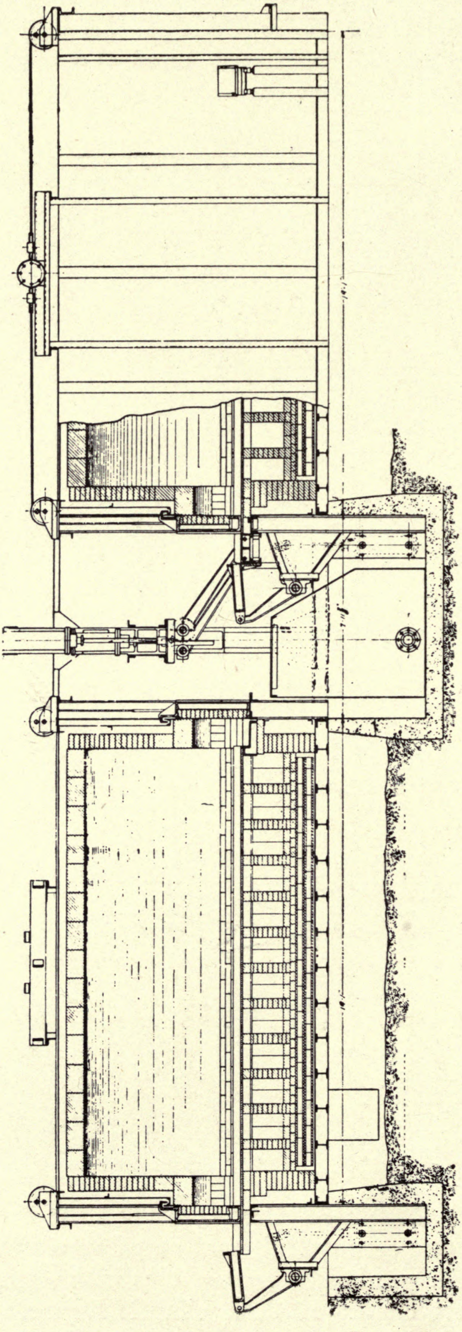

FIG. 44.—Pusher type.

Hearth Type (Figs. 43 and 43A).—Taking the place of the usual fuel-fired furnace, for stationary work. From 40 to 200 kw.

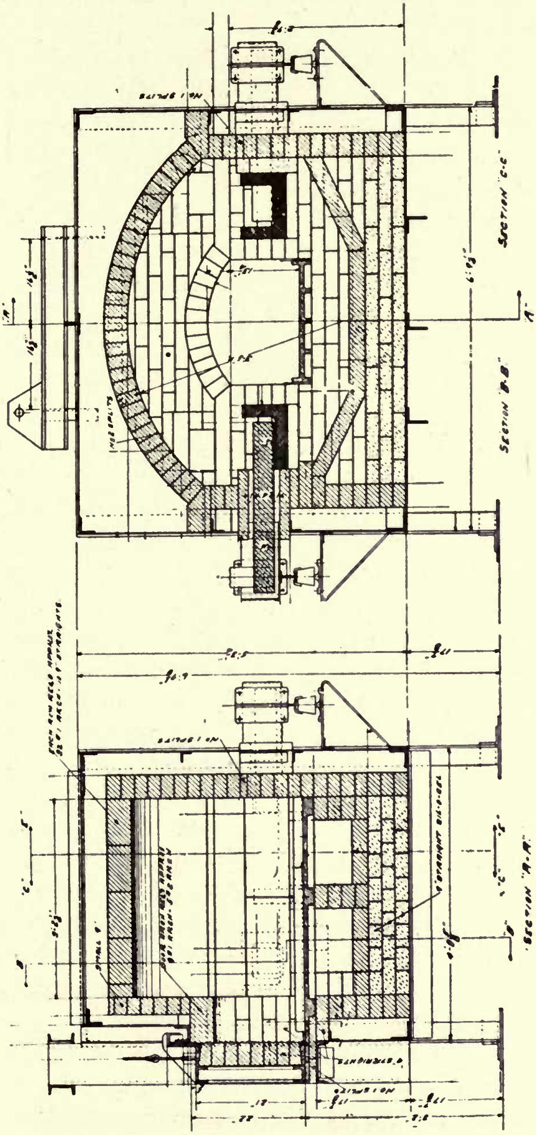

FIG. 45.—Showing carbon heating elements.

Continuous Pusher Type.—In which the work slowly travels, or is periodically pushed along at the right moment for quenching. From 100 to 900 kw.

Car Type.—In which the work is placed upon trolleys, either continuous or non-continuous, 150 to 900 kw.

Automatic Continuous Heat-treating Sets. To treat 1,000 to 6,000 lb. of material per hour. Kilowatt capacity, 200 to 900.

Continuous Recuperative Pusher Type for Large Tonnage.—As an example of one of these types the kind of furnace used by the Pierce Arrow Motor Car Company for their gear treatment work will give a fair idea of the principle of the whole. The furnace is of sheet metal, the enclosure being rectangular in shape, and lined on the inside with suitable fireclay brick, this lining being backed up with a high-grade heat insulation between the brick and metal.

It has a capacity for heating 200 lb. per hour to approximately 1,600° F., is rated at 40 kw., and designed for single-phase, 25-cycle operation, as shown in section in Fig. 44.

Along either side of the furnace from front to back run two troughs, made of a highly refractory carbide mixed with a binder, so that it can be easily moulded. These troughs, which are rectangular in shape and open at the top, are filled with resister material, consisting of broken carbon or graphite, to which the current is fed by means of electrodes fastened to the ends. The function of these troughs is to generate the necessary heat, which is then radiated mainly to the roof, and from there reflected down on to the hearth and the material being processed (Fig. 45).

Such construction is known as a resistance reverberatory-hearth type furnace, and can be likened to two huge glowers, similar to the filaments of incandescent lamps, contained in a simple but substantial heat-insulating enclosure.

The furnace is charged and discharged through a door at one end. This door is insulated in the same manner as the furnace enclosure, is counter-weighted, and slides up and down vertically. The whole construction is both substantial and reliable, allows of small radiation loss, and provides a strictly commercial furnace, since all materials used are readily obtained in the open market. It also ensures accurate control of the three vital points of proper heat treatment, that is, atmosphere, time, and temperature.

Three-phase, 25-cycle current stepped down to 400 volts is supplied from Niagara Falls, or from the isolated plant on the premises, as the Pierce Arrow Company generates part of the total electric power used. This current goes to a special regulating transformer, which is of standard design, and furnished with all heat-treating furnaces. It is provided with nine taps in the form of oil-insulated, hand-operated, selective, oil-break switches (Fig. 46), by means of which the voltage, current, and hence the heat of the furnace are controlled and adjusted to suit the requirements of the particular process going through.

In addition to the usual control switches on the board there is a wattmeter and a double-pole, double-throw switch, by means of which the furnace-heating troughs can be separately controlled. They are run in parallel. In an adjoining space, separated by a partition, are mounted two recording pyrometers, one a Leeds and Northrup and the other a Bristol. These are connected by a thermocouple inserted through the roof, and protruding well into the furnace. Thus a close and accurate check on, as well as record of, the temperature in the furnace enclosure is had at all times.

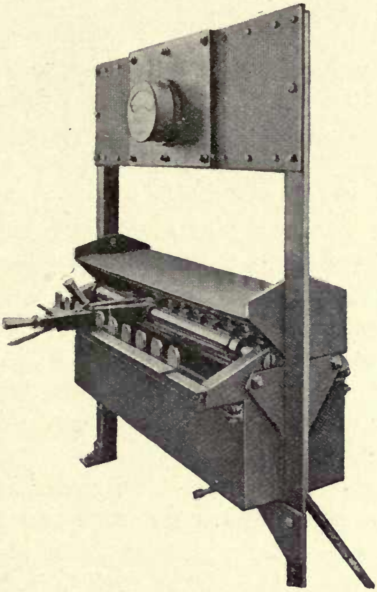

Fig. 46.—Electric nine-step oil break switch.

As soon as the main switch is closed, current flows through the resister material in the troughs. This material, due to the negative coefficient of carbon or graphite, when cold is a poor conductor, and at the start offers resistance to the passage of the current.

This action in turn transforms the electric energy into heat energy, and the material soon heats up. The hotter it gets the better conductor it becomes, hence more current flows since there is less resistance to its passage. As soon as there is any indication of the furnace becoming overloaded, as shown by the wattmeter, the operator closes one of the control switches, cuts down the voltage, hence the power input, and can in this manner regulate and hold the temperature constant.

The Pierce Arrow Company is turning out about forty trucks a day, ranging from two to five tons, and as there are fifteen or sixteen gears per truck the total number heat treated daily is from 600 to 640 gears, ranging in weight from 3 to 15 lb. each. These are preheated in an oil furnace to a temperature of approximately 1,250° F., at this temperature there being no danger of scale, and held there thirty minutes. They are then immediately transferred to the electric furnace and heated for half an hour at a definite temperature around 1,450° to 1,500° F. In charging the electric furnace care is taken to ensure that no one gear is nearer the door than 1 ft., thus avoiding any tendency towards uneven or non-uniform heating of the entire charge, which consists of several gears.

At the expiration of the heating period, which is accurately timed, the gears are withdrawn one at a time, and immediately quenched by plunging them into an oil bath, which is located alongside of the electric furnace, requiring only a few seconds to make the transfer, and thus exposing the heated gears to a minimum time in the cold air.

Again, when removing the gears from the electric furnace for quenching, the door is only raised to a sufficient height for a quick removal, hence the danger of oxidation is reduced to a minimum, since the furnace atmosphere is a reducing one, because of the nature of the resister material, and the slight amount of air admitted in this manner is quickly absorbed.

After quenching, the majority of the gears are allowed to cool in air, but some are drawn at a temperature of about 500° F.

The temperature of the oil in the quenching tank is maintaine dconstant at some point between 90° to 120° F. After undergoing this treatment the gears show the following average physical characteristics :—

1. Brinell hardness on core	350
2. Brinell hardness on outside	444
3. Scleroscope hardness on outside	85
4. Elastic limit on core	150,000 lb.
5. Reduction of area on core	50 %

According to Mr. Miller,* some of the advantages of an electric furnace are elimination of oxidation; uniformity of temperature; accuracy of control, which enables work to be heated to within 10° F.; certainty of duplication; clean work; saving in labour and material, since it is not necessary to remove scale; and absence of smoke, fumes, and noise.

The Wills Sainte Clarie Co., of Marysville, Michigan, have produced the first American car to be built entirely of super steel. More than that, it is the first car to have all its forgings subjected to scientific treatment in electric furnaces. Such a car represents the ultimate in strength and service.

The heat-treating equipment of the C. H. Will Company consists of a set of two similar electric furnaces, each with a hearth substantially 5 ft. long, having an electric capacity of 400 kw. for the combined unit, and a heat-treating capacity of 1,500 lb. per hour. As the material to be treated consists of a large number of parts of different sizes, ranging from the axles and crank shafts to the smallest parts entering into construction of the car, it was necessary in order to get the most convenient operation to place all the material in pans or containers. The parts remain in these pans through the hardening and quenching operation, and through the drawing operation as well. Electric motors, actuated by a time clock mechanism, raise and lower the furnace doors, advance the material through furnaces, and quench, and make it unnecessary to have any conveying mechanism within the hot zone of the furnaces.

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* Dwight D. Miller, Society for Electrical Development, New York.

CHAPTER VI

WORKSHOP HEAT MEASUREMENT

WHAT would be said of a mechanic who proposed to carry on his workshop without the aid of even a foot-rule ? And what would be thought of the products of an engineer's shop in which such a thing as a micrometer were unknown ? Answers are unnecessary ; and yet, at the present day, we hear of steel-treatment establishments in which thermo instruments of precision are either taboo or entirely unknown.

With regard to the latter, we may withhold judgment until we have heard the hardener's story about pyrometers ; but with regard to the man who has never even tried one, his case would appear hopeless.

Accurate Heat Measurements.—There is at the present time no evading the fact that accurate measurements form the basis of even moderate success in steel treatment by heat. Uniformity and standardization are ideals that bid fair of attainment. Given a standardized steel product, we possess the basis of uniformity and certainty of results in the finished steel part.

Standardized Steel.—It would scarcely be in order to speak of even reasonable uniformity or standardization in the heat-treatment shop if the steel-maker could not supply a fairly uniform and dependable steel. But that he can and does now produce a steel accurately to specification, with an error less than 5 per cent., there can be no question. The chemical analysis of straight carbon and alloy steels is now well understood. The changes through which the molecular structure of the mass passes, under the influence of heat, have been the subject of accurate scientific investigation, and this study has led up to the production of steels of standardized and uniform qualities.

The Treatment Man's Part.—Having at immense cost and labour secured dependable steel, it is certainly " up to " the man in the heat-treatment shop to bring his department into line. It would be idle to speak of the necessity for change, if change were not absolutely necessary, from the old order of things to the new. It is natural for man to resist change, especially when change involves the taking of additional pains with the work in hand.

To those " in the know " there was no mystery in the fact that the Ford Company in America got ahead of the whole automobile world in their use of steel of superlative quality for their cars. There was no luck or chance in it, as is now well known. It was chiefly due to the heat-treatment man carefully following data supplied by the Ford laboratories.

Heat Measurement not All-sufficient.—But in this particular art heat measurement must be correlated with *Time* measurement. Hence our hardening shop must work with two instruments, the *Pyrometer* and the *Clock*.

The element of time is found to be just as essential to success as degrees Fahrenheit, and correlated to both is the human element of intelligence and the determination to arrive at the best product.

For some time to come this human element will be the *weak* link in the whole chain of processes through which steel has to pass before it is embodied in the finished machine. And why ? Simply because steel heat treatment is a new art, especially in reference to the magnificent range of alloy steels now at our service. The old-time smith was at first the only skilled man to employ upon its treatment, which, however, was so essentially different from anything within his ken that any intelligent man, not of this trade, could be more quickly initiated into the procedure throughout the new processes, because he would not have anything to *unlearn*—which is, indeed, the hardest kind of learning.

In the treatment of the alloy steels the writer has attributed his success mainly to employing a youthful class of labour, fairly grounded in scientific facts, and prepared to work under direction and quite free from prejudice, certainly never hampered with a load of outworn guesswork and rule-of-thumb experience. It may be accepted as an axiom that a high degree of skill should at all costs be encouraged in labour engaged in the heat treatment of

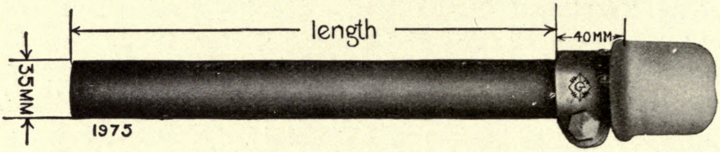


FIG. 47

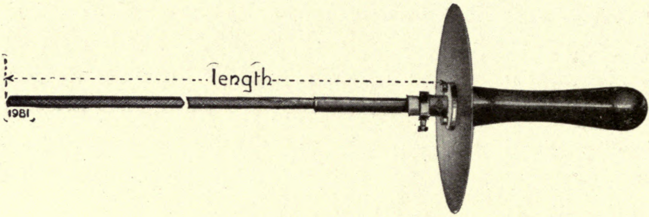


FIG. 48.

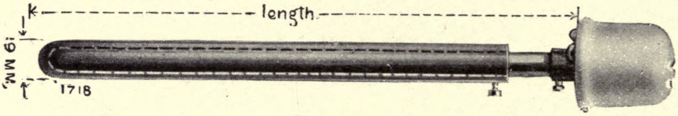


FIG 49.

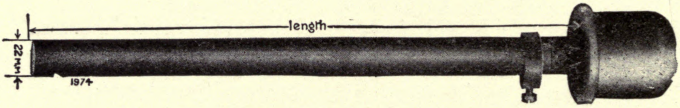


FIG. 50.

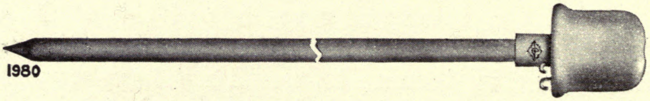


FIG. 51.

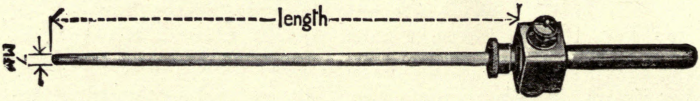


FIG. 52.

Six thermo-couples.

steel. Economy, or let us say false saving, in this department is the sheerest form of waste.

The Pyrometer.—For the purpose of registering the heat to which the steel is to be subjected, we may use an instrument for indicating the degrees upon a dial or scale apart from the furnace. Equally important is the provision of an ordinary clock. Here we have the two elements of measurement, heat and time, for all our purposes.

Probably the most generally successful and used pyrometer is the thermo-electric couple, but it is only one of several systems at the service of the heat-treatment shop. It consists of a recorder, or a dial, or a scale, with a pointer. A "hot-end" for placing in the furnace, a "cold end" kept away in the cool place, and a pair of "leads," or leading wires, for connection. The action of this instrument depends upon an interesting and scientific fact. Looking back for a moment to the discovery upon which it is based, we find that if a semi-circle of bismuth is joined to another semi-circle of antimony, the two forming a complete ring, we have a thermo-electric couple. If now one of the junctions of the ring be heated, while the other remains cool, a current of electricity at once begins to flow in the circle. This electromotive force is, of course, feeble, but it is quite sufficient to actuate a needle of the sensitive galvanometer included in the circuit. The voltage of the electromotive force is roughly proportional to the difference of temperatures between the hot and the cold ends or junctions in the circuit —it is, in fact, a differential potentiometer in itself.

A number of the different forms and arrangement of the generally used thermo-couples is shown in Figs. 47–52.

In practice, such metals as those mentioned are not, of course, used. Any two dissimilar metals can be made to act, but for pyrometer use refractory metals, such as platinum, are perforce employed. In practice, again, the circuit consists of two insulated wires having a small section of each of the dissimilar metals joined together at the hot end—that is, the end placed in the furnace. The cold end is some distance from the source of heat, and is frequently kept cool for tests by being immersed in water at 32° F., freezing temperature. The galvanometer is hung upon a near wall, and its needle points to a scale of degrees of heat, either Fahrenheit or centigrade. A good instrument of this type will indicate, if forced up, as high as 3,000° F., which is beyond the melting-point of steel.

Troubles with the Pyrometer.—Instruments of this, or indeed of any type, do not remain accurate indefinitely. They all call for frequent checking. This check is called the calibration test, and is either carried out at the workshop itself, or at a nearby Bureau of Standards, as at the National Physical Laboratory in England, or at the Government Bureau of Standards at Washington, U.S.A. Perhaps a still better plan is to keep a standard pyrometer at hand, which can be placed temporarily in the furnace and the two readings compared. Of course the standard instrument should occasionally be checked, which can be easily done as follows :—

Pyrometer calibration experience in the use of thermocouple pyrometers has brought home to heat-treatment men the fact that without a *weekly* standardization dependence should not be placed upon the instrument. The varying treatment it is subjected to will readily account for this condition of things. Even if the pyrometer is seldom used, the test should not be neglected.

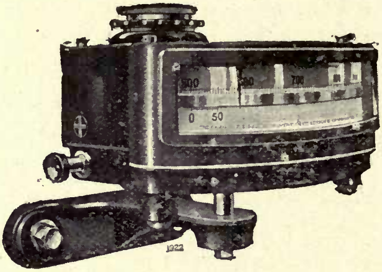


FIG. 53.—Wall type and selector type indicators of temperature.

Melting- and Freezing-points of Common Table Salt.—It is found that our daily table friend (NaCl) possesses freezing- and melting-points a convenient distance apart for our purpose. The salt should be melted in a clean plumbago or fireclay crucible, or, failing this, an iron pot. When the temperature has been raised to 1,475° F. the salt will begin to run. The heat is now further increased until it attains about 1,600° F. at least. The salt being molten, the pyrometer is warmed, and its hot end plunged into the melt for the depth of 3 in. and allowed to remain so for several minutes to ensure that the end is really at the temperature of the salt.

At this stage the crucible should be removed and allowed to cool. At the same time the reading of the pointer on its scale should be noted, and the needle watched. The pointer will begin to fall, and will gradually drop, until at 1,472° F., which is the freezing or solidifying point of clean and pure common salt, there will be a pause. The reading taken *just as the salt is solidifying* will, if the instrument is correct, be in the Fahrenheit notation 1,472°, and on the centigrade scale 800°. This should be correct within a few degrees either way.

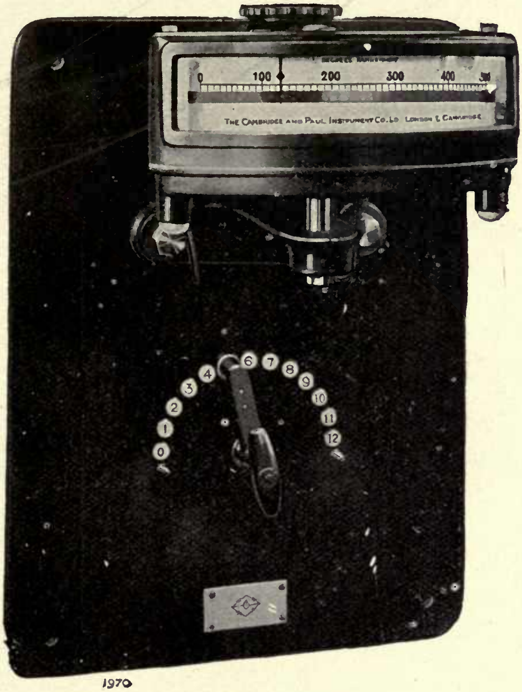


FIG. 54.—Indicator for use with more than one thermo-couple, showing selector switch reading from 300° to 1,400° C. (572° to 2,552° F.).

This error may be due to two causes, first a radical fault at the hot junction (or hot end), or much more likely to neglect of keeping the cold end of the circuit at the correct temperature for that make of pyrometer. The cold junction should, either under test or in regular use, be kept uniformly at the degrees of heat stamped upon it, or furnished with the instrument. For scientific testing it is usual to keep this end in freezing water. But for convenience in workshops the cold end is supposed to be maintained at 75° F., which can easily be arranged. It is obvious that as the reading depends upon the *difference* of temperature between the two ends of the circuit, this precaution, to isolate the cold end from possible heat of the furnace, also from cold air, must not be overlooked. A "hot end" must always be freed of salt and washed in hot water after exposure to a salt bath to avoid deterioration.

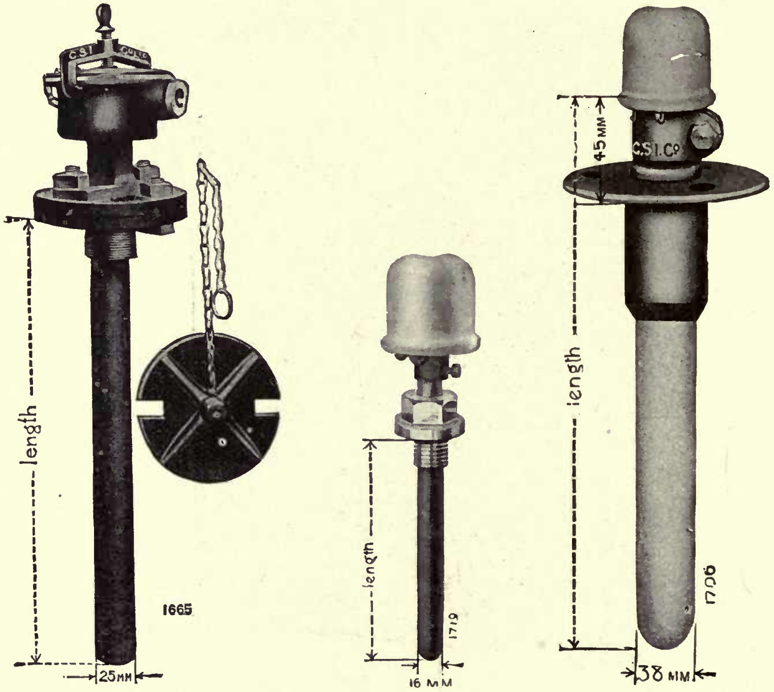


FIG. 55. FIG. 56. FIG. 57.

Armoured type of thermo-couples.

A wall-type of indicator for one couple is shown in Fig. 53, and an indicator taking the current from any one of twelve couples in Fig. 54. Armoured thermo-couples are shown in Figs. 55–57. In Fig. 58 is shown an oil-filled vacuum flask for maintaining the cold junction at a uniform known temperature.

One of the leading makers of instruments suggests the plotting of a curve, or graphic representation of the rise of the pointer on the scale, using as co-ordinates the time in seconds, and the temperatures in degrees. While this is an interesting illustration as to what is taking place in the melted and freezing salt, and in the circuit of the instrument, it is not considered necessary for ordinary workshop use.

It is, of course, preferable to set the pointer itself at the fiducial mark, many pyrometers being so arranged as to permit of this correction or adjustment of the resistance (coil) kept in circuit ; it must be carefully done.

Fig. 58.—Oil-filled vacuum flask for cold junction.

As before suggested, it is advisable to take this simple test at least each week, and in large works oftener, unless a standard testing circuit and hot end can be kept at hand for comparison daily with the working hot end. In works keeping a number of heat-treatment furnaces going the standard instrument itself should be frequently checked by the salt-bath method described above, and then a test made of all the other thermo-couples in the shop daily by the simple procedure of inserting the standard hot end side by side with the doubtful hot end, allowing sufficient time to elapse to equalize the temperatures, and comparing the indications of the two pointers. In checking the accuracy of thermo-couples it is useful to remember that :—

Water freezes at	32° F.
Water boils at	212° F.
Tin freezes at	450° F.
Lead freezes at	621° F.
Zinc freezes at	786° F.
Aluminium at	1,216° F.
Common salt	1,472° F.
Potassium sulphate	1,958° F.
Sulphur boils at	832° F.

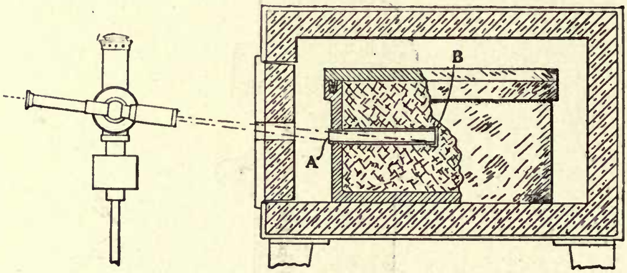


FIG. 59.—Pyroscope sighted upon carburizing box.

Pyrometers Still Imperfect.—Although we have now a wide range of heat-measuring instruments under trial at the present time, it cannot be said that, except for low readings, there is a single one that does not tend to vary in its indications. This especially applies to the higher heat values, perhaps starting at 1,000° F. Instruments to continue to record faithfully at temperatures varying upon the melting-point of steel are very difficult to devise and construct. "Titan" base metal thermo-couples, available for heat as high as 1,832° F. (1,000° C.), have proved very successful. Thermo-couples capable of reading up to nearly 2,552° F. (1,400° C.) are made of platinum and platinium-rhodium. Although the first cost of the latter is higher, it is known that they continue to read more accurately and last longer than the so-called base-metal couples. There is, of course, protection provided for the thermo-couple wires, which usually takes the form of a porcelain or quartz tube. For workshop use a further shield is provided in the form of a steel tubular sheath, but the fireclay sheath is recommended for temperatures over 2,012° F. (1,100° C.). It may be readily understood that at temperatures in the neighbourhood of molten steel the thermo-couple has about reached its limit of usefulness, and other means of measuring the degree of heat must be resorted to.

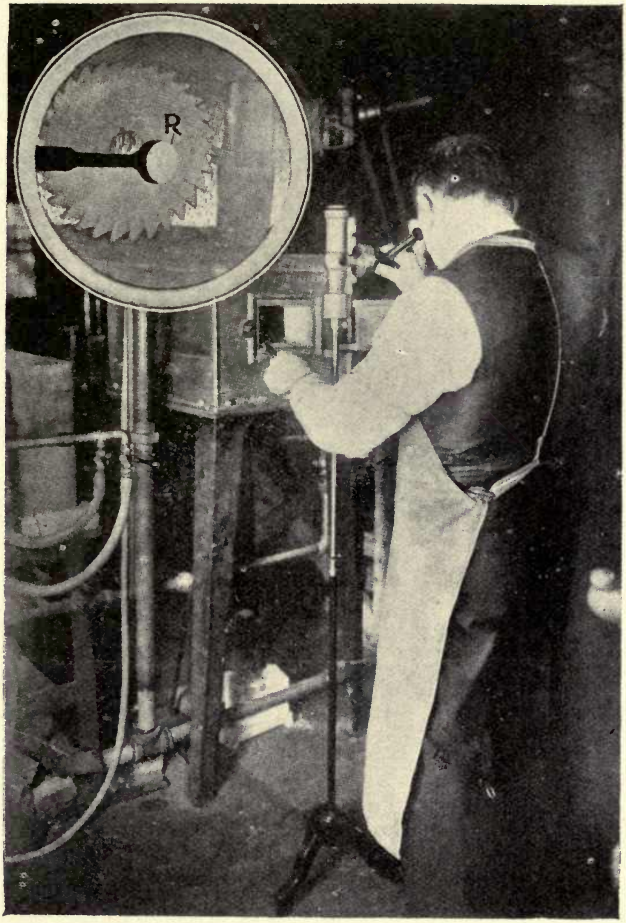


FIG. 60.—Pyroscope sighted upon object in furnace.

Radiation and Optical Pyrometers.—Considerable advances have recently been made in the invention of radiation and optical means of determining high heat values. One of the most successful of these is the Cambridge Optical Pyrometer, for measuring temperatures from 1,292° F. (700° C.) to an outside temperature as high as 4,000° C. This instrument can be used mounted upon a tripod, or it can be carried in the hand. To take a reading the pyrometer is sighted on the hot body and the eyepiece rotated until a beam of red light from the hot body is seen to be adjusted to equal intensity with a beam of similar coloured light from a small electric lamp contained within the instrument. The temperature can then be read directly from the circular scale on the shield of the instrument. Since the two beams of light are of the same colour, and have only to be brought to the same intensity to give the correct reading, no colour matching is required. The instrument can be used by any intelligent workman, and accurate reading can be taken repeatedly by different observers. The pyrometer is particularly suitable for sighting on small objects.

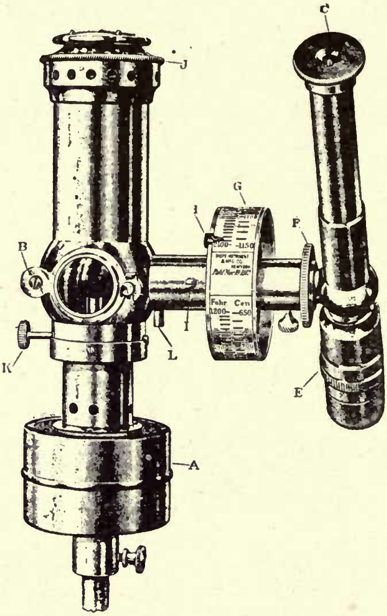


FIG. 61.—General view of pyroscope.

As the accuracy depends upon the constancy of the light from the electric lamp, a small ammeter and regulating resistance are placed in the box containing the accumulator to ensure that, whatever the voltage of the battery may be, the current through the lamp is constant. As the lamp filament ages, the current necessary to produce the correct illumination will change, and a provision is therefore made for checking the lamp from time to time against a standard amylacetate lamp, and so ascertaining the correct ammeter reading when the lamp is giving the required illumination. This test only needs to be made at long intervals. This pyrometer can be fitted with one or more temperature scales of any desired range, from 1,292° F. (700° C.) upwards. A National Physical Laboratory certificate of accuracy is furnished with each pyrometer.

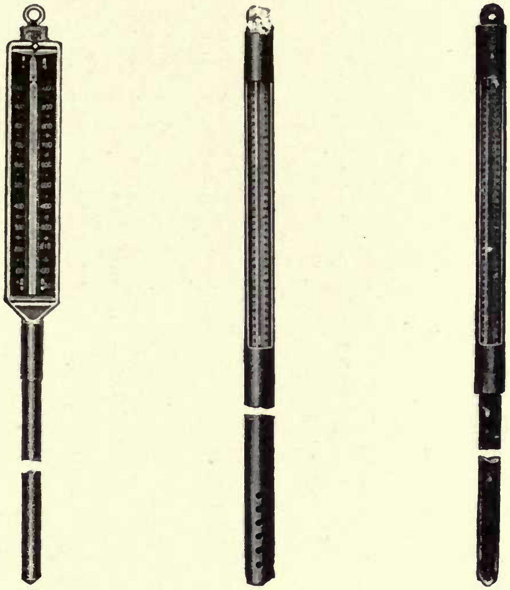


Fig. 62. Fig. 63. Fig. 64.

Mercury thermometers.

Shore Pyroscope.—Dependent upon the same principle employed in the above pyrometer, the Shore instrument uses the flame of a kerosene lamp, and also a coloured diaphragm. The telescope can be sighted directly upon an object, or it can be used in conjunction with a "sighting tube," having a blind end, placed within a case-hardening box of parts as shown in the sectional view, Fig. 59. It is clear that this application is alternative to the use of the test rod.

In Fig. 60, R is an enlarged view of the cutter within the furnace, shown not yet heated to the intensity of colour of the comparison disc at R, seen in the telescope. In Fig. 61 the lamp is situated at B, and the scale upon the drum G.

Of the many practical difficulties besetting the use of thermo-electric pyrometers, not the least have reference to the necessity to subject some part of the apparatus to the full heat of the furnace, and the difficulties in the way of carrying this out. In a furnace in regular use this can be largely overcome by providing a permanent fireclay tube, reaching from the top of the furnace, through its walls, until its extremity reaches half-way down towards the floor of the chamber. The lower end of this fireclay tube is closed, and it is merely used as a protective sheath to receive the pyrometer hot end while a test is being taken.

In a gas-fired furnace, where the heat is presumed to be regular, a test taken now and again is all that is required, and the pyrometer is not left in the test tube, but withdrawn and used elsewhere. The greatest difficulties encountered by the makers of these instruments have reference to the rough treatment they are apt to be subjected to. There is obviously only one remedy for this, and that is to entrust the testing of these instruments to one individual, who is to be held responsible for all rough-handling damages.

Mercury Thermometers.—For purposes of heat measurement in the lower reading there appears no type which in use surpass the mercury instruments, which are graduated from 32° F. up to 1,000° F. Their tubes are made of boro-silicate glass, which will withstand high temperatures. They are generally furnished with closed steel sheaths to guard against sudden heatings and coolings. They are very extensively used for heating up baths of fusible salts; for tempering baths, whether of salts, oil, or water. The instruments intended for oil or water are generally fitted with sheaths open at the lower end, to add to their sensitiveness. No open-sheath thermometer should be used with fusible salts, because the freezing or solidifying of the salt will generally break the glass. The instruments are variously graduated, and vary in length from two to three feet. Three of the most useful forms of this instrument are represented in Figs. 62–64.

Recorders.—The same class of instrument is made to show the temperature upon a scale, generally circular. A very useful form is that made by the Cambridge Instrument

Company, and so fitted as to give a graphic chart of its movements. In both of these types the steel bulb of the instrument is connected by steel capillary tubing to a form of steel Bourden spiral. The whole system is filled with mercury, and changes of temperature in the bulb give rise to corresponding changes of pressure in the system which are magnified and indicated or recorded by means of the usual pointer or pen mechanism. It is useful to remember that the tubing may be of any length up to 75 ft. In the indicator type the scale is made amply large, on an 8-in.

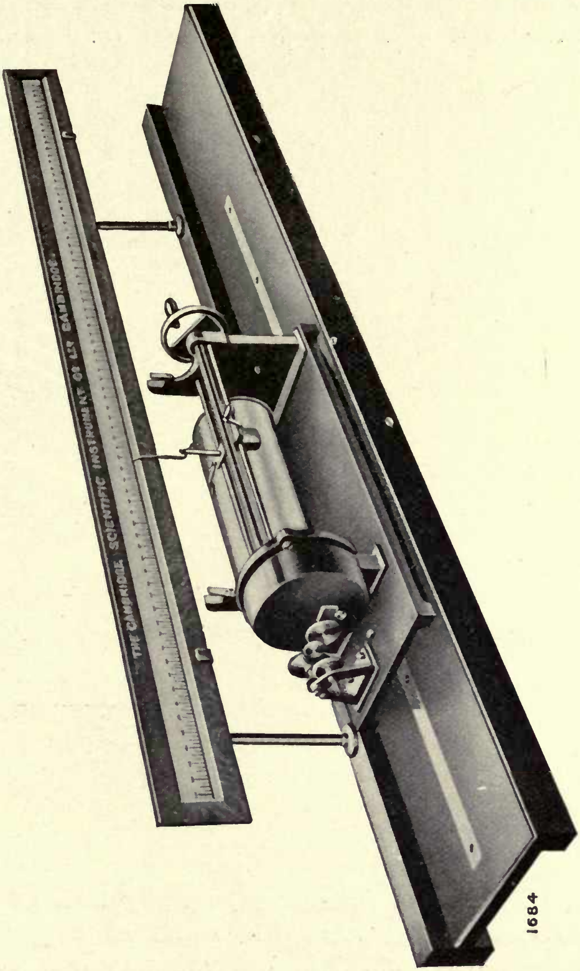


Fig. 65.—Brearley curve-tracing apparatus.

dial, giving a scale 14½ in. long. For distance positions a 12-in. dial is used, giving a scale 28½ in. in length.

The Thermographs have charts upon a drum 9½ in. in diameter, which is revolved by clockwork either once in twenty-four hours or seven days. In a shop where the work is systematized, it is a valuable aid to be able to obtain charts of the actual temperatures of particular salts, melts, or tempering and quench baths to refer to. As may be supposed, this class of instrument, equally with all of the mercury thermometers, have the merit of dependability and great accuracy, which is unvarying to a most satisfactory degree.

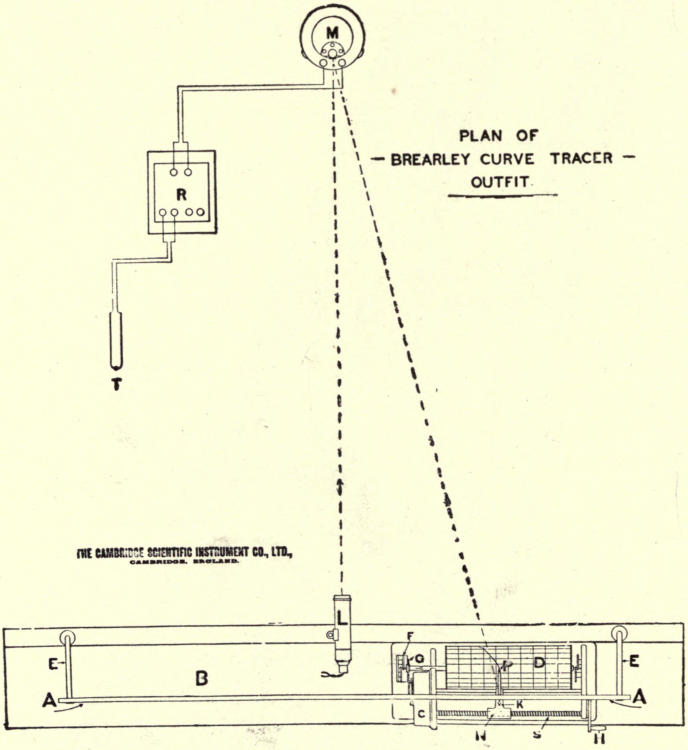


FIG. 66.

Different Systems.—A very great number of most ingenious instruments are in use; so many that the space at our disposal is too limited to deal with them all. They each claim, or actually possess, some salient merit. Perhaps the small fusible plugs, having a length of 1 and ½ in.

in diameter, made of various salts, are not the least interesting. They are placed in the furnace, and melt at a definite temperature, marked upon each plug.

THE BREARLEY DECALESCENCE CURVE TRACER.

The Brearley Curve Tracer is illustrated in Fig. 65, and shown diagrammatically in plan in Fig. 66. It consists essentially of a drum, D, resting on friction wheels, F, and driven by clockwork through a gear wheel, G. In front of the drum is a long screw, S, which can be turned by a handwheel, and by means of which a sliding carriage, N, can be moved in a direction parallel to the axis of the drum. On this sliding carriage are mounted a pointer, K, and a recording pen, P, which marks on the surface of the drum. The drum makes one complete revolution in ten or thirty minutes, as desired, and takes charts 360 mm. (14 in.) long and 300 mm. (12 in.) wide. As this width of chart need only represent one or two hundred degrees, it will be seen that a very open scale is obtainable. The curve tracer is shown mounted on a platform, a graduated scale of length 1½ metres. The curve tracer itself is quite separate from the scale and platform, and can be moved along the latter so that the range of the drum can be made to correspond with any 300 mm. of the scale. In cases where the long scale is not required, the instrument can be provided with a scale 500 mm. long, which can be mounted on supports fixed to the instrument itself. The platform is not then supplied.

The complete arrangement for drawing, heating, or cooling curves is shown in the plan in Fig. 66. A thermo-couple, T, is connected to a reflecting galvanometer, M, which is arranged so that the light from a lamp, L, falling on the galvanometer mirror is reflected back on the scale A. In the plan, the lamp L is assumed to be supported above the working table. The sensitivity is so adjusted by means of a resistance, R, in series with the thermo-couple T that a full-scale deflection across the 1½-metre scale A corresponds to a range of, say, 0–1,500° C. when the platform is fixed at a distance of about 2 metres from the galvanometer.

Assuming that a recalescence curve of a sample of steel is desired a small hole is drilled in the specimen, and into this is inserted the hot junction of the thermo-couple T.

The specimen is then placed in a suitable furnace, and a preliminary heating is made to ascertain the approximate position of the recalescence point on the long scale A. The curve tracer is moved to such a position on the platform that the recalescence point shall be within the range of the chart drum D, and the proper test is then carried out by gradual heating of the steel specimen, during which the deflections of the spot of light on the scale A are noted. When the moving spot of light comes within the range of the tracer drum D the handle H is turned so as to keep the pointer E coincident with the spot; at the same time the clock drive C is released, so the drum D begins to rotate, with the result that the pen P traces out on the chart a time-temperature curve. In the introductory chapter to this work, on page 9 is reproduced (Fig. 2) on a reduced scale a recalescence record obtained in this way.

CHAPTER VII

CARBURIZING MATERIALS

The first thing that will strike a novice in the art of case carburizing or case hardening is the great number of proprietary case-hardening compounds offered for sale upon the market. He will be very doubtful which make to select, and he will probably commence operations with the wrong one. Of one thing he may be quite sure; he will be purchasing common materials, combined and sold under a fancy name, unfortunately sometimes at a fancy price. There is, however, something to be said for the proprietary compound. Someone's name is involved, and the necessity of maintaining, at least, the purity or uniformity of the product is always there.

The chief objections to fixed and definite proprietary carburizers are that one mixture is sold claiming to be universally useful, while it may be quite unsuited to certain grades of steel or iron. It may be quite unsuitable except at certain temperatures, and it may be quite unsuitable in reference to both depth of carburization and time required to effect it. Further, certain of the compounds contain substances distinctly deleterious to the resulting case. As an instance, both sulphur and phosphorus are, in some cases of carburizers, to be carefully avoided, yet there are several compounds from which a considerable percentage of these substances, particularly phosphorus, is forced into the steeled surface, resulting in a short brittleness particularly undesirable.

Proprietary articles, the nature of which is distinctly declared and from which all deleterious substances have been excluded, and which are also free from saltpetre, are frequently desirable.

Since the object aimed at in the carburizing process is essentially the forcing into the iron or steel surface, to a certain depth, of a pure carbon, and keep out substances which the steel-maker has endeavoured already to eliminate from it, care has to be exercised to select the best agent for the purpose.

It should be an axiom with the case hardener *to work only with materials of known composition.* No secret compounds should be used. He will be thus purchasing his material at market price ; and if more than one is required he can mix them himself.

The Leading Carburizing Substances.—In general use, for different purposes we have : WOOD CHARCOAL, ANIMAL CHARCOAL, BARIUM CARBONATE, YELLOW PRUSSIATE OF POTASH, the WHITE CYANIDE OF POTASSIUM, SODIUM CHLORIDE (common kitchen salt). Highly carbonaceous fats and oils may also be cited as examples, and these are very frequently mechanically mixed with the various charcoals. Lamp-black is also a useful enricher. There are, in addition, numerous chemical compounds, by means of which superficial work can be done ; but they are not of interest to the regular worker in the art of case carburizing.

Animal Charcoal. — Although the animal charcoals cannot be obtained entirely free from some objectionable substances, they form the most important groups of cementation materials at our disposal. They consist of charred leather, horn, hoofs, bone and hair, all of which are rich in volatile hydrocarbon. Compounds from them are now produced commercially. Those made by turning hard leather into charcoal are without doubt the least objectionable, as being freer from phosphorus than those from crushed bone. In many works a department is kept at work making cementation charcoal from the above substances. This procedure has the merit that an unadulterated product is secured at first hand. The waste cuttings from the press-rooms of shoe factories are generally used for the purpose. The charcoal is made by packing the substances into cast-iron boxes or retorts, which are kept at a sufficient heat to char the mass to its centre.

Bone Charcoal is made in the same way, but for this substance the application of heat should be further prolonged with the object of ridding the mass of some part of its phosphorus. Care is necessary in every case to provide only a pressure-vent in the retort, for if the outside air is permitted to enter the layer exposed to it will lose it carbon and blackness, and will be reduced to white and useless ash, which must not be used in any carburizing operation. In some cases the bone, instead of being merely crushed fine, is procured from manufacturers of bone articles, such as buttons and knife handles. In this case celluloid sawdust and turnings from this inflammable substance are apt to become intermixed with the regular bone product. When a mixture is heated in a closed retort there is every risk of an explosion, an accident which has occurred more than once, to the writer's knowledge. Persons supplying case hardeners should be called upon to give a guarantee against an admixture of this kind.

Whatever substances are used to produce animal charcoal, the process of charring it should not be carried beyond the charred-black stage. This can easily be certified by withdrawing a sample from the mass. Much of the richness of the charcoal departs by the vent when the process is prolonged. Bone-black, a valuable commercial article when pure, is simply the above substance. It should be kept dry.

Wood Charcoal.—This article is easily procurable commercially, and is not liable to adulteration. But the wood from which it is made is a matter of some importance to the case hardener. Oak and beech charcoal are probably the most suitable. For carburizing purposes the charcoal, which is usually in lumps as large as hazel nuts, should be further powdered, especially if it is to be used in packing small articles.

Neither Animal Charcoal nor wood charcoal is used alone, except rarely, for carburizing. They are usually intermixed on a 50 % basis, or, preferably, allowing only 40 % of the wood charcoal. The leather-horn charcoal is of a finer and purer quality than the bone charcoal, and its combination with wood charcoal forms an ideal carburizing material for producing a *tough and hard* surface upon the articles being carburized.

Effects of Sulphur.—In many of the bone charcoals, and less frequently in leather and horn charcoal, sulphur, as well as phosphorus, is in appreciable quantity. This substance produces effects which make it a most undesirable ingredient in the carburized zone. It has been proved that sulphur, at the ordinary carburizing temperature, combines with both iron and manganese, forming sulphides of these constituents. The effect, since the sulphides, along with ferrite crystals, are close to the surface, is to produce a soft outer skin, and to produce a short brittleness in the casing zone. To some extent a rather high temperature in the carburizing tends to drive both the sulphur and phosphorus deeper into the zone, to the advantage of the outer case. These considerations have led to more work being done with the help of a high percentage of barium carbonate, which is free from sulphur and phosphorus.

Barium Carbonate.—We have here a substance which, in a nearly half-and-half combination with wood charcoal or animal charcoal, forms perhaps the best carburizing material yet discovered. *Witherite,* as it is called in its natural state, is too coarse in grain for use direct, so that it should be powdered before being mixed with the other half of the cementation material. Precipitated barium carbonate is obtainable commercially, and is sufficiently finely divided to permit of mixture direct with either wood or animal charcoal. The employment of barium carbonate alone as a carburizer is open to some objections; chief of which is that the resulting case, while hard, has little of the quality of toughness, so much so that upon bending a sample carburized with it numerous fine cracks may be found over the stressed portion of the sample.

Soft steel, having a percentage of 0·25, will permit of a very deep penetration of carbon when the carburizing box is packed with the best wood charcoal 60 %, with 40 % fine barium carbonate. There is a slight falling off if animal charcoal, as from leather, is used in place of wood charcoal. Penetration is reduced by about 25 % if wood charcoal alone is employed. But while depth of case in a given time is greater with the first-mentioned mixture, the second compound is generally to be preferred, on account of the greater strength and toughness of the carburized zone. Barium carbonate is the most economical carburizing substance in use by reason of its curious property of self-regeneration after it has done its work, when it is exposed to the air after a carburizing operation. This property is due to the chemical process, in which the barium oxide formed during the carburizing, by dissociation of the barium carbonate, absorbs carbon dioxide from the air, resulting in a completely combined barium carbonate. To ensure that this change back is permitted to take place, the barium, when it is spent, should be exposed to the air in a thin layer.

Before it is again used any sign of spent wood or animal charcoal should be made good, with a small addition of fresh material. Hence, boxes packed with this twin mixture can be kept supplied indefinitely by simply adding charcoal now and again. Whether the charcoal is spent or not can be recognized by the burnt wood-ash appearance of the charcoal portion. This grey appearance is apparent equally with wood or animal charcoal.

Yellow Prussiate of Potash.—We have in these cyanogen compounds a means of rapid *superficial carburizing* in either iron or mild steel. None of the prussiate salts is regarded as of much account by case hardeners. They are used only when small jobs must be got through quickly, for it is doubtful whether carburizing by their aid is ever made to penetrate the surface of the steel even to the sixty-fourth part of an inch. The above substance itself and the fumes from it when fused are highly poisonous. It is usually in the form of yellow crystals.

Cyanide of Potassium.—We have here also a rapid superficial hardener, of the same nature as the yellow prussiate. But while the use of the latter is mainly confined to minor operations, such as may be conducted with the smith's fire or the blowpipe, the white cyanide is extensively used in crucibles as a fluid mass. Indeed, a great proportion of small objects in a works, such as screws and studs, are given a superficial hard skin by this means. In the case of small screws the very inefficiency of this salt is turned to an advantage ; for, if small screws were subjected to the hardening influence of the more powerful cements, the penetration obtained would result in so deep a dead-hard skin that breakage of the thread of the screw or the stripping of the head might result. Cyanide of potassium for hardeners' use is sold in the form of a white powder. It should be pure. It is regarded as the best rapid-hardening salt bath in use and for die-faces, and similar work cannot be matched by any of the more powerful cements already spoken of. Its main disadvantage lies in the fact that, like all cyanogen compounds, it is poisonous, and the fumes arising from it, when fused in the crucible, are to be carefully avoided. This latter disadvantage is combated by providing a hood, having a clear vent, over the crucible. This kind of hardening bath is practically useless for depth hardness, even if the article be kept immersed in it for hours.

CHAPTER VIII

CEMENTATION AND CARBURIZATION

The cementation of the steel manufacturer is a process to which he subjects Swedish iron with the object of converting it into steel. Its feasibility does not only suggest that metals are more or less porous to carbon, but that other elements may enter which have suitable affinity, if such pores can be opened wide enough. The affinity that iron has for carbon and other elements, and the extent to which the pores can be opened by heat to receive them, constitute the essential elements of the science of cementation and case hardening.

When iron is heated to a sufficient degree it will absorb different gases to which it is exposed, among them carbon in its gaseous state, which combines with iron to form a solid. It fills up the pores to the saturation-point at a given temperature. The filling up being done in the heated or expanded state implies that on cooling the steel has increased in volume, but it must be understood that this increase, being so minute, is not often taken into consideration.

Most of the elements alloyed with iron either resist or favour the absorption of carbon. Nickel, aluminium, silicon, and perhaps vanadium oppose it, and tungsten, manganese, chromium, and molybdenum favour it.

Self-resistance of Carbon.—Infusion of carbon is resisted by carbon itself. The recognition of this fact is of the greatest importance. Uniformity of results depends upon it. If mild steel be heated in contact with a carburizing material to a temperature of 1,350° F. a casing of 0·50 % carbon will result, and no further continuance at this heat will further enrich it, this being the saturation-point normal to that temperature. As the temperature is raised, increasing carbon contents become normal to the increase of temperature, so that at about 1,650° F. 0·80 % carbon can be infused, but not more unless the temperature is raised still higher. The meaning of this is of great importance in regular practice, and indicates that uniform temperature must be used, or the results obtained will not correspond with calculations based on the average heat and the time allotted to carburization.

To illustrate. If the steel is carburized at, say, 1,650° F. a skin of about 0·80 % carbon will be formed. If the temperature is then allowed to drop, the skin formed at the higher temperature will have closed up the pores, and will thus prevent further carburization. Raising the temperature to 1,800° F. may yield a 0·90 % carbon case.

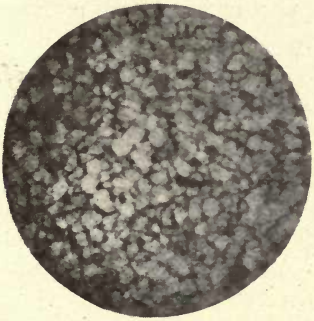

× 500.

FIG. 67.—Low carbon steel before carburization. Nearly pure ferrite.


× 500.

FIG. 68.—After carburizing and quenching direct from box. Coarse structure.


× 500.

FIG. 69.—Structure after cooling in box and subsequent quenching at 1,200° F.

Figs. 68 and 69 exhibit clearly the result of quenching direct from the hot box, and the improved structure obtained by cooling out, reheating and quenching.

CASE CARBURIZING.

The term "case hardening" in general use is often loosely applied. A great deal of carburizing is done independently of hardening, upon articles never hardened. This is case carburizing simply. If the article is taken red-hot from the carburizing box and plunged into water, it is both case carburized and case hardened.

The carburizing process, which forms the basis of all case hardening, has for its object the enrichment of the outer zone of the article by the addition of a certain percentage of pure carbon in a form that will become, *if required,* glass-hard when suddenly cooled from the red-hot condition, as when plunged into cold water or oil. But, as already mentioned, the process need not be carried so far. A large proportion of articles treated are simply carburized, and not hardened. This is an effective way of improving the toughness and strength of many parts of machinery that for different reasons it is not desired to harden. Not the least of these reasons has reference to the fact that, in the act of being suddenly cooled for hardening, there is always a tendency to produce deformation, or slight distortions that might have the effect of destroying the usefulness of a part when assigned its place in a machine.

Again, carburizing only has been brought to the front lately largely from the fact that, after the part to be treated has been carburized all over, it is desired to have some salient or other part of it made hard. In this case it is only necessary to bring this required section to a dull red-heat and plunge it in cold oil, or water, at a moderate temperature. In the case of a fairly large part this is generally done on the smith's hearth; and in the case of smaller articles, where the heat is required to be localized, in the flame from a gas blowpipe, using air under moderate fan-pressure, or, alternatively, by heating up the salient section in the barium-chloride bath kept for steel heating in all hardening shops. There are, however, two kinds of barium baths very often kept fluid in a hardening shop. These are the barium-chloride bath, which *does not carburize,* and is only used as a heating bath, and the barium-carbonate bath, which *does carburize,* and is not used for work already carburized in the regular way in boxes.

It may be contended that this second heating up of a particular part of an article may be rendered unnecessary by a simple act of withdrawing the part from the carburizing box while it is still at a red-heat, and plunging the required part in water. This has, however, several objections. The article is more liable to distortion, and the qualities of its case will suffer in both strength and toughness. It is better practice to permit the article to cool out with the box.

Rapid Case Carburizing.—In the case of small and light parts, which are generally made from a mild steel, such as the open-hearth variety, having a carbon content of 0·25 %, which are required at short notice, the prussiate process may be resorted to. In many of such applications the article is not to be hardened. Powder yellow prussiate potash is provided upon a tray. The article is dipped into a heavy brine and then rolled in the powder. The heating is done in a flame. But if this flame is under pressure, its force must be moderated, otherwise the prussiate will be blown off the article. A few moments will suffice to fuse the salt upon the steel, and at this stage the pressure on the blowpipe may be increased. After being brought to a bright red-heat and this condition maintained for one minute, the article should be slowly cooled, if not required hard. After the cooling all trace of the salt should be scrubbed off in hot water.

The same effect is secured by dipping the article for a short time into the cyanide bath so extensively used in workshops ; but time is likely to be wasted here by having to arrange fastenings to prevent the body of the article falling into the cyanide crucible, so that the blowpipe or Bunsen burner is to be preferred in dealing with one section only of a machine part. Sometimes the prussiate is simply sprinkled upon the red-hot part, but this involves a certain amount of undesirable oxide forming upon the surface before the salt fuses upon it.

The same kind of carburizing as already described is effected by fusing a carburizing salt, preferably cyanide of potassium, in a crucible to a temperature sufficient to raise any piece of metal placed therein to a bright red-heat. In order to case harden the article it is only necessary to plunge it into water, for great hardness of surface, or into oil for a moderate degree of hardness. The carburizing effect is obtained in a few minutes after the piece has remained in the fusible salt and has attained its maximum temperature, which should not be under 1,400° F., and may be a few degrees higher. If a fair depth of hardness is desired, a space of fifteen to twenty minutes' immersion will be sufficient.

The work should, if of a small description, as screws or studs, be placed in an iron wire basket suspended from a convenient handle lever, resting upon the rim of the crucible. Heavier pieces must be permitted to remain in the melt long enough to ensure a thorough soaking before the carburizing period is begun. All pieces, except those suitable for basket dipping, should receive a preliminary heating, to ensure that placing in the melt will not cool and freeze it. Upon being withdrawn the work can either be quenched at the time for final hardness, or it can be cooled slowly, washed free of cyanide in lime-water to neutralize the cyanide, and reheated for hardening. The reheating takes up additional time, but there is a general consensus of opinion that reheating and hardening after slow cooling ensures a finer grain or texture in the case carburizing zone, even in the case of the superficial steeled zone produced under the above conditions.

Over-doing Small Parts.—It will be obvious that small articles, especially screws, if kept over a few minutes in the melt, after they have attained the full heat, are very apt to absorb carbon to such a degree that, if suddenly cooled, especially in water, they may be liable to snap, or lose their heads when under the screwdriver. Experience only must be the guide in this matter. Hardening in oil is a precaution. If, by inadvertence, a batch of screws become over-carburized, they can be reclaimed by placing them for a time in a vessel of fish oil or melted tallow, kept at a temperature of 430° to 460° F. This will bring about a great modification of the brittleness and will toughen the articles.

In a factory run on modern lines the cyanide room is an important branch of the establishment. There will be installed large and small fusible-melt vessels, usually heated by gas. These must be carefully hooded and provided with chimneys leading to a flue, through which a current of up-cast air is moving. It should be remembered that should any article be placed in the melt which is wet there is apt to be a spluttering of the melt. A spot of this burning fluid falling upon the skin of the operator's hand is likely to cause a troublesome sore.

Carburizing in Boxes.—The carburizing boxes, or pans, used must be inside measurement 3 in. longer than the longest piece likely to be treated. The depth will depend upon the number or bulk of pieces to be treated in one box; and the whole is controlled by the floor space and the depth of furnace to be used and the necessity of providing against too great depth or width of carburizing space.

Taking articles 12 in. long by 4 in. wide, a carburizing box 15 in. long by 7 in. wide, and about 10 in. deep, is required. As to the material of the pans, as they are often called, there can be no doubt that a welded half-inch boiler-plate box is likely to give great satisfaction. It will last long and keep its shape well. There must be a cover, flanged, to fit loosely over the top, because the heating-up is sure to alter the squareness of the box. The cover may, however, be of cast iron, and it should be strongly ribbed to prevent deformation and buckling.

But in cases where only a limited quantity of work of a given size is to be carburized, there may be reasonable objection to provide costly boiler-plate pans. In such case the choice lies between cast-iron pans or sheet-iron pans. Of the two, the writer prefers sheet charcoal-iron pans, if of dimensions not exceeding 12 in. square. Sheet of No. 18 gauge may be used, and a cast-iron lid will be satisfactory.

Test Holes and Rods.—For a pan 2 ft. long the cover should be drilled, centrally of its width, with three $\frac{5}{16}$-in. holes; the end holes being 4 in. from the ends. Two holes should suffice for a 12-in. pan. These apertures are for the reception of $\frac{1}{4}$-in. mild steel test rods, which can be withdrawn, one by one, after the box has attained its maximum heat. The heat to which the rod has been raised will prove very closely the heat of the parts being treated. The rods should be inspected at least twice during a heat; first to test the temperature, and later the depth of penetration of the carburization. The latter is ascertained by quenching the end of the rod in water, drying, and fracturing it. No vents will be required in the cover when test rods are used, and the rods should be withdrawn one at a time, and afterwards replaced, to prevent wastage of the carburizing material.

"Life" of Carburizing Boxes.—There is no doubt that the wrought-iron box has the longest life of any. It will give way, first, at the bottom corners, until a hole appears. Next in order is the cast-iron pan, which, if ½-in. thick, should last two-thirds of the life of the boiler-iron box. Finally, the comparatively temporary sheet-steel or iron box, which, if well made, should give good service for at least six carburizing operations or more, according to the length of time it is exposed to the heat of the furnace. It should be remembered that the sheet-iron box is very inexpensive to begin with, a very good example, 1 ft. square and 8 in. deep, being easily made at the rate of thirty shillings per dozen, whereas a wrought-iron welded pan of equal capacity will cost for a single one twice as much.

The economy of the sheet-iron pan does not end here. Its walls are so thin that the heat is quickly through it. The time is reduced by a very desirable percentage, and the capacity in output per day per furnace greatly increased. A cast-iron cover, fitting *over* the pan, and *not into* it, is preferable in all cases; because space within is saved, and the flanged lid checks heat-distortion of the top of the pan, where it is most apt to occur, rendering an *in-fitting* cover useless after the second heat.

But the description of carburizing box will always be governed by the size of the articles to be treated, the quantity, and the depth of case required upon the work; the latter condition determining the life of the box used. Cast iron is so greedy for carbon that a box of this type will absorb much of the "nature" of each packing of carburizer.

Cast-iron boxes are generally cast wider at the mouth than at the base, for convenience of emptying. They are often cast with feet or bottom ribs, for support and stiffening; and, if large, with lugs for gripping irons. Rounded corners are not so quickly burned through as sharp corners. Boxes must not be so large that the centre parts will remain uncarburized while the outer layers are overdone. To overcome this difficulty wide cast-iron boxes are made with a fireway along the centre when required. But it is questionable whether from 6 to 8 in. is not the limit that can be allowed between the outer wall and the centre of a carburizing box, owing to the time required to bring the middle parts up to the temperature of the outer sections.

Sand Sealing.—Cast boxes should be patterned to provide a sand gas trap around the mouth—a channel being cast to receive a line of fine sand into which a bead upon the cover drops, so rendering fireclay sealing unnecessary.

Want of Uniformity in Carburizing.—From the remarks above it will be apparent that absolute uniformity of treatment is difficult to attain when a deep and wide box is used. There can be no cure for this save the use of comparatively shallow boxes. This is a matter which has given rise to more difficulties amongst case hardeners than any other—the outer (hot) layers are overdone and the middle (cooler) portions under-carburized.

Tubing Boxes.—An ideal way to pack long, thin parts is to use a piece of wrought-iron pipe, screwed at either end, as a carburizing box. The ends are closed with the usual screwed caps. But a vent-hole should be drilled in one end to obviate the risk of explosion when the gases begin to come off the carburizer. A great deal of work is done in wrought-iron tubes in this way. The chief objection to it is the difficulty of keeping the article to be treated from the walls of the tube ; but unless this involves a considerable area of actual contact, the part will not suffer in the least, and the parts actually touching the walls will usually be found as well carburized as the rest. A spiral of iron wire slipped over a long article will ensure freedom from contact with the walls. The smaller sized gear wheels can be most successfully treated in tubing. Given tubing large enough, all gears should be boxed in tubing. Taking a lot of, say, twelve gear wheels, they are placed in the tube one by one, as the material is packed upon each to the depth of 1 in., until the tube is filled. A test rod can be run through the end cap and the condition of heat at the centre thereby determined.

At the loading end of the tube a screwed cap is apt to be troublesome after being exposed to heat. Time is therefore saved by fitting a thick disc here, kept in place by pins. In the case of a tube casting, the door may be hinged.

Since the carburizing of gear wheels has special reference to the teeth, the condition of the centre will always lag behind the condition of the periphery ; so that the operation can be stopped before the centre shows the depth of penetration required upon the teeth themselves.

A batch of gear-packed tubes, placed upon the furnace floor, should be kept *on the move* every fifteen minutes, in order to equalize the heat around the gears. This precaution may be essential to the production of uniform penetration. In this way a perfect distribution of heat is secured. The tube form of box is undoubtedly one of the most successful up to a certain size of article. There is a little difficulty sometimes in the disposing of the carburizer in sufficient firmness around the parts. This difficulty can be largely overcome by gently knocking the lower closed end of the tube upon the floor, as the packing proceeds. The disposal of the test rod also may cause some thought. But it is seldom that it cannot be placed either centrally, right down to the bottom, or, alternatively, at one side. When a central position can be taken up, the cap can be screwed on last, after the rod is in position. If it must be situated at one side, the rod must be insinuated after the tube is packed and the cap screwed into place.

Tube Boxing and " Cold-mouth " Furnaces.—Many furnaces have the great defect of failing to maintain the average heat of the body of the chamber at the entrance, or mouth. This is, in fact, the commonest and most troublesome defect found in both gas and coke furnaces. The failing has special reference to the case of using long, tubular carburizing boxes, of the kind spoken of in the preceding paragraph, where the length may compel the exposure of the entrance ends to a lower temperature than that assigned to the inner ends and middle. Uniformity of product cannot be obtained under this condition. Tubes sufficiently short must therefore be used.

Cast-iron Tubular Boxes.—The great advantage of the wrought-iron tube in the carburizing of small gears has led, in many cases, to the employment of the same form of box, made in cast iron, for larger sizes of gear wheels. This is well worth doing, for in no other shape of packing box can the periphery of the wheel receive such impartial treatment. In casting these tubes it must be remembered that cast iron tends to porosity, or is apt to become porous. A good quality of grey iron should be therefore used, and the lower end should be closed with a cast-iron over-flanged cover pinned on, and, if required, luted with fireclay to prevent escape of the gases. These tubular gear-carburizing boxes should be provided with axle pins, cast on the covers.

These drop into U slots in a pair of supports laid upon the furnace floor. In this way the cylinder-box can be partially rotated from time to time, by inserting a rod through an inspection door of the furnace, thus ensuring uniform heating to every part of the circle of teeth. To admit of the rotating rod doing its work a circle of studs is cast around the middle of the length of the box. To meet the objection that cast-iron boxes are "greedy" of carbon, it may be pointed out that this is only true of the first firing.

Packing for Carburizing.—The main consideration in packing a box, after the carbon mixture has been decided upon, is the disposal of the pieces to be treated with two ends in view: equality of heating, and their disposal so as to obviate the risk of bending or deformation under the influence of the red-hot temperature. It must not be forgotten that a stiff machine part may become quite plastic at a good red-heat; that any overlying weight will tend to bend it; that the comparatively unyielding surface of the bed of carbon mixture, while it is cold, changes under continued heat, no longer affording the support of a firm platform.

Hence, in the case of a square-shaped box, a bed of mixture is first tamped down to the thickness of an inch. Upon this, and well bedded, are placed the heavier pieces, allowing about 1½ in. of space clear to ends and sides. Over this layer is spread another, allowing a thickness of half an inch above the parts, and so on until the box is filled to within the same space of the top as was allowed below. It will be plain that if there are any light articles to be dealt with, likely to deform under heat, they should be reserved for the last two layers, for the reasons adduced above.

Regard should be had to the need of inserting the inspection rods after the box is filled. A wooden templet should be kept at hand, pierced with the positions of these rods. By placing this over each layer a trial rod can be inserted for the test of position, so that the pieces below may not have to be slightly moved to permit of the test rods being lowered to the bottom of the box.

When the box is well filled the cover may be put on, but as even an outer-flange cover will not be gas-tight, plastic fireclay or asbestos cement is used to ensure this. To apply it, damp the edges of the box and the interior of the flange. Apply the clay around the box edge and press down the lid, wiping smoothly round. As there will not be developed any appreciable gas pressure, it will be unnecessary to fasten down the cover.

Firing the Boxes.—When work need not be rushed through, the temperature of the furnace, at the time of inserting the boxes, should be only a little above the working heat, because of the cooling effect of the packed boxes. It is quite usual to provide a fierce heat at the beginning, until the boxes have become red-hot themselves, but this is apt to play havoc with the edges of the boxes exteriorly before the general heat-up has diffused itself. When the boxes have attained all over a uniform cherry red-heat, the temperature of the furnace should be gauged by the pyrometer, unless the attendant has attained sufficient skill to see at a glance whether the red-heat reached is correct or not.

The heat should seldom, *for the first hour*, exceed 1,300° F. If this heat is attained gradually, a great economy of carburizer is assured, for there is nothing more wasteful of the rich gases than the sudden heating up of boxes. It should be known that gas begins to be evolved at a comparatively moderate heat long before the parts being treated are hot enough to absorb it, and this rush of gas is much more rapid and wasteful if a high initial heat is provided. Apart from this consideration, the gradual heating up of the parts in the box is less apt to cause distortions, twists and bendings than the rapid heating up mistakenly carried out in many shops.

According to the depth to be penetrated the box will have to remain some time in the furnace before it is at a red-heat throughout. One hour is an average time to allow for a moderate size of box before an estimate of the time taken to fully carburize the contents be made.

The heat must now be pushed up to 1,750° F. for a short time, then up to 1,830° F., and maintained at or rather above this bright red temperature. Parts carburized at this temperature, and afterwards slowly cooled, will harden well at as low a heat as 1,380° F.

After heating through, one hour should give a penetration of about $\frac{1}{32}$ in., which is considered a light case, and three hours should give $\frac{1}{16}$, which is considered a deep case. These depths are conditional upon so many factors, as heat, carburizing material, carbon content of the steel used for the parts, and so on, that it is impossible to fix them exactly. The withdrawal of the test rod will show the heat, and its rapid cooling and its subsequent fracturing will exhibit the required information to the naked eye. It is common practice to run the carburizing operation for six or eight hours, when great depth is required.

The Depth of Case.—Before packing in a box for carburizing some consideration should be given to the question whether all the pieces are required to be steeled to the same depth. It is seldom that this is the case. Light pieces, if to undergo hardening, should seldom be cased deeper that $\frac{1}{32}$ in., unless they are to go into the grinding machine afterwards. All pieces that are to be ground for accurate fit and other reasons must be cased rather heavily, or about $\frac{1}{16}$ in. in depth. Heavier pieces, whether for the grinder or not, may with advantage be cased deeply. Fig. 70 exhibits clearly the after-effects of faulty carburizing and still more likely faulty quenching.

Depth and the Time Factor.—Reverting now to the question of time required for the firing of average-sized boxes, regard must be had to the condition of the contents of the box. If a box is fired for *too long* a time, the whole of the contents may be destroyed. All the carburizing gas may have entirely departed from the box, taking along with it the carbon at first made to penetrate the surface of the steel. This is by no means a rare occurrence in the hands of the unskilled. Under the mistaken notion that the depth of case can be indefinitely increased, the box is left exposed to the heat, without regard to the constant evolution of gas therefrom, until there comes a time when *the carburizing mixture is exhausted*, and the decarburizing of the steel sets in. This may go on until the steel becomes brittle, crystalline, pitted and scaled iron. Upon uncovering the box the carburizer will be found, under these conditions, to be reduced to impotent *white ash*.

Such an untoward accident is unlikely to this extent; but it may *partially* occur, especially at the top of the box, if only a thin layer ($\frac{1}{4}$ in.) of material is provided there above the parts.

From these considerations it will be clear that there is a safety limit to be set to the long-firing ideas of inexperienced hardeners. If great depth must be got, then there must be arranged two things in packing: extra depth of carburizer all round, and great care taken to confine the gases. A uniform temperature must be maintained throughout the operation. There is no difficulty in securing this in the case of gas-fired furnaces fitted with an efficient gas regulator, so that the town's pressure, which varies with the hours, is equalized.

The object of these precautions is simply to obviate the risk of depleting the carburizing material of all its gases, which is quickly followed by depletion of the carburated zone on the parts being treated. Vents for safety must be provided, but they should be of the smallest possible size. No extra vents are required in the case of a box provided with $\frac{5}{16}$-in. holes, nearly filled with $\frac{1}{4}$-in. test rods. If no vent at all is provided, the gas pressure will speedily either lift the cover or break through the fireclay luting.

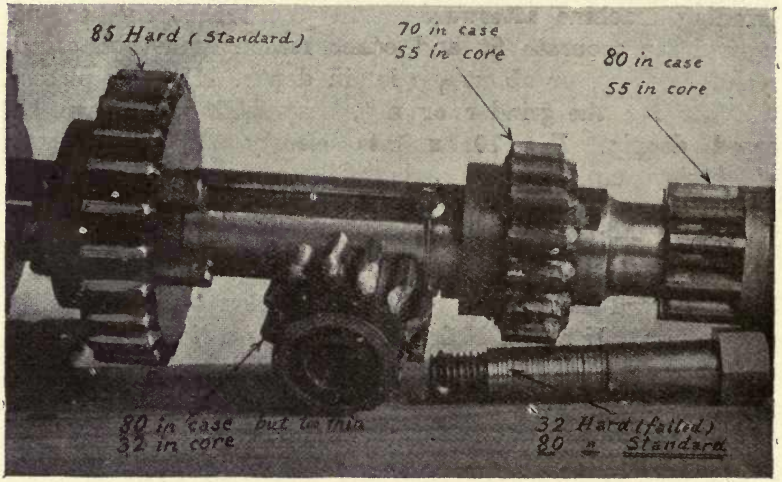


FIG. 70.—Automobile gears. Soft and hard spots due to faulty carburizing or unequal cooling. Standard of 80 scleroscope hard fails in places.

Second Firing.—In most cases of efficient box packing the firing can be kept going, without undue risk of damage, for about eight hours as a limit. But this must always depend upon extent and body of material; proportion between the bulk of this and the parts being carburized; also the temperature of firing and the amount of vent open to the air. If an extra deep casing is required it is better to ensure it by putting the parts through a second firing than to attempt too much with a single firing.

Handling the Test Rods.—Some little practice is needed in obtaining the best results by the help of the test rod. The first thing that may happen will probably be a difficulty in withdrawing the rod if it is dropped vertically into the box. This will occur because the height of the furnace roof will often be insufficient to permit of the rod being fully raised. In this very common case the remedy is to use a jointed rod, which, after it is withdrawn as high as the roof will permit, can be folded horizontally. In the case of horizontal rods this particular trouble need not arise, since the rod can be pulled out and re-inserted at the mouth of the furnace. This is, however, open to some objections, chief of which is the necessity of uncovering the outer end of the box, and so exposing it to the air, leading to rapid cooling. In such case a test-rod hole can be provided drilled through the firebrick door of the furnace. The smaller this is made the better.

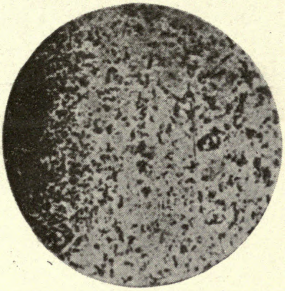
The test rod should be inspected, for appearance of central heat only, one and a half hours after the exterior of the box appears to be at the required heat. If the rod exhibits a nearly equal heat, the box can be "timed" from the minute for carburizing effect. After another interval of an hour and a half the rod can again be withdrawn, when one inch of its hot end should be quenched in cold water, and the rest of it cooled slowly off. It may then be gripped in the vice, and a smart tap from a hammer will probably break off half an inch of the hardened part. An inspection of this fracture will show at once the progress of the steeling and its extent of penetration. A zone of fine steel will be seen to have been imparted to the rod, and it is the depth of this rather than its molecular appearance that will be of immediate interest. The depth of the case obtained will probably be under $\frac{1}{32}$ in. in the first one and a half hours, and this will form some guide as to the time required for the complete carburizing of all the parts packed in the box.

Carbon Percentage and Degrees of Heat.—Economic considerations demand that the speed of penetration and its richness in carbon in relation to temperatures shall be definitely determined. We have seen that at as low a heat as 1,300° F. mild steel or iron parts will begin to absorb the carbon gas. If this low heat is maintained, the total percentage of carbon in the affected zone will probably not exceed 0·3. This being too low for most purposes, it becomes necessary to increase the heat, which, at the usual lowest temperatures of successful carburizing, will register at least 1,780° F. At this point a percentage as high as 0·6 may be secured. At 1,750° to 1,820° a saturated condition showing a percentage as high as 0·85 to 0·90 should be obtained. This percentage may or may not be required in the work.

For many parts a fairly low carburized zone is safest, especially where the parts are of slender section. In the case of heavier parts, and especially in those exposed to impact or percussive action, or to abrasive wear, a highly carburized zone is essential. This is secured by a combination of high temperatures and reasonably long exposure.

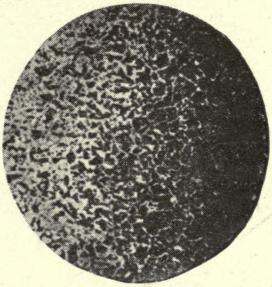
It must not be forgotten that factors other than degrees of heat and time enter into the above questions. The main points are the class of mild steel from which the parts are made and the nature of the carburizing material used for packing. The mild raw steel will probably range from 0·11 % carbon up to 0·25, carbon. From the higher grade steel the maximum of 0·9 % casing is easily produced. In treating the lower percentage steel a longer exposure and a rather higher temperature are required. The carburizing material may be taken as a 60 % mixture of animal charcoal with 40 % of barium carbonate. The addition of 5 % of cyanide of potassium in white powder serves to greatly increase the actual scleroscope and Brinell hardness values of the surface ; while it also increases the brittleness. It may, however, be taken as a well-established fact that the ordinary carburizing mixtures will yield a surface sufficiently hard for all purposes required in machinery and also for cutting tools used for paper and wood, if the latter should be required as made from carburized mild steel.

Influence of High and Low Temperatures on Strength.—Probably the most important consideration in the case carburization of mild steel and iron has reference, not to the depth of steel case aimed at, nor to the percentage of carbon throughout the zone, nor to its hardness after quenching, but to the *actual test strength* of the steel after it has been fully treated. It will be recognized that it is a serious matter to subject costly machine parts to a process



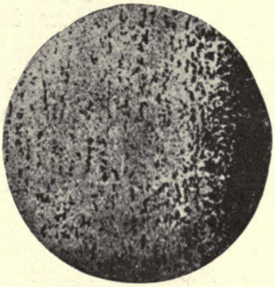
× 100.

FIG. 71.—0·11 % steel carburized in charcoal at 1,725° F.



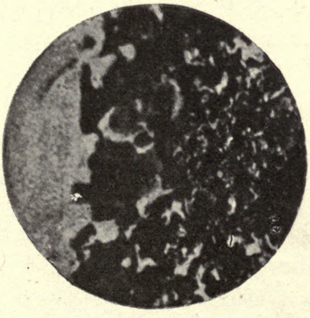
× 100.

FIG. 72.—0·11 % carbon steel carburized in charcoal at 1,925° F.



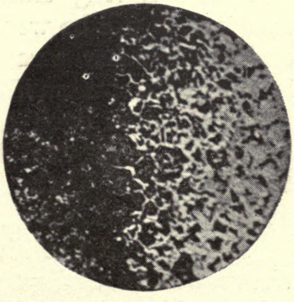
× 100.

FIG. 73.—Same as above, but carburized under Ac 3.



× 100.

Fig. 74.—Marked sulphur diffusion in carburization.



× 100.

FIG. 75.—0·11 % steel carburized at 200° F. over Ac 3. Nolly and Veyret.

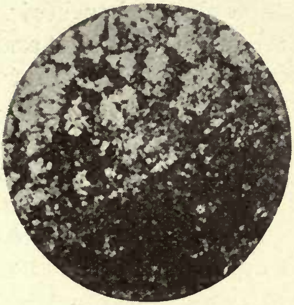
which, while properly conducted, may result in a steel that will show tensile strength of perhaps 20,000 lb. greater than another sample, unskilfully handled. In plain words, the case-hardened parts will be weak or strong, dependent upon their treatment under heat, while of two samples, good and bad, no one can say upon looking at them which is which.

To prove this, even without a strength test, let two pieces of the same steel be carburized, the first at a gradually rising temperature beginning at 1,300° F. and finished at a maximum heat of 1,830° F. Let the treatment of the second piece be rushed up, and it may receive most of its carbon at heats ranging from 1,800° to 1,900° F. Let both pieces cool gradually. Let them be reheated to only 1,300° F. and quenched in water. A fracture now taken from each piece will exhibit a great difference of grain; the crystalline structure of the low temperature fracture will be fine; that of the other coarse. The fine grain piece will test out at a greatly higher figure; it will withstand treatment, shocks, and bendings that will cause a failure of the other.

The only difference between the treatments of these two samples has reference to easily controllable factors, heat and time. It is true that, upon a larger output, there will be a saving of treatment expense if the work is rapidly rushed through; time is also saved in working at a very high temperature, but at what an ultimate cost! It is well known, of course, that many parts carburized and hardened are never afterwards subjected to any strains. In such case the policy of speed shows some justification. But once having trained particular hardeners to work in this way, it will be well to confine them to this class of work, and make other arrangements for treating valuable parts intended for automobiles or machines where they will be under great or even normal stresses.

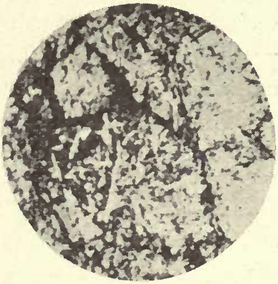
Figs. 71–75 exhibit, micrographically, the effects of temperature and time. The extremely weak structure of sample 74 is due to sulphur in the cement.

Relation to the Critical Ranges.—The instances given above will be understood to bear a direct and illuminating relationship to the Ac 1 or first critical stage (already touched upon on page 6) of the molecular change which takes place in steel under heat. The first critical stage of change takes



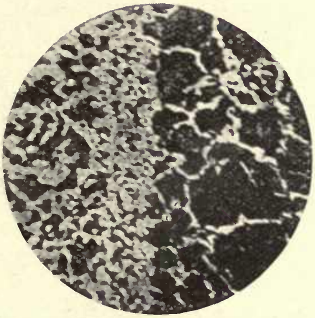
× 100.

FIG. 76.—Nickel 3·44 %, carbon 0·176 %, carburized and air cooled.



× 100

FIG. 77.—Nickel 3·44 %, carbon 1·76 %, carburized and air cooled. Sauveur.

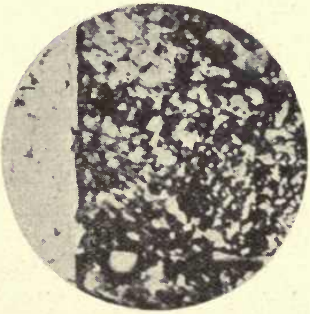


× 100.

FIG. 78.—Badly mixed carburizing, due to chilling too late.

× 100.

FIG. 79.—Excessive diffusion of sulphides, due to excess temperature in carburization.



× 100.

FIG. 80.—Sulphides in hardened carburized steel. Grayson.

place at about 1,330° F., and at this stage also carbon begins to enter into the already complex structure of ferrite and pearlite. The first stage, in which the pearlite changes into austenite, and begins to absorb the free ferrite, is accompanied by the absorption of carbon from the material surrounding it. At the Ac 2 stage the ferrite is probably 50 % absorbed or transformed. This stage is represented by degrees of heat nearly corresponding to 1,430° F. As the temperature rises more and more of the transformation takes place until, at the Ac 3 degree, which is the third critical stage, represented by degrees of heat corresponding to about 1,650° F., the transformation into austenite is complete. But still the absorbtion of carbon goes on, and is adding to the depth of the new carbon zone rather than its percentage. Now, since we find that, in order to secure the depth of carburized zone aimed at, a temperature as low as the Ac 3 stage, which, as we have seen, is some 1,650° F., is not found effective, at least in a reasonable time, an increase of heat considerably above the upper critical stage becomes a necessity. The Ac 3 stage is therefore passed at about 1,650° F., and the temperature raised to over 1,800° F.

Figs. 76–80 exhibit clearly the effects of good and indifferent treatment in the cementation of different materials.

Effect of the Absorbed Carbon.—The molecular structure of the steel throughout the carburized zone is found to undergo a change. At about the Ac 2 stage, assuming an absorbtion of carbon up to 0·9 %, the Ac 1 stage is lost, and is absorbed into one with the Ac 2 stage. As the heat rises, the two lower degrees are absorbed by the upper Ac 3 stage. This may be regarded as a property of high carbon steel only. In fact, we have transformed the zone of carburization into a fine hardening, cutting-tool steel. But while this is quite true, chemically speaking, the quality of this product will not bear comparison with the wrought and crucible cast steel produced expressly for turning and drilling tools. It may be asked, Why not ? Here we touch upon the history of the iron from which cutting-tool steel should be made. This history begins with the ore, as it comes from the earth. If the ore is not of a certain kind, no manipulation will endow it with the superlative qualities of the best Sheffield carbon tool steel.

All of these considerations are bound up with the final stage—the cooling-out or quenching. This final operation is nearly as important in its effect as the heat treatment itself. It is indeed the point towards which all of the preceding operations are directed.

Carburization of Nickel Steel.—This important process, which has come into prominence of late, should be studied by all who wish to produce the highest class of steel goods. In the first place, the material itself is of immense strength, which is not only increased by the carburizing process, but is furnished thereby with an extremely hard armour, or a super-tough casing, as may be required. Nickel steels are more costly than the carbon steels, but for an immense number of the moderate sized machine parts the higher cost may be largely compensated for because of the thinner sections and weights that may, with perfect safety, be used in specified positions.

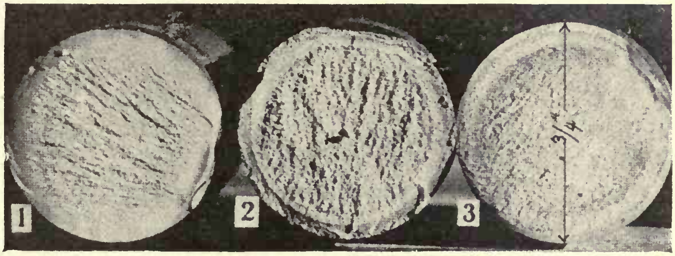


Fig. 81.

An enlarged photo of case-hardened bars of the following material: No. 1, vanadium steel; No. 2, chrome nickel steel; No. 3, nickel steel. Temperature used 1,680° F. for four hours. Fig. 2 shows a circular crack which was developed in the hardened case upon breaking, by a lesser contraction of the carburized case, due to the former's increase in volume by carbon absorption. No. 3 shows the demarkation line of high carbon steel nearest the outside due to the variation of the carburizing heat.

The principles of case hardening already set forth may be said to apply to nickel steel also, but there are certain peculiarities which should be noted.

Nickel steel of 5·0 % will carburize more slowly than carbon steel. It is seldom necessary to carburize nickel steel of a higher grade than 5 % to 7 %.

The carburized zone will not be as hard as that of carbon steel unless specially treated, but it will be incomparably more enduring, and less liable to crack or chip.

A high temperature is usually recommended in dealing with a nickel steel, especially those over 3·0 % nickel. While 1,600° F. is usually sufficient in the case of carbon steel, temperatures as high as 1,700° and even up to 1,850° are common in dealing with nickel steel (see Fig. 81).

Concentration of carbon in the cemented zone will be less in the case of nickel steel as compared with carbon steel. For example, it is rare to find a carburized zone upon nickel steel equal to the eutectoid ratio (0·90 %), while this is the ordinary ratio in the case of straight carbon steels. In nickel steel the ratio may vary with the cement and temperatures from 0·3 % up to 0·7 %. Except rarely, the ratio is always within the hypo-eutectoid range.

For most purposes this ratio is ample, and more effective in application than the usual 0·90 %.

An immensely strong, hard and tough nickel steel is obtained by carburizing at full heat in the usual materials for two hours or more, and merely air cooling the parts. No quenching is called for unless the case be desired very hard, in which case oil quenching is desirable. It is obvious that on the whole nickel steels can be treated more quickly than the carbon steels.

The development of the highest tensile strength of a carburized nickel steel can be secured by the double quench process, which is carried out as follows: Carburize as usual, but at a rather high heat (over 1,600° F.). Continue for not less than two hours after attaining full saturation. Cool out in the carburating material. For 2½ % nickel steel, heat at least at 1,550° and quench in oil, until the red vanishes from the surface; reheat to a rather less temperature (about 1,375° F.), and finally quench in oil. Temperatures in the case of 3 % nickel steel may be some 25° lower than the above.

It may be useful to recall here that if a pyrometer is not employed the appearance of the full carburizing heat in the furnace as above will be a very bright red. The appearance of the regenerative heating will be a bright red, and the appearance of the final quenching will be full red.

Gas Carburizing.—The use of the words "gas carburizing" are for the present understood to be confined to the new process, in which gas only is employed as a carburizer in place of the charcoals and other solid cements used in the earlier box processes.

The following are given in the order of their value :—Carbon monoxide, acetylene, methane, illuminating gas.

For many years the use of carburizing gas direct upon the steel has been the dream of advanced workers in this industry. But it is only recently that the matter has been taken up in earnest. It is now making considerable progress, and in time may largely supersede the more solid cementation methods. Many difficulties are being met with. But it would appear as if these troubles are due more to over-ambitious attempts to produce, not only a new process, but to make this automatic in its operation, than to the requirements of the process itself. Advances are, however, being made on practical lines, and the American apparatus lately introduced bids fair to lead to a semi-automatic process of carburizing.

The interesting history of direct gas cementation is too wide a subject for treatment in these pages, but referring to recent advances, it is interesting to record that the work of Professor Giolitti, of Genoa, Italy, has been specially fruitful in this field of enterprise.

A concept of the gas process of carburization, due largely to the labours of Giolitti, may be gained from the consideration that cementation cannot take place in the absence of gas, even if the solid cements are present. In the absence of the gas the carbon of the cements, such as charcoal, has been proved to be incapable of penetrating steel or iron. Commercially speaking, any of the recognized carburizing materials will, with the aid of their occluded air or gas, carburize steel raised to the requisite temperature ; and the slow decomposition of any of them will force carbon into the steel.

From this consideration it is obvious that the employment of a carburetting gas alone should suffice to enable us to eliminate the solid carburizing materials altogether. All that seems to be required is a rich carbon monoxide gas. In an ordinary carburizing box, when the temperature has been raised sufficiently high, the oxygen of the air always occluded in the material forms a reaction to produce this carbon monoxide. Following this, as the temperature rises, we can form a conception of the semi-fluid condition of the heated steel surface "*with open pores,*" permitting the entry of this carbon-laden gas, and simultaneously the incorporation of the carbon atoms with those of the gamma iron or ferrite, and other constituents of the steel. The surface is quickly permeated with carbon, and the progress of this diffusion proceeds inward to some extent as long as the heat and supply of carburetting gas continue.

Following the line of Giolitti's investigations, he points out that the addition of small quantities of volatile hydrocarbon (the various charcoals, etc.) merely raises the concentration of the carbon in the external layers of the cemented zones above the value which would result from the use of pure carbon monoxide under identical experimental conditions. This increase is greater the larger the proportion of the hydrocarbon contained in the gaseous mixture, as long as this proportion does not reach a value such that the velocity with which the free carbon is formed by the decomposition of the hydrocarbon does not surpass the velocity with which this carbon passes through the stage of carbon monoxide into solution in the iron. From this limit the excess of carbon which is liberated begins to deposit in the steel, and the concentration of the carbon in the external layers of the cemented zone reaches the maximum value corresponding to that which is obtained by cementing with solid cements, or with cements which behave as such; and from this point onwards the concentration and the distribution of the carbon in the cemented zone no longer vary markedly, even if the proportion of the hydrocarbon is augmented.

It is therefore quite evident that we can obtain by means of mixtures of carbon monoxide added to vapours of volatile hydrocarbons cemented zones in which the maximum concentration of the carbon in the external layers for a definite value, lying between a minimum corresponding to that which would be obtained by working under the given conditions with pure carbon monoxide only, and a maximum which would be obtained by working with vapours of hydrocarbon alone. This is achieved simply by using gaseous mixtures containing a proper proportion of hydrocarbon, varying with the conditions under which the cementation is to be effected, such as temperature and pressure.

From the above considerations it is clear that the use of carbon monoxide gas alone does not satisfy the requirements of industrial case carburization. That the presence of a certain percentage of the more solid cementation materials of commerce is desirable is apparently beyond question. Also that the speed and throughness of carburization is greatly stimulated by the combination of the two carbon-yielding agents.

The actual apparatus evolved from the researches of Giolitti therefore take the form of retorts of cylindrical form, two of which are provided, in order that one of them may be at work while the other is being charged with the fresh pieces to be carburized.

The work is charged into the retort along with a suitable percentage of wood charcoal. When the usual temperature of cementation has been attained a jet of carbon oxide gas is injected and maintained as long as may be required to provide any depth of case, no precaution being taken to renew the charge of charcoal, which presumably remains almost unaffected.

Two muffles are provided in the furnace; the object of this is to enable the operation of treating parts to be almost continuous. The muffles and the retorts are of cylindrical form, heated by gas. Further developments of this new system will probably result in considerable simplification in the working.

American Carburizing Machine.—The American Gas Furnace Company have lately introduced a machine designed for almost automatic control of the whole operation of carburization. This, also, is a gas carburizer, pure and simple, inasmuch as it requires not even the aid of wood charcoal in its retort. It is interesting inasmuch as ordinary illuminating gas is used both for heat production and cementation in the retort.

Arrangements are provided for continuously rotating the whole of the apparatus, in order to ensure absolute uniformity in the heat distribution. The machine exhibited is designed to receive work 20 in. in length and 5 in. in diameter.

The evolution of the gas processes (as they are now spoken of) has not as yet proceeded sufficiently far to enable a reliable judgment to be arrived at as to their advantages as compared with the simple box-and-muffle system so well understood. It is quite certain, however, that if the new processes can be proved to offer any advantages whatever, either in efficiency or economy, the case carburizing industry will hasten to take advantage of them. Whatever arrangements may be evolved will leave the art of carburizing unaffected in its basic requirements, which are, simply, the exposure of mild steel while at a certain temperature to the penetrating influence of a carbonaceous gas.

CHAPTER IX

QUENCHING

THE roughest and most destructive treatment of carburized parts, until quite lately so common, will, it is hoped, have soon given place to the more enlightened treatment now practised in the most advanced hardening shops of engineering works.

The outrageous directions frequently given, even by some firms making a business of preparing and selling carburizing materials, are to-day a disgrace to the intelligence of even novices in the necessary treatment of steel.

To give an instance. It is quite common to see it stated that when the process of carburizing is complete, and while the box and its contents are presumably at a temperature as high as 1,830° F., the cover should be removed from it and its contents thrown wholesale into a tank of water.

Here, indeed, we obtain some kind of cooling. But it is certain that no two pieces will have cooled at the same rate, and no two sections of a single piece are likely to exhibit the same steel structure. The main consideration, however, has reference to the decalescence and recalescence heat-points of steel. Here we have an instance in which care has been taken to ensure that the decalescent point (1,800° F.) has been slightly exceeded, as required; that the excess allowance has not been exceeded; and, just at the critical point, when the steel is in the *worst condition for rapid cooling*, it is ruthlessly thrown into water.

Now, we know from previous considerations that this typical box of case-hardened parts should, to obtain even moderately good results in the usefulness of the steel, be allowed to cool out before being unpacked. That the parts should, when cool, be freed from adhering carburizer, and reheated in any convenient way to about 1,400° F., and *then* quenched. Here we have a temperature *four hundred* *degrees* greater than the decalescent point at which ruthlessness throws the whole contents of the box into water.

A not unusual medium course of treatment permits of the cooling of the box to at least 1,425° F., the withdrawing of the parts, preferably singly, and cooling in moving water (for extreme hardness) or fish-oil for toughness and a high degree of hardness.

But it can be shown, by means of test pieces, that even this modified treatment falls short of the most desirable requirements of the steel.

In some cases, indeed, the box is permitted to practically cool before its contents are thrown into the tank. Here we have two-thirds of the contents falling into water at 212° F. (brought to this heat by the dumping) and a few of them into colder water.

The Ornamental Colourings.—Although scarcely in proper sequence, we should here, pertinently to the foregoing, touch upon one of the main arguments in favour of the throwing of a box full of parts quickly into the cooling tank. Of course this should be carried out, if colouring must be arranged for in this way, at the proper temperature, just under 1,400° F.

If bright and perfectly clean mild steel or iron parts are packed for carburizing in dry material, and well excluded from the air, they should leave the box, after treatment, nearly as colourless as when they were packed. But an instantaneous oxidation of the bright surface is produced by exposure to the air while still at a fair heat. If no precautions are taken, the bright surface becomes a dull blue or black. If, however, the contents of a box be tipped suddenly into the quench, a considerable proportion of the bright parts will strike the water before the oxidizing influence of the air has done its work.

Various colours, but seldom a perfect brightness, are thereby produced; chiefly by the oxidizing influence of the occluded air always present in ordinary tank water.

Some of the most striking, and even beautiful, effects are produced by skilful manipulation of the tank water. We have seen that the occluded air in ordinary water has an immediate effect upon the hot surface of the steel, producing an ornamental oxidizing, which is highly regarded in the case of small parts, which, chiefly on account of cost, it would be prohibitory to nickel plate. The parts of small-arms and various tools are generally treated in this way. The oxidation is more ornamental than that produced by heating in the sand bath, because it is variegated in an infinitely great number of patterns, whereas plain oxidation in the open air merely produces colours varying from pale yellow down to deep blue.

Those attractive effects cannot easily be produced if the steel parts are quenched at too high a temperature. They are not so striking if an attempt is made to produce them by quenching in water which has been boiled and is not permitted to absorb air by agitation. It would probably be found that no oxidizing effect whatever would result if the water used could be freed of its air entirely. We should then obtain a nearly bright patternless steel surface, if it could also be arranged to prevent all contact with the air while transferring the parts from the carburizing box to the cooling tank.

If, on the other hand, air is forced into the water of the tank, or it is merely aerated by agitation, a great oxidizing effect is produced in a more striking variety of patterns. A cooling tank from the bottom of which arises a rush of water and air, meeting the descending parts, while still at a red heat, is very effective for this purpose. It is only necessary to produce violent agitation of the water; there will always under these conditions be plenty of air occluded to produce the required oxidation; but many operators prefer to add an air pipe also.

The production of gaudy colours is greatly stimulated if the carburizing mixture contains even a small percentage of cyanide of potassium. From five to ten parts in one hundred will be found sufficient. In all cases where cyanogen compounds are used a final washing in strong lime water should be given. All ornamental or colour case-hardening should be oiled after finishing.

In the case of very slender case-hardened parts, which it is desired to finish with colours as above, quenching in water is not only apt to produce deformation by too sudden cooling, but will make them too hard and even brittle. In the first operation they should not be carburized longer than one hour. In the quenching a bath of oil should be used. For colour purposes, in order to make this quench effective, air under pressure must be forced upwards from the bottom of the tank, preferably emerging from a perforated pipe. If there are sufficient air bubbles ascending, a colouring of the parts will follow. All parts intended for colouring must be polished bright, and be perfectly clean, and free from grease before being packed in the carburizer.

Smaller parts for colouring should be packed and fired in a length of gas pipe, having an easily fitting plug at the entrance end. In quenching, a tube presents an advantage, inasmuch as there is only a small orifice open to the air. The open end of the tube can be held close to the water, and the parts passed into the quench almost without air contact. While the contents flow from the tube, it should be moved rapidly across the surface of the water in order that a fresh quenching space shall constantly be available.

Brine Quenching for Colour.—Some slight modification of effect may be secured by providing a salt-water bath. This is generally supposed to act more sharply than plain water, and is generally preferred when an extra hard surface is desired.

Quenching Tank.—It is useless to give specifications for cooling tanks, conditions of work varying greatly. All that is required is a tank large enough, and more especially *deep* enough. It is the depth that tells more than the area. For work of the size of locomotive parts, a tank of good area and with a depth of 3 ft. should be provided. There should be means of forcing water into it from below and the delivery pipe should be folded at least two lengths, and perforated freely. An overflow at each end should be arranged. In order that parts being quenched may not fall upon the bottom or the water pipe, a grating of wood should be provided. If this shows signs of burning, through red-hot parts falling upon it, the depth of water in the tank should be increased.

Double Quenching Preferable.—No case-hardened part should in any circumstances be quenched while still at a temperature exceeding 1,500° F. Quenching may indeed begin at 1,350° F., but far more satisfactory results are obtained by allowing the box and its contents to cool slowly until it is well below the critical stage of the steeled surface (1,200° F.), and then reheated, either in the box as it stands or in the open, to a point slightly exceeding 1,450° F. This covers the lower critical stage of most operations; and then should follow the quenching. In order to still further improve the refinement of the crystalline structure (" grain ") a reheating to as high as from 1,650° to 1,720° F. should be followed by quenching in cold oil.

Most careful investigations, conducted by a committee of the American Institute of Testing, have conclusively demonstrated that a still further and material refinement is secured, accompanied by increased tensile strength, by a second quenching, and this followed by a third heating and quenching. The third quench should be at a temperature as low as 1,450° F.

In outlining these apparently complex treatments, it must be borne in mind that we are dealing with, not one, but two masses of steel, consisting of the carburized case and the original raw steel core. Regard must be had to both of them when we seek for efficiency in both, while they must be treated together; but what must be aimed at is the maximum refinement of the structure of the case and as great a reduction as permissible of the coarse crystalline structure of the core.

Influence of Carbon Content of the Raw Steel.—As bearing strongly upon the temperatures to be observed in quenching, a knowledge of the initial carbon of the steel to be case hardened should be kept at hand. The mild steels used may be taken as beginning with a carbon percentage of 0·05, and rising to 0·25. We have assumed in the foregoing that a 0·25 % steel is involved, and the various temperatures are given approximately for this value. But the heat treatment of the 0·05 % raw steel will always demand an increase of at least 125° F. over that required for raw steel of 0·25 % carbon, for the reason that its critical points are found to stand higher to that extent.

But here we are faced with the fact that in most case-hardening operations, except in those conducted with cements or materials not rich in carbon, the ultimate carbon content of the carburized zone is usually as high as 0·90 %, or, let us say, the saturation point. Now the critical change point of this steel is generally as low as 1,350° F., and it will harden at or below this degree of heat (or a dull red), but more effectively at about 1,380° F.

Take, now, the material forming the core of the steel. Its carbon content may be as low as 0·05 %. Here we have a critical range, as we have seen, 125 to 150 degrees higher.

It is obviously impossible to establish a heating or quenching point normal to both of these steel structures. All we can do is to so treat the core that it will attain its maximum strength and toughness under the circumstances imposed upon us by the necessity to refine and harden the carburized casing.

Plain Water or Brine.—In all quenching operations, the object aimed at is the abstraction of heat. Hence the heat conductivity of the quench is a matter of first importance. The work of the hardeners' shop is practically confined to the following abstractors of heat :—

Ordinary water (Hard)
Soft or rain-water
Sea-water
Salted water (Brine)
Acidulated water (Sulphuric)
Spray of water
Mercury (Rapid)
Compressed air
Oil, Mineral (Heavy)
Oil, Cotton-seed
Oil, Linseed (Gummy)
Oil, Whale (Expensive)
Oil, Lard
Oil, Fish (Offensive odours)
Oil, Mixed (Proprietary uninflammable)
For tungsten steel, Light kerosene group

Taking water first, as being the most generally useful, it must be understood that, whether this is hard and limey or pure and soft, as rain-water, does make some difference, especially in treating tool steels. Case-hardened steels are of less importance, and they are almost invariably cooled out in the ordinary service water of the district. Fine tool quenching is always conducted upon a more restrictive scale, and as it is not so necessary to keep a circulation in the tanks no large supply is required. All water used for quenching must be kept clean, and free from oil or grease.

Salted Water or Brine may be made of any density. But this and sea-water are rapid coolers. The heat conductivity of brine is greater than that of plain water, so much so that it is seldom used upon steel liable to crack in hardening or cooling off. Brine may be used for parts where there is no liability to fracture or deformation due to ultra-rapid chilling. The advantage gained, if any, is entirely in reference to the harder skin secured upon the work.

Water Spray, especially if under pressure, is a most rapid hardener, quite equal, or superior, to brine. But there is a special field for pressure spray. It can be arranged as a fine or as a copious spray, and it offers the advantage, useful for some classes of work, of rapidly chilling the exterior while leaving the core ductile. Work treated with the spray is generally left in hot water (up to 200° F.) afterwards to gradually relieve stresses.

Mixed Quench.—A great deal of work is, at the present time, being done in a bath composed of soft water, bearing upon its surface a layer of oil. The depth of this layer will determine, to a great extent, the hardness produced. One inch of oil floating upon the water will generally be found sufficient. The object aimed at is a moderation of the rapidity of the cooling effect of the water. As the steel is lowered through the oil it carries a layer with it; the water chill is delayed. A quench of this kind is generally used for delicate parts; they must be chilled in water, somewhat checked in its activity. The oil used should vary from light mineral, through linseed and other grades, to lard oil, which may be regarded as the heaviest required. The quickest hardening is produced when light oil is used, in this kind of quench. Precautions must be taken to avoid raising steam under the water; most of the oils being inflammable under heat.

Acidulated.—Here we have an ordinary plain water quench. But for the class of work intended for treatment it should be of soft water. A small addition (3 to 5 %) of sulphuric acid should be used. This quantity should be first well mixed in a bucket of water, and then thoroughly incorporated with the quench itself. The object aimed at is merely the clearing-off of any oxide left upon hardened tool steel. It is useful for tools, such as taps and reamers, the flutes of which cannot be brightened after hardening. It is well to remember that any description of acid is apt, unless thoroughly neutralized, to afterwards corrode the surface. The best neutralizer is probably a scrubbing with hot soda-water, and washing off in plain water, and final oiling while warm.

Undiluted Acid Quench.—There are several objections to the use of pure sulphuric acid. Its only advantage appears to be the elimination of steam bubbles, so ensuring a *very uniform* hard surface, together with a certain greater depth of hardening. It is difficult to clear the metal of all trace of the acid after treatment, and this appears to be the chief disadvantage of all acid quenches. A lead vessel must be used.

Mercury.—The most rapid absorber of heat in use is probably mercury. It is used for tool steel requiring a very hard surface. This quench is expensive to work, as a considerable bulk of it must be at hand or in use. The heat is rapidly disseminated throughout its mass, and is not an easy quench to keep cool. The surface must be kept free from scale or oxide.

Compressed Air.—The cold air blast is, as might have been expected, not sufficiently rapid for either case-hardened or carbon tool steel. Its use is practically confined to chilling the nearly fused surface of tungsten, and similar high speed tool steels. But a great deal of such work is done in oil, without the help of air. The main reason for the use of air lies in its mild attack. High speed steel cannot withstand sudden cooling ; it is extremely liable to crack. Its hardening is generally carried out in one of three ways. From a nearly fusing heat it is simply left to cool upon the often warm hearth ; here we have air cooling without urging the air. Or it is brought to a nearly or quite equal heat and plunged into the rapid current of air. Or, thirdly, it is plunged momentarily (just to secure a black appearance) into fish or whale oil, withdrawn, and left to cool gradually ; or, alternatively, withdrawn and cooled off in the air blast.

Freak Quenches.—It may be taken for granted that, ever since steel was invented, hardeners have sought for some desired magic hardening method ; and every possible substance and combination has been laid under contribution. The basic fact, however, that hardening consists in withdrawing heat, either quickly or slowly, cannot be ignored. Nothing will effect this better than plain water or oil. All the secret " notions " of hardeners, if found to be more than usually successful, ultimately revert to the art of heating up to and chilling at the critical point of the particular steel.

The Magic of " Notions."—This will always be found, not in the mysterious nature of the quench, but in the treatment of the steel before it touches the cooling medium. Those hardeners who, in past days, were so skilful can be shown to have been working, without being aware of it, at the scientific decalescent point of steel. This they found by trial and error method, until they could by the naked eye recognize the exact temperature desired. To-day we can exhibit both the decalescent and recalescent changes of the steel graphically and automatically upon a chart, and the molecular changes they denote are quite clearly understood by all students of the subject.

Development Related Entirely to Heat Applications.—Until we understood clearly the absolute changes that could be brought about in steel by means of heat there was, naturally, a vague belief that a great part, if not all, of the virtue gained by hardening lay in the quenching. As soon, however, as the actual microscopic transformations of the constituents of the metal were proved to be due to heat alone, it was seen that the only part played by the quenching was to *fix* the molecules in the condition to which heat had brought them.

Take a sample of 0·5 % carbon steel in the raw state. Let it be fractured in this condition. Observe with the microscope, or even with the unaided eye, the appearance of its "grain," or crystalline structure. Now bring a piece of the same bar slowly up to some 1,800° F. and let it remain at that stage for a few minutes. Cool it slowly, and do not quench. Let this piece be fractured. Little or no change or refinement has taken place as far as we can now see. Taking a third piece of the bar, put it through the heat treatment, and quench it while it is still at about 1,800° F. Fracture again. There is now a transformation—a *fixed* transformation consisting of a great refinement of the grain. Reverting to the case of the sample first heated, we know to-day that it also had arrived at this refinement state, but that there being no quenching to follow this condition, the microscopic constituents, through slow cooling, reverted to their former coarse crystalline structure. Now, it is of no consequence what means we have taken to suddenly cool this steel; mercury, ice-water, brine, or just water, the result is the same. No chemicals or freak mixtures whatever will permit escape from the fact that the change has been brought about by heat, and that our quench is merely a fixer or arrester of the changes that this heat has effected.

Rapidity of Quench.—We are on safe ground in accepting the following list of quench or cooling speed for the different *media* available for practical work.

The comparative speeds of quench are derived from experiments under the author's direction with bars of 0·9 % carbon steel ½ in. by ¼ in., heated up to 1,400° F.,

Speed in Seconds.	Fastest.	Speed in Seconds.	Slower.
1·5	Mercury	3·0	Kerosene
2·0	Water pressure spray	3·2	Light mineral oil
2·5	Sea-water	3·5	Fresh fish oil
2·5	Brine	3·6	Old fish oil (used)
2·2	Rain-water	3·6	Lard oil
2·5	Hard water	3·9	Boiled linseed
4·0	Lime	3·9	Raw linseed
4·5	Sand	4·0	Fresh cotton-seed oil
6·0	Compressed-air blast	4·2	Cotton and mineral mixed

over a length of 2 in., and immediately plunged into the quenching media. The short time limit ensured a hardness sufficient to permit of the facile fracture of the steel in the middle of the chilled zone. For regular work the hardener would generally allow the steel to become quite cold in the quench. The air temperature and that of the quenches above was approximately 60° F.

It will be observed that there is shown a difference of about three seconds in quenching effect between the fastest and slowest of these common cooling materials. The effectiveness of water is fairly constant until its temperature is raised to 80° F.; at 100° F. its hardening power falls off. Brine retains its chilling power at considerably over 100° F. Brine is very apt to crack high carbon steel. Undoubtedly the water quenches are the most useful for hardening operations in tool steels for case hardening; while the oils are more particularly adapted for toughening, which also implies a certain degree of hardness.

Precautions Necessary with Oil Quenches.—Kerosene or paraffin is often recommended as a quench, especially in America. This is presumably due to its standing at the head of the oil group in point of rapidity. But both in the use of kerosene and the light mineral oils care is necessary to prevent an outbreak of fire. A heavy heat of steel plunged into either will set the tank on fire, and if a sliding cover is not at hand there is apt to be an overflow that may eventuate in a great blaze. This trouble is not so apt to occur with the heavier oils, but any of them can be set aflame by sufficient heat. Operators will do well to prepare for these eventualities. In the matter of the use of some of the oil quenches, notably *fish* and *whale oils,* the most intolerable offensive odours are to be expected, and if quenching is not conducted under a hood, having an up draught, their use for this reason is sometimes prohibitory. Partly owing to the risks of fire, oil quenches should never be kept in vessels other than riveted iron tanks. A soldered tank will give way under the first flare-up, and the flaming oil will escape. A clay vessel, however thick, will be apt to crack, with similar results. In all cases of partially chilling high speed steel the heat is so great that a flame is certain to be started, and it will follow the movement of the exciting cause. High speed chilling work should always be done in a heavy high flash-point oil, and even then with precautions.

Oil Quench Cooling.—The usual, and perhaps the most effective method of cooling oil tanks is the obvious one of having cold water pipes fitted around and across the tank. This plan is more effective if the pipes are arranged near the surface of the oil, and not underneath it. The usual alternative to the above is circulation of the oil itself. This implies the use of large volumes of oil, and consequent extension of plant. Placing the oil tank within a water tank is a useful plan for small operations.

In the case of works carrying on the treatment of large articles, from the dimensions of locomotive parts up to armour plates, the extensive use of oil circulation is imperative. In this case oil-cooling radiators are placed in running water, and the oil constantly pumped through them. Fresh oil is thus always available in the tanks.

Precautions.—In all cases where water is used for cooling oil, through pipes, a leakage of water into the oil may occur. This water will sink below the oil, and it may remain unnoticed. If, now, a red-hot part is sunk in the oil, it may, and often does, retain its red-heat until it strikes the water lying below. The result may be an explosive rush of steam, which may cover the operator with burning or hot oil. —*Verb. sap.*

Forced-air Cooling of Quench.—If cold air is forced through perforated pipes, at the base of either water or oil-quenching tanks, it will gradually cool the contents. But this must be effected, unless specially arranged, while work is not being treated in the quench. The reason is, that the rising air bubbles will tend to produce soft spots upon the steel by clinging to the surface and insulating the metal from the cooling action of the quench. But, as already stated, under the heading of Colouring, we have here an almost ideal arrangement, because the colours produced are largely due to area of different hardnesses.

Compressed air may, however, be used to cause merely a circulation of the oil or water, but it must be confined to areas of a tank through which work is not passed for cooling. It has been found that air circulation is better adapted to the mineral and fish oils than to either vegetable or animal oils. This drawback is due to the oxidizing effect of air upon these groups of oils.

Handling the Quenching Tank.—In the lay-out of a modern hardening shop, arrangements are such as to permit of the use of two only quenching tanks. These are the water and the oil tanks.

The heating furnaces are all in a line. Upon the floor of the shop is provided a narrow-gauge rail line. The two tanks are provided with wheels to move thereon. In this way they can be moved opposite to whichever furnace is ready to unload. Midway of the rail-line, beneath the floor-level, there are laid the air or water-cooling pipes, provided with faucets opposite to each furnace. By arranging the rails close to the furnace front the tank can be brought quite near to it, which is imperative when the parts being treated are easily cooled. Tanks accommodating many barrels of oil are handled in this way with the utmost ease and great economy of time.

Dipping.—When a heated article has a great length in proportion to its width, the dip should always be vertical, otherwise deformation is almost certain to occur. It is only articles that are comparatively round or square that may be dipped in any position. Disk-shaped parts, as rings or wheels, should always be dipped edgeways. Recessed and drilled parts, and thus forming pockets, must be noted before being placed in the furnace. For example, a part has a pocketed hole, bored several inches or feet in depth. This is a *cul-de-sac*. If the article of which it forms part were to be dipped with the mouth of the hole *downwards* there would ensue, in water, a great evolution of steam under pressure within the *cul-de-sac*. This would be troublesome in various ways, besides leaving the walls of the hole unhardened. The remedy is obvious. Let the recesses be kept uppermost. Or, alternatively, let the pocket be filled with fireclay before heating; but this is only applicable when the walls of the pocket are required soft.

Irregularly shaped parts, in which there are heavy and light sections, should be cooled heavy part first. Work should never be dropped into the quench and allowed to lie at the bottom of the tank. In most cases, if of fairly heavy section, they will lie in sight at the bottom while still red-hot, surrounded by a film of steam. The final result is that the part is not rendered hard. Movement during quenching is all important. This implies movement to and fro and up and down. The descent into the quench should not be rushed nor irregular, but a uniform downward course. The heavier the part, the more necessary is this sideways motion.

The operator must realize that in dipping parts of length, such as shafts, the hot end entered first forms an area of hot water around it. Obviously the shaft must not continue to descend into this hot ring, since the consequence would be to have the upper part of the shaft semi-hard, or even soft. The obvious course is to begin at one end of the tank and traverse it, forming an oblique path from top to bottom of the quench, so ensuring fresh cold water for every part of the shaft.

Horizontal Dip Stairway.—So much trouble was experienced by a large automobile works in this country with the system of vertical shaft cooling that they instituted, with considerable success, a horizontal quenching arrangement. This consists of a kind of right- and left-hand ladder, reaching from the top to the bottom of the deep tank. The " steps " of the ladder consist of two round steel rods, forming an inclined plane through the quench to a depth of a foot. The shaft here drops off the first step on to a second, inclined in the opposite direction. In this way it descends step by step back and forth across the cooling quench until it reaches a receptacle at the bottom. This method should be very effective, as it secures both descent and change of position in the quench, from top to bottom. By the simple hand method of horizontal quenching it is a matter of considerable skill to harden a shaft without producing a curve in it. Hence the vertical dip still holds its own in the absence of appliances such as we have described.

If the shaft is not too slender, if it has not suffered bending in the heating up, or rather after it has become soft while red-hot, and if it is skilfully gripped and dipped quite vertically, with sideways motion, it will always come out of the tank hard and quite straight. If it fails to do this, the cause is to be found in some stress undergone by the steel while being forged, or possibly by cold straightening before being placed between the centres of the turning lathe.

All such stresses should be provided for by an annealing previous to the turning operation. Round, slender parts of the kind spoken of are usually hardened, or rather stiffened, not in water, but in oil. In the case of trouble with this, or any other shape of article, it must be remembered that there is always a reason. Also that the reason, apart from blundering in heating and quenching, is usually found in tied-up effects of stresses unrelieved by annealing. Steel for machining operations, such as turning, should always be *at rest*, and not under any stress. The anneal need only consist of heat application up to 1,400° F., or a cherry-red, followed by *slow* cooling. This, of course, applies to steel as yet not machined.

Expansive Force of Hardening Steel.—An irresistible force can be exerted by steel during the cooling process. This fact should never be lost sight of. It accounts for untold trouble to heat treatment men. A hardened and cooling envelope may resist it by simple expansion.

Locomotive Axles.—A great deal of experimental work has been carried out by locomotive works, here and abroad, in both hardening and stiffening axles. The diameter of these may be as great as twelve inches. We have here a heavy mass of solid steel, which it is practically impossible to harden throughout. It is impossible to cool the centre, or near it, quickly enough to ensure even a degree of hardness, if indeed such a condition should be required. Heavy locomotive forgings are always carefully annealed before being put into the turning lathe. If they are to be "hardened," it is usually done in oil, and the axle is dipped vertically. The result is generally more of a stiffening than a hardening. The centre of the bar is unaffected.

In many shops the bar is always drilled, or bored, with a fairly large drill, throughout its length. As this operation, if not overdone, does not appreciably take from the strength or stiffness of the part, it offers a great advantage in the subsequent hardening process. Crank pins are especially improved by being bored; as the diameter of a crank pin is never excessive in a locomotive, there is no reason for abandoning hardening this and similar parts.

Bored axles, if well done, can be greatly strengthened by oil-quench hardening. But so much trouble has been encountered by some locomotive builders in the heat treatment of their axles that some of them have, with reluctance, returned to the use of unhardened steel of a sufficiently high degree of tensile strength.

It would not be satisfactory to leave this latter statement without an endeavour to point out the reasons adduced for the abandonment of the hardened or semi-hardened axles in favour of practically raw steel.

In the United States the manufacture of locomotive axles has become a specialized trade in itself. It has become a common practice to produce the axles from 0·42 to 0·45 % carbon steel and to harden them either in water or oil. In some cases this treatment was not followed up by any modifying process, such as tempering. Such axles would frequently fail in work, by cracking. The reason for these failures was not far to seek. Here we have a mass of steel so heavy or thick that there can be no hope of securing hardness except within a narrow zone of the exterior. The hardening of this heavy envelope, while the core was still at a red-heat, formed a battleground between the enormous outward pressure exerted by the cooling of the core against the unyielding hardened envelope. For some time the existence of this tremendous strain would remain unnoticed. If, as often happened, it was of sufficient intensity, it would manifest itself by bursting through the envelope while the axle was yet warm, or at least not yet put into service.

A very loud report would herald the discovery of a serious crack in the axle, usually while it lay cooling out.

Two leading methods have been adopted for dealing with this state of affairs, and with a great degree of success. In fact, stress-cracking has become an almost unknown accident in this branch of manufacture. It will therefore be useful to outline this later procedure, since it is applicable to almost every form of heavy forging, or mass of steel.

It has been determined, to begin with, that steel for heavy sections with a carbon as high as 0·50 % must not be used at all when subsequent quenching in water is intended. 0·41 % carbon appears to be the limit permissible, and this probably safe in oil quenching only, complete quenching in water being ruled out. This grade of steel may be treated as follows with perfect safety:—

Heat up slowly and thoroughly between 1,400° and 1,500° F. Dip quickly in water, vertically, until the surface has lost its redness. Transfer at once to the oil quench until the surface appears quite black, or has lost all appearance of redness. Remove and bury in lime or ashes until cold. Here we may suppose that the tremendous outward pressure in process of cooling of the still hot core can ensure its equilibrium by a gradual adaptation to the moderately hard envelope surrounding it. As before pointed out, a very great modification of its bursting or cracking tendency, of outward pressure, is brought about by drilling out the core, to as large an extent as permissible. This permits of the flow of the quenching medium into the interior of the mass, ensuring greater equilibrium between core and envelope.

Water quench, however partial, has, however, been condemned by many engineers, who hold that far better results in the elimination of cracks is secured by oil quenching only and the still more moderate treatment as follows:—

Most satisfactory results are reported to have been attained in the treatment of these heavy forging by resorting to oil quenching, only permitting the mass to remain in the oil until all colour has disappeared, and at once transferring to the lime or ash pit.

It should not be lost sight of that these everyday treatments are based upon a given carbon content. It is unquestionable that if water is to be used at all, carbon must be kept down to 0·41 % and under. The objection to the use of a steel too low in carbon, apart from its lower tensile resistance, has reference largely to the necessity for a high degree of heat before quenching. In other words, in order to ensure against hardening fractures we are faced with the necessity to use an inferior grade of steel and subject it to extreme heat in order to ensure the most desirable degree of hardness.

Again, a tensile strength of 80,000 lb. per square inch is usually demanded in steel to be used for locomotive forgings. This high figure cannot be easily attained by the use of steel of lower grade than that covered by the 0·50 %

carbon specification. The annealing temperature of this steel should be rather higher than its critical range, which will be in the neighbourhood of 1,425° F. Removal from the furnace while at 1,450° and partial cooling in oil is as near an approach to hardening as is in general use for this grade of steel. A second treatment of the same kind, at a rather lower temperature, is found to still further enhance the tensile strength and toughness aimed at. This treatment is generally known as the double-quench method of bringing out the best qualities of steel of medium carbon content. The actual period of time permitted for the oil quench to take effect is the important point, and authorities differ somewhat in their estimates; but one condition is common to all: the permitting of the still hot core to gradually give up its heat to the surrounding hardened zone and so "tempering" the exterior down to a condition of great tensile strength. It is claimed that the bearing (or abrasive) wearing qualities secured under this treatment are very high.

Spray Treatment of Heavy Sections.—Of late there has developed a general application of an effective hardening of the surface of large or deep sections of 0·50 % carbon steel. Since we have seen that there are great objections to attempting to secure a hard surface upon heavy work by the usual quenching method, with the ever-present risk of incipient cracks, any system that will secure a hard surface sufficient for wear must be worthy of attention. We know that case-hardening will secure this, but the process is costly as applied to large masses, and it is slow. In the case of the 0·50 % carbon steel it is unnecessary to carburize at all, since sufficient carbon is already in the steel throughout.

The spray treatment is very effective, without putting strains upon the mass of the steel. When the part, say a shaft or axle, is taken from the furnace, its lower end is dropped into a receptacle which is made to revolve. The upper end is supported in a collar. A fine spray of water is played upon the red-hot steel. The amount of water being discharged upon it will determine the depth of hardness secured. This should be limited, and can be limited, by the initial temperature of the steel also. The spray can be continued until all trace of external heat has departed. The shaft can be left to dissipate its internal heat, and so bring about a tempering toughening.

The spray nozzles are flattened in a vertical plane, unless drilled nozzles are preferred. At least three outlets from the spray should be arranged in each foot of height. The same system can be used when the revolving part is arranged in a horizontal plane.

Cast-iron Hardening.—The hardening of cast iron, although the necessary treatment to produce a satisfactory effect has been known in this country for some time, has not been generally practised. But there are numerous applications of cast iron in which additional hardness of the exterior is a great gain. This has been quickly recognized in the United States, where, at the present time, enormous quantities of iron castings of moderate size are straight-hardened. The term "castings" has reference here to both unmachined and machine-finished parts of cast iron.

There is nothing abnormal about the process used as far as heating is concerned, but the quenching arrangements employed are decidedly novel.

Heating is arranged so that the parts are well soaked, finishing at a temperature between 1,500° and 1,600° F.

Quenching.—A vessel of lead is used, of ample size to receive the largest parts with room to spare, so that the parts need not touch its sides. This generally takes the form of a cast or sheet lead pot or jar about 24 in. deep and 12 in. in diameter. Lead has to be used because an acid quench is employed. The quenching pot must be stood in an outer tank of cold running water, because the action of the acid causes rapid dissipation of heat, which must be quickly got rid of. The nature of the quench itself, as used in American practice, is as follows: Anhydrous sulphuric acid of 1·8 specific gravity, 1 gallon, to which is added, at the rate of $\frac{3}{4}$ lb. to the gallon, red arsenic crystals, well mixed with a glass stirring rod, and left a day or two to thoroughly dissolve.

The cast-iron parts are quenched in this mixture until all colour has left them, and then transferred to the water portion of the tank. They must be afterwards well scrubbed in hot lime water to remove all trace of the acid quench.

The object in using anhydrous acid is rapidity of quenching. In plain water there is always a film of steam upon the red-hot surface delaying the cooling. Cast iron requires a quick chilling, and acid, free from water, is found to be the most effective for that purpose.

It need scarcely be pointed out that this idea of obtaining a rapid chilling of the surface, through the avoidance of steam formation is not new *per se*, but its application to cast-iron parts will be a novelty to many. For many purposes connected with carbon steel tool hardening an acidulated quench is well known. Its rather sharper action in suddenly cooling steel is due, of course, to its greater heat-conductivity, also to a certain effect regarding the formation of steam, a film of which is always produced when red-hot metal is plunged into plain water.

To render the formation of steam practically impossible, an acid free from water is no doubt the best available medium for the purpose.

Heavy Steel Castings.—At the present time the treatment of steel castings has to a great extent been brought into line with that of rolled and forged parts of carbon and the various alloy steels. They are not permitted, as heretofore, to pass into service without heat treatment. Steel castings are rapidly being developed and improved, not only in the composition of the melt, but in the moulding; a great deal of skill being devoted to producing not only fine-grain metal, but towards the total or almost complete elimination of moulding defects and blowholes. But it is idle to expect castings of intricate design to be free of strains and stresses just as they leave the castings department.

It is here that the heat treatment so highly developed by experience in handling wrought steels comes into play, aiming at two things: elimination of stresses and refinement, of "grain," to be followed by a kind of tempering that ensures maximum tensile strength. Within the past few years the demand for high tensile strength in steel castings, in order to bring them up to the standard of the ordinary wrought steels, has led to various attempts to meet the requirements of the case by means of slight alloy with suitable tenacious metals such as vanadium. This is a costly remedy, and worse still, it has not been entirely successful. At the present time excellent results are being achieved by means of the heat treatment methods adopted for ordinary carbon and alloy steels, with certain modifications.

For Castings of 0·10 to 0·20 % Carbon.—Heat slowly up to about 1,700° F. Allow to cool slowly. When the heat has dropped to below 900° F., reheat to 1,400° F. and quench in oil. Reheat to about 700° F. and cool slowly.

For Castings of Higher Carbon, 0·20 to 0·35 %.—Heat slowly up to 1,700° F. Allow to cool slowly. When the heat has dropped to below 900° F., reheat to 1,400° F. and quench in oil. Reheat to about 700° F. and cool slowly.

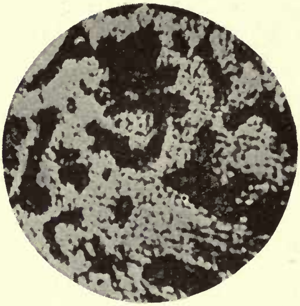
These directions apply to fairly hard castings, of considerable thickness of section. Castings of intricate design and thinner section will generally demand a higher figure in the final drawing temperature, or from 1,000° F. to 1,200° F. This will produce maximum ductility in the thinner sections.

CHAPTER X

THERMAL TREATMENT PROCESSES

(*See also pages* 90–101)

THE incorporation of nickel with pure iron was at first considered so difficult a matter that for a time steel compounders almost despaired of effecting a practicable product upon a large and standardized scale. The chief trouble was associated with the "laminating" nature of nickel when worked with the ferrite of a high grade of iron. Happily the working up of nickel and ferrite is an art that at the present time has reached a high, if not perfect, stage of development. There was at first a tendency to both "lamination" and piping (channels longitudinally through the bar). But by improving rolling methods, together with handling the alloy in moderately large ingots and utilizing only the most perfect portion of the ingot, a really first-rate grade of nickel steel is secured. Nickel is found, especially when in combination with carbon, to add enormously to the strength and ductility of the product. The chief advantage of the nickel content is its affinity for the ferrite, or the pure iron component. There is easily formed what may be termed an emulsion between the two with startling results, for as small an addition of nickel to the iron as 1 % will cause an augmentation of tensile strength of from 1,000 to 3,000 lb. per square inch. The nickel component may be increased to at least 15 % for certain purposes, but when the alloy includes only 5 % of nickel it will exhibit an increase of tensile strength and elastic limit up to 5,000 lb. per square inch. To develop the full effect of the alloy, however, it has been found that a percentage of carbon is necessary. It is found that a small percentage (0·25) of carbon is all that is necessary for ordinary purposes. Taking a nickel carbon steel showing a carbon content



× 650.

Fig. 82.—Nickel 2 %, carbon 0·25 %. Savoia.

× 650.

Fig. 83.—Nickel 4·86 %, carbon 0·115%, carburized and air cooled.

× 650.

Fig. 84.—Nickel 5 %, carbon 0·25 %. Savoia.

× 650.

Fig. 85.—Nickel 7 %, carbon 0.25 %. Savoia.

× 650.

Fig. 86.—Nickel 12 %, carbon 0·25 %. Savoia.

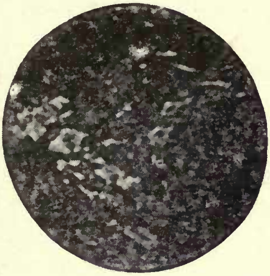
× 650.

Fig. 87.—Nickel 20 %, carbon 0·25 %. Savoia.

of 0·25 % and 3 % nickel, a tensile and elastic limit test will show a figure as high as could be attained with a straight carbon steel with 0·45 % carbon.

Microphotographs 82 to 88, mostly due to the investigations of Savoia, form a series of microscopic pictures of the conditions of carbon-nickel steels under various treatments, the 25 % nickel being almost unworkable.

Heat Treatment of the Nickel Steels.—In many respects the heat treatment of the nickel group may be said to be less risky than the treatment of straight carbon steels. To illustrate: a carbon steel is heated for quenching and hardening, and by accident the critical point is exceeded; even the permissible range is exceeded by, say, 50° F. If this is allowed to go on, for a short period measured in minutes, the crystalline structure of the steel will coarsen, and its ultimate tensile strength will greatly diminish; hence the straight carbon steels must be handled with great caution in this operation.



× 650.

Fig. 88.—Nickel 25 %, carbon 0·25 %. Savoia.

Take now a good specimen of nickel steel. It is found that not only can the critical range be exceeded, but that with an actual benefit to the refining of the grain; and that treatment which would be ruinous to straight carbon steel may be actually necessary in the case of nickel steel.

That nickel steels are subjected to more prolonged and higher temperatures than carbon steels in general practice, with a corresponding advantage, there can be no doubt. Indeed, it is not difficult to demonstrate, by fracturing differently treated specimens, that carbon steel treatment is not applicable, without modification, to the nickel group in general use. It may thus be said that, while nickel steels undergoing heat treatment are not to be regarded as "fool-proof," they are less easily destroyed by errors than are the carbon steels. This feature will be generally recognized as of considerable value in itself, from a commercial point of view. Again, given sufficient time to "soak" nickel steel will permit of hardening at a lower temperature than straight carbon steel. While it is always advisable to maintain the critical heat of nickel steel longer than is usual with carbon steel, it might be objected that this reduces the capacity of the heating plant in dealing with quantities. But, while this may be true from one viewpoint, there must not be overlooked the advantages (and they are not inconsiderable) of a smaller percentage of failures and losses, accompanied by a diminished demand for a high grade of skill on the part of the hardener himself, so that the "human element" need not count as of superlative importance, as it generally does in the case of at least high carbon steels. But the remark must not be taken as advocating the employment of any but the best available talent in the treatment of steel of any kind, for if there is in the engineering trades a branch in which a poor grade of intelligence and skill will lead, more than in any other, to rapid losses, it is surely in the steel department. Indifferent workmen can here destroy as much material, or so maltreat it that it must inevitably lead to failure in the finished machine in one week, as any of the machine hands could possibly wreck in a year.

Regenerative Quenchings of Nickel Steel.—The objects to be aimed at in the quenching treatment are: Firstly, an annealing simply, which may be carried out upon the raw steel for ease of machining or merely the relief of stress after machining. Secondly, quenching for toughening, still leaving the steel comparatively soft, except on the surface or near. Thirdly, quenching for hardening and toughening combined.

Carburized Nickel Steel.—Let us consider the treatment of case-hardened parts first. We are here dealing with a ductile core and a much harder casing. This casing may be left soft or treated to become anything from unhardened high carbon nickel steel, or toughened; or by more rapid and effective cooling made dead hard. The case of carburized nickel steel is, in the heating part of it, scarcely on a par with the treatment of straight carbon steel, especially in reference to the degrees of heat attained. And this for the reason that we are dealing with a nickel body containing only a small percentage of carbon, and, perforce, simultaneously with a carburized case with a carbon content of as much as 0·4 to 0·9 %.

The carburizing, then, should be effected in the usual case-hardening box, and with, say, a mixture of crushed charcoal and charred leather. The temperature having been brought up to 1,650° F., or possibly between that figure and 1,720° F., is maintained for at least one hour in the case of small articles, and two, or even three, hours in the case of heavier material. The box and its contents are allowed to cool out slowly. Clearing the parts now of all adhering matter, they may be heated to a temperature of 1,560°, and not higher than 1,620° F., plunged into an oil-bath, or, failing this, water at 75° F. until the *surface* appears almost black, and allowed to cool in the air if regenerative treatment, apart from hardness, is the object. But to harden, the article should be taken rapidly from the quench, just as soon as there appears the surface blackness, and returned to the heat. Here the temperature reached should not exceed 1,350° F. The final quench should be in either oil, or in slightly tepid clean water. The articles should now be glass hard on the surface, and to a depth of at least one thirty-second part of an inch, according to the time given in carburization. We have given here the minimum temperatures for both treatments, but it should be noted that the practice in France and in America is to use a higher regenerative temperature, frequently as high as 1,775° F. in the case of a nickel content of 2 or 2½ %. But however high the first heat is taken, and there are considerable differences of practice here, the final heat should be as *low* as would ensure a hard case. How low this may be, in the case of effective carburizing, may be judged by the fact that dead hardness is often secured when the quench takes place at a very dull red-heat. This is always a sign of a high and fine carbon case.

In the case of a higher nickel content, the hardness quenching is very frequently dispensed with and air cooling resorted to. This latter has the advantage, while it does not secure a glass-hard case, of avoiding the risks of distortion attending all quenching operations. The treatment of steels with a higher nickel content, which is general in automobile work, even reaching 6 %, differs but little from the foregoing, except that the carburizing may be easily conducted at a lower heat, and the subsequent hardening secured with a warmer quenching bath—all of which are advantages towards the toughness and strength of the product. All nickel percentages over 5 % are difficult to machine.

Influence of Mass on the Result.—The foregoing figures for nickel steel and case-hardened parts of this material may be expected to approximate to requirements in the case of moderate mass. This may mean substance in parts as massive as a bar 1 in. in diameter. The same treatment cannot be expected to approximate to requirements in the case of articles of greater mass, and a slight modification should be made both in time and temperature in respect of smaller masses. And here we may consider the importance of firing all articles of a heavy section together, keeping the moderately bulky and the small articles in batches by themselves, as it will be obvious that the time limit must in all cases bear a reasonable relationship to the masses to be treated.

Physical Test versus Section.—Under heat treatment there can be no doubt that the finer and more moderately thick section work receives the maximum of benefit. It is as well to recognize at the outset that heavy sectional nickel steel (let us say over 1 in. through) does not, as far as is known, increase in actual strength, under test, to anything like the same extent as the thinner sections. But the actual relative percentages covering this fact do not appear to have been satisfactorily investigated and determined by experimenters.

Some results, plotted by Messrs. Mathews and Stagg, and dealing with nickel steel of the following composition, have, however, disclosed some most interesting results as far as the Brinell hardness tests can be relied upon in reference to physical strength are concerned: Percentage nickel, 3·47; ditto carbon, 0·25; heat in furnace, 1,600° F. oil quench.

½ in.	section,	Brinell hardness	465
1	,,	,,	330
1½	,,	,,	295
2	,,	,,	293
2½	,,	,,	284
3	,,	,,	245

While these figures do not appear to be conclusive, they nevertheless exhibit to some extent the great effort of mass upon the effect of quenching of the above average class of nickel machinery steel.

Costly Nickel Steels.—A great deal of money may be expended unnecessarily upon the higher-priced alloy steels. Frequently this occurs under the impression that the higher-priced steels need not be heat-treated. But experience has shown that it is not so much the price that has been paid for the steel as its heat treatment that determines the ultimate suitability for work such as automobile construction. A very moderately priced specimen of nickel steel can be so transformed by heat treatment that it will perform in work and withstand tests, just as well as the more costly articles.

The above observations may be said to have reference not only to normal nickel percentages steels, but to

High Nickel Steels.—We have here a product which is so rich that it cannot be subjected to the ordinary heat treatment, or at least this treatment will only secure negative results. Reference is, of course, made to steels intended for situations in machines where extraordinary stress and shock may be expected.

A good example of this is the inlet or exhaust valve of an engine running at high speed. We have here a percentage of nickel as high as from 25 to 35, in combination with a percentage of from 0·3 to 0·5 carbon. The result is a product extremely dense, and difficult to machine in the unannealed state. To anneal, the temperature may be as high as 1,450° F., followed by very slow cooling. After this treatment this steel will frequently show a tensile strength 85,000 lb. with an elongation in 2 in. of 30 %.

Nickel-Chromium Steels.—There is a greater variety of these alloy steels than of any other class in use at the present time. They may be roughly graded as high, medium, and low percentage steels, dependent upon the proportion of nickel and chromium present. We have in addition the Nickel–Chromium–Carbon group, which occupies a most important position, especially in the automobile industry.

With a carbon content as low as 0·25, we have a material eminently adapted for gear-wheels intended for light case-hardening, and for forged parts, axles and frames. This combination of alloys forms a steel almost of the strongest description, is rather difficult to work, and benefits enormously by the proper after heat treatment. The chromium content varies from 0·5 to 1·5 %, with nickel from 1 to 3·5 %. This grade, alloyed with 0·25 to 0·5 % carbon, fulfils most of the requirements of a high-grade "strong" steel. When the carbon percentage is as high as 0·5, we have probably the finest gear steel yet produced, but as toughness is sacrificed somewhat to this amount of carbon, it is yet suitable for numerous parts calling for great stiffness and reliability. With carbon as high as 0·5 %, and even less, the steel can be hardened outright without resort to carburizing.

Annealing of these hard steels, as received from the maker, is generally advisable in order to facilitate the machining operations. It is carried out in the same manner as in the case of nickel steels.

Case-hardening Requirements.—A very low carbon content is advisable when case hardening is to be the finishing operation, so as *not to overdo the carbonic richness of the shell.* This especially applies to gears in what are known as clash positions, such as the speed change gears of automobiles. For constant-mesh positions a rich carbon case may be a distinct advantage. There is a great abrasive resistance in the chromium–nickel–carbon steels. When toughness is of importance, as in parts subject to bending stresses, the use of a low carbon alloy is recommended. Stiffness is greatly augmented by even a small percentage of carbon, with, of course, corresponding brittleness. With appropriate treatment this may be greatly modified. For constant mesh bevel gears, a carbon content (0·5) sufficiently high to ensure direct hardening is advisable. It forms a tougher tooth than any case-hardened product, and is sufficiently hard for long wear. It may be assumed that oil hardening is much less risky than water quenching. Water colder than 80° F. should not be used. Oil hardening, being less sharp, may be conducted at a lower temperature of quench.

Forging.—In handling these steels upon the anvil a plastic heat must be maintained. It must not be forgotten that here we have alloys that will not withstand cool or cold hammering, such as is frequently carried out with iron and low carbon ferric products. *Cracking* and flaws are apt to be developed. Plasticity must be maintained, but overheating must also be avoided. There is what is known as *Hot Shortening*, at excessive heats, which results either in faults or in actual fracture right across the section. Managed with reasonable skill, these high-grade steels can be worked with perfect confidence, and flaws or hot shortness need never be encountered. It is, of course, assumed that the firing arrangements used by the smith are adequate in the matter of producing a *uniform plasticity* in the parts to be hammered. It will be obvious that the thinner portions which are usually the outside or exposed parts shall not be overheated, even if they are not to be touched upon the anvil.

Although under the heading *Heat Treatments* full directions are given, yet these words do not include forging. The smith's part of the procedure is largely a matter of ordinary skill in handling the common steels, and in which the human element may be said to be supreme.

The Chromium-Vanadium Steels.—We here touch a very fine grade of steel. It is made with a content of from 0·15 to 0·2 % carbon, which may be regarded as the softest grade, up to 0·45 %, suitable for case-hardened parts of any kind, gears especially. The 0·45 variety is largely used for the best class of springs for automobile work ; and the same grade can be hardened direct in the case of gears without resort to carburizing. The lower grade, again, is used extensively for the best class of constructional parts, as axles, steering equipment, and universal joints.

Varieties in General Use.—The low carbon chromium steels are commercially produced with 0·20 % ; the high carbon variety with from 0·45 to 0·6 %. Direct hardening of the low carbon sort should not be attempted ; resort should be had to carburizing by the ordinary case-hardening method. Direct hardening of the high carbon variety can be easily effected ; at a bright red heat, quenching preferably in cold oil. We will have in this case a fairly good depth of hardening, and a tough core less hard. A higher quenching heat, combined with a colder quench, will secure greater depth of hardening.

The Unbreakable Gear.—While speaking of gear wheels, made from the more expensive alloy steels, it may be well to state here that the objects aimed at by makers who prefer these complex steels are, simply, reliability and freedom from appreciable wear. In plain words, this means a hard, non-brittle outer skin and a tough, strong body, assuring practically endless wear of the teeth, and strength sufficient to easily withstand shocks. Such a gear will be unbreakable. But it can be shown that the employment of costly material is really not necessary in order to approach the above desirable result, since we have in good mild, basic low carbon steel (0·20) all the requisite qualities provided that it receives the proper treatment, which is, after all, quite simple.

Procedure for Low Carbon Steel.—Anneal the rough blank at a low red-heat and cool slowly. After machining, pack for case hardening in a charred leather material, which may be mixed with a proportion of barium carbonate—about half and half. After bringing the temperature up to a cherry-red—to be exact, 1,600° to 1,650° F.—keep it in that condition for one hour for light gears, and allow to partially cool off, still in the carburizing box, until it falls below dull red. Remove and uniformly heat, in the open, to a temperature of 1,450° F., a dull red, and quench in cold oil. It will be observed by those readers possessing some knowledge of the subject that we here recommend moderate temperatures throughout. Heats as high as 1,850° F.—a very bright red—are frequently spoken of by experts in treating mild steel in the carburizing box. In the absence of a considerable percentage of impurities in the steel (sometimes as high as sulphur and phosphorus, each 0·05 %) there does not appear to be any warrant for this, unless, indeed, the carburizing must be hurried through. A low temperature is here also advocated for the final quench simply because, with a pure carbon case, free from the phosphorus and sulphur of charred bone, dead hardness will follow cold quenching at a surprisingly low red temperature. If there should be any indication of softness in the teeth, the gear should be reheated to rather higher colour and *requenched* in cold oil. The result should be a glass-hard case about $\frac{1}{32}$ in. deep, hard throughout this thickness, resting upon a tough interior.

This depth will be quite safe for gears having rather slender teeth. In the case of heavy gear wheels, the carburizing should be continued for two or three hours, until a heavy high carbon case is secured. Deep carburizing should never be attempted upon light gear wheels or other parts of comparatively slender section liable to stress shocks, because breakage of the teeth at the root is apt to follow.

A second reheat is often recommended for the carbon steel gear as well as for nickel steel. Each reheat tends to improve the body of the gear in the direction of toughness. In every case, whatever reheating is carried out, the final heat must be sufficiently high to ensure hardness of the exterior. No heat must be permitted to be so high that there is any evidence of scale upon the finished surface. And in quenching, if there is any difficulty in securing dead-hard results by the oil-quench alone, resort may be had to a combined oil-and-water quench, consisting of clean water, of ample bulk, bearing a depth of 1 in. of oil floating upon the surface. The parts are slowly lowered through the oil to the final quench below.

Figs. 89–96 are fairly representative of the chrome nickel group of steels, under different treatments, of which Figs. 94, 95, 96 are examples of extremely dense physically strong steels.

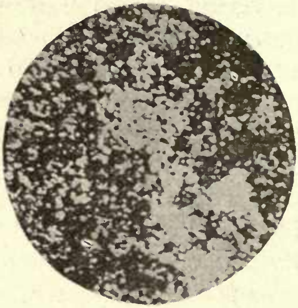
A Nickel Steel Gear may be treated as follows: Anneal the blank. Rough it out on the lathe and gear-cutter. Anneal again. Finish cut in the machines. Carburize as above. Withdraw when partially cool, and reheat to 1,500° F.; quench in cold oil. This should leave the teeth glass-hard for a depth of one-thirty-second of an inch. The most suitable nickel steel for this work is carbon 0·02, manganese 0·65, nickel 3·50, sulphur and phosphorus not exceeding 0·04. We have here an ordinary commercial nickel steel, at moderate price.

"Stopping Off."—It is frequently desired to harden only the toothed part of a gear wheel. In the absence of possible distortion, which may, in some cases, be more likely when "stopping off" is arranged, there can be no doubt that the hard tooth and the softer centre is the ideal of what a gear wheel should be. There is no need whatever for a hard wheel body, so long as the teeth can stand up to their work. This fact has led, of late, to a practice of high-carburizing the tooth ring only. If carefully carried out, there can be no objection to it. If we find fault, it must be in reference to the risk of "dishing," or even flattening such a gear as a large bevel wheel. With uniform heating, and the following precaution, this should not occur.

The parts to be protected from the carburizing action are coated to the depth of at least one-fourth of an inch with a plastic fireclay of the finest kind, such as is used for

× 500.

FIG. 89.—Chromium 1·75 %, carbon 1·0 %.



× 500.

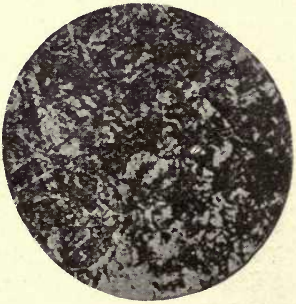
FIG. 90.—Chromium 1·75 %, carbon 1·10 % annealed.

× 500.

FIG. 91.—Chromium 1·75 %, carbon 1·10 % overheated.

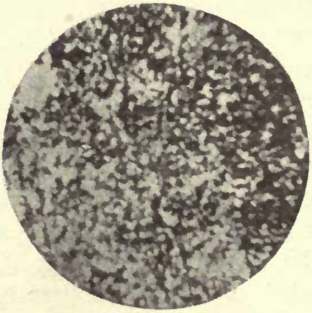
× 100.

FIG. 92.—Chromium 1·75 %, carbon 1·1 %. Attempt to anneal at too high a temperature.



× 100.

FIG. 93.—Chromium 1·75 %, carbon 1·10 % forged



× 100.

FIG. 94.—Chromium-vanadium steel annealed. Chromium 0·92 %, vanadium 0·20 %, manganese 0·48 %, carbon 0·26 %.

repairing gas furnaces. This is allowed to become nearly dry before placing in the box. The bore and keyway are quite filled. After carburizing, and before quenching, this coating should be rapidly knocked away, except in the bore. This can be best effected by laying the gear on the hot carburizing material, clearing one side, and reversing. Very slight fall of temperatures need in this way occur. Then quench, edgeways, as usual. There cannot, in the case of mild steel from which the supposed gear is made, be any hardening upon those parts covered by the fireclay, and they will be found soft, while the teeth are glass-hard.

"Local Hard."—A very useful proprietary material is now procurable under the name "Local Hard." In the form of powder, it is mixed to a thick paste in boiling water, and allowed to dry in a warm place. Its action is so effective that it not only protects mild steel from carburization, but is said to be quite effective upon high carbon steel also—in this case preventing the quench from reaching the red-hot tool or part so coated. This would appear to be suitable to gears made from hardening-throughout steel, or as made from chromium-nickel, and other alloys. It is obvious that there are numerous parts that call for local hardness only, and in most cases this can be secured by the judicious use of fine fireclay, or the preparation mentioned above. It may be useful to point out that, when a gear wheel, rich in hardening properties, is quenched, it should, as a rule, be withdrawn while still quite hot, but yet having lost all trace of redness, and transferred from a cold quench,


× 100.

FIG. 95.—Chrome-nickel shaft steel, oil hardened.

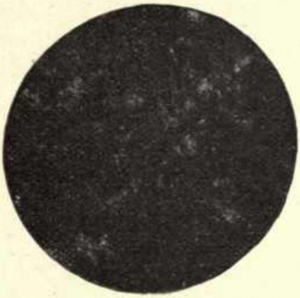

× 100.

FIG. 96.—Chrome-nickel steel shaft, oil hardened and tempered at 1,000° F.

such as water, or brine, and finally cooled off in oil. It appears to be a mistake to withdraw from a cold quench while warm, and to allow cooling off in the air, on account of liability to cracks, due to high carbon content.

Manganese Steels.—Taking carbon steel as a basis, it is claimed that, in the most advantageous heat-treated condition, each 0·10 % of manganese, up to 2·0 %, will increase the tensile strength approximately 1,500 to 2,000 lb. per square inch (see Campbell's formula, p. 39). Percentage of manganese must, however, be sufficiently high to bring the steel into the austenitic condition at or above the Ac 3 point. In this respect it will be inferred that manganese behaves similarly to carbon, but the resultant hardness should be greatly in excess in the case of manganese in all conditions short of that resulting from sudden cooling.

Quoting Sir Robert A. Hadfield, the inventor of manganese steel: "This fascinating material has the peculiar quality of being extremely tough when it should be brittle; and seeing there is no less than 88 to 90 % of iron in its composition, of being non-magnetic when it should be magnetic; as well as the valuable quality of offering in the products made of it exceedingly high resistance to the wear and tear of modern engineering service. After heat treatment, manganese steel possesses the high tenacity of 60 to 70 tons per square inch, and yet elongates no less than 50 to 60 %."

In reference to the extreme toughness and hardness of manganese steel, it is perhaps not generally known that the helmets issued to the British Armies during the late war were made from this material. When it was first suggested that this country should follow the example of France in providing head protection for the troops, it was realized that manganese steel would prove the best material for the purpose. But at that time it was considered an almost impossible feat to reduce the hard substance manganese steel from large-sized ingots to thin sheets only 0·036 in. in thickness, such as was required for helmets. And if it had not been for the war pressure and the serious losses occurring through head wounds, it is doubtful whether this steel would ever have forced its way to the front for this particular purpose.

In France, General Adrian had two millions of mild steel helmets manufactured for his troops. The resistance of this material to shrapnel bullets was, however, so low that at about 900 ft.-seconds velocity bullets perforated no less than three French helmets placed in a row, whereas one of the same pattern of helmet of manganese steel attacked at the same velocity could not be perforated.

An important application of manganese steel was sprockets and gears used in tank construction, this being the most highly resistant material that could be found.

The non-magnetic qualities of manganese steel were made good use of during the war in the construction of the sea mine. A considerable portion of this mine was made of this non-magnetic material of high tenacity, the result being that the enemy could not detect the presence of the mines, as would have been the case had these been made of ordinary iron or steel.

Commercial Manganese Steel.—The general requirement of a manganese steel demands a percentage of manganese as high as from 6 to 8 for the lower grades to as much as 15 to 20 % for the high manganese steels. A useful steel will contain 10 to 12 % of manganese, and as much as 1·0 to 1·20 % of carbon. Too high a percentage of manganese makes the steel brittle, unfitting it for any service of stress.

Saturation Heating Important.—The period of saturation has a very great influence upon the reduction of area in the case of manganese steel under test—in fact the reduction of area is a measure of the heat saturation. It will thus be clear that while it is possible to obtain a high figure of tensile strength, elastic limit and elongation with a minimum period of heating, the fullest possible development of these qualities is not to be expected except the heat saturation has been sufficiently prolonged. There appears to be little difference here between manganese and nickel steels, both of which will safely withstand prolonged heating.

It is well to bear in mind that in the case of most of the alloy steels, and particularly manganese, there is no parallel between them and carbon steels in this important stage of saturation-heat prolongation. And, further, while this maintained saturated condition, is of great effect at the upper critical point, it appears to be no less important in reference to the drawing or tempering stage. Certain it is that, while a drawing heat may, in the case of carbon steels, be of short duration, the same cannot be held to apply in the case of either nickel or manganese steels. They both, but particularly the latter, benefit greatly by a prolongation at the drawing temperature.

What is practically implied by the term "prolongation" will be better understood if the case of the manufacture of revolver barrels for a recent Government contract be cited. Under the normal prolongation of the drawing heat of one hour, considerable difficulty was experienced in the drilling and rifling operations, there being a percentage of failures. When the effect of extending the drawing and equalizing heat to more than double the time was tried, the number of rejections became negligible. The explanation is simple—hard "spots," or areas, were left unannealed under short period drawing, presenting sufficient resistance to the drill to cause what is known to machinists as "running out." Moreover, there is not, in the case of nickel and manganese steels, found to be any loss of tensile qualities, elastic limit, or elongation under effective drawing heat.

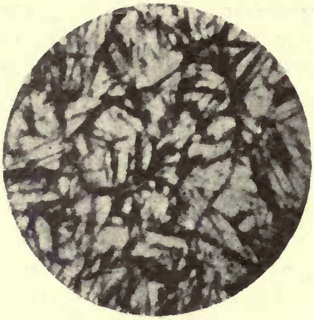

× 100.

FIG. 97.—Manganese steel fully annealed. Bullens.

Decalescence.—In the absence of carbon, it is found that manganese steel has no critical points. But for practical purposes, since carbon is usually present, the critical range normal to nickel-carbon steel may be taken as equally applicable to manganese steels of commercial brands. In the case of low manganese steel, the relation of the carbon to the physical properties of the steel must be accepted as the criterion.

Various Steels and Heat Treatment.—In the following pages is given a list of the different steels that enter into the construction of high speed machinery and automobiles. This is followed by a list of various processes, known as heat treatment, intended to develop the toughness, strength and hardness of the material without undergoing which it would be entirely unfitted for most of the parts used in automobiles. Raw steel cannot be made to approach the qualities attained by appropriate management. The various treatments are numbered under the specifications of various steels. Taking the basic open-hearth steels first :—

BASIC OPEN-HEARTH STEELS.

Low Phosphorus and Sulphur.

Carbon.	Manganese.	Process.
0·10	0·45	No. 1
0·20	0·65	No. 1
0·30	0·65	No. 2
0·40	0·65	No. 3
0·50	0·65	No. 4
0·80	0·35	No. 4
0·95	0·35	No. 4

NICKEL STEEL AND TREATMENT.

Low Per Cent. Impurities.

Carbon.	Nickel.	Manganese.	Process.
0·15	3·50	0·65	No. 6
0·20	3·50	0·65	No. 6
0·25	3·50	0·65	No. 6
0·30	3·50	0·65	No. 6
0·35	3·50	0·65	No. 6
0·40	3·50	0·65	No. 6
0·45	3·50	0·65	No. 6
0·50	3·50	0·65	No. 6

NICKEL–CHROMIUM STEELS AND TREATMENT.

Low Per Cent. Impurities.

Carbon.	Nickel.	Manganese.	Process.
0·15	1·00	0·50	No. 6
0·20	1·00	0·50	No. 6
0·30	1·25	0·50	No. 6
0·35	1·25	0·60	No. 6
0·40	1·25	0·60	No. 6
0·50	1·50	0·65	No. 7
0·15	1·75	0·45	No. 7
0·20	1·75	0·45	No. 7
0·25	1·75	0·45	No. 7
0·30	1·75	0·50	No. 7
0·35	1·75	0·45	No. 7
0·40	1·75	0·45	No. 7
0·45	1·75	0·45	No. 7

Higher Nickel–Chromium Steels and Treatment.

Carbon.	Nickel.	Manganese.	Chromium.	Process.
0·15	3·50	0·45	1·50	No. 8
0·20	3·50	0·45	1·50	No. 9
0·25	3·50	0·45	1·50	No. 9
0·30	3·50	0·45	1·50	No. 9
0·40	3·50	0·45	1·50	No. 10
0·45	3·50	0·45	1·50	No. 11

Chromium–Vanadium Steels and Treatment.

Carbon.	Chromium.	Vanadium.	Manganese.	Process.
0·15	0·90	20	0·65	No. 12
0·20	0·90	20	0·65	No. 12
0·25	0·90	20	0·65	No. 12
0·30	0·90	20	0·65	No. 12
0·35	0·90	20	0·65	No. 12
0·40	0·90	20	0·65	No. 12
0·45	0·90	20	0·65	No. 13
0·50	0·90	20	0·65	No. 13

Specifications of chromium–vanadium steels, as supplied by the makers, vary somewhat as follows: Type for light work and sections:—

Carbon.	Vanadium.	Manganese.	Silicon.	Chromium.
0·26	0·92	0·48	0·20	0·20

Type for heavy section—shafts 6 to 10 in. diameter:—

Carbon.	Chromium.	Manganese.	Silicon.	Vanadium.
0·50	1·02	0·92	0·65	20

Specifications of nickel–vanadium steel vary considerably. The following is a medium type:—

Carbon.	Nickel.	Manganese.	Silicon.	Vanadium.
0·29	3·41	0·45	0·090	0·20

Heat Treatment Processes.*

No. 1.—For machined parts, case-harden preferably in a 50 per cent. mixture of charred leather and barium carbonate, at a temperature 1,500° to 1,700° F. Cool in box to blackness, remove (if desired) while still hot, and reheat in the open to 1,450° to 1,500° F. and quench in cold oil for hardness. If for glass-hardness, quench in water at 80° F. Keep parts moving in the quench.

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* Approved by the Steel Division of the Society of Automobile Engineers, U.S.A., 1912, and extensively used in Europe since that date.

No. 2.—Carburize as in process No. 1, allow to cool in the box. Reheat in the open to 1,450° or 1,500° F., quench in oil. Reheat in open to 1,450° F., quench in cold oil or water at 80° F. Moderate the hardness by withdrawing from the last quench before the steel is cold, and leave in hot oil, 300° F.

No. 3.—Heat in the open to 1,450° to 1,525° F. Quench in cold oil, or water, at 80° F. Reheat to from 650° to 1,200° F., and cool in a warm place.

No. 4.—Heat small or medium-sized pieces in a muffle, by preference, to 1,500° to 1,525° F. Quench in cold oil; while warm reheat to 1,400° F. and quench again. Reheat to 600° to 1,110° F. and cool in a warm place.

No. 5.—Heat in muffle, or in the open, to 1,450° to 1,525° F. and cool slowly. Reheat to 1,400° to 1,450° F. and quench in cold oil. Reheat to 600° to 1,200° F. and cool slowly.

No. 6.—Heat uniformly, after any necessary hot-bending or forming, to 1,425° to 1,475° F. and quench in oil. Reheat to 400° to 700° F. and cool in a warm place.

No. 7.—Carburize at a temperature of about 1,680° F. and cool in box. While still warm reheat to 1,450° to 1,500° F. and quench in oil or water at 80° F. Reheat to 1,300° to 1,400° F. and quench in oil. Reheat to 250° to 450° F. and cool in hot water.

No. 8.—Heat to 1,500° to 1,550° F. and quench in oil. Reheat to 600° to 1,200° F. and cool in warm place.

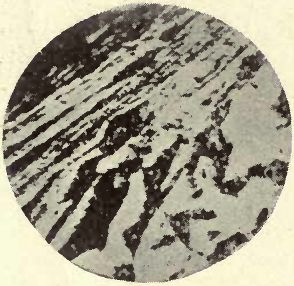
No. 9.—Heat to 1,500° to 1,550° F. Quench in cold oil. Reheat to 1,300° to 1,400° F. and quench in oil or water at 80° F. Reheat to 600° to 1,200° F. and cool slowly.

No. 10.—Case harden at 1,600° F. and cool in the box. Reheat to 1,400° to 1,500° F. and quench in water at 80° F. or cold oil. Reheat to 1,300° to 1,400° F. and quench in oil. Reheat to 250° to 500° F. and cool in a warm place.

No. 11.—Heat to 1,450° to 1,500° F. and quench in cold oil. Reheat to a temperature between 500° to 1,250° F. according to the circumstances of use and cool slowly.

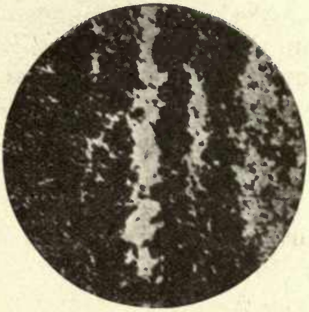
No. 12.—Heat to 1,450° to 1,500° F. and quench in oil. Reheat to 1,375° to 1,425° F. and quench again. Reheat to 500° to 1,250° F. according to circumstances, and allow to cool in a warm place.

No. 13.—Heat to 1,475° to 1,525° F. and maintain heat



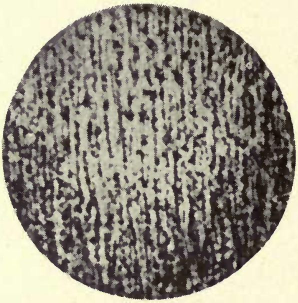
× 100.

Fig. 98.—Cold rolled 0·25 % carbon plate.



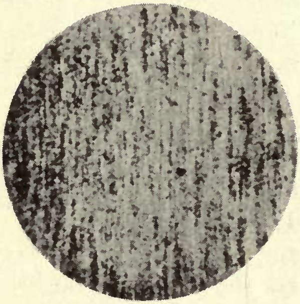
× 30.

Fig. 99.—0·28 % carbon steel annealed at 1,425° F. Campbell.



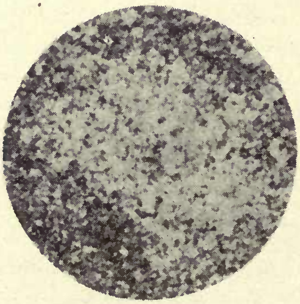
× 100.

Fig. 100.—Chassis steel—the raw plate.



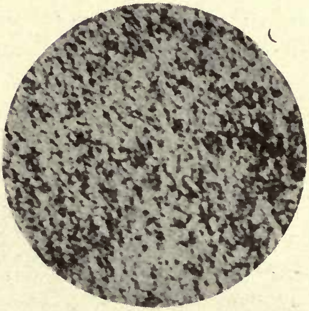
× 100.

Fig. 101.—Chassis plate half annealed.



× 100.

Fig. 102.—Chassis plate annealed.



× 100.

Fig. 103.—Chassis steel (chilled), showing granular pearlite.

until thoroughly soaked and cool slowly. Reheat to 1,450° to 1,500° F. and quench in cold oil. Reheat to 250° to 550° F. and cool in a warm place.

No. 14.—Case carburize at 1,600° F. for 1 to 3 hours and cool in the box. Reheat to 1,600° to 1,650° F. and quench in cold oil. Reheat to 1,475° to 1,525° F. and quench again. Reheat to 250° to 550° F., according to circumstances and cool slowly.

No. 15.—Heat to 1,525° to 1,600° F., allowing a thorough soaking and cool slowly. Reheat to 1,650° to 1,700° F. and quench in oil or water at 80° F. Reheat to 350° to 550° F. and cool in a warm place.

Microphotographs Figs. 98–103 are representative of carbon structural steels before and after treatment.

Silico-Manganese and Silicon Steels.—There has only been a restricted use for silicon steels. Of late trials have been in progress of a promising silico-chrome steel. The main disadvantage of the silico-manganese steels is their extreme sensitiveness in heat treatment, calling for skilled handling.

In addition to these varieties there is the interesting *Carbonless Silicon Steel*, used in the making of electrical transformers, and known as low hysteresis steel. It is more magnetic than the usual iron employed in electrical work, reduces losses arising from eddy currents, and thus saves also in copper windings in such apparatus.

Silico-manganese steel has been used for the making of gear wheels in situations of great stress, and also for the making of springs.

Hadfield's straight silicon steel, of high magnetic permeability, consists of iron alloyed with from 2·75 % to 3·25 % silicon. Carbon, manganese, sulphur, and phosphorus are eliminated as far as possible.

The thermal treatment for this steel is, first, heating to about 1,950° F. and cooling quickly, reheating to about 1,380° F. and cooling slowly. A third treatment at 1,475° F. is recommended.

A useful gear steel is specified as follows :—

Silicon	1·50 %
Manganese	0·60 %
Carbon	0·44 %

The critical ranges of this steel are about Ac 3, 1,560° F., Ar 1,410° F.

CHAPTER XI

TOOLS AND THEIR STEELS

THE two ranges of steel used in the production of tools are the various grades and qualities of carbon steel, and the widening range of alloy steels.

The carbon steels cover a great deal of ground, from tools used for cutting substances as soft as wood up to tools adapted for the machining of the most refractory alloy steels themselves. To a great extent a carbon steel is mainly composed of pure soft iron, carrying a proportion of carbon. The cutting property of the steel and its hardness depend upon its carbon content, the iron itself acting as a matrix or carrier. A very limited percentage of carbon will suffice if the material to be operated upon by the tool is of a soft nature. As the hardness and toughness of the material increases, so must the carbon content of the steel increase.

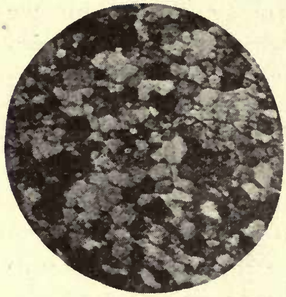
There is another quality in steel which is not so obvious, and it has more reference to the base of steel than to the compound itself. A "low grade" of steel, in point of "quality," may be impregnated with carbon to a high degree; but it may be a poor product, not capable of standing up to the task of cutting refractory materials. In other words, the cutting carbon is there, but the matrix which presents it to the work is inefficient, and the edge breaks down. We here touch the matter of the origin of the iron, which is the beginning of steel. If the ores used as the base of the steel are not of a certain quality, no after treatment can invest the product with the superlative qualities of good carbon steel. For centuries the iron ores and charcoal irons of Sweden have been most highly esteemed for the manufacture of fine steel; so that when we know that a steel is produced from these ores, by the skill so highly developed in Sheffield, we may confidently expect the best of service from the tools formed from this material. A high degree of cutting quality in a steel may be secured by the use of the best ore iron in its manufacture, allied with a very moderate percentage of carbon. It must not, then, be forgotten that a high-carbon steel is not necessarily a good steel.

But steel manufacturers are usually cautious in this very matter. They seldom do associate low-grade ore iron with high carbon, but rather tend to the opposite, and, as a consequence, a high carbon steel is in most instances associated with high cutting quality.

Grade, Quality, Temper.—The carbon steel maker generally catalogues his productions under the designation of "temper," really meaning grade, and by possible inference quality. But the word "grade" should really be confined to its reference to the origin of the iron and the care expended upon it in eliminating impurities, and its combination with the necessary carbon. The highest grade should be beyond question the best that can be made in every case, whether it be of high or lower carbon "temper." This highest grade steel is used for cutting, screwing, punching, and die work, in which the first cost is a comparatively unimportant consideration. A lower grade will answer every requirement for scores of other cutting and pressing operations, for various reasons, better than the highest.

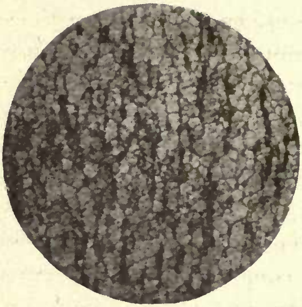
For the moment we must postpone consideration of the undoubted advantages of the newer alloy steels and confine ourselves to the field of carbon steel, in its different grades and tempers.

When the steel-maker labels his bars Temper I, Temper II, and so on, he generally means carbon content first and second. With regard to the word "grade," its use has rather fallen off of recent years, since the battle between the carbon steels and the alloy steels has promised the partial extinction of the former. One consequence is that at the present time the general quality or grade of carbon steel is distinctly higher and more uniform than it has ever been. There is still another reason, which has reference to the difficulty of certifying, by analysis, the origin of the ore from which a carbon steel has been made ; while the constituents of the later alloy steels can generally be ascertained beyond question, and are quite patent. It is said of a fine Sheffield carbon steel that it has "plenty of backbone," but what



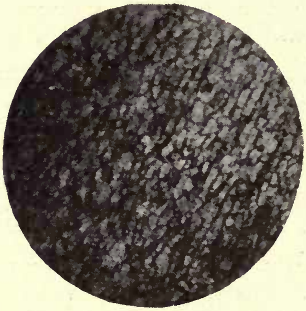
× 500.

Fig. 104.—Approximately pure iron (ferrite), carbon 0·06.



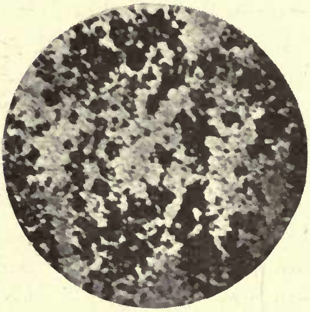
× 500.

Fig. 105.—0·08 % carbon, hard drawn wire and annealed. Nearly pure ferrite.



× 500.

Fig. 106.—0·08 % carbon steel, partly wire drawn.



× 500.

Fig. 107.—Raw open-hearth steel, carbon 0·28 %, weak structure

× 75.

Fig. 108.—0·49 % (overheated) carbon steel. Ferrite (white), pearlite (dark).

× 75.

Fig. 109.—Steel overheated, above 2,000° F.

this backbone really consists of cannot be quite put into words, for it really means the highest grade of ores and the purest iron as a base of operations.

Unfortunately, the word "temper" has drifted of late into two almost different meanings. The steel-maker means, roughly, carbon content. The tool-maker, on the other hand, takes it to mean, and rightly persists in using it as, degree of hardness in his productions. There need be no confusion here if the steel man is left in sole possession of this word as applied only to raw steel, the word "raw" (or untreated) meaning steel as it leaves the rolling mills.

At the present stage of technical knowledge of steels, there is one point upon which the tool-maker should be very emphatic in his demand for full specifications. Steel-makers arbitrarily label their grades as they please, and everyone in a different way, using the word "temper," as already described, with no mention of percentage of carbon, manganese, sulphur, and phosphorus, the last two being undesirable impurities, difficult to eliminate. No steel should be bought simply under the grade and temper number. All stock should be accompanied by full, accurate specification, which can be given generally within a small percentage —*absolute* accuracy cannot generally be guaranteed, especially in machinery steels and the cheaper grades of tool steel, a "working margin" must be allowed.

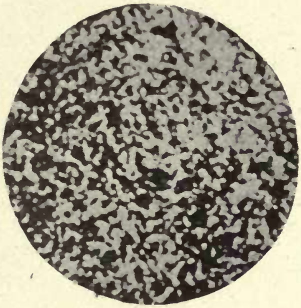


FIG. 110.—Overheated steel reclaimed by long anneal.

Crucible Cast Steel.—This is steel of the highest quality, of the carbon variety. It is distinguished from what is known as open-hearth steel by the greater care taken in its manufacture throughout. Open-hearth steel may be regarded as more adopted for machine-part manufacture than for tools, notwithstanding a large carbon content. The chief matter that concerns the tool-maker, after having assurance that his steel-maker is of good repute, is the selection of a suitable carbon content in crucible cast steel for his particular purpose. And to some extent he may rely upon the steel-maker's advice in choosing, when any question arises that he cannot settle for himself.

RANGE OF THE CRUCIBLE CAST STEELS.

Percentage Carbon.	
0·50	Best machinery steel, or crucible machinery steel.
0·60	Hot forging dies, rivet headers, hot swages, fullers.
0·70	Hot sets, drawing tools, general forge tools.
0·80	Cold sets, riveters' tools, anvil chisels, anvil dies, large and small hammers, stone-working tools, vice jaws, shear blades, large mandrels.
0·90	Blanking dies, punches (cold), cold wedges, hand chisels, cold drop dies.
1·00	Spring steel, cutting dies, rock drills, large swaging-machine dies, drifts, large reamers, mandrels.
1·10	Finer spring steel, fine punches, large screw dies, taps, wood-work machinery form-cutters, saws, picks, milling cutters, slotting cutters, end mills, inserted mill blades, anvil faces, fine vice jaws.
1·20	Drills, flat or twist, screwing dies, fine taps, edge tools, knives, watch-case dies, silversmith's rolls, files (large), brass-turning tools, ebonite-turning tools.
1·30	Files (small), fine cutting dies, wire drawing dies, watchmaker's tools, fine cutlery, razors, lathe and planer tools, relieving and backing-off tools.
1·40	Turning tools for refractory work, hard duty drills, heat-treated armour-plate tools, hard roll turning.
1·50	Chilled roll and corrugating work, deep rock drill points.

Engineers' Small Tools.—The above line of tools call for a skilful handling throughout their heat treatment. While a proportion of them is produced from high carbon steel, a great many lines are now made from the alloy steels of recent development.

The former series of tools are amenable to treatment more or less familiar to working engineers ; simple treatment carried out easily at the forge or blowpipe, and elaborated in description in working mechanics' manuals.

The latter series of tools, the treatment of which forms the subject of controversy or discussion at almost every meeting of mechanical engineers, are not yet as well known

Colour Tempering.

Tools and Materials

Degrees of Heat.		Soft End of Scale. Colour.	Remarks.
Fahr.	Cent.		
570 to 610	299	Deep blue	Watch and clock and machinery springs, wire gongs
560	293	Blue	Heavier springs, small arms springs, circular wood saws
550	288	Deep purple	Wood saws, planer cutters for wood anvil tools, meat saws
540	282	Lighter purple	Riveter's tools, anvil chisels, anvil dies, chisels for wood, hard saws, punches for soft metals, soft material cutters.
530	277	Light purple	Chipping chisels, carpenters' tools, the soft press tools
520	271	Deep brown	Milling cutters for soft metals, cutlery, instruments, axes
510	266	Lighter brown	Wood-working tools in general
500	260	Dark straw	Drilling tools in general, augers, metal saws, drawing dies, press dies for soft metal punches, blanking dies, drills, lathe and planer tools, milling cutters, chipping chisels, hard punches, stone drills
480	249	Yellow	The harder grade of metal-working tools, taps and screwing dies, drills, milling machine tools, turning tools, knives, razors
470	243	Pale straw	Surgical instruments, small cutlery, ebonite and ivory cutting tools, heavy duty turning tools and drills, hard grade dies and punches, hard screwing equipment, drifts for heavy duty
450	232	First change	Extra hard tools of every kind ; first grado below glass-hard
		Hard End of Scale.	

in every engineer's shop. The treatment required is not yet a familiar matter, like the hardening of carbon tools.

For the reason implied in each of the above premises it is proposed to set forth in brief form not only the essentials of the handling of carbon steel tools ; but to offer a more extended review of the heat treatment of the various kinds of alloy steels—treatment which is of so recent a growth that it is largely unknown outside a few establishments.

Carbon Steel Tool Temper.—Before the novice makes a beginning in the treatment of carbon steel, he must be armed with at least two things: first, a thermometer suitable for temperatures at least as high as 650° F., which is above the highest tempering heat of all cutting tools used for metals; and secondly, a chart of the various degrees of heat applicable to different tools, embracing a word description of the colours thrown up by oxidation upon the surface of bright steel at various known temperatures. It is no longer disputed that these interesting oxide of iron colours bear a definite relation to known fixed temperatures, but what does remain matter for reasonable differences of opinion is the definition in words of what a particular colour really looks like. What would be simply a purple colour (540° F.) to one person is promptly named a light purple (530° F.) by another, and so on. It is, of course, all wrong to use these colours at all in scientific, or even merely accurate, steel treatment; because, no matter how carefully a chart may be made, or how minutely explained, a description of a colour cannot be given within, perhaps, 20° with any chance of accuracy. Apart altogether from the difference of opinion as to what constitutes a blue or a light blue, it must not be forgotten that a considerable percentage of observers are either partially or wholly colour-blind, so that all persons do not see alike.

Thermometer or Not?—But however this matter may be argued, it is beyond question that the colour test of temper can become *an individual acquired art*, accurate, almost as a thermometer to that individual alone, but not to be transmitted by written or spoken word to another person with any degree of certainty. The personal equation is far too much, and is apt to lead to many faults. Once educated into the significance of colour in tempering, a particular operator can work by means of it as his only guide, to a surprising degree of accuracy. It being, then, for him, quite unnecessary to trouble with the handling of a thermometer, he soon learns to carry on without it for his particular purpose of determining the hardness of steel tools.

But for a novice, before he has "tested out" his impressions of colours, from a chart, upon the steel itself, it is folly to rely upon word description of colour as it stands for degree of hardness. He should use his thermometer and be assured.

It should be stated here that colour-tempering is falling into disuse, except in the case of odd tool handling at the forge or in the blowpipe, and in cases where the later immersion-processes of tempering cannot be employed. In tool manufactories where thousands of tempered tools are produced daily, colour tempering would soon land a firm in a great unnecessary expenditure of labour and time, besides producing results destructive of standardization.

Precision in the Treatment of Steel.—A few observations of Mr. S. N. Brayshaw, the well-known steel-treatment authority, are particularly opportune here. He says: "Recent research has shown the great importance of treating steel with accuracy and precision. Slight errors in treatment may render potentially good steel useless, and the best results are only obtainable by the introduction of better methods for the observation and regulation of temperature than have been generally used in the past. Even when the old methods produced good results, they were incapable of consistently giving the best results, and in this connection the difference between good and best is very great. There is frequently a considerable range over which reasonably good results may be obtained, but the best results often demand more precise treatment. When, however, this precision is attained, the efficiency may be enormously increased beyond what was formerly accepted as good."

Heat Treatment of Tools.—The raw steel from which tools are fashioned is supposed to be in a workable condition. This implies that it is not too hard for cutting and turning. High carbon steels are, however, much more difficult to saw and turn than mild steels. As the bars or plates leave the rolling mill there is always a hard, partially chilled skin left upon it, which often proves troublesome. For this reason the steel works are always willing to anneal both mild and high carbon steel bars at a cost slightly higher than the ordinary price. The bars are "coffined" in long, channel-like annealing boxes, packed in ash or lime, and left at red-heat for several hours, cooling out in the "coffin" slowly. It is well to have this done on fairly large lots of stock, because the cost at the works is small, and very much smaller than it could be done for in a tool shop, while the advantage of saving of time in cutting up is considerable.

Forging.—Steel to be forged need not be works-annealed. We may here state, without fear of contradiction, that tool steel is more extensively spoiled in the process of forging than in the subsequent operation of hardening. The blacksmith's forge system of working is chiefly to blame for this condition of things, and this is now so generally recognized that the use of furnace heating is superseding the old bellows smiths' hearth.

In his learned paper, read before the Iron and Steel Institute, March 27, 1919, Mr. S. N. Brayshaw says: "I wish mainly to direct my remarks to showing how profoundly carbon tool steel is affected by heat treatment prior to hardening. Perhaps it will some day be considered that treatment before the hardening is as about as important as the hardening itself, and should receive equal care and thought."

These suggestive remarks refer to forging heats and to want of care in so-called annealing, unskilfully carried out.

The same authority continues: "Now we return to the expression that the steel must not be heated 'too quickly.' I submit that what is meant is that steel must not be overheated on the outside. When the steel is being treated in a smith's fire, or an atmospheric gas furnace of any kind, it is impossible to heat it simply without heating the outside beyond the desired temperature, and this fact appears to the ordinary man like an inevitable accomplishment of swift heating. It is easier and more natural to give an instruction not to heat swiftly than to give a warning against overheating the surface. The fact that swift heating, as ordinarily carried out, is objectionable has naturally led to the general belief that swift heating is in itself an objection. I submit that if it be possible to heat swiftly without the least overheating on the surface, there is no objection to such a practice. . . . But the swift heating of a hardened tool might crack it, as we might readily understand, and in the case of annealing tools a warning against swift heating is not out of place."

Mr. Brayshaw's reference, in the preceding remarks, on the practicability of rapid heating, without endangering the quality of the steel, has special reference to the heating in a fused salt bath, and by no means to a smith's fire or blowpipe.

The series of photo-micrographs shown in Figs. 111-116

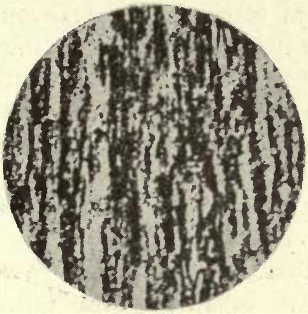


Fig. 111.—Hammered 0·45 carbon steel. Savoia

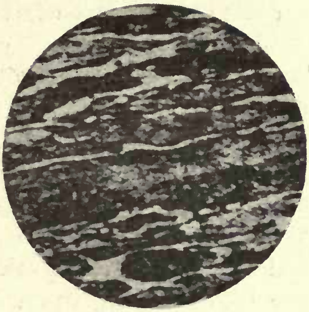


Fig. 112.—Cast steel forged at too low heat, showing distortion of "grain."

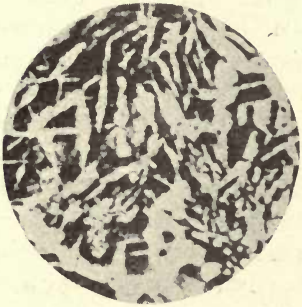


Fig. 113.—Fracture of cast-steel ingot. Tensile strength 77,000 lb., elastic limit 50,000 lb.

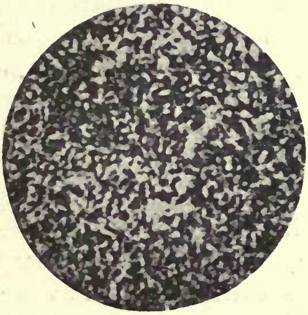


Fig. 114.—Cast-steel ingot (forged). Tensile strength 85,000 lb., elastic limit 50,000 lb.

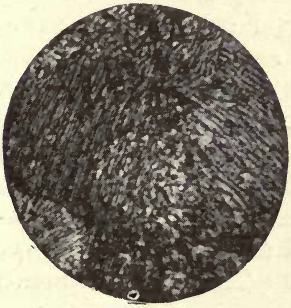


Fig. 115.—0·85 % carbon steel, wire drawn and annealed.

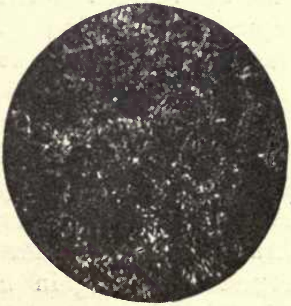


Fig. 116.—0·85 % carbon steel, wire drawn, highly compressed.

are especially instructive to the tool forger, Figs. 115 and 116 exhibiting great compression and refinement.

Steel cannot be forged without the aid of heat, but this degree of heat should never exceed what is called a full red heat, which, by pyrometer test, is equal to 1,375° F. The fine crystalline structure of the steel is apt to be coarsened, and the steel ruined by a heat far below what we call a white heat. When a tool is slowly heated to a full red, it should at once receive treatment upon the anvil, the blows falling upon it being kept up until a dull red is reached below which it is not advisable to continue forging. A slow reheat is in order if the first gives insufficient time to properly shape the steel.

"Treatment on the Anvil."—Many skilled tool-makers, who have a reputation for producing turning and planer tools of superlative quality, owe their success chiefly to what is known as good treatment on the anvil. It is well recognized that the cutting and lasting qualities of a tool depends greatly upon the hammering it receives upon the anvil. The effects of forging in influencing the specific gravity of steel do not appear to have received adequate attention at the hands of experimenters. But that the density does increase there cannot be much doubt.

Another peculiarity is that a rather dull red-heat is the condition selected as the best time to compress the "grain" of the steel, and not at a full plastic heat. So strong is the belief in the efficacy of this, that many tool forgers continue to rain blows upon the steel after its plasticity has departed; and there is risk of damaging it by splitting. In following up this idea, it is undoubted that a tool that has been much worked up under the hammer is greatly superior in lasting qualities to a tool simply cut out of the raw steel. *But no heat above a red-heat is permissible,* and the single heat is more effective than multiple heating.

Turning and Planer Tools.—In the case of this supposed tool we have in mind an ordinary turning or planer tool for metal, and we may now follow it to completion. After shaping upon the emery grinder, where it must not be overheated, it is ready for hardening and tempering. The heat required will again be a red-heat. The water quench must be clean.

The tool is taken from the fire or furnace while *its heat is rising, and not falling.* No carbon steel article should be hardened during a falling heat. It will not do to heat up the tool by inadvertence so high that, before quenching, a pause must occur to allow it to arrive at a safe quenching heat. An excess heat must not be put into it at any part of the process. The quenching is simple, but still most important. The point of the tool, to a depth of perhaps half an inch, is slowly dipped into the clean water and two motions imparted to it—a vertical motion to a slight extent, to avoid a horizontal line of hardness, and a lateral motion to a considerable extent, to ensure its remaining in *cold* water. All this occupies, perhaps, five seconds, and the tool is hardened.

In the case of turning and planer tools the necessary tempering may be given without reheating the tool. The heat in the stem portion of the steel is utilized for this purpose as follows: As soon as the point is hard, or has lost all colour and appears grey or black, it is withdrawn quickly from the water; a long strip of the point rapidly rubbed perfectly bright and clean by means of a piece of emery stone, and a close watch kept upon the bright area. The back-heat now creeps towards the point, which will be seen to colour, and when this colour appears to be of a medium straw tint, the operation is quickly brought to a close by quenching the tool entirely. The complete operation does not usually occupy more than a minute of time, so that prompt decisive motions must control it. It is usually a mistake, in the case of turning and planer tools, if we except parting or cutting-off tools, to quench the whole tool and draw the temper down by reheating. To be effective, the reheating should come from the back towards the point, and it will be clear that, if the tool has again to be put into the fire for tempering, it should be the stem end that must be heated. In this case the procedure is the same as before, except that only a moderate degree of heat need be applied to the end of the tool. The heat must creep up towards the cold point; it must not be applied to the point itself, direct.

Chiselling Tools.—We have here tools that, while they must possess a good degree of hardness, must also withstand percussive action or hammer blows, so that rather more skill is called for in preparing and hardening them.

Chipping chisels are generally made from bar steel of the carbon content specified in the table given in this chapter. The bar being of the shape and dimensions required, it is only necessary to cut off a sufficient length to form a tool. Before forging the point to shape the blank should be brought bodily to a good red-heat, uniform all over, and then entirely quenched in *oil*. When withdrawn it should be nearly hard enough to resist the action of a file. This preparation will provide a stiff stem that will not batter out of shape under the hammer in use. The forging is carried out at a red-heat, keeping all but two inches of the end out of the fire. The hammer should do its work with light blows in one heat, keeping up until all red has departed. Overheat must be guarded against. After grinding to form, it is hardened in water, heating 2 in. of the end and plunging about 1 in. or less. Vertical motion must be kept up to avoid a distinct line of hardness. This latter precaution is essential in a hammered tool. The colour tempering is carried out with the hardening heat, brightening the end with the emery stone as before. Reference to the foregoing table will show that chipping chisels should not be left as hard as lathe tools.

Rivet-setting Tool.—This is usually a cupped tool, the cup being the size and the shape of the rivet-domed head. Any attempt to harden and temper this tool in the usual way, by dipping into water, is bound to end in failure, since the edges of the cup strike the chill first and become dead hard before the water touches the roof of the cup. The water within the cup is immediately heated up, and the centre of it turns to steam, which prevents chilling the interior of the cup. An attempt to put this rivet set to work ends by the rim of the cup cracking away from the body of the tool.

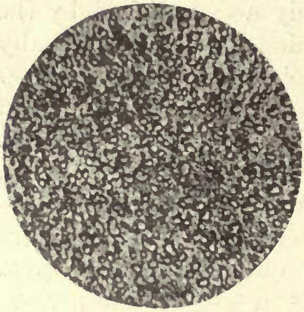
A rush of water can be made to enter the cup by holding and moving the tool rapidly in a horizontal plane. This plan can be made successful if there is plenty of horizontal surface to sweep the tool across, and a fair degree of uniformity and hardness can be thereby secured. A still better plan is to simply bring the cup under the water-tap and to suddenly turn the water on, so striking the interior of the cup first. There is no steam here to impede the action. A third plan is to bring the cup over a vertical jet of water. The object aimed at is, of course, the chilling, first, of the dome of the cup, since the rim is so exposed that it hardens all too easily.

Tempering a rivet set is not easily accomplished by the back heat, as in the case of a turning tool. It is usually most convenient to cool out the tool entirely and to draw the temper down to the colour required in a molten lead bath (p. 296), or less troublesome in a salt bath (p. 117). The rim of the tool should be polished and quite clean, the cupped end being keep upwards in sight. After the colour has shown itself, usually a deep straw tint, the tool should be quickly cooled out in oil. It may appear unnecessary to detail the precautions, usually of an obvious nature, that should be taken to ensure a good degree of success in hardening and tempering. They can only be acquired by actually doing the work ; but there is one very useful matter to remember in special reference to colour tempering : in brightening the hard steel of any kind of tool or part, in order to provide an area for the play of colour oxidation, it is not enough to merely clear a patch near the end—more than one area should be cleared upon a round tool. But an observation *path* should be cleared, stretching in the direction of the stem of the tool, with the object of *tracing the creeping colour towards the hard end.* In this way assurance will be had that the rear of the tool is softer than its "business" end, and the extent and degree of this softness will be clearly apparent.

All tools that are to be subjected to the hammer action should, before they are hardened at the operative end, be toughened throughout by heating to a fair degree of red and cooling out in *oil.* This treatment will prevent, to a great extent, the usual burring over and splitting of the hammer end, which is the usual cause of failure in percussive tools.

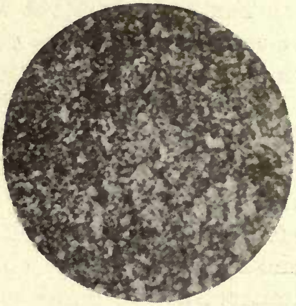
Drills.—There are, roughly, the two leading varieties of drills—flat drills and twist drills. There are also fluted drills—a very excellent shape, and twisted steel drills. Rock drills are usually simply revolving and percussion chipping chisels, and may be treated as such. The flat drill is usually a short pointed drill, and may be treated as a chisel, but left harder at the point. The twist drill and the fluted drill, and the twisted drill—made from a flat bar and twisted—may be taken as of one kind for hardening and tempering purposes.

Except in an emergency, drills of this class should be treated in one of two ways. An ordinary gas-fired tool



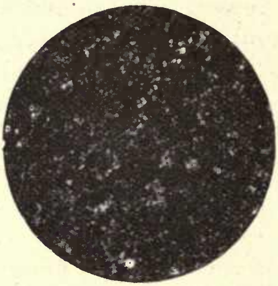
× 100.

Fig. 117.—0·85 % carbon steel, well annealed.



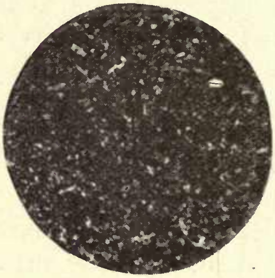
× 100.

Fig. 118.—0·20 % cast steel quenched at Ac 3.



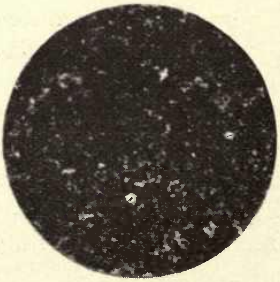
× 250.

Fig. 119.—High grade file once hardened.



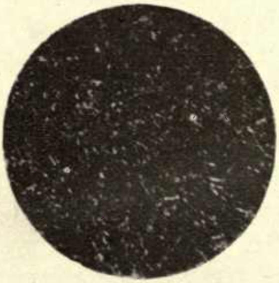
× 250.

Fig. 120.—High grade file twice hardened



× 250.

Fig. 121.—Fine hard high carbon steel, water quenched



× 250.

Fig. 122 —Fine hard high carbon steel, twice hardened.

furnace may be made to answer perfectly; or a molten lead bath kept up to about 1,400° F., or a salt bath (p. 117) at the same temperature. For systematic working on moderate-sized drills the salt bath will be found by far the least troublesome. In the case of this group of drills, a considerable length of the whole must be hardened. In twist drills the rule is to extend the hardening to within an inch of the termination of the twist, so that the drill may be ground away, as necessary, for its whole useful length.

Twist drill hardening demands a uniform degree of heat, or nearly so, from one end to the other of the grindable zone. This is not quite easy to manage in either a lead bath or a salt bath. In a tool-heating furnace it is a comparatively simple matter, because the drills lie horizontally. In a lead bath, used for this special purpose, the heating jets should not strike the bottom of the pot only, but be arranged around its walls, nearer the bottom than the top. The same remark applies to the salt bath. If a bottom heat only is used, the bath will only be fit for use in the case of end-hardened tools. Bottom heating necessitates stirring up, especially in the case of lead, in order to distribute the heat.

Given an efficient heating equipment, a slightly higher degree of heat, 10° to 20°, at the bottom is an advantage in the case of long drills. The business end of these can always permit of being hardened to a greater degree than the upper end, which must be tougher, to withstand the strain upon the point in drilling.

This group of drills must be quenched in a perfectly vertical line, but at the same time the lateral movement must be considerable, to ensure the cold quench continuing to surround the drill. Cold oil should be used in preference to water, and for this reason a slightly higher heat should be given to the drill in the furnace or bath than is used for water quench. No back heat is used for tempering. Colour tempering cannot usefully be brought into service for drills. It is much better to temper them in a high flash-point oil, heated to about 460° to 480° F., in which they may be left for several minutes, cooling off in oil.

The group of micro-photographs covered by the Figs. 117 to 122 exhibit the finest grades of carbon steel, starting with a high grade fully annealed.

File Test.—An experienced hardener seldom has to use a file to test the hardness of his work. He knows beforehand how a given carbon steel will turn out under the heat and quench operation. It is, however, useful to state, once again, that the hard steel will resist cutting by the file absolutely, while the tempered steel may show a suspicion of yielding, dependent upon the quality of file used.

Drill Manufacture Preparations.—A twist drill appears a simple manufacturing proposition, but if certain preparations of the material to be used are not made it will be found a difficult matter to produce *straight* drills in quantity.

Drills are generally made from die-drawn bars, of a high carbon steel. The bars are either "parted" or cut up into lengths in a hollow mandrel parting tool automatic lathe, with wire feed, or in a back-saw machine with wire feed, so that this part of the work is simple and mostly automatic. In the parting-off operation in the lathe a cutting-off tool is so shaped that it performs two operations, separates the steel and shapes the conical end of the bar.

A quantity of the blanks are charged into the furnace packed in line in an iron box, and annealed at a dull red-heat (1,175° F.) for eight hours, being allowed to cool out with the furnace overnight. The blanks are now in a ductile condition, favourable for milling.

The next operation is examining for straightness. For this purpose a hole in a block of steel as thick as the length of the drills reamed quite straight and through the block is selected of the exact size to admit the blank, and no larger. If the blank can be pushed through this, it is passed as straight. If it fails to pass, it is thrown aside amongst others that are not straight. When a sufficient quantity of these "faults" are ready they are heated up in bulk in the furnace and straightened by being quickly driven through a hole in the block, a shade larger than the one already used. The larger hole, which need only be from $\frac{2}{1000}$ of an inch to $\frac{5}{1000}$ of an inch over the size of the first, is intended to receive the expanded drill blank. The test-plate is itself, of course, kept at a fair heat (500° F.), so that it does not harden the red-hot blanks being passed through it. Blanks that leave the test-plate are straight, and should still be a dull red upon emerging. They drop into hot ash or lime, and cool slowly. If they are free from all colour upon emerging, the block is too cold or the blanks are not hot enough, and the operation may have to be repeated. They should not require to be again annealed. The blanks are now ready for the milling and other machines.

An alternative method of straightening consists of a pair of planed rolling plates, in constant motion, between which the hot blank is rolled back and forth.

Machine-swaged drills may or may not require to be re-annealed to relieve swaging stress. If the swaging machine is accurate, relief of strain should not be necessary. No heating up of blanks after they have been partially machined is permissible unless it be either in the lime or salt or lead bath; otherwise the finished surface will be defaced.

Hardening Milling Cutters.—If milling cutters are heated in a gas tool furnace, certain precautions must be taken to obviate the risk of destroying the keenness of the edges, especially in the case of fine tooth cutters. A muffle containing a small quantity of charcoal may serve, but a still better plan is to use the floor of the furnace, and make the entrance door serve as a flue. This is the working principle of the excellent Richmond Tool Furnace. All the products of combustion must leave the furnace by its entrance door, thus ensuring the prevention of air entering and consequent oxidation. The tools are heated in a gassy atmosphere, which, to an almost perfect extent, protects their finer edges at a red-heat.

Oxygen exclusion, hinted at above, is a most interesting and important condition. It is constantly required in the treatment of steel in the furnace. A muffle is a fireclay or iron case placed within the furnace; its object being to enclose the articles being heated, and so protect them against direct contact with the air and the hot gases of the fire. But unless the mouth of the muffle be sealed, it is useless for that purpose, and will not prevent oxidation. Indeed, if the muffle mouth be exposed to the atmosphere at all the muffle is nearly useless as a means of excluding oxygen unless it contains a flooring of charcoal. Whether a muffle be used or not, if the space surrounding the steel be *already fully occupied* by an atmosphere of a gaseous nature containing no free oxygen, the exclusion of fresh oxygen is easily prevented. This is frequently carried out in furnaces by providing a means of supplying an increased proportion of gas during the final heat up, which suffices to absorb any free oxygen that may find its way into the chamber. This is easily effected by diminishing the proportion of air in an atmospheric burner furnace. But more frequently it is effected by simply *providing no top flue* to the furnace and utilizing the entrance opening as a flue. This is done in the case of a plain oven furnace, in which the work is placed upon a fireclay or iron tray directly above the burners. There is no opening above the flames, save through the entrance, which is left practically open for this purpose. Here we have the *hazy reducing atmosphere* so useful in using up the oxygen of any chance air that may find its way to the work. It is the atmosphere that is so beloved of experienced steel men, who know what beautiful, clean, effective work can be done in it. An extension of the same idea is carried out in many furnace designs by providing for a *pressure* of these products of oxygen-free combustion to surround the steel.

These remarks are rather out of their proper sequence, but the importance of the subject of heating finished steel work of the nature of milling cutters and the like in a perfect manner must be our justification.

Hence, bright finished work that is of slender or sharp form should never be heated up, in free contact with the atmosphere, while there are so many means of prevention available. So far, we have only spoken of furnace heating, and for work that must not be left bright surfaced there is probably nothing as good. But the salt bath and the lead bath should not be forgotten. The former especially appeals to the bright steel-tool hardener, for the reason that by the use of ordinary care an oxidized surface can be avoided altogether. It can also be obviated by using the lead bath, taking the precaution of previously painting the steel surface with the bone-black, linseed oil, and common salt mixture before immersion. In the salt bath already described, the work leaves the bath with a film of adhering salt, which freezes upon striking the quench and falls off.

Water or Oil Quench.—Continuing our consideration of the case of milling cutter hardening, slender work of all kinds should be hardened in oil at about 1,250° F., heavier work in water at 1,175° to 1,200° F. A good high-flash mineral oil is probably the least objectionable. Reference to the chapter devoted to Quenching will clear up doubtful points as to maintaining the coolness of the oil.

The necessity of quickly removing work heated in an open furnace to the quench need not be emphasized, in order to obviate long exposure to the oxygen of the air. Cylindrically shaped cutters should be dipped with the axis in a vertical line—not plumped in, but slowly lowered, accompanied by a lateral movement in a circular path to ensure fresh quench surrounding the work. Heavy work in water will hiss, or " sing " ; as soon as this singing noise ceases the cutter should be taken quickly to the oil tempering bath and fully immersed. This latter move will generally obviate the risk of cracking.

Cracks.—These are rare in oil hardening. They are comparatively common in water hardening. If a steel persists in cracking, and it is of fair quality, the fault will be in one of two directions : 1st, overheating before quenching, and 2nd, sharp V corners, as at the root of teeth, and, more particularly, the corners of *square keyways*. These keyways should be avoided wherever possible, and D keyways used instead. We have never seen a crack originate at an arch keyway, but many due to square keyways. It is a very good rule to *always* fill up the bore and keyway of a cutter with fireclay, mixed stiffly and tightly packed in. This precaution is also in order in reference to thin disk cutters, or other parts having holes.

Unequal Hardening.—Taking the case of a milling cutter of a moderate size, for example, 3 in. in diameter and length, the simplest and usual procedure, according to equipment, may be as follows :—

Plug up the bore and keyway with stiff fireclay and allow to dry slowly. Tie around the cutter lengthwise a loop of strong binding wire, forming a hooped end for lifting purposes in order to avoid using any kind of tongs. Heat it up in an oxygen-free atmosphere to a red-heat, allowing plenty of time for this operation. Lift out by means of the wire loop, and dip vertically, slowly, in water not colder than 70° F., moving it up and down and to and fro for a few seconds until it ceases to sing. Transfer to hot oil at 460° F. Allow to temper fifteen minutes, and cool off in cold oil. This treatment may, and frequently does, for this size of cutter produce fairly good work, but it will not produce the best work. The reason is that one end of the teeth will frequently be harder than the other. The harder end will be the one first quenched, given equal heating from end to end. Leaving out of consideration the mode of heating, and assuming that it can be made quite uniform, the too rapid hardening of the end first quenched can be very simply retarded. A disk of steel the same size as the cutter should be attached by the lifting wire to the lower end, heated with the cutter, and quenched with it. This will be found to retard the action of the quench sufficiently to ensure equal hardness throughout the length. One disk only should be used, and it should be bound firmly against the end.

It is sometimes desired to harden the bore as well as the body and teeth. In this case considerable risk is taken in the matter of cracks. Square bottom keyways lend themselves to the starting of cracks. The arch keyway is, as already mentioned, a remedy for this tendency. If a bottom disk is used, it must be drilled to the size of the cutter hole, or slightly larger. The result of quenching should be hardness throughout. But it will generally be found that the bore will be slightly out of round, and these cutters have frequently to be put upon the internal grinder to true up the hole. This bore-hardening is generally followed by bore-tempering, by placing the cutter upon a red-hot rod of iron and slowly revolving it until an even colour is secured around the teeth. The cooling-out should be in warm oil.

Pack-hardening—that is, heating up in a box of powder charcoal—is commonly used for the smaller cutters, and especially for thin cutters. The latter are very apt to become deformed, as to flatness, if carelessly packed. They should be firmly pressed down upon a bedding of the charcoal and well covered. If a quantity of disk cutters have to be heated, they may be arranged in the firing-box in layers, with about an eighth of an inch thickness of charcoal between each pair. When the box is drawn from the furnace, after ample time has been given to it—from one to two hours—it must rest upon a hot plate to prevent cooling of the lowest layers. As the disks are hooked out for quenching there should be a very uniform degree of heat distributed throughout the batch, the lowest layer being of the same heat as the highest.

The charcoal powder used for packing can be made much more reliable by mixing it with any of the commercial case-hardening compounds. The best material is charred leather powder. It should not be forgotten that if a box be packed with charcoal in this way, and if it should be kept in the furnace for hours, the upper part of it will, being exposed to the air, burn into ash, and cease to act as protection to any steel near the surface. To prevent the risk of this, a box of valuable cutters is worth the trouble taken in providing an effective cover. The cleanest and most handily made is a thick tinplate or thin sheet-iron cover, which will serve through several operations. Failing this, a layer of sand, 1 in. thick, forms an effective protector. The plate cover can be kept flat upon the mixture by dropping a length or two of heavier iron upon it, which will prevent its buckling under the heat.

Water quench is not to be recommended for disk-cutter hardening. If it be desired to use water, a broken hardening quench can be made by pouring oil upon the surface of the water to a depth of half an inch. The cutter passes through this before touching water, and the shock is lessened. Absolutely vertical dipping is essential. Rain-water should, if possible, be used. No tongs must be used in handling disk cutters. They should be lifted by means of a long pointed and hooked rod, caught in the bore of the cutter.

Screw Slot Cutters.—These are usually about three inches in diameter. They vary in thickness from about one-thirty-second to one-eighth of an inch. They are made from a good, but not the best, carbon steel. The thick saws will generally harden without buckling, but not the thin saws. Before they are hardened, they should be annealed at a red-heat for an hour, and while still red-hot passed through a "flatter," or foot-press fitted with a pair of planed plates, kept hot, which rapidly clamps the blanks, one by one, and corrects any buckling that may appear. It is seldom that the disks will again change from the perfect plane during the reheating and quenching. Still another "flatting" plan is to take a few gross of saws and thread them upon a shaft screwed at each end. Two thick plates serve as clamps, and the whole is screwed up sufficiently to remove all buckling. This should be done before the disks are toothed. The block of disks is now kept at a red heat for an hour, and permitted to cool slowly. When released, they should be flat, and will remain so. No attempt should be made to *harden* disks in this way.

For heating these thin plates for quenching a salt bath will be found extremely useful. A dry kind of quench is often used for flatted disks, but it cannot be used for blanks heated in salt. It consists of the foot-press and plates already spoken of, and two operators work it; one to bring forward the disks from the hot box, and the other to operate the press. If this press is not fitted with heavy plates, it will not harden many disks before it becomes too hot. The plates are kept smeared with oil.

End Mills.—These are milling cutters formed upon a tapered stem that fits into the socket of the milling machine, or into the drilling machine if for vertical operations. It is obvious that only the operative end need be hardened and tempered. Of the same class of tool is the T-slot mill, which has a wide operating end and a necessarily thin shank just behind it. As these tools are required to run true in the machine, heat distortion is fatal in their case. The best way to ensure against this is to anneal the steel well before it is machined. In the case of a T-slotter, not only should there be an anneal before the first turning, but another after the tool is roughed out in the lathe, leaving only a little of the metal to be removed after the second annealing.

No method of heating is so effective in the case of these tools as a salt or lead bath, but in using either of these sources of heat certain precautions must be observed, otherwise cracking is very apt to spoil the tool. Here we are dealing with partial immersion, and the method used in dealing with it is equally applicable to any other form of tool that is only heated throughout a portion of its length.

If a salt bath be used, there will be no trouble in keeping the steel in position. The tools should be well warmed or heated—say in boiling water—before being placed into the bath. In the case of a T-slotter, the active end and also the narrow shank just above it are to be freely immersed, also half an inch of the thick part of the stem. The tool must not be allowed to remain in the melt without motion. *A straight line of heating must be avoided,* just as a straight line of cooling must be prevented in hardening. With this reservation the heating up is a straightforward operation. If the back heat is to be utilized for tempering a T-slot tool, the heating should extend 1 in. and the quenching $\frac{1}{4}$ in. above the neck. The neck will then show the temper colour creeping towards the cutter. In the case of an end mill, this back-heat tempering is generally inadmissible for the reason that, in the case of long flutes, the upper end of the flutes would be soft, while the extremity would be hard. It is generally necessary to cool out end mills all over until they can be handled for brightening, and to effect the tempering upon a red-hot plate; or, better still, in the oil tempering bath. It should not be forgotten that the T-slotter is in a different category, inasmuch as it is necessary to ensure that the narrow neck is left soft, or at least spring colour (blue).

Reamers.—These tools have, generally, five, seven or nine long flutes, extending, in the case of a 1-in. hand reamer, to the length of 6 in. There is usually a stem 3 to 4 in. long. Since these tools, being of such length that they would require a deep lead or salt bath, are not easily handled, they are generally pack hardened, in the usual charcoal charred leather mixture and heated as usual on the gas furnace floor. Uniformity of heat is the important point. A heat of 1,200° F. will suffice for water quenching and 1,250° for oil. Vertical dipping, with lateral and vertical motion, well over the flutes, is mandatory. Reamers need not be hardened through. They are made much more reliable if the teeth only are hardened. This is done by a *rapid quench*, until colour is off, rapid withdrawal, instant brightening and waiting for the required straw colour; then, quick, full quench in cool oil. If this operation is well managed, and not bungled by hesitation, a first-rate tool is the result. The teeth throughout their length will be hard, but tough at the root, and the body will be tough and soft, where toughness is most desirable. Small reamers, having very little mass, are not easily handled in this way. Probably the $\frac{3}{8}$-in. size is the limit downwards.

The miniature reamers are oil-hardened through, and tempered in the oil bath, the colour heat required being about 460° to 480°. They may, being short, be heated by pack, lead or salt bath. The hardness does not extend beyond the flutes.

In pack hardening quantities of these tools, the trouble is always the maintenance of the heat while they are taken from the box, especially if there should be several layers of them in treatment at a time. It is much more convenient to heat them in a wide, shallow lead or salt bath.

Trouble will certainly be met in causing the small reamers to maintain a vertical position in the lead. This is got over by using a ring of iron, in which twelve holes are drilled, and set-screws fitted to them. The ring is held in a horizontal plane by means of a handle of wood, well above the hot lead. The small reamers are fitted into the holes, point downwards and fastened. The whole of them may then be handled as one, and kept quite vertical in the lead, it being a simple matter to keep them in motion to equalize the heat. The same jig is used for the hardening quench in oil. This quench being effected, they are all transferred, still in the ring, to the tempering oil.

In hardening reamers in lead, the pot containing the latter must not depend upon bottom heat only. Lead is apt under this condition to be hot below and a hundred degrees cooler at the top. A ring of gas-jets must be arranged about two-thirds of the height of the walls of the container, as well as at the bottom. Even with an apparently perfect distribution of gas heat, lead must be kept stirred up, and the surface covered with powdered charcoal and dross frequently skimmed off. Pure lead *must* be used, otherwise soft spots, and even pits, may be found upon the hardened tools. The most injurious adulterant is sulphur.

Bright Hard Reamers.—There are several compounds that may be applied to the bright reamer to prevent oxidation on withdrawal from the lead bath. Certainly the simplest of these is a 25 % solution of white cyanide of potassium (dissolved in hot water), into which the reamer is dipped. It must be quite dry before it is immersed in the lead.

If a salt bath is used for heating, the tools will leave the bath bearing a skin of salt, which will fall away upon immersion in the quench.

Spring Treatment.—No spring, except for a special purpose, should be made from a hyper-eutectoid steel—that is, a steel super-saturated with carbon above the eutectoid point, or 0·90 %. Hypo-eutectoid steel, containing less than 0·90 % carbon, will, for many purposes, make excellent springs, and the handling of steels of these moderate carbon contents is more easily carried out. Heavy springs are frequently made from steel as high in carbon as 1·10 %, but the main reason for this lies, probably in most cases, in the difficulty of hardening heavy sections (over $\frac{1}{4}$ in.)

perfectly to the core, which therefore demands a higher carbon content in the portions that are really fully hardened.

Spring hardness is really a high degree of toughness, which amounts to resiliency. It must be clearly understood, however, that this desirable condition cannot be attained except as a sequence of *complete* hardening. No spring temper can be put into steel direct ; it must be heated to the usual degree, quenched, certified hard, and finally sufficiently softened before it will withstand curving and be capable of recovery of form.

Owing to the thin section of steel presented by most forms of springs, the work of heating, quenching, and tempering is by far the most difficult in the whole art of steel heat treatment.

The spring may be a heavy mass that can be normally handled in the ordinary furnace, or, at the other extreme, it may take the form of a watch hair-spring, which is so delicate that the heating-up for hardening has in one process to be effected in a bath of molten glass.

The spring-making operations that call for the best judgment and skill are those involved in production and repetition of work, and effective springs having varying thicknesses in the one spring. But given a systematic procedure, even this class can be handled with confidence. The art of spring production is not in the same advanced condition as the heat treatment of heavier steel ; but as heat treatment of such sections as, for example, automobile frames aims primarily at this degree of hardness, it will be obvious that a spring is merely a toughened piece of steel of a lighter section, and that, therefore, the general heat-treatment methods call for simple modification of the processes practised in general.

The Steel.—Carbon spring steel for heavy sections may be specified as high as 1·10 % carbon, 0·40 % manganese, 0·02 % sulphur, 0·02 % phosphorus. Silicon should not exceed in any case 0·20 %. A far more generally useful spring steel is the 0·90 % carbon variety, with as low a percentage of sulphur and phosphorus as possible.

In the absence of special experience in spring-making from different tempers of steel, it should not be overlooked that many makers specialize in spring steel manufacture. It is well to get into touch with such a firm, submit a sample of the spring or springs to be produced, and to leave the choosing of the steel to them. There are several matters that profoundly influence the performance of a spring that are the special business of the steel-makers only, and their advice is usually of great practical value. Cost is, in this matter, a secondary consideration.

Alloy Steel for Springs.—Of the several alloy steels that are adapted for spring making, the experience of automobile frame spring-makers points to a chrome-vanadium alloy steel as the most easily handled, and as resulting in a spring that cannot be easily broken. For this special purpose, and for all springs of heavy section, which puts the spring to the severest tests known, the chrome-vanadium spring cannot be surpassed at present. The enormous difference between the relative tensile strengths of this alloy and a "best" carbon spring steel is, in figures, as follows: Carbon 130,000, alloy 200,000 lb. per square inch. Hardening treatment for alloy steels is described at page 229.

Taking the treatment of carbon steel springs first, the importance of thorough annealing before curving to a particular form cannot be overestimated. Chassis springs for automobiles are shaped in templets or jigs to definite predetermined forms. This is spring-smith's work, and need not vary in principle from the general practice which has obtained for a century or more, except that at the present time the necessities of mass production have compelled the use of many ingenious labour-saving appliances in the way of *form-presses*, and so on.

Springs are extensively shaped in dies in ordinary presses. Any method of heating that will ensure uniformity of temperature, both throughout the section of steel and a continued uniformity of heat in successive springs, will answer the purpose in view.

For the smaller springs used in general machinery the gas furnace, the lead bath, and the fused salt bath are all extensively employed.

Hardening.—The most helpful view to take of a spring is that it is a piece of moderately high carbon steel, but perhaps of a fragile substance, that has to be hardened and afterwards tempered until the temper colour passes the straw and purple-brown stages, finally reaching a light or a dark blue. In other words, while the temper of a cutting tool may be arrested at 450° F., a spring is permitted to soften until it reaches 570° to 600° F. At this stage the steel will be found to possess great resiliency, but there is a limit to this. If a spring be bent in a curve sufficiently acute, the steel will snap. It is impossible to make a spring that cannot be broken by bending. As in gauging the safety limit of constructional steel work, so must the steel-maker have his information as to how far a spring will have to bend under working stress, allowing an ample margin for safety.

For the sake of illustration, suppose a spring has, in regular work, to stand up to continued bending out of the straight to the extent of 45°, it might be expected to withstand bending to an angle of 65° without snapping. It is the spring-maker's business to know how many more degrees of curve over this figure this spring will stand before it breaks.

It is manifestly impossible to give figures covering these questions unless accompanied by full specifications of form, mass, and material; not forgetting heat treatment, which in itself varies greatly, profoundly influencing the behaviour of springs. Taking an old-time rapier or sword, a fine straight specimen may permit of its being curved upon itself until the point touches the hilt. The recoil may permit of its regaining its perfectly straight form. This is no doubt an extreme case for a heavy blade, yet wood-cutting saws, produced to-day in England and America, can be found that will withstand this test, although they were not made as springs, their resilience being due to the coincidence of tempering being spring temper also. It is conceivable that if the drawing heat of a specimen of this kind were to be 10° less, the sword or saw would snap, also if it were 10° greater it would fail to recoil to the straight.

This 10° is quite within working compass in producing springs at least of the lighter variety, and a spring-maker has to continue his tests until he finds the degree of softness that meets the case in hand.

Flashing.—In the rough-and-ready method of producing a spring, the steel is brought to a red-heat. It is cooled out in oil, is withdrawn while still hot, and held over a hot fire or flame until the oil upon it flashes into flame, and this flame dies out through failure of the supply of oil upon the surface. The spring is finally cooled out in the oil, and is supposed to be a good spring. If it snaps upon first use, or if it fails to spring at all, and collapses, the steel-maker is frequently blamed—"The steel is no good." And yet thousands of springs are daily made in this way. We venture to use the word "springs" without qualification—they are just springs. They may be good or bad; they may last long or they may fail quickly in service; there is certainly no dependence except it be on chance. Now, even while these rough methods may produce good results, they were incapable of consistently giving the best results, and here again the difference between good and the best is very great.

Whether the operation of flashing or burning off the oil to produce the proper temper is to be commended at all depends upon the kind of work in hand and the experience of the hardener. It is abundantly clear that this rough method of tempering cannot be used with any fair degree of success upon any but the *lightest* class of springs in which the surface heat penetrates through the whole of the steel. Spring tempering cannot be effected, for example, in the interior, or at the core, of steel plate as thick as even one-eighth of an inch by merely blazing off oil on the surface. There will be a spring temper near that surface only, and the body of the steel will be too hard. The rough-and-ready man "gets over" this difficulty by double and triple flashing—that is, he dips again in the oil, and again burns it off. This may have to be done three times before the steel will act as a spring without breaking. Here we have softness at the skin and hardness at the core—the very opposite of what is required for making a perfect spring. If the spring be heavy, the use of tallow instead of the quenching oil is called in to aid in the softening of the steel, because the flash-point so secured is higher.

Spring Temper Heat and Flashing.—The heat required in tempering springs is in the neighbourhood of 600° F. If the flash-point of the quench oil be not within a few degrees of the proper heat required for the spring, it is obvious that the spring will be left either too hard or rendered too soft. Notwithstanding this drawback, attention is not always paid to the choice of an oil with a proper flash-point, and the spring may be good or bad, dependent upon chance.

Flashing Strongly Denounced.—So much really good work has been done in tempering springs by flashing, in the hands of experienced men, that there is considerable justification for its continuance in the same hands for the same classes of work. But it would be altogether wrong to recommend this process as part of the technical education of future workmen. Laboratories all over the world, now working upon scientific lines, strongly denounce this chance method of producing one of the most vital parts of machinery.

Correct Spring Temper.—The proper method to be adopted in the production of springs is, briefly: Heat up the spring (after shaping) by any of the recognized methods; cool it out in sperm oil; while still warm, transfer it to a 600° bath of the highest flash-point oil for a few seconds, and cool out in the sperm oil.

No doubt the chief reason why the flashing method of tempering springs came to be adopted was the difficulty at one time experienced in obtaining an oil with as high a flash-point as 600°, otherwise the immersion method which is now recommended would have been used in preference to burning off the oil. At the present day, however, there is no difficulty in obtaining high-flash oils, well over 600°, which is generally recognized as a sufficient heat for all ordinary work. Nor are we confined to 600°, even if the flash-point of an oil happens to be at that figure. We can go on heating the oil if there is no flame near enough to set it on fire. We can use a bath of boiling tallow. Sperm oil mixed with melted tallow makes a good bath.

In every case of using an oil bath for tempering springs, since the old colour indication is not available, the use of a good protected mercury thermometer is absolutely indispensable.

A rough test of an oil-temper bath can be made, however, by the aid of the colour method, but it is only indicative of the heat of the oil at the moment of use, unless the source of heat—for example, gas—be quite uniform. It is as follows: Heat up, and harden in oil a long strip of the spring steel. Brighten that portion of it that will stand out of the tempering bath, and see that it is absolutely free of oil near the bright part. Plunging the dull part in the hot oil will speedily bring up a colour upon the bright part nearest the oil surface. If this deepens to a full blue, and does not go on changing towards a greenish blue, the heat is almost as perfect as if ascertained by the aid of a thermometer—it will be approximately 600° F. If this heat can be maintained uniform, tempering of light steel articles can be proceeded with for an indefinite time.

In every case where the words "oil bath" are used here, they should be understood to include melted tallow, heavy cylinder oil, sperm oil, and mixtures, such as boiling sperm and linseed. Nor must we exclude other substances than oils from this category. Lead, which, when unalloyed, melts at about 612° F., lead and tin alloyed make a good bath for heavy articles. Since tin melts at about 500° or less, a mixture of these two can be made to keep molten, with a margin, at about the temperatures required. Nor are the drier substances, such as fine sand, rather coarse emery powder (fine emery will cake), and lime to be excluded. A very great deal of work is tempered in hot sand, which is clean, and will not cake nor stick to the work.

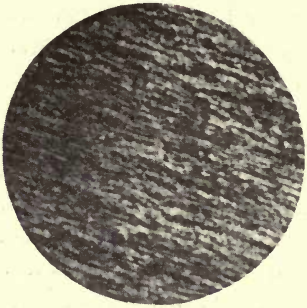

× 100.

FIG. 123.—0·08 % carbon hard rolled soft steel.

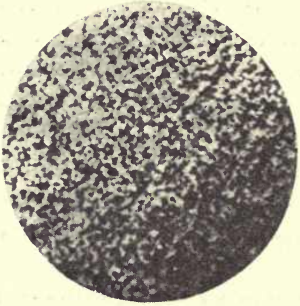

× 00.

FIG. 124.—0·85 % carbon steel as above. Rapid hardening.


× 100.

FIG. 125.—0·80 % carbon steel, drawn, heated at 600° F.

Scale Strikers.—An old-time hardener will dissolve a piece of resin in the oil or tallow bath, with the object in view of casting off any heat scale left upon the steel when it leaves the furnace. It may be taken for granted that this scale is proof positive that the steel has been overheated. If it is argued that the steel will not harden effectually at a lower heat, a higher carbon steel should be used, and greater care taken to temper it down sufficiently. There is always an oxide found in the case of open hardening, but its thickness should be negligible. This can be entirely avoided by pack-hardening, heating in a hazy non-oxidizing atmosphere, or heating in a lead or salt bath, as already spoken of. A very light scale does not matter; a heavy scale should never be permitted.

" Full Relax."—All springs should be at *full relax* before heating for hardening. Some slight allowance may have to be made here for *increased relax* brought about by heating to full hardening temperature.

The Actual Hardening Heat.—In the case of springs of a heavy character, such as carriage and automobile springs, which are of robust section, there is nothing in the heating process that is not common to all other articles of the same size. No chassis spring of over ¼ in. cross-section should be made of carbon steel. They are usually laid direct upon the floor of the furnace, and arranged in criss-cross fashion until the furnace is charged. Uniformity of heating throughout the piece is absolutely essential if a spring that will remain in work is sought. The heat required is rather higher than is usual in the case of a higher carbon steel. It should in every case pass the A 2 critical stage if it has been certified that in annealing or heating for forming the upper critical stage had been passed. Since the higher stage falls below 1,525° F., a hardening heat of 1,450° should then be sufficient to cover the lower and ensure a refined grain. A low carbon percentage calls for a high heat, and vice versa.

The appearance of the three micrographs, Figs. 123–125, will give some idea of the condition of the carbon steel after treatment to form springs.

To the naked eye, in diffused daylight, what would be termed a bright cherry-red would occur at the above hardening temperature. The upper critical stage would not have been passed until the red colour would become more intense, and almost touching a salmon tint.

The quenching of such springs as we have been considering should be done in a high-flash oil, the blades or leaves being dipped edgeways and not vertically. Cooling will occupy a few seconds of time, when the leaf should, while still hot, be transferred to the tempering oil. The quenching oil must be kept as cold as circumstances will permit. Steel will not harden in hot oil.

File Test.—Unless the hardener be quite sure of his steel and his heat, file-testing is mandatory. It is more positive if done just as the steel leaves the quenching, but a little experience will enable the hardener to test springs after they have been tempered. Before tempering, the file should not cut. After tempering, it will cut the steel slightly. It must be remembered that, in the case of tempering a spring by colour, the coming up of a colour is no guarantee at all that the hardening has been effected. Steel that is quite soft will colour beautifully, so that a blue tint does not constitute a spring temper.

Heat for Light Work.—If very light springs be pack hardened (hardened in a box surrounded by ground charcoal) the heating *must not be prolonged*, otherwise the carbon content of the steel may be increased, owing to the nature of charcoal. Lime or ash can, it is true, be used, but nothing exceeds the cleanliness and general good effect of charcoal powder. It also acts as a safeguard against burning of the steel, and entirely removes any risk of scale. Hence, a few minutes after the heat required has been attained, the process should be stopped by withdrawal, and quenching in sperm oil. Tempering follows the rule above. It may be done in oil, hot tallow, a mixture, or even in sand—all heated to about 600° F.

Tempering Bath and Fire Risk.—Oil at 600° is generally prepared to burst into destructive flames. But a light must be touched by the vapour to start this. Containing vessels must be of metal, and not soldered. Means should be at hand to cover the blazing oil, and so smother the flame in case of accident. No oil that is not of a guaranteed firing-point exceeding 600° can be used for spring tempering. Here we may mention the absurdity of the method of burning or "flashing" the oil off a spring to secure a spring temper, since there are numerous quench oils that will flash at 400° or less.

Fine Springs.—The treatment of long, thin springs is not quite the same as that adapted to the case of heavy springs, and a few particulars of the methods practised may prove of value, even to a hardener used to heavy work.

Heating.—One of the best means of getting up the hardening heat of such as watch mainsprings and clock springs, or any thin section form of spring, is to use a gas furnace having a spacious floor, which can be uniformly heated. Shallow sheet-iron trays or boxes, having a suitable depth for the work, or about 2 in. in depth, can be used. In order to minimize the risk of excessive oxidation, a bed of ground charcoal is prepared and the springs pressed down upon it. They are then lightly covered with the same material, leaving, however, portions of springs at different parts of the area of the tray for inspection of the degree of heat. A cover is an advantage, but it must have an inspection slot cut in it, or otherwise permit of a view of the springs when required.

In such a box, with its oxygen-absorbing surroundings, the springs will be well protected. When at a fair red-heat (1,300° F.) the springs may be transferred to the cold oil quench. Sperm oil, to which has been added 10 % of melted tallow, makes a good quench. If the springs are too hard working from test-pieces, increase the tallow percentage.

If too soft, slightly increase the heat and diminish the tallow. The tallow and oil should—an equal quantity of each—be melted together by heat before making up the quench, which must be cold. If the furnace arrangement is so defective that excessive oxidation occurs, amounting to the slight scaling, the addition of resin to the quench will be found to have a slight clearing influence. Transference from the heat to the quench should be rapid, not only on account of the oxidation, but to prevent cooling below the hardening colour. This precaution is repeated here with emphasis.

All Springs at Full Relax.—A great deal of such hardening is done in tubes with closed ends. One of the ends forms a plug, which is easily removed. Springs are lightly placed with charcoal powder in the tube. No packing must be done, as it distorts the springs. When a sufficient heat is secured the tube is inverted on the quenching tank, the plug withdrawn, and the contents shaken out—*but not all at one spot.* Cool oil must be sought for each spring as it drops. In this way an absolutely non-oxidizing condition of the steel is secured.

As previously explained in reference to heavier work, the risk of oxidation can be overcome, in the case of very light work, by means of the 25 % solution of cyanide of potassium dip, drying off slowly before firing. In some cases this is effective even in an oxidizing atmosphere, but is perfectly so in the shallow trays just spoken of.

Boracic Acid in powder, or crystal borax, may be used as an antidote. A strong solution of it is made in boiling water, and the springs immersed. If a sufficient coating of the borax has been thereby secured, this cannot be burned off in the hardening heat, and will prevent all oxidation.

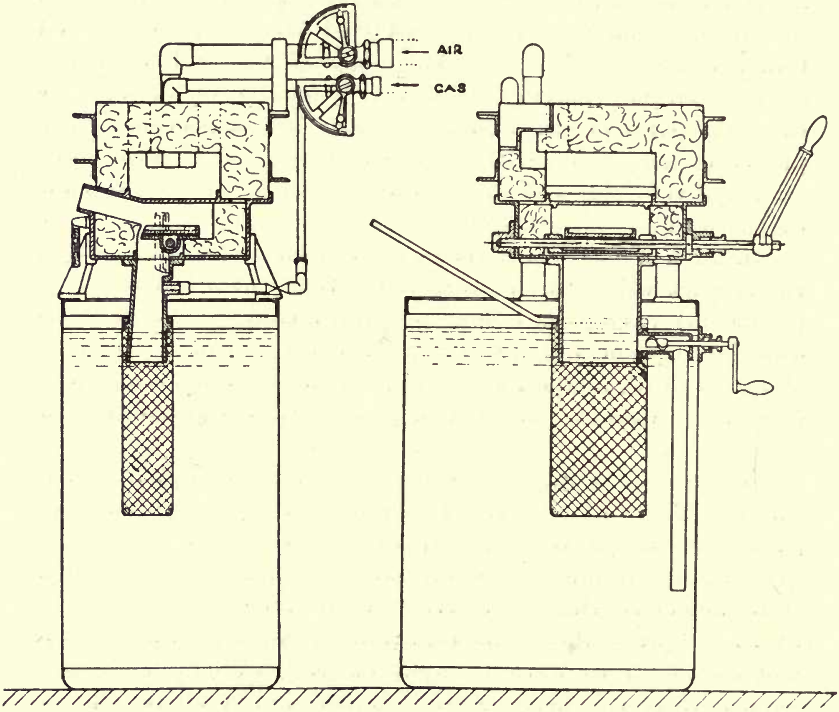


FIG. 126.—Bright hardening furnace.

Chloride of Zinc.—When quite pure, this anti-oxide may be used for some kinds of springs. It is expensive, which precludes its use for large surfaces. Springs protected by it must be well washed in hot water after being through the tempering oil.

Bright Hardening Furnace.—Although not strictly in its proper sequence, mention should at this stage be made of Brayshaw's bright hardening furnace, one of the most recent developments, depicted in Fig. 126.

This has been specially designed for the hardening of needles and other small work where it is essential that a bright surface without discoloration be retained after hardening. The articles to be hardened are heated in a muffle, the floor of which may be tipped up by means of a hand lever. The work is placed upon this floor, and when it reaches the desired heat is dropped through a shoot into the oil tank below. *A coal-gas atmosphere* is maintained both in muffle and shoot, entirely preventing oxidation of the work while heating and dipping. The loading door of the muffle is 6 in. wide and 2 in. high. The floor is 6 in. × $5\frac{1}{4}$ in. The furnace is heated by means of a "Flamous" burner, the heating chamber being placed above the muffle, and separate from it by a partition of special non-oxidizing metal. Gas at town's pressure is required, and air at 6 in. to 8 in. water gauge. Quadrant taps are provided for controlling the temperature. The furnace is bolted on to the top of a suitable oil tank, and a strainer is provided to catch the work as it falls through the shoot.

Here we have a practical development of the idea tentatively brought into use when an iron box is filled with charcoal powder and steel articles, heated up and suddenly tipped into the oil quench. This is one of the oldest methods of dealing with bright steel articles, the surface of which it is desired shall not undergo oxidation. But even in a charcoal surrounding, followed by a dexterous tipping into the quenching oil, it is difficult to entirely overcome signs of the oxidation by the means of this cruder method of handling.

Watch-spring Test.—Before a test spring is put through the hardening and tempering, a self-impressed diagram of the spring is taken by placing the open, relaxed spring upon the back of a flat sheet of carbon paper. A flat glass plate is then lowered upon the spring, and a slight pressure exerted evenly upon it. Thus is secured a diagram of the spring in its soft state, straight from the coiling machine. The hardening temperature and conditions throughout are noted, together with the time element. If the spring has been hardened and tempered throughout without any sign of oxidation, a very ordinary condition, it will consist of a bright steel ribbon. It is then usual to colour it, for two reasons: First, as a protection against rust; and secondly, for the sake of appearance. This colouring is done in a hot-air sand-bath. Fine sand is heated up to about 540° F., corresponding to a purple colour. The spring is laid upon it and covered up for a few minutes, at the end of which time it is withdrawn of a purple colour.

After being washed in paraffin or petrol it is ready to be coiled up to full tension. A binding wire is put around it, the machine detached, and the bound spring left in a normal atmosphere for twenty-four hours. At the end of this period it is gradually released, placed upon its own diagram, and careful note taken of the change that has taken place. A certain margin is permitted, and those springs that do not come within this margin are re-treated; possibly for greater hardness, and equally, perhaps, for increased softness.

This is only one of the rigid tests that different makers' watch and clock springs have to undergo. There are also dynamic tests and others, which cannot be fully discussed here.

False Spring Colours.—The popular mystery of a watch mainspring bearing upon its surface a light golden colour, indicative of hard steel temper (480°), which could never be used in a spring, is thus explained.

Cold Steel Springs.—There has developed of late a system of spring-making that appears to have much to recommend it. When steel is highly compressed, it can be made to acquire a high degree of resilience.

A good example of this can be found in the steel wire known as piano wire. We have here a carbon steel somewhat under the eutectoid ratio of carbon, subjected to a repeated drawing, at the end of which it becomes extremely hard, and also extremely tough, with a considerable increase of density. When this wire is coiled tightly around a mandrel, forming a spiral, it will, when released, uncoil to a certain extent, but it will retain its spiral form, being now about one-third wider than the mandrel upon which it was coiled.

A helix thus formed makes a superior kind of spring, calling for no heat treatment. So useful is this kind of spring that it has largely displaced heat-hardened springs where cost of material is a secondary matter; for piano steel wire is a costly product, most excellently bright drawn. Under the file this wire will be found quite as hard as steel, the temper of which has been drawn to 600°, or a deep blue. An additional advantage lies in the rarity of breakage of springs made in this way.

Patented Process for Wire.—The process known as "patenting" wire is of recent origin. It covers the range of medium carbon steels, between 0·35 and 0·85 %. The high strength of patented wire, allied with great toughness, is due to its micro-structure, which undergoes considerable modification during the drawing and compression through the dies.

The first step is to heat the rod to a temperature above its critical range. The next step is to cool the rod rapidly just below its critical range, the micro-structure produced being dependent upon the *rate* of cooling.

The process is a continuous one, the wire running through a tubular furnace at a stated rate. The cooling is done by conducting the running wire through an air or a molten lead bath. The subsequent die-drawing produces a wire of great strength. This is mostly due to the peculiar formation of the sorbitic pearlite—the usual plate-like structure being unsegregated, as contrasted with the segregated plate structure of entire pearlite. When well conducted the process should render the cold drawing of wire unnecessary.

CHAPTER XII

PRESS TOOLS

DIES used in drop forging operations, and also press tools for stamping-out and drawing, are amongst those tools that have to withstand the most severe treatment of any implements made of steel. They must not only be made from suitable grades of steel, but must be handled by the steel treatment shop in the most skilful way.

These tools vary in size from examples an ounce in weight up to several hundredweights. The treatment applicable to the heavy masses will not, therefore, be applicable to the medium and smaller tools. A large tool of this kind is spoken of as a die block, and a small tool as a press die simply. The treatment of the die itself and that of its bolster or under-die is the same. They both take their share of the impact or steady pressure, as the case may be. In certain forms of bolster or female die there occurs not only the vertical pressure, but a great deal of splaying or bursting pressure. On account of this it is necessary to make some allowance for the expanding force of the upper die in the temper of its counterpart.

All of the smaller tools, weighing up to, perhaps, two pounds can be handled in the usual way by tongs. But in the case of large die blocks, which must be moved about by mechanical means, provision has to be made for the crane grapplers or jaws. This provision is already, in many cases, formed upon the block itself in the shape of its dovetail head, formed for fitting into the press itself; but there are numerous blocks made with no such arrangement; and it becomes necessary to provide grip-pits or simply holes, at either side, near the top, to receive the grips of the crane tackle. None of these recesses should be deep, because recesses often lead to distortion or trouble with the hardening, or may give a chance to an incipient crack to start and spread.

Press Tool Material.—Until quite recently carbon steel of various degrees of fineness was used exclusively for this class of work. But the rapid adoption of the alloy steels for other stress positions has led to the employment of three or four varieties of the nickel–vanadium–chromium group for die work. This tendency has been specially marked in the case of the more expensive medium size dies, such as are used in the production of silverware and the best class of copper and even brass goods.

Economic considerations generally compel the selection of a comparatively mild machinery steel, possibly with a carbon content not higher than 0·10 %, for making large die blocks for certain classes of work. By itself and in the raw steel this material would, of course, be quite useless for press work, since it could not be straight-hardened. But even this material can be made into a hard wearing die by case carburizing, to a sufficient depth, its working face. This process is indeed closely associated, in one way or another, with all but the smaller press tools. These can be made, without much expense, from a high grade of straight-hardening steel, without resort to carburizing heat of any kind.

When a suitable material is selected it is not necessary to arrange for a hard-all-over die in the case of the medium and larger tools. Indeed, modern practice is rather tending to confine all hardness to the working face, so long as it ensures a suitable depth of this full hardness. If there is any shallowness here, the die cannot be expected to retain its truth for long, for the working face will tend to sink, especially towards the middle, where, doubtless, hardness is never so perfect as it is nearer the outsides. Ductile steel is compressible, and given sufficient force, the hard is pushed into the softer back of the die. All carburizing, then, in this case, aims at a depth and degree of hardness that will ensure this part of the block being able to stand up to its work alone, without any risk of deformation.

It will be seen that this tough back to the die is a distinct advantage, especially in percussive press work, for it acts as a kind of buffer to the very hard face ; and having a certain amount of resilience saves the front from possible fracture under heavy or rough treatment.

Mild Carburized Die Blocks.—Great quantities of these are used when the work to be done in the presses permits of it, since press work as tinplate, copper and brass pressing, foldings and edgings of any kind of sheet metal vessels are within the compass of treated mild steel die blocks.

Specification of the Steel.—The three chief constituents of the mild steel to be employed, apart from the ferrite, are: Carbon, manganese, sulphur and phosphorus. We will not concern ourselves with the other matters making up the mass. But of carbon we must *not* have too much; of sulphur and phosphorus we must have as small a percentage as the steel-maker can guarantee—in other words, we want *no* sulphur and phosphorus, but this we cannot expect in mild steel.

Carbon content may vary from 0·10 to 0·25 %, the former being suitable for the less expensive class of die block; and the latter for a harder and stiffer block throughout. Carbon of 0·25 % should rarely be exceeded for die blocks intended to be deeply carburized. Where we exceed this percentage we cross the line into the field of partial or complete straight-hardening of the steel. The term "straight-hardening" here means the capability of the heated steel (of thin section), upon being quenched, of hardening throughout, without the aid of any carburizing process whatever. We are dealing now with steel intended to be furnished with a hard steel facing.

Sulphur and phosphorus should not exceed, either of them, 0·02 % and a lower percentage should always be looked for. Their presence adds to the risk of short brittleness in dies, upon which a great deal of labour has been expended. Dies with delicate corners and edges are apt to suffer if there is much sulphur and phosphorus present.

Manganese is rather to be welcomed, and a percentage as high as 0·30 % need not be objected to.

Silicon, which is generally present, will seldom exceed 0·015 %, and may be overlooked.

We have here an inexpensive steel suitable, with treatment, for a vast variety of dies and other work. As it leaves the steel-works it will test out at a tensile strength of 50,000 lb. per square inch, with an elastic limit of 35,000 lb. After treatment these figures will be greatly exceeded.

In the making of the die blocks, when the above steel is used, extra care need not be taken to avoid sharp-angled corners in the cuttings, as there is small risk of cracking.

In the case of steel with higher carbon, and especially with straight hardening grades, this precaution is ever before the man shaping the die pattern.

Carburizing.—Before preparing for packing, if the die block is a heavy one, arrangements must be made for both its handling while red hot, and its quenching. With regard to lifting and moving about the preparation is obvious. In the case of the quenching, if the block is large, with fairly deep cutting or pattern, the important thing to make sure of is a copious *rush* of water from a pipe, directly upon the centre of the face. Except for very large work, a pipe with an inch outlet will suffice, under a good pressure. The same supply of water, distributed amongst three nozzles will, if they are upon a four-inch circle, suffice for a block as large as eight inches square. It should be understood here that the object aimed at is the rapid cooling of *the centre* of the mass, for it is here that there is a great backing of heat, and if cooling is not quickly accomplished, the outer portions are sure to be harder than the centre, while the very opposite is to be desired. The corners of the block are apt to be over-hard, while the centre is under-hard. Now the working life of the centre of the block cannot be greater than the life at the corners. Or, if the centre is not *deeply* hardened, this may "give" or begin to sink, and deformation commence there instead. Hence, if the centre can be hardened, there will be no difficulty with the outer parts. It is even an advantage if the corners turn out to be not quite so hard as the middle. The die will be found to stand up to its work longer for this condition of things.

These conditions being understood, the cooling arrangement is a matter of providing a fierce rush of water upon the centre of the face of the die, to be followed by immersion of the whole body of the block in the agitated water to a depth of several inches. A hose-like outlet for the rush of water should be arranged in the centre of the water tank, the pressure to act *upwards*, at about the level of the tank water. After this has been played upon the inverted face of the die for a few seconds, the water level of the tank should rise, or the hose-pipe nozzles should gradually drop before the descent of the die. It will thus be clear that the object of these preparations is to secure the hardness both in the centre and at the outer edges.

To recapitulate, at the risk of being thought tedious, we must, in dealing with a large die block remove it from the heat while it is somewhat above the temperature we wish to harden it at. Within a few seconds of time there must be projected upon its face, centrally, a rush of cold water to ensure that no film of steam will retard the hardening effects of the water. Again, within a few seconds of time the water level must be pushed up, or the block must be lowered into it to a depth of several inches to ensure hardening of the outer shell, round the face. While attention is being given to the face itself, we must not lose sight of the outer edges, *which are apt to fall too low for hardening without being observed.* It is at the same time assumed that the quench is being kept violently in motion, and that fresh cool water is being supplied during the cooling.

Cooling Off.—Assuming that the die face has been satisfactorily dealt with, much heat will have remained in the body of the block, but not, it is assumed, as high as a hardening heat. In any case, since the steel the die is composed of is low in carbon, there will be no risk of overhead hardening if the whole block be cooled off, and the operation finished.

Carburizing the Die.—We might, at this stage, refer the reader to the chapter on carburization ; and he would, no doubt, obtain sufficient information on treating work in general to enable him to carburize dies. But there are certain arrangements necessary, peculiar to die hardening that necessitate going a certain way into the matter of carburization in this place.

The object aimed at is to increase the carbon content of the face, and parts adjacent to the face, sufficiently to ensure deep hardening, for steel with only 0·25 % of carbon will not straight-harden as it stands. We must increase the carbon to some 0·60 to 0·90 % in the parts to be hardened. The operation is quite simple, and, fortunately for the novice, quite certain of result.

There is required a source of heat. An ordinary gas furnace is by far the most generally useful. A tool-heating outfit will serve very well for small dies, perhaps up to four inches square. A larger or muffle furnace is required for heavy dies. Since the carburization has to be carried on for several hours on end, a gas heater is by far the most serviceable kind of furnace. Almost equally serviceable are the oil-fed furnaces, now supplied by all makers of gas furnaces.

Packing the Die.—Procure an iron box from four to six inches wider than the die, so that there will be at least two inches of clear space surrounding it. A sheet-iron box, rather deeper than the die block, will answer the purpose very well. Make a fair mixture of barium carbonate and leather charcoal half and half. In the absence of a good leather charcoal, or bone-black, a good wood charcoal may be used, when finely powdered. It must be well mixed with barium carbonate. It should be known that carburized leather, hoofs, or even bone, can be used alone, in place of the barium carbonate. But the resulting case will not be quite as strong, especially if any form of bone is employed. Reference may be made to the chapter on "Carburizing Materials" for fuller information on this point.

A firm packing of two inches in depth of the mixture is placed in the bottom of the box. The face of the die, if it has slender edges or delicate markings, should be deeply painted with paste formed of bone-black and linseed oil. The die is then lowered into the box, centrally, and pressed firmly upon the underlying mixture. The space around is to be packed firmly with the mixture, as far upon the height of the die as may be required. In the case of an eight-inch die, at least three inches of it should be packed in the carburizer. The remaining space may be filled with dry fine sand, which should be at least two inches deep. Fireclay may be used if preferred, and is generally considered to be an effective gas stop; but it should not be too slack or wet. Two inches of fine sand will be found quite effective for firing exposures of eight hours or longer.

The packing and the sand should, jointly, cover the die, having an inch of sand over all. Fireclay may be carried up, if preferred, to the top, but the crown of the die should be so left that its sand covering may, while it is still in the furnace, be pushed aside so that the degree of redness of heat attained can be judged. If the height of the furnace will not admit of a view of the exposed top of the die being obtained, a pair of test rods of $\frac{3}{16}$ in. round wire can be pushed into the box, touching the die itself. The withdrawal of these, at different times, will prove whether the heat has attained the degree required.

Assuming that the die is of medium size, or four inches square, it will require to remain in heat, with the walls of the furnace as hot as 1,500° F., for two hours before it is fully heated through. Not until this condition has been attained do we begin to estimate the hours for carburization. The firing should now be run for at least six hours, and in most cases eight hours, before a proper depth of steeling can be secured. In the case of larger dies, the heating up alone will occupy anything up to five hours.

It must be clearly understood that in no case carburization will begin until the whole mass has attained red-heat.

But what is Red-heat?—It is what is called cherry red or full red, but this is by no means clear. When a pyrometer is placed against a mass of steel at cherry red, it will register, if it is correct, 1,375° to 1,380° F. The figures below will give a fair idea of the visual appearance of the various heats used in the treatment of steel:—

Slightly red	900° F.	Brilliant red	1,550° F.
Blood red	1,050° F.	Salmon yellow ..	1,650° F.
Bright blood red ..	1,180° F.	Orange	1,725° F.
Cherry	1,250° F.	Light yellow.. ..	1,975° F.
Full cherry	1,375° F.	White heat	2,225° F.

Once determined, the gas consumption will have to be watched, or an overheat will soon be attained. It is quite permissible to vary the heat in carburizing by one or two hundred degrees. But any variation should be upwards, not downwards. If the heat is permitted to fall, carburization will slack off or may stop altogether. The heat must be brought up to about 1,400° F., and not permitted to fall below it, for the whole length of the run.

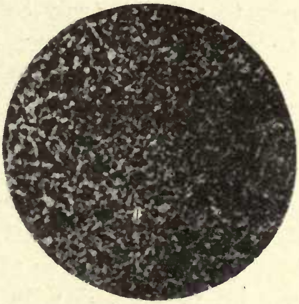
On the other hand, too great a heat, such as 1,600° F., will rush matters. It will burn away the best part of the carburizing material before it has had an opportunity to pour its carbonaceous gas into the steel, and the steel block itself will begin to *decarbonize*, to be shortly followed by burning, scaling and destruction of the pattern and outline. It will thus be clear that a proper amount of heat must be arrived at and neither exceeded nor reduced in order to attain to the full beneficial effects of carburization.

Carbon Content Attained.—Analysis of the steeled parts of the block will generally prove that its carbon content has been raised from, perhaps, as low as 0·10 to 0·90 %.

This is really a fine tool steel, and in the practical absence of adulterants, such as sulphur and phosphorus, it will act as well as crucible-cast tool steel in operations such as press die work.

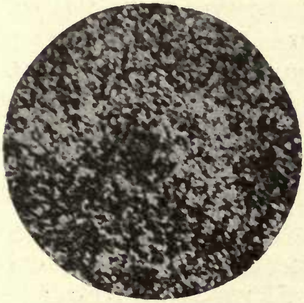
Figs. 127–129 depict the micro-structure of a mild carbon steel entirely penetrated by the cement in the three stages of quenching.

Tempering.—When the die block has been cooled or hardened, according to the suggestions already given, it may or may not be ready for work in the press. Whether or not it should be tempered or its hardness "let down," can only be decided from a knowledge of the pattern upon its face and the nature of the stresses it will be expected to stand up to. If there are delicate projecting parts upon it, or if it has been so shaped that there is any "weak metal" about it, full tempering will be indispensable. This matter should be decided before the block is quenched;



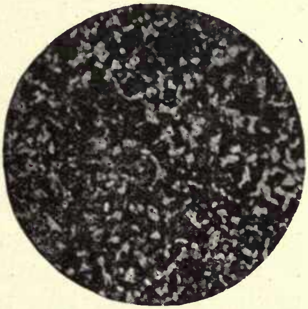
× 30.

FIG. 127.—0·28 % entirely carburized carbon steel hardened at 1,520° F.



× 100.

FIG. 128.—Low carbon steel quenched well above Ac 3.



× 500.

FIG. 129.—0·45 % entirely carburized steel, soft condition.

for if tempering is to follow, the quenching need not be completed. After all the face or pattern part has been chilled through, the top may still be at a dull red. If, at this stage, the face of the die is turned up and patches at three sides of it rubbed to brightness by means of a fold of coarse emery cloth wrapped around a file or lath, a watch can be kept for the oxidizing effect of the air upon the bright steel when heat has returned to it from the still hot upper half. There will appear, first, a slight straw colour, which will gradually deepen to yellow straw colour, beyond which reduction of hardness should seldom be permitted. A thermometer (of the high-reading mercury type) placed upon the steel face will show at 430° F. a light straw colour, at 440° a light yellow straw, and at 460° a full straw colour. Full cooling off in oil should follow this.

In many cases it is inconvenient to temper a die or tool by its own back heat. It will frequently be more suitable to permit the cooling off to proceed to the full extent. The tempering may then be proceeded with at any time. No tempering should be attempted, however, at the face only. All such heat must come from the back, so that the working face remains the hardest part. Tempering from the cold state will either be done in the furnace, if the die be heavy, or upon a thick piece of red-hot iron if it be light. In the furnace, the brightened face of the die can be kept exposed at the door, and it is necessary to watch it closely after it has become warm.

Quenching Must be Prompt.—Rapidity of final cooling must be arranged for *on the instant* when the colour required is becoming apparent. Any hesitation here to at once plunge the steel into the quench will result in a steel too soft. Dependent upon the amount of the heat coming from behind, the lightest of straw tints upon the bright steel will be followed rapidly by full straw and even dark straw colour, denoting only a fair degree of hardness. It must be understood that these changes are a matter of *seconds* not minutes.

This matter is important from the consideration that if, by inadvertence, the steel is permitted to become too soft, there is no remedy short of complete reheating and requenching. This double operation is not at all welcomed by the cutter of a die, for if care is not exercised in the reheat, any delicate work upon the die face may suffer through the risk of overheat scaling, which may not be obvious to the eye. If a fine die of this kind has to be reheated, the face should be painted heavily with the boneblack and linseed-oil paint, and the reheating should be done in the carburizing box, on a thin bed of carburizing material. With these precautions, the face of the die will emerge as clear as at first, and cannot be injured in any way. As a matter of fact this double treatment, if properly conducted, is a distinct advantage in strengthening all the parts of the die.

File Test.—As a matter of course a file will be tried upon the hard steel. If a sharp file can be made to cut it, the process of hardening has been a failure. This cannot occur if the ordinary course of carburizing and cooling has been pursued.

Die Tempering in General.—To the die maker and also the die user the question whether a die will "stand up to the work," to use a colloquialism, is of the first importance. Granted fair treatment in the carburizing process, followed by sufficiently prompt and effective cooling from the centre outwards, the tempering or toughening, when this is required, is by far the most important matter for consideration. We know that if a light piece of steel is slowly heated, there will appear successively upon its surface a series of colours, somewhat resembling those of the rainbow. We can also predict that the expected colour will appear approximately with the rise of the temperature, by the thermometer, to a given degree of heat. But it is not positively assured that the colour is a dependable guide as to the real condition of the steel underlying the surface.

A simple experiment will illustrate this debatable point. If a piece of bright steel be placed upon another, the heat of which can be kept uniform, and if the heat is never allowed to exceed what we associate with a light straw colour, or 430° F., the colour that will, in course of a slow heating appear upon the bright surface will correspond with our conception of light straw. But if the piece be left upon the hot plate for some time there will be observed a deepening of the light straw to a dark straw, and even darker still. In fact, the colour ultimately developed may be quite equal to the tint we associate with a brown, at the temperature of 500° F.

Here we have an instance of the influence of the time element in colour tempering. It is doubtful whether the steel which under the above conditions exhibits a brown straw colour is really as soft as it appears. It is much more probable that the gradual deepening of the colour is due to a *thickening* of the film of oxide, which we know to be the base of the colours obtained. However this may be viewed, the result of the experiment points to the importance of *sufficient heat* behind the observed surface to bring up the colours *promptly*, otherwise a false reading of the sign may be obtained.

While it is a debatable point amongst steel men as to whether or not colouring for tempering should be fast or slow, we are at least sure that a dead slow progress is apt to be deceptive when we work to a table of temperature and a chart of colour changes.

Again, in reheating a die in order to bring it down to the required temper its shape and substance should determine how or where the reducing heat is to be applied. If it is a block die, such as a piece either square or oblong, there will necessarily be a mass of metal behind the working face. In such case the heat must come from the back exclusively. But if such a die were to be pushed into a hot furnace, without care, what would happen would be the rapid heating up of the corners, or exposed parts, which would exhibit temper colour long before the centre became warm ; and it would be impossible then to temper this die except by repeating almost the whole process of heat preparation.

The object to be aimed at is the equal heating of every part of the die face up to the 430° F. required for general work. The slowest heating up from the back only will be found the most effective procedure, failing the initial heat partially quenched at the beginning. The placing of the die over a single Bunsen burner, if small, and over a gas-ring, if larger, will be found effective. Watch being kept for the first signs of colour, further observation must be made as to where this colour first appears, and the back heating shifted away from the side first affected ; otherwise one side of the die may be softened more than the other.

Local Heat for Colour.—In some cases dies are not of uniform shape. There may be outlying parts. Those parts will not, until late, receive any of the body heat, and they will remain too hard. The remedy for this is the application of a Bunsen flame, from flexible pipe, held in the hand and projected towards the back of the parts being left cool by the back heat. It will not suffice, however, to wait until the thick parts appear to change colour. If a thermometer is not at hand to indicate exactly the heat, dependence may have to be made upon the feel of the metal to the hand, a wetted finger being useful here, borrowing a wrinkle from the laundress. It may be relied upon that if the heavy parts are seen to turn straw colour before there is any sign of it upon the outlying parts, it will not be an easy matter to check the one and accelerate the other and so bring them into line.

The use of an oil tempering bath is not often required for die work, but it may be incidentally described here as applicable to press tools of unusual shapes and possessing outlying parts.

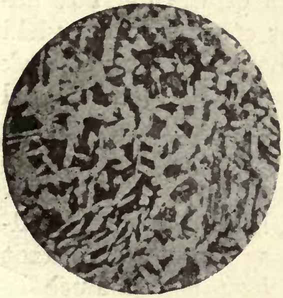

× 40.

Fig. 130.—0·40 % carbon steel overheated at 2,012° F., furnace cooled.

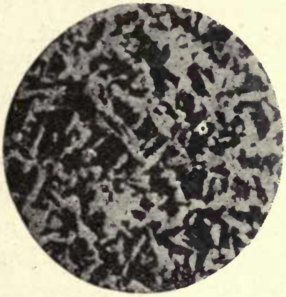

× 40.

Fig. 131.—0·40 % carbon steel heated at 1,832° F. and furnace cooled.

The tempering bath is simply a metal vessel of heavy mineral oil with a flash-point not lower than 500° F. It is heated by gas. A thermometer is kept immersed and the reading must correspond with the colour (temper) desired. The die is placed in the oil at any low reading, and the heat gradually increased to within 20 deg. of that finally required. The heat must be kept in check, for if the full heat is permitted to remain for an appreciable time there is risk of overstepping the effect aimed at. There will be no colour to observe, because the oxidation which is the cause of it does not occur below the surface of oil. It may also be observed that colour in tempering cannot be obtained at all unless the surface of the metal is clean, bright, and quite free from oil or grease.

It should be observed that dies, being generally of heavy metal, require a long period of soaking in any kind of heat to distribute the effect equally throughout the mass. Rapid heating up is always a mistake, and generally results in a soft exterior, leaving a harder interior.

It is a useful practice to cut the heat off entirely when the oil bath has attained the temperature required, and to allow the die to cool out with the oil.

Figs. 130 and 131 have both been overheated; the former very much so.

Faults.—The die may be improperly heated in the furnace while being carburized. The most common fault is hurry in bringing the temperatures up. The next fault is failure to observe whether all parts of the die box are receiving equal heat. Very few gas or other furnaces yield a perfectly uniform heat. The box should be turned back to front more than once during the heating. Upon removal for the quenching, the lowest heat that will harden the steel face is always best. But this degree of heat will depend upon the quickness and efficiency of the cooling jet of water. A thin piece of high carbon steel will harden at a dull red-heat; but a heavy body of steel such as a press die cannot be expected to do so. The body of heat is too much to permit of the quench having sufficient chilling effect. The *rate* of cooling is a most important factor. This will depend upon two things, the temperature of the water and its volume and force of motion. With very cold water, under a good pressure, and plenty of it, hardening may be depended upon at a moderate cherry red-heat. *Warping* is a common fault. It is, perhaps, the most destructive of all, for a warped die cannot be cured save by resinking. *Warping* or deformation of any kind is generally due to unrelieved strain. Any risk of this kind can easily be avoided by slow annealing of the die block *before* it is cut into a die. This is the time, and not after work has been expended upon the block. A block that has had all strains relieved will not change in shape afterwards unless it is subjected to bad treatment in carburizing and quenching. The words "bad treatment" imply unequal heating; bungled in the quench in the form of chilling one corner by inadvertence, or other partial cooling faults. *Cracking* is seldom heard of in case-hardened steel, but even this may occur when the steeling has been carried out to a great depth. It is usually due to overheating and too rapid cooling, but cooling is very seldom indeed too rapid ; it only becomes so if the die has been overheated, so that the cause of cracking originates in the furnace.

Limitation of Foregoing Processes.—All the foregoing suggestions, taken as a whole, are applicable *only to carburized* steel die work. This grade of die making is most easily handled of any, and an acquaintance with it is a fine apprenticeship to the more difficult art to die treatment when the material used is a raw high carbon steel, or a complex alloy steel, such as is now freely used for the highest grade of fine dies.

HIGH CARBON DIES.

While some of the foregoing process is equally applicable to the first class of dies, it cannot be said that the high carbon die is as safely handled as the mild steel die. More skilful judgment has to be brought into play in order to avoid destruction of the die, which may easily be a piece of work involving months of skilled labour, and this upon a block of steel itself of a costly nature.

Materials.—Carbon steel for die work usually exceeds in carbon content the result of carburizing. In our case-hardening example the carbon content secured about the face, *and for a short space behind it,* will have a carbon content of about 0·90 %, which is indeed high in itself, as it will harden easily at a very low degree of heat.

The general range of the die steels are as high as from 0·50 % to 0·70 % in carbon ; the former being used for the dies employed upon metals not of the most refractory nature. The 0·70 % carbon steel is sufficiently hard and strong for the greater part of heavy, hard and even percussive work in presses and drop hammers.

We have occasion, further on, to refer to the nature of the immensely strong alloy steels, the use of which is extending for the production of the highest grade of dies. But it must not be supposed that a good carbon steel has been superseded thereby. Nothing better than carbon steel can be obtained for the construction of the greater majority of dies of everyday use. It is the business of the steel-makers to produce the forgings required for heavy die work. Up to a certain size, perhaps six or eight inches square, a piece sawn off the bar may be selected. Specification of the nature of the steel gives its carbon content, manganese, silicon, sulphur and phosphorus.

Typical Specification of Die Steel.—Carbon 0·50 %, manganese 0·35 %, sulphur 0·02 %, phosphorus 0·15 %, silicon 0·40 %. A rather tougher steel will read: Carbon 0·70 %, manganese 0·35 %, sulphur 0·020 %, phosphorus 0·015 %, silicon 0·40 %.

The first cost varies, somewhat as carbon content. But in the case of the best class of forming dies cost of material in the dies is always secondary to cost of preparation. In the absence of personal knowledge, the steel-maker is generally a safe man to entrust with the selection of a steel, provided that he has the fullest information as to the use to which it is to be put. He will be found to grade his best steels into several divisions, under the designation of Temper I, Temper II, and so on. This use of the word "temper" when describing raw steel must not, however, be understood to refer to the grading of hardness in tools, generally known as the art of Tempering. It merely has reference to the specification figures, in which the carbon content is the most important. Indeed, carbon is generally regarded as synonymous with "temper" in raw steel.

The great distinguishing feature, under heat, of the high carbon steels is their powers of hardening upon heating and quenching. In other words, they are straight-hardening steels as distinguished from low carbon steels which will not harden until they have been additionally carburized, as already spoken of respecting the making of ordinary dies.

High or Low Cost.—There can be no question as to whether a costly steel is the best for press work (as distinguished from percussive work), but its selection must depend upon a degree of hardening skill available in its production as a die. It should be clearly understood that a high carbon steel die is a much more risky proposition than a lower carbon die. There is always a risk of cracking in the hands of an unskilled man. This risk may almost be said to diminish in proportion to dimunition of carbon content. There is always, fortunately, a highly skilled firm of hardeners in most large cities to which the work of finishing an expensive die can be entrusted.

We have said that this highest grade steel is specially adapted for pressure work. This implies that it is not quite so well adapted for a hammering or percussive machine. This arises from the superior quality of *toughness* of the lower carbon steels. There is a grade, and not quite the highest, which is distinctly superior in reliability to the highest temper or grade, while it possesses all the hardness that can be desired. The reference to reliability here is, in other words, the diminished risk of breakage in use.

Preliminary Heat Treatment.—Before a block of steel from which it is intended to form a die is touched beyond the roughing out to shape, it should undergo a thorough annealing. If this is neglected, every hour of work expended upon it may be fruitless. The pattern worked upon it may become distorted, and the level and truth of the die upset. This change would not occur until the heating up for hardening had taken effect. Then the steel would be relieved of all strains and would settle "at rest." There is a chance that nothing of the kind would occur, but it is well-established knowledge that it does frequently occur.

Take the case of a forging, produced for a heavy die. Under the steam hammer the body of it will be pounded and forced into shape. When the required shape is attained, frequently by heavy blows delivered upon it while still scarcely red-hot, it may be thrown upon the floor to cool off as best it may. This mass of steel will be full of strains, ready to unbend as soon as heat loosens the bonds.

Even a block cut from a bar is not free of stress. It has left the rolling mill under great force, and it, too, is thrown down to cool off. The next visit to the furnace sets these stresses free; but not, it may be depended upon, without some alteration of the shape of the mass.

The anneal should therefore follow the rough shaping of the piece. In a case of this kind the procedure is simplicity itself. The piece is placed in the furnace, which is then started. A very slow heating up should follow, up to bright red, which will be reached just under 1,500° F. This may with advantage be continued for one hour. The gas may then be turned off, *and the flue closed up* to prevent the starting of a chilling current of air rising through the furnace. This precaution is not required if a muffle is used. The steel should be left to cool off in the furnace.

Double Annealing.—If an extremely ductile condition of the steel be desired, a longer period in the active furnace will be a benefit. But what is known as double annealing is much more effective and produces a block of steel as soft as it is possible to make it, and at the same time quite free from the effects of forging and other stresses undergone in the rolling, cutting off or hammer work of shaping.

A double annealing also implies working at two temperatures, one for each firing. The first firing calls for a temperature between 1,400° F. and 1,450° F., or well over the higher critical range of a high carbon steel, so as to secure the full emulsifying effect upon the constituents of the mass. The second firing need not exceed 1,300° F. Its effect is to bring about full relief of any stiffening effects left by the higher temperature over the critical range of the first firing, and to ensure the full benefit of the refinement of grain due to it. Temperatures must not be too high, because an excess temperature is apt to recoarsen the grain.

The overheating here hinted at is generally due to the fault of placing the steel in an already hot furnace and forcing matters by turning on more and more gas and air in order to secure centre-of-the-mass effect without delay. We may thus have a block of steel so overheated that all around its central portion there may be a mass of coarse grain steel, surrounding a refined core.

Anneal Packing.—In order to obtain the best results, it is scarcely worth while to conduct a double anneal in the open furnace. The work must be packed in a box with some mixture that will ensure its insulation from rapid change of temperature. Mica powder, fine sand, a mixture of fine ashes and wood charcoal are a few of the more useful packing materials that may be employed. If the skin, or extreme surface of the steel, is not to be planed off before the sinking, or cutting the die, a proportion of wood charcoal should be used in every case. It is questionable whether any of the active carburizers, unless partly spent, should be used for this work.

The heating up is the most important matter to attend to. Starting with a cold furnace, only a slight heat should be turned on until the mass has had time to absorb the effect to its core. Plenty of time must be allowed, and no part of the furnace should register over 1,600° F. at any stage of the operation. When the block is thoroughly heated throughout to the required degree (1,400° F.) it should remain there for at least one hour. Gas may then be turned off, and the steel allowed to cool, still in its packing. If the furnace should be required for other work, the box may be removed and allowed to cool off in a warm place.

The second heating is arranged in the same way, but the full temperature of this should be from 150° to 200° F. less than that of the first anneal. It is an advantage to prolong the second anneal to twice the time of the first. The slowest possible cooling in the box is required after the final anneal.

Hardening.—A full measure of ductility having now been secured in the block of die steel, the work of fashioning and sinking should be carried through. In some cases, however, the carrying out of this operation involves a great deal of chipping and hammer work upon one face of the block. It must be left to the judgment of the worker as to whether he has subjected this side of it to undue stresses, or not. If there is any doubt upon this point, a brief anneal should be given to the die before the final work is carried out upon the pattern. We have used the word " die " in the singular hitherto, but dies are almost invariably produced in pairs, an upper and under. The under die is frequently referred to as the bolster, whether it acts as a bolster or not.

Crudity of Surface.—Before sinking, or in any way forming a die, especially if for fine work, the outer surface or skin should be planed off. A thickness of $\frac{1}{16}$ in. is an effective quantity. The chief reason for discarding the skin of the block has reference, firstly, to surface roughness and crudity of metal ; and, secondly, to the fact that the surface of raw steel has to a slight extent suffered decarburization in forging heats if, by inadvertence, these latter have been allowed to rise far above the upper critical range. Steel is cleaner, purer, and more refined beneath the skin than it is on the surface. It will be recalled that in the foregoing suggestions for double anneal it is recommended to surround the steel with a mild carburizer, such as wood charcoal. The real object aimed at here is to obviate a tendency to decarburization which may possibly happen if excessive temperature is by any mischance developed. For the mere chill-insulation of the steel, sand or mica dust alone will be quite sufficient. But, as pointed out, a planing away of the surface permits of any form of insulation being used, and exposes the best qualities of the die block. It is, of course, a general and necessary practice to plane a die block all over before operating upon it, but there are other reasons for planing than the attainment of flatness, squareness and truth of "set."

A finished die is not complete when it has the design put upon or into it. The subsequent handling of the block, especially if it be large, must be arranged for. This matter has been touched upon sufficiently in the foregoing pages, and need not be extended here.

Every care of the finished surfaces must now be taken. The heating box already described (page 173) need not have a bedding of material deeper than one inch. It should be quite level and free from pits. The surface of this bedding may be level provided that the face of the die to be treated be level also. In the case of a hollowed out or cupped die, particular care must be taken to see that the hollow part is quite filled by the carburizing material, by application of movement and pressure. The surface of the die should be thickly painted over with a mixture of linseed oil, bone-black and fine steel filings. The object in view in employing steel or iron filings is to trap any possible tendency to oxidation of the finished surface, and to bring it forth from the quenching in all its original brightness. An alternative course is frequently resorted to. The surface is thinly brushed over with linseed oil and bone-black paint. Upon this adherent surface is dusted refined, dry, table salt. When the heat has risen sufficiently (1,475° F.) it will fuse, forming a protective coating upon the fine steel work until it is plunged into the quenching tank, when it will freeze and fall off.

When the die is bedded down into the mixture a further packing of this may be placed around it to a depth of half an inch to ensure covering the edges. A further half-inch of sand will improve matters. The upper part of the die block may be left exposed ; it will come to no harm.

Heating up should be very slow, starting with a cold furnace. A die as large as eight inches square may require to be in the heat three or four hours before it is soaked through and through, since it is not permissible to allow the furnace wells themselves to exceed some 1,300° F., for fear of overheating the exterior of the block before the centre is red-hot. The upper part of the die is kept under frequent observation until it begins to show unmistakable signs of red-heat. A pyrometer, if at hand, should be placed upon it at intervals until it shows about 1,250° F. If the eye is the only available guide, it may here be mentioned that the blood red is approximately 1,050° F. and a maximum cherry colour 1,250° F. A first-class carbon steel will harden at 1,100° F., if the bulk be not an impediment against easy handling. But at 1,250° F. the die may be hardened, and very thoroughly hardened as far back as we care to carry the process. But there is very little in favour of hardening a die of this kind deeper than one or two inches above the face.

Reference to the preceding pages (196, 230) should be made for quenching particulars, the procedure being the same as for the carburized die. A high carbon steel is, however, more easily hardened than a mild steel. But there is a possibility of cracking if a reasonable heat has been exceeded. Fortunately this risk may be ignored if obvious overheating is avoided. Instead of chilling off this class of die in the water, it should be removed while still as hot as boiling water and placed in oil to settle and cool off gradually.

In the hands of an inexperienced operator, who is either unable to judge by the eye what appearance a temperature of 1,250° F. presents, and who has not access to a pyrometer, it is well to err on the side of caution, and, if the steel fail to harden, a lesson will have been learnt, and no harm whatever will have happened to the die. It should simply be repacked and hardened at a higher temperature.

The "Singing" Heat.—When a heavy piece of red-hot steel is quenched in water, and the surface becomes black, a characteristic singing or hissing noise is emitted, by reason of steam evolution and heat vibrations, which may continue for some seconds. Just as this song is ending it is a good rule to remove the steel to an oil bath, which can afterwards be heated up to about 440° F., and so effectually temper the steel. If this is properly carried out, it will not as a rule be necessary to resort to a dry heat tempering, as already described. If the die must be left very hard, 420° F. of oil heat will be approximately correct. If the work upon it involves slender sections, liable to snap under stress, an oil bath of from 440° to 470° F. should be used. This die should remain in the hot oil for some time to permit of thorough diffusion of the heat. If the die is removed from the water while still at 212° F., a short immersion, of one hour, in the hot oil should suffice.

Proof of Hardness.—Whenever a die is removed from the last quench cooling or tempering, a proof of its hardened condition should be taken by means of the file test. A sharp, new file of good steel quality should be selected. The file should be tried upon all four sides, and if possible at the centre. Even after tempering at 440° F. the file should fail to cut or scratch the hard die at any of the above positions. There should be no difference of hardness between the outer and inner portions of the die. If there should be found a soft centre and a hard edging, it is a proof that, given an equal heat of the block, the quenching jet has not been effective. If the rush of water from the pipe is too widespread, it will harden the outer parts even more quickly than the centre. The water jet must aim at the centre first, and the surrounding edges should be held back until the centre has been two or three seconds under the cooling rush. The edges should be chilled, not by the jet, but by the rise of the surrounding water, or simply by lowering the die. The continued rush from the jet will serve to agitate and cool the water.

In the case of a high carbon die block the greater hardness of the centre is not so important as it is in the case of a carburized mild steel die. The first has an almost non-compressible body, not liable to "give" under the pressure of the centre. The second has a softer body, which may permit of a slight sinking under continued heavy work, and so put the die out of commission.

ALLOY STEEL DIES.

Considerable experience in the use of high duty dies made upon alloy steel blocks in France and in the United States within the last few years, has led to a great deal of die making in this country, upon blocks of chromium–nickel and vanadium tool steel, and what is now known as chromium–vanadium steel.

One of the salient advantages of the chrome-vanadium group of steels, as far as they apply to the making of press tools, and especially block dies, is the valuable property of this alloy to yield a deep hardened zone.

To illustrate, taking the case of a block of carbon steel, even of the highest grade, and eight inches square; it is not an easy matter to glass-harden more than three-quarters of an inch in depth when, as in die work, one face only is to be treated. This rough estimate will vary according to the heat of the block as it leaves the furnace and the conditions of quenching. Taking, now, the case of a chrome–vanadium of equal bulk, and under similar treatment except a rather higher initial temperature, a depth of dead hardness quite 25 % greater is to be expected without any additional risk of fracture or faults.

OUTSTANDING STRENGTH OF CHROME–VANADIUM.

Another unmistakable characteristic of this alloy is its immense dynamic strength, tenacity or toughness, and hardness. Hence it is not only adapted for heavy press work, but is extensively used for the hardest of all steel tool work—drop forging dies.

A notable characteristic of these steels is their great density and almost unequalled fineness of "grain." When these characteristics are allied with toughness and hardness, we have a material unrivalled for work which quickly destroys ordinary carbon steel tools. For these specific purposes chromium–vanadium steel is probably unequalled by any other alloy yet produced. It must not, however, be inferred that there is a field of universal usefulness for this material. For the present we will content ourselves with considering its application to press and percussion tool-making.

Specification.—Chromium 0·10 %, vanadium 0·16 %, manganese 0·50 %, carbon 0·50 %, silicon from 0·10 to 0·20 %.

A fine vanadium steel, omitting the chromium constituent, is extensively produced from the following specification: 0·16 % vanadium, 0·50 % manganese, 0·60 % to 0·70 % carbon, with a low percentage of silicon.

A notable characteristic of the vanadium group of steels is the necessarily higher quenching heat required. This peculiarity is, however, due, not so much to the inability of the steel to harden at a low rate in cold water as to the precautionary measure of oil quenching, to obviate any possible risk of cracking, which might otherwise manifest itself.

The treatment given to these steels in the United States, where they are now brought into extensive use for dies, is as follows :—

For chrome-vanadium : slowly produced quenching heat, 1,500° F., oil quench ; reheat to 1,435° F., water quench, but not complete submergence. In the case of a large die, the under jet method is to be used, as in carbon steel, and the back heat reserved for tempering as far as for carbon steel.

For vanadium : slowly produced quenching heat, 1,525° F., face quench in oil in motion direct as before. This high temperature, followed, as it is, by a cold quenching oil bath, should produce the requisite hardness. A water quench direct is also extensively used. In this case the quenching heat should not exceed 1,400° F. Back heat may be used for drawing the temper, or an oil bath at 430° F., producing a hardness equivalent to light straw colour temper. The oil temper drawing bath is available for either of the above examples of vanadium steels.

Anneal.—The necessity to ensure a thorough annealing of any heavy mass of alloy steel follows the practice in use with carbon steels, accompanied by the wisdom of planing off the skin of the whole before commencing the work of die-making.

File testing, after tempering, according to the foregoing suggestion is also in order, as is scleroscope testing.

Tool Fatigue.—Hammer dies, subject to percussive action, good examples of which are drop hammers and the pair of dies used in a swaging machine, are liable to suffer, after a time, from "steel fatigue," leading to a crystalline formation of the constituents. This can generally be relieved by fresh heat treatment, which applies equally to both carbon and alloy steels. The most thorough method to follow is to paint the pattern with the bone-black paint, lay it upon a shallow bed of carburizer as before, and heat up to over the critical range : Carbon 1,350° F., alloy 1,450° F., and quench. Slow heating is essential. In the case of a water quench being required for hardening, as in carbon steel, it is still better practice to quench first in oil, bodily ; to reheat to just under the critical range, and quench in water, as before. This treatment will be found to regenerate the grain and add to the working life of the tool.

Refractory Nature of Chromium Steel.—It should not be overlooked that, even after annealing treatment, the steels just spoken of offer greater resistance to cutting, drilling and working than any of the carbon group previously discussed. Under unfavourable conditions they are difficult to work, but are quite amenable to annealing treatment. Whatever view is taken of this drawback, it is after all only a source of initial trouble in preparation. There are hundreds of patterns of tools that can as easily be fashioned in these alloys as in carbon steel, and it is only the complex sunk dies that may turn out refractory propositions.

Long Life of Dies.—It is a safe estimate that if a carbon die be good for a thousand operations a chrome-vanadium die will be good for five times as many, given equal skill in preparation in both cases. While this is true of a drop forging die, it is safe to estimate still more favourably for vanadium in work of a less destructive nature.

MASS PRODUCTION OF DIES.

The production of great quantities of dies is a speciality of some firms, and in the United States has reached a high degree of perfection.

" Continuous " furnaces are at work in many establishments. These are nearly automatic. The receiving end of the equipment is a kind of preheating chamber. Without leaving the long furnace the dies travel on multiple runways from the cool and onwards to the hottest finishing end, whence they are removed fully ready for hardening in the quenching tank. A great deal of work can be handled in this way.

The use of fuel oil or natural gas, both copiously produced in America, are a valuable asset in work of this kind, especially since it must be conducted at specific temperatures, which are easily controlled and regulated by consuming either gas or fuel oil.

THE SMALLER PRESS TOOLS.

Blanking Dies.—Here we consider the treatment of press tools, generally of a smaller size than the usual run of dies, but in the treatment of which the same degree of skill is required as applies to the larger press dies.

The blanking die is made in every conceivable shape and form. It is generally required in duplicate, upper and lower; the under die being an exterior counterpart of the upper.

A great many of the blanking dies are cupped, or, in other words, are bored out, forming a chamber or *cul-de-sac.* The effective hardening and tempering of this form of die presents in many cases interesting problems.

In the preliminary preparation of the raw steel for small dies and punches, certain precautions are necessary. In the first place, the majority of the dies are made from the raw steel cut from the bar, and this material calls for some preparation before it is fashioned into a die.

Grade of Steel.—For ordinary pressings upon soft steel, brass and copper, carbon steel of the tool steel grade is generally used. Taking the hardest grade of die first, the steel used should come under specification: Carbon 1·15 %, manganese 0·30 %, sulphur 0·02 %, phosphorus 0·05 %, silicon 0·40 %.

A grade of carbon steel somewhat tougher is in general use, and suitable for blanking punches: Carbon 0·95 %, manganese 0·35 %, sulphur 0·02 %, phosphorus 0·02 %, silicon 0·40 %.

Pieces cut off the stock bars for blanking dies should always be annealed. The furnace can be charged with a box full of them, packed in ash or lime, and kept at a fair heat (dark cherry, 1,175° F.) for several hours, being allowed to cool out with the furnace overnight. This treatment will ensure ductility and freedom from stresses.

All raw steel "skin" should be planed or turned off. After the die is fashioned, the hardening process will depend upon its shape and dimensions. If the dies have expensive work upon them, open flame hardening should never be used. A bath of melted lead is one of the best heating agents, and although lead bath heating has to a great extent been superseded by the gas muffle furnace, it forms a valuable part of the small shop equipment. With a minimum amount of attention a pot of lead may be maintained at a uniform temperature for any length of time, especially if heated by a gas ring.

Dependent upon the bulk of the dies to be heated, the size of the lead pot should be as great as convenient, because a limited bulk of the molten metal will be easily chilled by the introduction of fresh work. An iron vessel which would contain a gallon of water is a useful size for small and medium dies. The heat to which the lead should be brought should seldom exceed 1,200° F., for the reason that, at about this temperature, lead begins to volatilize, giving off fumes that are most obnoxious and unwholesome. The surface of the melted lead must be covered with powdered charcoal to stop the formation of dross and oxides. And in addition to this precaution the lead must be frequently stirred to equalize the heat, if the source of this is of a local nature such as a gas ring. In every case of employing a lead bath, the use of a hood to carry off all fume into the flue should be insisted upon.

Temperature.—A lead bath kept at or just under 1,200° F. will be found hot enough for hardening fine carbon steel dies of all but the large sizes. But dies of intricate design present some difficulties by reason of the lead tending to stick between projections, in holes and serrations. Lead, having a very high specific gravity, steel will float in it, so that some ingenuity is called for in arranging to keep the dies below the surface of the bath. As to temperature certification, the simplest is the use of a test-rod of steel constantly kept in the bath, fixed to the bottom of the pot with its upper end projecting just above the surface of the molten lead. The appearance of this rod will serve as a fair guide of the degree of red heat attained, after a time, by dies sunk in the bath. A cherry red is usually quite sufficiently hot for hardening carbon steel. The use of a pyrometer is a great aid in the employment of heating baths of any kind.

The risk of overheating steel in a lead bath is very small. All the lead used should be pure and of good quality. Impure lead frequently shows a percentage of sulphur, which is apt to reduce the toughness of steel being heated, and may even ruin its fine surface. A test easily settles this point. The lead must be frequently stirred up if bottom heat is only used, otherwise there will be hot metal below and cool above.

When the heated steel is removed from the lead on its way to the water or oil quench, it is apt to oxidize to some extent, which may or may not be objectionable. Many file factories, which harden their work in the lead bath, are compelled to use a paint, owing to the tendency of lead to stick between the serrations and so leaving soft spots. The paint generally used is very effective, and is made as follows :

Powdered charred leather and fine table salt, of each 1 lb.; flour, 1½ lb. These ingredients are made into a smooth paste with water, after thorough mixing.

This paint is brushed all over the work to be protected, and allowed to dry. If work so treated be put into the lead while still wet, the lead will fly in every direction. The drying of the paint should not be hurried.

Common salt fuses at 1,475° F., which is rather high for die steel heating. But if the work be kept in the lead until the salt fuses, and then slowly withdrawn and quenched, its actual dipping temperature will be somewhat lower. The advantage of employing protective paint lies in the absolutely clean surface left after the quenching water has touched the steel and the avoidance of trouble with lead lodging in shallow places. In every case, if the work to be heated in lead is at all heavy, it should not be placed in the bath cold, but should be brought to a reasonable heat, even approaching a dull red, otherwise the lead bath will be found a slow method of heating. Its chief advantage, of course, lies in the certainty of *uniform* heating of all parts. In all die work, the greatest care should be taken to quench at the correct heat, and never to *exceed* a good red, or 1,275° F. Steel that will harden well below this high heat need not be brought up to it.

Before heat treating any die steel, a test should be made with disks sawn off the stock bar. Three of these should be heated to different rednesses, and quenched. The *lowest* heat should be selected, for the regular hardening temperature of tools from that stock, provided that the test piece will stand a trial with a sharp file, and will fracture, revealing a fine grain.

Salt Bath Heat.—The lead heating bath has been superseded in many cases by a bath of common table salt, with admixtures, which provide means of working at temperatures as high as 1,650° F. A useful mixture is: common table salt 70 %, potassium chloride 30 %. The admixture of a greater proportion of potassium chloride (fusing at 1,345° F.) will reduce the fusing point of the bath. No such temperature as 1,650° F. should be used in treating die steel, the hardening temperature of which should seldom exceed 1,250° F.

One of the great advantages of the salt bath lies in its evolving no fumes, even at the highest temperature.

Another advantage incidental to its low specific gravity is that steel cannot float in it, and no trouble need be taken to keep the pieces being heated in position. Further, it is not mandatory to maintain the bath at or near the proper hardening heat. In practical working the temperature may with advantage be kept much higher, taking the common precaution to withdraw the dies being heated when they attain the actual apparent heat certified by the test piece trials of the batch of steel being worked upon.

Furnace Heat for Dies.—For continuous profitable working there is nothing better than a small tool-heating gas furnace. These are now a common part of equipment, sold by all tool merchants. A muffle to use with it is not a necessity. The smaller dies and punches under consideration should not be put direct into the furnace. Except they be simply plain dies for punching or blanking, with little or no pattern worked into them, they should in every case be painted over with the salt paint just described. An iron tray, some two inches deep, should have within it a mixture of charred leather powder and powdered charcoal. The dies should be buried, face down, in this protective bedding. The heat to be attained, in the absence of the pyrometer, must be chiefly judged by the eye. It will run from a red up to a cherry red. At the latter heat any good die steel will harden with certainty. It is a doubtful practice to endeavour to harden even this steel at *too low a heat.* File hardness may, it is true, be secured at a minimum heat, but exterior file hardness is apt to be deceptive as to the actual condition of the steel beyond the first $\frac{1}{16}$ in. Great numbers of tools "give" and fail through timidity in hardening. Hardening is a violent reaction of nature, and cannot take its full effect in the absence of the great compelling power of *sufficient heat.*

In cutting test pieces from the stock bar, they should not be less than $\frac{1}{4}$ in. in thickness. Each one that is hardened at its own heat should be tried for fracture by placing two edges of it upon supports upon the anvil. A blow from the pane-face of a hammer should suffice to crack it across. The test must go deeper than merely endeavouring to cut it with a file. The centre of the thickness should also resist the file completely.

It will then probably be found that there is one piece that defies the file exteriorily, but yields to it in the centre.

Here is an instance of under-heating, which is no better than over-heating, except that an under-heated tool can, later on, be rehardened if it be detected before the work it is doing destroys it. Overheating either weakens the steel or quite destroys its crystalline structure, and steel so injured is practically not worth regenerating.

Chilling.—For die-face hardening there is probably no better arrangement of the water than that previously described in reference to the case of the larger dies (p. 275), but a still more simple arrangement of pipe and tank can be made to serve for hardening small dies. A smaller jet, for example, and a slower rush of water will suffice. If the dies are not of the undercut and cupped variety, a jet may be dispensed with and a swift movement of the hot die across the surface of the water will suffice.

Level-faced Dies.—Except when the tool to be hardened is very small, a mere dipping into still water is not generally effective. The end of the tool should be immersed to a depth proportional to its diameter or bulk, and moved quickly from side to side to ensure fresh water surrounding it until the hardness has been assured. Running water is very convenient for hardening of every kind, except cupped or hollow-faced dies. There being no upward rush of water, and only movement in a horizontal plane, a sufficiently exact level of hardening can be assured. But the novice must be aware of keeping a die quite still vertically in a quenching tank. This would result in hardening up to an exact line, accompanied by a very great risk of a crack right around the steel of the tool at this height. Sharp-line hardening may in some cases be a success, but in most instances it precedes a fracture, *either at once or later* ; this break will appear upon the fixed hardening line.

Especially in the case of dies subjected to a percussive or hammering action, fixed-line hardening must be avoided. It is necessary, if such tools are to remain in service a reasonable time, that a graduated zone shall be effected between the hard and the soft sections of the steel. This is, of course, easily assured by moving the die up and down in the quench, during hardening. The vertical movement need not exceed ½ in. in the case of small tools.

Cupped-faced Dies.—When these are small they are apt to cause considerable trouble if adequate arrangements are not made for dealing with them. When a die of this kind is plunged into still water only, there will occur a quick hardening of the outer rim and the face, but the hollow part will be filled with steam, and no water will reach it for some time. It will therefore remain soft. Some hardeners arrange for an overhead water jet to meet this difficulty, but this course is not always successful because it floods the whole die body below it, and hardens a greater part that is intended to be left in the soft state.

The rising jet is much more manageable if it be of small volume, because the cup of the die can be lowered right down upon it, shutting off the spreading effect ; and then, by a little skilful manipulation, ensuring water as cool in the hollow as it is elsewhere. A depressible jet is by far the best arrangement, but it must not be permitted to throw water where it is not wanted. Let the jet be in gentle action at the surface of the water, a stream quietly flowing from it. Let the cupped die be placed directly upon it, and pressure used to sink the die to the predetermined depth of hardening, which is seldom required higher than 1 in. The movement of the jet water in a cupped part will prevent the development of pressure of steam there, and a perfectly uniform rate of hardening will result. This continued action of the jet renders unnecessary any lateral movement of the die during the chilling operation.

We have devoted particular attention to the details of the water hardening of small dies, chiefly because the arrangements employed in the case of large dies are quite useless and are not applicable ; and again any scheme suitable to the case of plain tools is quite ineffective in the hardening of hollow-faced dies, where the quench becomes at once steam-trapped.

Disposal After Quenching.—There are in daily use a number of different treatments of hardened dies, in order to secure the required tempering. It may at once be assumed that the glass-hard condition resulting from the water quenching must be modified before the tool is put into use, otherwise it will probably, being in a brittle condition, break up upon the first motion of the press. The old-fashioned way was to withdraw the tool from the water as soon as all colour of redness had departed, indicating full hardening. This is done while the upper part of the tool is still very hot. A quick application of an emery stick to the hard part reveals the bright steel. The heat meanwhile is creeping back into the chilled end of the tool. In a short space of time, seldom exceeding one minute, the oncoming of the upper heat will be observed in the changing brightness of the cleared spot—at first a faint straw yellow, gradually deepening.

What "straw colour" really is no man can say, because straw is of all colours, from the faintest tint of yellow gold to light brown. Let each man cherish his own notion of what straw colour is like ; meantime we will be content to fix it more definitely by naming a temperature of 450° F. as a heat that will cause bright steel to assume a light golden colour by oxidation. This degree of hardness, or softening, is found to be very effective in prolonging the life of a press tool such as is used for blanking and general cutting out. For tools intended for hammering action, a slightly higher heat (10 deg.) secures a rather tougher surface and backing of the steel.

At this stage, no time is lost in throwing the tool into a vessel of cool oil, which arrests the further progress of the tempering heat. The carrying out of the foregoing apparently simple process really calls for some dexterity, keen knowledge, and quickness, and when all these are allied, a very good result is assured. But in the absence of any one of these desirable elements, failure is probable.

A far more successful method lies in the use of an oil-tempering bath in the case of small dies. A description of this has already been given as applicable to large dies ; but it may be convenient here to recapitulate, in reference to this, to the extent of mentioning that the oil-tempering bath is merely a vessel of high flash-point oil (600° F.), kept in heat by a gas ring, and fitted with a high degree mercury thermometer. The heat generally required is, as stated above, about 450° F. Dies placed in the oil will absorb its heat, which it should be allowed to recover without increasing the fire below. Time should be allowed for thorough penetration of the heat, according to the bulk of metal in the bath. Dies so treated will resist the file, and will be found to possess to a remarkable extent the qualities of extreme stiffness and toughness. It is assumed that the die is placed in the tempering oil as soon as its working end is hard and its upper half free of the wetness of the quenching bath ; otherwise the hot oil may be caused to splutter by contact with moisture.

Deep Chambers in Dies.—The procedure dealt with in the preceding pages covers the requirements of ordinary die treatment in hardening with the die turned face down. There are, however, occasional instances of tools of this class that are quite out of the ordinary run; and with reference to hardening a tool of this description the difficulty of dealing with a deep depression or series of depressions, having no outlet, is probably the greatest.

The problem that presents itself is how to force cold water into these chambers so quickly that steam formation cannot impede hardening. Instances of this kind have come under our observation so difficult to harden that an unusual procedure had to be resorted to. Fortunately it is quite simple and also quite effective. One of the cases in point had two deep chambers or pits drilled upwards into the face of the die. An attempt at hardening, using a strong jet of water for each hole, was a partial failure—the steam pressure developed kept the water back. It then occurred to the hardener that he must get rid of this steam pressure in some way. A small pipe syphon was tried and was successful; but simply drilling a vent hole from the crown of the chamber to the upper part of the die was still better. A small $\frac{1}{16}$-in. hole sufficed, and the vent was, after hardening, plugged up with a piece of hard steel wire.

Attempts to deal with these pits by turning the die *face up* are open to two objections: first, a die hardened face up cannot be treated so effectively as one turned face down, chiefly because the overhead water supply falls all over the die, quenching off too much of the back heat and unduly hurrying the hardening of the walls; and secondly, because any jet of water projected into a deep hole is promptly thrown back by the steam, as in under-hardening.

Hard Through Holes.—Long holes, as, for example, in a long ring-die, if narrow, may present a difficulty. But this can be got over by the simple expedient of employing a length of brass or iron tubing half the diameter of the hole, with closed end, and its walls pierced with a number of holes. This is connected to the water supply, the pressure being turned on the instant the hole is dropped over the tube. Such a hole-hardening device has proved very effective and never fails to secure a uniform hardness throughout the length of the hole.

Exterior cooling of a die having a through hole, as in the above instance, may in most cases follow the actual chilling of the walls of the through-way. One dash of water upon the walls of the hole should be followed by chilling of the outer parts. In most cases this is accomplished by simply lowering the whole into the quench, with such agitation of the water that the quenching does not take place in hot water, which is the leading cause of most hardening failures. Water intended for quenching must also be quite clean and free from grease.

CHAPTER XIII

HIGH SPEED TOOLS

A REVOLUTION in mechanical engineering practice was inaugurated by Mushet's discovery that by alloying tungsten with carbon steel, tools made from this product could be used for cutting metals at unprecedented speeds.

The rate of cutting revolving metals by means of carbon steel tools was limited by reason of the frictional heat developed, causing loss of hardness in the cutting edge. The "red hardness" of tungsten steel is its most remarkable and valuable property, since a cutting rate that develops friction sufficient to make the point of the tool red-hot, does not put the tool out of commission—it still remains hard and unyielding. No carbon steel can stand this treatment, without being untempered and rendered quite soft.

Not only did the new alloy prove its capability to continue to cut at great speeds, but its great density and extraordinarily fine microscopic structure endowed it with strength to withstand the pressure of cutting so deeply that the very machine tools themselves proved incapable of withstanding the strain of the full efficiency of tungsten tool steel. More powerful turning lathes and other machine tools had to be provided, speed ratios revolutionized, and a fresh apprenticeship undertaken by the tool-maker in respect to heat treatment of the new tool steel.

Grindstone Test of High Speed Steel.—Carbon steel throws a bright white spark upon the emery wheel. *A good grade of high speed steel throws a dull-red spark only.* A poor grade of high speed throws a mixed red and white spark. In this way, pieces of high speed steel can be separated from carbon steel.

Figs. 132–135 are representative of the "semi high speed" steels, highly magnified and referred to in the text.

If a piece of hard carbon steel be fractured and the microstructure of it minutely examined, and this compared with a similar fracture of tungsten steel, a striking dissimilitude will be at once observed, and one reason for the great tenacity and strength of this steel will be apparent to the eye at least.

Taking an ordinary high carbon hardened steel tool, we know that if a temperature of anything above 400° F. be developed by the friction of cutting, the softening of the edge speedily follows. Practically the same steel, alloyed with 16 % of tungsten, and also hardened, will retain its full cutting powers unimpaired at a temperature of over 1,000° F. Taking a Brinell test, it is easily demonstrable that *increasing* hardness follows raising the temperature of the tool from 1,000° to 1,200° F., the Brinell value for

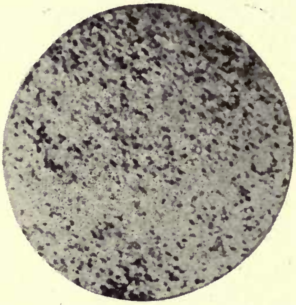

× 100.

FIG. 132.—Low tungsten steel, heated at 732° C., water quenched. Brayshaw.

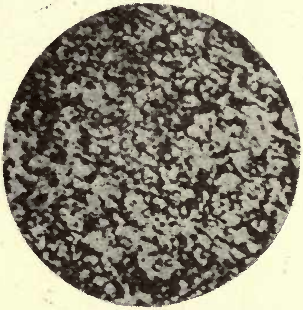

× 500.

FIG. 133.—Low tungsten steel, heated 4 hours at 732° C., water quenched. Brayshaw.

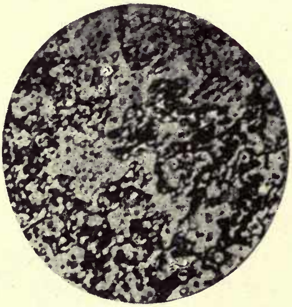

× 500.

FIG. 134.—Low tungsten steel, heated 8 hours at 732° C., water quench. Brayshaw.

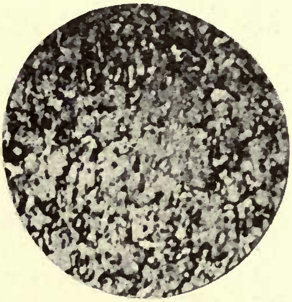

× 500.

FIG. 135.—Low tungsten steel, heated 12 hours at 732° C. Brayshaw.

the former being 540 and for the latter 630. The practical significance of these figures will be more readily realized when we remember that a temperature of 1,200° F. brings tool steel to a blood-red heat. Touching this point, Arnold (*Chem. News*, 1916, p. 218) found that the thermal stability of carbon steel is considerably under 575° F., but that the compound hardenite of high-speed steel may be rendered stable up to 1,292° F. The same authority, however, calls in question whether a Brinell hardness number has any relationship to speed-cutting efficiency.

High speed steel is a name which is to-day applied to other alloys than the tungsten alloy, but tungsten remains an important factor in almost all of them. It may still be regarded as the determining factor in reference to red hardness.

The more recently developed high speed steels are composed of certain proportions of tungsten, chromium and vanadium in alliance with the usual components of carbon steel. Carbon and manganese are present in all of them as well as the usual traces of silicon, sulphur, and phosphorus.

Taking a simple tungsten steel (carbon, tungsten, manganese), we have a combination which leaves little to be desired in point of hardness, and the quality of ripping up steel. There is, however, something lacking in point of finish in the surface cuts of such a tool. There is a lack of that silky surface which is so characteristic of the fine carbon steel tool. In plain words, a tungsten steel, while undoubtedly effective in getting through the work, leaves it lacking finish.

Here it is that the chrome–vanadium alloys, especially the former, appear to exert a powerful influence upon the usefulness of the tool in point of finish upon the work. If the term be advisable, they supply the lack of *toughness* so characteristic of the tungsten steels, and doubtless are the main factor in the very fine edge which the later high-speed steels can maintain under adverse conditions. This fine edge is the determining factor in the production of a good finish upon the work. The advantage of using the chromium–vanadium alloy is not so apparent when the sole use to which a tool is put is the ripping off of large sections from the stock in the lathe. A tungsten steel is apparently all that is required. But the uses to which the new steels are put are so various that it is scarcely a profitable proposition for the steel-maker to produce only the plain tungsten steel, when the market for a better all-round article is so well assured.

Hence, we have most of the makers only vending the more complex alloy high speed steels, of which the following is an average example: Carbon 0·76 %, tungsten 18·85 %, chromium 2·95 %, manganese 0·42 %, silicon 0·33 %. This steel is produced in England, and is known under the name of Novo steel. It is a very fair sample, and is not surpassed by any of the high speed group of steels made either here or abroad.

The Bedel steel, well known in France, is specified as follows: Carbon 0·90 %, tungsten 22·80 %, chromium 8·10 %, manganese 0·27 %, silicon 0·20 %.

A well-known brand of American steel is specified as: Carbon 0·67 %, tungsten 17·5 %, chromium 4·0 %, vanadium 0·82 %, manganese 0·25 %, silicon 0·25 %.

German steel-makers are well to the front in the production of high speed steels, in which they are notable in respect of complexity of constituents. The following is a leading steel of this description: Carbon 0·75 %, tungsten 16·10 %, chromium 4·20 %, vanadium 0·85 %, molybdenum 0·90 %, silicon 0·30 %.

Heat Treatment of High Speed Steels.—Every prominent steel firm produces a high speed tool steel having some special characteristic. It will, therefore, be surmised that the number of different brands of this steel in use to-day is legion. A beginner in the use of this kind of steel will be bewildered by the different claims made on behalf of different makes. But there is no reason to hesitate. He has only to select a high speed tool steel, made by any steel-making firm of repute, and he will find it just as good as any other of equal market price.

Taking a round dozen of different makes, we will find almost every one ticketed with special directions for treatment.

We may observe this treatment if we prefer, but it is not necessarily essential in producing a good tool.

The author has tested, in his own works, a large number of different makes of high speed steels, produced by firms of good repute, and can state his conviction that one simple treatment in both forging and hardening is all that is required to bring out the most useful qualities of the different brands. The kind of steel referred to is the ordinary turning-tool variety, in which hardness, at a cutting speed sufficient to raise the temperature of the point of the tool to over 800° F. is retained—the " red hardness " so often spoken of in connection with tungsten steel. This treatment is described further on. The natural sequence of handling the tungsten steel must be followed here by dealing with the annealing and forging treatments, and then the hardening and tempering process.

Annealing.—Bar steel that has to be cut up into short lengths for making turning and planer tools does not require preliminary annealing. But all steel intended for drill, milling cutter and die-making should be annealed, otherwise the cost of tooling them is greatly increased. The cost of annealing is probably not 5 % of the increased cost of tooling if annealing is neglected.

There is nothing very special about annealing high speed steel. It is substantially the same treatment as is used for carbon steel, already described, with the exception of a rather high temperature in the furnace and a longer exposure to it. Wood charcoal is the best material to use in packing. There is a risk of producing hard spots if lime or mica powder be used. The steel should be kept away from contact with the bottom or sides of the firing box. The heat to be maintained, for several hours, should in general be as high as 1,500° F., which is approximately what would be recognized as a bright red colour. This can be ascertained in the usual way by means of a test rod. The heat should be kept as uniform as possible, for not less than five hours if the pieces be heavy. Light plates, disks or rods can be treated in from two to four hours. Slow cooling in, or with, the furnace is advisable. If this simple treatment be carried out, the contents of the box will be found to yield to cutting and drilling as readily as high carbon steel.

Parting.—This is cutting up into lengths. The best way is to cut up with the power hack saw, run at a low speed—under 100 strokes per minute. Breaking should always be preceded by deep hot nicking, if done at all.

Forging.—Treatment upon the anvil of tungsten steel alloys follows the lines of forging applicable to high carbon steel in the main. But no high speed steel should be hammered at a dull red heat. Also, the initial heat (when taken from the fire) should be at least as high as 1,500 F. or a bright red. A light hammer should *not* be used, for this will affect the core, and by chilling the exterior before the work is done may be the cause of subsequent cracking. Rapid treatment, using a rather heavy hammer, is the most successful method of forging high speed steels. Blows must cease as soon as the bar has lost its plasticity, and a reheat taken, if necessary for finishing.

Liability to Crack.—Throughout any kind of treatment of high speed steel it is necessary to bear in mind that this material is very liable to self-fracture. This tendency to crack may be induced by a variety of causes, such as hammer blows when in the non-plastic state, and sudden, violent, changes of temperature, as the contact with water or other good heat conductor while at a high temperature.

Hence, in hardening, the surrounding air, an air blast, or a momentary plunge into whale oil are the cooling media used, water or mercury cooling being entirely prohibitory.

Hardening and Tempering.—The treatment accorded to carbon tool steel is of no use in the case of the tungsten alloy material. It is only necessary to heat carbon steel to a blood red and plunge it into water to secure dead hardness. Almost every make of high speed steel must be heated until it is nearing the fusing point, before it is cooled in air or oil. The procedure in this operation calls for some little forethought and care.

Typical Hardening Operation.—Most of the high speed steels marketed to-day can be hardened so as to act as serviceable tools by carrying out the following simple directions: Place the tool (lathe or planer or slotter tool) where its business end can be heated up *gradually* to a red-heat, or 1,500° F. If cracks are to be avoided, this preliminary heating must not be hurried. The end of the tool is now to be *rapidly* heated up until it appears upon the point of fusing. This appearance will occur at an intense white-heat, about 2,000° to 2,200° F. The point of the tool should be either placed in an air blast or dipped into whale oil, until it shows black. It may then be laid down and allowed to finish cooling slowly. The really important point about these directions is the observance of the *high* heat. If any mistake be made here, the point of the tool will either be quite melted (fused) or it will be insufficiently heated, in which latter case it will not harden. In the case of a fused point the tool will be hard, but grinding will be necessary to restore the shape of the point. The cooling is only a secondary consideration. If the heat be sufficiently high, neither air nor oil cooling need be used. In the original Mushet steel, in which tungsten played the chief part, the tool was brought nearly to fusing heat in a smith's fire, and then thrown upon the ashes to cool out. No further treatment was required, other than a grind upon a water-stone to fit it for its place in the tool box of lathe or planing machine. This material was known as Mushet self-hardening steel. Here we have the rough essential treatment, under which any first-class high speed steel will yield a serviceable, although not the best, tool.

Now it will be obvious that, except in the case of those tools that can be ground into condition after hardening (such as turning and planer tools), the foregoing heating directions are not applicable just as they stand. Take the case of a relieving or forming tool, for use in the lathe, the semi-fusing of the point would destroy the pattern, unless it were of a rough description. The same difficulty presents itself, but in an accentuated form, in the case of milling cutters and drills.

For at least twenty years the above difficulty precluded the use of high speed steel for any tools but those that could be shaped upon the stone after effective hardening. For several years past, however, the difficulty of effectively hardening fine high speed tools has been overcome, and no difficulty is now experienced in manufacturing the finest tools from the chrome–vanadium–tungsten steels—tools with which the finest carbon steel tools cannot bear comparison in length of life. The processes involved are fully treated further on ; but we must now continue our consideration of the simple hardening and tempering of the ordinary turning and shaping tools.

At the Bethlehem Steel Company's works a valuable series of investigations were lately undertaken by Messrs. Taylor & White, in reference to the different methods of hardening, such as turning and planer tools, and Mr. F. W. Taylor's paper, read before the American Society of Mechanical Engineers, has become a classic among writers upon the treatment of steel. It is essentially a practical paper, written by a practical man, and although it was published in 1906 a quotation from it at the present day is well justified :—

"For some years past it has been rather amusing to us to hear the special directions given by various manufacturers of steel suitable in chemical composition for making the high speed tools. Very frequently a tool steel-maker implies or indirectly states that the chemical composition of his particular high speed tool steel requires 'special treatment.' The fact is, however, that our recent experiments demonstrate beyond question the fact that no other method which has come to our attention produces a tool superior in red hardness (i.e. high speed cutting ability), or equal in uniformity to the method described, the essentials of which follow:—

"Heat the tool slowly until it attains a bright red (1,500° F.) and then rapidly from that temperature to just melting-point. The tool is then placed quickly in a lead bath maintained at a constant temperature of 1,150° F. and held there until it has reached that temperature throughout (its cutting end). It is then withdrawn and allowed to cool out in the air. If tempering be desired, it is reheated in a lead bath to between 700° and 1,100° F. and again cooled out in the air. No air blast or oil is used in either of these treatments.

"It will be obvious that the tempering bath is only to be used if the tool is intended to cut the softer materials, or is of a kind having slender unsupported edges. While the harder, untempered tool was adapted to ripping off the stock, regardless of finish or smoothness, the softer tool was intended to retain a finer edge, upon the softer steels."

The remarks relating to Messrs. Taylor & White's experiments intended to exhaust the subject of hardening and tempering are illuminative. The paper continues:

"In cooling from the high heat we experimented with a large variety of methods. After being heated close to the melting-point, tools were immediately buried in lime, in powdered charcoal, and in a mixture of lime and powdered charcoal; thus they were cooled extremely slowly, hours being required for them to get below a red-heat. And we wish clearly to state the fact that tools cooled even as slowly as this, while they were in many cases quite soft and could be filed readily, nevertheless retained the property of red-hardness in as high a degree as the very best tools, and were capable of cutting the medium and softer steels at as high cutting speeds as the best tools which were cooled more rapidly and which were much harder in the ordinary sense.

" Tools were also cooled from the high heat in a muffle or slow-cooling furnace with a similar result. On the other hand, we have secured excellent high speed tools by plunging them directly into cold water from the high heat and allowing them to become as cold as the water before removing them. Between these two extremes of slow and fast cooling—cooling in lime, charcoal or a muffle, on the one hand and in cold water on the other—further cooling experiments covering a wide range were conducted. We tried cooling them partly in water and slowly for the rest of the time; partly in oil, and then slowly for the rest of the time ; partly by a heavy blast of air from an ordinary blower, and the rest of the time slowly ; partly under a blast of compressed air and then slowly. We also reversed these operations by cooling first in water and afterwards in oil.

" By every one of these methods we were able to make a good high speed tool, i.e. a tool having a large degree of red-hardness and capable of cutting at very high speeds. But by none of these processes were we able to obtain tools as uniform and regular as those produced by our lead bath and air cooling."

As throwing light upon the real nature of high speed steel in reference to its tenacious cutting qualities, Mr. Taylor's remarks above, in which he instances the free cutting of the softer steels while the tool was not in the hardened state at all, we may recall the nature of both tungsten and vanadium, the former acting as a preventative of the transition of the austenite into pearlite, and so maintaining hardness, and the latter in greatly lowering the temperature necessary for the production of an adamantine condition. It is further worth noting that the present-day high-speed steel manufactured by the same company responsible for the foregoing experiments is issued with the simple instruction to heat the point of the tool to a white-heat, and to cool out in a *dry*, cold air blast, there being no mention of the advisability of quenching in a lead bath. Again, referring to the Bethlehem Company's high speed steel, as made into milling cutters, the instruction of to-day is to heat (presumably in a barium chloride bath) to nearly fusing-point and cool out in oil, afterwards drawing the temper to a straw colour, as in carbon steel treatment.

Dry Air.—It is necessary here to draw attention to the above reservation with regard to the nature of the air blast to be used in chilling the point of the tool. Dry air is specified. It is perhaps needless to point out that moist air is many times (dependent upon its percentage of moisture) more rapidly heat-abstracting (or conducting) than dry air.

So great is the difference between moist and dry that the author has repeatedly observed in his own works the faces of shell-band grooving tools cracked by using moist air, but never in the use of air passed through an anhydrator. The anhydrator used consisted simply of a tube containing a loose mass of dried lime, through which the aid supplied by a Root's blower was made to pass before it was delivered to the nozzle. The lime should be dried daily.

All of the foregoing treatments of high speed tools are applicable only to such types as may be ground into shape after they are hardened. The necessarily high heat, approaching the melting-point, would generally blunt or destroy the fine edges of other tools, such as milling cutters, or forming tools, so that the open furnace high-heating system is confined to a rather limited class.

In using these tools for other than plain turning tools, it is well to study the manufacturer's directions.

Soft Skin on Hard Point.—It is a common experience to find that a grindable tool, after hardening, will not cut well unless it is ground, and a fresh surface produced upon the cutting edge. In almost every case of open furnace heating there will be found a comparatively soft skin upon the parts brought nearly to fusing-point. The depth of this skin has been variously estimated at from $\frac{1}{1000}$ to $\frac{5}{1000}$ in. Put to work in this condition, the tool will not cut keenly. The only remedy is to grind up a fresh edge, when the *real hardness* of the point will be found just under the surface.

Nitrogen the Softening Agent?—At the high temperatures used, it would appear that the nitrogen of the air, combining with the carbon, and so forming methane, would account for the softness of the surface.

To a great extent this trouble with lathe, planer and form tools can be obviated by withdrawing the tool from the high heat, before it reaches the white-heat stage, and dipping it into barium chloride, or a mixture of common salt and barium chloride. Powdered borax may also be used, as also the white cyanide of potassium. But the latter gives off obnoxious fumes.

If it were not for the ease and rapidity of simply heating a high speed tool at the forge, it is doubtful whether writers or lecturers on this subject are justified in advocating the exposed heating of high speed steel for hardening purposes. At the present time, when every kind of fine cutting tool can be made from high speed steel, this view is worthy of emphasis. In the past, when tungsten steel was practically confined to the making of turning tools, there was no necessity to set up a salt bath for heating. To-day, the salt bath, or its equivalent, is a necessity in every tool shop.

Grinding.—A carbon steel tool, duly hardened, can easily be made soft again by careless treatment upon the grinding wheel. A little too much pressure upon a dry emery wheel, and the tool is untempered. The same thing happens to a certain extent in the case of a high speed tool; but the two cases are not parallel. In the carbon steel we endeavour to avoid "blueing" the steel—or softening it; in the high speed tool a good deal of heat will fail to soften it, but a little *undue heat may cause cracks* in its face.

Hence, with carbon steel it is softening that must be guarded against. In the case of high speed steel it is local heating, *causing a tendency to crack*, that must be avoided. For this reason, makers generally give directions as to the kind of grinding wheel or stone to use with their particular brands. In almost every case the advice is to use a wet emery wheel and preferably a wet sand-stone, and to be sparing with the pressure applied. Plenty of water should be used. One or two brands actually mention a dry wheel, but the majority recommend a wet sand-stone, which from long experience the author endorses.

Fine High Speed Tools.—We here enter upon a more delicate class of work and treatment. By reason of the high temperature required in the hardening of the steel a particular procedure is required in order to ensure success, but it is not necessarily difficult if the operator proceeds upon correct lines.

Until lately the production of fine cutting tools, such as milling saws and fine drills, upon a commercial scale, was regarded as a doubtful proposition when the material required was a good grade of high speed steel. We had "semi-high speed" and the like, which were no better than carbon steel tools, and certainly had no red-hardness to boast of, although sold at enhanced prices.

It must not be supposed that the valuable property of red-hardness is the cause of the extending production of high speed steel fine cutting tools. As was pointed out at the beginning of this chapter, the microstructure of a good high speed steel, if examined, even by the unaided eye, tells its own tale to the experienced machinist. He can see from the appearance of the fractured surface that here is a substance that is going to "stand up" to unlimited work, and that re-grinding will be a very rare occurrence.

To illustrate this point, the writer has had in use a gear-cutting machine, running three sets of toothing cutters upon a single spindle. The gears to be cut were banked in three rows of twelve each, forming a length of nearly solid mild steel of twelve inches. For some years the machine was run with three sets of toothing cutters or saws made from the best grade of high speed carbon steel. The depth of cut was about three-eighths of an inch. There was an oil drip upon each set of cutters. From long experience the carbon steel cutters had to be re-sharpened about every week. The dismounting and re-setting up of the gear cutter with its three sets was a long job, and much time was lost thereby. As soon as the high-speed steel could be utilized it was tried upon this gear cutter. The result was a revelation. With a good set of cutters duly mounted, the necessity for re-sharpening almost disappeared. Week after week of production would go by and no sign of dull edge upon the cutters would appear. Barring accidents, the high speed saws would continue in work indefinitely. Working eight hours per day upon Bessemer steel the machine has been observed to continue producing, without re-grinding or re-setting, for months at a time. We also found that both the peripheral speed and the rate of automatic feed could be increased 30%. In plain words, there was no comparison between the efficiency of carbon steel cutters and high-speed cutters.

Now this particular case had no special reference to the quality of red-hardness so valuable in a turning lathe geared to run at great peripheral speeds. There was no necessity to run the gear-cutting engine at a speed that would result in making the saws or cutters red-hot. On the contrary, they were quite cold, and the lubricating oil did not even smoke during the deepest part of the cutting. The steel used for the making of the cutters was of the usual type, or as specified: Carbon 0·76 %, tungsten 18·85 %, chromium 2·95 %, manganese 0·42 %, silicon 0·33 %. The cutters used were made from rolled plate ¼ in. thick. The actual thickness at work was ⅛ in.; twenty teeth were spaced around the disk, which was 3 in. in diameter; the bore was ¾ in. They were hollow ground across the portion at work, affording ample clearance. Hardening was effected after pre-heating to a dull red in a salt bath, at a temperature approaching 2,000° F. (a white-heat). The cooling out was done in whale oil. Tempering was done in hot tempering oil, at 460° F. equal to a straw colour upon carbon steel. There was no sign of scaling or heat roughness upon the finished cutters, which came through quite bright.

The above example would be regarded as that of a fine, delicate tool, working under considerable stress, although not under as great pressure as a twist drill.

Forming Tools.—During the high pressure period of the war, the writer was engaged in the production, amongst other work, of high-speed tools for use in some of the National projectile establishments. The tools were mostly of the "form" type, in which a particular pattern had to be preserved intact during the life of the tool. Two examples of these were used for cutting the copper band channel, and the wave-pattern within it upon the bodies of high explosive shells, composed of high tensile steel of the toughest nature. Here was a type of tool that could not be exposed, without risk, to open furnace heating for hardening, because the fine pattern might thereby be defaced. The tools were produced in quantity, mostly from annealed bars, 1¼ by 1 in. They were milled to shape and mostly hand-finished for smoothness. Top grinding only sufficed to preserve the pattern until the tool was too thin to use. The limit or margin of error was $\frac{1}{1000}$ in. Similar forming tools were produced in quantity in the circular form, consisting of a disk some 1 in. in thickness and 3½ in. in diameter, with a section cut away to form the cutting edge. These had a complete pattern, and were required to finish quite perfect and smooth. They were made from bar steel, the blanks being cut off by the power hack-saw machine running at a slow speed.

The above will serve as representative types of cutting tool, to be employed upon shell steel, and from which a long life was expected. They were all pre-heated in the furnace and heated for hardening in a salt bath, at a nearly white-heat, and cooled in whale oil without tempering. A crack was of rare occurrence, and a clean, undefaced pattern resulted.

Centering Drills.—A large proportion of the centering drills were made from high carbon steel, the treatment of which has been spoken of in an earlier chapter. The author produced many thousands of these drills, however, from high speed steel. The largest size was about $\frac{5}{8}$ in. in diameter and the smallest $\frac{3}{16}$ in. Since these tools had to be put through a relieving or backing-off process, they were made from bar steel, previously annealed. It may be necessary to mention that centering drills are usually short, not exceeding 3 in. in length, and also double-ended. Hence, they were troublesome articles to handle in the hardening. In order to pass them through the hardening salt bath, after furnace pre-heating, a wire holder, into which six widely spaced drills could be placed at a time, was used for the dipping. Two of these could be accommodated in the salt bath at a time. Movement in the cooling oil was necessary. The tempering was done in an oil bath heated to 400° F., each batch of twenty-five drills being given fifteen minutes' immersion. Cracking was unknown

High Speed Twist Drills.—The vulnerable part of a drill is its extreme chisel-point. It is here that the great advantage of high speed steel tells. If the drills are made from stock treated for annealing according to the directions already given, there is no difficulty in milling them. The metal should cut as easily as a high carbon steel. In many shops the pointing of the carbon twist drill is left until after the hardening. This should not be done in the case of high speed steel. The point should be formed, and only the finish grinding left until after tempering. All heating to the nearly white-heat required should be done in a salt "melt," already described (page 118).

Hottest at Point.—Reversing the usual order of things in reference to the salt or lead bath heating, in which every endeavour is made to attain a uniform heat throughout the depth of the bath, it will be found a practical advantage to permit the lower half of the salt melt to attain a rather higher temperature than the upper half, in hardening twist drills.

The effect of this arrangement will be that the drills immersed in the hot melt will attain a rather higher temperature towards the point, with the advantage that the lower third of the drill, containing the part of the length of it most likely to be used (probably to the exclusion of the rest), will harden more intensely than the upper two-thirds, which will, by shallower milling, be structionally stronger and will not call for the hardest treatment in the chilling off.

The Oil Dip.—Both celerity and exactitude of action are necessary in transferring the drill from the melt, in its white-hot state, to the cooling oil. The oil used should be light whale or cotton-seed oil. It is not necessary to hold the drill in the oil until it has cooled out. When black, it should be at once transferred to the tempering bath, and allowed to remain there several minutes. In first cooling, vertical dipping is absolutely necessary. It will be found a great advantage to pre-heat the drills in a salt bath, and not in an open furnace.

Temper.—Four hundred degrees F. will be found suitable for twist drills of a size from ½ in. upwards. Smaller drills should be drawn to 450° F. or even lower, according to strength and length.

High Speed Taps.—The handling of taps, except long and thin specimens, will be found much easier than the treatment of twist drills. There is, of course, an advantage to be gained by making taps of tungsten–vanadium steel, but the old type of high carbon steel makes so good a tap that the gain is not as great as in the case of milling cutters and drills. All suggestions given regarding drill-hardening apply equally to the case of taps.

CHAPTER XIV

STAINLESS STEEL

THE discovery by Brearley[1] that the incorporation of a percentage of chromium imparted to ordinary carbon steel the property of virtual stainlessness, appears to mark the beginning of an age of incorrodible steel. The significance of this to the whole engineering world is very great.

Reference to increasing resistance to corrosion exhibited by steel bearing a small percentage of chromium has already been made in Chapter X, and this property has for some years been noted by compounders of the later alloy steels; but it is probably within the past five or seven years that organized attempts have been made to produce a stainless, and possibly an incorrodible steel.

While it cannot be said that a full measure of the latter property has been attained, yet, under favourable conditions, a stainless steel can resist corrosion and erosion which would entirely destroy ordinary steel, while full stainlessness is undoubtedly secured in the case of every kind of cutting implement, and even elsewhere, under conditions permitting a smooth surface being maintained, upon the articles exposed to ordinary staining media.

In many important respects stainless steel differs physically from straight carbon steel. The mechanical properties of the ordinary straight carbon product depend chiefly upon the percentage of carbon carried. In the normalized condition, these steels increase in tensile strength by successive additions of carbon up to about 1 %, but beyond this exhibit notable signs of brittleness. They also decrease continuously in ductility as the percentage of carbon rises.

A somewhat similar relationship between the mechanical

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[1] Mr. Harry Brearley, a Director of Brown Bayley's Steel Works, Ltd.

properties and the percentage of carbon applies to stainless steel, but it is by no means so clearly marked, and there are important differences. Free cementite may appear in stainless steel if the carbon exceeds 0·3 to 0·35 %, and this appearance is associated with a falling off in the toughness of the steel, both in the normalized and in the hardened and tempered condition. Hence, the most useful varieties of stainless steel should always contain less than a maximum of 0·45 % carbon.

Stainless steel may be classified into the following varieties :—

Stainless Iron.—Containing less than 0·10 % carbon.

Tensile strength varies between 30 and 70 tons, according to the heat treatment.

Easy to forge, drop stamp, machine and cold work.

The ideal stainless material for general engineering purposes.

Mild Stainless Steel.—Containing between 0·1 and 0·2 % carbon.

Tensile strength varies between 40 and 80 tons, according to the heat treatment.

Easy to forge under power hammers.

Suitable when hardened for complicated tools in cutting soft materials.

Medium Stainless Steel.—Containing between 0·2 and 0·3 % carbon.

Tensile strength varies between 45 and 90 tons.

Stainless Steel.—Containing between 0·3 and 0·4 % carbon.

Tensile strength varies between 50 and 110 tons.

Forge without difficulty into simple shapes under power hammers. Too hard to forge by hand. Harden intensely and need to be carefully cooled. Suitable for cutting tools required to keep a sharp and durable edge and for engineering purposes requiring hard-wearing surfaces.

Hard Stainless Steel.—Containing over 0·5 % carbon.

Difficult to forge, therefore useful where great strength at high temperatures is required.

Makes ideal wearing surfaces.

Is less stainless than milder varieties.

The above steels are usually branded as follows :—

1, Stainless Iron ; 2, Mild Stainless Steel ; 3 and 4, Stainless Steel ; 5, Hard Stainless Steel.

Percentage of Chromium.—The percentage of carbon in these varieties will vary considerably, but the percentage of chromium will vary from 11 to 14 %. Of other materials there may be from 2 to 3 % of nickel, tungsten, silicon, manganese. But these are generally considered to confer no material benefit if the material is intended to be forged and hardened and tempered to produce cutting tools or tough structural parts.

Forging and Heat Treatment.—Stainless iron forges about as easily as 0·45 % carbon steel. Four to six times as much work may be done on it at one heat as may be done on ordinary stainless steel.

Forging becomes more difficult as the carbon content increases, and the harder varieties are almost as difficult to forge as high speed steel. Stainless iron may be easily forged by hand into such difficult objects as spurs, but a power hammer is indispensable for large articles, or articles made from the harder varieties of stainless steel. Between temperatures of 2,102° F. (1,150° C.) and 1,652° F. (900° C.) stainless iron and stainless steel may be forged quickly and by rapid blows without danger of splitting; but below 1,562°–1,652° F. (850°–900° C.) it is less readily deformed, and if forcibly deformed by heavy blows it will be unduly stressed or broken. If allowed to cool in the air after forging the steel is hard. How hard it will be depends on the exact composition of the steel, the highest temperature to which the steel was heated before being finally hammered, and the sectional area of the finished product. The variation in the hardness may be very great. The hardness may, for example, correspond to a Brinell number of 500 if the temperature before hammering was 1,832° F. (1,000° C.), and to Brinell number of only 250, with steels of certain compositions if the temperature before hammering had reached 1,200° C. We cannot, therefore, recommend that any general use should be made of the hardened condition of air-cooled forgings. We would also discourage attempts to hammer blades or thin forgings till they are cold with the object of making them springy, as such articles, being strained, are unreliable and more likely to corrode or rust. It is practicable, however, to work small sections from an initial temperature of 1,292°–1,472° F. (700°–800° C.). The material when thus heated flows without any danger of cracking, but requires very heavy pressure, and on that account very few mills or forging appliances are powerful enough to deal with bar finishing greater than a square inch in cross-section. When worked from these low temperatures the material is soft, and finished with a very fine surface. The whole process is a kind of cold working, and is perhaps of greater value to the steel-maker who wishes to produce small bars and strips, and has every facility for controlling temperatures, than it is likely to be to the general user of stainless steel, for if the given temperatures are exceeded the material may prove defective. The heading of small bolts is an example of the kind of operation which might be carried out at 1,292°–1,472° F. (700°–800° C.).

Drop Stamping.—Stainless steel may be drop-stamped between temperatures of 1,832°–2,191° F. (1,000°–1200° C.). It is better, however, to use stainless iron whenever possible, as this flows more easily, and wear and tear on the dies is consequently much less. It is advisable to do as much of the work as possible in preliminary shaping dies. The steel may be swaged without any unusual danger of causing the centre to split, and it may be up-ended providing this process is not carried too far in one operation without reheating. Laps should be carefully avoided, as cracks may start from them when the stamping hardens subsequently on air-cooling. The fash should be cleaned off whilst the stampings are still hot, or, if allowed to cool, they should be reheated to low redness before clearing off the fash, as they are otherwise apt to crack. Many table blades are cracked on the heel and bolster because the value of this precaution is not realized. Finished stampings should not be thrown on to damp floors or in places where excessive variations in cooling may occur. It may be advisable to recharge hard or intricate stampings into a furnace, the temperature of which is about 1,292° F. (700° C.). After the temperature of the forgings has been thus equalized, they should be soaked for about an hour, and may be then cooled further in the air without danger of cracking. A stamping withdrawn at red-heat as suggested will be magnetic while hot. If found to be non-magnetic, either the temperature is too high or the soaking has not been sufficiently prolonged. In addition to avoiding the danger of cracking, this form of prolonged cooling leaves stampings or forgings in a softened state ready for machining.

Annealing.—To soften stainless steel is a very simple matter; it requires only to be reheated to 1,292°–1,382° F. (700°–750° C.) and allowed to cool in air, or, if preferred, it may be quenched in oil or water. After this treatment the hardness of the steel corresponds to a Brinell number of 131 to 277 (tensile strength, 30 to 60 tons), depending on the amount of carbon it contains, and in this condition, like all annealed steel, though softer, it does not machine so smoothly.

Hardening.—To harden stainless steel it should be heated to about 1,652° F. (900° C.), and may—

(1) Be allowed to cool in air if the section is small or a moderate degree of hardness only is required.

(2) Be quenched in oil if large in section and simple in design.

(3) Be quenched in water if the section is symmetrical and able to withstand great stresses; or, if practicable and convenient, as in the case of table blades, etc.

As hardened stainless steel is not appreciably softened at temperatures below 932° F. (500° C.), it is practicable to harden the steel by quenching it in a fused salt or metal bath whose temperature lies between, say, 302°–842° F. (150°–450° C.). Articles which otherwise would crack on hardening may be hardened and tempered simultaneously by quenching in the manner indicated.

Tempering.—The effects of reheating a hardened object intended for structural purposes are set forth in the tables given below.

The usual scale of colours cannot be applied to stainless steel, and the reader is recommended to carry out the tempering operation in a salt bath or some other medium, the temperature of which is regulated by a reliable pyrometer.

Mechanical Properties.—The mechanical properties obtainable by a particular form of heat treatment depend mainly on the composition of the steel. The range of variation is illustrated by the following series of test results. The bars heat treated were 1¼ in. in diameter, and the tensile test pieces were 2 in. by 0·564 in.

Stainless Iron.—Composition: C, 0·07; Si, 0·08; Mn, 0·12; Cr, 11·7; Ni, 0·57.

Treatment: Oil hardened from 1,742° F. (950° C.) and reheated as shown.

Reheating temperature	°F. 392 °C. 200	572 300	752 400	932 500	1,112 600	1,292 700	1,382 750
Yield point, tons per sq. in. ..	—	—	—	58·8	38·0	30·6	27·9
Maximum stress, tons per sq. in.	73·0	72·4	72·3	72·4	49·1	40·4	36·4
Elongation, % ..	12·0	15·5	15·5	18·0	22·0	26·5	31·0
Reduction of area, % ..	38·0	36·4	51·0	52·2	62·4	65·8	68·8
Izod impact figure ..	34	38	38	36	65	79	87
Brinell number	340	332	332	340	241	197	179

Mild Stainless Steel.—Composition: C, ·15; Si, ·09; Mn, ·16; Cr, 11·8; Ni, ·77.

Treatment: Oil hardened from 1,742° F. (950° C.) and reheated as shown.

Reheating temperature	°F. 932 °C. 500	1,112 600	1,292 700	1,382 750
Yield point, tons per sq. in.	—	42·0	38·0	31·2
Maximum stress, tons per sq. in.	89·5	56·4	46·8	43·9
Elongation, %	10·0	20·0	26·0	28·0
Reduction of area, % ..	36·0	52·2	58·1	61·5
Izod impact figure	16	35	60	68
Brinell number	402	255	223	207

Stainless Steel.—Composition: C, ·37; Si, ·19; Mn, ·15; Cr, 12·0; Ni, ·55.

Treatment: Air hardened from 930° C. and reheated as shown.

Reheating temperature	°F. 932 °C. 500	1,112 600	1,292 700
Yield point, tons per sq. in. ..	—	56·0	46·8
Maximum stress, tons per sq. in...	104	63·0	54·0
Elongation, %	9·0	15·0	21·0
Reduction of area, %	24·6	42·0	52·2
Izod impact figure	8	15	30
Brinell number	444	285	241

These results clearly indicate that for structural purposes the mechanical properties of stainless steels compare very favourably with those of the very highest qualities of structural alloy steels.

For other general purposes, to which tensile testing is not usually applied, the Brinell hardness number of tested specimens plotted against tempering conditions are given in Fig. 136. The maker of machine knives, springs, spindles, etc., will find his way to the selection of a form of heat treatment suitable to his particular requirements,

The figures given in the tables on page 325, and more especially the curve of Brinell hardness numbers in Fig. 136, show that hardened stainless steel is not softened to any great extent by reheating to temperatures not exceeding 932° F. (500° C.). Within this margin steel may be tempered in order to increase its toughness without lessening its hardness. Also on reheating the hardened steel at any temperature between 1,202°–1,382° F. (650°–750° C.), its tensile strength remains practically constant. This property is especially useful in commercial practice, since the effect of considerable variations in the reheating temperature are relatively unimportant. Moreover, the hardness and toughness obtained in steel treated within

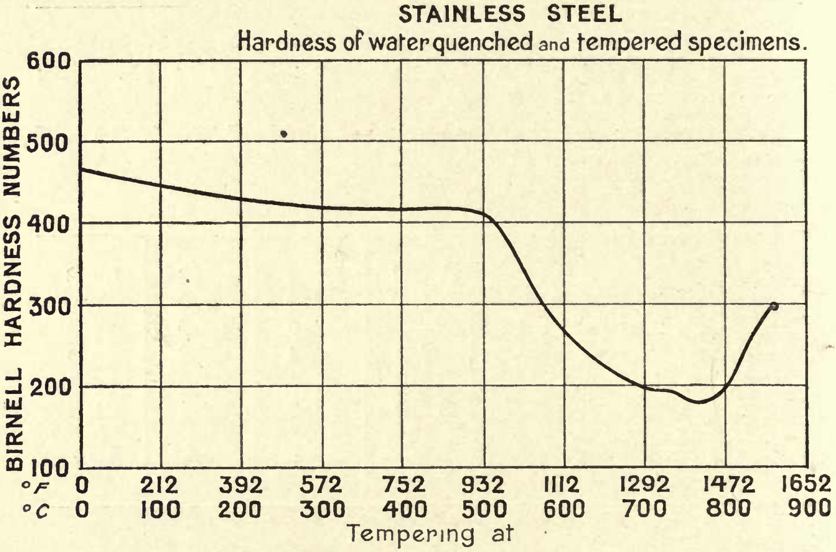

FIG. 136.

this reheating range are very suitable for a great variety of structural purposes.

Cold Working.—Stainless steel may be drawn into wire, rolled into sheets, or made into weldless drawn tubes. But it is necessary to modify the usual operations of these trades to some extent. It is not feasible, for example, to patent the wire before proceeding to draw it, as the temperature at which the patenting is done would make the wire rod hard and somewhat brittle.

It must always be remembered that stainless steel has distinct air hardening properties. To soften the material, whether in the form of wire rod, hot rolled sheet or hot rolled tube, it should be reheated to 1,292°–1,382° F. (700°–750° C.), followed either by slow cooling or quenching, as may be desired.

Softened stainless steel may be pickled in the usual way with sulphuric or hydrochloric acid, and after pickling it is ready for the first cold drawing or rolling process. The intermediate softening is carried out each time by reheating at the above temperature. A clean metallic surface tarnishes slightly at this temperature, but does not scale, and further pickling may not be necessary even when the method of close annealing has not been used.

Distortion by Cold Working.—All metals when distorted by cold work exhibit an increased tendency to corrode. This is amply illustrated in relation to steels by the appearance of broken tensile and bender pieces, which rust more readily on strained than on unstrained parts during a few hours' exposure to a moist atmosphere. Stainless steel is no exception to this rule, and it is not generally advisable to put the material into service after drastic cold working operations until it has been hardened, or hardened and tempered. This disadvantage may limit the use of stainless steel for certain purposes, but the hardening and tempering operations here referred to do not necessarily involve quenching in water or oil, as a reheating or two reheating operations may do everything required to revive the stainless properties. Where great mechanical strength is not mandatory it is possible to supply a kind of stainless steel which is less sensitive to the deleterious effects of cold work.

It follows from the preceding paragraphs that turnings or borings of stainless steel will rust, and for a similar reason the surface from which turnings have been rudely removed by rough cuts will also rust. Surfaces finished with a fine cut are less apt to rust because they are not so much deformed; ground surfaces are still less likely to rust, and ground and polished surfaces are immune from rust because they are not distorted.

It has been said that the non-corrosive properties of stainless steel are conferred by polishing, and are confined to the surface.

This is not correct. A highly polished surface is certainly a favourable condition because it does not provide lodgment for casual dirt or innumerable points of attack for direct corrosive agents. However rough the surface of a hardened or hardened and tempered article may be, if it is a clean metallic surface and not distorted it will be rustless. This statement is confirmed by the behaviour of fractured surfaces which have been made without accompanying distortion.

Grinding.—Stainless steel is more difficult to grind than ordinary steel of equal Brinell hardness. As grinding is a "wearing" operation of a kind, the relative difficulty in grinding may be taken as a rough index of wear. As a matter of fact, cutting tools, gauges, and ball races of hardened stainless steel have been found to "wear" much better than might have been expected judging from their Brinell hardness numeral. Grinding may be done so rashly on emery stones that the surface of soft steel is distorted and this would promote corrosion. On hardened steel the heat generated by rash grinding may produce soft places which might cause either cracks or staining.

Behaviour at High Temperatures.—The exceptional behaviour of stainless steel at high temperatures is one of its most valuable features. When heated gradually the polished surface of the hardened specimen assumes the well-known temper colours at the following approximate temperatures:—

Temperature.	Temper Colour.
512° F. (300° C.)	Pale straw.
662° F. (350° C.)	Brownish straw.
752° F. (400° C.)	Brownish purple.
842° F. (450° C.)	Bluish purple.
932° F. (500° C.)	Reddish violet.
1,022° F. (550° C.)	Purple blue.
1,112° F. (600° C.)	Light blue.
1,202° F. (650° C.)	Bluish violet.
1,292° F. (700° C.)	Greyish violet.
1,382° F. (750° C.)	Grey.

Specimens (half-inch square) placed in a heated muffle (whose temperature was as specified), and withdrawn after half an hour, were coloured on the surface as follows:—

Temperature of Muffle.	Colour of Specimen.
482° F. (250° C.)	Pale straw.
572° F. (300° C.)	Brown.
662° F. (350° C.)	Purple brown.
752° F. (400° C.)	Brownish purple.
842° F. (450° C.)	Purple.
932° F. (500° C.)	Purple.
1,022° F. (550° C.)	Violet.
1,112° F. (600° C.)	Violet.
1,202° F. (650° C.)	Blue.
1,292° F. (700° C.)	Steel grey.
1,382° F. (750° C.)	Brownish grey.

Temper colours are known to be due to very thin films of oxidised metal. As the temperature of ordinary steel rises the temper colour film passes gradually into a scale of measurable thickness, and at a very red heat the thickness of the scale increases with time. Stainless steel behaves quite differently.

Up to a temperature of about 1,562° F. (850° C.) the glossed surface due to polishing and heat tinting is permanent, and the specimen neither gains nor loses appreciably in weight.

The non-scaling property of stainless steel makes it specially suitable for many purposes in metallurgical and mechanical industries, where ease in machining and great strength at high temperature are also required.

Stainless steel is already being used in very large quantities for valves of internal combustion engines which are worked at high temperatures. The strength of the material and its resistance to erosion have been tested jointly by trials under working conditions, and the results exceed those obtained from any other material. As to the hardness of the material at high temperatures, that may be demonstrated by any person who will attempt to forge it. In order, however, to provide approximate data which the designer of internal combustion engines (or turbines) may use at his discretion, the following tensile test results obtained from test pieces (2 in. by 0·564 in.) pulled at the indicated temperatures are given:—

STRENGTH OF STEELS AT HIGH TEMPERATURES IN TONS PER SQUARE INCH.

Testing temperature ..	°F. 1,292 °C. 700	1,472 800	1,562 850	1,652 900
Mild steel (carbon) ..	6·85	5·0	4·1	3·0
3 % nickel steel ..	9·4	—	—	—
Nickel chrome steel ..	9·0	6·8	5·3	4·3
Stainless (low carbon) ..	12·1	6·6	6·6	4·8
Stainless (high carbon) ..	15·1	8·5	9·6	7·5
High speed (special) ..	17·7	10·3	11·1	8·8
High speed (ordinary) ..	14·7	7·1	9·6	7·4

Nickel chromium steels such as are described in Chapter X, while being highly resistant to stain, are not strictly stainless steels, are much stronger at high temperatures than either stainless or high speed steels.

Stainless steel is most resistant to the action of food acids, as vinegar, when in the hardened condition. When tempered subsequently at all stages from 202° F. (100° C.) to 932° F. (500° C.), the steel used for manufacturing table cutlery will not stain under test conditions. When tempered at 1,112° F. (600° C.) it will generally be stainless under test conditions. After tempering at 1,202° F. (650° C.) it may or may not be stainable, but will not rust under ordinary conditions. In the normalized or annealed condition, after slow cooling, it will stain and rust under test conditions, but very much less than ordinary steel.

Stainless steel is not appreciably attacked by nitric acid of any strength either in the cold or on boiling. This fact serves occasionally to distinguish stainless steel if it should have been accidentally mixed with ordinary steel, but it is not a reliable indication of whether a steel is in the stainless condition, as nitric acid does not attack drillings or cold worked articles which would stain readily or rust.

Marking and Etching.—A mixture of nitric and hydrochloric acids will etch stainless steel; or hydrochloric acid alone in which copper sulphate has been dissolved serves very well for light etching. For deep etching a mixture may be made as follows: Dissolve 170 grams of iron nails or mild steel drillings in 800 cubic centimetres of hydrochloric acid; add 100 cubic centimetres of nitric acid; also 100 cubic centimetres of water, and boil until brown fumes are no longer evolved.

Electrolytic Action.—Stainless steel does not corrode when in contact with other steel. It is, however, attacked in an otherwise non-corroding liquor such as sea-water when in direct metallic contact with copper or copper alloys such as gunmetal.

Applications.—The usefulness of stainless steel has been demonstrated for the following amongst many other purposes:—

Cutlery of all kinds, including dental and surgical instruments, palette knives, fruit and slicing blades, tobacco and leather knives, garden tools, pocket-knives, etc.

Sporting Tools, such as golf club heads, skates, rifle and gun-barrels and fitments, stirrups, spurs, harness fittings, etc.

Hydraulic Work.—Valves, valve seatings, valve spindles, rams, etc.

Origin of Stainless Steel.—The original object in view was to produce a material for ordnance purposes, to minimize the erosive effect of hot gases.

Tests made with machine-gun barrels show clearly its superiority in this respect. Failure in exhaust valves of aero engines, motor cycles, etc., are frequently due to erosion. Since stainless steel does not scale, because it is strong at high temperatures, and as it resists erosion, it is, therefore, an ideal material for all parts through which hot corrosive gases move at high speeds.

Surface Defects.—A bar of steel coated with scale will rust on the surface, and a hardened bar will rust unless the oxidized surface is removed. If the removal is incomplete and the clean surface is left pitted with scale marks, the scaled area will oxidize still further and tend to spread over the clean parts. It is, therefore, essential that the finished surface should be free from roaks, pits, or cracks, or even stamp marks which have been formed by pressing a lettering dye into the surface of the hot steel. Stainless steel bars which have been made from spongy ingots are unsuitable for exacting uses such as cutlery, as it is not possible to remove from their surface, either by grinding, sand blasting, or pickling, the small particles of occluded scale which act as centres of oxidation. The rust exuding from a surface defect spreads over the bright parts, but does not readily corrode them, and may frequently be cracked off the surface as though it were a layer of varnish.

The behaviour of stainless steel rods working through packing is astonishing. The wear of the rod is practically negligible; the life of the packing is increased three- to seven-fold. The saving on packing and costs of renewals quickly refunds the cost of a stainless steel rod.

Machine Parts, such as races and rollers for bearings, printing blocks, springs for chronometers and automobiles, water meters, cream separators, ice moulds, weighing machines, steam traps, &c.

Engine Parts, subject to erosion, such as exhaust valves working at high temperatures, turbine blades.

General Purposes, including pump rods, cotters, evaporating pans, hot punches, marine gearing, acid pumps, vacuum brake piston rods, and refrigerating plant.

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