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HEAT TREATMENT OF STEEL

HARDENING AND TEMPERING
CASE-HARDENING

SECOND EDITION

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CHAPTER I

HARDENING CARBON STEELS*

Originally the name steel was applied to various combinations of iron and carbon, there being present, together with these, as impurities, small proportions of silicon and manganese. At the present time, however, the use of the name is extended to cover combinations of iron with tungsten, vanadium, nickel, chromium, molybdenum, titanium and some of the rarer elements. These latter combinations are quite generally known as the *alloy* steels to distinguish them from the *carbon* steels, in which latter the characteristic properties are dependent upon the presence of carbon alone. The alloy steels are divided into the high-speed steels and the Mushet or air-hardening steels. The specific properties that distinguish these different steels are due in part to their respective compositions, that is, to the particular elements they contain, and, in part, to their subsequent working and heat treatment.

Effect of Difference in Composition of Steel

In general, any change in the composition of a steel results in some change in its properties. For example, the addition of certain metallic elements to a carbon steel causes, in the alloy steel thus formed, a change in position of the proper hardening temperature point. Tungsten or manganese tend to lower this point, boron and vanadium to raise it; the amount of the change is practically proportional to the amount of the element added. Just as a small proportion of carbon added to iron produces steel which has decidedly different properties than those found in pure iron, so increasing the proportion of carbon in the steel thus formed, within certain limits, causes a variation in the degree in which these properties manifest themselves. For example, consider the property of tensile strength. In a "ten-point" carbon steel (one in which there is present but 0.1 per cent of carbon) the tensile strength is very nearly 25 per cent greater than that of pure iron. Adding more carbon causes the tensile strength to rise, approximately, at the rate of 2.5 per cent for each 0.01 per cent of carbon added.

Carbon steels are divided into three classes according to the proportion of carbon which they contain. The first of these embraces the "unsaturated' steels, in which the carbon content is lower than 0.89 per cent; the second, the "saturated" steels, in which the proportion of carbon is exactly 0.89 per cent; and, the third, the "supersaturated" steels, in which the carbon content is higher than 0.89 per cent.

Effect of Heat Treatment

With a steel of a given composition, proper heat treatments may be applied which, of themselves, will first alter in form or degree some

* MACHINERY, October, 1909, and January, 1910.

of its specific properties, or second, practically eliminate one or more of these, or third, add certain new ones. Physical properties of size, shape and ductility are examples of the first case; an example of the second case is found in the heating of steel beyond its hardening temperature, which takes away its magnetism, making it non-magnetic; and an example of the third case is the fact that a greater degree of hardness may be added to steel by the process of hardening. In this connection it must be understood that, strictly speaking, hardness is a relative term and all steel has some hardness.

There are three general heat treatment operations, so considered: forging, hardening—with which this chapter will deal—and tempering. In all of these the object sought is to change in some manner the existing properties of the steel; in other words, to produce in it certain permanent conditions.

The controlling factor in all heat treatment is temperature. Whether the operation is forging, hardening or tempering, there is for any certain steel and particular use thereof a definite temperature point that alone gives the best results in working it. Insufficient temperatures do not produce the results sought. Excessive temperatures, either through ignorance of what the correct point is, or through inability to tell when it exists, cause "burned" steel; this is a common failing, resulting in great loss. Very slight variations from the proper temperature may do irreparable damage.

Due to temperature variation alone, carbon steel may be had in any of three conditions: first, in the unhardened or annealed state, when not heated to temperatures above 1350 degrees F.; second, in the hardened state, by heating to temperatures between 1350 and 1500 degrees F.; third, in a state softer than the second though harder than the first, when heated to temperatures which exceed 1500 degrees F.

The Hardening Process

The hardening of a carbon steel is the result of a change of internal structure which takes place in the steel when heated properly to a correct temperature. In the different carbon steels this change, for practical purposes, is effective only in those in which the proportion of carbon is between 0.2 per cent and 2.0 per cent, that is, between "twenty-point" and "two" carbon steels, respectively.

When heated, ordinary carbon steels begin to soften at about 390 degrees F. and continue to soften throughout a range of 310 degrees F. At the point 700 degrees F. practically all of the hardness has disappeared. "Red hardness" in a steel is a property which enables it to remain hard at red heat. In a high-speed steel this property is of the first importance, 1020 degrees F. being a minimum temperature at which softening may begin. This is some 630 degrees F. above the point at which softening commences in ordinary carbon steels.

The process of hardening a steel is best carried out in a closed furnace. Of the many sources of energy capable of producing the required heat, electricity offers the most attractive advantages. The electric resistance furnace, as now built in a variety of sizes of either muffle or tube chamber types, has one fundamental point of superiority over all coal, coke, gas, or oil-heated furnaces. It is entirely free from all products of combustion, the heat being produced by electrical resistance. This is important. It does away with the chief cause of oxidation of the heated steel. Further, the temperature of the electric furnaces can be easily and accurately regulated to, and maintained uniform at, any desired point. When electric power is generated for other purposes, the increased cost of this form of energy for operating furnaces is not sufficient to argue against it. Even when the current is purchased, the superior quality of work performed by this kind of furnace frequently more than offsets the slightly higher cost of operation.

In the actual heating of a piece of steel, several requirements are essential to good hardening: first, that small projections or cutting edges are not heated more rapidly than is the body of the piece, that is, that all parts are heated at the same rate, and second, that all parts are heated to the same temperature. These conditions are facilitated by slow heating, especially when the heated piece is large. A uniform heat, as low in temperature as will give the required hardness, produces the best product. Lack of uniformity in heating causes irregular grain and internal strains, and may even produce surface cracks. Any temperature above the "critical point" of steel tends to open its grain—to make it coarse and to diminish its strength—though such a temperature may not be sufficient to lessen appreciably its hardness.

Critical Temperatures

The temperatures at which take place the previously mentioned internal changes in the structure of a steel are frequently spoken of as the "critical points." These are different in steels of different carbon contents. The higher the percentage of carbon present, the lower the temperature required to produce the internal change. In other words, the critical points of a high carbon steel are lower than those of a low carbon steel. In steels of the commonly used carbon contents, there are two of these critical temperatures, called the *decalescence* point and the *recalescence* point, respectively.

Decalescence and Its Relation to Hardening

Everyone interested in the hardening of steel will have noticed the increasing frequency with which reference is made to the decalescence and recalescence points of steel, in articles appearing in the technical press from time to time. It is only during the past few years that this peculiarity in steel has come to the front, and there are still very many who do not possess even a rudimentary knowledge of the subject. The somewhat obscure references one usually sees in the treatises on hardening will not help the man in the hardening shop very much to a better understanding of the matter, and therefore an elementary explanation of the phenomenon will be welcome to many. It may be quoted that, as a matter of history, hardening has been done with more or less success, from the days of the famous Damascus swords up to only a comparatively short time ago, without anyone having discovered that steel possessed such a peculiarity as decalescence, but nevertheless its relation to hardening has always existed, and its discovery paved the way for much scientific investigation into a subject that had been previously controlled by rule of thumb.

The "decalescence" and "recalescence" or "critical points" (also sometimes designated Ac. 1 and Ar. 1) that bear relation to the hardening of steel, are simply evolutions that occur in the chemical composition of steel at certain temperatures during both heating and cooling. Steel at normal temperatures carries its carbon, which is its chief hardening component, in a certain form—pearlite carbon to be more explicit—and if heated to a certain temperature a change occurs and the pearlite carbon becomes cementite or hardening carbon. Likewise, if allowed to cool slowly, the hardening carbon changes back again to pearlite. The points at which these evolutions occur are the decalescence and recalescence or critical points, and the effect of these molecular changes is to cause an increased absorption of heat on a rising temperature and an evolution of heat on a falling temperature. That is to say, during the heating of a piece of steel a halt occurs, and it continues to absorb heat without appreciably rising in temperature, at the decalescence point, although its immeidate surroundings may be hotter than the steel. Likewise, steel cooling slowly, will, at a certain temperature, actually increase in temperature although its surroundings may be colder. This takes place at the recalescence point.

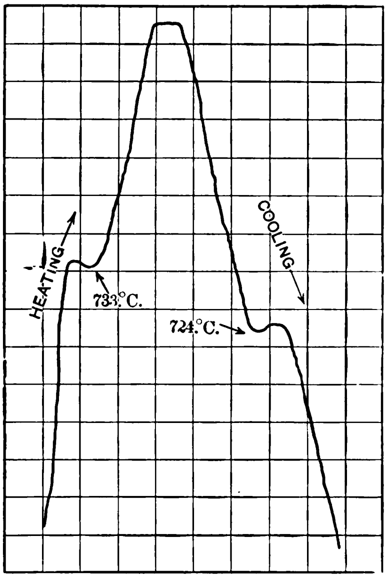

Fig. 1. Curve made by a Recording Pyrometer, showing the Decalescence and Recalescence Points

In Fig. 1 is shown a curve, taken on a recording pyrometer, in which the decalescence and recalescence points are well developed. From this it will be seen that the absorption of heat occurred at a point marked 733 degrees C. on the rising temperature, and the evolution of heat at 724 degrees C. on the falling temperature. The relation of these critical points to hardening is in the fact that unless a temperature sufficient to produce the first action is reached, so that the pearlite carbon will be changed to hardening carbon, and unless it is cooled with sufficient rapidity to practically eliminate the second action, no hardening can take place. The rate of cooling is material and accounts for the fact that large articles require to be quenched at higher temperatures than small ones.

A very important feature is that steel containing hardening carbon, *i. e.*, steel above the temperature of decalescence, is non-magnetic. Anyone may demonstrate this for himself by heating a piece of steel to a bright red and testing it with an ordinary magnet. While bright red it will be found to have no attraction for the magnet, but at about a cherry-red it regains its magnetic properties. This feature has been taken advantage of as a means of determining the correct hardening temperature, and appliances for its application are on the market. Its use is certainly to be recommended where no installation of pyrometers exists; the only point requiring judgment is the length of time an article should remain in the furnace after it has become non-magnetic. This varies with the weight and cooling surface, but may be tabulated according to weight, leaving very little to personal judgment.

It is difficult to quote reliable temperatures at which decalescence occurs. The temperatures vary with the amount of the carbon contained in the steel, and are much higher for high-speed than for ordinary crucible steel. Special electric furnaces are generally used for obtaining decalescence curves, but with care it can be done in an ordinary gas furnace, with a suitable pyrometer. All that is necessary is to bore a blind hole in a piece of the steel to be treated, to form a pocket to receive the end of the pyrometer. This must be of sufficient length to cover the resistance coil in the end of the pyrometer. The specimen should then be put in the furnace, with the pyrometer in, the gas applied, and, if the furnace is allowed to heat up very slowly toward a temperature of say 1380 degrees F. (750 degrees C.), the decalescence curve will be developed, if the pyrometer is a recording one. In the same way, if the furnace is allowed to cool slowly it will be seen that at the recalescence point, the specimen gives off heat and even increases in temperature for a time. Experiments of this kind are scarcely practicable for the average hardening shop, but when it is desired to find the lowest hardening temperature for a piece of steel, the magnet can be used to advantage.

Recapitulation

To sum up, the decalescence point of any steel marks the correct hardening temperature of that particular steel. It occurs while the temperature of the steel is rising. The piece is ready to be removed from the source of heat directly after it has been heated uniformly to this temperature, for then the structural change necessary to produce hardness has been completed. Heating the piece slightly more may be desirable for either or both of the two following reasons. First, in case the piece has been heated too quickly, that is, not uniformly, this excess temperature will assure the structural change being complete throughout the piece. Second, any slight loss of heat which may take place in transferring the piece from the furnace to the quenching bath may thus be allowed for, leaving the piece at the proper temperature when quenched.

If a piece of steel which has been heated above its decalescence point be allowed to cool slowly, it will pass through a structural change, the reverse of that which takes place on a rising temperature. The point at which this takes place is the recalescence point and is lower than the rising critical temperature by some 85 to 215 degrees. The location of these points is made evident by the fact that while passing through them the temperature of the steel remains stationary for an appreciable length of time. It is well to observe that the lower of these points does not manifest itself unless the higher one has been first fully passed. As these critical points are different for different steels, they cannot be definitely known for any particular steel without an actual determination. While heating a piece of steel to its correct hardening temperature produces a change in its structure which makes possible an increase in its hardness, this condition is only temporary unless the piece is quenched.

Quenching

The quenching consists in plunging the heated steel into a bath, cooling it quickly. By this operation the structural change seems to be "trapped" and permanently set. Were it possible to make this cooling instantaneous and uniform throughout the piece, it would be perfectly and symmetrically hardened. This condition cannot, however, be realized, as the rate of cooling is affected both by the size and shape of the treated piece; the bulkier the piece, the larger the amount of heat that must be transferred to the surface and there dissipated through the cooling bath; the smaller the exposed surface in comparison with the bulk, the longer will be the time required for cooling. Remembering that the cooling should be as quickly accomplished as possible, the bath should be amply large to dissipate the heat rapidly and uniformly. Too small a quenching bath will cause much loss, due to the resulting irregular and slow cooling. To insure uniformly quenched products, the temperature of the bath should be kept constant, so that successive pieces immersed in it will be acted upon by the same quenching temperature. Running water is a satisfactory means of producing this condition.

The composition of the quenching bath may vary for different purposes, water, oil or brine being used. Greater hardness is obtained from quenching, at the same temperature, in salt brine and less in oil, than is obtained by quenching in water. This is due to a difference in the heat-dissipating power possessed by these substances. Quenching thin and complicated pieces in salt brine is unsafe as there is danger of the piece cracking, due to the extreme suddenness of cooling thus produced.

In actual shop work the steel to be hardened is generally of a variety of sizes, shapes and compositions. To obtain uniformity both of heating and of cooling, as well as the correct limiting temperature, the peculiarities of each piece must be given consideration in accordance with the points outlined above. In other words, to harden all pieces in a manner best adapted to but one piece would result in inferior quality and possible loss of all except this one. Each different piece must be treated individually in a way calculated to bring out the best results from it.

Theory of Critical Points

The presence of the critical points in the heating and cooling of a piece of steel is a phenomenon. The most reasonable explanation is as follows:

While heating, the steel uniformly absorbs heat. Up to the decalescence point all of the energy of this heat is exerted in raising the temperature of the piece. At this point, the heat taken on by the steel is expended, not in raising the temperature of the piece, but in work which produces the internal changes here taking place between the carbon and the iron. Hence, when the heat added is used in this manner, the temperature of the piece, having nothing to increase it, remains stationary, or, owing to surface radiation, may even fall slightly. After the change is complete, the added heat is again expended in raising the temperature of the piece, which increases proportionally.

When the piece has been heated above the decalescence point and allowed to cool slowly, the process is reversed. Heat is then radiated from the piece. Until the recalescence point is reached, the temperature falls uniformly. Here the internal relation of the carbon and iron is transformed to its original condition, the energy previously absorbed being converted into heat. This heat, set free in the steel, supplies, for the moment, the equivalent of that being radiated from the surface, and the temperature of the piece ceases falling and remains stationary. Should the heat resulting from the internal changes be greater than that of surface radiation, the resulting temperature of the piece will not only cease falling but will obviously rise slightly at this point. In either event the condition exists only momentarily, but when the carbon and iron constituents have resumed their original relation, the internal heating ceases, and the temperature of the piece falls steadily, due to surface radiation.

Apparatus for Determining the Critical Points

From the foregoing sections it is evident, first, that there is a definite temperature at which any carbon steel should be hardened, and, second, that a great loss occurs, both of labor and material, unless the hardening is carried out at this temperature. The actual shop problem thus presented is to determine readily and accurately the correct hardening temperature for any carbon steel that may be in use. This can be done by the use of various types of pyrometers; the apparatus illustrated in Fig. 2, which is made by the Hoskins Mfg. Co., of Detroit, Mich., is well adapted for the purpose. This apparatus consists of a small electric furnace in which to heat a specimen of the steel to be tested, and a special thermo-couple pyrometer for indicating the temperature of this specimen throughout its range of heating. The specimen itself should be properly shaped for clamping to the thermocouple.

The furnace may be operated on either alternating or direct current circuits. The furnace chamber is 2 1/16 inches in diameter and 2½ inches deep. Heat is produced by means of the resistance offered to the passage of an electric current through the "resistor" or heating element which in the form of wire is wound in close contact with the chamber lining. The furnace is designed so that it can be used on standard lighting circuits to which ready connection is made with a twin conductor cord and lamp plug. In operation, it consumes 3½ amperes at 110 volts, and is capable of producing a chamber temperature of 1830 degrees F., which is considerably higher than required for a carbon steel.

The pyrometer consists of a thermo-couple, connecting leads and indicating meter. The thermo-couple is of small wire so as to respond

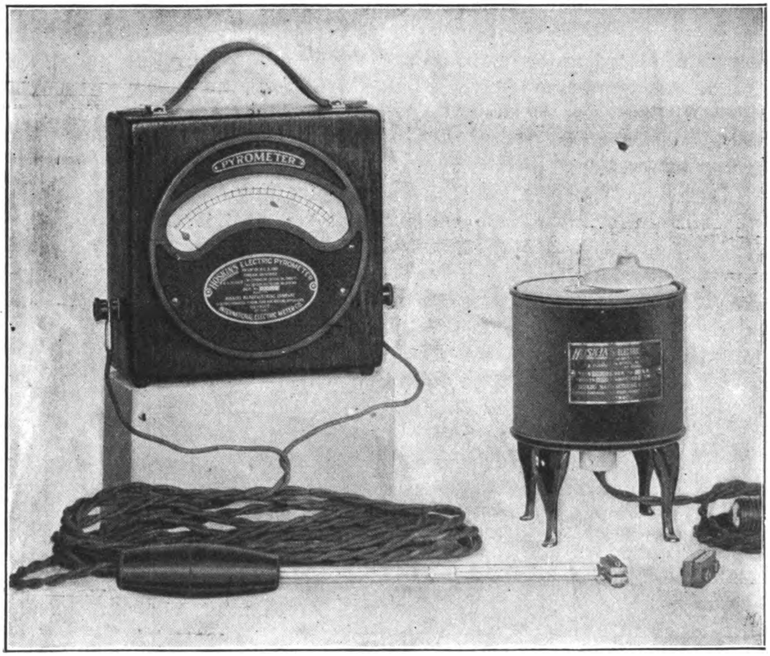

Fig. 2. Hoskins Electric Furnace and Pyrometer used for ascertaining the Decalescence and Recalescence Points of Steel

quickly to any slight variation in temperature. The welded end of this couple is slightly flattened to enable a good contact between it and the steel specimen. The meter is portable and indicates temperatures up to 2552 degrees F.

The specimen of the steel to be tested should be small, so as to heat quickly and uniformly. A well-formed specimen is made with two duplicate parts, each 1¼ inch long by ½ inch wide by ¼ inch thick. The pieces are clamped by means of two ⅛-inch bolts, one on each side of the welded part of the extreme end of the thermo-couple. Care is taken to form a tight contact, though not to cause an undue strain on the couple. The dimensions here given for the test specimen are not essential, though convenient; any pieces which will permit of tight contact with the thermo-couple and of heating in the furnace chamber, may be used.

With the specimen fastened to the couple as just described, the furnace is connected in circuit and the cover placed over the chamber opening. The temperature within the chamber rises steadily. When it becomes 1700 degrees F., the end of the couple, with specimen attached, is inserted in the chamber. The steel specimen rapidly heats, its temperature being constantly the same as that of the welded junction of the thermo-couple, due to the intimate contact between them. This temperature, indicated by the meter, will rise uniformly until the decalescence point of the steel tested is reached. At this temperature the indicating needle of the meter becomes stationary, the added heat being consumed by internal changes. These changes completed, the temperature again rises, the length of the elapsed period of time depending upon the speed of heating. With the furnace temperature kept nearly constant at the initial point, here given as 1700 degrees F., this "speed of heating" will be such as to allow of readily observing the pause in motion of the needle. The temperature at which this occurs should be carefully noted.

To obtain the lower critical point, the temperature of the piece is first raised above the decalescence point by about 105 degrees F. In this condition it is removed from the furnace and rested on top to cool. The decrease of temperature is at once noticeable by the fall of the meter needle. At a temperature somewhat below the decalescence point, varying with the composition of the steel, as previously mentioned, there is again a noticeable lag in the movement of the needle. The temperature at which the movement ceases entirely is the recalescence point. Immediately following there may occur a slight rising movement of the needle, as previously explained.

During these intervals of temperature lag, both during the heating and cooling of the steel, there may occur a small fluctuation in the temperature. In order to get results that are comparable, a definite point in each of these intervals should be considered each time a test is made. Hence, both the decalescence and recalescence temperatures are taken as the points at which the needle first becomes stationary. As all operations of heat treatment of a steel center around its critical points, the importance of knowing these exactly is realized; to make certain, each test should be checked by a second reading. The time required for this is small. A close agreement of two succeeding readings will give assurance of the correctness of the determination.

Results Obtained from Sample Specimens

In order to show graphically the necessity of working carbon steels at the proper temperature points, a series of specimen pieces of the same steel were treated at different temperatures. The steel used contained exactly 1 per cent carbon. A number of test specimens were made of this from adjacent parts of the same bar.

First the critical points of this steel were determined. Temperatures were recorded throughout both the heating and cooling. In the diagram, Fig. 3, these values have been plotted. The curve shows graphically the location of the critical points, and also the slight fall or rise of temperature as the case may be.

With this data obtained, seven specimens of the same steel were heated, in the electric furnace, each to a different temperature. As these pieces were removed from the furnace they were immediately quenched in water. The temperature of the quenching bath was held constant at 45 degrees F. The hardened pieces were then broken at right angles and the fractured surface of each was photographed under a microscope. An inspection of the photographs at once showed the

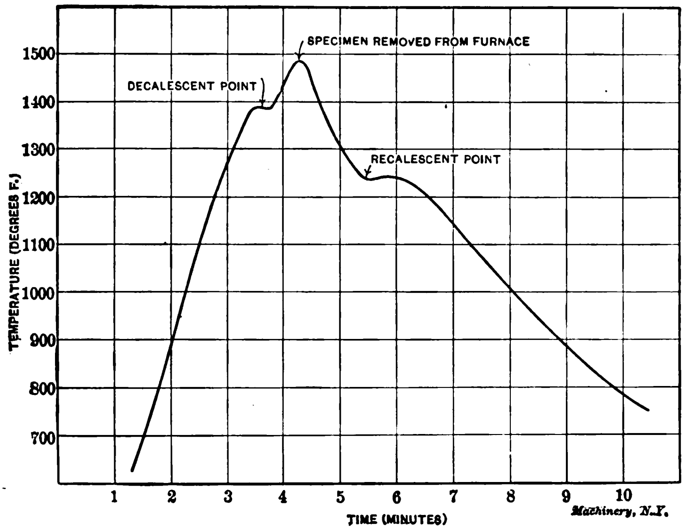

Fig. 3. Diagram showing the Relation between Time and Temperature when heating Steel, and the Critical Temperatures of One per cent Carbon Steel

serious effects of overheating on the structure of the steel and hence on its strength.

One specimen was hardened just as the temperature reached the decalescence point. This showed clearly the direction in which the hardening moves, namely, from the exterior toward the interior. This would naturally be expected as the temperature of the surface, which is exposed directly to the source of heat, reaches the critical point first. This condition indicates the necessity of heating the piece uniformly.

Conclusions

The hardening of carbon steels for highest quality and greatest saving entails, then, three things. First, a definite knowledge of what constitutes the correct temperature at which to harden the steel. The second point necessitates a positive means of accurately determining this hardening temperature for any carbon steel. The third consideration is that the correct hardening temperature, once determined, is actually carried out in the hardening work. A simple and effective way of doing this is by checking the temperature of the hardening furnace by means of a pyrometer. When there is a large quantity of work to be hardened, economy dictates a permanent installation of pyrometers. The convenience of such installations is manifest. A thermo-couple is placed in each furnace. A number of these, from three to sixteen, depending upon individual conditions, are connected by wire leads, through a selective switch to one meter. By a turn of the switch, the temperature of any furnace may be read at once from the meter. This makes it possible for the foreman to know definitely, at a single point, the temperatures of all of the hardening furnaces in use.

CHAPTER II

HARDENING CARBON AND LOW-TUNGSTEN STEELS*

The hardening of steel has always been considered an operation for which definite rules could not be laid down, but in which the experience and judgment of the hardener would almost exclusively have to be relied upon. Practically the only definite rules that have been laid down are that steel should be hardened at as low a heat as possible, and that there is a definite temperature for each kind of steel above which it must be heated to harden at all.

Apart from this meager information, a few generalities only have been furnished for the guidance of men doing this work, including directions for cooling, so as to minimize the risk of cracking; but definite information on the process of hardening is singularly lacking, and many have considered it impossible to shape rules for this operation, even as the result of careful experiments.

For this reason the experiments conducted by Mr. Shipley N. Brayshaw of Manchester, England, the results of which were reported in a paper read before the Institution of Mechanical Engineers at the April 15, 1910, meeting, and which are recorded in detail in this chapter, are all the more remarkable and of great interest to everyone engaged in mechanical work. These experiments appear to have been made with extraordinary care, and two of the points brought out in his investigations deserve to be particularly mentioned. One of them relates to the shortening or lengthening of steel in hardening. It has often been stated that steel is unreliable and not uniform in this respect, and that the same kind of steel has sometimes been known to shorten in hardening, and sometimes to lengthen. This phenomenon has been

* MACHINERY, June, 1910.

attributed to defects, or, at least, to special conditions in the steel, over which the hardener has no control. Mr. Brayshaw's experiments, however, show that the shortening and lengthening of steel in hardening follows a uniform law, and that steel hardened below a given temperature, which he calls the "change-point," will shorten when quenched; whereas the same steel, if heated above this change-point before quenching, will lengthen. He also shows that by heating the steel in two furnaces, first bringing it up to a certain temperature in one, and then soaking it for a given time at a definite temperature in the other, it is possible to harden steel so that it will neither lengthen nor shorten when quenched. This is, without doubt, the first definite information that has been published on the change in the length of steel in hardening, the uncertainty of which has caused considerable difficulty in making accurate taps, dies, etc.

Another interesting point brought forth by Mr. Brayshaw's experiments relates to the proper hardening temperature. While it is possible to harden steel within a temperature range of about 200 degrees, and obtain what to the ordinary observer would seem to be good results, the *best* results are always obtained within a very narrow range of temperatures, approaching closely the decalescence point, or the temperature at which steel changes into a condition when it can be hardened by quenching. It is interesting to note that this result agrees with the old theory that steel should be hardened at as low a temperature as possible. In a number of cases certain tools are found to last exceptionally well, while other tools in the same lot show only ordinary durability, although no difference can be detected in the grain of the hardened steel. Such differences can now be accounted for by the slight variations in the temperature at which the various tools have been hardened.

These experiments open up an entirely new field for investigation and new possibilities in the hardening of tool steel. They indicate that in cases where it is important to prevent the cracking of tools in hardening and the deformation of tools due to internal stresses, they should be hardened at a temperature higher than that which gives the best results as regards hardness only. Thus we find that certain of the desirable qualities in a hardened tool are antagonistic; that is, we are unlikely to obtain a tool having extreme hardness and elastic limit and which at the same time is not likely to crack or lose its shape. Under these conditions one of the necessary qualities must be partly sacrified to another, and a tool must be hardened so as to obtain good general results rather than the best specific one.

The influence of previous annealing on hardening is also of interest; and many of the points brought out in the abstract of the original paper are well worth considering.

Results of the Brayshaw Experiments

The experiments mentioned deal exclusively with the results obtained from two kinds of carbon tool steel that, except for minute variations, differed only in the fact that one of them contained about

0.5 per cent of tungsten. The steel contained on an average of 1.16 per cent carbon, 0.15 per cent silicon, 0.36 per cent manganese, 0.018 per cent sulphur, and 0.013 per cent phosphorus. The whole work of investigation was devoted to questions directly connected with machine shop hardening, with the aim in view of throwing light on the many problems met with in daily practice.

Hardening Temperatures

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 range of about 10 degrees F. or less. After the temperature has been raised more than from 35 to 55 degrees F. above the hardening point, the hardness of the steel is lessened by further increases in the temperature, provided the heating is sufficiently prolonged for the steel to acquire thoroughly the condition pertaining to the temperature. There is a "change-point" at about 1615 degrees 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 hardened in water at temperatures below that point, whereas the bar lengthens if this temperature is exceeded at the time of quenching. Practically the same results are obtained by heating low-tungsten bars to any temperature from 1400 to 1725 degrees F. and quenching in oil, as by quenching in water.

Length of Time of Heating

Regarding the effect of heating to various temperatures for various lengths of time before quenching for hardening, the following conclusions are drawn: Prolonged soaking up to 120 minutes at temperatures at which the hardening change is half accomplished in 30 minutes, does not suffice to complete the change. Prolonged soaking for hardening at a temperature of 1400 degrees F. has a slightly injurious effect on the steel, but does not materially influence the hardness. At a temperature of about 1490 degres F. a great degree of hardness is attained by quick heating, but the hardness is impaired with 30 minutes soaking. Prolonged soaking for hardening at a temperature of about 1615 degrees F. has a seriously injurious effect upon the steel. A specially great degree of hardness may be obtained by means of soaking at a high temperature, such as 1615 for a very short time, but even as long a time as 7½ minutes is long enough to seriously impair the hardness.

The temperature of brine for quenching is of considerable importance. Both low-tungsten and carbon steel bars quenched at 41 degrees F. were decidedly harder than bars quenched at 75 degrees, and quenching at 124 degrees F. rendered the bars much softer.

Effects of Previous Annealing

The method of previous annealing affects the hardness of steel considerably. The elastic limit of low-tungsten bars hardened at either 1400 or 1580 degrees F. varies according to the annealing they have undergone. The elastic limit is high after annealing at about 1470 degrees F. for 30 minutes, or 1290 degrees F. for 120 minutes, but it is seriously impaired by annealing at 1470 degrees F. for 120 minutes. If low-tungsten steel is annealed at 1725 degrees F. and hardened at 1400 degrees F., the elastic limit is inferior, and the adverse effect of the previous annealing is much more pronounced if the hardening is done at 1580 degrees F. The elastic limit of carbon steel annealed at any temperature between 1290 and 1725 degrees F. and hardened at either 1400 cr 1580 degrees F. does not vary by nearly such great amounts as the elastic limit of the low-tungsten bars, and the highest annealing temperature given above is not injurious so far as the elastic limit is concerned.

The hardness of low-tungsten bars hardened at 1400 degrees F. decreases from a high scleroscope figure to a low one as the temperature of annealing increases from 1290 to 1725 degrees F. The hardness is increased by prolonging the annealing at the lower temperature. The hardness of low-tungsten steel hardened at 1580 degrees F. is fairly constant at a moderately high scleroscope figure, whatever the temperature of annealing.

Effect of Heating in Two Furnaces

An interesting part of the experiments relates to the use of two furnace heats for hardening, heating the steel first in one furnace to a certain temperature for a given time, and then immediately, without cooling, soaking in a second furnace at a known temperature and for a definite time. These experiments show that low-tungsten and carbon steel bars heated for half an hour to temperatures between 1545 and 1650 degrees F. are not much affected so far as their elastic limit and maximum strength are concerned by a further immediate soaking for half an hour at 1400 degrees F. If, however, the temperature in the first furnace is 1725 degrees F., the low-tungsten steel is much improved by a further soaking at 1400 degrees F., but the carbon steel is much injured by the same treatment. Bars of low-tungsten steel heated for 30 minutes at 1616 degrees F. and then soaked at 1332 degrees F. for a further 30 minutes, give a high elastic limit and maximum strength, and are harder than if the second soaking were at a temperature of 1400 degrees F. The carbon steel, again, is but little affected by these variations in the second furnace.

The change of length in hardening, however, of both low-tungsten and carbon steel is much affected by the above variations in the temperature of the second furnace. Good results as regards elastic limit and maximum strength, and also as regards hardness, are obtained by very short soaking, first at a high temperature, say 1615 degrees F., and then at a low one, the results being best when the second temperature is near to or a little below the hardening point. If the furnace be at a sufficiently high temperature it is easy either by variations of the temperatures of the two furnaces, or by variations in the time of soaking, to arrive at a treatment of the steel, both low-tungsten and carbon, whereby they neither lengthen nor shorten. Under the same treatment carbon steel has a greater tendency to shorten than low-tungsten steel.

Miscellaneous Results

Other experiments showed that low-tungsten steel heated to 1530 degrees F. for 15 minutes and quenched in oil has a higher elastic limit and is harder than carbon steel similarly treated. As regards annealing, it was found that bars annealed at a temperature of 1470 degrees F. or below became slightly shorter by the annealing process, and this action was more pronounced in the case of carbon steel than tungsten steel. Annealing at a temperature of 1650 degrees F. causes both low-tungsten and carbon steel to lengthen.

It was found that recalescence of low-tungsten steel takes place gradually at a temperature of 1348 degrees F., and more readily at 1337 degrees F., and further that the recalescence at either of the above temperatures is very much retarded if the steel is cooled from a maximum heat of 1634 degrees F.

Regarding hardening cracks, it is shown that both for low-tungsten and carbon steel, such treatment as produced the highest elastic limit accompanied by the greatest hardness is frequently the most risky. The risk of hardening cracks is reduced if the steel is heated for a sufficient length of time to a temperature of 1650 degrees F. or a little above. Low-tungsten steel is more liable to crack in hardening than is carbon steel.

Effect of Tempering

Tempering experiments showed that little effect was produced by the tempering of carbon steel to 300 degrees F. for 30 minutes. Tempering the same steel to 480 degrees F. for 15 minutes, however, caused it to soften considerably and to shorten in length. For low-tungsten steel the elastic limit was increased considerably by tempering up to a temperature of 480 degrees F. The maximum strength of the same steel coincides with the elastic limit for bars either untempered or tempered at 300 degrees F. for 15 minutes, but it then rises rapidly with further tempering. The hardness, as measured by the scleroscope, was considerably reduced by tempering at 300 degrees F. and still more at 390 degrees F., but was not so much affected by further tempering at 480 degrees F. The length of the low-tungsten bars was reduced by tempering up to a temperature of 480 degrees F.; the higher the temperature, the greater was the reduction in length.

Effect on Tensile Strength

The following conclusions refer to low-tungsten steel, but there is no reason to doubt that they are also applicable to carbon steel. A variation in the hardening temperature of only 9 degrees F., the extremes being respectively above and below the proper hardening temperature or decalescence point, has a tremendous influence on the extension under load, but the maximum strength of the bars so treated did not differ much. A very good bar was produced by quenching from a temperature fully 108 degrees above the hardening temperature. A heat of only 5 minutes' duration produced a harder bar than a heat of 25 minutes, the maximum temperature in both cases being 1470 degrees F., or a little above; but the bar heated for a shorter time gave a much lower elastic limit. The maximum strength alone is not necessarily any indication of the condition of the steel in question, or of the treatment to which it has been subjected; nor is the hardness alone necessarily an indication of the condition of the steel or the treatment.

The following conclusions refer both to tungsten and carbon steels. Tempering up to a temperature of 570 degrees F. gradually increases the maximum strength and the elastic limit, although some irregularities enter which have not been fully accounted for. Tempering to this temperature reduces for a given stress, the extension under load and the permanent extension.

Conclusion

In conclusion it may be stated, that these experiments show that steel of the quality treated in these experiments may be hardened within a temperature range of about 215 degrees F. The lower end of this range is very sharply defined, but the highest temperature allowable is difficult to determine, and as far as the appearance of the fracture is concerned there is little evidence of improper hardening until the temperature of the proper hardening point has been exceeded by 270 degrees F. So wide, in fact, is the margin of 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 sight alone, and as a matter of fact this is being done all the time in the manufacture of such articles as pocket knives, small files, etc., which are hardened by the thousands with practically no waste. But, of course, it must not be understood that articles so hardened 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 final result.

While it is thus easy to harden so as to obtain reasonably *good* results, the production of the *best* results necessitates a high degree of accuracy which can never be obtained by sight alone, and it is also important to notice that the difference between good hardening and the best hardening is very great. As an example may be mentioned the hardening of razors. 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, however, would show to the eye practically the same fracture, and apparently seem to have been treated in the same way. The experiments referred to above, however, indicate that there may have been a slight difference in the hardening temperature and consequently in the subsequent condition of the steel, and also that it would be possible to harden every razor in a gross so that each one would be truly a duplicate of the best. The same, of course, holds true of a great number of other tools.

The author concludes by saying that there have, for some years, been efforts made by steel makers to discover new alloy steels, and splendid success has been obtained in this direction, but there is still a wide field for the steel users for discovering the best use of the material already known. It is of little avail that occasionally tools show marvelous results, unless the hardener can at any time produce the same results with the same steel. The time is likely to come when all the factors in the hardening of tool steel will be controlled with accuracy within predetermined limits, and any failure may be investigated and the cause located with as much certainty as if a mistake had been made in the machine shop.

Carbon Steel vs. High-speed Steel

The idea that the proper hardening of carbon steel will make it possible to obtain better results by the use of this steel than has ordinarily been the case in the past has been expressed in this country as well as in England. At least one large machine tool building and toolmaking firm has made extensive inquiries in the direction of determining proper methods for hardening ordinary carbon steel so as to obtain the best results, and several writers on mechanical subjects who have investigated the subject concur in the opinion that carbon steel, properly heat treated, can be made to produce better results than usually expected. One contributor to MACHINERY writes as follows: *

"High-speed steel is in fashion nowadays. This fact together with the high degree of skill required to get the best results from carbon steel has caused this steel to be neglected. For some kinds of work, however, carbon steel is superior to any high-speed steel on the market, if it is dressed properly and receives the proper heat treatment.

"The carbon in steel may be in one of two forms: Annealed steel has the carbon in the non-hardening or cementite form. Hardened steel has the carbon in the hardening or martensite form. That these are two distinct forms may be seen by taking a small piece of annealed steel and a small piece of hardened steel and dissolving each in hydrochloric acid. The annealed steel will dissolve, leaving a black residue, while the hardened piece dissolves, leaving no residue. This shows that in one case some of the carbon is in the free or graphitic form and does not dissolve in acid, while in the other case, the carbon is in the combined form and all dissolves.

"Another point that is important to the steel worker is that the carbon changes form suddenly at the critical temperature. This is shown in the sample reproduced in Fig. 4. This sample was made in the following way: A piece of steel ½ inch by 1 inch was heated and nicked parallel with the axis as seen in the engraving; then this piece was heated till it began to fuse on the end *A* the heat gradually decreasing toward *B*. The end *B* was not hot enough to harden. In this condition the piece was cooled as quickly as possible and then broken along the nick. The characteristic burned grain is seen at *A*. This gets finer as the part that is not so badly burned is reached.

* J. H. Gill, MACHINERY, June, 1910.

Just before the point *C* is reached we find the maximum fineness and the maximum hardness; as soon as the line *C* is crossed, we find the grain of the annealed steel. The sample is soft from *B* to *C*. This shows that there is a sudden change, on the rising heat, at *C*. The best condition for hardening is just after crossing this line."

Regarding the use of the magnetic needle for indicating the correct hardening temperature, the same writer says:

"There are two hardening methods which depend on the fact that steel loses its magnetic properties when the hardening point is reached. A piece of steel heated to a dull red and brought into the plane of a magnetic needle will attract the needle.* If heated until the temperature is above the hardening point, there will be no attraction and the needle will not be affected by the presence of the steel. In using this test, care must be taken that the presence of the tongs does not mislead the workman. The comparatively cool tongs may attract the needle even when the steel is above the critical point. An ordinary horse-shoe magnet may be used instead of the magnetic needle. It is less likely to mislead because of the tongs or cooler parts of the steel

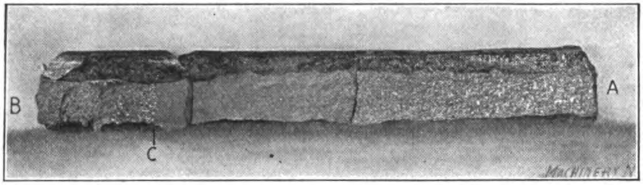

Fig. 4 Sample of Carbon Steel broken to show Difference in Grain at Different Hardening Heats

but is less sensitive. A bar magnet hung on a pivot at the center and provided with a handle can be used very satisfactorily. It can be introduced into the furnace to test the steel during the process of heating and is more convenient than either of the other methods. It is not necessary to test every piece of steel, but a test should be made whenever the person takes another grade of steel or whenever the light changes. The intensity of the light makes a great difference in the color of a piece of iron or steel at a given temperature."

General Rules for Hardening

If steel workers would observe the following in all cases when hardening steel, they would have better results: *Harden carbon steel at the lowest possible heat and always on the rising heat.* The last part of this rule is the one more often overlooked. Steel may be forged at a higher heat than the hardening heat but should in all cases be annealed before being heated for hardening. The grain of the steel corresponds to the highest heat it has received since it was black. If a piece of steel is forged at 1600 degrees F. and allowed to cool down to 1400 degrees F. to harden, it will have a grain corresponding to 1600 degrees.

* See MACHINERY'S Reference Series No. 46, "Hardening and Tempering," Chapter VII.

CHAPTER III

THE ELECTRIC HARDENING FURNACE*

This chapter consists of an abstract of a paper by Messrs. E. Sabersky and E. Adler read before the Faraday Society. A great many factors must be considered in the development of the design of an electrical hardening furnace. The practical requirements which should be fulfilled by an ideal hardening furnace may be summarized in a general way as follows:

1. The furnace should make it possible to obtain all hardening temperatures required in industrial practice, thus having a range of from 1400 to 2450 degrees F.
2. The steel should be heated to the required temperature easily and rapidly.
3. The temperature of the steel should be easily ascertained, and it should be possible to keep it well under control within a margin of, say, 50 degrees F. above or below the exact temperature required.
4. The steel must be equally heated all over, notwithstanding different cross-sections of the object, thus preventing the over-heating and burning of edges and points.
5. During the heating process foreign matter must not come in contact with the steel so as to change its carbon content, or affect it in other respects.
6. It should be possible to place the cooling tank close to the furnace in order to minimize the loss of heat during the transfer, and avoid the oxidizing influence of the air.
7. The furnace should not give off obnoxious or poisonous vapors of lead, potassium, cyanide, etc.
8. The total operating cost incident to the hardening process should be low.

In the following will be described an electric hardening furnace which fulfills to a considerable extent all of the previous requirements, and a general review of the advantages of electric hardening will be given.

Description of Hardening Furnace

In Fig. 5 are shown vertical and horizontal sections of the hardening furnace. A bath of metal salts is contained in a fire-clay crucible. Current is transmitted to the bath by two electrodes made of Swedish ingot iron, which is characterized by a particularly low percentage of carbon, and therefore has a melting point of as high as 2700 to 2900 degrees F. As shown in the horizontal cross-section, the electrodes end in iron terminals sweated in turn to copper conductors. The crucible is surrounded by an asbestos lining, a fire-clay receiver, and a layer of insulating material, the whole being contained in a cast-iron

* MACHINERY, Railway Edition, April, 1910.

case. This construction greatly reduces the radiation losses, and after ten hours' operation of the furnace at about 2450 degrees F., the cast iron case has a temperature of only from 85 to 105 degrees F. Over the bath a sheet iron hood is placed fitted with chimney and damper. These furnaces are made in several different sizes. In the smallest size the inside dimensions of the crucible are about 5 inches square by 5 inches deep, and in the largest size 12 inches square by 15 inches deep. The approximate consumption of current in kilowatts at various temperatures for the large and small furnaces are given in Table I.

The best composition of the bath depends mainly on the temperature required for the hardening. Table II gives the composition of various salts to be used for different processes.

The conductivity of the salts at normal temperature is very small while at high temperatures (when in a melted condition) they offer to the electric current a comparatively low resistance. When the mixture is sufficiently hot, the bath, therefore, forms an electric conductor, and each part of the bath produces its own heat. This feature distinguishes this class of electric furnaces from other types.

The heating of the salts prior to their becoming highly conductive is done by means of an auxiliary electrode and a piece of arc lamp carbon. The carbon is first pressed against one of the main electrodes and soon reaches a white glow, melting the salts immediately about it. The auxiliary electrode, which consists of an iron stick fitted into a wooden handle, is then drawn towards the other main electrode, the molten salt trailing behind it until a bridge is established between the two main electrodes. The current which now passes through the molten salt continues to raise the temperature of the bath until the required heat is attained. The articles to be heated are dipped into the bath, suspended by thin iron wires or held by tongs, and are allowed to remain in the bath until uniformly heated throughout.

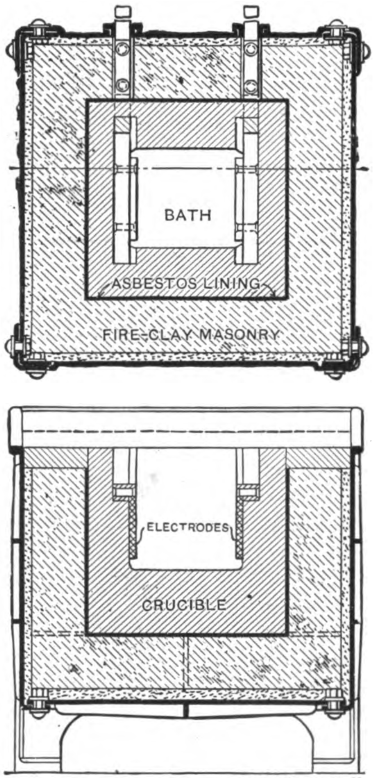

Fig. 5. Section of Electrical Hardening Furnace

The most striking feature of this furnace is the possibility of securing uniformity in temperature throughout the whole bath. Careful measurements with a pyrometer of the thermo-couple type at various parts of the bath have shown that the temperature varies only 5 or 6 degrees F., except in an upper layer about ½ inch thick, where, owing to radiation, the temperature is from 20 to 35 degrees F. lower. Alternating and not continuous current should be used; all frequencies between 25 and 60 cycles may be applied; with less than 25 cycles electrolytic phenomena appear. The furnace, having only two electrodes,

TABLE I. CURRENT CONSUMPTION OF ELECTRIC FURNACES IN KILOWATTS

Temperature of Bath, Degrees F.	Size of Crucible of Furnace, Inches			
	5 x 5 x 5	6 x 6 x 7	8 x 8 x 11	12 x 12 x 15
1400	2.5	3.5	7.5	17.5
1550	3.0	4.5	8.5	20.0
2100	5.5	9.0	16.0	36.0
2350	7.5	12.0	22.0	48.0

it suitable for single-phase currents only. If a single-phase supply is not available, a converter must be installed.

An important part of the hardening installation for electric furnaces is the pyrometer. The most reliable results for the temperatures in question are obtained by instruments of the thermo-couple type, but the instruments must be such that the terminals are kept outside of the destructive influence of the heat. The thermo-couple used is platinum—platinum rhodium, protected by Marquardt compo-

TABLE II. TEMPERATURE AND COMPOSITION OF HARDENING BATH

Process	Temperature, Degrees F.	Salts
Tempering Steel......	400 to 1075	Sodium nitrate and potassium nitrate
Annealing copper, alloys, etc...........	1200 to 1650	Sodium chloride or sodium chloride and potassium chloride
Hardening regular carbon steel.........	1400 to 2000	Potassium chloride and barium chloride
Hardening high-speed steels.......	1900 to 2450	Barium chloride
	2700 to 2900	Calcium fluoride or magnesium fluoride

sition and steel. A steel cylinder protects the parts projecting from the bath. This cylinder gets white hot and deteriorates unless protected against the oxidizing influence of the air.

When the salts are melted, the voltage necessary for maintaining the temperature is from 5 to 30 volts, while the heating-up voltage is about 70 volts. Such low voltages are not available from ordinary supply systems, and consequently a transformer must be used. The heat developed, and consequently the temperature of the bath, depends on the voltage. If it is desired to alter the temperature, this can therefore be done by a variation of the voltage. The use of the transformer makes the voltage control comparatively simple.

The Hardening Process

When heating carbon steel for hardening, it is advisable to heat it as rapidly as possible because the prolonged influence of the heat seems to affect the chemical constitution and mechanical structure.

In most cases it is advisable to pre-heat the steel to a certain temperature before the final heating in the bath takes place. This preheating should be done thoroughly in order to make sure that all portions are well heated. Unless this is done during the pre-heating period the heat during the main heating period must be directed to the parts not properly heated, which lengthens the process and may cause damage to the external portions of the tool, such as edges, projections, etc.

Each brand of steel requires a certain temperature to which it should be heated for hardening. For high-speed steels this temperature is about from 1800 to 2375 degrees F., and for carbon steels about from 1300 to 1650 degrees F. Generally speaking, the cooling process for alloy steels need not be so abrupt as for carbon steels. Instead of quenching the hot tool in water or oil, it is sufficient to expose it to a current of air or to dip it into molten tallow.

Advantages of Electric Furnaces

A great advantage of the electric furnace is that it is possible to cover a wide range cf temperatures with one equipment by only changing the composition of the bath. The tool can thus stay in the bath until it has acquired the temperature of the bath, and does not need to be removed before it has assumed the temperature of its surroudings, which is quite commonly the case in other heating processes. With the electric hardening bath, having a predetermined temperature, less dependence is placed upon the skill of the operator, and no account need be taken of the fact that smaller cross-sections heat up quicker than larger ones.

When dipping cold steel into the heating chamber, the temperature of the latter must drop. In fact, with gas-fired furnaces and salt baths it falls rapidly, unless the uncertain procedure of increasing the gas supply is resorted to. In the electric furnace, when the tool is dipped into the salt, the level of the salt bath rises, and the current of heat produced increases automatically. Besides, when it is necessary to immerse large solid masses, the current supply can be easily increased by the regulator, thus preventing a drop in temperature.

Of course, the smaller cross-sections of the tool will heat up quicker than the larger ones in the electric furnace as well as in other heating furnaces, but the delicate parts will not *over-heat* because they cannot assume a higher temperature than that of the bath itself. The bath equalizes all differences in temperature, and in a very short time heats the whole mass uniformly. This explains the very small loss from overheating in electric furnace plants as compared with others.

While the tool is in the bath, the air is, of course, prevented from coming in contact with it, but a thin coating of salt protects it still further when on its way from the bath to the cooling tank, and falls away first when the object is placed in the cooling liquid. This is a great advantage over all types of open-fire or muffle furnaces, but is common to all bath-type furnaces. Metal salts, moreover, offer the advantage that they do not give off poisonous gases, and unlike lead, they can be obtained comparatively pure at a reasonable cost. The salt coating also breaks up entirely in the cooling liquid, while when tools are heated in lead, small particles of it sometimes stick to the steel, leaving soft spots on the hardened surface.

During the heating-up period or when a certain temperature is exceeded, the melted salts give off a small amount of vapor, and therefore a hood and chimney are provided for the furnace, but during normal operation there are scarcely any vapors produced. The hood offers the further advantage that the radiation from the bath surface can be used for the preheating of the articles to be hardened. A grate may be fixed in the hod in which the articles are placed, prior to being dipped in the bath.

Comparative Operating Cost

The parts subject to wear in an electric furnace are the crucible and electrodes. The crucible has been found to have a life of from 1200 to 1800 hours at a temperature of 2350 degrees F., and up to 3000 hours at lower temperatures. This is much longer than with muffle furnaces, which is probably due to the absence of the destructive influence of the gases of combustion, and to the fact that the crucible does not transmit the heat from the outside to the inside. The most sensitive part of the electrodes is that which projects over the level of the bath, and which is protected by exchangeable tips. These tips have a life of from 400 to 800 hours, and the cost of their replacement is as low as fire-clay for other furnaces. The amount of salts lost by evaporation and waste under ordinary working conditions in a furnace 8 × 8 × 11 inches amounts to a little more than one pound for ten hours' continuous operation.

The ease with which the electric furnace can be handled makes it possible to use cheaper labor than that employed in plants where the success of the work depends on the skill of the operator. The speed of the hardening process is also much greater, and therefore a larger number of pieces can be handled per hour.

Special Bath for Tempering

In some cases electric furnaces with a special bath for tempering have been successfully used. An interesting observation which has been made in this connection is that a certain tempering color is not a function of the temperature only, but apparently time also plays an important part. It has, for instance, been possible to produce a dark blue either by 400 degrees F. for four minutes, or by 660 degrees F. for one minute.

CHAPTER IV

HEAT TREATMENT OF SPRING STEEL*

The present chapter is an abstract of a paper by Mr. Lawford H. Fry, read before the Copenhagen International Association for Testing Materials. A number of experiments were undertaken in 1907 at the Baldwin Locomotive Works to determine the effect of different kinds of heat treatments on the transverse elastic limit and the modulus of elasticity of steels commonly used for locomotive springs. The points investigated were the effect of annealing, the comparative effect of quenching in water and oil, and the effect of reheating the steel to various temperatures after complete cooling in water or oil. The steel experimented upon was basic open-hearth spring steel of the following composition:

	Per Cent
Carbon	1.010
Manganese	0.380
Phosphorus	0.032
Sulphur	0.032
Silicon	0.130

Method of Heating and Cooling the Test Pieces

The temperature at which the specimens were quenched was not varied because, as is well known, there is a definite temperature for any given steel at which that steel should be quenched in order to obtain the best results. Having once determined this proper quenching temperature it should always be used, any variation in the final degree of hardness being produced by a change in the temperature at which the temper is drawn. The temperature at which the steel should be hardened is called its point of decalescence. This temperature is conveniently ascertained by means of a magnet, due to the fact that steel becomes non-magnetic when it reaches its decalescence or hardening temperature. The steel experimented upon was found to reach its decalescence point at 1360 degrees F. Previous experiments with the steel had shown that for annealing it should be heated to 40 or 50 degrees above this temperature, and for hardening it ought to be brought about from 50 to 100 degrees above the point of decalescence. The present investigations were carried on with the following temperatures:

	Degrees F.
For annealing	1400
For quenching in oil	1450
For quenching in water	1425

All the operations were carried on at these temperatures and the heats at which the temper was drawn and the mode of quenching

* MACHINERY, Railway Edition, May, 1910.

TABLE III. RESULTS OF TESTS ON SPRING STEEL

Heat Treatment	Elastic Limit	Modulus of Elasticity	Diameter of Test Piece	Moment of Inertia	Breakage Deflection, inches†
Annealed in lead at 1400° F.	78,500	27,550,000	0.991	0.04730	....
Hardened in oil at 1450, drawn to 560° F.	137,500	28,700,000	1.000	0.04909	....
" " " " 1450, " " 500° F	160,400	27,150,000	1.000	0.04909	....
" " " " 1450, " " 400° F.	177,600	29,080,000	0.991	0.04730	....
" " " " 1450, not drawn.	187,400	28,610,000	0.993	0.04772	....
" " water " 1425, drawn to 1050° F.	180,700	28,070,000	0.997	0.04850	....
" " " " 1425, " " 900° F.	233,900	28,860,000	0.998	0.04870	....
" " " " 1425, " " 750° F.	240,800	29,220,000	0.994	0.04790	0.744
" " " " 1425, " " 600° F.	219,800	30,420,000	0.991	0.04730	0.175
" " " " 1425, not drawn.	212,800	29,960,000	0.991	0.04730	0.175

† The first seven test pieces did not break when deflected at the center 1.1 inch. The test pieces were placed on supports 12 inches apart, and load applied in the center.

were the only variables in the heat treatments. The results obtained from the experiments are indicated in Table III, where details are given regarding the heat treatment, the elastic limit, modulus of elasticity, etc. It will be seen that the highest elastic limit obtainable with the steel used, when quenched in oil after having been heated up to 1450 degrees F. was 187,400 pounds per square inch, and this was obtained when the temper was not drawn after quenching. The higher the temper was drawn the lower the elastic limit fell. When the steel was quenched at 1425 degrees F. in water, and the temper not drawn after quenching, the steel was brittle and broke when deflected 0.175 inch. Drawing the temper to 600 degrees F. after having hardened in water gave an elastic limit of 219,800 pounds. When the temper was drawn to 1050 degrees F. the elastic limit dropped to 180,700 pounds, but the test piece did not break at 1.1 inch deflection. The results of the tests show that the modulus of elasticity is practically constant, and apparently independent of the heat treatment given.

Conclusions

The following are the conclusions of the experiments: Steel of 1 per cent carbon when quenched in cold water at its "critical" temperature or slightly above, is usually too hard and, hence, too brittle to be used for the making of springs or tools. The theory of the hardening of steel tells us that there are two ways of modifying this hardness and brittleness of the steel. They are, first, the allowing of some of the carbon fixed in the hardening state by quenching, to change back to the annealing state, by reheating the steel above 400 degrees F. (the higher this reheating or drawing of the temper is carried, the softer the steel becomes), and second, the using of a quenching bath having less heat conductivity. The slower the steel is cooled from above the critical point to about 400 degrees F., the more carbon is allowed to change to the annealing state, and the less the steel hardens. By the second method, steel can be obtained of different degrees of hardness without drawing the temper after hardening the steel. These two methods of regulating the hardness of steel can also be used jointly.

These points are illustrated in the tests. The higher the temper is drawn after hardening, the lower the elastic limit falls; also a lower elastic limit is obtained with the test pieces quenched in the bath having less heat conductivity, *viz.*, oil. The tests show that the elastic limit of 1 per cent carbon steel can be made to vary from 78,500 pounds per square inch to 240,800 pounds per square inch by changes in the heat treatment, and that very small changes in the drawing of the temper are sufficient to affect the elastic limit of the steel. This proves once more that the heat treatment of steel is a delicate operation, and that to obtain good and uniform results, it is necessary to have means of heating the steel uniformly to the proper temperature and cooling it at the desired rate in a cooling medium, the temperature and heat conductivity of which can be kept reasonably constant.

CHAPTER V

HEAT TREATMENT OF ALLOY STEEL*

The rapid development of the automobile industry in America has awakened a quick, keen appreciation of the great importance of proper heat treatment of steel. Scientific heat treatment is quite as essential as the quality of steel. Ordinary steel may acquire good physical qualities with proper heat treatment, and the best of steel can be ruined by defective methods. There must be thoroughness in the various operations of annealing, hardening and tempering, for only treatment carried on with care, makes uniformity of product possible. This is particularly true in the production of drop forgings.

The difference between ordinary and the best steel is great. For example, the elastic limit of ordinary steel is about 40,000 pounds per square inch, with a reduction of area of, say, 50 per cent. Nickel steel properly heat treated has an elastic limit of 80,000 to 100,000 pounds per square inch of section, with a reduction of area of 50 per cent, or more. Brittleness does not follow proper heat treatment, the enduring quality being increased in a greater ratio than the elastic limit. Consequently crystallization, fatigue, or whatever we name the cause of breakage, is less likely to develop in a properly heat-treated and tempered material than in an annealed and soft material. This fact, discovered in the laboratory and established in actual practice, is now commonly accepted by metallurgical experts, notwithstanding that it completely overturns previous general belief.

Another commonly accepted belief disproved is that strength and stiffness are coordinate, or "the stronger a piece of steel, the stiffer it is." To illustrate, it was thought if one piece of steel were twice as strong as another, it would bend only one-half as much under a given weight; but actual test has shown that a chrome-nickel steel having an elastic limit of 150,000 pounds or more per square inch of section, bends under a given load the same amount as a carbon steel specimen, and this condition holds true as long as the load is within the elastic limit of the weaker material. The elastic limit of a well-tempered steel spring is about 150,000 pounds per square inch, but a spring can be made of soft steel. If it is not loaded beyond its elastic limit, the spring will return to its original shape after every deflection, but the deflection would not be sufficient to make a good spring. In fact, it would be hardly noticeable, and of course, would be of little value. Between these extremes lie the steels used by the spring makers in the past.

Not only has the automobile industry forced the spring makers to depart from their old materials and methods, but the change extends all along the line. Assume that a 0.20 carbon steel has been used

* MACHINERY, August and October, 1909.

with advantage for a given design of crank-shaft, neither bending nor breaking through long continued use, and that the bearing surfaces are as small in area as can be used without heating or excessive wear. A crank-shaft of properly treated chrome-nickel steel, having an elastic limit four or five times as high as the 0.20 carbon steel would be no stiffer, but would have greatly increased life and reliability. The steel makers must be prepared to meet these new conditions. Sound knowledge of steel has spread fast among intelligent manufacturers; from the knowledge obtained in the laboratories established, where all materials are physically and chemically tested, they have learned to discriminate in selection. With known characteristics, heat treatment scientifically conducted is sure of results that make high-grade steels

TABLE IV. NICKEL STEELS

Carbon	Manganese	Nickel	Elastic Limit, tons	Tensile Strength, tons	Elongation in 2 inches, per cent	Reduction in Area, per cent	Treatment
0 21	0 86	3.48	68	112	13.7	45	1550 F. oil 600 F.
0 25	....	3.50	85	109	13.4	..	1550 F. oil 600 F.
0 27	....	3.50	86	110	13.3	51	1550 F. oil 600 F
0.18-0.28	0.60-0.90	3.5	68	103	12.9	54	1550 F. oil 600 F.
0.18-0.28	0.60-0.90	3.5	84	116	12.4	48	1600 F. brine.
0.25	0 60-0.90	3.5	88	121	12.2	48	1600 F. brine.
0.23	0.61	3.54	103	114	14.0	50.7	1550 F. water 212 F.
0.14	0.63	3.64	78	88	15.0	54.6	1500 F. water 212 F.
0.14	0 63	3.64	30	41	33 5	72.4	1400 F. oil 1200 F.
0.35	0 45	3.39	77	84	15.5	55.5	1500 F. water 900 F.
0.35	0.45	3.39	130	137	10.0	36.3	1500 F. water 430 F.
0.25	0.86	3.45	31	45	31	60	Natural, as rolled.

comparable with ordinary steel in about the ratio they, in turn, bear to cast iron.

In a paper read by Mr. John A. Mathews before the Franklin Institute in 1909, a valuable contribution was made to the question of heat treatment of alloy steels, especially as employed in motor car construction. The cost of the materials used in automobile construction amounts to about sixty per cent of the total cost of production. In view of this fact, the kind of material best suited for the more vital parts is highly important. In the following the composition and treatment of some of the most commonly used alloy steels are reviewed.

Nickel Steel

Nickel steel is the most generally used of the alloy steels. The best quality contains 0.20 to 0.25 per cent carbon, 3.50 per cent nickel, 0.60 to 0.90 per cent manganese, and not over 0.04 per cent sulphur and phosphorus. With carbon and nickel as given above, the manganese content ought never to exceed the limits mentioned. A slightly lower carbon content is sometimes used for case-hardening purposes, and a higher carbon percentage is much used for crank-shafts. Nickel steel is usually made in the basic open-hearth furnace. It is an excellent steel for case-hardening, and is easier to machine than other alloy steels.

Chrome-Vanadium Steel

The chrome-vanadium alloy steels are preferably made in the crucible or electric furnace, although the open-hearth process is also much used for the purpose. The open-hearth product, however, is somewhat uncertain, and while springs of steel made by this process may be better than those made from ordinary crucible steel, they cannot be compared with springs made of crucible chrome-vanadium steel. For excellent quality the latter product constitutes the highest attainment of the steel makers' art.

TABLE V. NICKEL-VANADIUM STEELS

Carbon	Manganese	Nickel	Vanadium	Elastic Limit, tons	Tensile Strength, tons	Elongation in 2 inches, per cent	Reduction in Area, per cent	Treatment
0.34	0.17	3.88	....	29	43	27.3	54	Natural as rolled.
0.33	0.16	3.72	0.12	41	54	23.8	53	Natural as rolled.
0.33	0.16	3.40	0.24	49	66	17.8	40	Natural as rolled.
0.34	0.17	3.88	.....	37	51	16.5	51	1500 F. oil 1150 F.
0.33	0.16	3.72	0.12	51	59	24.0	61	1500 F. oil 1150 F.
0.33	0.16	3.40	0.24	59	62	21.0	61	1500 F. oil 1150 F.
0.34	0.17	3.88	...	59	66	15.5	55	1500 F. oil 600 F.
0.33	0.16	3.72	0.12	70	76	14.5	56	1500 F. oil 600 F.
0.33	0.16	3.40	0.24	82	85	15.0	55	1500 F. oil 600 F.
0.24	0.72	3.33	0.12	38	49	27.0	64	Natural as rolled.
0.24	0.72	3.33	0.12	71	100	11.6	36	1600 F. oil.
0.24	0.72	3.38	0.12	92	117	14.5	52	1600 F. water.
0.24	0 72	3.33	0.12	91	116	15.2	57	1600 F. brine 400 F.

Chrome-vanadium steel made with high carbon content is suitable for oil-hardened gears and springs. When made with a low carbon content it is used for case-hardened gears, and, when oil quenched and annealed, for axles, shafts and steering knuckles. When a better material than the best nickel steel is needed, the various kinds of chrome-vanadium steel are to be recommended. They can be easily forged and can be machined more readily than chrome-nickel steels of corresponding carbon percentages.

Chrome-Nickel Steels

Chrome-nickel steels are made either with a high carbon content, and used for oil-hardened gears and springs, or with a low carbon content, in which case the steel is used for axles, shafts, forged parts, and case-hardened gears. The high carbon steel carries about 0.5 per cent of carbon, while the low carbon alloy carries 0.25 per cent. The nickel content is from 2 to 3.5 per cent, while the chromium varies

from 1 to 1.5 per cent. A special nickel-chrome-tungsten steel is sometimes used for springs. Nickel-chrome steels possess excellent static qualities, but present difficulties in heat treatment, forging and machining.

Silico-manganese and silico-chrome steels with medium and low carbon contents are used to a considerable extent abroad for springs and gears. Their relatively low cost favors their use, but they do not stand up well when subjected to shocks, and are too sensitive to heat treatment. When handled with great care they give good results where the temperatures for the heat treatment can be accurately gaged.

TABLE VI. CHROME-VANADIUM STEELS

Carbon	Manganese	Chromium	Vanadium	Elastic Limit, tons	Tensile Strength, tons	Elongation in 2 inches, per cent	Reduction in Area, per cent	Treatment
0.26	0.39	0.78	0.17	44	68	20	64	Natural as rolled.
0.26	0.39	0.78	0.17	103	139	8	8.2	1570 F oil 400 F.
0.27	0.50	1.00	0.17	33	45	28	62	Annealed 1475 F.
0.27	0.50	1.00	0.17	52	63	21	56	Oil tempered and drawn to various degrees.
0.27	0.50	1.00	0.17	62	65	17	62	
0.27	0.50	1.00	0.17	70	74	17	57	
0.27	0.50	1.00	0.17	100	106	12	51	
0.27	0.50	1.00	0.17	112	116	11	39	
0.40	0.77	1.22	0.19	34	50	26	62	Annealed.
0.40	0.77	1.22	0.19	98	104	10	36	1650 F. oil 840 F.
0.30	0.50	1.00	0.16	71	76	16	56	1650 F. oil 1025 F.
0.38	0.73	1.19	0.18	41	65	22	67	Natural as rolled.
0.38	0.73	1.19	0.18	110	144	10.8	47	1660 F. oil 600 F.
0.38	0.73	1.19	0.18	64	113	12.9	53	1660 F. oil 850 F.
0.33	0.54	1.24	0.20	64	71	15.5	56	1500 F. oil 1125 F.
0.33	0.54	1.24	0.20	95	104	11.0	38	1600 F. water 600 F.
0.45	0.58	2.37	0.30	88	94	13.2	46	1600 F. oil 1125 F.
0.45	0.58	2.37	0.30	138	146	6.0	16	1600 F. oil 430 F.
0.36	0.21	2.78	0.24	60	104	4.1	38	Natural as rolled.
0.36	0.21	2.78	0.24	65	72	20	56	1500 F. oil 1150 F.
0.36	0.21	2.78	0.24	98	104	18	45	1500 F. oil 600 F.

Chrome steels with high carbon content are used to a considerable extent for balls and ball races. Tungsten steels are universally used for making magneto magnets.

Heat Treatment of Alloy Steels

While the best alloy steels are none too good for most of the parts in automobile construction, their qualities will not become pronounced unless they receive proper heat treatment. It is waste of money to buy good alloy steels without knowing how to properly treat them to bring forth their exceptional qualities. For gaging the heat a pyrometer is necessary, but it is too often supposed to take care of itself. The best pyrometer of the thermo-couple type should be regularly inspected. The protecting tubes should be frequently examined and renewed, and the electrical contacts looked over.

The heat treatment operations depend upon established scientific facts, and a lack of appreciation of this causes many people to buy high-priced alloy steels from which they get no better results than from carbon steel properly handled. As an example of the effect of heat treatment may be mentioned a chrome steel which in its rolled condition had an elastic limit of 158,000 pounds, 5 per cent elongation, and 9.4 per cent reduction in area. The same steel, oil tempered and annealed, had an elastic limit of 153,000 pounds, 14 per cent elongation and 52 per cent reduction in area. In other words, the material was transformed from brittle to tough without appreciably affecting its elastic limit. Nickel steel similarly treated will have the elastic limit raised twenty per cent, with its elongation unchanged and its reduction in area improved.

TABLE VII. CHROME-NICKEL STEELS

Carbon	Manganese	Nickel	Chromium	Elastic Limit, tons	Tensile Strength, tons	Elongation in 2 inches, per cent	Reduction in Area, per cent	Treatment
0.37	....	2 9	1 04	60	78	18 5	61	1475 F. oil 1200 F.
0.37	....	2.9	1 04	77	84	16.	56	1500 F. water 1100 F.
0.45	..	2.0	1.0	70	90	8.0	20	Oil-temp. and annld.
0.25	....	2.0	1 0	50	65	12.0	30	Oil temp. and annld.
0.25	....	3 0	1.5	57	64	15 0	65	Annealed.
0.25	....	3 0	1 5	110	116	6.0	40	Hardened—oil.
0.50	....	2.0	1 0	33	46	27.0	64	Natural as rolled.
0.50	....	2 0	1.0	72	184	6 0	23	Tempered.
0.30	....	2.0	1 0	35	53	18 0	45	Natural as rolled.
0.30	....	2 0	1 0	68	98	9.0	37	Tempered.
0.30	....	2 0	1 0	45	55	25 0	55	Oil-temp. and annld.
0.40	0 18	2 1	0.80	60	76	12 8	37	Natural as rolled.
0.40	0.18	2.1	0.80	58	66	17 5	40	1500 F oil 1150 F.
0 40	0 18	2 1	0 80	106	118	10 0	34	1500 F. oil 600 F.
0 40	0 18	2.1	0.80	70	79	15 5	48	Annealed 1150 F.

Tables IV to VII, inclusive, show typical analyses, treatment and tensile strength of nickel, nickel-vanadium, chrome-vanadium and chrome-nickel steels. Many sources of information have been drawn upon in the compilation of these tables, as, for instance, the data published by the American Vanadium Co., experimental data obtained by tests made by the author, and the commercial tests made on the steels of many makers. The elastic limit and tensile strength are given in tons per square inch, and the elongations are measured on 2-inch test specimens, ½ inch in diameter. It should be noted that the figures given must be used with some caution. Because a ½-inch test piece, oil tempered and annealed, gives an elastic limit of 75 tons per square inch, it does not follow that a 1½-inch bar similarly treated will have the same elastic limit. The hardening action in quenching does not penetrate very deeply in the large bar, while in a small one it may penetrate to the center.

In the column marked "Treatment" is given the temperature to which the steel is heated before quenching, followed by the liquid in which it is quenched; where a second temperature is given it indicates the temperature to which the steel is reheated to draw the temper or anneal. This will make clear such terms as "1600° F. oil 600° F."

For springs it seems that no material is better than crucible chrome-vanadium steel. The tempering of this steel is quite simple. The springs made from it should be heated to from 1675 to 1700 degrees F. and quenched in oil. The temper is then drawn according to the nature of the spring, and the duty expected. The drawing range is very wide, varying from 600 to about 1000 degrees F.

Case-hardened vs. Oil-hardened Gears

Both case-hardened and oil-hardened gears are largely used in automobile construction. As previously mentioned, the chrome-vanadium, chrome-nickel and silico-manganese alloys are made with both high and low carbon contents. The former contains about 0.45 to 0.60 per cent carbon and enough other hardening elements so that by merely quenching the steel in oil from a bright red heat, surface hardening is produced sufficient for ordinary wearing purposes, while the hardness does not penetrate deeply into the gear, but leaves a tough and strong core. The low carbon alloy steels, with about 0.20 per cent carbon, require to be case-hardened in order to produce sufficiently hard surface for wearing purposes. The author's observations lead him to prefer the case-hardened gear, the following conclusions being based on the results of direct tests on thousands of gears.

1. The static strength of case-hardened gears is equal to that of oil-hardened gears, assuming that in both cases steel of the same class of appropriate composition has been used, and the respective heat treatments have been equally well and properly conducted.

2. Direct experiments prove that case-hardened gears resist shocks better than oil-hardened.

3. The case-hardened gear resists wear incomparably better, although it is perhaps not as silent in action.

The strong objection to the case-hardening is in nine cases out of ten doubtless due to the fact that the case-hardening operation is not properly understood. The depth of the hard case or covering, the time and temperature required to produce certain results, and the exact control of the conditions, together with an accurate knowledge of the material to be treated, are factors which enter into successful case-hardening.

To obtain the best results in case-hardening ordinary carbon steel, the following rules should be observed. Steel containing less than 0.12 per cent of carbon, and with a low percentage of manganese (less than 0.30 per cent) should be used; the case-hardening should be accomplished by a chemically definite material, such as a mixture of 60 per cent charcoal and 40 per cent barium carbonate, and at a temperature between 1560 to 1920 degrees F. The higher the temperature, the more rapid will be the case-hardening. After the case-hardening operation, allow the steel to cool down to about 1100 degrees F. Then re-heat the work to be case-hardened, and quench it at 1650 degrees F. This heating and quenching has the effect of toughening the center, but the outside will be coarse-grained and brittle; therefore heat the material a second time to 1470 degrees F. to render the outside non-brittle.

This procedure is more elaborate than that most commonly used, in which pieces are dumped directly from the case-hardening boxes into water. The process, however, can be somewhat modified if one uses a good grade of nickel steel, low in carbon, and after having case-hardened it at the appropriate temperature, permits the material to cool off in the boxes before re-heating and quenching. In this case, if the material is re-heated but once to 1470 degrees F. the result will be fully equal to or better than those obtained by the most careful annealing and double quenching of ordinary carbon steels. It is, however, better to give a double quenching, as then extraordinary toughness and wearing qualities are obtained.

An ideal way of making a nickel steel gear consists in first annealing the blank, then rough machining it approximately to size, and then re-annealing before taking the last finishing cut. The gears are the packed in a mixture as mentioned, heated to a temperature of about 1625 to 1650 degrees F., carbonizing to a depth of about 1/64 to 1/32 inch. The gears are then permitted to cool in the boxes, are heated to 1500 degrees F., and quenched in a hot brine or calcium-chloride solution, and finally re-heated to 1375 or 1400 degrees F. and quenched in oil. The temper need not be drawn.

Another important point is that of drop forging small parts which can also be made from bars in automatic machines. No steel is improved by drop forging, although some steels are less susceptible to injury than others. In drop forging work, in order to give plasticity, the material must be heated very hot. An investigation of drop forging and bar cut gears, the former being the product of one of the foremost drop forging companies, showed that under static test the bar cut gears were fully 25 per cent stronger and their resistance to shock was also greater.

CHAPTER VI

CASE-HARDENING*

The present chapter contains an abstract of a paper read by Mr. David Flather before the Cycle Engineers' Institute, Birmingham, England.

The term "case-hardening" naturally implies the hardening of the skin of an article, and in order to fully understand the process and its object we must briefly consider the facts and laws upon which it is founded. Carbon has a very great affinity for iron and combines with it at all temperatures above faint red heat. Advantage is taken of this fact in the production of steel by cementation—in fact, the process of case-hardening is in reality incomplete cementation followed by water or oil-hardening.

For many purposes in machine work we require articles to have a perfectly hard surface and yet be of such a nature that there is no chance of their breaking in use. In many instances this result can be obtained with high-class crucible steel, but for axles, cups, cones, and many similar parts, it is extremely difficult to obtain perfect hardness combined with great resistance to torsional, shearing, or bursting strains. For such purposes nothing can meet these requirements so fully as articles which have been case-hardened. The greatest risks in the employment of all steel often occur during its treatment by the producer, and whether it be the finest cast steel or only common Bessemer, it is of first importance that it should be carefully and properly treated with a view to the work it has to do.

Both iron and mild steel have been employed as material for case-hardening; but this is the "steel age," and iron has long passed its day. The steel employed should be prepared, selected, and controlled from the beginning with the object of suiting it to its requirements. There are, of course, many points relating to its composition and treatment by the producer which can only be gained by long experience and by study of the requirements. Suffice it to say that the steel used should be low in carbon and capable of absorbing more carbon with great uniformity when heated under proper conditions; it should contain a minimum of deleterious impurities, and be perfectly sound and free from mechanical faults or weaknesses caused by overheating during the manufacturing processes.

The Case-hardening Furnace and Muffles

The furnace should be so constructed as to be capable of being raised to a full orange heat (1830 degrees F.), and maintained at that heat with great regularity. It should be so constructed that neither the fuel nor the direct flame can come in contact with the charge. The

* MACHINERY, August, 1905.

flames should uniformly impinge on the sides and roof of the muffle in such a manner as to raise them to a high temperature, thus heating the contents of the muffle by radiated and not by direct heat. A furnace designed on this principle not only gives the best result but is also most economical in the matter of fuel. The muffle chamber and flues must, of course, be constructed of firebrick, and the doors should fit closely and also be lined with firebrick. It is important that there should be a small peep-hole in the door, with a cover plate; a hole 1½ inch in diameter is quite large enough. This latter is a most important detail, as it provides against the need of opening the doors in order to judge the heat, and is indeed the most accurate means of estimating the temperature by the eye. The furnace must be fitted with a reliable damper plate or other effectual means of controlling the draft.

Fig. 6 shows a furnace which may be useful as a guide for the erection. The upper chamber in this furnace is not necessary for case-hardening, but it may be found useful to have such a chamber and employ it for annealing small articles while case-hardening is being done. This will add only very slightly to the amount of fuel used.

Hardening pots are made in both cast and wrought iron, the former being cheaper in first cost, but the latter bear reheating so many times that they are cheaper in the end. The pots should not be of too large dimensions, or there is great risk of articles in the middle of a charge not being carbonized to a sufficient depth. No pot should be above 18 by 12 by 11 inches for such parts as cycle axles, pedal pins, and the like; while for small articles like cups, cones, etc., 12 by 10 by 8 inches is large enough. The pots should each have a plate-lid fitting closely inside.

The carbonizers in general use at the present day are animal charcoal, bones, and one or two other compositions sold under various names, consisting of mixtures of carbonaceous matter and certain cyanides or nitrates. For very slight hardening, cyanides alone are still found very useful, but no great depth of casing is ever attempted with these. Theoretically, the perfect carbonizer should be a simple and pure form of carbon, and good charred leather gives the most certain and satisfactory results. Care should be taken to avoid poorly charred leather or that made from old boots, belting, etc.

Clay

As clay must be used for a luting around the pot lid, and is also frequently used for stopping off portions to be left soft, it is important to see that a good clay is used, and that it is free from grease. Clay contaminated with grease in any way will cause irregularity in the product.

Reheating Muffles

As all case-hardened articles have to be reheated before quenching, it is important that a suitable furnace should be employed for the purpose. It is not advisable that the reheating should be done in the case-hardening muffle, unless it is run specially for the purpose and at a lower heat. If possible a small gas muffle should be used for reheating, and indeed for all hardening work. A properly constructed gas muffle can be regulated with great exactness, and this is very important in all hardening.

Packing the Muffles

The carbonizer having been thoroughly dried and reduced to a fine powder, a layer of not less than 1½ inch in depth is placed in the

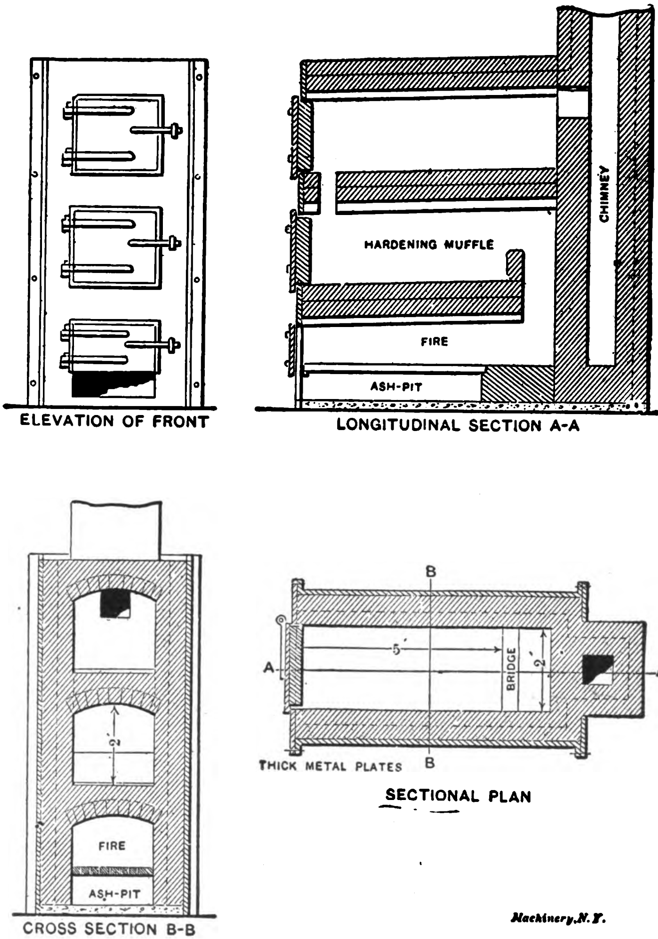

Fig. 6. Plan and Elevation of Flather Case-hardening Furnace

hardening pot and well pressed down. Upon this are placed the articles to be hardened. Care must be taken to leave sufficient space all around each piece to prevent its touching the others or the walls of the pot; a space of 1½ inch should be sufficient. Another layer of carbonizer is then put in and well pressed down, taking care not to displace any of the articles already packed, continuing until the pot is nearly full, and then finishing off with another layer of 1½ inch at the top. The object in view must be to make the contents of the pot as compact as possible, consistent with a sufficiency of carbonizer in contact with the articles. The more solidly a pot is packed the more complete is the exclusion of air. The lid is then put on, and the joint all around well luted with clay. By the time the proper number of pots have been filled, the furnace must have been raised steadily to the full working heat.

Furnace Heat

The proper heat for case-hardening is about 1800 degrees F., or a full orange heat and this should be maintained with great regularity throughout the operation. The length of time occupied in carbonizing is regulated by the depth of casing required, and indirectly by the dimensions of the article. At the close of the carbonizing period the pot is withdrawn from the furnace and placed in a dry place, where it is allowed to become quite cold. It is then opened, the articles taken out and brushed over to remove all adhering matter. If the pot has been properly packed and luted up, the articles should be quite white, or at least have only a slight film or bloom of a deep blue color; the denser and more inclined to redness is the surface, the more imperfect has been the packing and sealing of the pot.

Reheating and Hardening

The carbonized articles are now placed in a muffle furnace and steadily raised to a good cherry red (1470 degrees F.), and then quenched in cold or tepid water or oil, according to the purpose of the articles required. They should remain in the cooling liquid until they are quite cold right through the body of the metal, thus completing the process.

Although the proper temperature for case-hardening is about 1830 degrees F., this temperature may be modified to suit the purpose in view. The absorption of the carbon commences when the steel reaches a low cherry-red heat (1300 degrees F.); it begins, of course, at the outer surface and gradully spreads until the whole of the steel is carbonized. The length of time this requires depends upon the thickness of the metal being treated. The percentage of carbon absorbed is governed by the temperature, and although the increase of carbon is not in uniform proportion to the rising temperature throughout, it is perhaps sufficient for our present purpose to note that at 1300 degrees F., iron, if completely saturated, can contain no more than about 0.50 per cent carbon; at 1650 degrees F., about 1.5 per cent carbon; and at 2000 degrees F., about 2.5 per cent. These results, however, are only obtainable when the whole section of the iron has received all the carbon it is capable of absorbing at the given temperature, and is therefore in a state of equilibrium. From this it will be seen that if the process is stopped before the action is complete, the central parts of the iron must contain less carbon than the outside, and upon this fact the process of case-hardening is founded.

If we take two pieces of ⅝ inch diameter round mild steel, and heat one of them with a carbonizer at a cherry-red heat, and the other at a bright orange heat, for six hours, the first will be cased to a depth of about 1/32 inch, and the other to a depth of nearly 1/16 inch, while the amount of carbon taken up will be about 0.50 and 0.80 per cent respectively; so that, so far as regards the hardness of the skin, the piece carbonized at the higher temperature gives the best result. From this we learn that a temperature of 1830 degrees F. will give us sufficient hardness of case.

We have next to find which temperature has the least harmful effect on the mild steel core, and this can best be found by heating pieces of the mild steel at varying temperatures at and above the selected one for the same length of time, using lime or other inert substance in the pot instead of a carbonizing material, and afterward reheating and quenching in water. Suppose, for example, we take three pieces, heating at 1830, 2370 and 2730 degrees F., or full orange, white and bright white respectively. We shall find that those at 2370 and 2730 degrees break very short and have lost nearly all their original tenacity, while that at 1830 degrees appears tougher and altogether stronger than before.

Having arrived at a knowledge of the right temperature, it remains now to inquire as to the length of time requisite to yield a sufficient depth of case. At a full orange heat a bracket cup of ordinary dimensions should in two hours be hardened 1/32 inch deep, and a bracket axle 11/16 inch diameter in 6 hours would have a case 1/16 inch deep. From this it will be seen that the speed of penetration it not in exact proportion to the time of heating.

Results of Hardening without Reheating

We now arrive at that part of the process where a most important improvement has been made—*i. e.*, the final hardening by quenching in water. It formerly was customary at the end of the carbonizing period to open the pot and fling the contents headlong into a tank of cold water. Here and there some of the more careful workers took each article separately, but direct from the pot, and plunged it into water. These latter obtained better results, but even they had a great deal of trouble in the way of breakages and want of regular hardness. Finding that axles taken singly from the pot and quenched were better than those quenched in bulk, and that if allowed to cool down to cherry red they were better still, an application of the old rule to harden on a rising heat led to the now established principle of allowing the pot and its contents to become quite cold, afterward reheating to cherry red and quenching with water. By this means we obtain a case of great hardness with a very tough core—that is, of course, provided a suitable steel is employed.

To understand the reason of this improved method of working we must remember that the exterior of the steel is now of about 0.80 per cent carbon, and that steel of all kinds raised to and maintained at the high temperature employed for case-hardening will, unless subjected to mechanical work, show evidence of overheating, being very brittle and liable to easy fracture; and though quenched in water, and consequently hardened, the metal has little or no cohesion and readily wears away. Steel so hardened breaks with a very coarse crystalline fracture, in which the limits of the case are badly defined. It is known that when steel is gradually heated there is a certain point at which a great molecular change takes place, and that perfect hardness can only be obtained by quenching at this critical point. If quenching takes place below the critical temperature, the steel is not sufficiently hard; if above, though full hardness may be obtained, strength and tenacity are lost in part or completely, according as the critical temperature is exceeded by much or by little. This critical point lies between 1380 and 1470 degrees F., or cherry-red color heat. It may be asked why it is not sufficient, when taking the article out of the pot, to allow it to cool down to cherry red and then quench it. To this the answer is that the high temperature has already created a coarsely crystalline condition in the steel, and that until it has become quite cold and has again been heated up to the critical temperature, a suitable molecular condition cannot be obtained. When steel is cooled, whether slowly or not, it bears in its structure a condition representative of the highest heat it was last subjected to.

Case-hardening Practice of Pennsylvania Railroad Shops

It may be of interest to note the case-hardening practice followed by the Altoona shops of the Pennsylvania Railroad Company. The compound for case-hardening is made from 11 pounds prussiate of potash, 30 pounds sal soda, 20 pounds coarse salt, and 6 bushels powdered charcoal (hickory preferred). These ingredients are mixed thoroughly, using 30 quarts of water in mixing. The following method is pursued in packing the material to be case-hardened. The bottom of the box is covered to a depth of 2 inches with the compound. The parts to be hardened are placed solidly so that the compound is in contact with the bottom surface of the part, care being taken that the work does not touch the sides of the box or other pieces. After the first layer of the material is placed, it is covered on all sides and on top with the compound and solidly packed. After the first course is packed the process is repeated, care being taken to have a sufficient amount of compound between every course. There should be not less than 2 inches of compound on the top of the last course. Then the lid is thoroughly sealed with a luting of fire clay.

In the furnace the box rests on rollers to allow the flames to pass under it. When the material has been in the furnace a sufficient length of time, the box is withdrawn to a trestle flush with the floor of the furnace and parallel with and close to a water tank, after which the material is removed from the box and plunged into the water. This method makes it possible to obtain a depth of case on large material of from 1/16 to 5/32 inch in 14 hours, and of about 1/16 inch on bushings and small parts in from 2 1/2 to 3 hours. All parts to be case-hardened are thoroughly cleaned so as to be free from oil or grease.

CHAPTER VII

CASE-HARDENING FURNACES AND THEIR USE*

No doubt the majority of tool-steel workers know that heating high-carbon steel in a gas or any open furnace without packing, oxidizes and decarbonizes the steel, making it impossible to obtain a uniform hardness. Lead baths have their disadvantages and, in general, are of very little value. The method of pack-hardening and dipping described in this chapter has given the most satisfactory results, but first we must have a furnace suited to such work.

The Case-hardening Furnace

The case-hardening furnace shown in Figs. 7, 8, 9 and 10 is one of the best hard coal furnaces for pack hardening, case-hardening, mot-

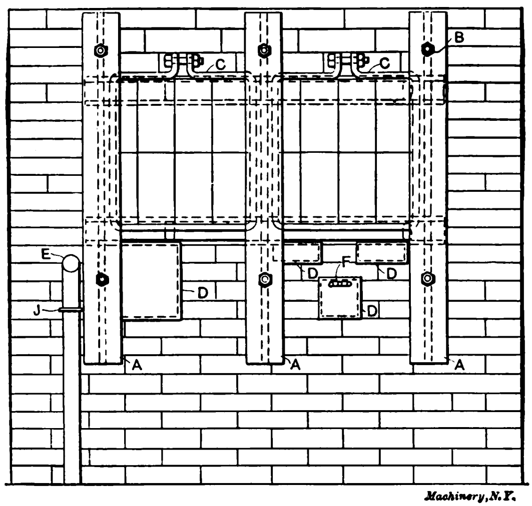

Fig. 7. Front View of Case-hardening Furnace

tling and coloring. It can be built from common brick and fire-brick, and is large enough for an ordinary shop. If a larger one is required, it will be necessary to use large tile in place of fire-brick for the bottom of the oven. A blast is used in connection with this furnace when starting the fire, but very little is required after the boxes containing the work to be hardened are red-hot, but this, of course, depends upon the draft in the chimney. A damper should be supplied in the pipe behind the furnace to regulate the heat. The following are the principal parts of the furnace: *A*, cast-iron buck-stays; *B*,

* MACHINERY, June, 1907.

⅝-inch stay-bolts; *C*, door frame, ¾ x 1¾-inch iron; *D*, sheet iron caps for flues; *E*, blast pipe, 1½-inch gas pipe, slotted; *F*, damper; *G*, damper support; *H*, cast-iron; *I*, grate support; *J*, blast shut-off; and *K*, stack.

Packing Steel for Hardening

In packing tool steel parts for hardening, do not use raw bone or leather unless a low-carbon steel is to be treated and more carbon to be supplied. The steel generally used for such tools as reamers, shears, etc., is high-carbon, and by packing in raw bone we shall get the cutting parts too brittle. Use instead only fine wood charcoal about the size of kernels of corn. Fig. 11 is not the best kind of box

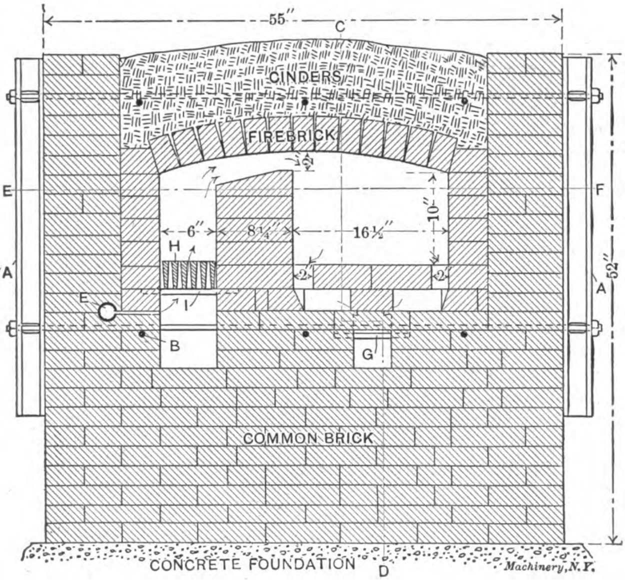

Fig. 8. Case-hardening Furnace. Section in A-B, Fig. 9

to use for this kind of work, as the parts cannot be properly packed in it, and if very long they cannot be gotten out without bending. Fig. 12 shows a better form. Seal the cover on with asbestos cement and put a few ¼-inch rods down through holes drilled in the cover. After the work has been in the oven a reasonable length of time, take out one of the rods; if hot enough, draw the box out, pick the work out, and dip; but, if the rod is not hot enough, replace the box, and after half an hour draw another rod, and repeat, if necessary, until one is pulled that shows that the proper heat has been reached.

Dipping Work

When dipping work of this kind use salt water, and never use clear water only, because the parts do not chill quickly enough. When dipping a tool in water, do not start off sidewise when immersing the object, the reason being that one side of the tool will be exposed to cold water, and hot water and steam will be coming up on the other side, thus causing warped work and uneven hardening. We all know that hot water comes quickly to the top, so provide a deep tank of cold salt water and start the work in straight; carry it clear down to the bottom of the tank and then raise it slowly up again. Instead of leaving it in the water until entirely cold, remove while quite warm to a tank of fish oil to draw down and relieve the strain. The reamers shown in the cut, Fig. 16, were heated in a large gas-pipe, the same as that indicated in Fig. 13, and were dipped in cold salt water just long enough to harden the cutting parts. They were then removed to a tank of fish oil and left there until cold. The illustration

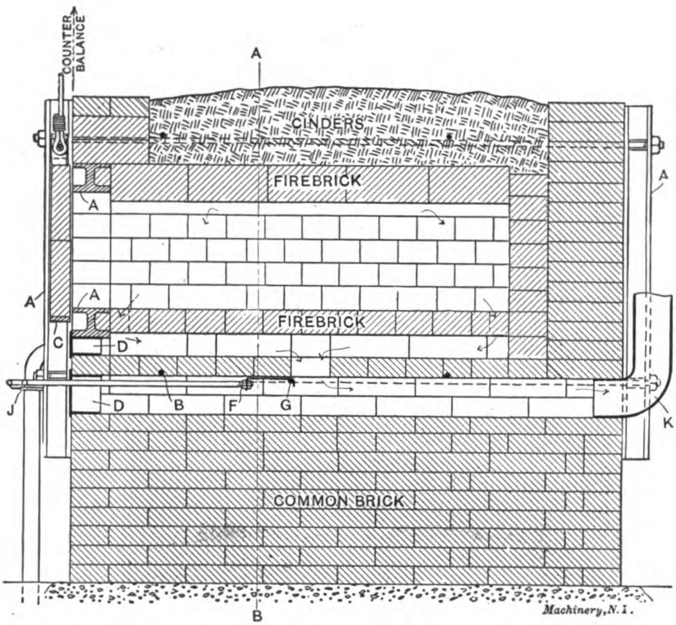

Fig. 9. Section in C-D, Fig. 8

shows them in a sieve as they were drawn from the oil. There are fourteen of the reamers, ranging in size from 1 to 1⅝ inch diameter, and in length of cutting edges from 5 to 12 inches. These reamers have given remarkable satisfaction. The method is much quicker than the old way of cooling completely in clear water, then cleaning up and drawing down the temper, to say nothing of the danger of cracking before this time-consuming and edge-destroying practice is completed.

The gas-pipe is a very convenient holder for packing work for hardening, as it can be rolled over easily to get a uniform heat. To make it, rivet a thin plug of machine steel in one end, and after the work is packed, plug the other end with asbestos cement. Take, for example, some long thin blades about 12 inches long or less, ½ inch wide and ⅛ inch thick; it is a difficult task to harden this class of work and keep it straight. The writer has repeatedly hardened such blades and kept them perfectly straight by arranging them as shown in Fig. 14. Make three small clamps like *C*, long enough to take in from 12 to 16 blades; then fasten one clamp on each end and one in the center of the blades. The blades should be a little higher than the clamp so as to allow the top part of the clamp *B* to bind on the edges of blades *D* when tightened down with cap-screws *A*. Then pack in the pipe or open-top box in wood charcoal, and heat and dip same as explained about reamers. High-speed steel blades can be

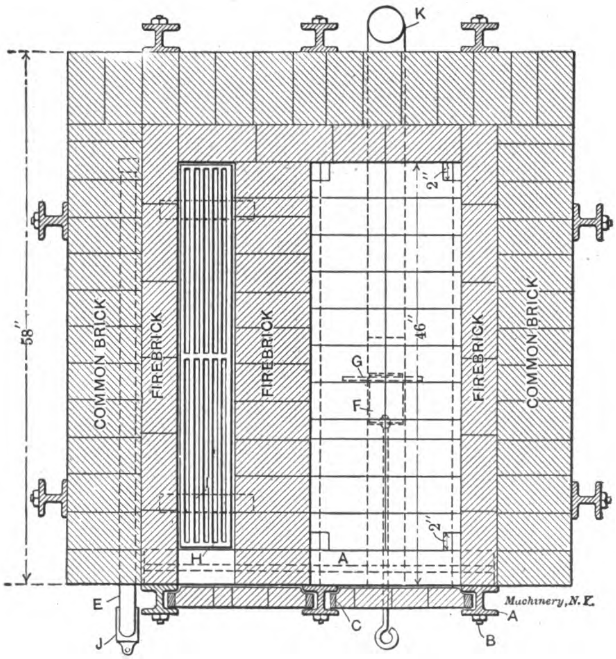

Fig. 10. Section in E-F, Fig. 8

treated this way, but must be brought to a much higher heat—just as hot as a hard coal furnace will make them. They should be dipped in hot salt water and removed to the oil bath while a little warm, and let remain there until cold. This treatment will make them very hard and at the same time keep them straight.

Use of Furnace for Cyanide Hardening

This same furnace is invaluable for hardening with cyanide. Put a box containing potassium cyanide in the furnace and heat it to a bright cherry red. Put the work to be hardened in an open furnace and heat to the same heat as the cyanide. Then place the work in the cyanide and let it remain for from five to twenty-five minutes, according to the depth desired. Then take the work out of the box and cool off in some light oil—kerosene is the best. Keep a cover on the box while heating the cyanide; just put it on loosely and do not seal. Cyanide should always be kept in air-tight cans, as it will air-slake if exposed, and will not melt if it has been exposed for any considerable length of time.

Hardening for Colors

When hardening for colors, a furnace like the one described is necessary. A very satisfactory method of coloring which at the same time

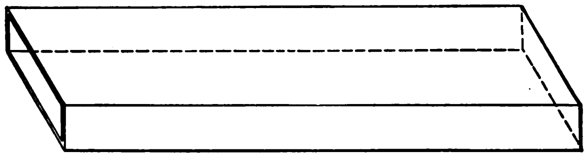

Fig. 11. Form of Box not Suited for Packing

hardens deep enough for the class of work which is to be colored, such as wrenches, crank levers for automobiles, nuts, etc., is as follows: Mix 10 parts charred bone, 6 parts wood charcoal, 4 parts charred leather and 1 part powdered cyanide. The charred bone may be ob-

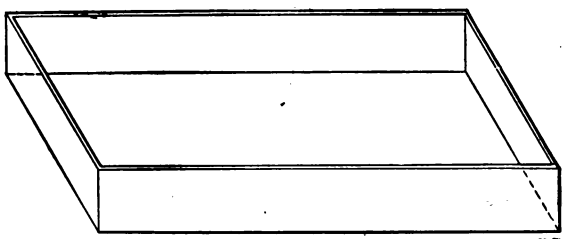

Fig. 12. Suitable Form of Box for Packing Work for Hardening

tained by placing a few boxes of raw bone in the furnace on Saturday night (if the furnace is not run over Sunday). If much fire is in the fire-box it should be drawn, as the heat in the furnace will be sufficient to char the bone to a dark brown. The charred leather may

Fig. 13. Gas Pipe used for Packing

be obtained in the same way. The leather should be black, crisp and well pulverized, and the four ingredients should be well mixed together. The object in charring the bone and leather is to remove all grease. The parts to be colored must be well polished and they should not be handled with greasy hands. These rules must be observed if a nice class of work is desired.

If the colors obtained are too gaudy, the cyanide may be left out, and if there is still too much color, leave out the charcoal. When packing parts to be colored and hardened, they should be be packed in a

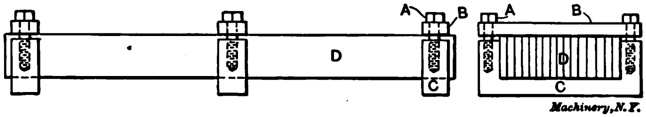

Fig. 14. Clamp for Long Thin Work

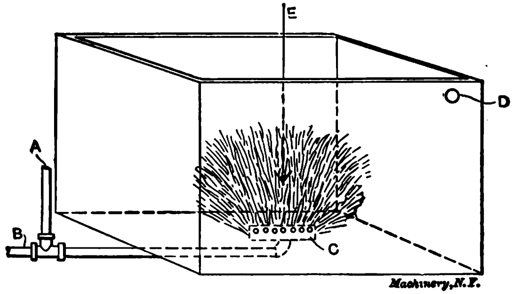

Fig. 15. Hardening Tank Arranged for Mottling and Coloring

common gas pipe, for the reason that when dumping into the water the parts must not be exposed to the air, and a pipe is much easier to handle than any other shape. The open end can be brought down

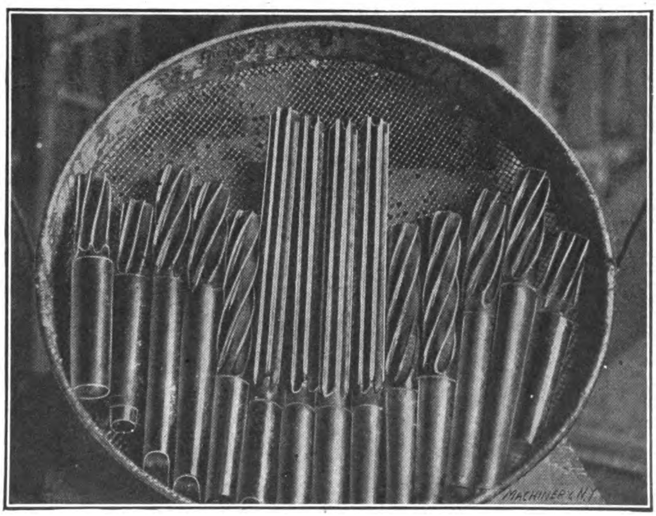

Fig. 16. Hardened Reamers, just Removed from Oil Bath

close to the top of the water before the parts are liable to come out, but not so with a box, for just as soon as a box is tipped a little the parts begin to fall out, and become exposed to the air.

In heating this class of work, heat to a dark cherry red and keep at that heat for about four or five hours; if heated too hot no colors will appear. To harden and color the work when dumped, a tank must be arranged as shown in Fig. 15. A compressed-air pipe *A* must be connected with the water pipe *B*, and a large cap *C* should be drilled full of ¼-inch holes on top and around the sides. An overflow *D* should also be supplied. Fill the tank with water, then turn

Fig. 17. Sample of Work Case-hardened for Colors

on air enough to fill the tank with lively bubbles and dump the work in the center, as shown at *E*. When the work is all dumped, pull up the sieve which should be in the tank for the work to fall on, pick the work out and place it in pails of boiling water drawn from the boiler; let it remain for five minutes and then remove it to a box of dry sawdust for half an hour; remove it from here and dust it off and give it, finally, a coating of oil or lacquer.

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