COMPOSITION AND HEAT TREATMENT OF STEEL

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COMPOSITION AND HEAT TREATMENT OF STEEL

BY

E. F. LAKE

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PREFACE

In preparing the matter that enters into this book no attempt has been made to go into details on the subjects of the ores, their melting down into iron, or refining the iron in steel making. This part has merely been covered in a general way in order to lead up to and give a better understanding of the effect of the elements present in and added to steels of the various grades and kinds.

An attempt has been made to cover all the materials that have been used, either commercially or experimentally, for the purpose of making better steel and improving the standard brands so they will have greater strengths; withstand strains and stresses better; possess a longer wearing surface; have a greater electrical resistance, conductivity, or magnetism; attain a greater hardness, ductility, resiliency, or malleability; be capable of taking larger cuts on other metals or machining them faster; produce a metal that can be easier rolled, hammered, pressed, drawn, forged, welded, or machined into shape; be non-corrosive, or, in fact, make a better metal for any of the many uses to which it is put. The effect these materials or elements have had upon the carbon and alloyed steels has been told as well as the data at hand would permit, and hints have been injected, as to what might be expected from many of the elements, in order to stimulate further investigations and experiments. Results have been obtained in this way in the very recent past that are truly wonderful, yet these are liable to sink into insignificance before the discoveries that may be made in the near future.

The different chemical compositions that can be made from the elements here listed and described are so numerous that it seems hopeless to expect that all of them will ever be compounded, and tests made, and the results recorded. However, with the many individuals that are working along these lines some combinations are bound to be made that will prove to be beneficial, and doubtless some steels will be produced that will cause as great a revolution as "Mushet" or "Bessemer" steels did in their respective lines. A very few of the possible quaternary steels have been tried, *i.e.*, alloys made by combining four different elements with the ferrite, and therefore many are yet to be investigated in the many different percentages in which it is possible to combine them. And this does not take into consideration the compositions that are possible with six, eight or more elements.

Following the ingredients of and materials used in steel, comes the heat-treatment, as the two have moved along parallel lines, in the many investigations, experiments, and improvements that have been made, and seem to be inseparable. Each change in composition seems to have altered the heat-treatment, and each improvement in heat-treatment seem to have altered the percentage, that is best to use, of some one or more element. Many different methods and various kinds of materials have been experimented with and consequently a great deal of useful information has been obtained and many improvements of a radical nature made. New methods, new materials, and new apparatus have thus been brought into use for the heat-treatment of steel. These have enabled the hardener to get more definite, positive, and uniform results, and in this way the metal has been improved to a great extent.

All of the information that could be obtained on this phase of steel making and working has therefore been recorded as carefully as possible. This also suggests ideas that would indicate that there is still room for important improvements or discoveries. One of these is the attaching of a positive and negative wire of an electrical circuit to the piece of steel to be hardened and place it in a quenching bath. The current can then be turned on, the piece heated, the current turned off, and the piece quenched without moving it or allowing the air to strike the metal and oxidize it. Another instance is the possibilities suggested by carbonizing steel with gases or chemicals and thus doing away with the old laborious method of packing the steel pieces in bone and charcoal. Still another is the 30-minute annealing of high speed steel and the possibility of a similar method being applied to carbon steel.

In gathering together the data necessary to add to my own, very little credit has been given to individuals, as to make this correct is not only a laborious but a hopelessly impossible task. To illustrate this I have seen professors claim as their own discoveries, new principles, new methods, etc., that were developed and perfected by students in their classes, and shop foremen and superintendents claim as theirs, inventions made by men in the shop. Two important discoveries that developed into new kinds of steel were made through the mistakes of workmen in steel mills. Two men on the same job added the correct percentage of a material and thus this element was twice as large as it was thought would give good results. In fact, it was believed that it would injure the metal to add more than a certain percentage, but when this maximum percentage was doubled the metal was given properties that were very beneficial for certain purposes. None of us can add but a mite to the knowledge that we have obtained from others and because we are enabled to write it so it will be recorded in books and papers does not give us the privilege of claiming to be the originators of certain ideas, principles, discoveries, or inventions. Every one who has worked in the steel mill or the laboratory is entitled to a part of the credit for any new ideas or information that may happen to be enclosed between the two covers of this book. To pick out a few individuals and give less credit than this would be working an injustice and stating an untruth, and to name all that should be given credit is a physical impossibility.

E. F. LAKE.

CONTENTS

COMPOSITION AND HEAT TREATMENT OF STEEL

CHAPTER I

The Making of Pig Iron

The iron that forms the base for all steel, as well as iron, products is first obtained from its ores, as a commercial product, from a blast furnace similar to that shown in Fig. 1. It is then in the form of an iron that contains a large amount of carbon, both in the graphitic and combined state. This makes it too weak and brittle for most engineering purposes, but about one-third of the total product is run out of the blast furnace into pigs of iron that is used only for castings that are to be subjected to compressive, transverse or very slight tensile strains, such as bed plates or supporting parts for machinery, stove plates, car wheels, etc.

The various kinds of steels are relatively increasing in proportion to the amount of pig iron used. To-day about two-thirds of this product is being turned into steel through purification by either the Bessemer, open-hearth, puddling, crucible, or electric methods. The carbon content is reduced to any desired point, the graphitic carbon being eliminated by any of these processes, and the silicon and manganese are oxidized out by the accompanying reactions, or as a condition precedent to the reduction of the carbon. The two impurities of the metal which are the greatest bane to engineers and steel makers alike are phosphorus and sulphur. These are reduced by either the basic open-hearth, puddling, or electric processes.

In making steel, the operation begins by making pig iron from the iron ore, which is a natural iron rust or a combination of iron and oxygen. The oxygen is removed by combining iron ore, coke, and limestone in a furnace, as shown in Fig. 2, and heating them to a high temperature by injecting superheated air into the bottom of the furnace. The coke is burned by the oxygen in the air; a part of it aids in maintaining this high temperature while the rest is useful in removing the oxygen.

This superheated air is usually produced by passing the blast through a hot blast stove. This has been previously heated by means of the combustible gases which have been conducted from the top of the furnace to the bottom through the pipe shown to the left of the furnace in Fig. 2.

Four of these stoves are shown grouped in pairs, to the left of the blast furnace, in Fig. 1. They are about the same height as the furnace,

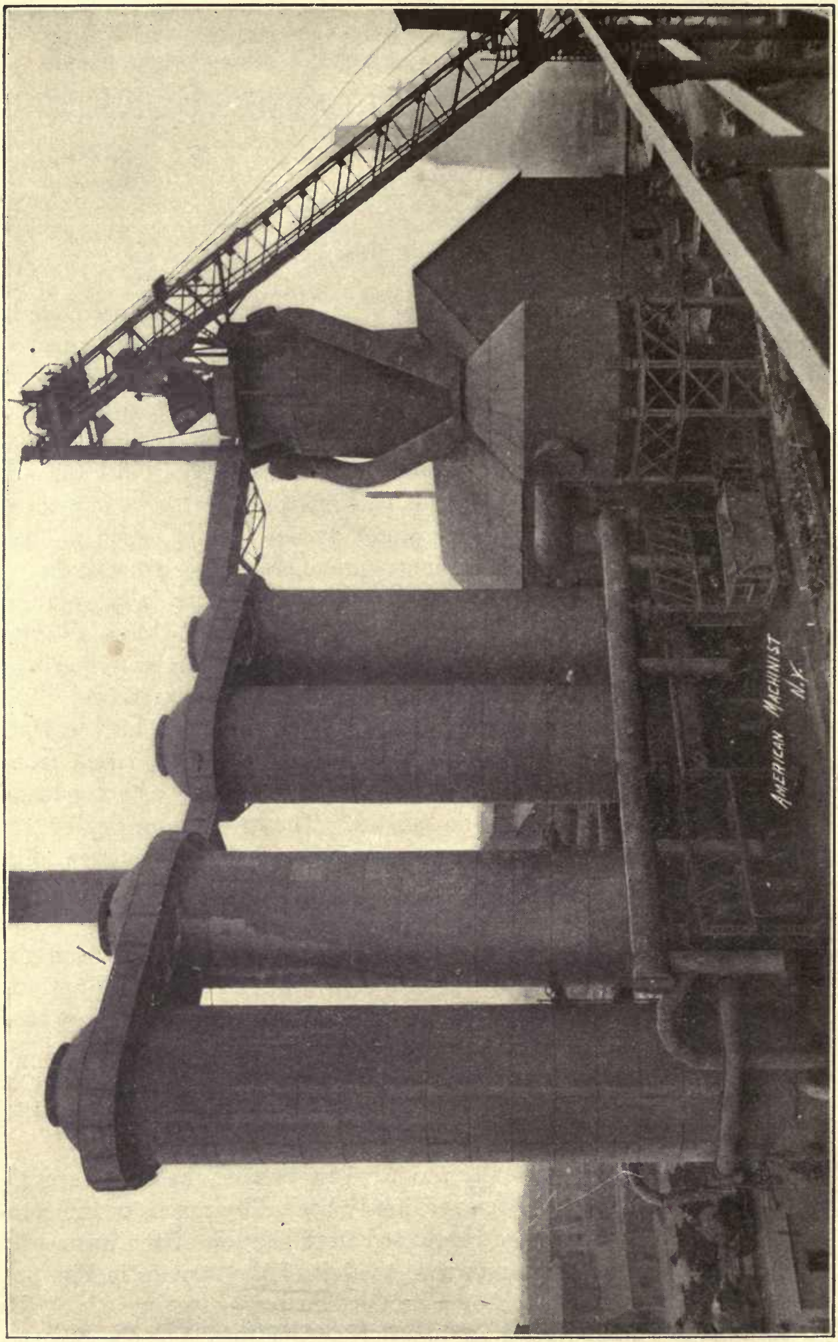


Fig. 1. — Blast furnace and its hot stoves.

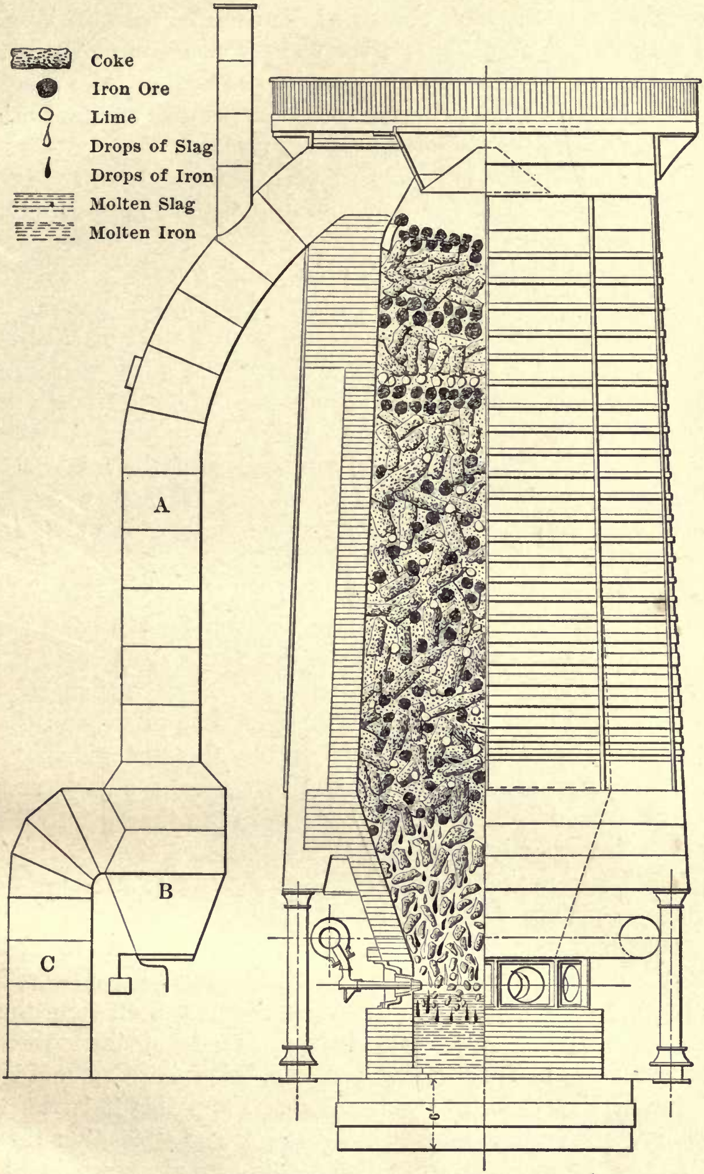


FIG. 2. — Details of blast furnace. Condition of charge at different levels.

which may be from 60 to 100 feet, and are round steel tanks that have a comparatively small annular fire-brick chamber in the center for nearly the height of the tank. This chamber is surrounded with brick work that is filled with flues. The gas from the furnace comes in at the bottom of the central annular chamber; burns on its passage up this; comes down through the flues in a heated condition, thus heating up the brick work, and then passes out the chimney as waste product.

When the brick work is heated properly, the gas from the furnace is shut off and the air blast from the blowing engines passed through the stove on its way to the furnace.

This heats the air in its passage up through the central chamber and down through the flues, and makes it a hot blast when it enters the tuyeres of the furnace. Thus it increases the temperature of combustion in the blast furnace. Four hot blast stoves are used with each furnace, so that three can be burning gas and warming up, while the fourth is having the air blast sent through it into the furnace.

The gas, which is a product of combustion of the materials in the blast furnace, comes down through the pipe *A* (Fig. 2), which is called the downcomer, leaves most all of its accumulated dirt at *B*, and then passes out of the pipe *C*.

From one-third to one-half of this gas is all that is needed to keep the stoves hot and the balance is generally burnt under the boilers where it generates the steam for the blowing engines. In some cases it is used directly in gas blowing engines. Often there is more than enough gas for the heat and power requirements of the blast furnace and the excess is used to generate a part of the power used by the steel mills.

The blast furnace is usually charged by means of a skip car running on an inclined track. The charge is dumped from the car into the top of the furnace through a hopper and bell, and consists of coke, iron ore and limestone. The change that takes place in these as they pass down through the furnace is plainly shown in Fig. 2.

The coke serves as a fuel for generating the heat that melts the iron ore, and the limestone unites with the earthy material as the ore is being reduced to a molten state. The resultant slag is run off from the top of the iron through a hole in the side of the furnace below the tuyeres. The metallic iron melts and collects in the hearth below this slag, and is tapped out of another hole, close to the bottom. From this it is run through channels into molds that form it into "sows" and "pigs," or the molten metal is tapped from the furnace into ladle cars as shown in Fig. 3, in which it is taken to furnaces for conversion into steel.

While the metal is in contact with the white-hot coke in the furnace it absorbs a certain amount of carbon, some of which is chemically combined with the iron and another part is held in suspension as graphite.

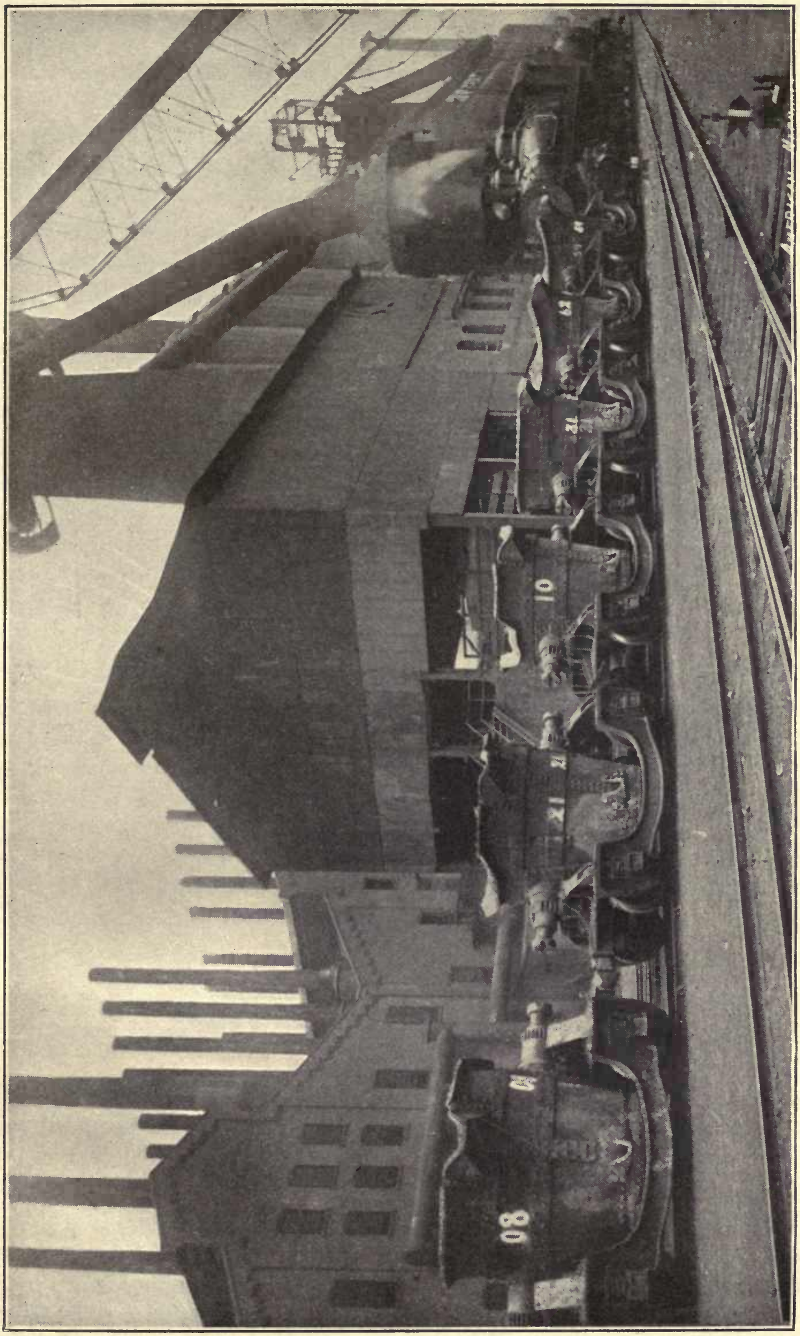


FIG. 3. — "Hot metal" ladle cars carrying molten cast iron to steel converters.

If the "sows" and "pigs" are cooled slowly it tends to make the carbon take the form of graphite. When such iron is broken it has a gray or black appearance showing loose scales of graphite, and the iron is soft and tough.

If the metal is cooled quickly, or chilled as soon as it comes from the furnace, the carbon has a tendency to be kept in the combined state. When fractured such metal will be white and hard.

Of this product about 20% is made into gray-iron castings, 3% into malleable-iron castings, 3% is purified in puddling furnaces to make wrought iron, and the balance, or 74%, is converted into steel by the various processes. Of the latter about 40% is converted by the Bessemer process, 31% in the basic open-hearth furnace, and 3% in the acid open-hearth furnace.

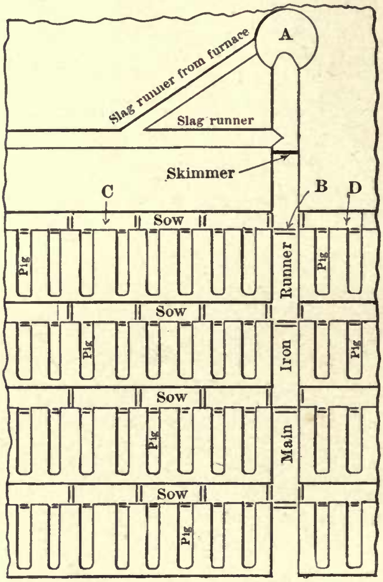


FIG. 4. — Section of sand bed for casting pig iron.

About 6% of the production of wrought iron goes into the manufacture of crucible steel. Recently the electric furnace has been brought into use, and this promises to take a certain percentage for conversion into the finer grades of steel.

The older method of casting the blast into pigs, and which is still used now by many is to have a casting floor in front of the blast furnace that is composed of silica sand. In this sand, impressions or molds are made for the pigs and these connected with runners called "sows," which in turn are connected to a main runner from the furnace. Fig. 4 shows how the floor is laid out. In front of and under the tap hole of the furnace a trough is laid into which the iron is run. From this the main runner for the iron goes down the center of the cast-house. Branching off on either side of this are the sows with the pigs leading off from the sows.

Removable dams are formed at the junction of each sow with the main runner. The iron is first allowed to flow into the sow and pigs at the lower end of the runner, *i.e.*, at that end farthest from the furnace. When these are filled the iron is dammed off by thrusting a "cutter" into the runner just below its junction with the next higher sow, the dam at the entrance of the sow being at the same time broken so that the iron can enter. This is continued with successively higher sows and rows of pig beds until all of the iron has run out of the furnace. After solidifying and cooling the pigs, sows and runner are broke up, loaded on cars and the floor remolded, ready for the next tapping. At the entrace to each pig and at stated intervals in the sows and runner, as shown by the double lines, a dam is formed that about half filled these, so as to make the metal thinner at this point and thus allow it to be broken more easily into nearly standard sizes and weights.

Automatic machines into which the pigs are cast, cooled, and then dumped into cars are now used at some blast furnaces, as the saving in labor is a big item; the pigs are more uniform in size, thus facilitating handling, piling, and storing, and they are free from the adhering silicious sand that is especially objectionable in the basic open-hearth furnace.

The pig molding machines are made in several styles, the most common forms of which are a revolving frame with the pig molds in a continuous series around its annular outer edge, as shown in Fig. 5, and a series of molds attached to an endless chain which carries them in a straight line from where they are poured to the cars into which they are dumped, as shown in Fig 5. In the latter, the empty molds travel back to the ladle underneath the filled ones, and in both the molds are sprayed with thick lime water, long enough before they are filled to allow the water to be dried out by the heat of the mold, and leave it covered with a coating of lime so the molten metal will not stick to the steel molds.

ELECTRIC SMELTING FURNACE

The experiments that have for some time been carried on for the electric production of pig iron seem to be fast approaching a successful culmination, and we may in the near future see this method used commercially, especially where an adequate water power is available.

The Noble Steel Company in California have built several furnaces in this country. Their first attempt was a 1500 kilowatt, three-phase, resistance type of furnace that was completed in July, 1907, but after running it a short time the mechanical difficulties which presented them-

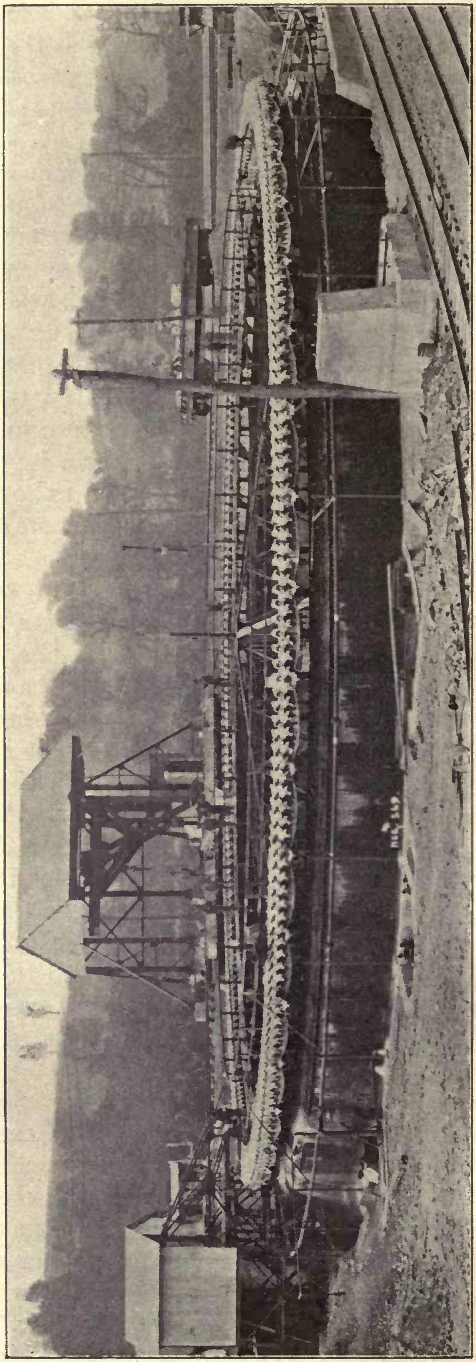


Fig. 5. — Revolving pig casting machine at Bethlehem Steel Co.

selves made this type of furnace impractical commercially, and it was abandoned.

A 160 kilowatt furnace of a different type was then constructed and run for 40 days. From this run data were gathered that were used in the construction of the present 1500 kilowatt furnace, shown in Fig. 7. The data obtained would indicate that with one ton of charcoal, costing about $9, three tons of pig iron could be produced with about 0.25 electric horse-power-year per ton.

The quantity of carbon used for the electric smelting of iron ores is only about one-third of that required for the ordinary blast furnace. Thus charcoal can be used and the product will be charcoal pig iron, which, owing to its comparative purity, would demand a higher price than the ordinary product.

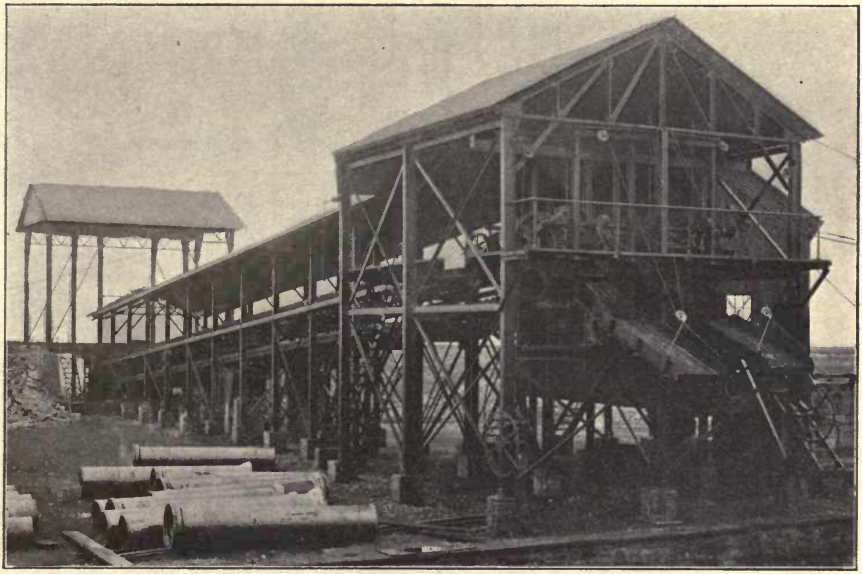


FIG. 6. — Double strand, endless chain, pig casting machine.

In the furnace shown in Fig. 7, the ore with its proper fluxing materials is brought in, in cars, and fed into the preheater, *A*, where it is dried and heated by the products of combustion piped from the combustion chamber of the furnace, *B*, through the flue, *C*. After drying it is dumped in the scale car, *D*, which runs around the top of the stack, on a circular track, so it can alternately take a charge of ore and flux from *A*, and carbon from the hopper, *E*, weigh them and charge them into the furnace in the proper proportions through the usual hopper and bell in the top of the stack.

Six electrodes (*G*) are arranged equidistantly around the furnace, and the electric current passing through between them melts the charge, the metal and slag collecting in the crucible at the bottom of the furnace, from which they are drawn as in ordinary practice. All the necessary heat is supplied by electrical energy, and thus no blast is blown in. This causes all of the solid carbon to be used for reduction, excepting of course the small amount that is dissolved into the pig iron. Above the level of the charge, however, are small openings at *F*, for admitting the correct amount of air, through valves, to burn the gases that result from the reduction of the ores in the lower part of the furnace.

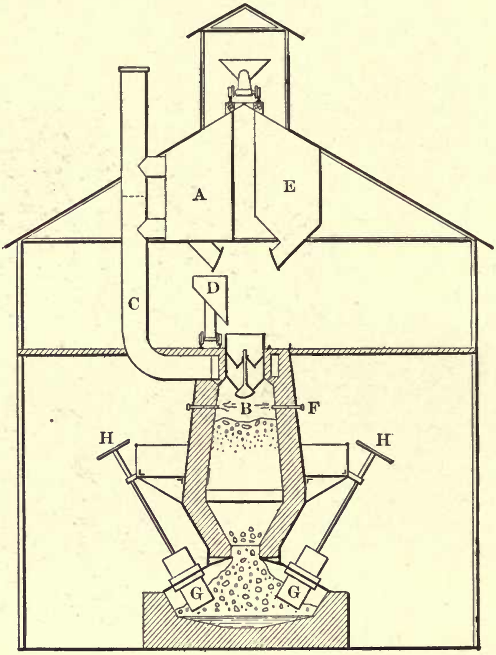


Fig. 7. — Electric pig-iron furnace at Noble Steel Co., Heroult, Cal.

In Fig. 8 is shown the combination of electric and blast furnace that has resulted from several years of study and experiments conducted by three Swedish engineers at the Domnarfvet Iron Works in Sweden. In this a large crucible with an arched roof is formed at *I*. An opening is left in the center of the roof, and over it is constructed a stack (*J*) very similar to the ordinary blast furnace; in fact, the only difference being that the bosh is contracted more at *K*, where the charge enters the crucible. This was made necessary by the fact that too large an opening would not retain the required heat in the crucible part of the furnace without increasing the power to generate the electrical energy to too high a point. It was feared that this contraction would result in the furnace clogging and an overhang form in the bosh, but with a continuous run of three months no such condition was apparent.

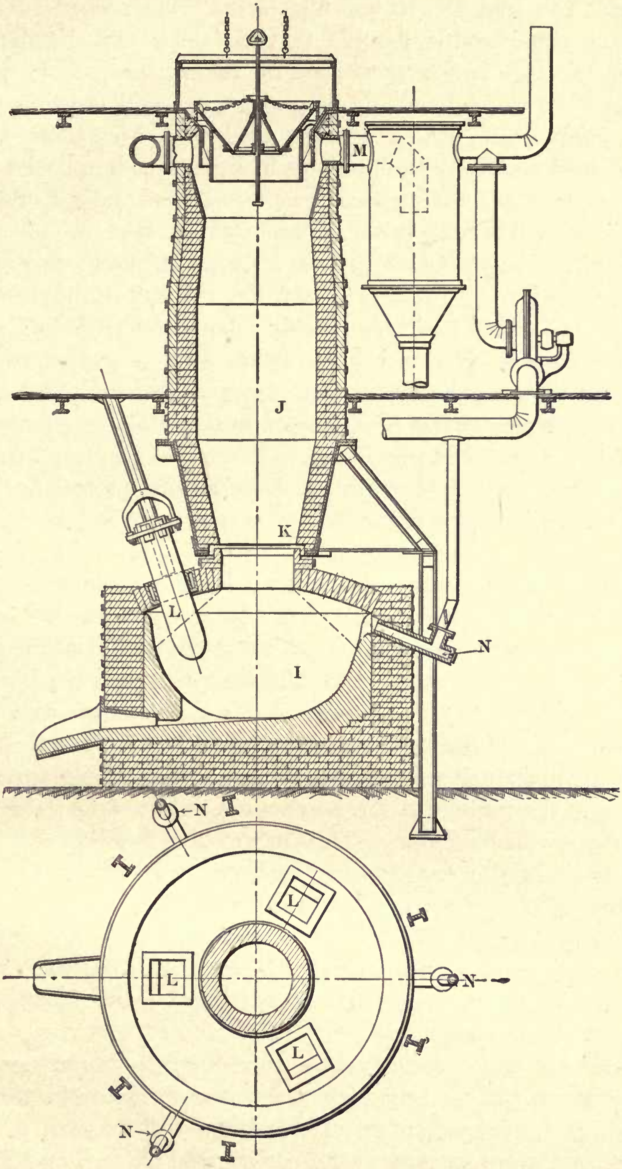


Fig. 8. — Electric furnace at Domnarfvet Iron Works, Sweden.

Three electrodes (*L*) that project into the crucible through a water-jacketed stuffing-box in the arched roof conduct a three-phase alternating current of 40 volts to the charge. The current is from 8000 to 9500 amperes, and the load 480 to 500 kilowatts. The arched roof over the crucible gave considerable trouble in the earlier experiments by being overheated, but this is now preserved by taking the gaseous products of combustion from the top of the furnace at M, and blowing them back through tuyeres at N, which are provided with peep-holes so the roof can be examined and the volume of gas increased or diminished as desired.

In the three months' run, that was terminated July 3, 1909, by the general strike in Sweden, it was demonstrated that the electrodes did not need readjusting oftener than once a day, and in one case an electrode was not touched for five days; that the consumption of energy was remarkably uniform even though the short run did not enable the furnace to approach its working condition until near the end; that the charge moved with regularity into the melting chamber; free spaces were maintained underneath the arched roof next to the outer wall, and the gases kept the roof effectively cooled.

This furnace was first constructed as an induction, but was later changed to a resistance furnace. It is started and worked the same as the ordinary blast furnace, and in the experiments so far only coke has been used, but charcoal can be used as well as the "prime ore briquettes" and "slig" which they get in Sweden. It has produced 2 tons of iron per electrical horse-power-year, but conditions would indicate that this could be increased to 3 tons. It being easy to make a pig iron in this furnace with a low carbon content, if the molten iron was transferred directly to electric refining furnaces, it would greatly reduce the time consumed in converting it into steel. It now takes a comparatively long time to reduce the carbon to the percentage required in the electric converting furnace when ordinary blast-furnace iron is used.

The carbon in the experiments with the Swedish furnace averaged about 1.80% in the three months' run, while in some previous experiments it ran as high as 3.20%, and in one tapping it was as low as 1%. The silicon varied between 0.20 and 0.07%, but in one case was 4.40%. The sulphur content has been as low as 0.005%, with 0.50% of sulphur in the coke that was used.

The ability of the electric furnace to reduce the impurities to a minimum may result in its becoming a prominent factor in the reduction of the ore, and the conversion of this into steel as soon as experience teaches the operators to control the carbon and silicon, and it is demonstrated that it is practical commercially. In Denmark there will soon be started another ore furnace, and in Canada negotiations are well advanced for an electric iron-ore reduction and steel plant with a capacity of 5000 horse-power.

CHAPTER II

BESSEMER PROCESS OF CONVERTING IRON INTO STEEL

IN converting the blast-furnace iron into steel the Bessemer process has formerly been the one most used, but the improvements in the open-hearth method have been such that it is replacing the Bessemer, in many places, for the cheap production of steel, and the product which it turns out is much better.

In the Bessemer process a converter similar to that shown in Figs. 9 and 10 is shown, it being pear-shaped and open at the small end. It is hung on trunnions so the metal can be easily poured in and out. Into this is poured the melted pig iron, which is usually taken direct from the furnace, although it is sometimes remelted, and through this is blown cold air in fine sprays in the proportions of about 25,000 cubic feet of cold air per minute to every 10 tons of molten metal, which is the usual charge for a converter.

Curious as this may seem to the uninitiated, the cold air raises the temperature of the molten metal to such a high degree that it is often necessary to inject steam or add scrap to cool off the metal. This rise in temperature is due principally to the combustion of the silicon, manganese and carbon of the iron when they come in contact with the oxygen of the air. The silicon and manganese are oxidized and pass into the slag chiefly during the first four minutes of the blow, after which the carbon begins to oxidize to carbon monoxide (CO), which boils up through the metal and is forced out of the mouth of the converter in a long bright flame that gradually diminishes, until at the end of six minutes more the carbon has been reduced to about 0.04% and the flame dies away.

Except for the impurities which poison the metal, namely phosphorus, sulphur, oxygen and possibly nitrogen, it has become for all practical purposes a pure metal that is very brittle. This makes it necessary to add certain ingredients that will toughen, strengthen, and harden it so as to make it useful and workable.

Carbon is added in different percentages while it is in the molten state to give it the proper degree of hardness and strength.

Manganese is added for the purpose of removing the oxygen which the metal has absorbed during the process of conversion, and which renders it unfit for use. It also combines with the sulphur and partly neutralizes the bad effects of this element.

Silicon is also added for the purpose of freeing the metal from blowholes, which it does partly by removing chemically the gases and partly through increasing their solubility in the molten steel. Of these last two elements but one-half to two-thirds of the percentages added will be found in the finished product, owing to their being partially oxidized and passing out into the slag.

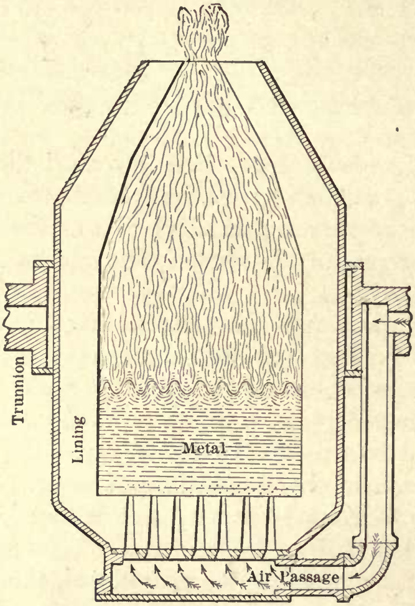


Fig. 9. — Bessemer converter purifying the metal.

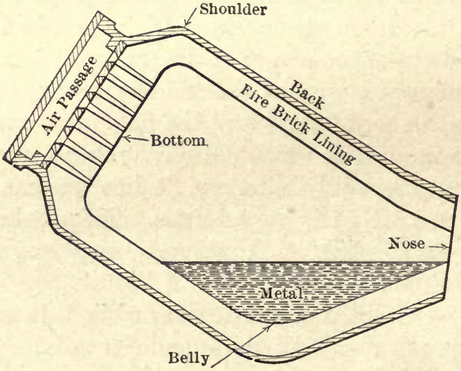
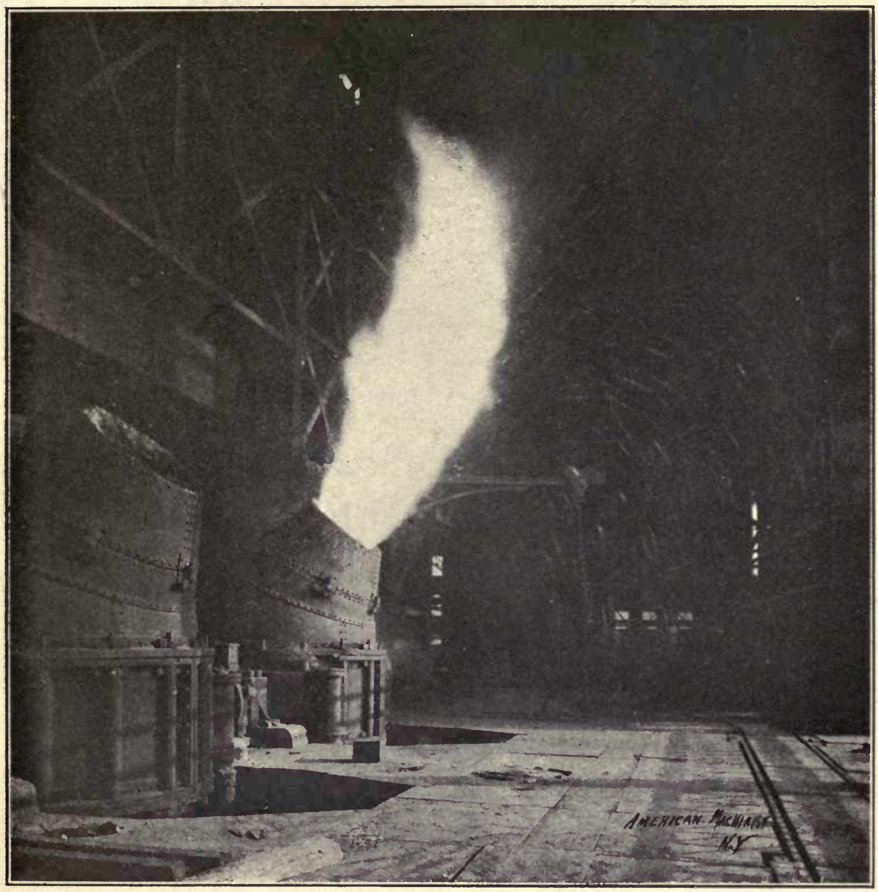


Fig. 10. — Bessemer converter tilted to pour finished metal into ladle.

These ingredients are added to the charge in the converter by first melting iron containing them in the proper amounts in a small cupola in the converter house, called the spiegel cupola. Pig iron high in manganese and carbon, called spiegeleisen, is mixed with other iron high in silicon until the right percentages of all three are obtained to give the 10 tons of metal in the converter its desired composition. The addition of this mixture is called recarburizing. After this the converter is tilted, as shown in Fig. 10, and the steel poured into ladles. These are bottom-pour ladles, as shown in Fig. 12. In these, as the name signifies, the metal is poured from the ladle through a hole in the bottom. This saves turning the ladle over and also draws the molten metal away from the slag. From the ladles the metal is run into cast-iron ingot molds placed on cars, which are moved beneath the pouring ladle. After the metal has solidi-



Bessemer converters at Lackawana Steel Co.

fied in the molds the ingots are removed and placed in soaking pits, where they become of an equal temperature throughout, and are then ready for rolling. The ingot molds usually are kept going through the

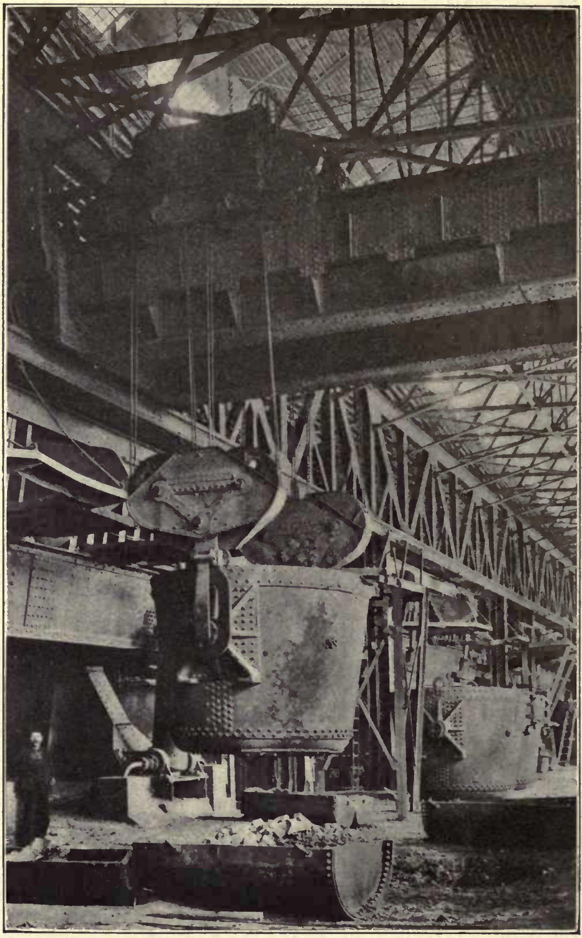


FIG. 11. — Tilting ladles.

converter house in a steady stream; coming in one side empty, getting filled and going out the other side.

Pig iron with about 1% of silicon is preferred for the Bessemer process, as the lower this is kept the shorter will be the blow, and as it is the chief slag producer it will reduce the iron loss by limiting the amount of slag made. If too low, however, the blow will be cold and it is only by working rapidly and allowing no unnecessary waits between blows, thus keeping the converter and ladles very hot, that as low as 1% of silicon in the pig iron can be used successfully.

In the acid Bessemer process it is impossible to reduce the phosphorus. All of the phosphorus that goes into the blast furnace in the ore and coke will come out in the pig iron, and after this pig iron has been refined in the converter it will be found in the steel. Hence it is necessary to start with ores and coke that are low in phosphorus if a good steel is to be produced.

In Europe, however, the basic Bessemer converter is used to a certain extent. This is the same as the acid, except that the lining of the furnace is of some basic material such as calcined dolomite. A basic slag is also carried, the chemical action of which removes the phosphorus, but pig iron low in silicon must be used.

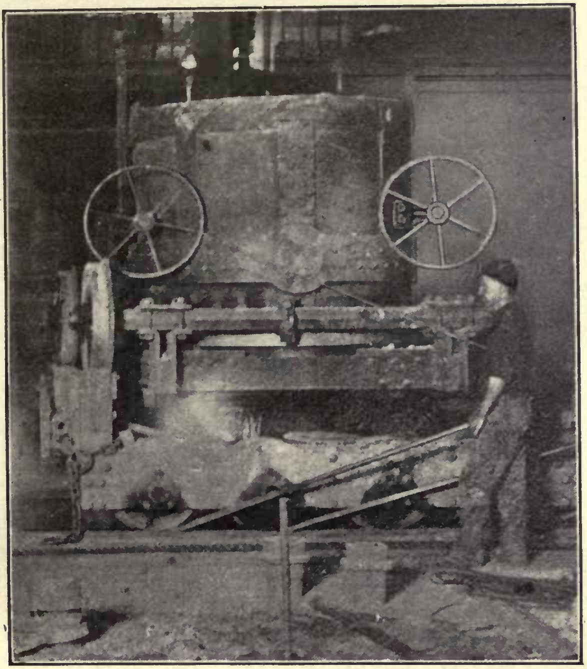


FIG. 12. — Bottom-pour ladles.

The Bessemer process being the cheapest way of converting iron into steel, much of the cheaper and ordinary grades of steel are made by it, such as steel rails, wire, merchant bar, etc.

Where several Bessemer converters are in operation it takes quite a number of blast furnaces to supply them, as it takes two furnaces to furnish iron enough for one converter. As the product of each furnace is liable to vary in chemical composition, it is necessary to have some means of mixing the product of the different furnaces, before they are poured into the converter, if a uniform grade of steel is to be taken out of the converter. For that reason a large reservoir, shaped something like the housewife's chopping bowl, but with a large spout on it, and capable of holding from 200 to 500 tons, is used. Into this is poured the metal from the various furnaces and from it are taken the charges for the converters.

This keeps the molten metal continually coming in and going out, and it does not get a chance to chill, as there is such a large mass. But should this happen it is supplied with gas burners that would bring the heat up to the proper temperature again. The metallurgist is thus able to control the composition to a large degree, as he can order the different furnaces to dump in the mixer the amount he desires. In conjunction with this he also has cupolas in which to melt any composition needed to bring the mixer bath up to the desired standard.

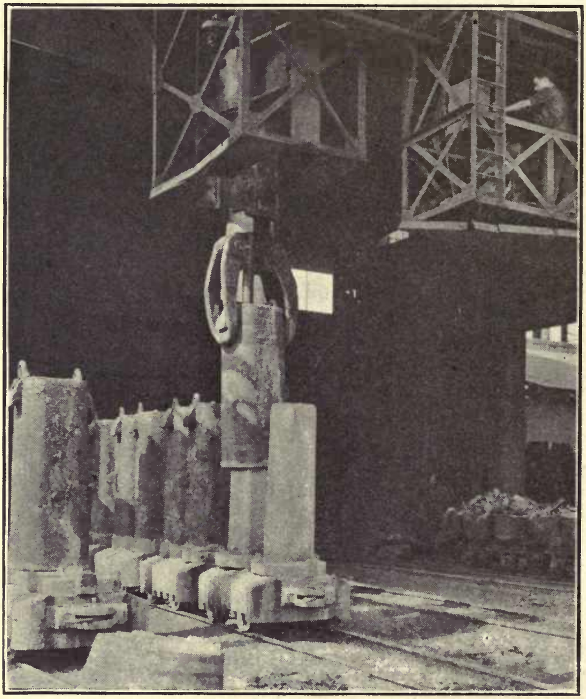


Fig. 13. — Stripping the mold from ingots.

When the ingots are poured and solidified the molds are at a red heat, and it has been a problem to find a metal for the molds that would stand the heat. Cast iron is used, but the molds can only be used about 100 times. Titanium treated iron is said to last much better as it does not heat up as quickly. Quite recently one of the large mills added about

1% titanium to their ingot mold iron, and when the ingots were poured it was found that the ordinary iron molds were red hot, while the titanium iron molds were dark colored.

As no fuel is used in the Bessemer process of converting blast-furnace iron into steel, it is the cheapest method of making steel as far as manufacturing cost is concerned, but it requires a more expensive pig iron as raw material and it also makes the poorest grade of steel, as the phosphorus and sulphur are apt to be higher than in steels made by the other processes, and the occluded gases are not removed to the same extent.

For the purpose of getting these occluded gases out of the metal a new material has been brought into use, in the shape of ferro-titanium, that greatly strengthens the metal and increases its wearing quality, when used for such purposes as steel rails. This ferro-titanium is an alloy of about 15% titanium with iron and usually some carbon. It is never necessary to add more than 1% of titanium to the steel, while in most cases very much less will give the desired results.

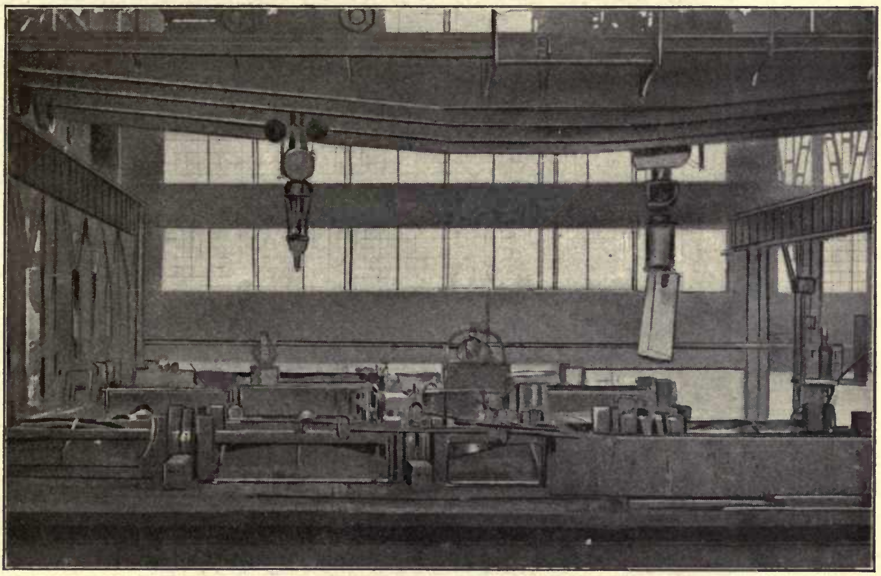


FIG. 14. — Soaking pit for ingots.

It is shoveled into the ladle while it is being filled from the converter and the ladle allowed to stand for at least 6 minutes, so the titanium will have time to unite with the nitrogen and other gases, for which it has a great affinity, and carry these off into the slag. It is difficult to get steel makers to allow a ladle of molten metal to stand idle that length of time, but the titanium prevents its chilling and in fact may leave the molten metal slightly hotter at the end of the 6 minutes than when it left the converter. In one case the metal was held in the ladle for 20 minutes and was still sharp enough to teem successfully.

Sulphur must be kept low in steel for rails and other products which are rolled, since, if high, it makes the metal "hot-short" so that it cracks in rolling. Phosphorus, on the other hand, if too high makes steel "cold-short," and some railroad accidents, caused by broken rails, could be traced to too high a percentage of phosphorus. High-phoshporus rails, however, have good wearing qualities, and when titanium is properly added to the molten metal it seems to remove to some extent the hot and cold brittleness that a comparatively high percentage of sulphur and phosphorus give to the metal.

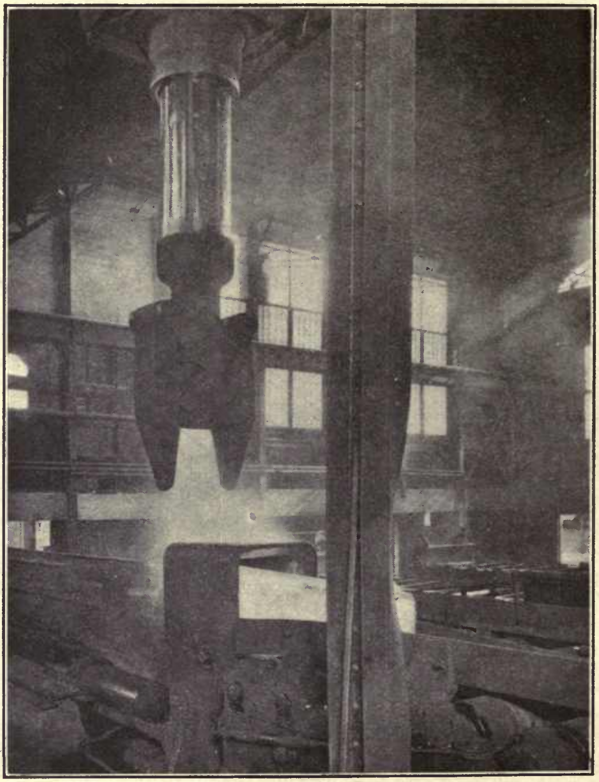


Fig. 15. — Carrying ingot from soaking pit to slabbing mill.

Many of the fractures in steel rails have been due to miniature gas bubbles in the steel, that have, when rolled, produced long microscopic cracks, and started the fracture; others have been caused by manganese sulphide which rolled out into long threads.

However, by the use of titanium these faults can be largely overcome and Bessemer rails can be made as good, if not better, than open-hearth rails, and the additional cost is only about $2 per ton. A part of this added cost comes from the extra time consumed in allowing the ladle to stand.

After solidifying the ingot the mold cars are run under the stripper, which is located in a tower, as shown in Fig. 13, and from there a long finger comes down on top of the ingot to hold it, while two iron loops come down over lugs on either side of the mold and lift it off the ingot. The ingot is then gripped by a huge pair of tongs on a traveling crane and these pick it up and carry it to the coaking pit shown in Fig. 14. After remaining in here long enough to reach a proper rolling temperature throughout, it is placed on the "buggy," which is an iron car operated by electricity, and carried by this to the slabbing mill where it is automatically dumped onto the rolls and the buggy returned for another ingot.

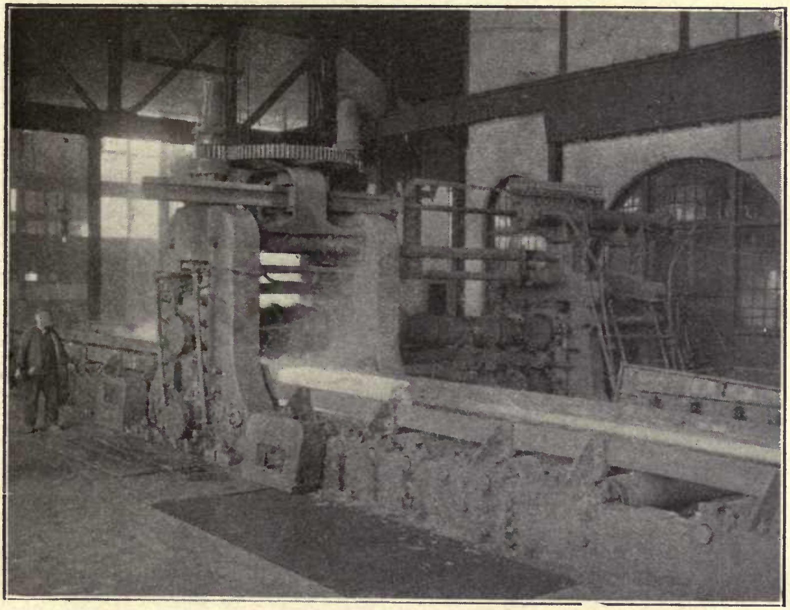


Fig. 16. — Slabbing mill.

In some cases an overhead traveling tongs, similar to that shown in Fig. 15, is used to convey the ingots from the soaking pit to the slabbing mill. A typical modern slabbing mill is shown in Fig. 16.

It was formerly the custom to roll them into "blooms" or large billets about 10 inches square, and reheat again before rolling them into marketable shapes, but in the more modern mills the ingots now are taken directly to the slabbing mill, which in some cases reduces their size 1 inch at a pass, and there rolled into slabs, which are transferred to other rolls and rolled into the desired shape before they get cold.

CHAPTER III

Open-Hearth Process for Making Steel

The open-hearth furnace for converting pig iron into steel is made and used in both the stationary and tilting styles, as shown in Figs. 17 and 18. As the name implies, it has an open hearth on which the metal is placed and where it is exposed to a flame which reduces it to a molten state; or, in other words, it is openly exposed to the action of burning gases.

This furnace must be a regenerative one to get the high temperature that is needed to melt and refine the metal. By this is meant one in which the heat carried away by the chimney flue is used to warm the incoming air and gas before they enter the furnace. This name has been commonly applied to the furnace as shown by the sectional view in Fig. 19, by which both the air and gas are heated before entering the furnace by sending them through passages filled with bricks which are stacked up so as to leave openings between them. Two sets of passages are provided so that one can be used to absorb the heat in the exhaust gases while the other is warming the incoming air and gas. These passages are supplied with reversing valves so that they can be used alternately and thus heat the gas and air to a yellow heat before they unite. This method gives a very intense heat.

From 30 to 75 tons of metal are purified in one of these furnaces in from 6 to 10 hours. It is then "recarburized," or in other words the proper percentage of carbon is added, and the metal poured into ingot molds from which it is taken and rolled or forged into the sizes and shapes desired.

As two of the main considerations in the modern steel mill are output and economy, the size of furnaces has been increasing and Talbot process open-hearth furnaces have been built of 250 tons capacity, while larger ones are to follow. Where blast furnaces and steel mills are located together the pig iron is taken in the molten state to the open-hearth furnaces, and converted into steel as fast as the blast furnaces turn it out. This practice has been an important factor in obtaining large outputs.

FIG. 17. — Stationary open-hearth furnaces at Bethlehem Steel Co.

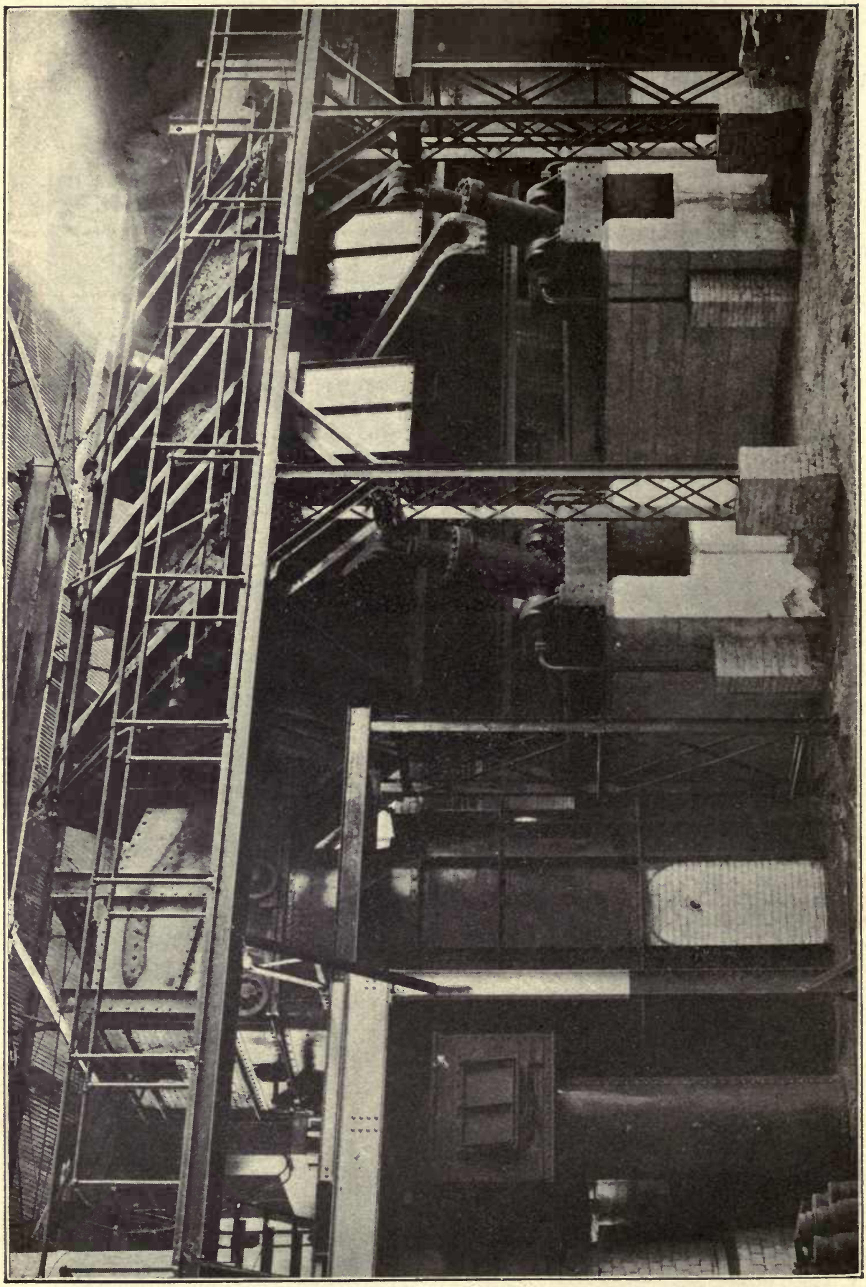


FIG. 18. — Tilting open hearth furnace. Tilted for pouring into ladle.

In the Talbot process the stationary furnace of the original Siemens-Marten process is changed to a tilting form so that the slag which forms, and which limits the rate of charging, can be more easily handled. The charge is worked down to the desired percentage of carbon by means of additions of ore and limestone in the usual manner. The slag is then removed and about one-fourth of the steel poured off and recarburized in the ladle as usual. To the metal remaining in the furnace ore and limestone are now added and through the slag thus formed, is poured a fresh charge of molten pig iron. The removal of the carbon, silicon, etc., under these conditions is rapid, but the reactions are not violent, owing to the dilution by the steel remaining in the furnace. The process is continuous and the furnace is completely emptied only once a week.

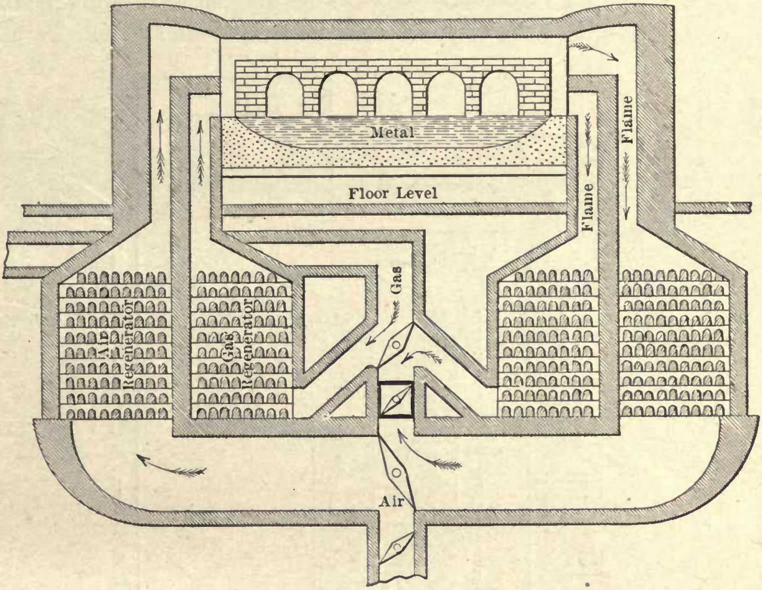


Fig. 19. — Section through regenerative open-hearth furnace.

There are also in use tilting open-hearth furnaces with a double hearth, as shown in Fig. 20, with a stationary top, and in Fig. 21 with a moving top. The tilting serves here not to discharge the furnace, but to carry on different operations simultaneously in the one furnace. The amount of tilt given the hearths governs the amount of metal or slag to be run from one hearth to the other, this amount depending upon the angle of tilt, gradient of hearth, length of hearth, and depth of bath.

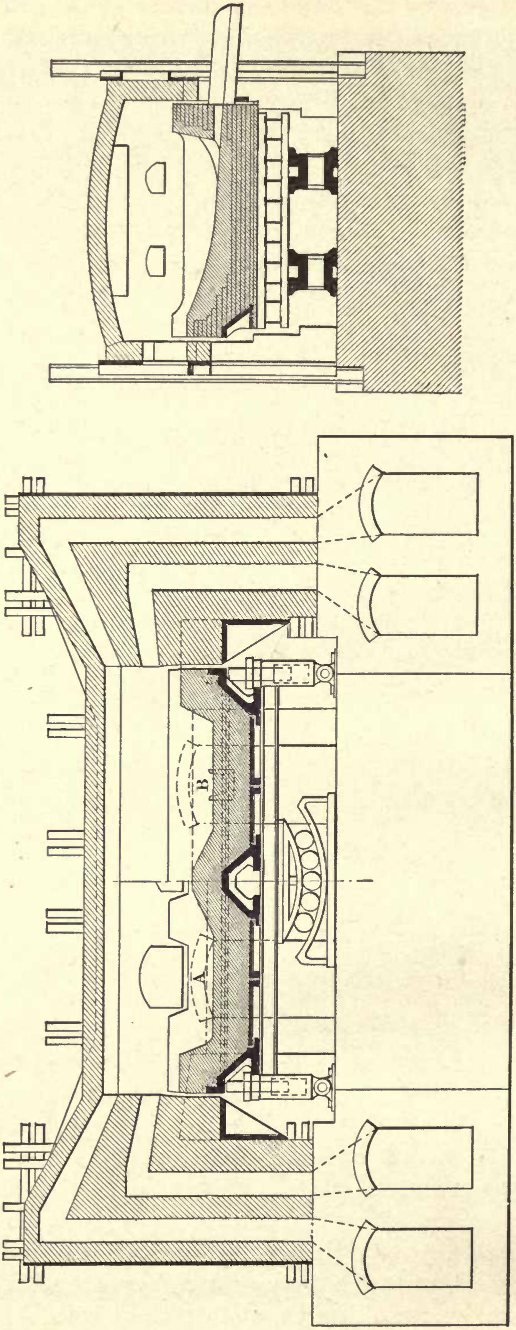


Fig. 20. — Double-hearth furnace with solid top.

The method of operation in the combined pig iron and ore process, which first suggested the furnace, is as follows: A charge is left only sufficiently long in hearth *A* to reduce the iron from the slag, this being already decarbonized. In order to free the charge from the iron-bearing slag and to pave the way for the final refining, the furnace is tilted so the slag flows from hearth *A* to hearth *B*. After the slag has been poured into *B*, molten pig is charged, the contact of the pig and slag sets up an energetic refining action and the iron is taken from the slag. Meanwhile the charge on hearth *A* is finished and tapped. The hearth is repaired as usual and the tap hole left open.

As the operation is a continuous one, the slags which have not been discharged must be poured when sufficiently low in iron. By a slight tilting of the furnace, the slag runs from *B* to *A* and out through the open tap hole. Or it may be discharged over the side walls of hearth *B* and the hearth *A* used at the same time for charging fresh material. In hearth *B* the heat generated by the decarbonization of the iron is made use of by the scattering of iron ore over the charge as long as the temperature holds. As all of the iron cannot be reduced from the ore, a certain amount of ore is slagged. The desired slag, heavy with iron, is thus obtained. It will be later poured off into hearth *A* where the operation is steadily going on, molten pig added, and the process continued as before.

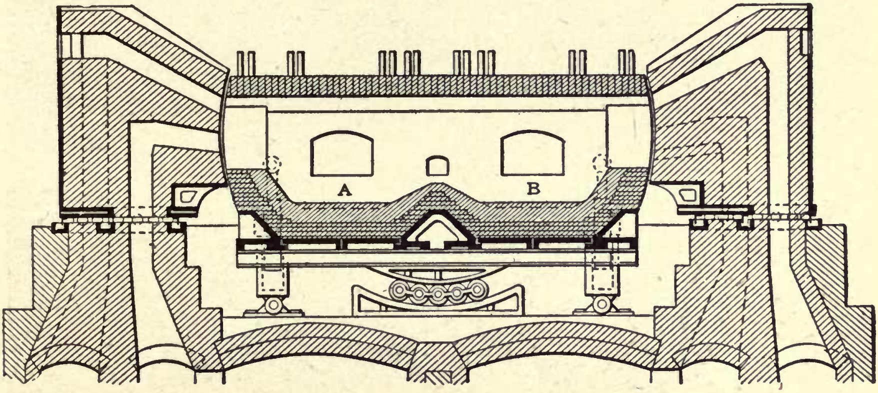


FIG. 21. — Double-hearth furnace with moving top.

Steel is made in two ways in the open-hearth furnace: one is called the acid open-hearth process and the other the basic open-hearth process. About 30% of the pig iron made in this country is converted into steel by the basic process, and 2 or 3% by the acid. For the making of open-hearth steel castings the acid process was used almost exclusively, but it is now giving way to the basic process owing to the fact that ores low in phosphorus and sulphur are becoming higher priced each year, and these elements cannot be reduced in the acid furnace.

The number of charges these furnaces will make into steel before having to be rebuilt is about 300 for the basic furnace, which would cover a period of from 15 to 20 weeks, and about 1000 heats from the acid open-hearth furnace, before doing any more to them than the usual patching at the end of the week's run.

Pig iron and steel scrap are the chief raw materials with the addition of enough iron ore to quicken the operation. In America, on an average, about one-half the charge is steel scrap but sometimes as high as 90% is used. This latter, however, is but little more than a remelting operation. In most American mills the steel scrap is first placed on the hearth and this then covered with pig iron, as the oxidation of iron is decreased while melting by the impurities in the pig iron. In some American and most of the English mills the pig iron is put on the hearth first and this covered with the steel scrap, with the understanding that the hearth is corroded less with oxide of iron, but unless the scrap is small not much corrosion will take place.

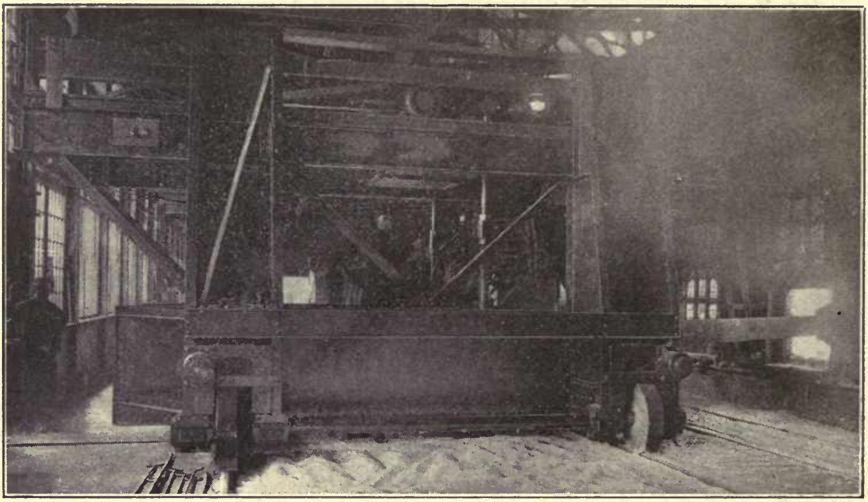


FIG. 22. — Machine for charging open-hearth furnaces.

In charging the acid furnace it is best to put the scrap on the hearth and the pig on top of it, while in the basic furnace we may put in a part of the scrap first, the limestone on top of that, then the pig, and cover the whole with the balance of the scrap, or we may charge the limestone on the hearth, the pig next, and cover the scrap over the top.

The charging machine used is shown in Fig. 22.

ACID OPEN-HEARTH

In this process the furnace is lined with silicious materials (sand). This lining influences the subsequent operations as the character of the bottom determines the character of the slag that can be carried, which, in turn, determines the chemistry of the process. The metal is heated by radiation from the high temperature flame. The impurities are partially oxidized by an excess of oxygen over that which is necessary to burn the gas in the furnace. This oxidizes the slag which, in turn, oxidizes the impurities in the metal.

The slag is about one-half silica (SiO_2) and the other half is composed of oxides of iron and manganese. Nothing is added to form a slag as the combustion of the silicon and manganese with what iron is oxidized and some sand from the lining in the bottom gives the necessary supply.

When the metal is melted iron ore is added, and the oxygen in the ore oxidizes the excess of carbon until the proper percentage is acquired. Recarburization is carried out in the furnace by the addition of a proper amount of ferro-manganese, together with any other materials that may be necessary.

In the acid process the percentage of phosphorus and sulphur depends upon what the stock contains that is put in the furnace, as neither of these are removed; but the amount of carbon in the steel, and therefore its tensile strength, depends entirely on the conduct of the operation. This latter is usually reduced to the right percentage and the charge then tapped out, but it may be reduced below the amount required and enough then added to make up the proper percentage.

The gradual increase in the temperature of the furnace caused by the regeneration of the secondary air first causes the oxidation of the silicon, which occurs mostly on the surface of the metal, by the oxidizing action of the flame. This causes the slag mentioned above to form and cover the surface of the bath, thus protecting the metal from any further contact with the flame from which it might absorb some of the gases, and be injured. After the silicon oxidizes out, the carbon begins to work out as a gas that causes bubbling or boiling throughout the bath. By the addition of iron ore this action can be augmented as occasion requires. When the carbon has been reduced to the percentage desired, the boil is stopped by deoxidizing agents, such as ferro-silicon or ferro-manganese.

The points in favor of the acid open-hearth process of making steel are that the operations are shorter, owing to the fact that the phosphorus cannot be reduced and no fluxes are added, except possibly a little silica at the beginning to prevent the lining from being cut by the iron oxide. The bath being more free from oxygen at the end of the heat, less trouble is encountered from blow-holes.

Most engineers and machinery designers agree that acid open-hearth steel of a given composition is more reliable, less liable to break and more uniform than either Bessemer or basic open-hearth steel, and this is doubtless due to its being more free from the occluded gases, although these are not removed as much in the open-hearth as in the crucible or electric furnace processes.

The principal and possibly the only reason this process is not used more, and especially in this country, is that ores low enough in phosphorus are scarce and consequently expensive. As the prices of these ores are gradually increasing, and have been for some time, the acid open-hearth process is steadily becoming of relatively less importance.

It is usually easy to tell the difference between basic and acid steel, but it is difficult to tell the difference between basic Bessemer and basic open-hearth steel or between acid Bessemer and acid open-hearth steel. Therefore, one has to depend on the honesty of the steelmakers, unless they wish to go into exhaustive tests of each piece of steel received.

BASIC OPEN-HEARTH

A regenerative open-hearth furnace, similar to that shown in Fig. 19 for the acid process, is used for the basic, but the lining is of a different material. It is composed of some basic material that is usually either magnesite or burned dolomite.

The lining or bottom of the furnace takes little part in the operation, but determines the character of the slag which can be carried. When the bottom is silica (sand) the slag must be silicious and when the bottom is basic the slag must be basic. The charge put in the basic open-hearth furnace is composed of pig iron mixed with steel scrap or similar iron products, the same as in the acid furnace. But in addition to this, lime or limestone is added, in order to make a very basic slag.

This slag will dissolve all the phosphorus that is oxidized, a thing that an acid slag will not do. In the acid open-hearth or Bessemer process the silicious slag rejects the phosphorus which is immediately deoxidized and returns to the iron. Sulphur is also removed to a limited extent, and pig iron with these impurities can be used in the basic open-hearth furnace. When the sulphur is high the slag must be charged with all the lime it will stand without becoming infusible and pasty. The slag can contain as high as 55% of lime (CaO) for this purpose. If the manganese is above 1% it makes the slag more fluid and aids in the removal of sulphur.

If the slag is basic enough not to attack the bottom it will hold the phosphorus, providing the stock does not contain over one half of 1%. With a higher percentage special attention must be given to the phosphorus to prevent its passing back into the steel when a high temperature is combined with violent agitation, as is used when the heat is tapped.

Although the phosphorus and sulphur are lower in the basic steel, the acid steel is considered better, owing to the increased liability of blow-holes and gas bubbles in steel converted by the basic process. Then again the process of recarburizing sometimes produces irregularities. The metal is also more highly charged with oxygen. All of these make a poorer quality of steel than is produced by the acid open-hearth process, but a far better one than is being made in the Bessemer converter.

In the purification of the metal the silicon and manganese are first almost entirely oxidized in the 4 hours or so that it takes the metal to melt, while the phosphorus and carbon are reduced to some extent. After this phosphorus is eliminated, and lastly the carbon is removed. It is necessary that the phosphorus be eliminated before the carbon as the latter protects the iron the most, thus reducing the loss due to melting. The melter controls this by adding pig iron to increase the carbon contents if this is being removed too fast; or he can add ore to produce the necessary reaction to hasten the oxidization of the carbon.

After being purified the metal must be recarburized to get back into it the percentages of the elements that are desired. This must not be done when a basic slag is present, or the manganese, carbon, and silicon in the recarburizer are liable to cause the phosphorus in the slag to pass back into the molten metal. Therefore the recarburizer is added to the molten metal as it is flowing from the furnace into the ladle, and the slag is allowed to float off from the top. As the spiegeleisen cupola cannot be used with the open-hearth furnace, the recarburizer usually consists of a combination of small lumps of coal, charcoal, or coke in paper bags and ferro-manganese.

When soft steel is being made the carbon in the bath is usually reduced to from 0.10% to 0.15%, and enough of the carburizer is then added to bring this up to the percentage desired in the finished steel. When high carbon steels are being made, another method is sometimes used, and that is to bring the carbon in the bath just below the percentage desired, and then recarburize up to it. Thus when a 1% carbon steel is to be made, the carbon in the bath is reduced to from 0.90 to 0.95%, and enough added with the carburizer to raise it to 1%. Many steel makers, however, reduce the carbon in the bath to the same point, namely, 0.10 to 0.15%, when making both high and low carbon steels, and then get the correct percentage by the addition of the proper amount of carburizer.

Among other open-hearth processes might be mentioned the Monell process, in which limestone and a comparatively large amount of iron ore are heated on a basic hearth until they begin to melt, and then the molten pig iron is poured onto it; the duplex process in which an acid Bessemer converter is used to oxidize the silicon manganese and part of the carbon, and the metal then poured into a basic open-hearth furnace to reduce the phosphorus and the balance of the carbon; the Campbell No. 1 process, in which a tilting furnace is used with a charge of molten pig iron and ore, the furnace being tipped backward to prevent the bath from frothing out of the door, and the operation continued for two or three hours, and the Campbell No. 2 process, which aims to combine the basic and acid open-hearth processes by working pig iron or pig iron and scrap in the basic furnace at a low temperature until most of the phosphorus and silicon and part of the carbon and sulphur are oxidized out, then transferring the bath to an acid furnace and working it at a high temperature to remove the rest of the carbon. The object is to get a low-phosphorus, low-sulphur steel.

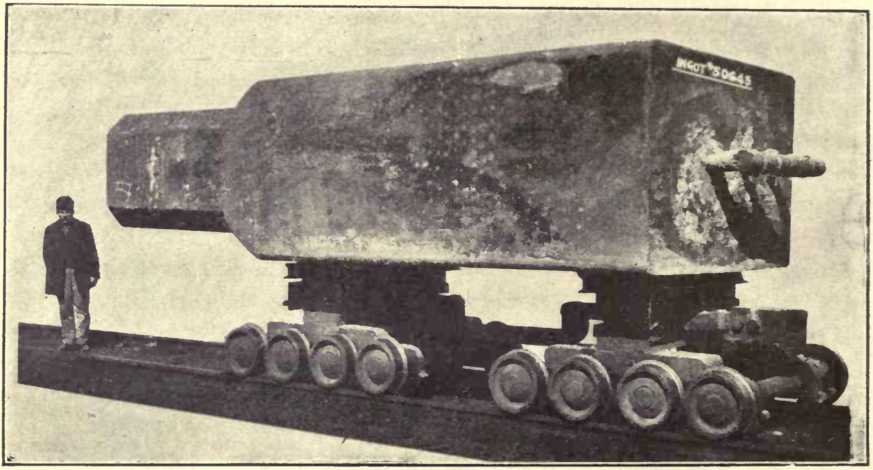


FIG. 23. — One of the largest ingots cast.

One of the largest ingots that has been cast from the open-hearth furnaces is shown by Fig. 23.

One of the greatest troubles of the steel maker is the pipe that forms in the top of each ingot and forces him to crop off and remelt a large part of it. Numerous ways have been tried to overcome this and the most successful of these is the fluid compressor of which Fig. 24 is an example.

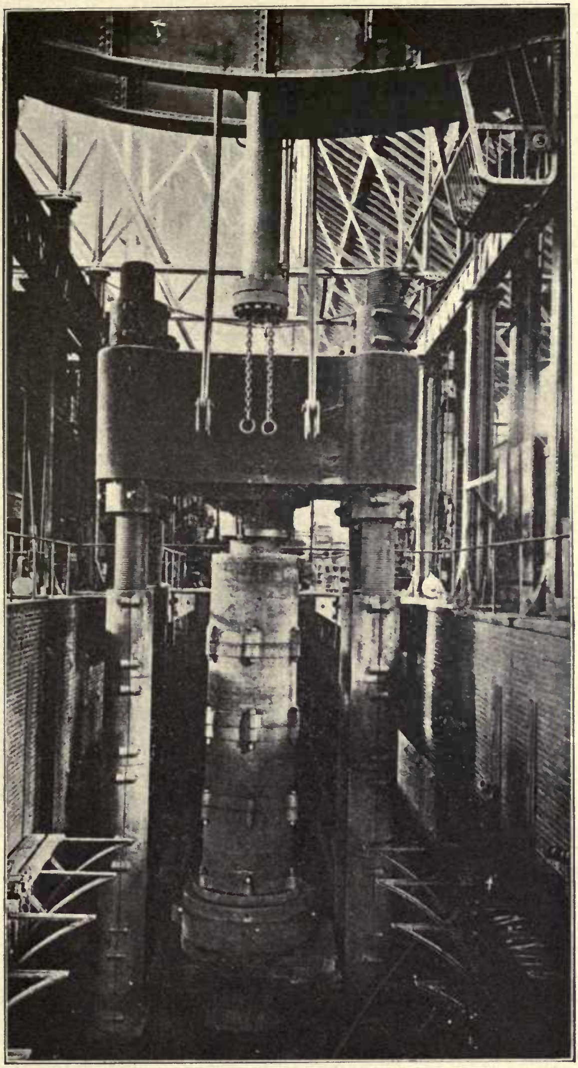


FIG. 24. — Machine for compressing ingots when fluid.

This consists of a large ingot mold, built in sections, into which the molten metal is poured. While the metal is solidifying a ram is pressed down into the mold by means of four screws. This compresses the metal as fast as it shrinks, and thus removes, or at least partly removes, the pipe by not allowing it to form.

CHAPTER IV

CRUCIBLE PROCESS OF STEEL MAKING

IN the crucible process a regenerative furnace is sometimes used similar to the one shown in Figs. 25 and 26. In this the heat does not attack the top of the metal as in the open-hearth, but heats crucibles which are covered and the cover sealed on with fire clay, so that the gases from the fuel will not attack the metal. In some places, however, coke furnaces or melting holes containing crucibles are used.

In Europe these crucibles are made of fire-clay by the steel makers, as they are comparatively cheap and no carbon is absorbed by the metal, as is the case with the graphite crucibles used in this country, and consequently this element can be more easily controlled in the finished product. They are usually made to hold 50 pounds of metal, as that is about the limit for the strength of the clay crucible. The molten slag on top of the metal cuts deeply into the clay, and the second charge has to be cut down to about 45 pounds to get below the slag-line, while for a third charge 38 pounds is about the limit, and after this they are thrown away, as it is not economical to use them. One or two steel makers in Europe only use the clay crucibles once, as they claim they can get a better steel, owing to the larger air space causing greater oxidization and the tendency of the metal to absorb and occlude some of the gases.

The graphite crucibles which are used to a large extent in this country are made by concerns that make a specialty of this business, and from a mixture that is about one-half graphite and one-half fire-clay. These generally hold 100 pounds and last for about 6 heats, but as carbon is given up by the crucible and enters the molten metal, it is more difficult to control this than when clay crucibles are used.

The crucible process is used only for the making of high-grade and special alloyed steels, such as high-speed, nickel, or vanadium chrome, etc. It is about three times as expensive as the next cheapest, namely, acid open-hearth, but for such work as cutting tools, armor-piercing projectiles, gears that are subjected to heavy or vibrational strains, high-grade springs and many other uses the crucible steels far excel anything that is made by the other processes. The reason for this superiority is largely due to the fact that it is made in covered pots, which exclude

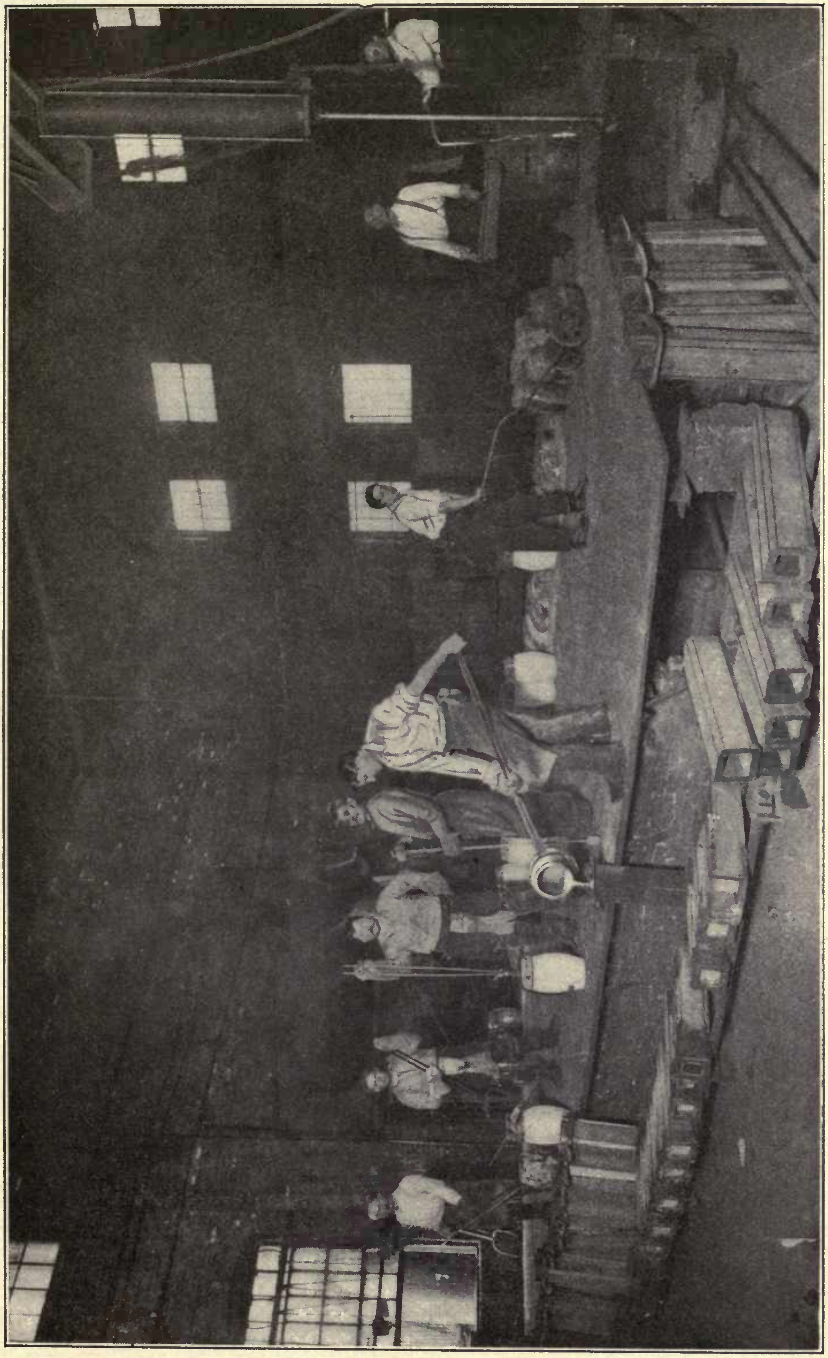


FIG. 25. — Crucible melting furnace of Columbia Tool Steel Co.

the furnace gases and air. It is therefore freer from oxygen, hydrogen, and nitrogen in the form of occluded gases.

The material used for conversion into steel by the crucible process is usually wrought iron and not pig iron as in the Bessemer and open-hearth processes. The wrought iron, in the form of muck bars, is cut up into small pieces and placed in the crucible with the desired amount of carbon, which is generally in the form of charcoal, but sometimes is introduced through the medium of pig iron. Some ferro-manganese or spiegeleisen are also added and when alloyed steels are desired such alloying elements as tungsten, chromium, nickel, etc., are added. Sometimes a small amount of glass or other similar material is used to give a passive slag, and various physics, such as salt, potassium ferro-cyanide, oxide of manganese, etc., are used by some. The ferro-manganese adds the desired amount of manganese to the steel and it is thought that the salt and oxide of manganese make a more fluid slag, while the ferro-cyanide might

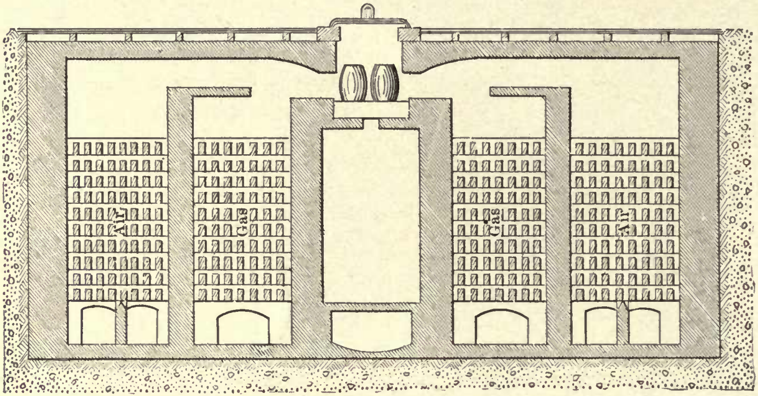


FIG 26. — Regenerative gas furnace for crucibles.

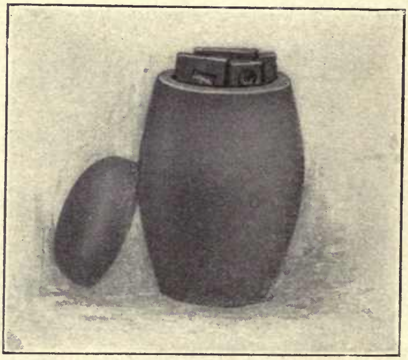


FIG. 27. — The charged crucible.

aid the steel in absorbing the carbon. In the pot are also a little air, some slag and oxide of iron, this last being the scale and rust on the surface of each piece of metal, and silica, and alumina from the scorification of the walls of the crucible. Sometimes some cheaper steel scrap is mixed with the wrought iron, but this always lowers the quality of the finished steel. A crucible that has been charged and is ready for melting is shown in Fig. 27.

Fig. 28. — Pouring ingots from crucibles.

Some time is required for the reduction of the silicon from the slag and lining as well as for the various reactions which occur. When this reduction has reached a point where the steel contains from 0.20 to 0.40% of silicon and the metal lies quiet and "dead," that is, the evolution of the gases have stopped so it will pour quietly and cast into solid ingots, the crucible is taken from the furnace and the contents poured into ingot molds, as shown in Fig. 28. After these have cooled they are usually reheated in a furnace and reduced to a size suitable for rolling by hammering under a steam hammer, as shown in Fig. 29. This reduces the grain and makes the metal more dense.

Crucible steel usually contains less than 0.40% manganese, more than 0.20% silicon, less than 0.025% phosphorus, and less than 0.030% sulphur, while the carbon content is usually made high, owing to the uses to which crucible steels are put.

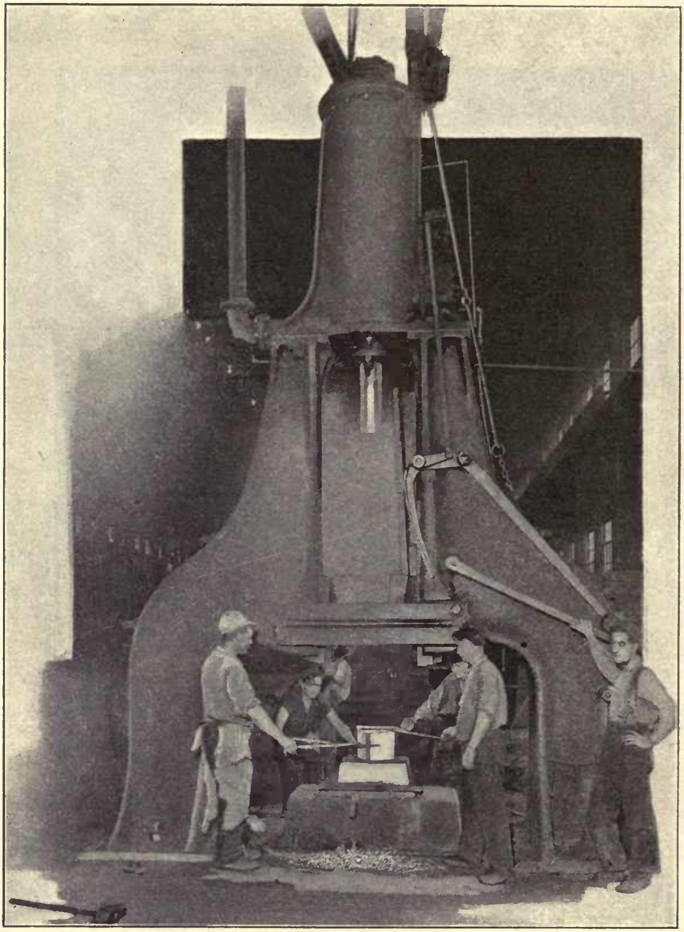


FIG. 29. — Hammering the ingot.

The main difficulty with this process is in making large ingots so these ingredients will be combined in a homogeneous mass. As the personal element is a factor in the charging of the crucibles, and these hold only 100 pounds or less, the steel made in each crucible is liable to vary some in the composition of its ingredients. Thus when a 1000 pound ingot is to be cast it requires 10 or more crucibles to fill it and the metal does not have a chance to mix thoroughly before getting cold, which will result in certain of the ingredients showing a higher percentage in some part of the ingot than in others unless great care is exercised in charging each of the 10 crucibles.

A large part of the crucible steel is hammered into bars, as shown in Fig. 30, and the accuracy and quickness with which a hammersman can turn out these bars is one of the surprising features of the steel business. They usually work by the ton, and it is difficult for the inexperienced man to tell the bars from rolled stock.

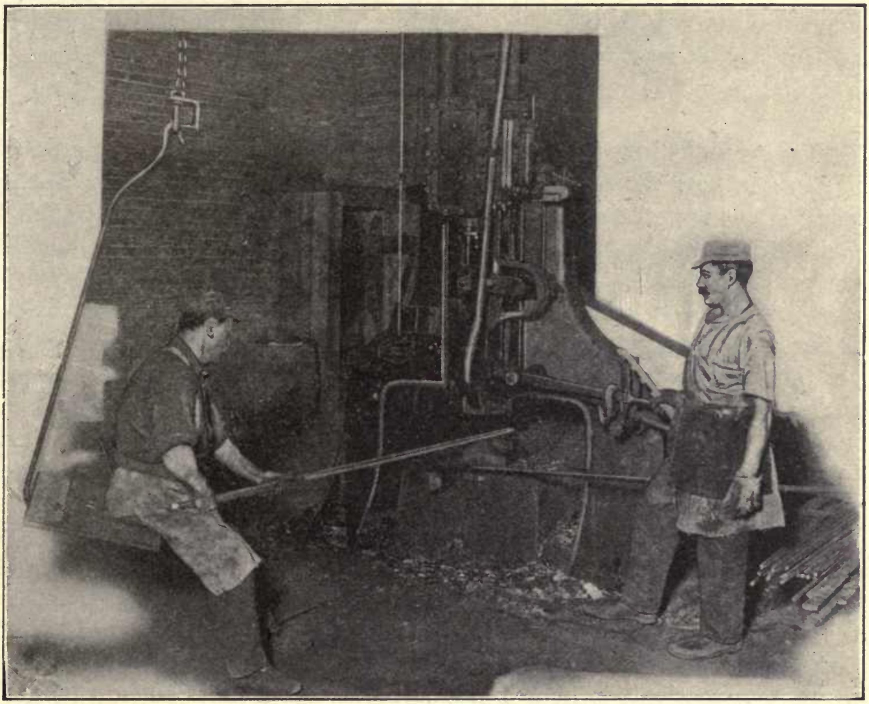


FIG. 30. — Hammering octagon bars.

This process has changed very little in the last 100 years or more, and its chemistry, which consists principally of eliminating the slag in the wrought iron and adding carbon silicon and manganese to the metal, is very simple. The progress which has been made in crucible steel is due almost entirely to the discovery of new alloying materials that have added strength, toughness, wearing qualities, cutting qualities, etc., to the metal. Thus more different kinds of good steels, and better steels, are being made to-day by this process, which is way above all the other processes for making steel of quality, than at any time previous.

The enormous and wonderful change that has been made in the steel business is due to the perfecting of methods and machinery for making steel quicker, cheaper, and in larger quantities. However, when we want an extra fine grade of steel we have to fall back on the crucible process which is still carried out in practically the same manner as was the case many years ago. The progress that has been made in electricity and the experiments that have been carried on with the electric refining furnace, however, would seem to indicate that in the not very distant future this might do away with the slow, laborious, and costly crucible process; if not entirely, at least to a large extent.

WROUGHT IRON

The wrought iron used in making crucible steel or for other purposes is also made by the same process and in much the same manner that it was 100 or more years ago. A reverberatory furnace hearth is "fettled" or lined with oxide of iron, that is, either good iron ore, roasted puddle cinder, or roll scale. On this, pig iron is melted, and some of the manganese and silicon being oxidized a slag with a high content of iron oxide is formed by absorbing this constituent from the lining. The impurities are then removed to a greater or less extent through a reaction between the carbon, manganese, silicon, sulphur, and phosphorus in the molten iron and the oxide of iron in the slag. This basic slag carries oxygen to the impurities and is assisted by the excess of oxygen in the furnace gases.

As the iron approaches nearer to purity it thickens, as the purer the iron the higher will be its melting temperature, and the heat in the furnace is not sufficient to keep it molten. When it reaches a pasty state the charge is rolled into balls, called puddle balls, that average about 150 pounds apiece. From the puddle furnace these balls are taken to a rotary squeezer that kneads and squeezes out a large amount of slag or they are taken to a drop hammer where the slag is hammered out. The balls are then rolled into bars, which removes more of the slag, leaving the rolled bars containing from 1 to 2%. These flat bars are then cut up into short lengths and form the muck bar used in making crucible steel.

Sometimes in this country and as a general thing in Europe, the squeezer is not used, in which case the puddle ball is worked under a hammer or "shingled" to remove the slag, and weld the particles of iron in the ball together. Puddling and shingling being extremely hard and hot work, however, efforts are continually being made to devise machines that will do the work. The rotary squeezer does that part of the work cheaper than it can be done by hand labor, and many different kinds of automatic puddling furnaces have been designed and built. With these latter the finished product has not been turned out as good, as yet, as it can be made by hand labor. The results obtained, however, with the mechanical furnace, have nearly reached those desired, and may yet be made satisfactory.

CHAPTER V

ELECTRIC FURNACES FOR STEEL MAKING

THE electric furnace has been brought into quite prominent use in the last few years for the making of steel. In certain ways it has proved itself to be a commercial success, while in others it is still in the experimental stage, but from the present progress (1910) in the art it would look as though the electric furnace was destined to supplant the expensive crucible method of steel making, and if electricity could be obtained cheap enough it might even be a strong competitor to the open-hearth method.

When a good ore can be procured the electric furnace can produce a metal with a higher degree of purity than any of the other processes, owing to the absence of sulphurous and oxidizing gases. Mr. Harbord, the Canadian government expert, said, "Steel equal in all respects to the best high-grade Sheffield crucible steel can be produced in the electric furnace at a less cost than by the ordinary crucible methods."

Owing to the extremely high temperature available a more perfect elimination of the detrimental metalloids can be secured and because of the neutral or reducing atmosphere it is possible to secure a more perfect deoxidation. It cannot remove arsenic and copper, but it practically eliminates phosphorus and sulphur, and thus removes the injurious effects of these. The sulphur is oxidized out until only a trace is left and the phosphorus remains in the metal only in very small percentages. For the high-grade steels such as tungsten, nickel-chrome, self-hardening and high-speed tool, which are made out of blast-furnace products and scrap it has given good satisfaction in several steel plants in Germany, France, Sweden, and Italy.

STASSANO REVOLVING FURNACES

In the Stassano furnaces, shown in Fig. 31, that are being operated in Turin, Italy, the heat is generated by three electrodes which come together in the center of an enclosed furnace immediately over the metal. This furnace is also mechanically revolved in order to agitate the metal and thus accelerate the chemical reaction and reduce the time of operation to a minimum. It is also built without the revolving mechanism for some uses.

The electrodes are cooled by water-jackets that surround them on the outside of the furnace, and the cylindrical melting chamber is enclosed so that the atmosphere throughout it will be neutral. The material treated is not in contact with the electrodes or other material, and therefore its composition is not subjected to any alteration, as the furnace only furnishes the heat to produce the reaction between the substances in the charge, and does not introduce other elements.

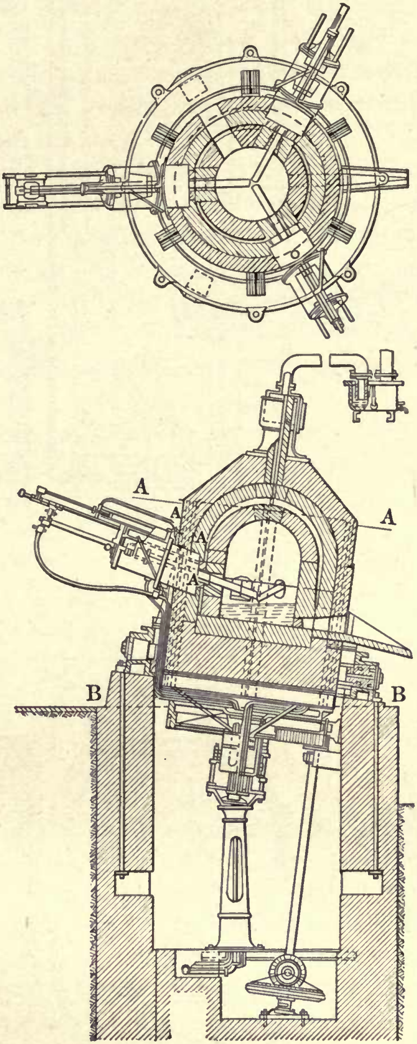
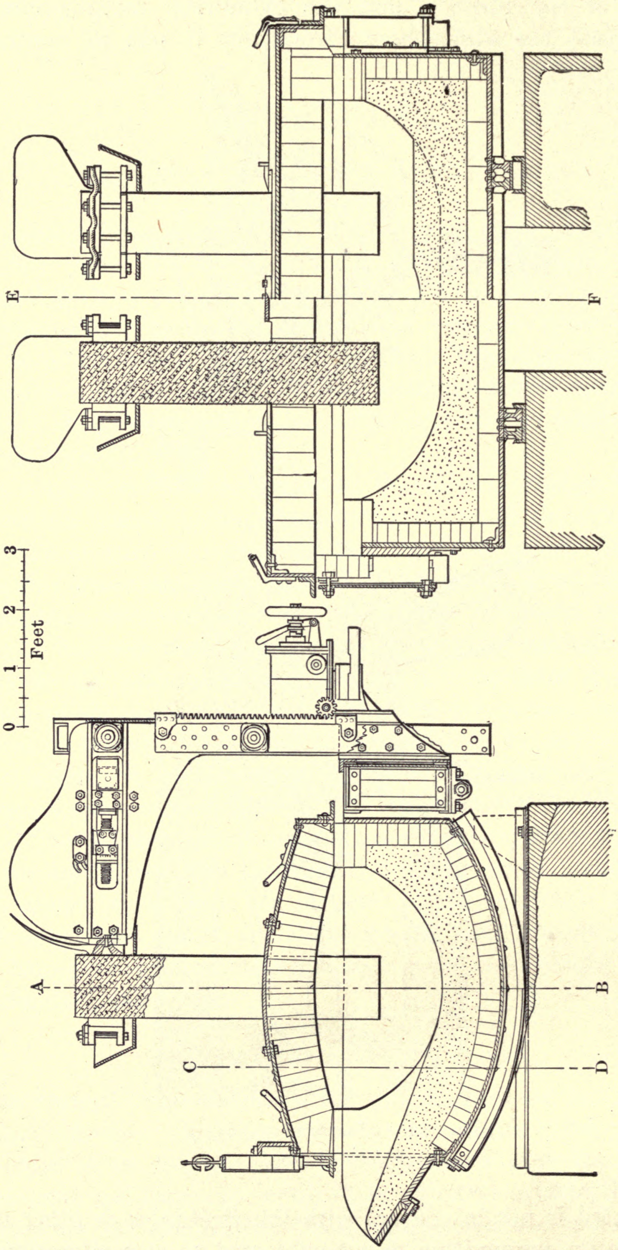


Fig. 31.—Stassano revolving electric furnace.



Longitudinal Sections A–B and C–D

Transverse Section E–F

FIG. 32. — Heroult arc and resistor furnace.

Among the different oxides contained in commercial iron ore that of iron is the first one which is reduced. The remaining oxides (SO_3, MnO, MnO_2, CaO, MgO, etc.) are, therefore, left unreduced and are forced to pass, with the assistance of a flux, into the slag. In the same way, if pig iron or iron scrap is used, mixed with slag-forming materials, the pig iron and impure iron may be successfully refined in the same furnace, and this is accomplished by starting from predetermined quantities without any tests during the process.

When refining pig iron or impure iron, oxide of iron must be added, which may be natural or artificial (hammerslag) or powder of rusty scrap. To make the slag, the common fluxes, used in metallurgy, are suitable and may be selected according to convenience and special requirements. Since the atmosphere in the furnace is chemically neutral and the operation can be carried out for any length of time desired, the metal can be freed almost entirely from its impurities without the risk of harmful oxidation.

Refined iron may be obtained direct from the ore in this furnace if it is charged with iron ore mixed with a reducing agent and the proper fluxes, in the correct proportions, to transform the gangue into a slag of a composition that will absorb the impurities in a single operation. Such a charge, being gradually heated with the exclusion of air, cannot absorb oxygen from it, and the flux maintains its quality at a rising temperature so that it is able to perform its mission when the right temperature has been reached.

HEROULT FURNACE

The Heroult furnace, as shown in Fig. 32, is but a modified open-hearth, with the heat introduced above the metal by the electric current in place of gas; no electrical parts being in the furnace proper. Thus the bottom and side can be patched as fast as they may be burned away without interfering with the work of the furnace.

In the later types of Heroult furnace the heat is introduced by means of two electrodes working in series; the current passing through the bath from one electrode to another, and vice-versa. The power being the same in both cases, this necessitates carrying only one half the current that would be needed if the current flowed from one electrode through the bath, and thence through a plate contact in the bottom of the furnace, as shown in Fig. 33.

In this case the heat is generated in the slag and not in the metal itself; thus making the slag the hottest part of the furnace, so that all impurities can be removed by the use of special slags. The poorest kind of scrap can therefore be used, as the sulphur and phosphorus are both removed at a low cost, and the metal can be converted into the finest grade of tool steel.

In a 5-ton furnace starting on cold materials one ton of metal can be melted and partially refined, with 600 kilowatt-hours; for the finishing slag 100 more would be necessary, making 700 kilowatt-hours all told. In a 15-ton furnace these figures would be considerably reduced. If molten metal is charged into the 5-ton furnace and this only needs to be deoxidized, desulphurized, and recarburized, it will take from 140 to 160 kilowatt-hours, and for a 15-ton furnace this would probably be cut down to about 100 kilowatt-hours. In cold melting and continuous work the consumption of electrodes is from 60 to 65 pounds for each

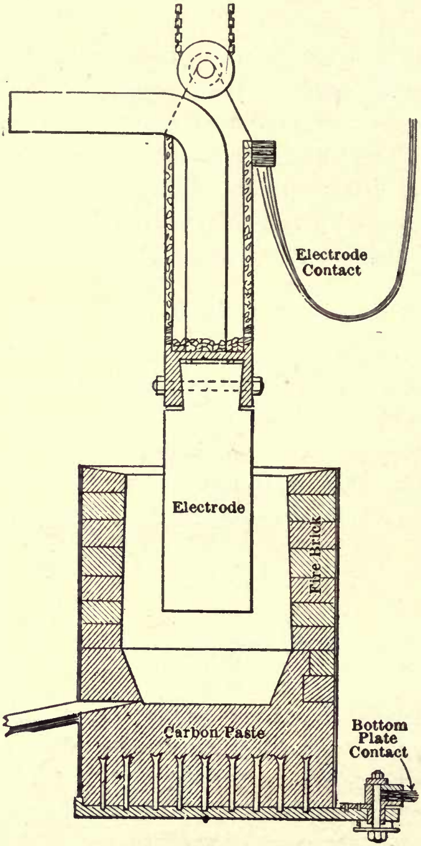


FIG. 33. — Heroult resistance furnace.

ton of steel, which includes the waste ends of the electrodes. When molten metal is charged into the furnace, this consumption is only from 10 to 15 pounds per ton of steel. The electrodes just touch the flux covering the molten metal and can be operated automatically or by hand.

About the best lining for this furnace is good magnesite mixed with basic slag, with tar for a binder; burnt dolomite can also be used successfully. The furnace can be lined by any one who can make a good bottom in a basic open-hearth furnace. The lining is never exposed to silicious slags, and can be repaired after each heat by simply throwing in magnesite or dolomite, as the case may be. This should make it last a long time, and with the furnace run with due care, one year is not too long for it to last, although furnaces have had to be relined in three months. The roof is damaged the most, and this usually has to be replaced once a month. For that reason an extra roof is kept on hand so the change can be made in a few hours.

Two 15-ton Heroult furnaces are now being used by the United States Steel Corporation (August, 1910), and this is about the largest size that can be successfully operated when two slags are used, owing to the difficulties that might be encountered in raking the first slag off the molten metal. The first slag used being an oxidizing one to remove the phosphorus, and the second deoxidizing for the removal of the sulphur and the gases. It is the intention to build 30-ton furnaces, however, where only one slag is used.

The detrimental features of this style of furnace, which are yet to be overcome, are the high electrode costs, and the possibility of increasing the carbon contents of the finished metal. For melting purposes as in steel foundry work it is also difficult to choose a suitable protective flux, that will act as a heating medium, and still not act on the ingredients of the molten metal.

KELLER FURNACE

The Keller furnaces are more or less of the Heroult type, but differ in constructional details. These are shown by Fig. 34, which is a sectional elevation. As will be seen, the carbon electrodes *A* are massive and are lowered into vertical shafts that are separated but connected below by a lateral canal *B*. The electrodes are surrounded by the raw material in these vertical shafts, and the electrical current passes from one electrode to the other, down through this material and through the lateral canal, in which it becomes molten. The molten metal is then drawn off by tapping. A central electrode is located at *C*. This furnace is well adapted for making steel castings, and it can be cleaned by dumping the bottom *D*. When thus used a central stack is added to the furnace shown, that feeds the raw material into the vertical shafts surrounding the electrodes.

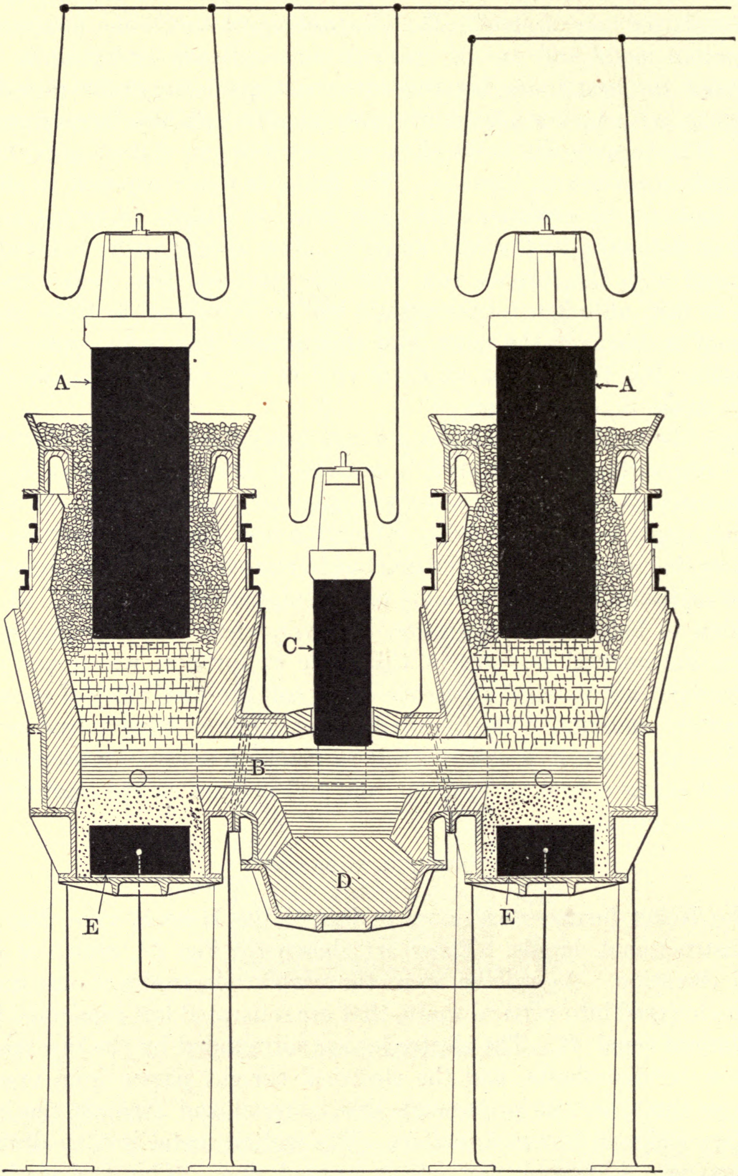


Fig. 34. — Keller electric steel furnace.

KJELLIN AND COLBY FURNACES

Resistance furnaces of the induction type were invented by Mr. E. A. Colby, in the United States in 1887, and independently reinvented by Dr. Kjellin in Sweden twelve years later. As a natural sequence a combination was formed and the patents of both are used on the same furnaces.

In Fig. 35 is shown the principle on which this simple induction furnace is built. It is in reality a transformer, in which the bath of molten metal forms the secondary circuit. The magnetic circuit *C* is built up of laminated sheet iron like the core of a transformer. The primary circuit is a coil *D*, consisting of a number of turns of insulated copper wire or tubing surrounding the magnetic circuit. The ring-shaped crucible *A*, made of suitable refractory materials, also surrounds the magnetic circuit, and when filled with molten metal forms the secondary circuit of the transformer. The annular crucible is supplied with cover *K*.

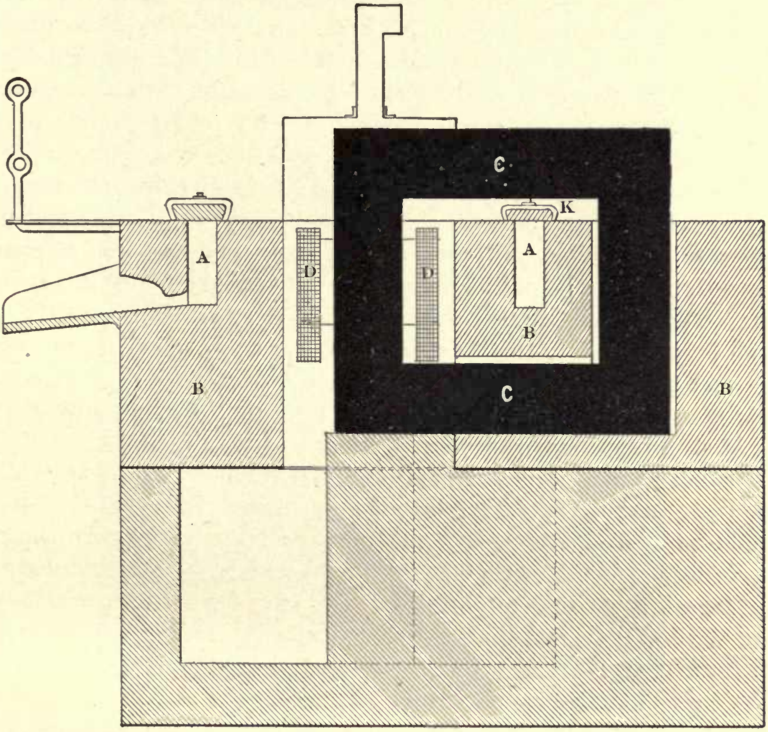


FIG. 35. — Kjellin induction furnace.

When the coil *D* is connected with the poles of an alternating-current generator, the current, when passing through the coil, excites a varying magnetic flux in the iron core and the variation in the magnetic flux induces a current in the closed circuit formed by the molten metal in the crucible *A*. The ratio between the primary and secondary current is fixed by the number of turns of the primary, and the magnitude of the current in the steel is then almost the same as the primary current multiplied by the turns of the primary coil. Thus, in a small furnace of this type a current of 500 volts and 280 amperes supplied to *D* induces a current of seven volts and 20,000 amperes in the metallic bath.

In this style of furnace the charge may be either in the hot molten state or in the form of cold scrap, pig iron, etc. When the latter materials are charged one or more metal rings, made of cast iron, wrought iron, or steel, must be placed in the hearth *A* to complete the electrical circuit and start the melting. When molten metal is charged, this of itself forms the circuit, and for continuous working it is customary to leave a sufficient amount of metal in the crucible *A* to establish the bath.

If the charge is made with molten metal a saving in time and power is effected in refining the bath. When scrap and pig iron is charged, the metal ring must be put in and the current turned on until this is melted down. The charge is then gradually added and melted until the full charge is obtained. After this the temperature is raised to any desired point and the necessary additions made to give the required percentages of carbon, manganese, nickel, chrome, tungsten, etc., according to the kind of steel that is to be produced.

This is primarily a melting furnace, and the best results are obtained in melting high-grade materials. As a commercial substitute for the crucible method it has several advantages: High and easily controlled temperatures are attainable, as the temperature is directly dependent upon the primary circuit; the process is clean and gases cannot attack and injure the bath; "overkilling" is practically impossible and a saving in labor is effected. A furnace that will produce 1000 tons of steel per year can be easily handled by three men and a boy per shift.

A Kjellin induction furnace is shown in Fig. 36, as it is tapping 1000 pounds of tool steel into a ladle for pouring into ingot molds. This furnace is hung in a frame on trunnions, and is tilted when it is necessary to pour off the heat, by the aid of gears, electrically operated by a switch from the furnace platform.

One of the difficulties encountered with furnaces of this style, the hearth of which is in the shape of an annular ring, is caused from what is commonly known as the "pinch" phenomena. When an alternating or direct current passes through a liquid conductor, the electromagnetic forces tend to contract that conductor in cross-section. This contraction is apt to localize itself at some certain spot and form a depression in the molten metal that gives it the appearance of being pinched by an invisible force.

This force is a function of the current, and size and shape of the cross-section of molten metal, and is independent of the resistance, voltage, watts, temperature, heat, length of channel, etc., except where changes in these effect the other quantities. Involved in the actual contraction is also the smoothness of channel, viscosity, fluid friction, weight of floating masses, etc.

The contracting force is small for a current with relatively low densities, but when these become higher the force is great enough to contract the cross-section of molten metal to zero and thus rupture the circuit. When increasing currents are small the level falls slowly at first and then more rapidly. When a certain unstable level is reached the contraction becomes very rapid for the same increments of current. There is also a certain critical current at which rupture might take place immediately.

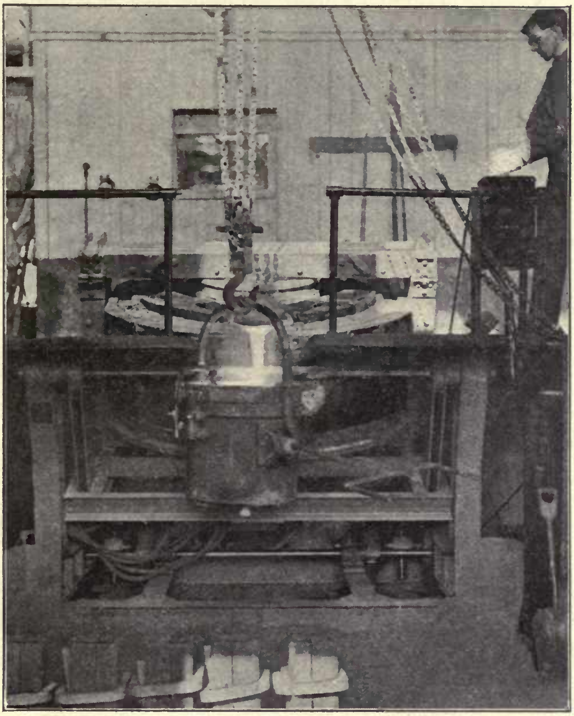


FIG. 36. — Kjellin induction furnace tapping 1000 pounds of tool steel.

Into the depression formed is liable to drift the more refractory, solid, floating materials that will prevent a reunion of the molten metal and cause a freezing of the charge before they can be removed. When this

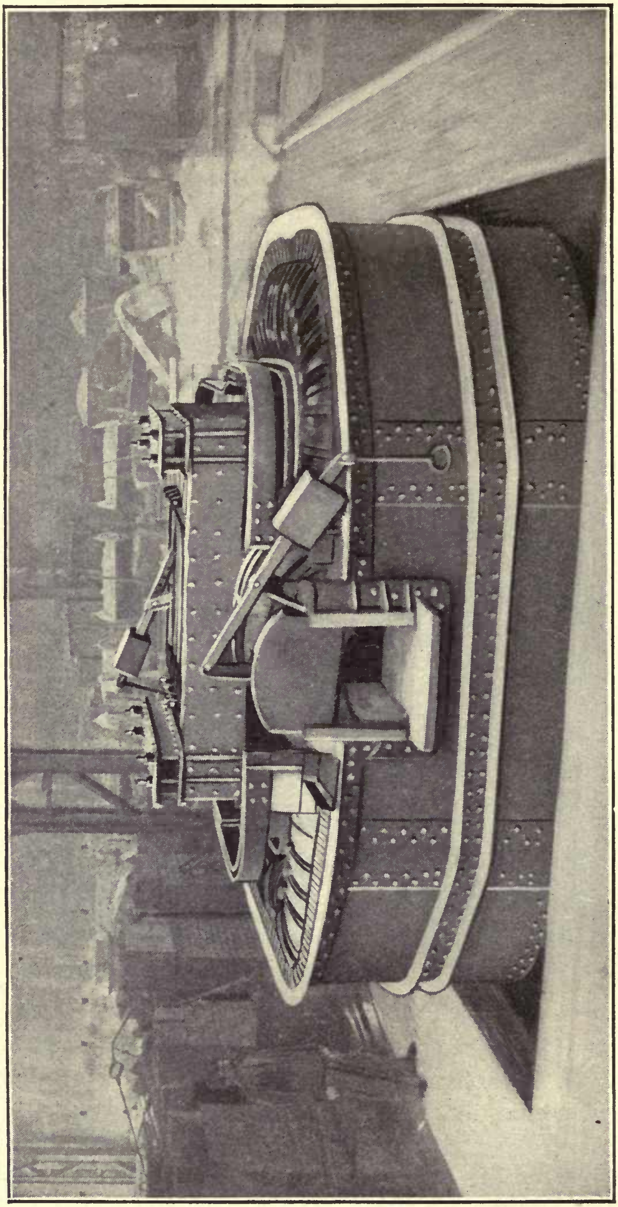


FIG. 37. — Röchling-Rodenhauser 8-ton electric furnace. Single phase.

occurs it is difficult to start the current flowing again so as to melt the metal, and the furnace usually has to be taken apart and rebuilt.

The "pinch" need not be feared in low current density furnaces, except when other causes might produce local contraction, as it only takes place at relatively high current densities. But when it does occur it means a frozen charge or a broken core, unless the separated metal can be quickly brought together by opening the external circuit for an instant and then follow it by a reduce current.

A positive limit, above which the current and thus the temperature cannot go, is fixed by the critical current. This limit is greater with a greater density, lesser viscosity, deeper channel, more regular and smoother channel, and a molten metal surface that is freer from heavy floating masses.

RÖCHLING-RODENHAUSER ELECTRIC FURNACE

The Röchling-Rodenhauser furnaces, of which one of the 8-ton furnaces is shown in Fig. 37, consists of the same arrangement of transformer and primary coils as is shown in the Kjellin furnace. In addition, however, it has a number of steel terminal plates embedded in the lining and these are connected to a few heavy turns of copper, placed outside the primary coils, that collect and feed the induced current in these turns to the terminal plates.

These are, therefore, termed combination furnaces, and are designed to suppress the magnetic leakage that would occur in large furnaces of the simple induction type; the auxiliary turns being located in close proximity to the primary coil and magnet core. The total result is that the main hearth can be made of much larger cross-section, and a good power factor can be obtained even in big furnaces without the use of a current of such low periodicity as was necessary with the original induction furnaces.

This furnace is built for single-phase or three-phase currents; the three phase being more suitable for large quantities of metal and for large daily outputs at a normal periodicity. The principles on which these furnaces are built can be seen in Figs. 38 and 39.

In Fig. 38, *H H* are the two legs of the iron core of the transformer. They are surrounded by primary coils *A*, connected with the alternating-current generator. Through the action of the currents in the primary coils, secondary currents are induced in the two closed circuits formed by the bath; these two circuits being connected so that the whole looks like the figure 8. The primary coils are so arranged that the induced currents in the common part of the two circuits, that is, between the legs *H H* of the iron core, have the same direction.

So far the furnace acts like two combined ordinary induction furnaces.

The difference consists in the use of extra secondary coils *B B*, surrounding the primary coils *A A*. From these secondary coils the currents are conducted to metallic plates *E*. The plates are covered by an electrically conducting mixture of refractory material *G*, that forms part of the lining of the furnace.

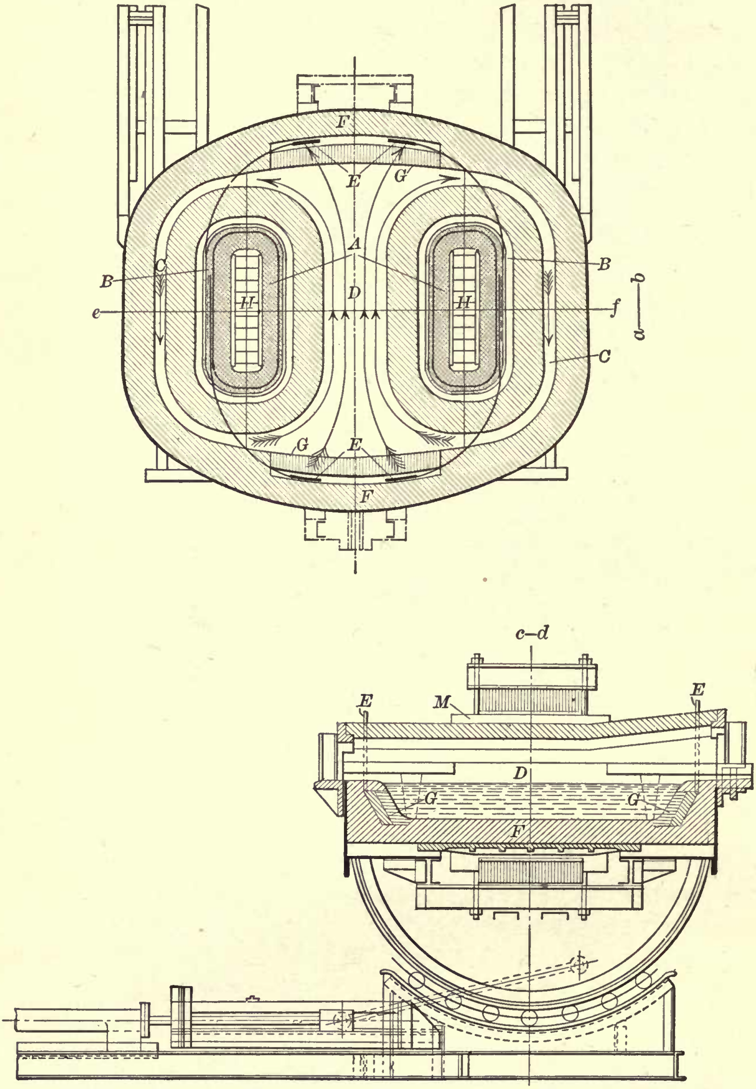


Fig. 38. — Outline sections of single phase. Combination furnace.

The currents from the secondaries pass from the plates *E*, through the lining *G*, and then through the main hearth *D* of the furnace. The channels *C* only act as conductors for the secondary currents induced in the bath. In the main hearth *D* we thus have the currents from the channels *C C*, and also from the extra secondaries *B B*.

The construction of the three-phase furnace is practically the same as that of the single-phase, except that a third transformer is added and therefore only a plan view is shown in Fig. 39.

The amount of extra power that can be given to the furnace by means of the extra coils is of course not unlimited, because increased power means increased current, and consequently increased current density in that part of the lining that conducts the current to the steel. This current density must not be driven too far, because the heat evolved when the current passes the lining will increase as the square of the current, and too high a current density would therefore result in the destruction of the lining.

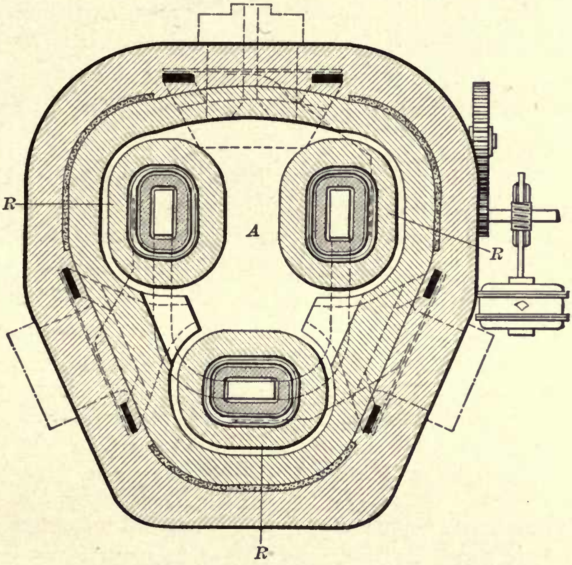


FIG. 39. — Plan view of 3-phase furnace.

This is the reason why a combination of induced currents and currents taken from the extra coils must be used. It would not, for the reason stated, be possible to conduct all the amount of current through the lining that is necessary for the working of the furnace, not to speak of the pinching effect that would very probably cut off the current at the contact between the steel and the lining, if the current density in the lining were driven too far.

The Röchling-Rodenhauser furnace was designed for refining fluid Bessemer steel from the converter, in order to produce a higher quality of steel rails than before, and also with the intention of making high-class steel in general.

For refining purposes the furnace is worked in the following manner: After tapping, fluid steel, from the converters, is poured into the furnace, and suitable materials — burnt limestone and mill scale — for forming a dephosphorizing basic slag are added. When the reactions are ended this slag is taken off by tilting the furnace. For making rails the phosphorus is brought down sufficiently low in one operation, but for the making of the highest class of steel the operation has to be repeated.

When the phosphorus is removed, the carbon in the steel (if carbon steel is made) is adjusted by adding pure carbon to the bath, and afterwards a new basic slag is formed in order to remove the sulphur. This slag is also formed of burnt lime, sometimes with the addition of fluxes such as fluorspar.

One necessary condition for successful desulphuration is that the slag be free from iron, and therefore sometimes ferro-silicon is added in order to quicken the reduction of the iron in the slag. How far this refining will have to be carried naturally depends on the quality of steel wanted. By repeated refining operation with fresh slag, the phosphorus and sulphur can be brought down to an exceedingly low percentage, but this refining, of course, takes a longer time and consequently more electric energy per ton of finished product.

GIROD ELECTRIC STEEL FURNACE

From the numerous experiments that have been carried on, has been deduced the fact that the best method of insuring practical success in the operation of electrical furnaces is to so design them that they will have the utmost simplicity in the construction of the necessary apparatus. Until the Girod furnace was perfected the Heroult was the simplest and to this was due its success, but now (June, 1910) the Girod heads the list of electrode furnaces in simplicity and safety in construction and operation.

The owners of the process are ready to guarantee the successful working commercially of a 25-ton furnace for refining steel previously made molten in an open-hearth furnace. While this is a cheaper method of producing a good grade of steel than that of melting down the raw materials in the electric furnace and then refining it, Mr. Paul Girod, the inventor of this furnace, claims that steel cannot be produced from a molten charge that has the same good qualities as that made exclusively in the electric furnace from pig iron, scrap, etc. Such qualities, for instance,

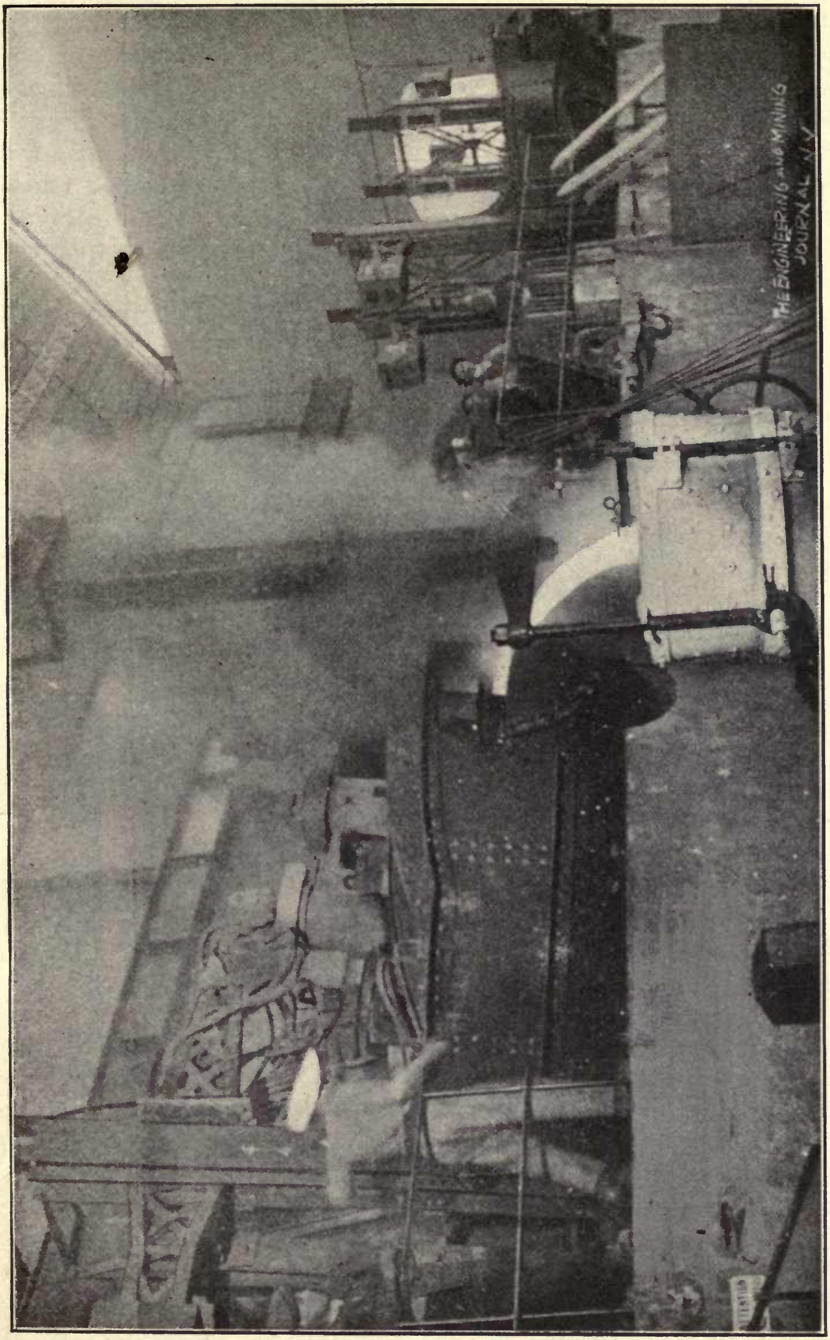


FIG. 40. — Pouring the charge from 12-ton Girod furnace at Ugine, France.

as resistance to shock; and in tool steels, hardness, tenacity, and durability after hardening. In this Mr. Girod is supported by others.

In Fig. 40 is shown a 12-ton Girod furnace as it is pouring the charge into a ladle by tilting. To the right of this will be seen another furnace; the picture being taken at the steel works started by Mr. Girod a few years ago in Ugine, Savoie, France. This company has a good water-power for generating their electricity, and are to-day (June, 1910) operating 19 electric furnaces, with from 400 to 600 electrical horse-power each, while 12 new furnaces are being constructed that will consume 1200 horse-power each. All kinds of steel are being made, from structural up to high-speed tool steel.

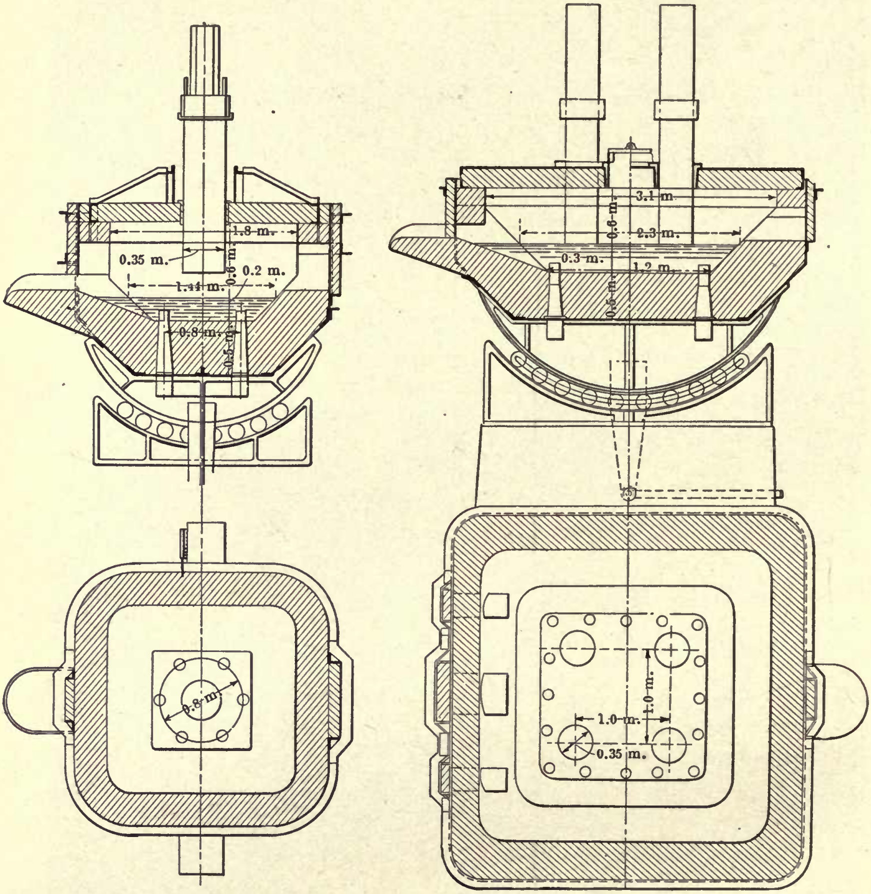


Fig. 41. — Plan and sectional elevation of 12-ton Girod electrical furnace.

The construction of this furnace can be seen by a study of Fig. 41.

While it is classed with the electrode furnaces it is in reality a combination of the resistance and arc heating and seems to work as well in large units as in small ones. One or more electrodes *A* according to the size of the furnace, are lowered through a hole, or holes, in the cover that is lined with silica brick, and the metal *M*, which is from 12 to 14 inches deep, serves as the opposite electrode. The current passes from electrode *A*, in the form of an arc, into the slag S, where a large amount of heat is produced, then into the metal *M*, and finally out through the contact pieces *C* to the current conductor. If a number of electrodes are used above the bath they are in parallel.

The most important principle in the Girod process is the effective manner in which the electric current is made to pass through the molten metallic body and cause it to become an important heat producer.

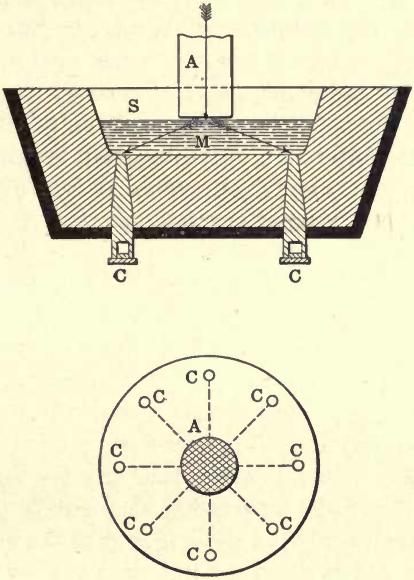


FIG. 41a. — Operating principle of Girod furnace.

Water is driven through a passage about 6 inches deep in the outer end of each contact piece *C*, so as to cool them and aid in regulating their temperature and resistance. The length and cross-section of the contact pieces are such that each will take up only a certain part of the whole current and thus none become overheated and greatly increase in resistance. They are made of pure iron to avoid any deterioration of the furnace charge, and are not only connecting rods between the furnace charge and the current generators, but also serve as regulating current distributors, by making the electric current pass uniformly from and to the centrally hanging carbon rod or rods in radial direction to and from the periphery of the bath. This is important, not only for uniformly heating the bath, but also for keeping every part of the liquid metal in constant motion. This movement accelerates the contact between the impurities of the iron and the refining slag swimming on top of the bath.

In operating on cold materials the electrode is lowered until it rests upon the heap of scrap; then the current finds no other way out than by means of numerous small arcs through the whole mass of material, thus breaking it down simultaneously in all parts of the hearth, with no sticking of cold pieces to the bottom. When feeding cold scrap one does not put in the whole charge at once. After the larger part of the charge has been deposited upon the hearth, the current is sent through the heap as described; then the rest of the charge is put into the furnace, together with the first batch of the refining ingredients. Taking the run of a 2-ton furnace as an example, the charge consists of 4500 to 5500 pounds of iron scrap, and the first batch of refining slag usually consists of about 175 pounds of lime (CaO) and 500 pounds of iron oxide ore. Together with the iron oxide that covers the scrap, the iron ore serves as an oxidizing agent.

The smelting of the iron charge and the first batch of refining slag requires 4½ to 5 hours. As the slag becomes exhausted of iron oxide and therefore of its oxidizing power, samples are taken and tested to ascertain the degree of refinement of the molten metal. According to the degree of purification, the furnace now receives (after the first slag has been skimmed off) a second, and if necessary a third batch of lime-iron-oxide slag. After the removal of the last slag the surface of the metal bath is thoroughly cleansed by throwing in about 75 pounds of lime and skimming this off after a while. The further treatment of the bath depends upon the impurities which could not be removed by the lime-iron-oxide refining, and upon the quality of steel to be produced. Thus deoxidizing or other refining agents are employed; such as, ferro-mangano-silicon, ferro-aluminium-silicon, ferro-mangano-aluminium-silicon, and other alloys.

The final step in the production of special steels is the addition of iron alloyed with metals like nickel, tungsten, chromium, and others, after these refining operations.

A removable cast-iron frame is fitted to the cover, and this contains water-jacketed ports through which the electrodes enter the furnace. While the metallic frame is not necessary it serves a useful purpose by stiffening the cover and keeping air from entering the furnace and attacking the bath. As the electrodes have the same polarity, when more than one is used, there is no danger of short circuits through the metal frame and collars and across the cover. The electrodes are easily regulated automatically by feeding from the generator, on the voltage, in the single electrode furnaces, or on the intensity of the current when this is fed by a transformer, or several electrodes are supplying current equally. The electrode consumption is about 38 pounds in 2-ton, and 31 pounds in 12-ton, furnaces per ton of steel produced.

Two 2½-ton Girod furnaces that are in use in France and Belgium, are shown in Fig. 42. One of this style is used in Switzerland for steel castings only.

SUMMARY

Many others have been and are experimenting with electric furnaces in the hope of improving them and cheapening their operation, among which might be mentioned Gustave Gin, Marcus Ruthenburg, E. A. Greene, F. S. McGregory, Prof. B. Igewsky, and others, but none of these have as yet passed the experimental stage, and been put to practical use. Horace W. Lash, of Cleveland, Ohio, U. S. A., has developed a process that is applicable to the electric furnace, but as it is also applicable to the open-hearth process it cannot be classed with the purely electric steels.

Some years ago Mr. Lash became interested in the direct production of steel from the ore, and made experiments. The outcome of this was a compromise between the direct and refining methods. He found that when an intimate mixture of iron ore, carbon, fluxes, and cast-iron borings was heated, a reduction took place; by proportioning the mixture properly, steel of the desired grade could be produced and practically the whole of the iron in the mixture recovered as good steel.

A typical Lash mixture is as follows: Granulated pig iron, or cast-iron borings, 23%; iron ore, 60%; coke, 11%; lime, 6%. To reduce this in the open-hearth furnace required the addition of pig iron or scrap. A typical charge for 100 tons of steel ingots being: Lash mixture, 122 tons; pig iron, 32 tons; ore, 2 tons. In the electric furnace pig iron or scrap is not necessary, and for 100 tons of steel ingots the charge would be, Lash mixture, 172 tons; ore, 2 tons.

The experiments proved that a superior quality of steel was obtained; the cost of its production was in general lower than when the regular methods of making steel were used; and that the electric furnace was the best method for the process. Companies have been organized in Cleveland and Canada for making steel by the Lash process.

That the electric furnace will produce as high, if not a higher, grade of steel than is produced by any of the other methods has been fully established; that it is cheaper than the crucible process, and may in time equal the open-hearth, is also pretty well recognized. That magnetite and hematite ores can be economically smelted; that sulphur and phosphorus can be reduced to a few thousandths of a per cent. even without manganese; that the percentage of silicon can be altered at will, and that ores containing titanic acid up to 5% can be reduced in the electric furnace, make of it one of the coming factors in the manufacture of steel.

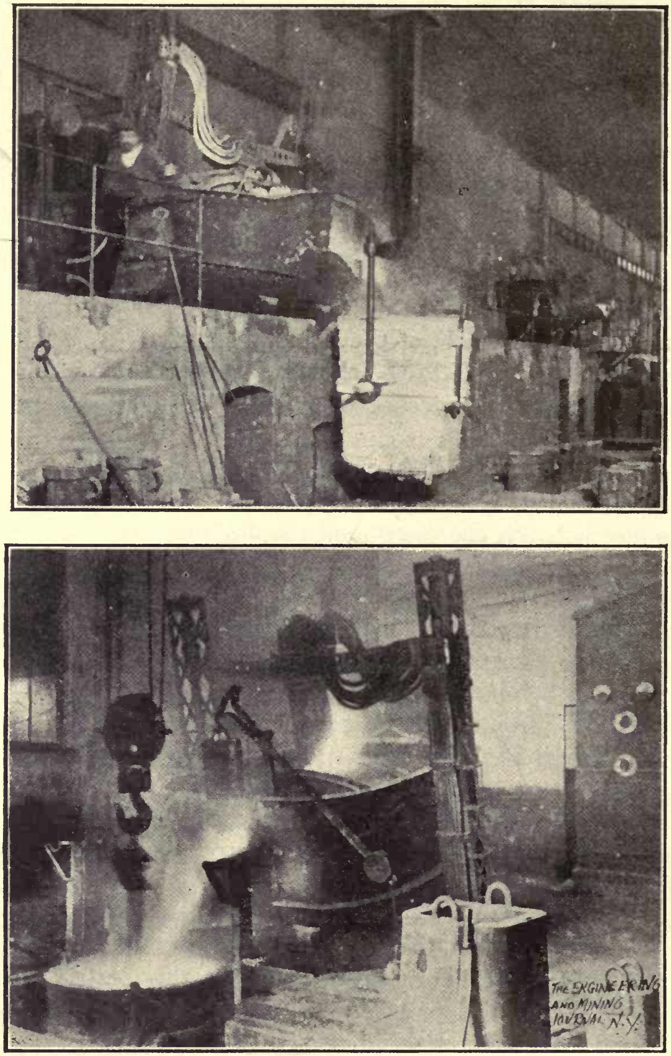


FIG. 42. — 2½ ton Girod furnaces in use in France and Belgium.

In two steels of the same composition, 1 inch square, one of which was made in the electric furnace and the other in a crucible, a considerable difference in torsion was noted. The electric steel was twisted cold until it looked like a corkscrew, while the crucible steel only took half as many twists before breaking. A Bessemer steel has been made better by merely submitting it to the heat in an electric furnace for a short time. In another case, a tool-steel maker found that he could produce his tool steel with smaller additions of silicon and manganese than was necessary in the crucible process.

The only explanation that appears probable is that the higher heat and reducing, rather than oxidizing, atmosphere of the electric furnace, expels some of the gases that are dissolved in the steel, and possibly aids the removal of the combined oxygen, thus making the deoxidation more complete than in the crucible.

The latest development in the electric furnace experiments has been the combination gas and electric heated furnace. As the United States Steel Corporation have a supply of natural gas at their plants in the Pittsburg district, they have built a tilting open-hearth furnace in which a cold charge is melted down with gas, after which it is turned off and electrodes lowered into the metal, through the top of the furnace, to refine the charge.

This is apparently the most economical method of making electric steel that has yet been suggested, as the natural gas can be obtained for less than 20 cents per thousand feet, and at this rate is much cheaper than electricity, and perhaps just as good for melting down the charge. The use of the electric current can then be confined to removing the impurities from the bath. This, however, is in the experimental stage and what the cost of operation will be, for the quality of steel to be produced, has not yet been established.

CHAPTER VI

INGREDIENTS OF AND MATERIALS USED IN STEEL

THE elements entering into the composition of steel have been studied and investigated in many ways and their effects have been carefully noted. Many new alloying materials have been brought into use in the past few years. These were made available by the high temperature obtained in the electric furnace, as this enables them to be separated from the elements with which they were found, and combined with iron to make ferro-alloys that could be added to the steel in its making. Many other elements are being experimented with, and some of these give promise of adding new properties to steel or bettering the properties already recognized as good ones, and thus we may be able in the near future to still further improve it in quality.

These new alloying materials have given us steels which, for strength, cutting qualities, wearing qualities, and ability to withstand vibrational and torsional stresses, attain a higher standard of excellence than would have been considered possible a short time ago.

CARBON IN STEEL

Of all the alloying elements entering into steel, carbon is the most important, as it is the quantity and condition of the carbon in the metal that makes the distinction between iron and steel. The distinctive features of different grades of steel are due more to the variation of the carbon contents than to the differences in any or all of the other elements.

One of the wonders of metallurgy is the effect that a small per cent. of carbon has upon iron. Pure iron, that is, iron that has been electrolytically deposited, has a tensile strength of 45,000 pounds per square inch, and if we add a few tenths of 1% of carbon, the tensile strength immediately rises to 60,000 pounds, and with 1% it reaches 120,000 pounds per square inch. This is a quantity so small that it is out of all proportion to the mass in which it is distributed.

Carbon unites with chemically pure iron in all proportions up to 4½ per cent. The capacity of the iron for carbon can be increased by using manganese, and when a high percentage of manganese is added to steel the carbon content can be raised to 7 or 8 per cent. Manganese, silicon, phosphorus, sulphur, etc., may vary widely in quantity, but the carbon usually decides the class in which the steel belongs; for the carbon gives greater hardness and strength to the steel, with less brittleness, than any other element.

To get the desired percentage of carbon into steel, various methods are used. In the melting in process, that is, adding the carbon to the steel when the metal is molten, the Bessemer, open-hearth, and crucible processes all use a different method. Besides this, there is the cementation process in which the carbon is put into the steel while in a solid state. Several methods are employed in this, and they consist of submitting the metal to the action of some carbonaceous material in the presence of heat.

In the Bessemer process, the charge of molten metal is put into the converter and air is blown through it. This air oxidizes out all of the silicon and manganese and nearly all of the carbon, the heat of combustion of these elements raising the temperature of the charge. The charge is then recarburized through an addition of molten spiegeleisen, after which the metal is poured into ingots.

In the open-hearth process, the charge usually consists of 50% pig iron and 50% of scrap, and these are melted up together. The pig iron usually contains from 3½ to 4% of carbon, and the charge is melted down and boiled until the carbon has been reduced by oxidation to the required amount. Tests are taken every half hour or so, to determine when the carbon has been reduced to the proper percentage, and when this is reached, the ferro-alloys are added to the bath and it is cast into ingots.

In the crucible process, muck iron and charcoal is charged, the crucible sealed up and the charge melted down. If the muck iron contains 0.10% of carbon, 100 pounds of muck bar and 15 ounces of charcoal, which is the form in which the carbon is put in the bath, will make a 1% carbon steel. With the muck iron higher or lower in carbon, the charcoal is diminished or increased to obtain the correct carbon content.

By the cementation process muck iron is changed into blister bars, or from a low to a high carbon metal by placing alternate layers of iron and charcoal in a furnace and covering the top with clay to prevent the charcoal from burning off. Much iron containing about 0.10% of carbon is usually used. By closing the furnace, heating it up slowly for a few days and then keeping it at a good yellow heat for about nine days, the iron has absorbed about 1% of carbon. This product is often used for making crucible steel by merely melting it down in the pot and adding the alloying materials that are desired to purify and strengthen the metal. This process is also used in Harveyizing armorplate, but in this case but two plates separated by one layer of charcoal are used, and about 30 days' time consumed; ten of which are used to slowly heat the metal up to the desired temperature, at which it is retained for ten more days, and the final ten days are consumed in allowing it to slowly cool. With this treatment the carbon has penetrated to a depth of from 1 to 1¼ inches and the surface of the plate will show about 2.50 per cent. of carbon when analyzed.

The Krupp process conducts illuminating gas over the surface of the armorplate instead of the charcoal. When the plate is at a good yellow heat, it decomposes this gas into carbon and hydrogen; the carbon being deposited on the plate in a finely divided state as soot, which is immediately absorbed by the metal, while the hydrogen escapes as a gas.

Both of these cementation processes are used with various modifications for carbonizing small pieces in special furnaces, and this subject is treated in detail under the chapter on Carbonizing. A low carbon iron or steel will absorb carbon from any carbonaceous material in the presence of heat; in fact, if two pieces of metal are heated to the proper temperature, one containing a high and the other a low percentage of carbon, the carbon will flow from the high to the low point. Its action under these conditions is very similar to the difference in potential of an electric current, which always flows from a highly charged body to that of a lower, until an equilibrium has been established.

The actual mode of existence of the carbon in the metal is of great importance in the working and treating of steel, and several words have been coined to define its different conditions. Ferrite means carbonless iron, and its chemical abbreviation is Fe. Cementite consists of three atoms of iron combined with one atom of carbon, Fe_3C. Graphite is the carbon that is uncombined, as, when an excess of carbon is present in iron, all that will combine will be taken up by the iron and form cementite, while the balance will remain in a free state or as graphitic carbon. Pearlite is a very intimate mechanical mixture of ferrite and cementite, usually in alternate layers, and Austenite is a solid solution of carbon in iron. Martensite, Troostite, Sorbite, etc., are transition forms that are taken up under the chapter entitled "Hardening Steel."

The term solid solution refers to that association of substances which is neither chemical combination nor mechanical mixture. A solid solution has all of the properties of a liquid solution, such as salt or sugar when dissolved in water, except liquidity. It is distinguished from a chemical compound because of the fact that the constituents may vary in the proportions in which they are present, and that it is not a mechanical mixture may be told by microscopic observation. Glass is a familiar example of a solid solution.

In heating and cooling steel, the carbon assumes different forms, as well as when in different percentages. In heating and cooling a piece of annealed steel that contains about 30% carbon or less, it goes through the changes graphically illustrated in Chart 1. With a steel containing not more than 0.90% of carbon, it is almost impossible to develop any graphitic carbon, as this is a eutectoid steel that contains about six times as much pure iron by weight as the weight of the cementite, and thus it is almost impossible to force the carbon into the graphitic state. The ability to produce graphitic carbon is greatly decreased as the carbon lowers in percentage.

Starting with a soft or annealed bar of low-carbon steel at atmospheric temperature, which has been designated zero on the chart, the temperature will rise uniformly until it reaches a point at about 1300° F. Here the temperature hesitates and remains stationary until certain internal conditions have been satisfied, when it again rises uniformly to about 1400° F., where the second transformation takes place in the metal, and the temperature again remains stationary until this has been completed, and it again rises uniformly to about 1550° F., where the third change takes place. These have been designated the recalescent points, and they have been named Ac1, Ac2, and Ac3. If suddenly cooled at the upper point, the steel will be made very hard, and the metal will be held in the condition it was placed by the applied heat.

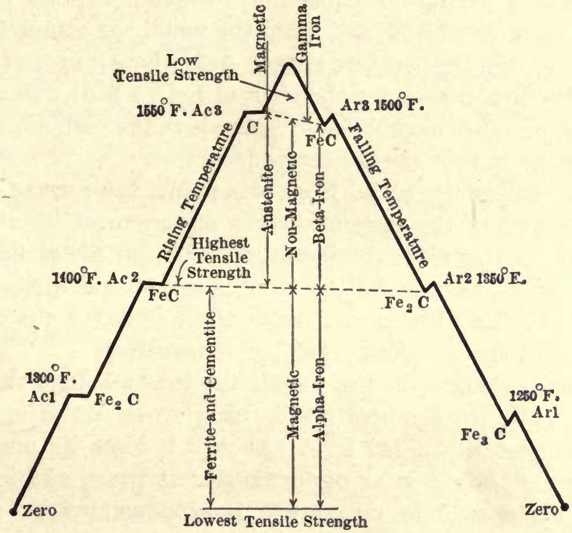


CHART 1.

If allowed to cool slowly or annealed, the temperature will drop uniformly until slightly below the temperature at which the transformation took place while the heat was rising, or about 1500° F., and the metal will then slightly rise in temperature. This point has been designated

Ar3. When the alterations in the structure and grain have been completed, the temperature again falls uniformly until it reaches a temperature of about 1350° F., at which point the second change takes place, that is the opposite of that on the rising temperature, and has been designated in Ar2. After the change has been completed at this point, it again lowers in temperature uniformly to the next point, or Ar1, at about 1250° F., and after this change takes place, it then gradually lowers to atmospheric temperature. These have been named the decalescent points.

While opinions differ on this point, what probably takes place is that while heating the steel up to Ac1 all the carbon is in the cementite form, or Fe_3C. When this point is reached, the heat that has been absorbed by the metal causes a partial decomposition to take place that results in the dropping of one atom of iron, and when the metal has completely assumed the form of Fe_2C, the temperature rises to Ac2, where it drops another atom of iron and the carbon assumes the form of FeC. With this change completed, the temperature again rises to Ac1, where the carbon goes into solid solution with the iron or the Austenite form.

On slowly cooling the metal from this point, the reverse action takes place, that is, at Ar3 the carbon absorbs one atom of the iron that has been dropped on the rising temperature, and the metal becomes FeC; while at the next point, or Ar2, it absorbs the second atom of iron that was dropped and takes the form of Fe_2C, while at Ar1 it absorbs the third atom of iron and again becomes Fe_3C, or cementite.

During these changes in the metal, the iron assumes three different conditions. While the temperature is rising up to Ac2 it is highly magnetic, and is called alpha (α) iron. At Ac2 it loses its magnetism and between Ac2 and Ac3 it is as non-magnetic as brass, and is called beta (β) iron. This change in magnetism is accompanied by a change in electric conductivity and specific heat. At Ac3 another change in electrical conductivity takes place and also in the crystalline form. Above Ac3 it is called gamma (γ) iron.

The carbon content of steel usually varies between 0.10 and 2%. Metal having more than 2% is called cast iron and used as such. Until recently wrought iron was about the only useful iron product that contains less than 0.10% of carbon, but this is made by a working instead of a casting process. Now, however, so-called "ingot iron," consisting of about 99.9% of pure iron, with only a trace of carbon, is made commercially.

With a carbon content of from 0.10 to 0.30%, steel is soft and cannot be hardened enough to prevent cutting with a file. It is then called machinery, soft, or low carbon steel. With a carbon content of from 0.30 to 2% it can be hardened so as to cut other steels or metals, and is then called tool, half hard, hard or high-carbon steel, according to the carbon content. Exceptions to the above statement may be made in hard steels, as a low-carbon steel can be made hard by either manganese, tungsten, or chromium, but it is true of soft steel.

Every increase in the percentage of carbon increases the hardness and brittleness, and therefore its liability to fracture when cold or when heated suddenly, while it reduces the elongation and reduction of area. The tenacity shows a relatively quick rise up to 0.90% of carbon, and a slow rise from there to 1.20% carbon, after which it decreases. The relative ductility decreases in an irregular curve with an increasing carbon content. These properties are graphically shown in the chart (Fig. 43), while the separation of the ferrite and carbon and the formation of graphitic carbon are shown by Fig. 44.

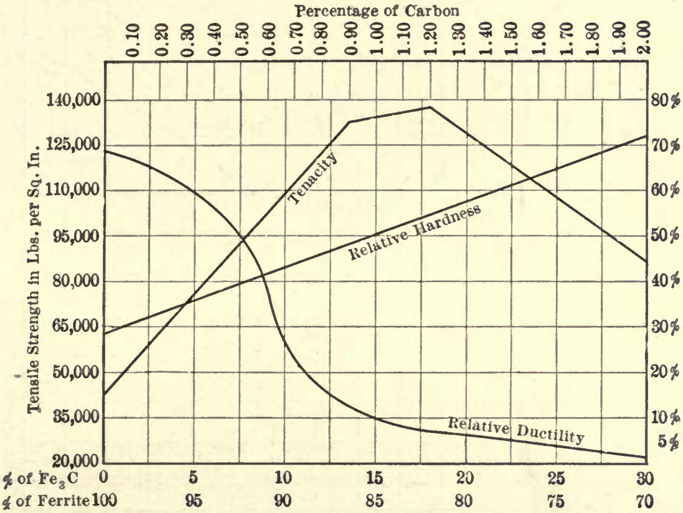


FIG. 43. — Effect of carbon on physical properties of steel.

The strength of steel is always secured at the sacrifice of some other desirable property, but the sacrifice is less in the case of carbon than with any other element. The tensile strength and elastic limit are raised considerably by hardening, and the higher the percentage of carbon the greater the degree of hardness that can be attained. But the greater the carbon content the less will be the elongation, as hardened high carbon steel is very brittle. This brittleness makes high carbon steel very easily damaged in heat treating or working, and the carbon content is usually kept as low as possible for the strength and hardness that is desired. "Sudden rupture" is a term which is especially applicable as a characteristic of carbon steel products, and a large amount of effort is being expended to discover either new ingredients, new methods of manufacture, or new ways of treating the metal that will overcome this characteristic.

Some investigations that have been carried on prove that beginning with pure steel, which has a tensile strength of 40,000 pounds per square inch, every increase of 0.01% of carbon, up to about 1%, increase the strength of acid open hard steel about 1000 pounds, and basic open hard steel 770 pounds per square inch. As the color method of determining the carbon content does not show all the carbon present, these figures, however, should be changed to 1140 and 820 pounds respectively, when the color method of analysis is used.

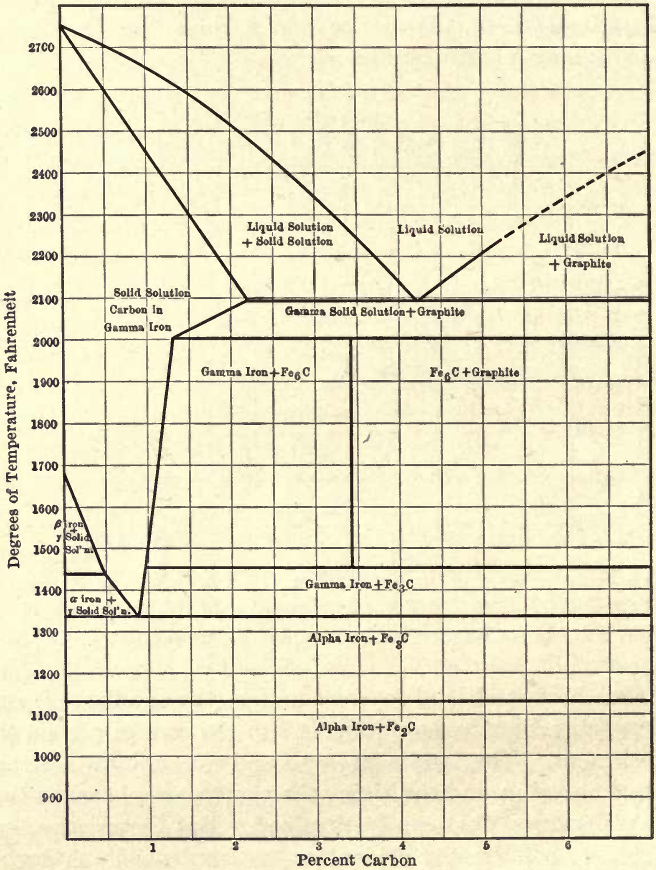


FIG. 44. — Effect of temperature on carbon.

Probably Bessemer steel would show lower figures than this and crucible or electric steel higher figures. This is doubtless due to the fact that some processes of steel making remove the oxides and occluded gases better, or to a greater extent, than others, and it has been pretty well demonstrated that these are injurious to the strength and life of steel.

alter these figures, but with all other conditions equal they will probably hold good.

That the maximum strength is placed at about 1% carbon is probably due, to a great extent, to the fact that the crystalline constituents form an intimate mixture near the eutectoid proportions, and hence the crystallization is very small comparatively. With more carbon (cementite) present the pearlite grains are surrounded with a network of cementite, while with less the pearlite grains are surrounded with a network of ferrite, and both of these decrease the cohesive force inherent in the metal.

One of the oldest theories as to what made high-carbon or tool steel harden was that the carbon in unhardened steel was partially in the graphitic and uncombined form, and when it was hardened all the carbon assumed the combined form. The most generally accepted theory, however, assumes that the hardness is due partly to the presence of the solid solution of carbon in iron, and partly to the iron being in the gamma or beta forms. This solid solution of carbon in gamma or beta iron is exceedingly hard and it is preserved in the steel by quenching from above the critical temperature.

MANGANESE

Manganese occurs in nature principally in the form of manganese dioxide (MnO_2), which is commonly called black oxide of manganese, but occasionally it is found in other compounds, such as braunite, manganite, carbonate, etc. Some of its compounds with oxygen and hydrogen are distinctly acids while others are distinctly basic, and it is in connection with the base-forming elements that it is of interest in steel making. For use in steel making the dioxide is separated from its oxygen, in the presence of charcoal or coke, either in the blast furnace or in an electric furnace. It looks like cast iron, is brittle and hard, and is combined with iron to form ferro-manganese. Sometimes silicon is added to form ferro-silicon-manganese.

Manganese is an element that is always found in steel, but its true properties and effects were not known until about twenty years ago, when they were discovered by R. A. Hadfield, a metallurgist and steel maker of Sheffield, England. Its effect when added to steel up to 2% with various percentages of carbon is best shown by Fig. 45, the actual mode of existence of the carbon in the steel being very important.

When more than 2% and less than 6% of manganese is added, with the carbon less than 0.5%, it makes steel very brittle, so that it can be powdered under a hand hammer. From 6% of manganese up, this brittleness gradually disappears until 12% is reached, when the former strength returns and reaches its maximum at about 14%. After this a decrease in toughness, but not in transverse strength, takes place, until 20% is reached, after which a rapid decrease again takes place. Manganese may affect the tensile strength and ductility of steel, either indirectly by retarding the formation of blow-holes, or directly by entering into chemical combination with the metal.

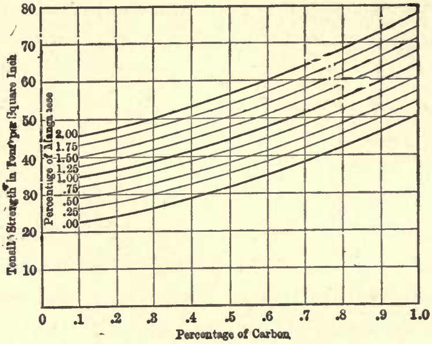


FIG. 45. — Effect of manganese below 2 per cent.

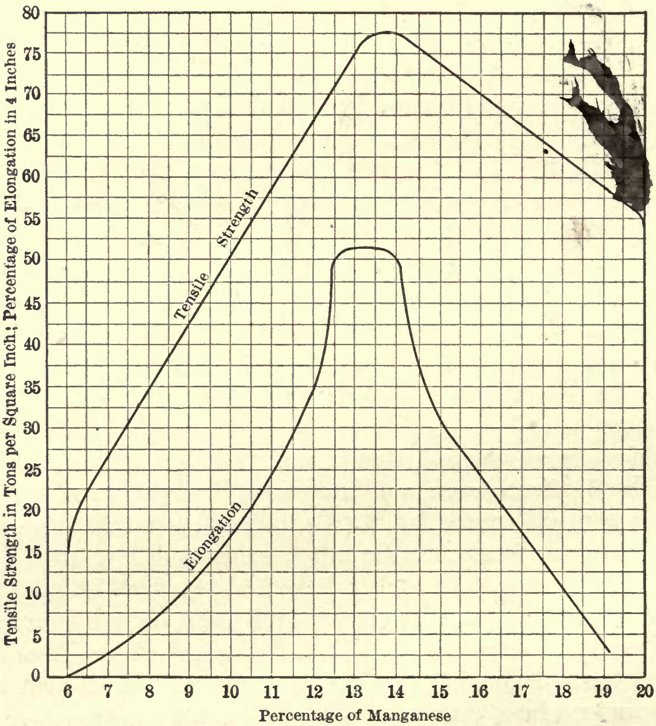


FIG. 46. — Effect of Manganese above 6 per cent.

Fig. 46 shows the effect of more than 6% of manganese on the tensile strength and elongation.

Steel with from 10 to 15% of manganese and less than 0.50% of carbon is very hard and cannot be machined or drilled in the ordinary way; yet it is so tough that it can be twisted and bent into peculiar shapes without breaking. This makes a steel that is only suitable for casting into the desired shape. A process has recently been patented however, for casting this steel into ingots, and then subjecting them to a heat treatment that enables them to be mechanically worked; that is rolled, forged, etc., and this might possibly be extended to machining operation.

Manganese in the form of a ferro-alloy containing about 80% of manganese is added to a heat of steel at the time of tapping, so that it may seize the oxygen which is dissolved in the bath and transfer it to the slag as oxide of manganese. Manganese prevents the coarse crystallization that the impurities would otherwise induce, and steels low in phosphorus and sulphur require less manganese than those having comparatively high and percentages.

Manganese has a greater affinity than iron for both sulphur and oxygen, and is therefore used in steel making as a deoxidizer and to neutralize the sulphur. Manganese oxide (MnO) and manganese sulphide (MnS) are formed, the first of which passes almost entirely into the slag and the second of which will pass partly into the slag if time is allowed. About four times as much manganese is needed as there is sulphur present, as it does not always catch all of the sulphur; thus if any great amount of sulphur is present a considerable amount of manganese is desired to counteract its effect. If the bath is kept liquid enough and enough manganese is present, but little oxygen or sulphur will be found combined with the iron, which is desirable as they are very injurious to the metal. The length of time and the care required, however, make it commercially impractical to reduce the oxygen and sulphur to a trace in this way. Therefore manganese is used to reduce them to commercial percentages, and other materials are used to still further remove them for the finer grades of steel. Manganese sulphide weakens steel greatly if segregated together with phosphide of iron, especially if the metal is rolled, as this magnifies the sulphide by spreading it out during rolling.

Manganese is not only useful to cleanse the bath of impurities, but it has other properties that aid in making steel better. The amount that can be left in the steel varies with the amount of various other ingredients that are added to the metal, and this is especially so of carbon. In effect it behaves in practically the same manner as carbon, as also does nickel. With a given carbon content the introduction and increase of manganese causes a series of structural changes similar to those that occur in carbon steels, that only contain small percentages of manganese.

While the action of these three elements upon iron is of the same kind, it is not of the same strength, as the equivalent of 1% of total carbon, that contains the maximum amount of hardening carbon, is 7.25% of manganese and 17.55% of nickel. All three of these cause a structural change in the metal from pearlite, that includes the sorbitic, to martensite, that includes the troostitic, and then to the polyhedral structure, and with none of them is a special carbide formed. Chromium has an analogous effect, but not as complete, as a double carbide of iron and chromium forms and this is not maintained in solution in the iron without tempering.

The critical temperature to which it is safe to heat steel is raised by manganese, owing to its resisting the separation of the crystals in cooling from liquid, and conferring the quality of hot ductility. It also assists in producing more uniform alloys, and tends to make steel crystals smaller by making the metal plastic, and thus counteracting the tendency toward crystallization that phosphorus causes, although the metal is more liable to crack when heating or suddenly cooling it from a red heat. The good qualities more than offset the bad, and it is a very useful factor in steel making if the proper percentages are used. It atones for many evils in steel by healing it up and producing a smoothly rolled surface.

In the ordinary steels this percentage is usually from 0.70 to 1.00%, while in many of the special alloys it runs from 0.30 to 0.50%. In the high-speed steels the manganese content is from 0.10 to 0.30%, and in steels for carbonizing this should be kept below 0.20%. When in very large amounts (from 6.0 to 15.0%) it reverses the effects of rate of cooling upon the ductility of steel; slow cooling making manganese steel brittle, while quick cooling makes it extremely ductile.

Magnetic qualities are not materially effected when the manganese is kept below 7.50%. When 8%, or more, is present, however, the magnetic attraction becomes *nil.* Manganese decreases the electric conductivity in greater proportions than any other element, except nickel. Thus third rails, or similar steels, must be given their hardness by materials other than nickel or manganese. A peculiar fact that was brought out by some experiments was that a pure nickel-iron alloy that contained from 12 to 13% of nickel was highly magnetic, but by the addition of 5% of manganese this metal became as non-magnetic as brass. While manganese steels are known to be non-magnetic, it was not known that manganese would have this effect upon nickel, which also makes a non-magnetic steel when added in certain proportion.

To sum up, manganese alloys with iron in all ratios, it being reduced from its oxides at a white heat by carbon. Its presence increases the power of carbon to combine with iron at a very high temperature (about 2550° F.), and almost entirely prevents its separation into graphitic carbon at the lower temperatures. Manganese permits a higher total carbon by raising the saturation point, and it is easily separated from iron by oxidation, as it is even oxidized by silica. While it does not counteract the cold shortness caused by phosphorus, it does prevent to some extent the red and yellow hot shortness caused by sulphur.

Manganese retards the formation of blow-holes, though not to the extent that silicon does, by preventing the oxidation of carbon, and thus the formation of carbonic oxide. It also increases the solubility of the gases in the steel while solidifying. It probably raises the elastic limit and slightly increases the tensile strength; adds fluidity to the metal; increases hardness; increases fusibility when present in considerable quantity, and gives greater plasticity and mobility to the metal at forging heats. Some recent investigations, however, make it doubtful that it diminishes ductility to any extent.

SILICON

Silicon is the second most important element in the solid part of the earth's crust, oxygen being first, and forms 27.21% of it. It is never found in the free state of nature, but, having a powerful affinity for oxygen, it occurs chiefly as silicon dioxide (SiO_2), which is commonly called silica, and in the form of silicates in combination with oxygen and such metallic elements as sodium, potassium, aluminum, and calcium. Silica will neutralize any base with which it comes in contact when molten, and all metallurgical slags are silicates thus formed. The silicon used in steel making has to be separated from the oxygen of the silica and united with iron to make ferro-silicon. Sometimes manganese is added to this to form ferro-silicon-manganese.

Many contradictory statements have been made as to the effect of silicon on steel. When the silicon is high in Bessemer steel, it is an indication that the metal has been blown too hot, and the metal is apt to be brittle. The percentage varies considerably, according to the heat of the charge, and this causes irregularities which may account for the difference of opinion. The melting point and specific weight of pig iron are governed chiefly by the silicon and the carbon, which are the principal elements. To obtain strength and density the silicon and carbon should both be low. The hardness should be controlled by a careful adjustment of the sulphur, manganese, and phosphorus, together with a study of their effect on the final condition of the carbon. In making castings high and low silicon irons should never be mixed. To get the best results in the steel the silicon should be eliminated as much as possible from the iron and a definite quantity added in the form of high percentage ferro-silicon, or ferro-manganese-silicon. This gives a very different effect from that of silicon left in the process of manufacture.

If silicon is added to steel in such a manner as to cause it to enter into solution as silicide, it confers upon the metal valuable properties; but if it forms a silicate it is injurious in many ways, even to the point of being dangerous. This latter seldom occurs, or at least occurs only to a slight degree, as the silicates of iron, manganese, etc., dissolve into each other very readily and form a slag; although manganese silicate probably occurs more frequently and causes more failures in steel than is generally supposed.

Silicon, having a great affinity for oxygen, it seizes this wherever found, and carries it off into the slag, whether in the form of gases, oxides, or dissolved oxygen. This prevents the formation of blow-holes, and makes the steel harder and tougher. Thus it is better able to withstand wear or crushing from continual pounding. This is only so, however, when the silicon has been eliminated as far as possible from the pig iron and is again added to the steel bath in the form of ferro-silicon or silicon spiegel. Otherwise the steel is liable to show brittleness and irregularity of percentage.

One steel maker found that if the percentage of manganese plus 5.2 times the percentage of silicon were made to equal 2.05, the metal would be entirely free from blow-holes, but the pipe would be large; if the total was made to equal 1.66%, the pipe would be smaller and numerous minute blow-holes would appear, but not enough to harm the steel for the use to which it was to be put. He also found that 0.0184% of aluminum would give the same result as the 1.66% of manganese and silicon.

In the Bessemer converters the silicon increases the temperature of the bath. Thus the lower the percentage of the silicon in the pig iron the shorter will be the blow. At the end of the blow, 0.2% of silicon is added to rid the bath of the gases. Thus the percentage of silicon is usually under 0.2 in Bessemer steel, and for steel rails many engineers are limiting it to 0.1%.

During the "killing" in the crucible process the steel absorbs silicon from the crucible and thus becomes sound by throwing off the gases. The graphite crucibles used in this country give up more silicon than the clay crucibles used in Europe, and consequently allowances have to be made when charging. Too long "killing" makes the steel harsh, brittle, and weak, owing to its absorbing too much silicon. Crucible steels nearly always contain more than 0.2% of silicon.

The influence of silicon on the results of quenching is similar to that of carbon in many ways. It is also dependent upon the coexisting amount of carbon and manganese. It neutralizes the injurious tendency of manganese to some extent.

An increase in the percentage of silicon slightly raises the tensile strength and lowers the elongation and reduction of area. Up to a content of 4%, silicon increases the tensile strength about 80 pounds per square inch for every 0.01%. Beyond this amount a weakening of the metal seems to take place. Without a considerable percentage of manganese, silicon steels show very low shock resistance, whether annealed or quenched. With 0.20% of silicon the tensile strength is increased about one-third more than 0.01% of carbon would increase it. Beyond a content of 5.0% silicon steels are but little used for any purposes.

Steels containing a little less than 1% of carbon and from 1 to 2% of silicon have been used quite successfully for hard-tool steels. Below a content of 1% silicon ceases to have an influence on quenching and the metal may be classed as a special carbon steel. Some makers of steel try to keep the silicon as low as possible, but many of the best steels contain from 0.20 to 0.80%. With the carbon content low the silicon may be raised to a fairly high figure, but with the carbon high the silicon should be kept low. It should also be kept low when the phosphorus is high.

Silicon steels are extremely fibrous with a remarkable resistance to shock in the direction of lamination, but practically no resistance in a direction perpendicular thereto. This quality makes them especially adapted for leaf springs.

Ferro-silicon, as now made in the electric furnace, with a silicon content between 30 and 60%, is very brittle and liable to disintegrate spontaneously, even though made of comparatively pure material. With the silicon in any percentage from 30 to 40 and 47 to 65, it gives off quite large quantities of hydrogen phosphide gas, especially when attacked by moisture in any form. This is generated from calcium phosphide, which in turn is formed from the calcium phosphate, that is present in the quartz and anthracite, when it is submitted to the high temperature of the electric furnace. Smaller amounts of hydrogen arsenide are also evolved, and both of these are highly poisonous. When the ferro-silicon disintegrates, the amount evolved is greater, owing to the largely increased surface that is exposed.

Several fatal accidents by explosions and poisoning have been caused from these gases since ferro-silicon has been manufactured in the electric furnace. Most of these have occurred when shipping it on boats, as there is then more moisture to attack it. When the silicon content is below 30 or above 65% these gases do not appear to evolve in amounts that are dangerous. As it is not really necessary to use the alloys between these percentages for the manufacture of any of the iron products, unless it be for basic furnace steel, their use, if not their manufacture, should be prohibited. Where absolutely necessary to use them, the ferro-silicon should be broken up into usable sizes and completely exposed to the air for at least one month before shipping. It should then be stored in a place where there is plenty of ventilation to carry off the gases. Ferro-silicon made in a blast furnace, however, does not give off any of these gases, and there is a movement started in Europe by the electric furnace ferro-silicon makers to abandon the manufacture of this alloy in the dangerous percentages.

PHOSPHORUS

Phosphorus always occurs in nature in the combined condition, in the form of phosphates, derived from orthophosphoric acid H_3PO_4, or in the form of organic compounds. It unites with metals to form phosphides. It forms two oxides, namely, P_2O_3 and P_2O_5, and also forms compounds of the same character and analogous composition to arsenic, antimony, and bismuth. It is consequently placed in the same chemical group as these.

It is always encountered in reducing iron ores, and is a very difficult element to remove entirely from the finished iron and steel product. In these materials it must be reduced to as low a percentage as possible, as phosphorus is without doubt the most injurious element that is found in steel, notwithstanding the fact that in the past many experiments have been carried on that apparently proved that phosphorus, up to about 0.12%, strengthened steel. When these same steels were put into actual use, however, failures occurred, and the cause was nearly always traceable to the phosphorus.

In the rolling mills phosphorus does not show any bad effect, as the heat under which the steel is worked seems to overcome this, but when the metal has become cooled and is subjected to sudden shock or to vibrational stresses, it breaks very easily. The lower the temperature and the higher the atmosphere the easier will the breaks occur. This has led to the term, "cold-shortness," as applied to the effect of phosphorus on steel.

Phosphorus diminishes the ductility of steel under gradually applied load, as shown by the reduction of area, elongation, and elastic ratio when specimens are pulled apart in the ordinary static strength testing machines. But when the steel is tested in rotary or alternating vibration testing machines, as well as with a pendulum impact machine, the decrease in ductility and toughness is shown to a greater degree. Phosphorus also reduces deflection, and the rigidity thus imparted might be considered an advantage for structural purposes except for the metal's weakness at low temperatures and when subjected to shocks.

Phosphorus steels are so capricious that they may show a reasonably high static ductility and still show very brittle when shock tests are applied. Therefore the safest rule to apply is to have the phosphorus in all steel products as low as possible. It is a very poor steel that contains 0.10%

of phosphorus. The ordinary grades contain as much as 0.08%, and the high-grade steels should have less than 0.04%, while in the very best steels it should be even lower than this. In fact, this has been reduced to below 0.01% in some of the electric furnace steels, and occasionally a mere trace is all that is left in the finished product.

Phosphorus gets into the metal by entering the blast furnace with the ores in the form of metallic phosphates, — the form in which it is usually found in nature, — and mainly as phosphate of lime, which occurs as a natural mineral named apatite. Many metallic oxides unite with it to form salts, especially iron and magnesium oxides and lime, but in the presence of silica, which is a stronger acid, it is driven out of the slags and returned to the iron until the silica has been satisfied with bases.

In steel, phosphorus has a tendency to cause coarse crystals to form, and this tendency is increased with each percentage of carbon. It forms the phosphide, Fe_3P, and this forms a series of alloys with iron. The eutectic of this series contains 64% of this phosphide, which equals 10.24% of phosphorus. A certain percentage of phosphorus will dissolve in pure iron and no eutectic will form to produce brittleness, but when carbon is added, each increase in percentage exerts an influence on the phosphorus that causes it to precipitate from the solid ferrite solution and take the eutectic form. Therefore the more pure the iron and the less cementite that is in the steel, the less will be the brittleness that is caused by phosphorus, while each increase in the percentage of carbon increases the tendency of the eutectic to form and the steel to assume a coarser crystallization, which makes it both weaker and more brittle.

Phosphorus is removed from steel to a different degree by the different processes of manufacture. Thus Bessemer steel usually contains the highest percentage of phosphorus, while the other steels contain gradually decreasing percentages in the order in which they are named: acid open-hearth; basic open-hearth; crucible; electric. The acid open-hearth furnace requires materials low in phosphorus, while in the basic it is removed by adding a sufficient amount of lime to the slag, and in electric furnaces it is removed by using the proper flux.

One of the latest methods consists of using an oxidizing slag in such a way that it will combine with the phosphorus and form a phosphate, and then adding a reducing material to the slag that will convert this phosphate into a phosphide. The reducing material is usually ground coke that floats on top of the slag and reduces the phosphate without interfering with the molten metal below. Owing to the strong combination of the phosphide, the phosphorus cannot be separated out by the iron, without first being changed back to phosphate, and this is impossible in a reducing atmosphere.

One charge that was dephosphorized in the Heroult electric furnace, when taken from a Bessemer converter, analyzed: phosphorus, 0.10%, sulphur, 0.16%, manganese, 0.10%, carbon, 0.07%, and silicon, traces. A 15-ton charge of this was put in the Heroult furnace and a black slag composed of 400 pounds each of mill scale and lime was added. This made an oxidizing slag that became fluid when the molten metal below was thoroughly oxidized, and all the phosphorus passed into the slag as phosphate of lime (CaO). Ground coke was then added to the top of the slag, and this reduced the phosphates there into calcium phosphide (P_2Ca_3). Without removing the slag the required amounts of carbon, silicon, manganese, etc., were added. That there was no return of phosphorus to the steel is shown by the analysis of the final product, which was, phosphorus 0.005%, sulphur, 0.005%, with the carbon ranging from 0.05 to 1.50%, and the manganese and silicon as desired.

A high phosphorus steel is sometimes used for the third rail in an electric railway, as phosphorus will increase hardness without decreasing electric conductivity as much as other ingredients would, and it also decreases the purity of the iron less than any other material. This gives the rails the necessary hardness and purity to withstand the abrasive wear caused by the contact shoes, without greatly lessening the conductivity.

Phosphorus in cast-iron reduces the melting point, makes the metal more fluid, and prolongs the period of solidification. This is made useful in such work as art castings, where a detail of figure is of more importance than strength, as the metal fills every minute crevice in the molds. By keeping the metal in a pasty state for a long time, or retarding solidification, the phosphorus allows the graphite to be expelled from the solid solution and occupy spaces between the particles of iron. This action causes the metal to expand and press into every tiny cavity in the mold, and the higher the percentage of phosphorus the longer will the solidification be delayed. Certain chemical conditions caused by too much phosphorus, too little silicon, etc., might overcome this by exerting a tendency to keep the carbon in the combined form. A decreased shrinkage because of this expansion may also be caused when the phosphorus separates from its solution in the ferrite and forms a eutectic. Phosphorus also increases the tendency toward segregation.

SULPHUR

Sulphur is one of the elements of the earth that is found in large quantities in the free state, especially in volcanic regions, as well as combined with metals in the form of sulphides. It is given off from the fuels used in reducing the iron ores and refining steel, and at the higher temperatures it combines with the oxygen of the air to form a dioxide, SO_2. Part of this is liable to be trapped in the metal unless precautions are taken or slags used to remove the sulphur.

When in steel in the form of sulphide, it causes the metal to crack, tear, and check in rolling, forging, heat treating, or hot working, and, therefore, the term of "hot-shortness" has been applied to its effect on steel. This is the opposite of the effect of phosphorus. Its effect on the properties of steel when cold has not been accurately determined, but it seems certain that the effect is not detrimental to any extent.

When steel is heated beyond a dull red, sulphur in the sulphide form is said to cause a crystallization to take place, and when high temperatures are reached the grain becomes very coarse, as the sulphur is dissociated and forms into a gas that diffuses between the iron crystals, thus separating them and preventing perfect cohesion. When contraction by cooling takes place this may cause microscopic cracks, or even cracks large enough to be seen by the naked eye. These, of course, weaken the metal. Sulphur and phosphorus increase the tendency toward segregation.

Sulphur takes two forms in steel, one of which is sulphide of iron, and the other sulphide of manganese. Iron sulphide (FeS) usually forms when the sulphur is high and the manganese low, as sulphur has a greater affinity for manganese than for iron. Until the manganese is satisfied, sulphide of iron is not liable to occur, and this latter form does not often occur in commercial steels. It is more brittle than manganese sulphide, and at the proper temperatures for rolling steels is in a liquid state, so that there is no cohesion between it and the molecules of steel. Instead of coming together in drops, as manganese sulphide does, it spreads out in webs or sheets, which are very pale in color and usually completely surround the manganese sulphide. These cover a comparatively large area, and the effect of iron sulphide is thus very injurious to steel, as it is very weak and liable to break along these webs or sheets. Owing to its liquid state iron sulphide is very liable to cause trouble at the rolling temperatures, whether this temperature be used for rolling or when forging, welding, or heat-treating the steel.

Sulphide of manganese (MnS) is formed by the uniting of manganese and sulphur, and it is invariably found in steel; this being the form that sulphur takes in all the good grades of steel, and if there is enough manganese present all of the sulphur in the metal will assume this form. It usually forms in globular spots, but when the metal is rolled or hammered, these generally elongate and under the microscope they show a pale state or dove gray color.

Opinion differs as to the injurious effect of manganese sulphide upon steel, but, however this may be, it is not as injurious as iron sulphide. It has been melted in coke-fired assay furnaces that would not melt mild steel, which would indicate that it was injurious when steel was heated to comparatively high temperatures. It frequently occurs with manganese silicate (slag) and it segregates together with phosphide of iron in the form of ghosts. In this case it may be very injurious to steel, and especially so where the sulphide is spread out into threads or ribbons by rolling the metal.

Sulphur, when added to soft cast iron that is low in sulphur, increases the strength of the metal, partly by closing the grain and partly by increasing the combined carbon. Owing to this tendency to increase the combined carbon and form an iron carbide, it has a hardening effect on the metal. Its effect on the tensile strength of steel has not been definitely settled, but up to 0.10% it does not alter the elastic ratio, elongation, or reduction of area to any extent. The actual percentage of sulphur at which steel ceases to be malleable or weldable varies with other ingredients. Each increment of manganese raises it, and it is lowered if the steel ingots are cast too hot.

Attention is being turned to the effect of sulphur, noted in the preceding paragraph, and the old theory that sulphur should be reduced to a mere trace in steel is beginning to be doubted, as some of these effects could be made beneficial if the injurious effects could be overcome. Some recent investigations have led to the belief that the oxides are the real source of weakness and failures in steel, and if these can be removed, the injurious effects of sulphur can at least be nullified, with the probability of its being made beneficial.

According to the old theory, 0.08% of sulphur made crucible steel absolutely worthless for welding, forging, rolling, etc., but I have recently seen samples of crucible steel that had the oxides reduced to a minimum, and the sulphur at 0.08%, that were forged under the steam hammer without any signs of checks. A piece of this same steel which contained 0.60% of carbon was welded onto machinery steel to form the cutting edge of an axe, and apparently the weld was perfect, as there was no signs of a crack when it was ground to shape. This axe was stood on an anvil with the cutting edge up, and given 20 blows with a heavy sledge before the edge broke, and even then the weld was not harmed.

Another test was to drift a hole 4 inches in diameter in stock 1½ inches thick and 4 inches wide without destroying the drift. In still another test a ⅜-inch set stood 200 blows from a 12-pound sledge without breaking. This same set was then used in the daily work at the mill until it was worn out, and it outlasted two sets made from stock steel. The tensile strength was a little better than the ordinary in this high sulphur steel.

The sulphur content was carried still higher in later tests and it was found that with sulphur up to 0.13 per cent. no injurious effects were apparent in the steel and the metal did not develop the "hot-shortness" that every one heretofore has attributed to sulphur. Above a sulphur content of 0.13% the metal began to show signs of brittleness and was clearly injured.

With steels as ordinarily made at present the sulphur should not exceed 0.10% for any use, but for tool making or other uses where the metal has to be repeatedly heated and cooled this should not be over 0.03%, and preferably as much lower as possible. Steel as now made would be much better for nearly all kinds of work if the sulphur could be reduced to a trace.

OXYGEN, HYDROGEN, AND NITROGEN

Of all the elements that enter into the composition of the earth's crust, oxygen forms nearly one-half, or, to be more explicit, 47.29%. It comprises eight-ninths of water and about one-fifth of the air. It occurs also in combination with carbon and hydrogen, and with carbon, hydrogen, and nitrogen. Besides this it forms a part of most manufactured chemical products. The iron ores that are chiefly used for making iron are combinations of ferrite and oxygen. At the higher temperatures it has a greater or lesser affinity for and unites with every other elemental substance known, except fluorine, helium, neon, argon, krypton, and xenon, and it acts readily upon a large number of compounds. At the ordinary temperatures oxygen does not act readily upon most things. Its simple compounds are called oxides, and these usually form with the production of heat. One of the elements that combine with it at low temperatures is iron, and this is coated with an oxide when heated to about 400° F., or at nearly any temperature in the presence of moisture.

Hydrogen is the lightest substance known, and like oxygen is a gas that is colorless, tasteless, and odorless. It has a high chemical affinity for oxygen, and is a good reducing agent. It forms with carbon something like 200 combinations, known as hydrocarbons. At a red heat it penetrates iron readily, probably forming a compound with it.

Nitrogen, owing to its inactivity, acts principally as a dilutent of oxygen.

These three gases readily dissolve in iron or steel when it is molten, but as it solidifies comes out of the state of solution, and then much the larger part passes away. A portion, however, is usually entrapped, and this portion if segregated in large bodies causes blow-holes, gas bubbles, etc. Carbon monoxide gas (CO), which may be generated during the solidification period by a reaction of the oxide of iron with the carbon when carburizing, is also a cause of blow-holes. These blow-holes are usually removed by the use of the deoxidizers, such as manganese, silicon, aluminum, etc. Another portion of these gases, however, is liable to remain in the steel in the form of occluded gases and oxides that are just beginning to be recognized as among the most harmful things in steel; oxygen probably being the most weakening element that can be left in steel, with hydrogen and nitrogen closely following.

As evidence of this, Bessemer steel, which is purified by blowing air through it, is the poorest and weakest of steels; while open-hearth steel, which is purified without this blast of air, but is not protected from the air striking the surface of the bath, comes next; and crucible steel being protected from air by the melting process taking place in a closed pot, is the strongest and finest grained of all the steels, except those made in the electric furnace, and this is also protected from the air. Another proof is the added static and dynamic strength, wearing qualities, etc., given to steels, by such elements as vanadium, titanium, etc., when they are used to cleanse the metal of these gases.

Oxide occurs in very small black specks throughout the metal and can only be seen when the surface has been perfectly polished and magnified at least one thousand times. These are invariably found in steels that produce blisters when pickling, and this leads to the conclusion that the blisters were formed by the reduction of oxide by the nascent hydrogen evolved during the pickling process. High-carbon steel rods that contain the same impurity occasionally fracture in the pickling bath and doubtless the same pressure that blows a blister in mild steel will cause a rupture in hard steel.

Owing to the gaseous nature of oxygen, and the fact that the drillings must be very fine, it is difficult to analyze steel for the oxygen content. A series of tests, however, was carried out by E. F. Law, of London, by cutting a piece from each of eleven bars of acid and basic Bessemer steel that contained from 0.10 to 0.18% of carbon, and only a trace of silicon. Each piece was then rolled into 24 sheets which were pickled and annealed by the usual process. An adjacent piece of the bar was analyzed, examined with a microscope, and the oxygen determined. The result of these tests was as follows: (See table on page 85.)

An examination of the table will show that as the oxygen content increased the number of blistered sheets increased, while the percentage of sulphur seemed to have no effect on the blistering; the set containing 19 blistered sheets only showing 0.071% of sulphur, while the set of sheets that did not blister at all contained 0.076, 0.069, and 0.061% of sulphur, respectively. By way of comparison a piece of basic Bessemer steel was analyzed just before the ferro-manganese was added, and this showed 0.062% of oxygen. The results shown here seem to forcibly confirm the oxide theory.

It might appear at first sight that the quantities present are extremely small, but in making comparisons we should not consider alone the amount of the elements present, but also the combinations of these elements that

TABLE SHOWING EFFECT OF OXYGEN ON BLISTERING

Kind of Bessemer Steel	Analysis			Microscopical Appearance	Sheets in 24 that Blistered	Percentages of Oxygen
	S	P	Mn			
Acid	.061	.049	.340	Very good	0	.021
Basic	.069	.034	.385	Good	0	.021
Acid	.076	.070	.350	Good	0	.022
Basic	.101	.126	.475	Fair	4	.025
Basic	.080	.066	.430	Moderate	6	.026
Acid	.106	.188	.320	Bad	7	.026
Basic	.079	.098	.440	Bad	7	.027
Basic	.045	.075	.473	Bad	8	.034
Acid	.061	.081	.350	Bad	9	.032
Basic	.080	.068	.450	Bad	12	.030
Basic	.071	.090	.480	Very bad	19	.046

influence the quality of the steel. Thus, we speak of 0.05% of sulphur, when in reality it is 0.13% of manganese sulphide that affects the quality of the steel. Oxygen has only half the atomic weight of sulphur, and is capable of forming larger quantities of compounds, therefore it exerts a greater influence. Thus, where 0.05% of sulphur corresponds to 0.13% of manganese sulphide, 0.05% of oxygen corresponds to 0.22% of ferrous oxide.

Another fact brought out in these tests is that the amount of oxide visible under the microscope was much less than would be expected from the amount actually found by chemical analysis, and this might be accounted for on the theory that a considerable quantity of oxide was in solution in the steel surrounding the black oxide spots. The oxide showing on the surface of a polished piece was also reduced by the aid of hydrogen and an electric current, and the pits thus formed occupied a much larger area than the spots of oxide seen by the microscope.

Steels containing oxides also apparently rust much quicker than those free from them, and with two pieces placed side by side the oxide steel will show rusting long before the other, while in dilute acid solutions steels containing oxides corrode more easily and much faster than those free from oxides. The same is true regarding the other impurities in steel and this has led to the production of a metal called "Ingot iron," in which the total impurities, except carbon, have been reduced to from 0.05 to 0.08% and the carbon content to 0.02%. A typical analysis showed carbon 0.02%; manganese, 0.01%; sulphur, 0.02%; oxygen, 0.03%, and phosphorus and silicon a trace.

In the making of this metal the theory that ferro-manganese was needed to produce a workable metal in the hot condition was doubted, and the usual ferro-manganese decarburizer was omitted. Open-hearth furnaces are worked entirely on cold pig iron low in silicon and sulphur, and with the phosphorus limited to the content for Bessemer working. An active basic slag is maintained that is composed of limestone and fluorspur, with a comparatively large amount of the latter flux to prevent the phosphorus from returning to the metal at the high temperature of 3000° to 3100° F., that is maintained toward the end of the process. A fairly large proportion of scrap is charged in the form of open-hearth mill scrap and low-carbon steel turnings, the larger part being of the latter. When sufficient mill scale can be obtained it is substituted for ore in the charge.

The removal of oxygen, probably in the metal in the form of oxides, is most important, and instead of manganese, ferro-silicon, or an equivalent material, is added to the bath to remove the oxides, while the other gases are removed by adding below 0.10% of granular aluminum in the ladle. The time consumed for each charge is about 10 hours, and the boiling is carried to a high temperature to thoroughly oxidize the impurities. This brings the temperature very high in the final stages, owing to the higher melting point of the purer materials. If there is too much oxygen in the steel it is liable to cause it to crack on the edges when rolling, owing to its creating a red-shortness.

COPPER

Copper is a widely distributed element of the earth's crust, and occurs in large quantities; sometimes in the uncombined condition, such as the native copper of the Lake Superior regions. It is very malleable and tenacious. In most of the copper ores used, sulphur and iron occurs, and in some of the iron ores used for making steel, copper occurs. A few contain as high as 1% of copper, and some of the Bessemer and open-hearth steels contain from 0.30 to 0.50% of this metal. That copper alloys perfectly with all steels and does not segregate until above 4% has been added is a well-established fact.

Copper can be alloyed in all proportions, with iron containing 0.15% of carbon, and with 0.09% of sulphur added to this no segregation will occur until 7.70% of copper has been added. With the sulphur low and the carbon at 0.20% no pronounced segregation appears until a copper content of 40% is reached, while with 0.40% of carbon it occurs with a copper content of about 30%; with carbon 0.60%, at 20% copper; with carbon 0.80%, at 12% copper; and with the carbon at 1%, copper segregation is liable to occur when the copper is 8%. This, however, is only a general rule, and it may be varied greatly by the various other ingredients and methods of making the steel. As the best results seem to be obtained when copper is kept below 5%, segregation will not be much of a factor in copper steel.

Hard and soft steels with a percentage of copper as one of the ingredients have been used for many purposes with the usual number of failures, but these failures have always been traced to other ingredients and none to the copper contents. Crank-shafts for the United States' battleships and gun tubes for 6-inch guns, have been made out of steel containing 0.57% copper, and they stood successfully all of the tests required by the Government.

Commercially steels containing over 4% of copper cannot be rolled and forged unless the percentage of carbon is very low, owing to its hardening effect and the consequent brittleness it gives to the metal. With percentages up to 4, the copper all goes into solution in the iron, but above that, saturation begins to occur. The point at which saturation begins appears to be between 4 and 8%; it being lowered as the carbon content is increased. When the copper content is increased to above 8% free copper occurs; in a fibrous form in the soft or semi-soft steels, and in nodules in the higher carbon steel.

When there is enough sulphur in the steel, it will form with the copper a copper sulphide, according to the formula (Cu_2S), but if there is an excess of copper it will combine with the iron. Steels containing copper and copper sulphide have an irregular structure, as regards the size and joining together of the ferrite crystals, as these imbricate with one another with curved junctions. This gives the metal a higher strength than that of steel without copper.

Copper and copper-sulphide principally distribute themselves between the crystals of ferrite, which they envelop. They also cause the quantity of pearlite to increase and the grains of this to assume a finer structure and permeate the metal more and more with each increase in copper. In fact, the structure so closely approaches the martensitic form that it has been mistaken for this in some instances, and in a 7% copper steel threads of cementite and of pearlite appeared. In this way they intensify the iron carbide and give to the metal a greater hardness as well as enable it to be hardened more easily when heating and quenching. Copper also lowers the recalescent point from 100 to 150° F. below that of ordinary steels, but it never brings this below 800° F. In this it about equals high-carbon steel. The 1 to 5% copper steels that are liable to become commercially successful should be quenched in water from about 1325° F. or in oil.

It is possible to find traces of copper sulphide in metal that contains only 7% of iron and 0.025% of sulphur. As a small amount of iron in solution in copper makes copper harder, this might suggest the idea of strengthening copper or copper alloys with iron.

Copper increases the hardness of steel, as the copper content increases.

When the carbon content is low it has a greater effect than when it is high; in some cases almost doubling the Brinnell hardness, and it reached its maximum increase in one series of tests at from 10 to 15% copper. It does not give any color to steel until 8% has been passed.

With the carbon content high, copper steel is difficult to work mechanically, but it can be easily cast into the shapes desired. If, however, the carbon is kept below 0.50%, steels containing as high as 4% of copper can be easily and successfully rolled and forged, and the heat treatment made a less delicate operation. Such steels seem to have a future as they have a greater tensile strength and elastic limit than the same steel without copper; a better elongation and contraction; more resiliency; a greater resistance to shock and torsional strains; a greater hardness without loss of ductility and a finer grain. The copper steels closely resemble nickel or chromium steel, and follow the same laws as to their increases of strength for each increase of percentage, but they are said to possess a higher elastic limit and maximum strength than nickel steel, as well as greater dynamic strengths. Copper has a more active influence on steel than nickel or manganese, and nearly approximating chromium, molybdenum, and vanadium, and it is a cheaper alloying material than these.

Copper steels as rolled show greater tensile strength with each increase of copper, and this is more manifest with the lower carbon percentages, but it is not dependable in this state. Annealing corrects this to a large extent, but does not leave the metal much if any stronger than the ordinary steel. Hardening and tempering after this, however, more than doubles the tensile strength and elastic limit, and brings the latter up close to the former with a good percentage of contraction. This would seem to indicate that if copper steels were well made they would be able to withstand shock, torsional, alternating, or vibrational strains, as well as the high-grade steels of the present day, and, owing to the comparative cheapness of copper, they could be produced cheaper.

Some corrosion tests were carried on that showed that corrosion was lower by something like 100% in copper steel than in steels that contained no copper. The electrical resistance is also increased in steels containing copper, and reaches its maximum in a 0.15% carbon steel at 2% of copper; in a 0.7% carbon steel at 0.5% copper, and in a 1.7% carbon steel at 0.35% copper.

ARSENIC AND THE ANALOGOUS ELEMENTS ANTIMONY AND BISMUTH

Phosphorus, arsenic, antimony, and bismuth all belong to the same chemical group, and in general form compounds of the same character and of similar composition. Like nitrogen they unite with metals to form binary compounds, called phosphides, arsenides, and antimonides. They all form two oxides, which contain 2 atoms of the above-named elements to 3 atoms and 5 atoms of oxygen. Of these elements phosphorus occurs most abundantly in nature; arsenic and antimony next, and bismuth last. The last three occur sometimes in the uncombined state, but phosphorus always occurs in combination with other elements.

Many steels contain an appreciable percentage of arsenic, as it combines with iron in forms that are similar to the sulphide which it frequently accompanies. The arsenides, which are its compounds with metals, occur very widely distributed, and often accompany the sulphides to which they are similar. The most common compound of this kind has the composition FeAsS, and may, therefore, be regarded as iron pyrites (FeS_2), in which one atom of arsenic has been substituted for one atom of sulphur. Simple compounds of pyrite and arsenic occur that are analogous to the sulphide FeS_2, and combinations of sulphur and arsenic form into sulphides.

When steel contains an appreciable percentage of arsenic it will give off an odor similar to garlic when heated to a red heat, and this odor may become very intense at a welding or forging heat. As an element it is not poisonous, but when oxidized it may become extremely so and it is easily oxidized.

If the arsenic in commercial steel does not exceed 0.20% it does not have any material effect upon the mechanical properties, as the elongation and reduction of area are not changed and the tenacity is but slightly increased. This leaves the bending properties unchanged at ordinary temperature. Above 0.20% the strength of steel is increased and the toughness decreased with each increase in the percentage of arsenic until 4% is reached, when the elongation and reduction of area become nil and the steel becomes very brittle. Even with 4%, however, it does not affect the hot working of the metal, and it can be alloyed with iron in proportions as high as 56% under certain conditions of mixing. These conditions, however, are difficult to fulfil.

By ordinary methods attempts have been made to produce alloys in various proportions up to 10% of arsenic, but when analyzed the sample showed that the maximum of arsenic taken up and retained by the iron was about 4%, this appearing to be about the largest amount that could be commercially added to steel. While steels with the higher percentage of arsenic are brittle, no special difficulty is met with in machining them with any percentage of arsenic.

Owing to the fact that arsenic, when present in acid pickling solutions, causes a marked reduction in the rate of attack by the acid, it was thought that if the arsenic was added to the iron it might resist the attacks of corrosion and become more durable. Numerous tests that were made, however, show no appreciable difference in the non-corrosive qualities of iron and steel that contained arsenic and those of the ordinary brand.

Any benefits derived from alloys of arsenic with iron or steel will probably be in connection with their magnetic properties, as some very interesting results have been obtained along this line. It alloys with iron practically in proportions of the solid mixtures, up to an arsenic content of 4%. With each increase of arsenic in steel up to 5%, the magnetic qualities of iron are made better and the arsenic alloys are on an equality with the best electrolytic material known in respect to magnetic permeability. When the metal is heated to 1250° F. and slowly cooled, so as to allow the grain to become normal and the forging or rolling strains to be removed, the metal shows a decided improvement. A second heating to 1800° F., with slow cooling, improves the quality in the lower ranges of the magnetic forces, but there is a falling off in the upper ranges of the curve. Quenching from 1650° F. shows no hardening and but slight changes in the magnetization curves. Arsenic added to iron imparts to the alloy magnetic qualities excelling those of the purest iron, and at least equaling those of the best material from which data is obtainable.

Antimony may be added to iron in quite large percentages, but above a content of 1% the metal is not forgeable, and only then with difficulty. It renders the metal brittle so that it is practically worthless, and it is of a lower grade magnetically than the ordinary electrolytic iron. Thus while antimony is in the same chemical group as arsenic, it makes iron products that are difficult to work and have no apparent value as a magnetic material. Antimony is useful in the non-ferrous alloys for the hardening effect it gives, and that it expands when solidifying makes it valuable for such uses as type casting. These same properties make it detrimental to iron and steel products, and luckily it does not appear in the crude materials used for making these.

Bismuth, like antimony, does not occur in combination with iron or in the products used for producing the iron ore when refining it into steel, conseqently it does not have to be removed as an impurity. To a greater degree than antimony it has the property of expansion when passing from the liquid to the solid state, and therefore it is useful in non-ferrous alloys.

When 2% of bismuth, the most diamagnetic element known, was added to iron, it improved the already high magnetic quality of the pure iron. The density values reached exceed those obtained from any of several hundred other different alloys that have been tested. How much bismuth remained in the metal after adding the 2%, however, was not known. With bismuth alloys there is but little increase in electrical resistance. Arsenic and antimony, however, give a decided increase in resistance to iron, and in some cases this was from 62 to 67%.

BORON

In nature boron chiefly occurs in the form of boric acid, or as salts of this acid, such as borax, a sodium salt, or two calcium salts. It belongs to the same chemical family as aluminum, and is very similar to it in the composition of its compounds, but its oxide is acidic, while the oxide of aluminum is usually basic. In some respects it resembles the members of the family to which nitrogen and phosphorus belong. It has a strong affinity for nitrogen, especially at the higher temperatures, and also combines readily with sulphur and chlorine. Some boron crystals contain carbon and aluminum, which seem to be in combination with the boron.

Ferro-boron can be prepared from borate of lime, in the electric furnace, without any special difficulty, and the above data would suggest that boron might have some qualities that would be beneficial to steel, but very little in the way of investigation has so far been done. What little has been done would indicate that boron acts like carbon in many respects, especially in adding hardness to the metal.

In some recent tests which were made on steel containing 0.20% of carbon and 0.20, 0.50, 0.80, 1, and 2% of boron, the Brinell hardness of the samples tested and quenched at 1460° F. was three times that of the annealed pieces, and equal to that of high-carbon steel similarly treated. Notwithstanding this the hardened samples could be easily filed, sawed, or machined, while 0.87% carbon steel, similarly treated, could not be scratched except with an emery wheel.

This is adding evidence to the statement that has been made several times, but disputed by some, namely: that hardness is not the same thing as the ease or difficulty with which steel can be machined with cutting tools. The tests also show that boron confers upon steel the property of tempering; but a tempering that is very different from that conferred upon the metal by carbon, in that it increases the tensile strength and elastic limit, without materially increasing the toughness or hardness to machine. On the other hand, the ability to withstand shock tests was doubled by quenching, and the elastic limit was brought up close to the tensile strength.

In heating boron steels they show a definite emission of heat at 2100° F., which resembles the recalescent point in high-carbon steel. Slightly marked critical points appear at 1900°, 1525°, 1350°, and 1225° F. The three latter are about the temperature of the points Ar3, Ar2, and Ar1 of mild steel. The point at 1240° F. is definitely shown in carbon steel, but when boron is added and the steel heated, this point almost entirely disappears, and is replaced by the point at 2100° F.

Boron may be said to give steel a hardness that increases its strength, up to a content of 2% of boron, providing the carbon is kept below 0.2%, but beyond a content of 2% boron or 0.2% carbon, the metal becomes so brittle that it is weakened and easily powdered under a hammer. Other elements might be found, with further investigations, that would overcome this brittleness and make boron more useful for special alloys of steel.

Microscopical examinations show intense black spots in boron steels that are polished and etched, first with picric acid and then with picrate of sodium. These increase in quantity with each increase in the percentage of boron. These spots may be a combination of boron-iron; a solid solution of boron-iron containing a very low percentage of boron; a borocarbide of iron, or a boride of carbon. In specimens thus treated the ferrite appears white, the pearlite grayish, and the special constituent very black.

On annealing, the volume of pearlite increases and the special constituent disappears by forming a eutectic with the ferrite that at times is strongly marked. By annealing in the presence of oxide of iron, so as to decarburize the metal, the pearlite is first caused to disappear and then the special constituent.

In carbonizing the special constituent is not increased by case-hardening, although at the edges a layer of pearlite is found and this is thinner if the metal does not contain boron. This would indicate that the penetration of carbon is delayed by boron, and that the amount of the special constituent depends upon the percentage of boron, and is independent of the carbon content.

In the quenched steels, the special constituent was hardly discernible when the percentage of boron was below 0.50, but large quantities appeared in the steels with the higher percentages of boron. This was not altered even when the quenching was carried to 2200° F. The percentage of carbon increases the solubility of the special constituent, and the higher the percentage of boron the less easily does it dissolve.

The above data probably indicates that the black spots were a borocarbide of iron, and its percentage of carbon very low; otherwise a phenomena would occur similar to that brought out in the investigations of the vanadium steels, *i.e.*, as the boron increased the pearlite would diminish; but in these steels the special constituent continues to increase.

Boron steels are very weak and brittle in the normal state, and, if heated to a very high temperature, crumble when forged or rolled. But if heated to a dull red they can easily be forged, rolled, or otherwise mechanically worked, as they act much like soft steel. This will make them useless in the raw state, but after quenching they possess a high tensile strength, a very high elastic limit, and are not any more brittle than the special steels that are in actual use at present.

Borax is a sodium salt from which amorphous boron, in almost pure form, can be obtained by heating with magnesium powder. It has been used by many misinformed people as part of a mixture for carbonizing steel, or in a special compound for hardening it, but they have never given any good reason for its use or shown any results that were obtained thereby. It, like boron, retards the penetration of carbon, but when used in a quenching bath may aid in producing a greater hardness, or preventing the metal from cracking or checking. Common table salt (NaCl), however, gives much better results, and is easier obtained and cheaper. Therefore borax is not useful here; its chief value is as a flux in welding.

TANTALUM

Tantalum is one of the rare elements. It is never found free in nature, but occurs in combination in the minerals columbite and tantalite, accompanied by niobium. In chemistry it is grouped with vanadium, niobium, and didymium, all of which are rare. Its rareness, and consequent cost, has prohibited it from being experimented with to any extent, but one series of tests that was conducted appeared to prove that it had a hardening effect upon steel, similar to that exerted by tungsten and molybdenum, and to a certain extent gave promise of being beneficial for high-speed steel tools.

In all of the eight tests made, the tantalum which varied from 0.42 to 1.69% increased the tensile strength, elastic limit, elongation, and reduction of area over that of the same steel without tantalum, but when nickel or chromium was added in place of the tantalum, the same strengths were obtained and in one case 1.10% of chromium gave about 10% greater strength than 0.43% of tantalum. The greatest increases in strength were obtained with the smallest percentages of tantalum.

Under the microscope a dark constituent appeared that was greater in quantity as the percentage of tantalum increased, and this occurred in a finely granular matrix that in the hardened specimens seemed to be martensitic and more or less homogeneous.

From the results obtained and its similarity to vanadium the suggestion occurs that it acts on steel as a scavenger similar to this, and the best results would be obtained in the quaternary steels, but no evidence has been submitted to prove that it is any better, or even as good as the alloying materials already in use, and which are much cheaper. It is also very difficult to separate it from niobium, with which it is always combined, and this element is liable to cause erratic results in steel.

PLATINUM

Platinum occurs in nature associated with five other elements, more rare than itself. They are divided into two chemical sub-groups commonly called the platinum metals. These nearly always occur in an alloy in which the platinum is from 50 to 80%, while the other five compose the balance.

It forms two oxides and two sulphides. It is very ductile and is a grayish-white metal that looks like steel. It can be welded at a white heat. An alloy of platinum and silicon can be formed by bringing it in contact with red-hot charcoal and silicon dioxide. Nitric, hydrochloric, or sulphuric acid will not dissolve it. Platinum, when finely divided, has an extraordinary power of condensing gases upon its surface; for instance, it absorbs 200 times its own volume of oxygen, also other gases similarly. The oxygen is then in the active condition, and oxidizable materials are easily oxidized when brought into contact with it. Thus when sulphur dioxide and oxygen flow together over spongy platinum, or even the compact metal, they form sulphur trioxide by a unity of the two gases, or when hydrogen flows against the spongy platinum it takes fire.

Iridium belongs to the same chemical group and, when this is alloyed with platinum in the proportions of 1 to 9 respectively, it reduces the malleability of platinum, which can be easily drawn into very fine wire; makes the alloy harder; more difficult to fuse; as elastic as steel; unchangeable in the air, and capable of taking a high polish.

While platinum is but little cheaper than gold, the above properties have led to its being investigated as an alloying material for iron, but as yet the experiments have been very few, and limited in their scope. Platinum has no transformation points, and it consequently reduces those of iron when mixed with it. Up to 10% of platinum, two transformation or recalescent points occur, while with the platinum from 10 to 40% but one point is produced. The melting-point diagram shows considerable analogy to that of the nickel-iron alloys, but this is stronger when the alloys are rich in iron than when they are rich in nickel or platinum.

The hardness of the platinum alloys decreases from 0 to 5% of platinum, and then gradually increases from there to a platinum content of 40%, after which it remains fairly constant until 90% of platinum is reached, after which it declines again. At 50% of platinum the greatest brittleness occurs.

From 0 to 90% of platinum all the alloys are magnetic, and this diminishes in the same ratio as the iron in percentages of from 80 to 20 of that metal. Alloys with the platinum from 10 to 50% lose their magnetic power when heated to from 1475° to 1200° F., and it returns at a much lower temperature when cooling. Alloys with the platinum from 60 to 90% regain their magnetic power at a temperature even lower than this.

NICKEL

The chemical sub-group in which nickel belongs is composed of iron, cobalt, and nickel, and in many respects they are very similar. It occurs native in meteorites, and the iron meteorites always contain nickel. The principal minerals that contain it are nickeliferous pyrites and garnierite. Large deposits of minerals containing both nickel and copper have been found. The metals are reduced together and put on the market under the name of monel metal.

Nickel, however, is separated in the pure form for many uses, and one of the most important of these is as an alloying material in the manufacture of special steels. It is a white metal with a slight yellow cast, and is very hard and capable of being highly polished. It is very brittle in its ordinary condition, but when deoxidized by magnesium becomes very malleable.

Nickel reduces the size of the crystalline structure and increases the toughness of steel. It brings the elastic limit closer to the tensile strength, and microscopic cracks, that are liable to develop into larger cracks and produce rupture, do not appear as quickly in steels containing nickel as those without it. In certain proportions it also makes steel more resilient or springy, increases the hardness, raises the tensile strength, and segregates only slightly.

Nickel was first added to steel for the purpose of overcoming the property of "sudden rupture," which is inherent in all carbon steels. This it does to a large extent, making steel better able to withstand severe shock and torsional stresses, as well as compressive stresses. This is not due to hardening, as soft steel cannot be made hard by the addition of nickel, except in large quantities, and it is considered that 17.55% of nickel is the equivalent of only 1% of carbon.

The properties of nickel steel depend as much upon the carbon content as on the nickel. The fact that a 2 or 3.5% nickel steel is used means nothing unless the carbon content is right for the use to which the steel is to be put. To illustrate, a steel containing 2% nickel and 0.12% carbon has a good tensile strength with a great elongation, and is useful for some purposes, while a steel that is equally useful for another purpose may contain 2% nickel and 0.9% carbon, and this would give it a high tensile strength with very little elongation. With a high carbon content nickel steel is difficult to harden, especially locally, as fissures and cracks tend to develop in quenching. It also has more tendency to warp in quenching than other steels and may be decarbonized by heating. These tendencies may be overcome to a great extent if the metal is thoroughly annealed before it is machined to size, in order to relieve all of the internal strains. Then, when quenched, the piece should be immersed in the bath so that the liquid can cover the greatest possible surface at the instant it strikes the bath, and it should be agitated while cooling.

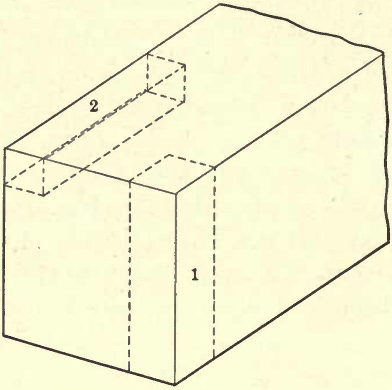


FIG. 47. — Cutting test bars.

Nickel also gives steel a tendency to show laminations, and makes it weaker at right angles to, than in line with, the direction in which it is rolled. The higher the nickel content the greater will be the contrast between the strength in these two directions. This is best shown by tests which were made on test bars 1 and 2, cut from a piece of 3.5% nickel steel as indicated in Fig. 47. Test bar 1 showed an elongation of 12% and a reduction of area of 17%. Test bar 2 gave an elongation of 25% and a reduction of area of 65%. The good qualities which nickel

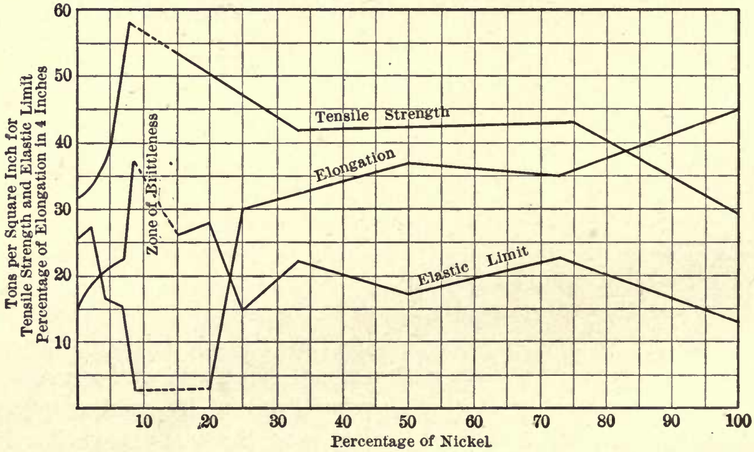


FIG. 48. — Effect of nickel in different percentages.

gives to steel offset these bad qualities to such an extent that it makes a much better steel for gears, crank-shafts and pieces which have similar work to perform than the ordinary carbon steel.

Nickel greatly reduces the tendency of steel to be damaged by overheating, and also increases the effect of hardening in raising the strength of the metal. One series of tests which were made showed a tensile strength of 88,000 pounds per square inch, an elastic limit of 60,000 pounds per square inch, an elongation of 28% and a reduction of area of 58% when in the annealed state. These figures were changed by hardening to a tensile strength of 225,000 pounds, an elastic limit of 224,500 pounds, an elongation of 8%, and a reduction of area of 19%. A good quality of carbon steel might give the same results in the annealed state, but they could not be increased to nearly the same extent by means of the ordinary hardening.

Nickel has one peculiarity in its influence on steel which is best shown by Fig. 48. It increases tensile strength and elastic limit, but steels containing 8 to 15% of nickel are so brittle that they can be powdered under a hand-hammer; at 15% of nickel the toughness begins to be restored; from 20 to 25% the elongation rapidly increases, and from there on to 50% a gradual increase is shown.

Steel with percentages of nickel from 30 to 35 gives good results for valves on internal-combustion engines, as the nickel makes the steel wear better and it is not as good a conductor of heat as other metals. Nickel steel can be purchased in the open market in nearly all percentages of nickel from 1 up to 35%, and with varying percentages of carbon.

In Fig. 49 is shown the actual results that were obtained from a series of twenty tests, in which the nickel varied from 0 to 20%, and the other ingredients remained fairly constant. Ten of the tests were with forged steel and ten with cast steel. They give a good idea of the strengths that can be expected in nickel steels, although, as has been said many times, nickel steel in the annealed or natural state is but little better than carbon steel, but if properly heat-treated it will greatly exceed carbon steel for static and dynamic strengths, wearing qualities, etc.

COBALT

The principal minerals containing cobalt are smaltite and cobaltite, and in each of these iron and nickel take the place of a part of the cobalt. It, like nickel, forms compounds that are analogous to ferrous compounds, and also a few that are analogous to ferric compounds. In the latter case, its power is greater than that of nickel. Cobalt is harder than iron, melts at a slightly lower temperature, and has a silver-white color with a tinge of red.

In the matter of cobalt-iron alloys, investigations up to a cobalt percentage of 60 have been made. The mechanical properties were but little modified in these, but the breaking strength and the elastic limit increase slowly, while the elongation and the reduction in cross-section are inversely modified. Notwithstanding its similarity to nickel the cobalt steels so far examined have no industrial interest and do not present any of the qualities of the nickel steels.

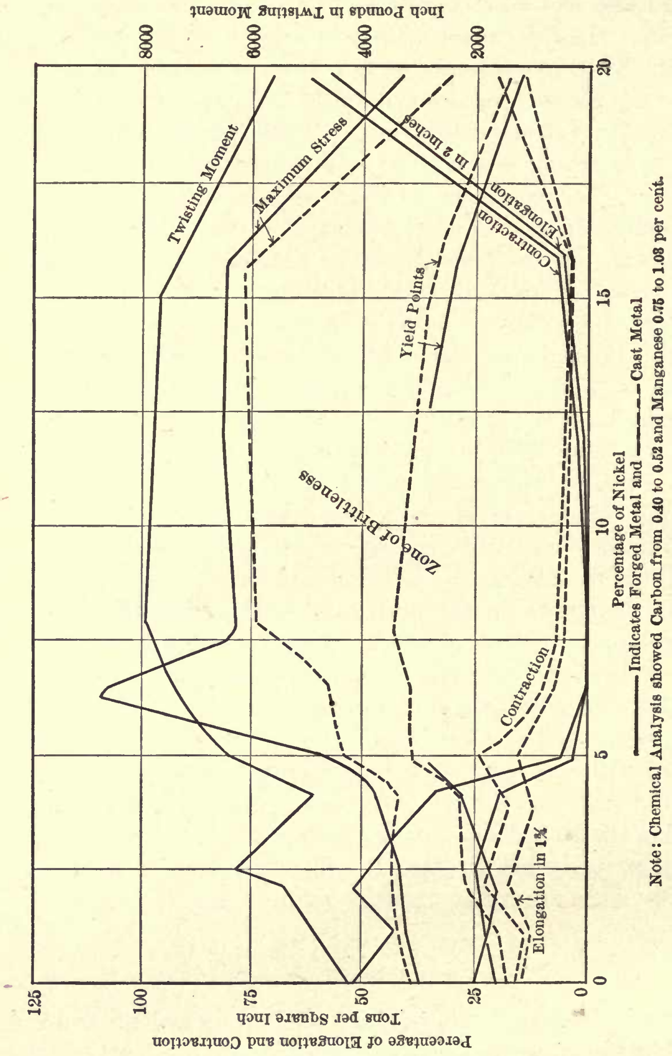


FIG. 49. — Strengths of nickel steel annealed at 1475° F.

In general, cobalt in steels enters into solution in the iron, and the carbon exists therein — at least in the range of the experiments made

— in the shape of iron carbide. The mechanical properties of these steels do not seem to promise any industrial application; but they show very clearly the marked difference between tin, titanium, and silicon steels on the one hand, and nickel and cobalt steels on the other.

CHROMIUM

Chromium, tungsten, molybdenum, and uranium are in the same chemical group, and all show some resemblance to the elements in the sulphur group. Each forms a trioxide which is acid in character, and lower oxides which have little or no acid character.

Chromium forms three series of compounds. It occurs in nature principally in the mineral chromite, which is commonly called chrome iron ore, or chromic iron, with the composition $FeCr_2O_4$. It is a very hard metal and can be highly polished; has a bright metallic luster, and is difficult to fuse, its melting point being nearly that of pure iron. It burns brilliantly in oxygen, though it is not changed by exposure to the air at ordinary temperatures. In steel making it is used as a ferro-chromium, containing 60% chromium and 40% iron, which is made in an electric furnace from chrome iron ore.

Chromium gives to steel a mineral hardness, and refines the grain remarkably, owing to its tendency to prevent the development of the crystalline structure; but it gives no self-hardening properties, although it is the element used in combination with tungsten to produce the quality of "red-hardness" in high-speed steels.

Chromium added to steel in percentages up to 5 increases the tensile strength and elastic limit of hardened steel. In the annealed state the tensile strength is raised until 6.5% is reached and the elastic limit is raised up to 3%, and this does not lower to any great extent until 9% is reached. After these percentages are passed a decided reduction takes place. This is best shown in Fig. 50.

Extreme hardness may be obtained in chromium steels as the chromium intensifies the sensitiveness of the metal to quenching, and greatly reduces the liability of fracture that is found in carbon steels. This is due to the chromium making the critical changes of steel take place much more slowly. Chromium steel practically shows no grain or fiber and possesses a high power of resistance to shocks. This has made it almost universally used for armor plate.

With 2% of chromium, steel is very difficult to cut cold, and is quite brittle; with higher percentages than this it is impossible to finish it with machine tools except by grinding. When chromium is combined with nickel or vanadium, it makes the strongest, toughest, and best wearing steel on the market, and it can be machined and forged much more easily than when chromium alone is used. Small gears can be made with these alloying materials added to steel, that if properly heat-treated will be so tough and strong as to make it almost impossible to break out a tooth, even with a sledge hammer.

Some of the best grades of chrome-nickel or chrome-vanadium steel contain from 0.75 to 1.50% of chromium. If more than this is used the metal is too brittle and it is difficult to preserve the high strengths which are given by the lower percentages. The carbon content is also kept comparatively low, as a percentage of 0.45 of carbon makes the metal about as hard as can be cut with machine tools, even when thoroughly annealed. Many of these steels contain only 0.25% of carbon as the chromium gives the metal a hardness similar to that given by carbon, but one which makes the cohesion of the molecules greater. This makes the metal much more homogeneous, and gives it the ability to resist shock and torsional stresses. Thus, this alloy is one of the best steels for crankshafts of internal-combustion engines or other parts of machinery which have to withstand similar vibrational stresses.

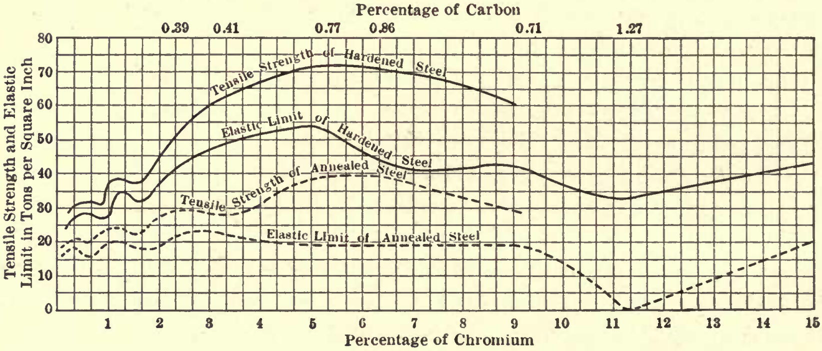


FIG. 50. — Effect of chromium on tensile strength and elastic limit.

The nickel-chrome steels are difficult to forge, as it is dangerous to hammer them after the temperature has dropped below that which makes the metal a bright yellow. It must be heated many times to forge pieces of any size or of intricate shapes. The chrome-vanadium steels, however, are no more difficult to forge or machine than the 0.40% carbon steels. Chrome steels for armor plate are made with the chromium content about 2%, while as high as 6% is used in some of the high-speed steels when the tungsten or molybdenum content is high.

TUNGSTEN

Tungsten forms a large variety of compounds, two of which are with oxygen, namely: the dioxide (WO_2) and the trioxide (WO_3). The trioxide forms salts with bases analogous to the molybdates. It occurs in nature as tungstates, the principal one of which is wolframite ($FeWO_4$), an iron salt that always contains some manganese. It is very hard, difficult to fuse, and forms lustrous steel-colored laminæ or a black powder.

The tungsten metal has recently been used quite extensively for incandescent lamp filaments but was extremely brittle and hence hard to work. This brittleness was considered an inherent property of the metal that could not be overcome. Recently, however (April, 1910), ductile tungsten has been produced at a cost that is not prohibitive. This promises to make a radical change, as when reduced several times in drawing it into fine wire, about .001 inch in diameter, a tensile strength of 610,000 pounds per square inch has been obtained. This is nearly double that of piano wire, the strongest metal known.

Tungsten as an ingredient of steel has been known and used for a long time, it having been used in the celebrated Damascus steel, but its actual effect was not known until Robert Mushet, after much experimenting, brought out the famous "Mushet steel." This caused some radical changes in treating crucible steels, and much progress and improvement has been made since that time.

The effect of tungsten on steel is to increase hardness, but it does this chiefly through its action on the carbon. In other words, it intensifies the hardening power of the carbon. If the percentage of tungsten is high with a proportionately high manganese content the steel will be very hard even when cooled in air, and thus is made possible "air-hardening" tool steel.

As the principal use of tungsten is in high-speed tool steel, and as a high percentage of manganese makes steel that is liable to fire-crack, to be brittle, to be weak in the body, and to be less easily forged and annealed, the manganese is now kept low and chromium is used in its place. The tungsten-chromium steels when hardened retain their hardness when heated to a dull red by the friction and pressure of chips in cutting. This has led to the term "red-hardness" as applied to this class of steel, and it is this property which has increased the cutting speeds of tools.

Tungsten when added to steel does not make it any more self-hardening than the carbon tool steels if the manganese and chromium are low, but every increase up to 19% increases the red-hardness if chromium is increased proportionately. Beyond 19% of tungsten, the red-hardness is decreased no matter what the percentage of chromium may be. The increase in red-hardness is about 50%, with an increase in tungsten from 6 to 19%, and that with manganese as low as 0.15%. With the chromium in the proper percentage tungsten will make steel self-hardening in all percentages over 0.85, but if the chromium is too high proportionately the steel is liable to become injured by overheating when the lower percentages of tungsten are used, but when the higher percentages of tungsten and chromium are used, the metal can be heated to just below the melting point and then quenched without injury. In fact, with the tungsten at 18% and the chromium 6% the best results for cutting tools are obtained when hardening at this high temperature.

The carbon content of these steels is kept low as compared with ordinary tool steels, or the air-hardening steels of a few years ago. The carbon content in the high-speed steels of to-day usually varies between 0.65 and 0.80%, whereas it was used in varying percentages up to 2.4 in the older air-hardening steels. This latter percentage was used in Mushet steel.

The quality of red-hardness given steel by the tungsten-chromium ingredients increased the cutting speed of tools about 45% over that of the older air-hardening steels, when cutting hard forgings or castings. Similarly an increase of about 90% was made when cutting softer metals. This has led to their almost universal use to the exclusion of Mushet steel, which but a few years ago filled 50% of the sales of tool steel.

Tungsten either in combination with manganese or chromium has greatly lessened the skill and knowledge required in heat-treating tool steel. To get the proper degree of red-hardness in the best grades of high-speed steel, they should be heated nearly to its melting point, which is about 2500° F. If this temperature were reached it would soften the steel so that the point of the tool would run. This would not harm the cutting qualities as it would not lessen the red-hardness given the metal by the tungsten and chromium. If a greater temperature were reached it would melt the steel, so it can easily be seen when the melting temperature is reached. On the other hand, if a temperature of 2300° F. is reached, the same red-hardness will be given the steel, so that there is a range of about 200° that will give the same results in heat-treating.

The carbon tool steels, however, have to be heated to a few degrees above the recalescent point and then quenched to obtain the greatest degree of hardness. After this they must be drawn to remove the brittleness caused by the high temperature. This requires a great deal of skill to judge the correct temperatures, as a variation of 25 degrees will make quite a difference in the temper and consequently in the cutting and wearing qualities.

MOLYBDENUM

Molybdenum, like tungsten, forms a large variety of compounds, among which are four oxygen compounds that include a mon-, bi-, and tri-oxide. It occurs, principally, in nature as molybdenite, which is the sulphide, MoS_2, and as wulfenite, the lead molybdate ($PbMoO_4$;) also less frequently as the trioxide (MoO_3).

Molybdenum is often used in high-speed steels in place of tungsten, as its action is very similar. Where 2% of tungsten is used, 1% of molybdenum will give the same results, that is, one molecule of molybdenum appears to have the same effect as one molecule of tungsten, its atomic weight being double that of tungsten. The cost of molybdenum is so much higher than that of tungsten that its use is prohibitive, unless much better results can be obtained, but a few high-speed steel makers consider this to be the case and are using it to replace the tungsten or else in combination with this element.

Many experiments have been made with molybdenum in place of tungsten, and molybdenum combined with tungsten, but these showed considerable irregularity as compared with the tungsten-chromium steels. The cause of these irregularities was not determined definitely, but the molybdenum tools seemed to run at their highest cutting speeds when heat-treated at a lower temperature than the tungsten steels. This would indicate that the heat-treating would require more skill in judging the temperature, as it is very difficult to judge a definite temperature by the color of the steel after it has passed a yellow.

Molybdenum also has a tendency to make the steel more brittle, and, therefore, weaker in the body, as well as giving it a tendency to fire-crack, which is a serious defect in tool steel.

URANIUM, which also belongs to this same chemical group, has stronger basic properties than either tungsten or molybdenum, and differs from chromium in that its trioxide forms salts with acids. Uranium occurs chiefly in nature, in the mineral pitchblende, or uraninite, which consists of the oxide (U_3O_8), and this is heated in the electric furnace with charcoal to isolate the metal. It has the color of nickel.

Owing to the fact that uranium resembles nickel and has many of the characteristics of the other members of the chemical group to which it belongs, many experiments have been carried out to see if it could not be made a beneficial ingredient of steel. None of these experiments, however, have shown that it was as good as the other materials used daily in the composition of steel, and its chemical actions, as described above, would not make it appear that anything could be expected of this element that could not be obtained with cheaper materials, while some detrimental effects might be obtained.

VANADIUM

Vanadium occurs in nature in the form of vanadates or salts of vanadic acid (H_3VO_4), which is analogous to phosphoric acid. When used in steel making its direct action is of minor importance, but it acts as a powerful physic, cleansing the steel from dissolved oxides. It gives the best results in the quaternary steels, such as vanadium-chromium-manganese-carbon, vanadium-nickel-manganese-carbon, and vanadium-tungsten-chromium-carbon. It has an affinity for oxygen and oxidizes out of the steel whenever it comes in contact with this element. Therefore it has the property of elusiveness to a marked degree, and has to be handled carefully by the steelmakers in order to keep it in the finished metal.

Vanadium renders possible the natural formation of the sorbitic structure, which makes the steel better able to withstand wear and erosion by adding to its self-lubricating properties. It retards the segregation of the carbides, which renders steel susceptible of great improvements by heat-treating. Vanadium produces soundness mechanically as well as chemically, and toughens the steel by acting as a physic on the other ingredients and scavenging out the oxides and occluded gases; by so doing it increases the molecular cohesion. The percentage of oxygen in the steel, however, should be reduced to a minimum by other materials, before adding the vanadium, to take care of what cannot otherwise be removed, as it is too expensive a material to use as a deoxidizer.

Vanadium seems to lessen to a marked degree those mysterious failures of steel characterized as due to "fatigue," "sudden rupture," etc., but which is better named crystallization. This is doubtless caused by the fact that the cohesive force which binds the molecules of the metal together has become weakened by the work that the steel has been called upon to perform, and instead of combining one with the other they form into microscopic crystals. This it does by making the metal much better in its dynamic qualities, that is, resistance to repeated stresses, alternating stresses, and simple repeated or alternating impacts. Vanadium removes nitrogen, which is very detrimental to steel even in infinitesimal quantities. Its also toughens the constituent called pearlite and, when used in combination with chromium, reduces the mineral hardness given to steel by this element, so that it can be machined and forged as easily as an ordinary carbon steel.

Vanadium has made great strides in the past few years as an alloying element, and is used in steel castings, cast iron, and the bronzes and brasses, as well as in steel mill products. In one respect it is similar to carbon in that very small percentages give the desired results. It is used in percentages varying from 0.16 to 0.18 for the moving parts of machinery and springs, while for case-hardening steel, 0.12% is sufficient. In high-speed steels it has given good results in from 0.28 to 2%. If used in too large a quantity, that is, much over 0.30%, it dynamically poisons the metal, and the dynamic qualities for which vanadium steels are noted are rendered no better than, if as good as, the ordinary carbon steels. In high-speed steel, however, the cutting qualities are considered of greater importance than the dynamic strengths, and the best high-speed steels that have been placed on the market contained 1% of vanadium. These steels increased the cutting quality of tool something over 10% when working on hard steel or castings.

While the cost of vanadium-chrome steel is from 6 to 10 cents per pound, one firm, which builds gasolene engines, claims that it is no more expensive in actual practice than carbon steel, and is much cheaper than nickel steel, owing to the ease with which it is machined and forged, the lighter weight of the parts, owing to its great strength, and the greater accuracy obtainable, owing to the uniformity of the metal.

Vanadium steel is used largely for crank-shafts, connecting rods, piston rods, axles, crank-pins, gears, gun barrels, springs, locomotive side frames, or other parts of moving machinery that are submitted to vibrational, impact or torsional strains and stresses.

TITANIUM

Titanium belongs to the same chemical group as silicon, and three other elements which are quite rare. In some respects it resembles carbon. It forms a compound with oxygen, namely, TiO_2, and this titanium dioxide occurs in nature in three distinct forms. The principal one of these is the titaniferous ores that contain ferrous titanate ($FeTiO_3$).

It is very difficult to reduce in the blast furnace and thus make beneficial to the metal, but when separated in the electric furnace and made into a ferro-titanium, that contains from 12 to 15% titanium, about 6% of carbon, and 5% of all other impurities, with the balance iron, it greatly improves steel and iron, if added in the proper proportions.

Titanium burns more energetically in oxygen than any known substance. When heated in oxygen it creates an instantaneous dazzling flame like lightning. Its combination with nitrogen gas is attended with the evolution of heat; it being the only undisputed example of the combustion of an element in nitrogen. While nickel, chromium, molybdenum, and tungsten add certain good qualities to steel, none of these combine with nitrogen and thus remove it from the metal as titanium does.

Titanium has a great affinity for nitrogen and carries this off into the slag; nitrogen being, at least, as detrimental to the physical properties of steel as phosphorus, and present in larger percentages than has hitherto been supposed. It also has a strong affinity for and removes oxygen. By removing the oxygen and nitrogen it prevents the injurious effects of these elements on the steel. Titanium forms with oxygen an oxide and with nitrogen a stable nitride that shows as tiny red crystals under the microscope. Both of these substances are then carried off into the slag. The quantity of slag that is removed or lifted from the molten metal is also increased. Unless an unnecessary quantity of the alloy is used, the titanium itself passes off with the slag, and will not show on the analysis of the metal. The titanium itself is of no special benefit as a component of the finished steel, and only enough should be used to remove the impurities. Any excess above this will remain in the steel, and if proof is wanted that one is buying a titanium-treated metal, enough of the alloy could be used to show by analysis, as a small percentage left in the steel is not harmful.

One instance of the removal of nitrogen was shown in some ordinary Bessemer steel rails that were found to contain from .013 to .015% of nitrogen. When 0.50% of ferro-titanium containing 15% of titanium was added, the nitrogen was reduced to from 0.004 to 0.005%. As it also has a strong affinity for oxygen it provides a simple means of thoroughly deoxidizing steel.

Titanium, by removing the oxygen and nitrogen, prevents the formation of blow-holes in steel. It also reduces the size of the pipe, as it makes the bath more liquid by freeing it from the free oxide and slag. This makes the metal subside in the mold while cooling, and the pipe will be smaller and flatter. It also makes it roll well. In this connection the record of a day's work in rolling, as taken from a pyrometer, showed an increase of not less than 30° F. in the heat of the metal at a given point. That is, 30° above that of untreated metal at the same point, while passing through the roll. The metal almost invariably does not boil but lays dead in the ingot molds.

Due to the removal of nitrogen and oxygen from the steel, the physical properties are improved and its density increased. The tensile strength, elastic limit, reduction of area, transverse strength, hardness, elasticity, wearing qualities, resistance to shocks, and torsion, are greatly improved. Thus titanium gives practically the same results as vanadium, and the ferro-titanium can be produced for a fraction of the cost. One example of its ability to withstand torsional strains was shown with a bar 4 feet long and 1⅛ inches square. This was twisted through seven complete revolutions without the sign of a fracture. The Brinell hardness test shows titanium steel to be softer than ordinary steel rails of the same analysis and section, and this is probably due to the finely divided ferrite network.

A ferro-titanium alloy that contains from 10 to 15% of titanium gives the best results, as this goes into almost instant solution. When a higher percentage is used the titanium is always liable to segregate, as it has a much higher melting point than that of steel. Thus when a 25% alloy was tried nothing was gained by its use. When, however, an alloy is used that will allow the titanium to enter into solution in the molten metal it retards the segregation of the other ingredients and produces a very homogenous steel.

One per cent of the 10 to 15% ferro-titanium alloy is all that is necessary to add to the steel, as this amount will seize all of the oxygen and probably all of the nitrogen that has been left in the bath. In many cases this can be reduced to one-half of 1%, and after some experience in its use the one-half of 1% might be sufficient for all steels. This small amount removes the bulk of the blow-holes and segregation found in Bessemer steel, and in the case of steel rails it only increases their cost about $2 per ton. With the titanium steel rails numerous use tests have been made, and all of these prove that they wear about three times as long as the ordinary steel rails, while in some cases they have outworn six of the Bessemer rails.

In the Bessemer and open-hearth process of steel making it is always best to add the ferro-titanium in the ladle. It should be shoveled in loosely, and never preheated but used cold. The first shovelful should be put in after the bottom of the ladle is well covered with molten metal and after the ferro-manganese has been added. One shovelful at a time should then be thrown in while the ladle is filling, so as to give it the benefit of the swirling and churning motion of the molten mass. The last shovelful should be added before the ladle is three-quarters full. One reason for this is that the alloy is lighter than iron and would not sink and disseminate through the bath if it were added near the top. Another reason is that if it were near the slag it would unite with the oxygen in the slag and consequently would not benefit the metal.

The alloy should never be used in connection with aluminum, as aluminum adds brittleness and titanium removes brittleness; hence the two alloys are antagonistic, and the titanium will do its work much better alone.

In crucible steel making it is sometimes preferable to add the titanium alloy with the charge of metal that is to be melted down, and in this case it should be added well down toward the bottom of the crucible. It has, however, been successfully added after the metal is melted, and when the manganese is added. At this time the titanium alloy should be added after the manganese. In fact, at all times it should be the last material added to the bath.

After adding the alloy the ladle of metal should be held for from 5 to 15 minutes before pouring in order to allow the titanium to do its work and scavenge out the oxygen and nitrogen. There is little danger of the metal in the ladle becoming chilled by holding it, as the reaction caused by titanium tends to cause its temperature to rise rather than lower, and the metal is in better condition for pouring after standing than before. In one case a ladle of steel was held for 20 minutes after tapping and adding the titanium, and is said to have then been in better condition for pouring into ingots than is steel without titanium soon after it is tapped.

Titanium also prevents steel from heating up as quickly as steels in which it is not used. An instance of this was some titanium-treated ingot molds that did not show red in the dark when filled with molten steel, whereas, the ordinary ingot molds, standing beside them, were distinctly red hot. The metal is also comparatively slow in heating from friction, and this is one of the causes why metals treated with it are much more durable than others. Steels treated with titanium heat up more slowly than others when machining them. The cutting speed can therefore be increased, and the machine work done more quickly. This also makes it very advantageous to use in tool steels; whether of the carbon or high-speed kind.

Owing to the fact that titanium increases the heat of the molten metal to a very marked degree, it is seldom necessary to use much ferro-silicon, as silicon is largely used for this purpose. Silicon, however, is not so efficacious and is known, at times, to precipitate phosphorus with disastrous results. Thus, when titanium is used the proportion of ferro-silicon should be decreased and, if possible, eliminated entirely. If not eliminated entirely, it could be reduced from time to time until no further improvement is noticed. If defects are found in the surface of the finished steel, a slight increase in the ferro-manganese and a decided decrease in the ferro-silicon used will overcome that.

Steel castings that have been treated with titanium are more blue in color, free from blow-holes and brittleness, and heat less under cutting tools than ordinary steel castings; thus they can be machined more easily and rapidly. The transverse strength has been increased from 17 to 23% by its use.

Titanium increases the breaking strains, wearing qualities, and hardness in the chill of cast iron, and hence is very beneficial for such castings as car-wheels, but it decreases the chilling effect.

Titanium also promises some good results when used in copper, brass, or bronze, in which case a cupro-titanium instead of a ferro-titanium is used. This has been used in about the same proportions as the ferro, but the best results have been obtained in copper with from 1½ to 2% of the cupro-titanium.

ALUMINUM

Aluminum is the third element in the earth's crust in importance, and comprises 7.81% of it. It occurs widely distributed and in many forms of combination; one of the most common of which is clay, where it exists in various conditions of purity. It is only within recent years, however, that it could be separated from its impurities cheaply enough to make it a commercial metal.

Since aluminum has come into prominence in metallurgy it has found many uses, and one of these is in the making of steel. This element, however, is only used as a purifier, as it adds nothing to the strength of steel except in so far as it removes some of the impurities.

Aluminum suppresses the evolution of gas either by increasing the metal's solvent power for that gas or by removing the oxygen, and thus preventing the later formation of carbonic oxide, or by both means jointly. This makes the metal more dense by removing the microscopic bubbles formed, and greatly decreases the tendency to segregation, as the aluminum has a quieting effect on the molten metal.

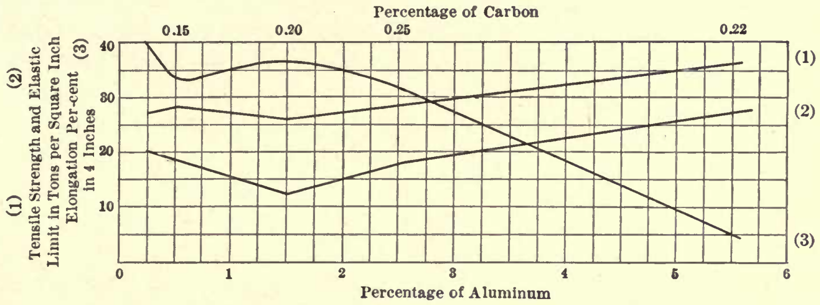


FIG. 51. — Effect of aluminum on steel.

Only enough aluminum is used to cause this effect, and thereafter work out of the metal. If the solid alumina produced remains suspended in the metal it causes a lack of continuity of the metallic structure, and thus a loss of strength.

Fig. 51 shows the effect of aluminum on the tensile strength, elastic limit, and elongation of steel with various percentages of carbon.

OTHER ALLOYING ELEMENTS

Some tin steels have been made. These cannot be rolled. If there be more than 1% of tin present they are extremely hard and brittle. Annealing has the same effect upon these as upon the ordinary steels and there is in no case precipitation of the carbon in the state of graphite.

Yttrium has been mentioned as an alloying element for steel, but it is only found in combination with a few rare minerals, and consequently is only seen in the laboratory. It belongs to the same chemical group as aluminum, and if it were found to be beneficial to steel it could not be obtained in sufficient quantities for commercial use.

Cerium and lanthanum have been combined with iron in the electric furnace to make an alloy that will give off luminous sparks. The maximum sparking effect seems to be obtained with about 50% of iron, and this will light illuminating gas. The sparks are obtained by striking the alloy with steel similar to the way flint was used before the days of matches. Some such combination might be used for generating the spark in internal-combustion engines. One such alloy was sold to the match trust and killed, as they feared competition from its use.

CHAPTER VII

WORKING STEEL INTO SHAPE

Rolling

AFTER the iron ore has been reduced to pig metal, and this refined and combined with the other ingredients that go into the making of the different grades of steel, and then cast into ingots, the ingots are sent through slabbing rolls, as shown in Figs. 52 and 53. The slabs thus formed are then rolled into the numerous shapes that are used for manufacturing purposes.

The slabbing mill, with a single pair of rolls and stationary table, which is used by many steel makers, is shown in Fig. 52. In Fig. 16 is shown the mechanically operated grip that has just brought an ingot from the soaking pit, and dropped it onto the carrier that conveys it to the rolls, and Fig. 17 shows the same ingot just as it has made its first pass through the slabbing mill. After this the mill is reversed and the ingot passes back through another section of the rolls to further reduce it. After some four or five passes back and forth through the rolls, during which time it is turned over so as to roll all four sides, it is sent to other rolls that reduce it to commercial shapes.

In Fig. 53 is shown the three high mill with tilting table. This has a double set of rolls, and for the first pass of the ingot the end of the table next to the rolls is lowered to receive it as it comes through. The rollers of the table are then reversed, and while reversing the end of the table is elevated, as shown in the illustration, and the ingot sent back through the upper rolls. The rolls, as well as the tilting table, are controlled from the platform of the pulpit, shown to the right of the picture. In this design a much narrower mill can be used for the same number of passes than in the design of mill shown in Fig. 52.

After slabbing the metal, various kinds of rolling mills are used to get the steel into the shapes desired. Many times the different mills are combined so as to make the rolling operations continuous from the steel furnace to the finished product. In some cases the desired shape is finished before the metal has had time to cool off after leaving the fur-

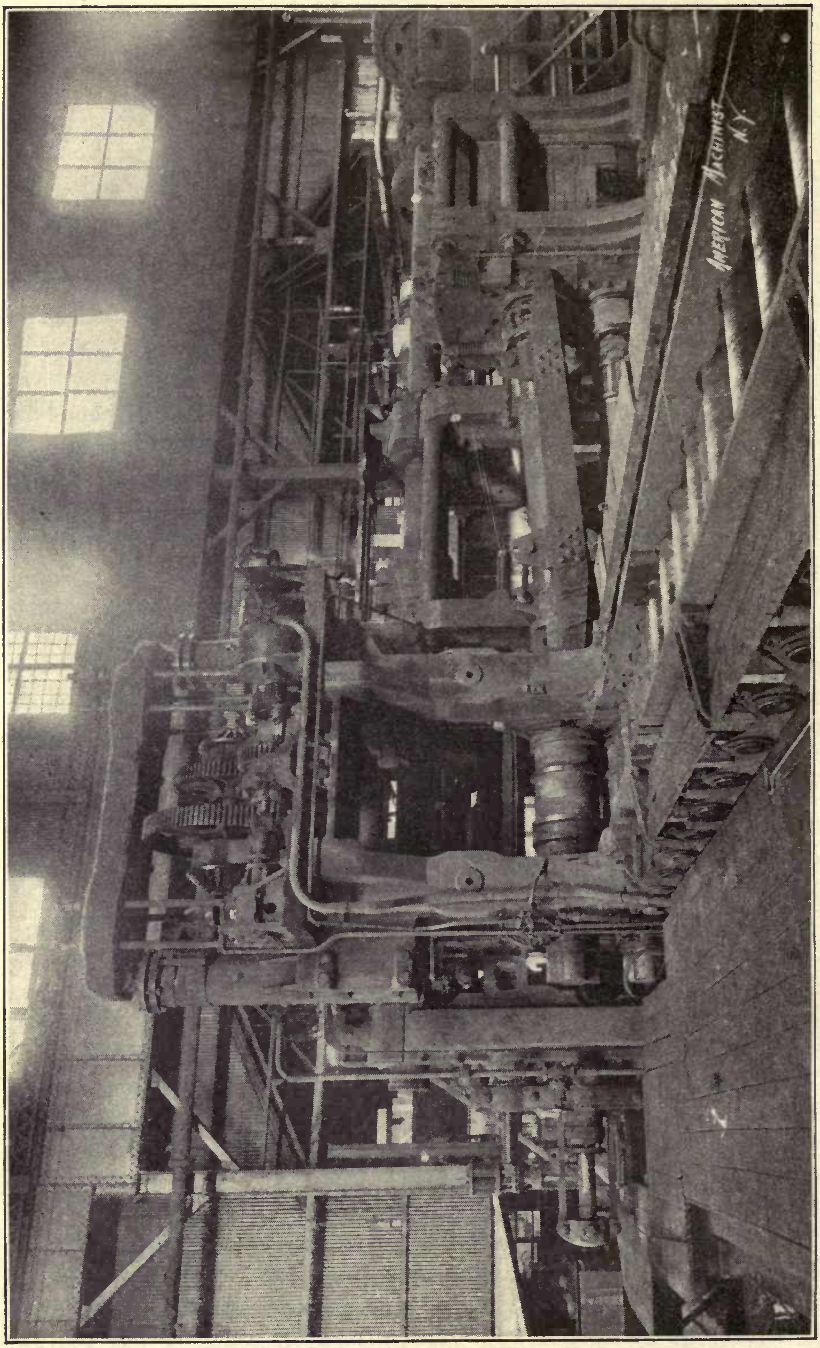


Fig. 52. — Slabbing rolls; first roll that ingot passes through.

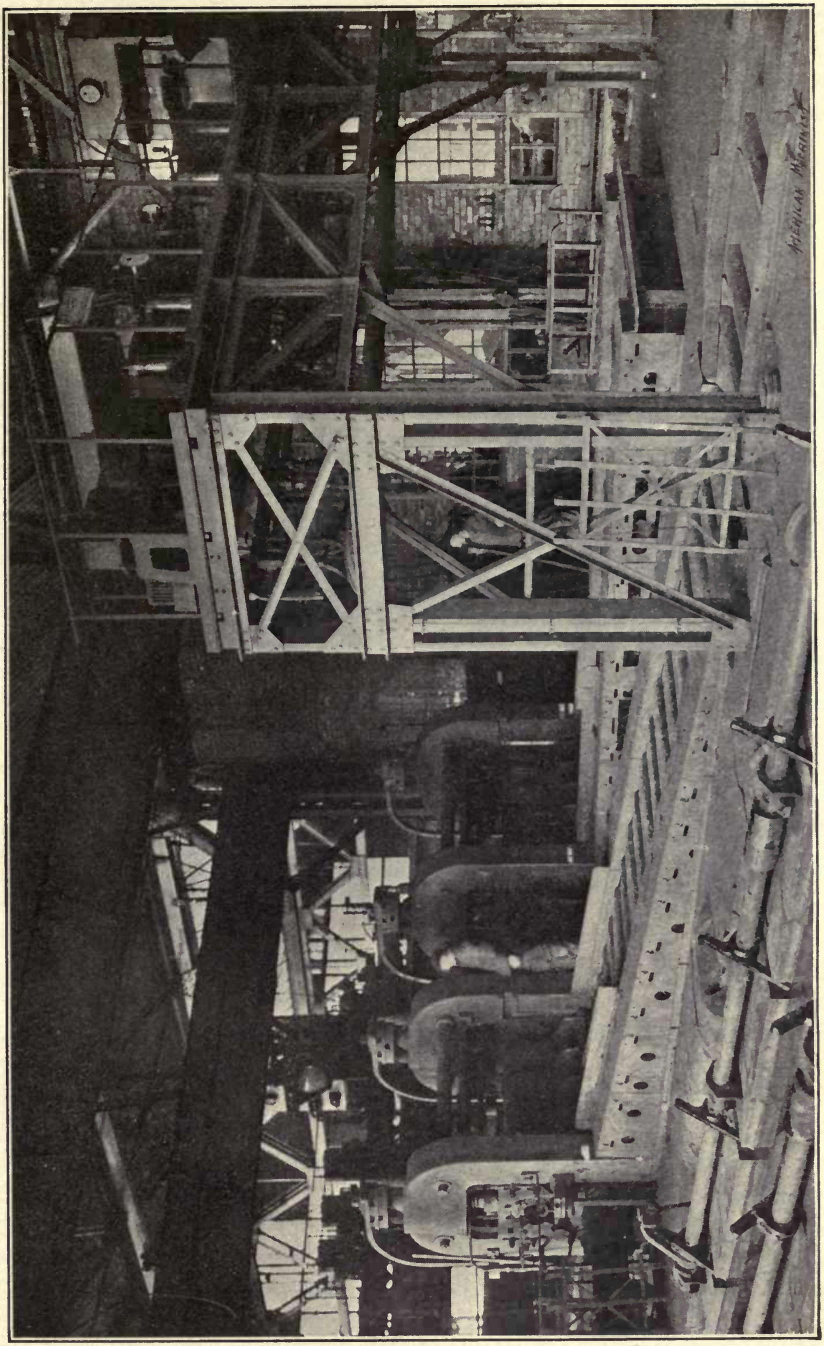


FIG. 53. — Rolls with tilting table and pulpit.

nace in which it was refined. In Fig. 54 is shown the metal being reduced to rods in a wire mill, and the kind of rolls used. Here the rods run into a track as they leave the rolls, and this guides them to the next roll that further reduces the metal in size.

CRYSTALLINE STRUCTURE OF METAL

Steel that has cooled slowly from the liquid state, as is the case with that which has been cast into ingots from the converter, furnace, or crucible, forms into crystals which do not show the same structure throughout. The outer shell of the ingot will have a different structure from the rest of the mass due to its cooling quickly, and therefore it is under strains until the center of the ingot has cooled. The top of the ingot also has an area of abnormal crystallization which is due to segregation. There is, however, the same general crystalline character in the largest part of the ingot.

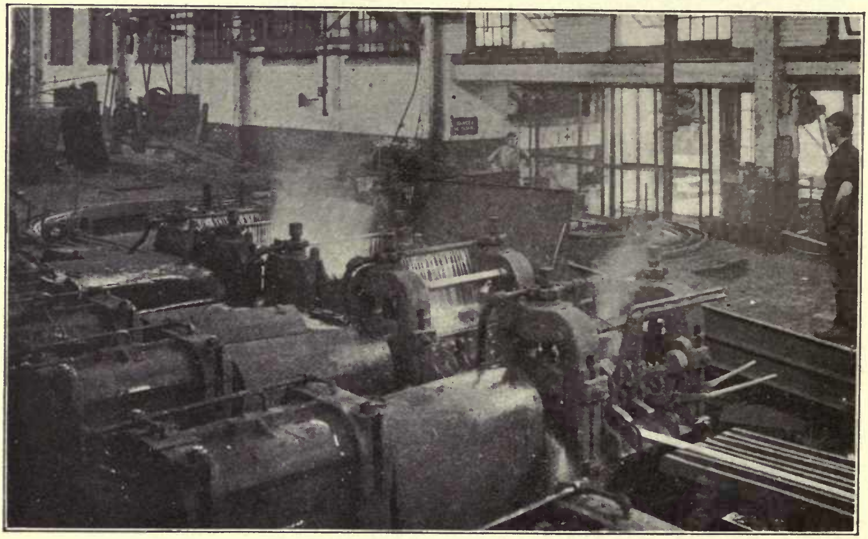


FIG. 54. — Rod mill with track and water-cooled rolls.

In passing the steel between rolls, to reduce it to the sizes and shapes wanted in the finished material, this crystalline grain is broken up and a new grain which is much finer takes its place. The best results are obtained if the rolling is completed at a temperature just above its highest point of transformation, as at or just above this point a new grain structure is born which makes the metal more homogeneous.

This formation of grain continues after the steel leaves the rolls and until it has cooled below its lowest point of transformation, below which point no more change will take place.

In rolling steel it is frequently heated to from 2000° to 2400° F., and it would seem that this would seriously damage it. This would be so if it were not for the fact that the mechanical pressure exerted upon the metal by the rolls breaks down the large crystals formed by this high temperature, and reduces them to a small size. The final size of the crystals is, therefore, dependent upon the temperature of the steel at the finish of the rolling process.

Finished steel has a finer grain structure if the last rolling operation receives the metal at a temperature which is falling from 1650° F. to 1400°, which are the highest and lowest points of transformation, than if it was finished at 2000° F., or any temperature above the highest point of transformation. On the other hand, if the rolling be continued after the temperature of the steel has fallen below the lowest point of transformation, strains are set up which make the piece unfit for most uses until it has been thoroughly annealed.

RULES FOR ROLLING

Four rules might be established in rolling steels which will affect the final size of the grain so as to make it what it should be, and these are:

First.—The rolling operations should be continuous from the highest temperature employed down to the finishing temperatures, as long waits, such as are generally made necessary when the metal is formed roughly to shape and size at a high heat, then allowed to cool and a little work done upon it at the lower temperature, are liable to cause a coarse grain that cannot be made fine by the last rolling.

Second. — There are better results obtained if the steel is passed several times through the rolls with a small reduction in the size of the metal each time, than if a large reduction is made with a very few passes.

Third.—In rolling a large piece a great reduction can be made during the first pass through the rolls, and the amount of reduction gradually decreased with each passage through the rolls until the finishing roll gives it just the right amount of reduction conducive to the making of the grain as fine as the steel will assume.

Fourth. — The steel should reach the finishing roll so that the temperature will be falling from 1650° F. to 1400° while it is passing through the rolls. It should not be allowed to go below 1300° until all the rolling operations have been finished.

HIGH AND LOW TEMPERATURES

Steel is so mobile at very high temperatures that it yields to distortion by the crystals sliding past one another, but as the temperature decreases the mobility of the mass becomes less, and less sliding is possible. The crystals then crush against each other, and at the lower temperatures a crushing of the crystals only takes place.

To obtain the very best qualities in a 0.50% carbon steel that it is possible to produce, the work of rolling should be completed just at the time when the ferrite is separating from solid solution. Rolling the work below the temperature at which this occurs, which is while the metal is cooling from 1650° F. to about 1300°, greatly increases the brittleness of the metal. Rolling the steel at a higher temperature lowers the strength, owing to the coarser grain which is given the metal. For steels of all other carbon contents it is logical to assume that the same rules hold good, but it is possible, although not probable, that further investigations may change them.

Steels are rolled in a large variety of standard shapes, such as round, square, oblong, hexagon, octagon, tubes, and L, T, U, I shapes, etc., and can be obtained in nearly any special shape desired, providing enough is wanted to pay for the making of rolls.

Casting

APPARATUS FOR MELTING

Casting steel consists of pouring the metal in a fluid state into molds which give it the desired shape. These shapes can be given most any kind of an intricate form owing to the shape being given the mold by a pattern and cores.

Many different methods are used for melting the steel, and some of these are the same in principle as those used for converting the blast-furnace metal into steel.

Pig iron and steel are melted together in the cupola, but this is not a normal product. It is a hybrid metal sometimes called semi-steel which is useful for special purposes, but fundamentally different from any kind of steel. It is a little better than cast iron, and is a very cheap mixture comparatively.

The open-hearth furnace is used a great deal for melting steel, for steel castings, and might be considered the cheapest method of turning legitimate steel into castings. Scrap steel and iron are used in this furnace, but they are melted under an oxidizing flame, and the metalloids are almost entirely eliminated, thus giving a definite starting point from which a known and regular metal can be made by the addition of recarburizers. Both the acid and basic open-hearth processes are used for steel castings.

The Bessemer converter in small sizes, often known as "the baby Bessemers," is extensively used for making steel for castings. There are many modifications of these small converters, such as the Tropenas converter, the Stoughton or long tuyere converter, and others. The Tropenas converter process is largely used when making steel castings, and this if properly run gives good results in the castings. In the Bessemer converter the blast is blown in at the bottom, while in the Tropenas process the air is blown at a low pressure upon the surface of the molten metal. Some four to seven inches above this set of tuyeres is another set, which supplies air to burn the carbonic oxide, the upper set not being operated until the blowing is well under way.

The crucible process has been used to some extent for small castings, and to cast some of the special alloyed steels. Its condition of "dead-melt" gives a more quiet metal, generates less gas when the metal comes in contact with cold surfaces, and the castings are more apt to be free from blow-holes; in fact, a German foundry, by using special care in the mixing of the metal, melting it, and making the molds, guarantees castings free from blow-holes, and makes castings of any composition of metal from wrought iron to high-carbon or high-speed steels.

This method produces the best steel castings, but it is the most expensive way of making them.

The electric furnace is just beginning to be used for melting the metal for steel castings, but it promises very good results as the phosphorus and sulphur can be reduced to a trace, and the oxygen and nitrogen can be very materially reduced.

RISERS, GATES, ETC.

In making steel castings about 40% of the melt is used to supply risers, sprues, gates, etc., and there is consequently a loss in remelting these.

The risers, which are sometimes called sink-heads, run from the top of the mold to the casting and are put on all thick sections of the casting to feed the metal to it while it is cooling and shrinking. These must be kept from solidifying until after the casting has become solid.

The sprue is the name given the opening into which the metal is poured, and this runs from a basin in the top of the mold to a pocket, which is usually located near the bottom of the casting. From this lower pocket to the opening in the mold, which is to form the casting, are cut other openings so the metal will be able to flow in. These openings are called gates. This arrangement is made necessary to prevent the liquid metal from tearing up the mold, as it would do if poured directly into the opening that forms the casting. The metal left in these when the casting is poured has to be broken away from and chipped and sawed off of the casting. They are then remelted to make other castings.

COMPOSITION OF STEEL CASTINGS

Steels with various alloying materials and of numerous different compositions are being used for castings to-day. The carbon content of these varies with the use to which the casting is to be put. Over 0.70% carbon is seldom used in castings, owing to its making the steel too hard to machine, and in complicated shapes the shrinkage cracks are liable to become dangerous.

In the ordinary steel castings manganese should not exceed 0.70% for soft castings and 0.80% for hard ones, as more than this is liable to make the metal crack when shocks are applied to it. Silicon may have a percentage of 0.10 in the soft castings, and 0.35% in hard ones without diminishing the toughness. Aluminum is used by many in making castings, as it has a great affinity for oxygen, and will remove the last trace of this from the iron. It also aids in dissolving the gases. It has a tendency to make the metal sluggish, but it enables it the better to run through small passages as without it the metal foams and froths when it comes in contact with cold surfaces, thus impeding the flow and chilling the advance guard of the stream. Aluminum should oxidize out of the steel, and not show over 0.20% when the steel is analyzed, but it is better if only traces are left, as it decreases the ductility.

Sometimes the phosphorus is allowed to be as high as 0.08%, but when the castings are to be submitted to physical test the phosphorus and sulphur should be kept below 0.05%.

The physical properties of ordinary steel castings should be above the figures in the following table:

	Hard Castings	Medium Castings	Soft Castings
Tensile strength in lb. per square inch.....	85,000	70,000	60,000
Elastic limit in lb. per square inch........	38,500	31,500	27,000
Elongation percentage in 2 inches.........	15	18	22
Reduction of area per cent...............	20	25	30

A chemical composition which has given good results for locomotive side frames analyzed as follows:

Carbon	0.27	per cent
Manganese	0.57	" "
Silicon	0.26	" "
Phosphorus	0.048	" "
Sulphur	0.033	" "

Test bars from this showed a tensile strength of 68,870 pounds per square inch, an elastic limit of 36,450 pounds per square inch, an elongation of 20% and alternating vibrations of 4707.

VANADIUM-STEEL CASTINGS

Vanadium has given such good results in rolled steels that it has been taken up by some of the steel foundries. In one case the usual mixture gave a steel showing a tensile strength of 68,580 per square inch, an elastic limit of 36,290 pounds, an elongation of 20%, and resistance to alternating vibrations of 4706. To the above mixture was added 0.22% of vanadium. With this product added the following figures were obtained: tensile strength, 77,160 pounds per square inch; elastic limit, 46,450 pounds per square inch; elongation in 2 inches 20%, and resistance to alternating vibrations, 14,971.

It is in resistance to vibrational stresses that vanadium shows its great superiority. The above tests were made on an alternating bending machine by gripping the test bar rigidly at one end and bending the free end upward and downward ⅛ inch from its axis. It gave a total length of stroke of ¼ inch, and this at the rate of about 30 strokes per minute.

Before adding vanadium in the furnace it is necessary to have the oxides all removed from the metal, as vanadium has a great affinity for oxygen. If any of the oxides remain in the metal, the vanadium will scavenge them out and go off in the slag; but as vanadium is too expensive to use as a scavenger, the oxides should be removed as completely as possible before it is added to the steel.

Many failures in the use of vanadium in the past have been due to this elusiveness or its affinity for oxygen, as many thought that if they put the vanadium in the steel, it must be there after pouring. As a matter of fact, it might have completely oxidized out of the metal and not given it any of the desirable properties of which it is capable.

With the oxides removed and other necessary precautions taken, the vanadium can be added with an assurance that it will be in the metal when analyzed; or more correctly speaking, that 90% of it will show on analysis, as a loss of more than 10% in the melting is uncalled for.

In using the acid open-hearth furnace for melting steel, the vanadium is added to the mixture just before tapping. The slag is raked from the top of the molten metal, the ferro-vanadium thrown in and the whole allowed to stand a few minutes, so that the vanadium will thoroughly mix with the metal.

As about 40% of the steel melted for castings goes back to the furnace, in the shape of risers, gates, and sprues, to be remelted, the vanadium is lost in these, owing to its oxidizing out during the melting process.

TITANIUM

Owing to the difficulty of obtaining the ferro-titanium, up to the present time, it has not been used to any extent in steel castings. Owing to its great affinity for oxygen and nitrogen, it removes these from the metal. This should make the steel castings free from blow-holes, and make a more homogeneous metal. That it does increase the static and dynamic strengths, as well as the wearing qualities of steel, without increasing the hardness, has been amply proven.

The ferro-titanium is not an expensive alloying material, and, as it is best to add it to the ladle after tapping, it is easy to handle without greatly increasing the cost of castings. After adding the ferro-titanium the ladle of metal should be held about six minutes before pouring the molds, in order to give the titanium a chance to do its work. This does not chill it, as might be supposed, as titanium has a tendency to retard the cooling of molten steel, and it will pour as freely and smoothly at the end of the six minutes as a ladle full of ordinary steel will directly after tapping. It also adds some good properties to iron castings.

NICKEL-STEEL CASTINGS

Nickel added to steel in percentages of from 1.50 to 3.50 combines a high tensile strength and hardness, and a very high elastic limit, with great ductility; therefore it is being used for steel castings with good results.

For some time it has been cast in large castings, such as rolling mill gears and pinions, and it is now being cast by a few foundries in small castings such as are used for automobile parts. It is difficult to cast in castings that have a thinner section in any of their webs, ribs, etc., than $\frac{1}{4}$ of an inch.

The ductility which lessens the tendency to break when overstrained or distorted, combined with the very high elastic limit, makes it valuable for such parts as crank-shafts on internal-combustion engines. These have been cast of nickel steel and given satisfaction in use, although forgings are much better for this purpose. Front axles, of I-beam section, have also been used successfully on automobiles.

Nickel-steel castings show a tensile strength of from 78,000 to 88,000 pounds per square inch, an elastic limit of from 50,000 to 58,000 pounds per square inch, an elongation in two inches of from 25 to 30%, and a reduction in area of 40 to 48%. This brings the elastic limit up nearer to the tensile strength than in the ordinary steel castings as well as increasing this and the elongation and reduction of area. This would indicate a greater resistance to shock and compression and the rendering of castings more ductile and tough than those made of the ordinary steel.

DIRECT STEEL CASTINGS

In this process the metal is taken direct from the furnace to a heated mixer where the proper materials are added to make the required quality of steel. The metal can be kept liquid as long as desired in the mixer, and its chemical properties adjusted by the addition of different materials. The mixer is kept full by transferring metal from the furnace. When the metal is wanted for casting the mixer is tapped and the metal run into ladles, from which it is poured into the molds as in other castings.

It produces a better and finer grained metal by the mixer reducing the gases which come in contact with the metal in the cupola or furnace.

Castings of direct steel can be obtained with guaranteed physical properties as follows: tensile strength, 70,000 pounds per square inch; elastic limit, 35,000 pounds per square inch; elongation in 2 inches, 25%, and reduction of area, 40%.

These castings can be forged, welded and case-hardened, and will machine as easily as machinery steel. They can also be bent freely when cold before breaking.

MANGANESE STEEL CASTINGS

Manganese steel with the manganese ranging from 12 to 15%, and the carbon contents high, is being successfully cast and used for such parts as have to resist wear from gritty substances such as are encountered in rock crushers or in machinery used around concentrators.

Manganese steel has the peculiar properties of being so hard that it cannot be machined in combination with a malleability which enables it to be headed cold when made into rivets, and a toughness which gives it remarkable ability to resist wear and shock stresses as well as cold bending.

When they leave the mold manganese steel castings are about as brittle as cast iron, but by heating them to about 1850° F. and quenching in water, they are given their properties of great toughness and ductility.

Owing to their being too hard to machine, all finishing must be done by grinding, but where it is desired to make a fit by machining, such as boring out a hub, a piece of metal that can be machined is placed in the mold and the manganese steel poured around it. By making this piece with numerous fins the manganese steel will shrink around it so that it will be nearly as firm as a solid casting.

The gases generated in pouring the metal are so low that the molds can be rammed very hard and with a fine sand. In this way surfaces are obtained that are nearly as smooth as finished castings, and but little grinding is required when a finished surface is desired.

Its shrinkage is about double that of ordinary steel when cast, and it cannot be cast in any very intricate shapes, nor can it be cast in any section which is thinner than $\frac{1}{4}$ of an inch.

When properly heat-treated manganese steel castings will show a tensile strength of 140,000 pounds per square inch, an elastic limit of 55,000 pounds per square inch and an elongation in 2 inches of 45%.

CHROME STEEL CASTINGS

Where a great hardness is desired such as that required in the manufacture of projectiles, chromium is added to steel that is to be cast. This gives the metal a mineral hardness that cannot be obtained with any other alloying material, and also refines the grain.

The uses to which these castings can be put is limited, however, owing to the difficulty of machining. The castings cannot be made in any intricate shapes or thin sections, owing to the difficulty of making the metal flow easily, but for such things as projectiles no better steel has been found for casting, and its use is increasing.

Forging

For those parts which cannot be produced from the rolling-mill shapes, or have not the proper strength when made in castings, forging is resorted to and there are several different ways of turning out these forgings: by hand, under a steam hammer, in a hydraulic press, or in a drop-forging press. The cost of these different methods of production depends largely on the number of pieces required of the same shape, but the size of the piece to be forged, as well as the components of the steel, have an influence on which is the best as well as the cheapest method to use.

FORGEABILITY OF DIFFERENT STEELS

Some of the special alloy steels are very difficult to forge. Chromium steel is the most difficult of all, owing to its mineral hardness. If kept above 220° F., however, it can be forged successfully, and it should never be allowed to fall below this. Nickel added to this steel, giving nickel-chrome steel, makes it slightly easier to forge, but even then the metal should be kept at a bright yellow color during the forging operations. As steel melts at 2500° F., this means that a forging of any size will need reheating several times before it is completely formed into shape. Nickel steels are more easily forged than those mentioned above, but they must be handled carefully, owing to the tendency of fissures to appear.

The vanadium steels are more easily forged than either of these, and if due care is taken to increase the heat gradually at first — that is, this steel should not be plunged into the heat all at once — no trouble will be experienced afterward. Titanium steel is similar to vanadium as to its forgeability, but it heats up more slowly and retains a forging heat longer. It also has less of the "hot-short" property than other steels, and hence should forge well.

Silicon in small percentages does not affect the forgeability of steel, but in large amounts it gives steel a fibrous grain, and is therefore used principally for springs. But in the last few years this steel has been forged into gear blanks to quite an extent. In this case the blanks should be made in the form of forged rolls, and not cut from bars, in order to avoid the fibrous structure.

The aluminum, tungsten, manganese, and other alloyed steels are not used to any extent for forgings, as those before mentioned show superior qualities, and some of the last named are much higher in price.

Some of the carbon steels, particularly those that are high in carbon, cannot be heated to a temperature over 1800° F., without burning the metal, and when once burned it cannot be returned to its former state without remelting. A vanadium-chrome steel will give as great strength as a nickel-chrome, and can be forged as easily as a 0.40% carbon steel.

The higher the carbon content the more danger there is of burning, and a steel with 1% of carbon is very difficult to forge at all, owing to the comparatively low temperature to which it is possible to heat it, and the comparatively high temperature at which the forging operations must be finished without danger of cracking the piece, owing to its brittleness. Thus high carbon steel should not have the heat fall much below its highest point of recalescence, which is above 1650° F., during any of the forging operations. Those forgings will be strongest that are finished just as the temperature reaches this point. The smith must also regulate the weight and effect of the blows so that the forging will be finished just as it reaches this point. This will prevent the formation of large crystals, give the piece a dense, homogeneous grain with the molecules holding together with a high cohesive force, and result in the steel having an increased strength. Any kind of steel can be forged if the proper temperature is maintained while passing it through the different forging operations, and the forgings will be much stronger than steel castings, and in many cases stronger than rolled steel.

Thanks to the electric and autogeneous welding process in combination with die-forging with either the drop hammer or the hydraulic press, all of the highest grades of alloyed steel can be turned into forgings successfully, and their strengths and elongation retained, but this is almost impossible by the hand or hammer-forging methods, especially if welds are made necessary by the shape of the piece. One of the alloy steels that is being manufactured into die forgings has the following chemical composition: chromium, 1.50%; nickel, 3.50%; carbon, 0.25%; silicon, 0.25%; manganese, 0.40%; phosphorus, 0.025%; sulphur, 0.03%.

In the annealed state this shows the following physical characteristics: tensile strength, 120,000 pounds per square inch; elastic limit, 105,000 pounds per square inch; elongation in 2 inches, 20%; reduction of area, 58%.

When properly heat-treated, that is, quenched in oil and drawn, these characteristics became: tensile strength, 202,000 pounds per square inch; elastic limit, 180,000 pounds per square inch; elongation in 2 inches, 12%; reduction of area, 34%.

EFFECT OF TEMPERATURE ON THE GRAIN

The high temperatures, of from 2000° to 2400°, that steels are subjected to when forging would seem to indicate that the metal is weakened by overheating, but such is not the case, as forgings show greater strength than the same metal formed into shape in any other way, unless it be the rolled steels.

Steel, when heated to the above temperatures, coarsens in grain and the grain becomes crystalline in nature. This makes it so mobile that it yields to distortion by the crystals sliding past one another, but as the temperature decreases the mobility of the mass becomes less, and less sliding is possible. If then forged the crystals would crush against each other; and when cool the crystals themselves will crush.

These coarse crystals, that are formed by the high temperatures, are reduced by the hammering process in the drop-hammer press, or the squeezing process in the hydraulic press, until the crystalline structure is broken up and a new grain that is much finer takes its place.

If the piece is not allowed to cool below its highest recalescence point during the forging, and the forging is finished just as it reaches that point, or a little above it, a new grain structure is formed, that makes the metal more homogeneous. This formation of grain continues, after the steel leaves the press, until it has cooled below its lowest recalescent point, at which point it sets, and no more change will take place until it is reheated to the recalescence point. These two points occur in most steels at about 1650° and 1400° F., but some of the special alloys show a wide variation from this.

Thus it will be seen that if a forging is finished while it is too hot, the grain will be coarse and crystalline and the metal will not have the cohesive force that it should, and therefore the piece will not be as strong as a forging should be. On the other hand, if it is hammered, or squeezed, in a forging press after it has become too cold, the crystals will be crushed and the result will be the same, but if it is forged at the proper heat, the grain will be fine, dense, and homogeneous, and the cohesive force will be greater than was the case before it was forged. This will naturally increase the tensile strength and elastic limit.

Many poor forgings are turned out by raising the temperature of the metal too suddenly. Certain molecular changes take place in the heating of all steels, and of the alloy steels in particular, which are liable to cause fissures in the core of the metal. These may not show in the finished product as they do not always break through the skin or outer shell of the forging. Thus, by heating suddenly, the outer shell becomes red before the core has had an opportunity to absorb any heat, and the outer shell expands, causing great strains on the core of the piece. In the case of a high percentage of nickel these fissures become more pronounced than with the other alloys.

At a temperature of about 600° F., or a bright blue, most steels lose their ductility, and are not fitted to resist strains imposed upon them by the differential expansion of an unevenly heated metal. Therefore the rise in temperature from the normal to 600° should be a gradual one, but after this it may be brought up to the forging heat as quickly as is desired.

To remove the internal strains caused by working the metal, all forgings, no matter how they are made, should be annealed before using, as the shocks to which the forging may be submitted will concentrate at the point where these internal strains are the strongest, causing it to break at that point. The case is very similar to the machinist notching a bar in order to break it. The heat treatment that is given the pieces after they are forged is an important factor, if the greatest strength and the best wearing qualities are to be given the metal, as the best forgings can be ruined by improperly heat-treating them afterward.

Small forgings are usually tumbled, and large ones pickled in a diluted solution of sulphuric acid to remove the hard outer skin or scale that the finished forgings have. This is done so they can be machined more easily, as this skin or scale has a mineral hardness that will dull cutting tools very quickly.

Forgings that are made with a knowledge of metals, temperatures, etc., and with the proper skill and care, are stronger, and will stand the strains and stresses that are put upon them much better than the same steel when formed into shape in any other way, unless it be the rolled stock, which should be worked under the same temperatures.

HAND FORGING

When small pieces and but few of a kind are wanted, hand forging is undoubtedly the cheapest; but for large pieces, or where a large quantity is wanted, hand forging is the most expensive way of producing them and the strength is not apt to be as great as by any of the other methods. With a blacksmith shop properly equipped, a skilled smith can make forgings that are stronger than a rolled bar from the same ingot. To do this the piece must be hammered between the proper temperatures, which varies with the different grades of steel.

The steel that is the best adapted for forging under the hammer has about the following composition: carbon, 0.15%; silicon, 0.20%; manganese, 0.52%; phosphorus, 0.06%; sulphur, 0.04%. This steel in the annealed state will show the following physical characteristics: tensile strength, 55,000 pounds per square inch; elastic limit, 30,000 pounds per square inch; elongation in 8 inches, 29%; reduction of area, 60%. When fractured it will show a silky fiber.

But for many purposes a steel of much greater strength than this must be hand-forged and then it becomes necessary for the smith to understand the nature of its component parts so he can forge it successfully, as many of the high-grade alloy steels can be rendered no better or stronger than the ordinary carbon steels by over or under heating and poor workmanship.

In many cases welds are absolutely necessary to produce the required shapes, and a steel of the following composition is the best suitable for welding: carbon, 0.080%; silicon, 0.035%; manganese, 0.110%; phosphorus, 0.012%; sulphur, 0.007%. In the annealed state it should show the following physical characteristics: tensile strength, 48,000 pounds per square inch; elastic limit, 25,000 pounds per square inch; elongation in 2 inches, 27%; reduction of area, 69%.

STEAM-HAMMER FORGING

For pieces of considerable size and bulk the steam-hammer is substituted for the hand-forging process. These hammers vary in size, from the small Bradley cushioned hammer that strikes a blow of about 500 pounds, as shown in Fig. 55, to those that strike a blow of many tons, as illustrated by Fig. 56, which is that of an 8-ton hammer, in use at the Bethlehem Steel Works. While this is not the largest hammer in use, it is about as large as is practical, owing to the difficulty of building a foundation that will prevent buildings near it from being wrecked, and other machine foundations ruined. Another style of steam hammer is shown in Fig. 57. This, however, is usually used for drop forgings.

In this method of forging, the hammer should be of a size to suit the size of the work. The hammer-man must exercise a good deal of skill and judgment as to the power and speed of the blows delivered to the piece, as a too powerful blow will crush it, and in the case of a high percentage of nickel, fissures and cracks are liable to develop which it will be difficult to get out, and which may show in the finished product.

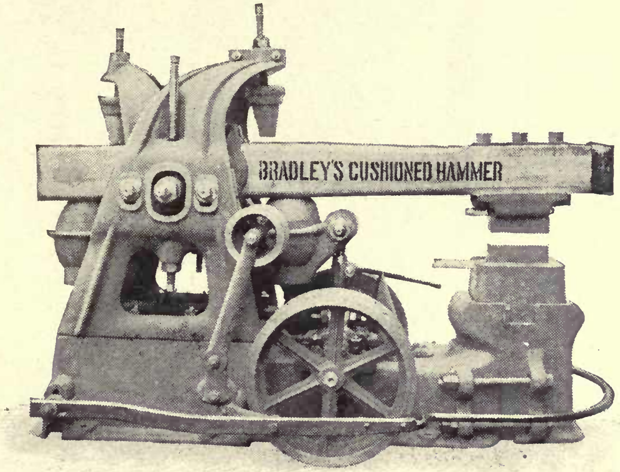


FIG. 55. — Bradley cushioned hammer.

This is especially true if the piece is allowed to fall below the forging temperature, or if the blows are not distributed evenly. If the blows are from a light trip-hammer, delivered at high speed, only the surface of the metal will be bruised and the core not affected, thus causing the core to be coarse-grained without the proper cohesion to insure the necessary strength.

With a heavy hammer, descending at a low speed on work that is held at the proper temperature, the force of the blow will penetrate the mass to the center and allow the particles of metal to flow to their proper position, insure a fine grain of even texture and be uniform throughout its entire size.

The keeping of the heat to a good forging temperature is more difficult than in the hand-forgings, owing chiefly to the difference in the size of the piece forged, as the hand-forged piece is usually small enough for the smith to put in the fire and reheat the minute the temperature falls below the best forging heat. But the hammer-forged piece is many times large enough to be handled with a crane, and is therefore liable to be kept under the hammer as long as a blow will have any effect on it.

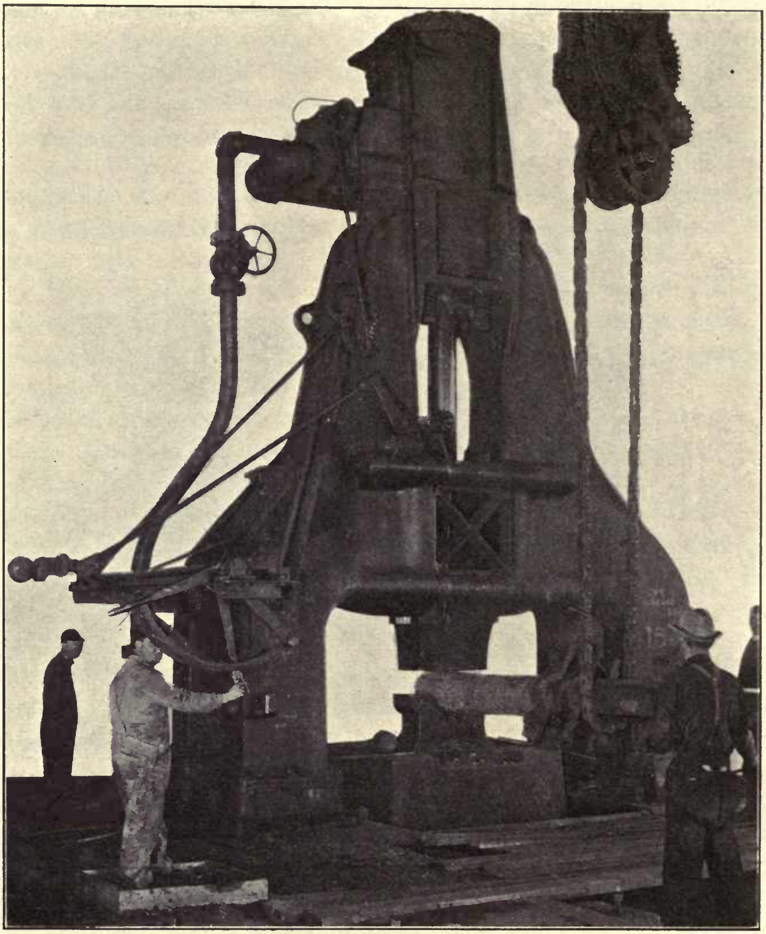


FIG. 56. — Steam forging hammer, 8-ton.

This results in a very uneven structure, as when the metal is hot the blows will penetrate to the center, and as it cools they have less and less penetration until only the skin is affected, and the annealing, which is resorted to afterward, cannot bring it back to the proper homogeneity, as some parts will have a denser grain than others, and therefore be stronger.

The effect on the metal when the blows are not powerful enough to penetrate to the center, or the steel is not hot enough to allow them to do so, is shown in Figs. 58 and 59. When too light a hammer is used, the effect shown in Fig. 60 is usually obtained. These same effects are often encountered in drop forgings and hand forgings, as well as in steam-hammer forgings. They are generally overcome by the use of a hydraulic forging press, as with the press the metal is squeezed and consequently must be hot enough to flow into shape, and this affects it clear to the center.

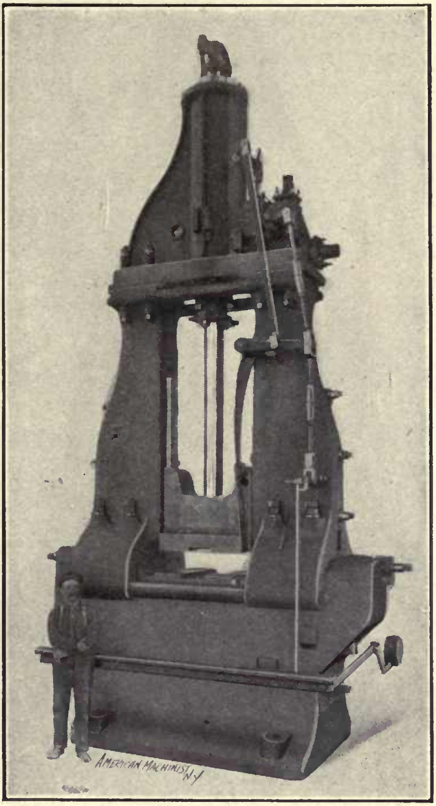


Fig. 57. — Erie steam hammer.

DROP-HAMMER FORGING

When enough pieces, of one shape, are wanted to warrant making a set of dies, the cheapest and best way of producing these in either the common carbon or high-grade alloy steels is by the drop-forging process. They can then be made in one piece without welds, except in pieces which are many times longer than a section through them, and these are so difficult to keep at the proper temperature that they are usually forged in two or more pieces and then electrically welded together. The oxy-acetylene blowpipe has also been brought into use for welds of this character, as well as for other forms of welding, and good results are being obtained.

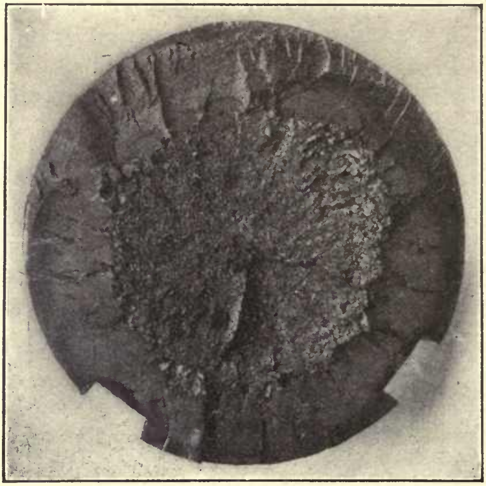


FIG. 58. — Effect of hammer forging.

FIG. 59. — Another sample of hammer forging.

A good illustration of this is the front axle of an automobile, which is usually forged in I-beam section, 4 inches from the top to the bottom of the I, $2\frac{1}{2}$ inches across the flange, with the web $\frac{1}{4}$ of an inch thick, and a length of from 48 to 54 inches. These are generally forged in two halves and electrically welded in the center, but a few of them are forged in one piece, although the first cost of the dies and the liability of their breaking, owing to the axle cooling before the forging operation is completed, has made this method very expensive.

The dies that are necessary for this kind of forging are usually made of a 60-point carbon steel and in two halves: an upper and a lower one. They are generally parted on the center line; but the shape of the piece controls the location of the parting line. The upper half of the die is fastened to a ram that is connected to the piston in a steam cylinder, and this is used as a hammer to strike the hot steel, held over the lower half of the die, a series of blows. This forces the metal to fill both halves of the die, and thus the piece is formed into shape. Dropping the upper half die onto the lower with a hammer-like blow has given this kind of forging the name of drop forgings.

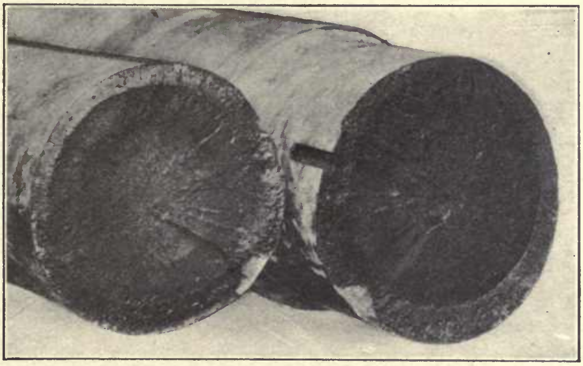


FIG. 60. — Piece forged with relatively light hammer.

The dies are always given from 5° to 7° draft, so the forging will fall out easily, and they are left open on the parting line from $\frac{1}{8}$ to $\frac{1}{4}$ of an inch, according to the amount of metal in the forging. The amount of stock is always greater than in the finished forging, so it will completely fill the die, and the surplus is squeezed out at the opening on the parting line. This fin is afterward trimmed off. With hard or brittle steels it is best to make the dies with shorter steps between the different pairs than for the ordinary carbon steels.

One of the first and most important points in die forging is the setting of the dies, as the upper half, which is fastened to the ram, and the lower half, which is fastened to the anvil block, must come exactly in line to produce a perfect forging.

The lower half of the die should have a current of air blowing in it that is strong enough to remove all of the scale that works off from the piece being forged. The air blast should be directed so it will not cool the hot metal while being forged. Steel-wire brushes can be used for this purpose, but the air is quicker, and if well adjusted is more positive. The upper half of the die should be kept well oiled so the scale will not stick to that. This can be done by rubbing a swab, well soaked in oil, through the die every time it is raised off the work.

With the dies properly set and the press adjusted so the two dies will come together on the parting line, the work can be turned out to one thirty-second of an inch of the finished size, thus making much less machine work than by the hand or steam-hammer forging processes, and when grinding is to be used in finishing, the work can be brought to within one one-hundredth of an inch.

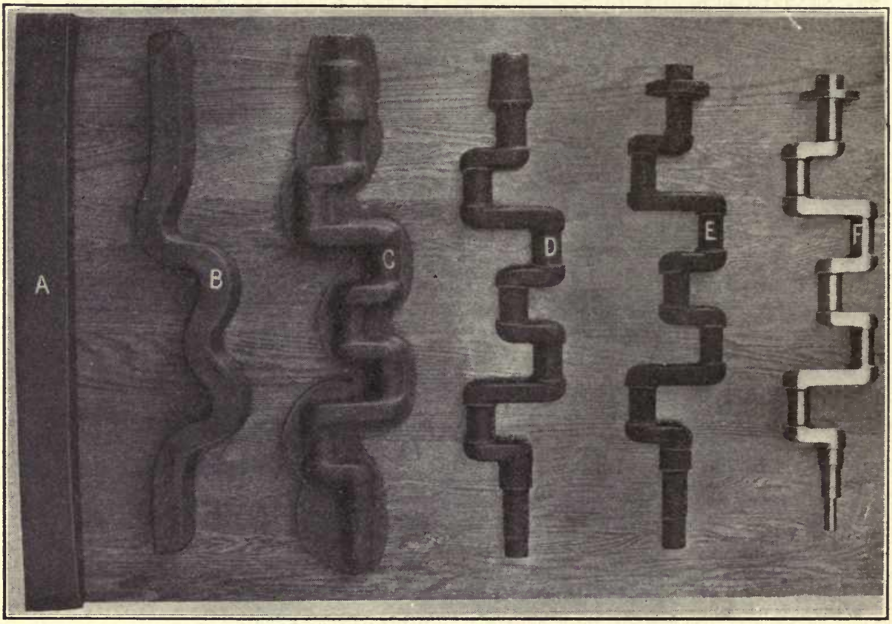


FIG. 61. — Different operations on forging a crank-shaft.

The cost of drop forgings depends on the number needed, and the number that can be turned out at one setting of the dies, as well as on the quality of the steel used.

Some of the largest pieces that are being made by drop forging are the crank-shafts for internal combustion engines, and the different operations in forging these are shown in Fig. 61. At *A* is shown the straight bar, cut to the proper length. This is first bent to the shape shown at *B* in the bending press. It is then drop-forged, and when it leaves the dies, it is similar to the piece shown at *C*. The dies are usually left $\frac{1}{4}$

inch apart on the parting line for this size of forging, to allow the excess metal to squeeze out between them, which forms into the fin that is shown at *C*. This necessitates the making of an extra pair of dies for shearing off the fins. After this is done the crank has the appearance of that shown at *D*. On this particular shaft there was a comparatively large flange on one end, as shown in *E*. This would be difficult to form in the dies when forging the rest of the shaft, and for this reason an extra amount of metal is left on the shaft at this point and the flange is formed in another set of dies after the rest of it has been forged. This completes the forging operations and the shaft is ready to be machined; the machined crank-shaft being shown at *F*.

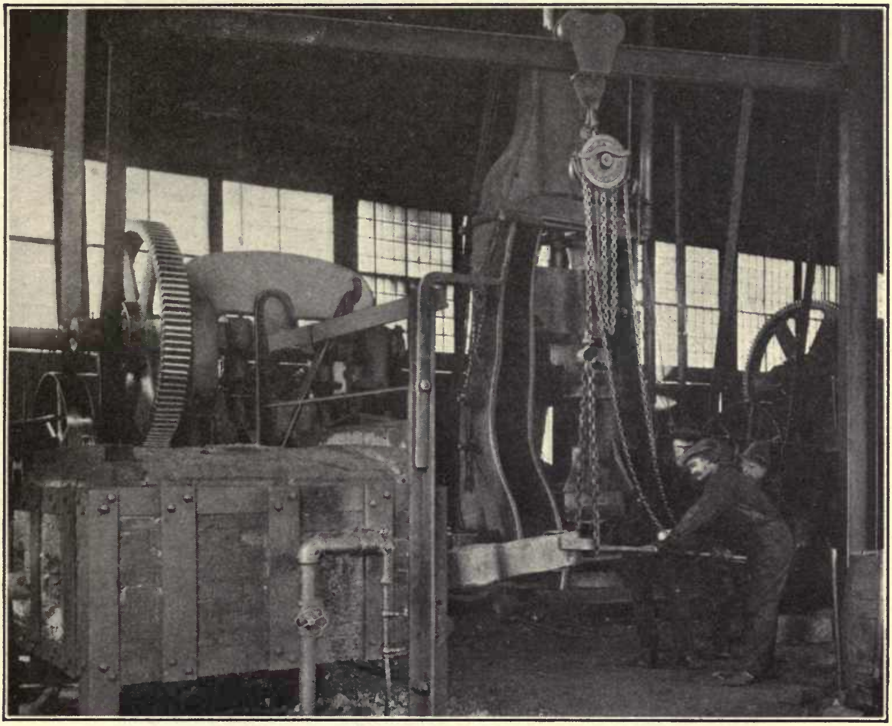


Fig. 62. — Taking crank-shaft from furnace to hammer for first operation.

One of the largest drop forgings that has so far been made (June, 1910) is a two-throw crank-shaft, made by the Bethlehem Steel Company, that when finished weighs 400 pounds. The operations are similar to those shown in Fig. 61. Fig. 62 shows the piece, after it has been bent and heated, as it is being taken from the furnace to the 5000-pound drop-hammer for the first operation. Back of the furnace can be seen the top of the bending press, which bends the straight bar to the shape shown by the partially forged crank in Fig. 64. Fig. 63 shows the piece being held under the hammer ready to drop the die on it. Fig. 64 shows the crank-shaft after it has been partly formed and as it is being taken back to the furnace to be reheated for the final forging operation under the hammer. Fig. 65 shows the crank-shaft as it was being taken out of the dies after the final forming operation. In front of the hammer is shown a finished crank-shaft with a 5-foot rule standing beside it to show its length.

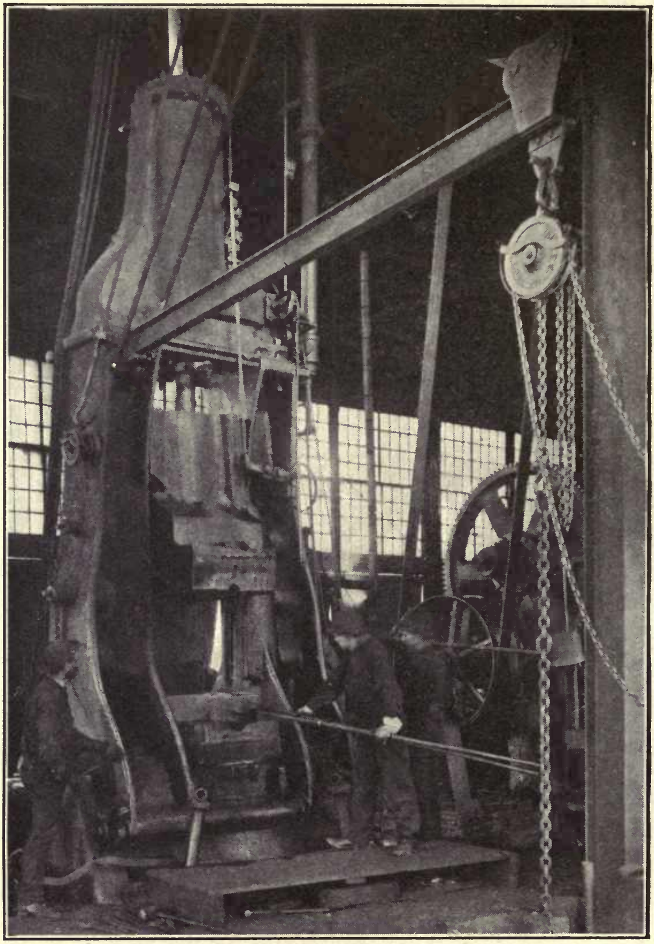


Fig. 63.—400-pound crank-shaft under hammer ready to drop the die.

An idea of the variety of shapes, sizes, and styles of machine parts that can be economically made by the drop-forging process can be obtained from Fig. 66. At the lower edge of the half-tone is laid a 5-foot folding rule, and just above it is the 400-pound crank-shaft that has just been described in its forging operations; while at the top of the picture are forgings that will require about twenty to weigh one pound.

PRESSED FORGINGS

The inferior quality of many die forgings is undoubtedly due to the drop-hammer process, as this has a tendency to produce only a bruising effect, owing to the top die descending at a high speed and delivering a light blow which has no penetration. The hydraulic, pneumatic or steam press, on the other hand, produces forgings of a far superior quality because it slowly squeezes the metal into the shape of the die, thus allowing it more time to flow into place and assume its new shape,

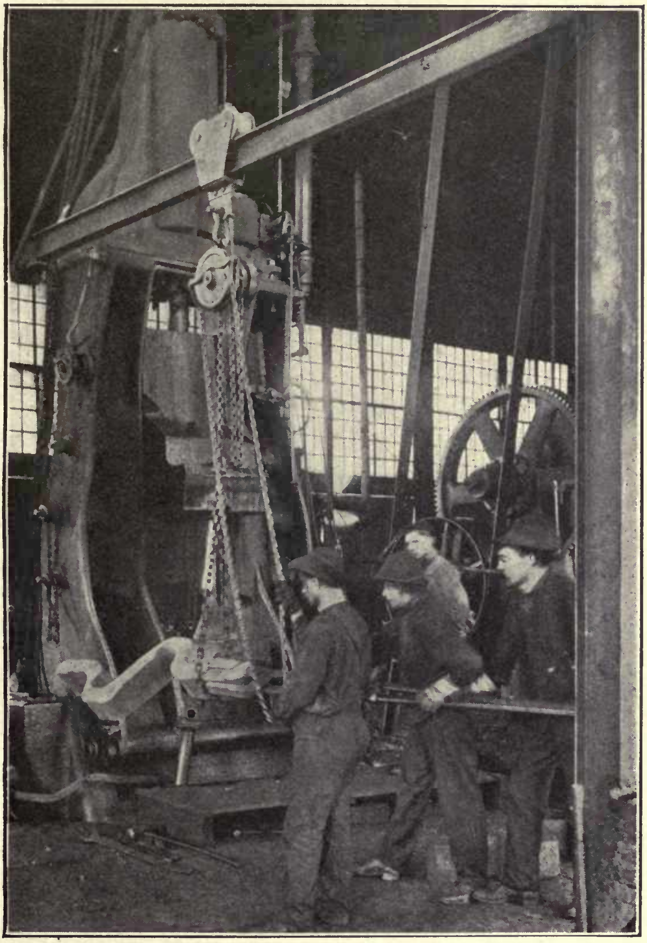


FIG. 64. — Removing partially forged 400-pound crank-shaft.

and therefore making it more uniform in quality and with less internal strains.

With the hammer blow in forging a wavy grain is obtained, as shown in Figs. 58 and 59, *i.e.*, directly under each blow of the hammer a dense grain is produced, while around the edge of the blow it is less dense. This causes the ridges shown in the fracture of the fine-grained metal around the outside of the bar. In conjunction with this is the inability of the blow to penetrate to the center. In one or two places, where one blow did not overlap another, the shape of the metal affected by the blow can be plainly traced. Where the steel is pressed or squeezed into shape this variation in the density of the grain of the piece would not show, and it would be condensed clear to the center, as the steel being operated on would have to be hot enough to flow into the shape desired under the high pressure used, or it could not be worked.

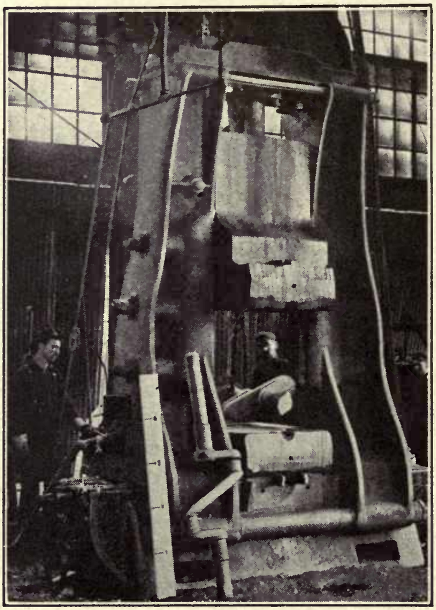


Fig. 65. — Final forging operation.

That the press makes a more homogeneous metal than the hammer, or even the rolls, and hence a stronger and tougher one, is well illustrated by the German government specifications for steel forgings worked by rolls, hammer, or press which says: "Forgings made from rolled or hammered steel must have the initial section at least eight times that of the finished section; while those made from pressed steel need have an initial section only four times the finished section."

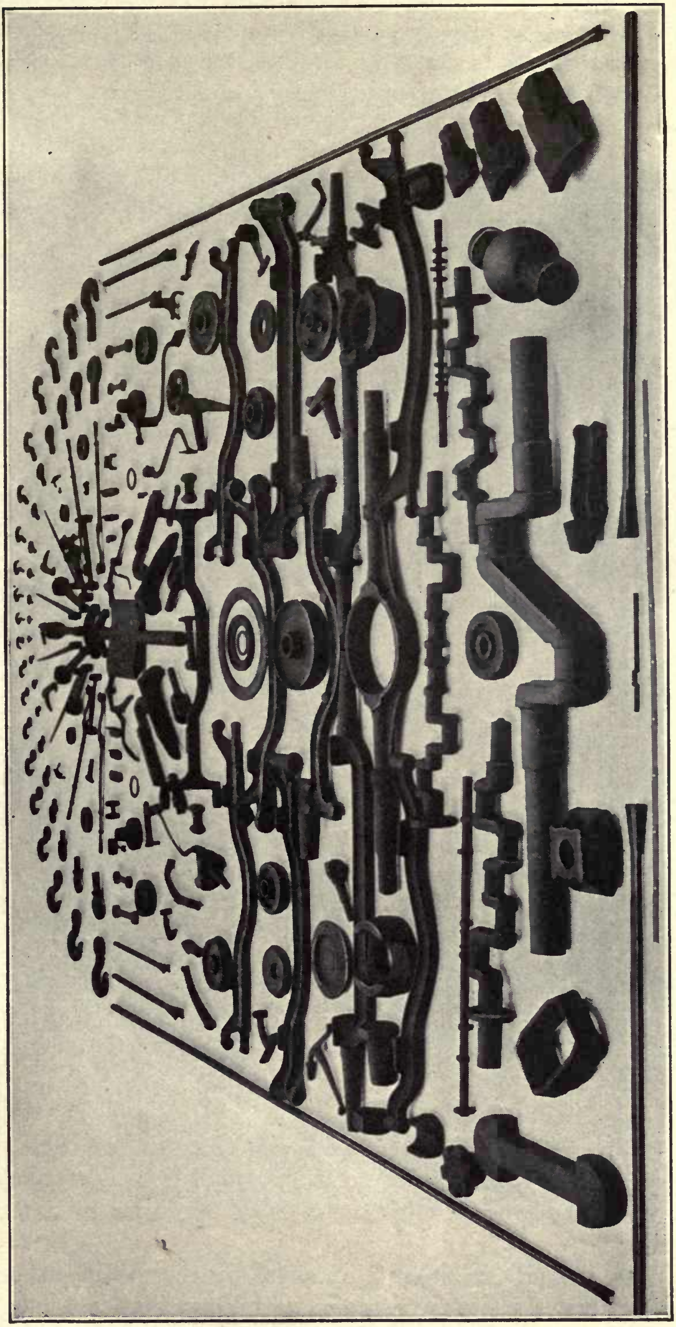


FIG. 66. — Group of drop forgings made by the Bethlehem Steel Company.

With the press, rounds, flats, squares, and irregular shapes can be forged without dies, as with the steam hammer, or two halves of a die can be pressed together to make die forgings, the same as with the drop hammer. When forging metal into shape, a much greater force can be brought against it, with the press, than with the hammer, owing to the absence of any jarring. As a consequence of this the steel works are all adopting presses for their heavier work. Some of these operate at a very high speed, when compared with the hydraulic presses of a few years back.

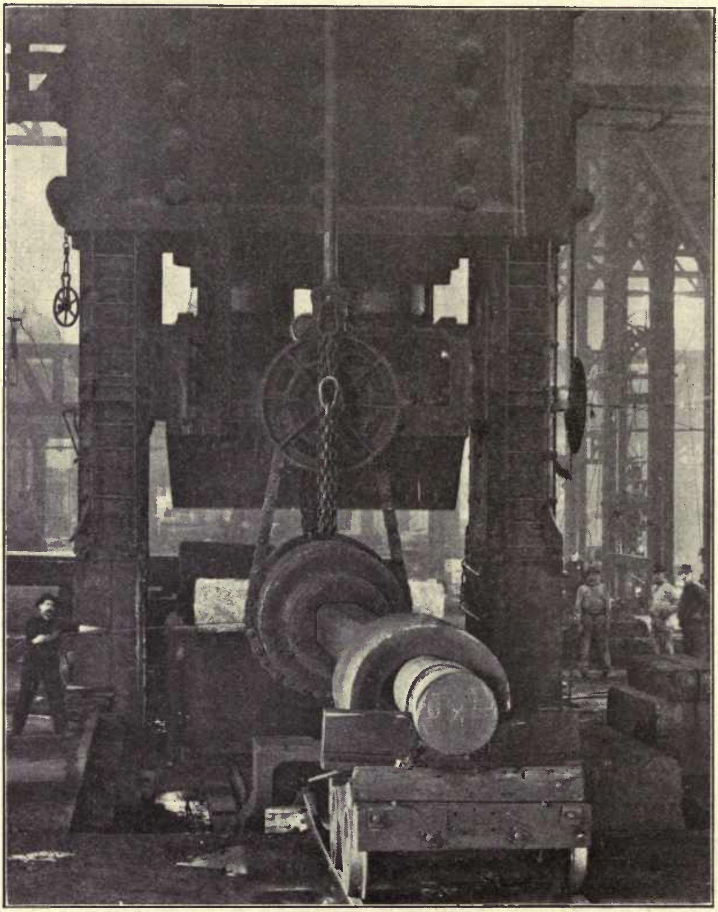


Fig. 67. — A 1400-ton forging press.

The power behind the press is obtained by the use of either water, air, or steam, but the hydraulic press is the one that has been almost universally adopted. A large-sized press of this kind is shown in Fig. 67.

This is a 14,000-ton press at work on a forging, but it is typical of the style of hydraulic presses, and they can be obtained in much smaller sizes.

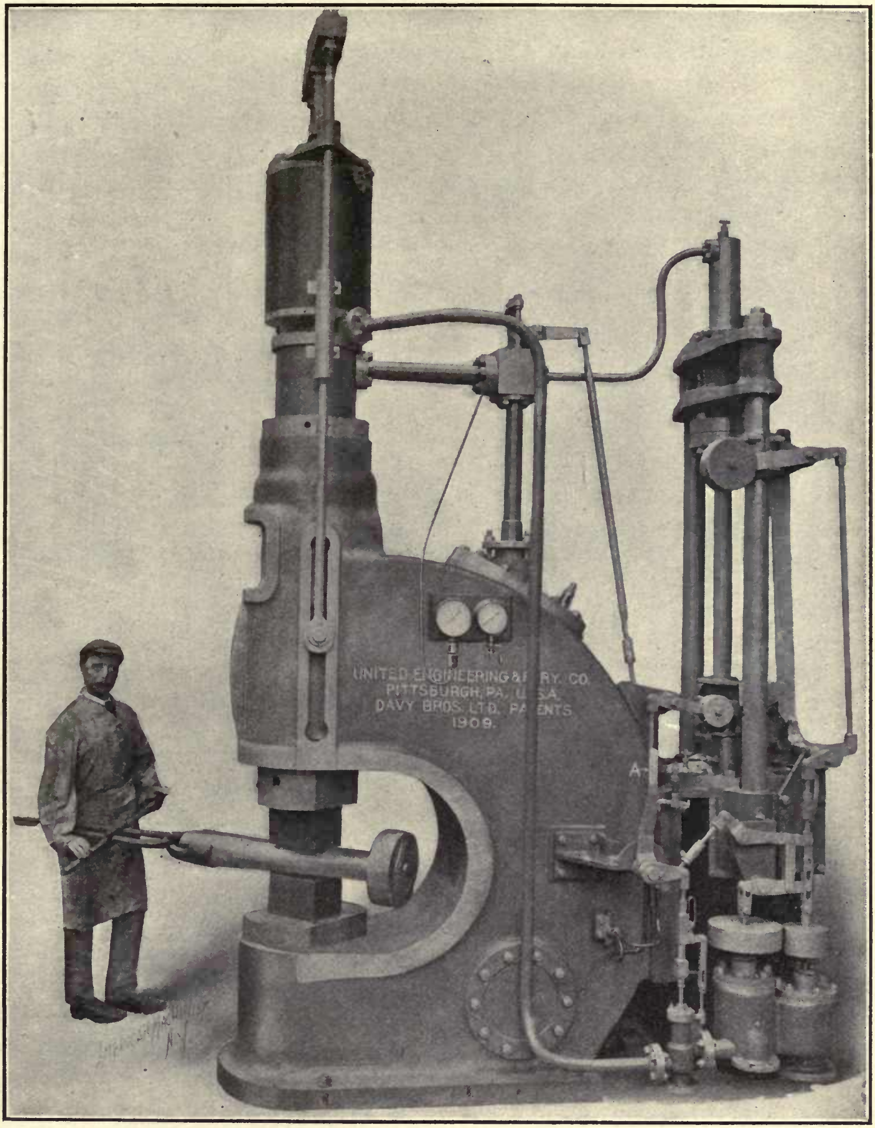


Fig. 68. — Small high-speed steam-hydraulic forging press.

In place of the upper and lower press blocks used, others can be inserted that will form rounds, octagons, etc., or the two halves of a die can be put in their place to form irregular shaped pieces.

A combination of the steam-hammer and hydraulic press has recently been placed on the market, and this promises to have a very useful field.

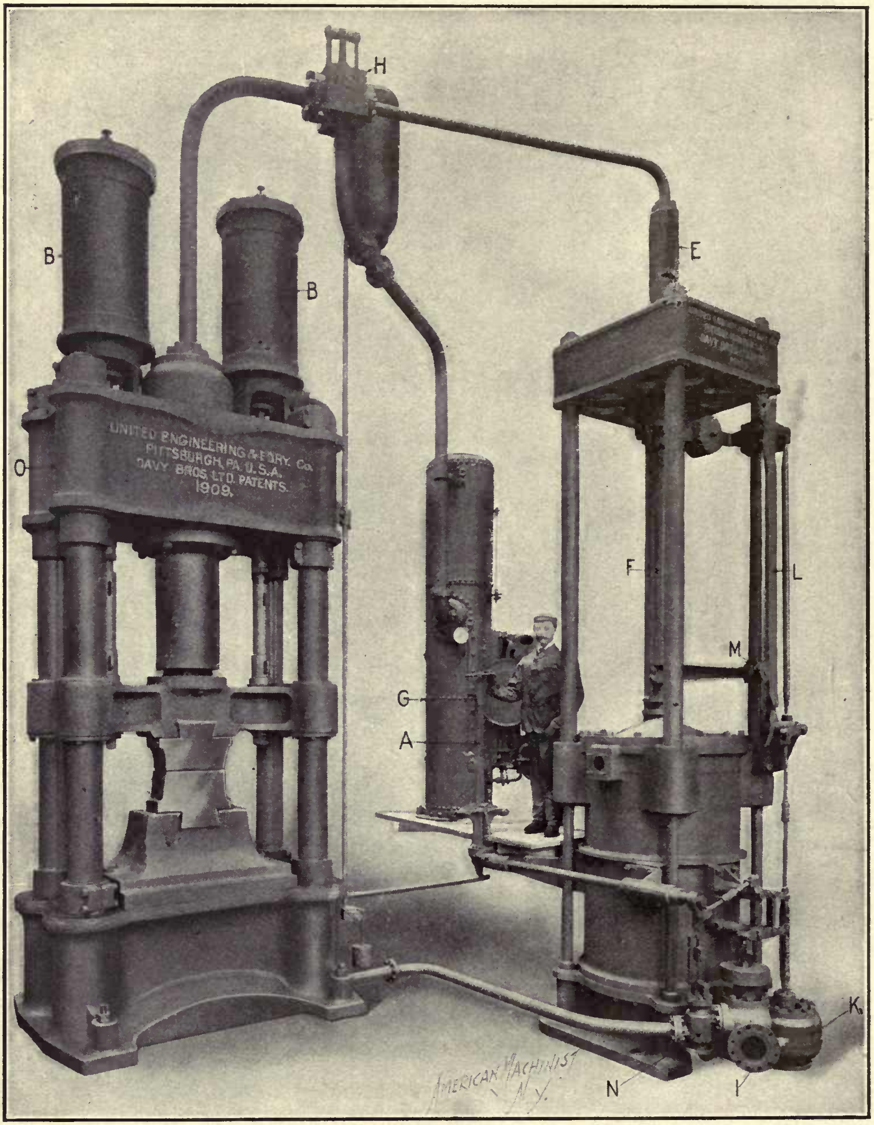


FIG. 69. — Large high-speed steam hydraulic forging press.

One of the smaller sizes, with a single frame, that is built in sizes from 150 to 400 tons, is shown in Fig. 68, and a large size with four columns, in sizes from 300 to 12,000 tons, is shown in Fig. 69. These machines raise the ram and lower it onto the work, which can be done with a blow if desired, and then the water pressure is turned on to squeeze the piece into shape. It also can be used with or without finished dies in the making of forgings.

With the hydraulic press it is possible to make simple, inexpensive dies that will forge quite complicated pieces. Pieces that are impossible to make in the drop-hammer and are very expensive to make by hand-forging can be made remarkably cheaply and accurately. As an example of this, the piece shown in Fig. 70, after the machine work was done, was forged in a hydraulic press with the apparatus described below.

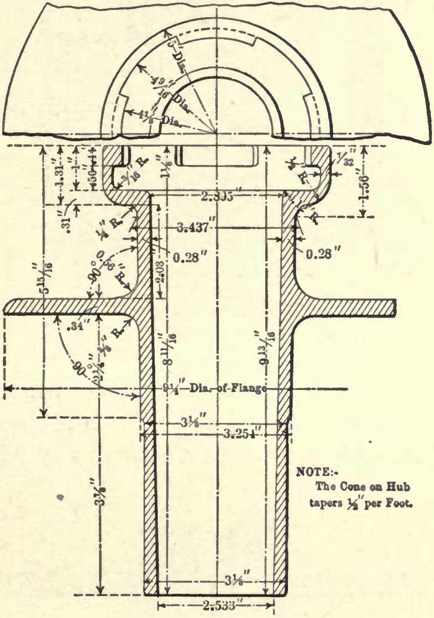


FIG. 70. — Wheel hub to be forged in hydraulic press.

A piece of 3½-inch round stock was cut the required length and put in the die, as shown at *G* in Fig. 71. Here, *A* is the die-holder; *C* the die block, which is put in loose, and *E* the flanging punch. A loose block is put under the piece *G* and when it leaves the press it is the shape shown in Fig. 72. The next operation is to punch out the center and spread out the top to form the shoulder, and this is shown in Fig. 73. Here the die in Fig. 71 has had the loose block in the bottom taken out, and the two halves of the die block, *D*, *B* (Fig. 73), placed on top of the forging. When the punch is pressed down it forms the piece into the shape shown in Fig. 74, and when the bottom of this is trimmed off it leaves ⅛ of an inch finish all over.

Thus, while the press makes forgings with much better metal than those turned out with any kind of a hammer, it also presents greater possibilities to the maker and user of forgings in the way of difficult shapes that can be economically made. The example given is merely one of a large variety of shapes that can be made in a similar way with the use of loose dies. Fig. 75 shows a few more shapes that have been made in the hydraulic press; some of which were made with loose die blocks, and these will doubtless suggest to the student many more that can be made.

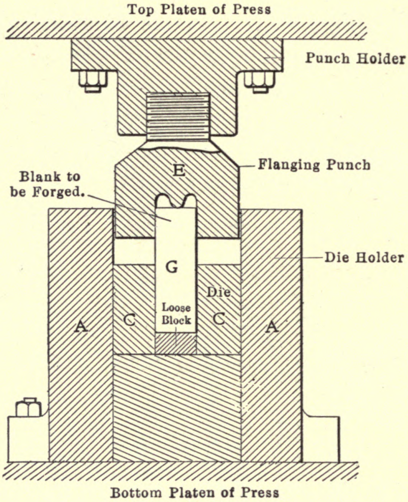


Fig. 71. — Stock in die ready for first operation.

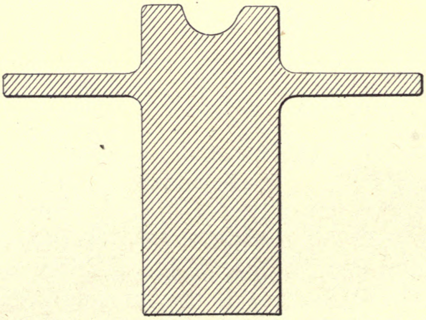


Fig. 72. — Cross-section of forging after first operation.

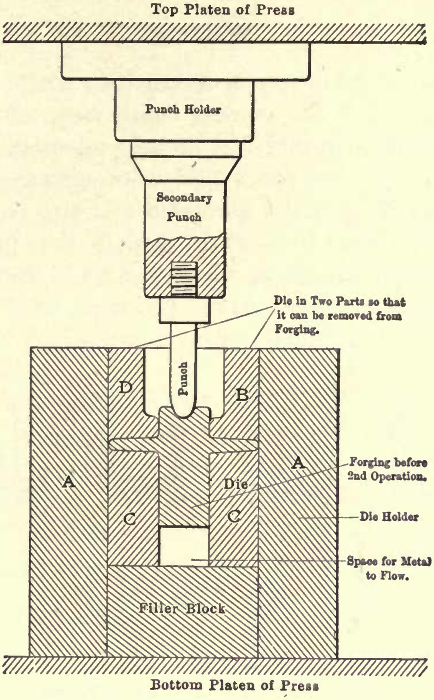


FIG. 73. — Forging in die ready for second operation.

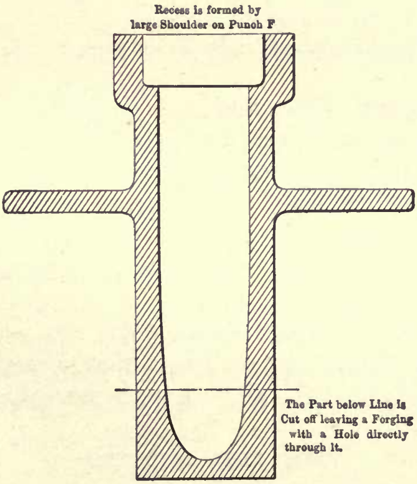


FIG. 74. — Forging after second operation, ready for machine shop.

Welding

In many of the more intricate shapes that are hand-forged, resource is had to welding, and if the average smith were told that he could not make a perfect weld he would feel greatly insulted. But from a large number of so-called perfect welds that were examined very few showed a strength equal to 50% of the unwelded section. With the alloy steels it is difficult to get a weld that will even show that percentage, as nickel, chromium, vanadium, tungsten, aluminum, and some other alloys do not lend themselves to the welding process. It is difficult to make welds at all by the hand methods in a blacksmith's forge, when these elements are ingredients of the steel to be welded. Some of these steels have been welded, but an efficiency of over 25% is seldom obtained.

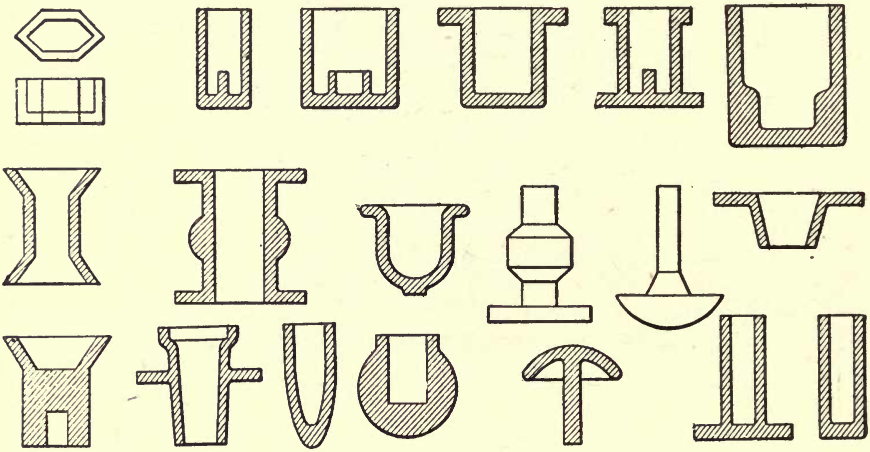


FIG. 75. — More shapes made in hydraulic press with loose die blocks.

Carbon, however, is the principal enemy of welds, and with this as low as 0.15% it must be handled with great care at the welding heat, while with 0.20% of carbon the steel is very unreliable, and with 0.50% of carbon the steel is liable to be burnt at a temperature well below the welding heat.

Thus to make hand-forgings where welds are necessary, the pieces must be from two to three times the size of that necessary for the required strength, and with some of the alloyed steels even this will not suffice.

PRINCIPLES INVOLVED

Welding consists of heating two pieces to a high temperature, then dissolving off the iron oxide, which has formed on the surface, by the use of some flux, such as borax, and then firmly pressing the pieces together. Welding plates are sometimes put between the pieces to be welded in place of the borax. These are special preparations which are made for this purpose, and are covered by patents.

The exact temperature at which to heat pieces for welding is not known, but it is near the melting point, as the steel must be in a soft, almost pasty, condition. The pieces are usually upset or enlarged at the ends, so that the section at the weld will be larger than the rest of the piece. In the ordinary weld they are hammered continuously until the metal has cooled to a dull red. This breaks up the coarse crystals which have been produced by the high temperature, and by finishing at a low temperature a small grain is secured.

This small grain is obtained, in the metal close to the weld, by proper welding, but there is always a place within a short distance of the weld that must have been heated to a high temperature, which means overheated, and has not received the mechanical treatment given at the weld by hammering it down to the proper finishing temperature. This will cause the metal to have a coarse grain at this point, which is usually from 4 to 8 inches from the weld, and the steel to break when submitted to strain much less than the original strength of the metal welded. Thus, while the average welder may say that if no break occurs at the weld it is as strong as the original piece, this is not true and welds are seldom made by hand methods that have more than 60% of the efficiency of the original piece. In a large number of tests which were made it was found that the chief cause of damage was the bad crystallization adjacent to the weld.

All steels that have been welded would give better results if they were reheated to a little above 1650° F., as this heating would restore to a large extent the grain size of all parts.

Steel is burned when the first drops of melted metal begin to form in the interior of the mass. These segregate to the joints between the crystals and cause weakness. The second stage of this is when the molten drops segregate as far as the exterior and leave behind a cavity filled with gas. The third and last stage is reached when gas collects in the interior under sufficient pressure to form miniature volcanoes and break through the skin. This projects liquid steel and produces the well-known scintillating effect of this temperature. Into the openings formed by these miniature explosions air enters and oxidizes the interior. Steel that has been overheated to this extent cannot be fully restored by either mechanical working or heat refining.

ELECTRIC WELDING

The hand method of welding being a slow, laborious process when large pieces were to be welded, and the efficiency of the welds being low, it became necessary to abandon welding, in many cases, as a commercial possibility, or to invent some other means of performing the welding operation. This necessity brought into use two electrical welding processes and several gas processes.

In the electrical resistance process the pieces to be welded are usually butted together and clamped so there will be a pressure against each other. Two electrodes are then placed on each side of the joint to be welded, and the current of electricity passing through these also passes through the steel at the joint. This softens the metal by heating it nearly to the melting point, and the pressure of one piece against the other squeezes them together until they are welded.

This process has many advantages over the hand method. The heating can be localized and held in the immediate vicinity of the weld, and the hand can be held on the metal but a very few inches back from the weld. This prevents the metal from crystallizing 6 or 8 inches back as in the forge-heated piece; the temperature of the surfaces to be welded is always under control, which reduces the danger of overheating the steel to a minimum. The pressure between the abutted pieces may be regulated to any pressure desired and very irregular shapes may be butted together and welded in a very accurate manner. The efficiency of the weld has been increased 50%, and in some cases 100% over that of hand welding.

The other electric welding process is called arc welding. In this a carbon electrode is placed in a holder so it can be held in the hand close to the work, which is placed on an iron or steel-topped table. This table is connected to a rheostat, and that to the power supply, as is also the carbon electrode. A water rheostat is usually used. With the proper connections made, the electric current flows through the rheostat and the carbon electrode and strikes an electric arc, the same as do the arc lamps seen in the street. This creates an intense heat that melts the metal on each side of the joint, and by holding a rod in the other hand, new metal can be fused with the old metal in the joint, and the two pieces stuck together.

This is a process of casting steel into the joint, and hence rolled or forged metal cannot be made as strong as the original stock except by leaving a ridge at the weld, so the metal will be thicker. Even this, however, will make a stronger weld than can be made by the blacksmith with a hammer, anvil, and forge fire. If the arc electric welds were hammered after welding, while the metal was still hot, and before it had cooled to a dull red, the weld could be made much stronger, as this would change the grain from the coarse crystalline one of a casting to the more dense grain that approaches that of a forging.

Alloyed steels that do not lend themselves readily to welding by hand can be successfully welded by the electrical process. The density of the metal is much more uniform when welded by electricity than by the hand method, and the weld is made in a fraction of the time. The amount of work required in finishing after electric welds is very small, as it leaves it comparatively smooth; a slight ridge right at the weld being practically all the deformation there is in the metal.

This has aided greatly in the production of forgings, as they can be made in two, three, or more pieces and afterward welded together. It has also been found in many cases to be a better method than brazing, and is sometimes substituted for this.

WELDING WITH GASES

Several different processes of welding with gases and a blowpipe or torch have recently been developed, and these have become quite a factor in the manufacture and repair of metal parts of all kinds. The gases used for these various processes are acetylene, hydrogen, liquid gas, city gas, and natural gas, which are burned either with oxygen or with air. All of these processes operate in the same way as the arc electric; *i.e.*, they melt new metal into the joint and fuse it with the old.

Of the several gas processes the oxyacetylene has taken the lead, and this consists of heating the metal with a torch, using oxygen and acetylene gas. With this the metal is heated to the melting point, and a steel rod is passed along with the flame, when steel is being welded, and the metal melts off from the rod and flows into the joint until it has been filled.

The flame is largely carbon monoxide, but at the tip where the heating takes place it is converted into carbon dioxide. This gives a flame that will neither carbonize or oxidize the metal. In lighting the blowpipe or torch the acetylene is first turned on full, then the oxygen is added until the flame has only a single cone whose apex has a temperature of about 6300° F. Too much acetylene produces two cones and a white color, while an excess of oxygen is shown by the flame assuming a violet tint and a ragged end. The best welding results are obtainable with 1.7 volumes of oxygen to one of acetylene.

The oxygen for the process is obtained by either using a special generator that generates oxygen from chemicals, or by buying the oxygen that is stored in steel bottles and sold in the open market. It is used at a pressure of about 15 pounds per square inch. The acetylene gas is manufactured in the ordinary way from calcium carbide, and used at a pressure of 2 or 3 pounds.

Through a system of piping, the flame is easily carried to the work, which saves the labor of moving large pieces of work to a forge or hammer for welding. Pieces one inch thick have been successfully welded with this process, but its best application is in welding thinner sheet metal, as joints of great length can be easily welded. In fact, its only limit is the length of the joint and the time needed, and this latter can be carried out indefinitely.

Oxyacetylene welding gives its best results in the welding of steel, but cast iron is being welded successfully as well as copper, brass, and bronze.

The different metals can also be welded together as is shown in Fig. 76, in which four plates were butted together and welded. One plate was steel, as shown by the white square; another brass, as shown by the darker square in the diagonally opposite corner; and the two very dark squares were copper and bronze respectively. After welding these they were bent and broken at the joints to see if they were thoroughly welded, and from the appearance of the fractures they would indicate a perfect weld. The steel welded to the copper and bronze as well as the brass did. Owing to the high heat of the flame, however, some of the lead and zinc in the brass and bronze melted out, leaving holes in the metal.

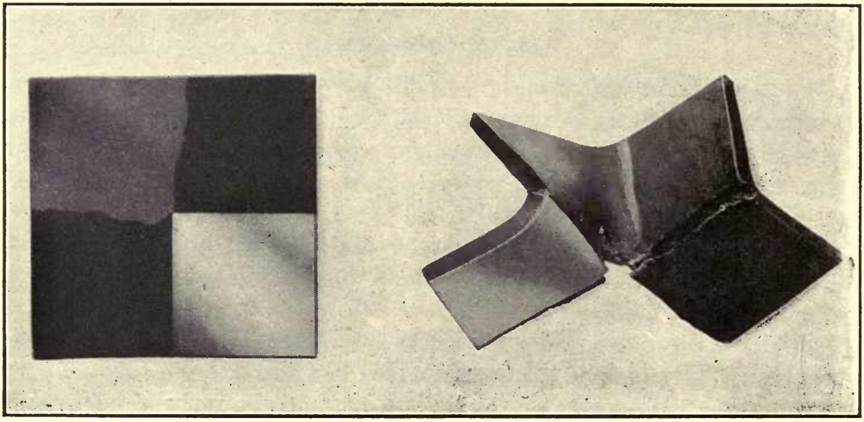


Fig. 76. — Steel, copper, brass, and bronze welded together.

This welding process, as well as all the other gas processes, makes the weld by casting metal into the joint in the same way as does the arc electric welding process. Therefore, on rolled or forged metal the joint is not as strong as the original metal, but it is stronger than a weld made with a forge fire, hammer and anvil, and metals can be welded that it is impossible to weld in the latter way. In some cases an efficiency of 90% has been claimed, but if the work is properly done an efficiency of at least 80% can be obtained with any metal.

The oxyhydrogen process only differs from the oxyacetylene in that hydrogen gas replaces the acetylene gas. The oxygen and hydrogen are used in the proportion of from 2 to 4 parts hydrogen to 1 of oxygen, and the hottest part of this flame is about $\frac{3}{8}$ of an inch from the point of the burner.

Two parts hydrogen to one of oxygen will give a flame with a temperature of about 4350° F., but if a flame is desired with a reducing action it is necessary to use 4 parts of hydrogen to 1 of oxygen, and this will have a temperature of about 3450° F. This flame will melt iron or steel, and cause it to weld even if the surfaces are not clean, as any rust present will be reduced. It is also a very good flame to use for the cutting up of metals. This lower temperature of the flame is really better for sheets up to $\frac{1}{8}$ of an inch thick, as the melting of the metal is less rapid and less explosive, giving a welded joint that is cleaner and with fewer scars and blisters.

The oxyliquid gas welding process consists of replacing the acetylene or hydrogen with liquid gas, and as this combination generates a heat of about 4000° F., it will make welds that are equal to either of the above processes, and for all practical purposes it is as good. The liquid gas is a product that is made from crude oil and stored in steel bottles, similar to oxygen, at a high pressure. At this pressure it is a liquid, but when allowed to expand to the 15 pounds pressure required for welding, it becomes a gas, and is mixed with the oxygen in a torch, the same as the other processes.

Another process uses city or natural gas and oxygen. These are combined in a torch, to get the proper mixture and generate the necessary heat for welding. For many purposes this is very useful, but the flame does not have as high a temperature as the others.

Still another process consists of combining city or natural gas with two blasts of air; one of which has a high pressure and the other a low pressure. These are sent through a special torch and have been used to successfully weld cast iron and the non-ferrous metals. It does not seem to develop enough heat to weld steel, and therefore its field seems to be limited to metals of a lower fusing temperature than steel. Acetylene has also been used in addition to the above gas and air with good results.

THERMIT WELDING

The thermit process of welding is radically different from all the other processes, and is useful for an entirely different class of work.

In this process, a sand mold is built around the pieces to be welded and the metal poured in this. The mold is made of sand and clay, which should be mixed thoroughly stiff and as dry as possible, as the less moisture there is in the mold the better will be the results obtained. For this reason the mold should be dried in a furnace or oven at a low temperature for from six to eight hours. To test the dryness of the mold, two or three wires can be rammed up in the thickest section of it and these pulled out after drying to see if any moisture remains.

With the mold completed the thermit is placed in a special receptacle which is located over the mold. The thermit consists of aluminum and oxide of iron. A little ignition powder is placed in this and lighted with a match. Immediately there sets up a tremendous chemical action, which produces a superheated liquid steel and superheated liquid slag consisting of aluminum oxide. When the mass is entirely molten it attains a temperature of 5400° F. The bottom of the receptacle is then tapped and the liquid metal runs into the mold and into and around the joint to be welded. The high temperature of the liquid mass causes the ends of the pieces to be welded, to become molten and pasty, and fuse with the thermit.

Welds were made with this process on a bar of rolled steel, 2 by 4½ inches, which was broken, then welded, and afterwards tested. The tests showed an efficiency of 97% in tensile strength and 88% in elastic limit.

The greatest usefulness of this method of welding is for the stern frames of steamships which have broken, locomotive side frames, driving wheels, connecting rods, and other things of a similar nature, but the building of the mold makes it commercially prohibitive where autogeneous or electric welding can be used economically.

CHAPTER VIII

Furnaces and Fuels Used for Heat-Treatment

In working steels it is very important that they be properly heat-treated, as poor workmanship in this regard will produce working parts that are not good even though the stock used be the highest grade of steel that is procurable. And by improperly heat-treating them it is possible to make high-grade steels more brittle and less able to support a load or withstand stresses than ordinary carbon steels. All steels are improved in tensile strength, elastic limit, elongation, or reduction of area by annealing, hardening, or tempering them. The different treatments are divided into three distinct classes, the first of which is hardening, the second annealing and reheating, and the third case-hardening, carbonizing, or cementing.

The theory of heat-treatment rests upon the influence of the rate of cooling on certain molecular changes in structure occurring at different temperatures in the solid state. These changes are of two classes, critical and progressive; the former occur periodically between certain narrow temperature limits, while the latter proceed gradually with the rise in temperature, each change producing alterations in the physical characteristics. By controlling the rate of cooling, these changes can be given a permanent set, and the physical characteristics can thus be made different from those in the metal in its normal state.

The results obtained are influenced by certain factors as follows: First, the original chemical and physical properties of the metal. Second, the composition of the gases and other substances which come in contact with the metal in heating and cooling. Third, the time in which the temperature is raised between certain degrees, or the temperature-rise curve. Fourth, the highest temperature attained. Fifth, the length of time the metal is maintained at the highest temperature. Sixth, the time consumed in allowing the temperature to fall to atmospheric or the temperature-drop curve.

The third and sixth are influenced by the size and shape of the piece; by the difference in temperature between it and the heating and cooling mediums, and by the thermal capacity and conductivity of the latter. Each of these may vary widely within the temperature range to which the piece will be subjected.

The first, second, third, and fourth are but elements of the heating process, and the sixth of the cooling. The method of heating the alloy steels is very important, as mechanical injuries are liable to occur, in the external layers of the metal as well as the internal, from a too rapid rise in the temperature, especially at the start.

The highest temperature to which it is safe to submit a steel for heat-treating is governed by the chemical composition of the steel, and this temperature should be about 40° F. above the highest point of transformation in the steel considered. This pure carbon steel should be raised to from 1450° to 1650° F., according to the carbon content, while some of the high-grade alloy steels may safely be raised to 1750° F., and the high-speed steels may be raised to just below the melting point. It is necessary to raise the metal to these points so that the desired change in structure will be secured. If raised far above these temperatures in an oxidizing atmosphere, the surface of the piece becomes covered with a scale of iron oxide and oxidation extends to the elements combined with the iron.

When these oxides remain within the metal, they tend to form a film of separation between the metallic grains, thus destroying the cohesion between them, and the metal is said to be burned. After burning, it cannot be brought back to its former strength without remelting. If the temperature is maintained within the crystallogenic zone, disaggregation proceeds, so that the longer it is subjected to this temperature and the higher the temperature, the less homogeneous it becomes and the coarser its grain after cooling. Steel in this state is called over-heated. It can be partially returned to its former strength by repeated forging when heated above the critical temperature, followed by positive quenching, or it may be restored by a proper method of heat-treating.

When, as always happens, the grain has become coarsened by overheating it must be refined again to bring it back to its original condition. To do this it is necessary to heat the metal to the point where a new crystal-size is born, as the coarsening of the grain is merely a growth of the crystals, and these crystals grow with every increase in the temperature above the point necessary for hardening or annealing. If we barely pass the degree of temperature at which this new crystal-size is born we will obtain the smallest grain size that the steel is capable of. This temperature varies with the carbon content of the steel. The higher the percentage of carbon the lower the degree of temperature that will be required; a low-carbon steel must be heated to 1650° F., a 0.40% carbon steel to 1475° F., and so on. Some of the special alloying materials also affect this temperature as well as the size of the grain.

FURNACES AND THEIR FUELS

Owing to the nature of most steels they must be handled very carefully in the processes of annealing, hardening, and tempering; for this reason much special apparatus has been installed in the past few years to aid in performing these operations with definite results. This apparatus is divided into two distinct classes; that is, the apparatus for heating the metal, and that for cooling. In heating the metal four methods are used; namely, furnaces using solid fuel, liquid fuel, gaseous fuel, and electricity.

The forge fire was at first used for burning solid fuels, such as coal, coke, charcoal, etc., to heat metals. From this developed the enclosed furnace, as shown in Fig. 77, and consequently these are the most numerous. In the furnace is a grate on which to burn the fuel, and over this an arch to reflect the heat back to a plate on which the work is placed. This plate should be placed so that the flames will not come in contact with the pieces of metal to be heat-treated. For this reason cast iron or clay retorts are sometimes used in the furnace to place the work in, while the necessary heat is obtained by the flames encircling these. They only have an opening on one side, and this is placed opposite the front door, so the work can be easily passed in and out. The oxidation, sulphura-

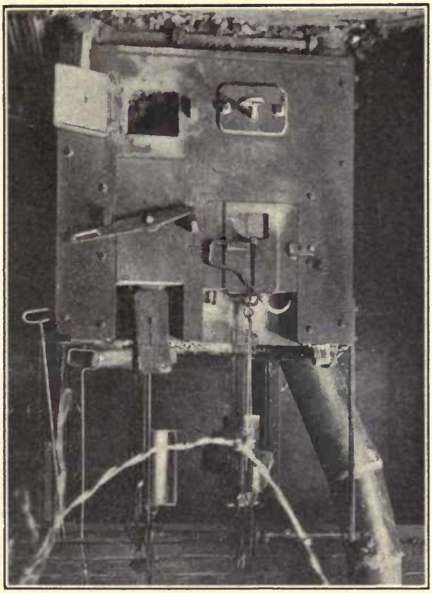


FIG. 77. — Hard fuel furnace for heat-treating steel.

tion, etc., that spoil the smooth surfaces of the work, and are largely caused by the products of combustion of the hard fuels, are thus eliminated as much as possible with this kind of furnace and fuel. With this furnace it is necessary to keep the heat in and the cold air out as much as possible, and therefore the doors should open and close very quickly to aid in the rapid handling of the work. For this reason the sliding doors with counterbalancing weights, as shown, should be used.

The disadvantage of this style of furnace is that it is almost impossible to keep a constant temperature, and as a chimney must be provided, much heat is lost through that. By not being able to keep a constant temperature, it is impossible to measure the heat with a pyrometer, and the heat must be judged entirely by the color, as seen with the eye, and this makes the results depend entirely on the skill and experience of the workman. Also the atmospheric air or gases generated by combustion or a mixture of both come in contact with the hot metal. These are liable to cause the metal to lose some of its carbon content, especially at corners or on thin delicate sections, from the oxidizing influence of the oxygen in the air. The fuel is also liable to contain injurious ingredients, such as sulphur, which may enter the steel.

LIQUID FUEL

Furnaces that use a liquid for fuel, such as crude oil, kerosene, gasolene, naphtha, etc., are becoming more numerous every day, owing to the ease with which the fire is handled and their cleanliness as compared with a coal, coke, or charcoal fire.

Crude oil and kerosene are the fuels generally used in these furnaces, owing to their cheapness and the fact that they can be obtained nearly everywhere. The adoption of oil for fuel has resulted in a considerable saving in the fuel bill over that of the coal-burning furnaces, and has also made a big improvement in the cleanliness of the hardening room. In fact, where natural gas is not obtainable at about one-quarter of the usual price of city gas, crude oil is by far the cheapest fuel that can be obtained for heat-treating furnaces. An exception to this might be made in the future when considering producer gas, but at present enough data has not been obtained by which to draw comparisons.

One of the simpler of these oil-burning furnaces is shown in Fig. 78. With any of the oil furnaces gas can be used as a fuel by merely changing the burners. With a properly designed furnace the temperature can be raised quickly to the point desired; can be maintained at this temperature for any length of time, and an even heat can be kept throughout the entire chamber of the furnace. With the proper fuels and valve for regulating this, the temperature in the furnace can be raised or lowered as rapidly or as slowly as necessary for the different kinds of work. In the annealing of metals also the rate of cooling can be made as slow as needed if the proper equipment is installed. All of this can be accomplished without the customary smoke, soot, ashes, dust, gases, and foul odors that are met with in hardening rooms where the old hard fuel furnaces are used. The saving in the time consumed by the operator in running the furnace is also an important factor, as when the proper temperature is once obtained and the valves set, practically no time is required for this part of the work.

The installation of the furnaces and their necessary equipment is very important for the proper operation of the same. For safety, it is best to have the fuel supply in a tank outside of the building and pipe it, underneath the floor, to the furnace. As a blast of air is necessary, this can also be piped, under the floor, from the fan, blower, or air compressor. The air and fuel pressures must be steady and uniform, and there must be volume enough to give the furnaces their proper temperature and maintain it at the point desired. This, of course, varies with the kinds of material to be heated.

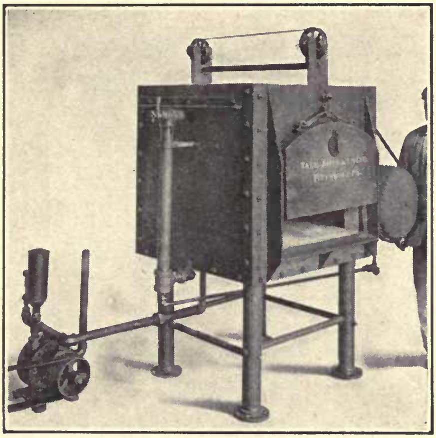


FIG. 78.—Oil-burning, annealing, tempering, and hardening furnace.

Where accurate temperature control is not necessary, and pressure under 14 ounces will suffice, a steel fan or pressure blower, that will give the proper volume, will do the work. Where pressures from 2 to 5 pounds are required the positive pressure blower is needed, and when an air pressure above this is necessary a compressed-air plant will be needed. In some cases good dry steam will give better results at a high pressure and effect a saving in the fuel. In that case steam pipes take the place of the air pipes, and these connect up to the steam supply. The quantity of fuel needed varies with the temperature required, material treated, and speed at which it is handled, but the fuel pressure must always be uniform. For the oil 5 pounds pressure is sufficient.

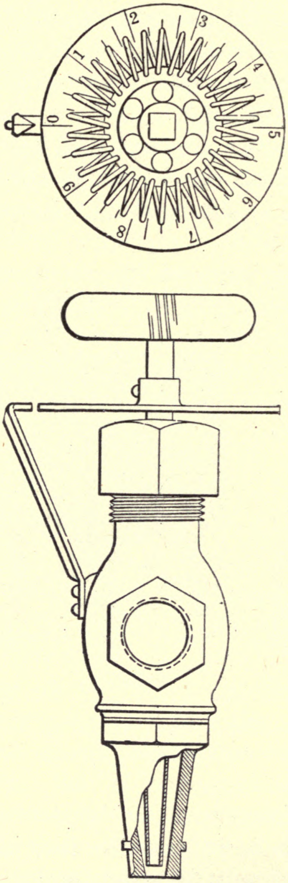


Fig. 79.—High-pressure oil burner.

In some cases between the tank and furnace is located a coil of pipe through which the fuel flows and over which a stream of water is flowing to keep the liquid at a low, even temperature when it enters the burners, which are located in the furnace.

The burner to be used is an important factor in economical production, and it is not practical to have one burner that will do all kinds of work. Whether high or low pressure air or steam is to be used for the blast makes a difference in the kind of burner that should be used to get the greatest efficiency with the minimum fuel consumption, as well as the temperature that it is necessary to maintain in the forge, and the nature of the work that is to be done. In Fig. 79 is shown a good design of high-pressure oil burner.

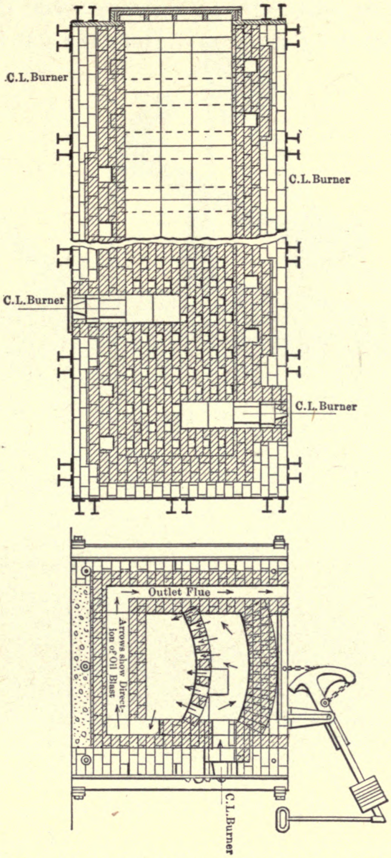


Fig. 80. — Details of construction of over-fired furnaces.

The dial with the figures and the pointer at the bottom have been added for fine adjustment. The sectional view at the tip shows the method of controlling the volume of atomized oil that is injected into the furnace.

With this fuel hardly any work is required to keep up the fires, as they can be lighted in the morning and the temperature regulated by the turning of a few valves and cocks. A more even temperature can thus be kept in the furnace than with the solid fuels, but the opening of the doors to handle the work reduces the temperature of the furnace the same as with the solid fuels. The action of the gases of combustion or the oxygen of the atmosphere in attacking the hot metal gives the same disadvantages.

The furnaces are built in the over-fired and the under-fired type. In the over-fired furnace, as shown in Figs. 80 and 81, the atomized gas from the oil burner is sent into an opening over the heating chamber that is separated from it by an arch. Here the gas is burned and passes through numerous openings in the arched roof of the heating chamber, as indicated by the arrows in the right-hand view in Fig. 80. The burned gases then pass out through holes in the side of the heating chamber, close to its floor; then under it and up through flues on the opposite side.

Fig. 81. — Small over-fired furnace.

Thus the entire heating chamber is uniformly filled with the products of combustion and the spent gases utilized to heat the floor of the working chamber. This gives a soft uniform heat throughout the working chamber, and the temperature is so easily raised, lowered, and controlled that overheating or burning the metal can only result from gross carelessness.

This uniform heat in the heating chamber also reduces to a minimum the distortion and warping that results from uneven heating, and a more even hardness can be obtained throughout the piece than can be produced with a hard fuel or under-fired furnace.

With the proper fuel supply and valves to control the same, the temperature of the heating chamber can be maintained for an indefinite period, within 25° F. of any temperature between 600° and 2000° F. On test runs of $1\frac{1}{2}$ hours each, at certain temperatures, the variation was not over 10 degrees.

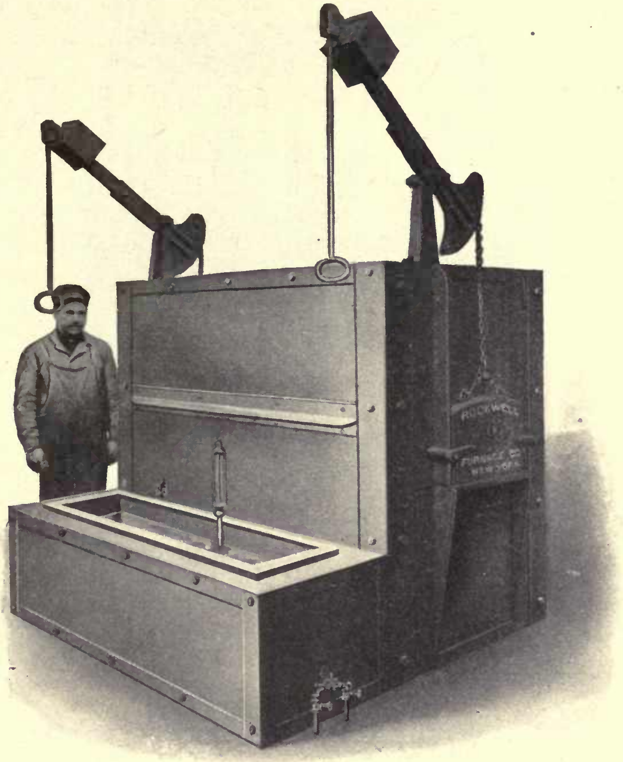


FIG. 82. — Double-end furnace with tank for quenching bath attached.

For high-grade alloy steels, where the most accurate results are required, the muffle furnace should be used, in order to avoid the action of the products of combustion on the metal, since it is liable to absorb some impurities from the gases. These impurities might weaken the metal and leave it less able to withstand the strains and stresses put upon it than would be the case if the metal were protected from them. For ordinary work, however, the injury is so slight it can be overlooked, and the fuel consumption is much lower in the oven than in the muffle furnace.

A furnace open at both ends, wth a tank attached to hold the quenching bath, is shown in Fig. 82.

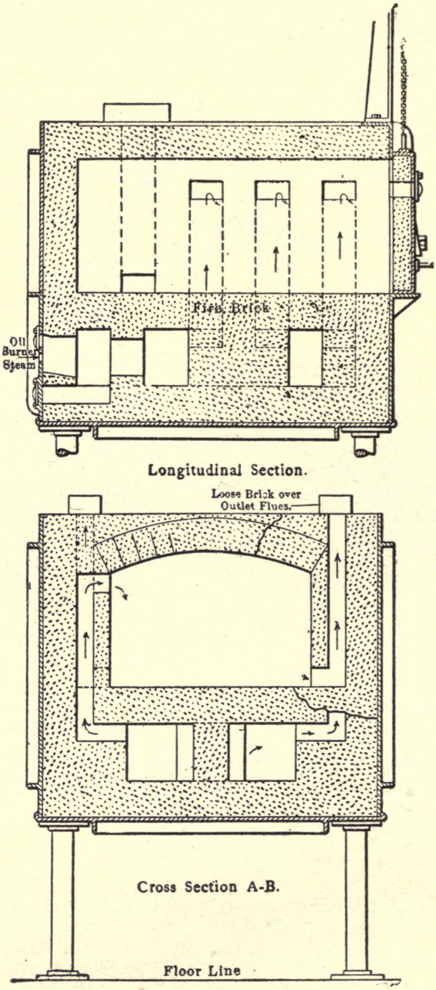


FIG. 83. — Details of under-fired furnace.

In the under-fired furnace, as shown in Figs. 83 and 84, atomized gas is injected into an opening underneath the heating chamber, and there the combustion takes place. It then passes through flues into the top of the heating chamber, and out of here through openings near the floor into flues on the opposite side. These conduct it out of the furnace. The burners and the flues on this, as well as the over-fired furnace, are staggered on opposite sides of all the larger furnaces, to make the heat uniform in all parts of the heating chamber.

The construction of this furnace is simpler, and hence its first cost is less than that of the over-fired type. It is also much easier to reline and repair when burned out. The fuel consumption, however, is slightly greater than in the over-fired type and a uniform heat in all parts of the work chamber is not as easily obtained, especially in large furnaces. In the smaller under-fired furnaces the heat is easily controlled, and with oil fuel a high temperature can be attained and maintained throughout the day. This makes it very useful for tool hardening and tempering.

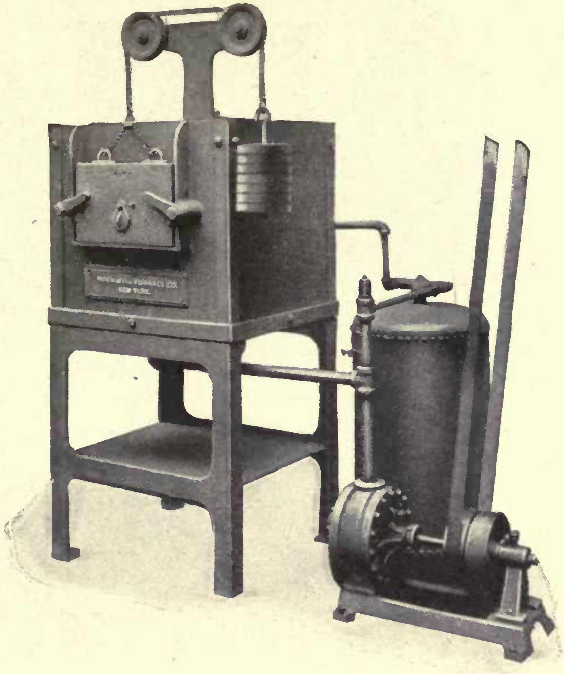


Fig. 84. — Small under-fired furnace with complete oil-burning outfit.

In Fig. 85 is shown an oil-burning furnace with a self-contained outfit that makes it portable, and Fig. 86 shows one with a water-cooled front. The latter is made of fire-brick, with any size or shape of openings desired, and is very useful for heating the ends of tools and keeping the bar cool enough to handle. In both of these furnaces a temperature of 2500° F. can easily be maintained, and thus any kind of high-speed steel can be hardened.

Another style of oil furnace is the muffle furnace. In this the gases surround the heating chamber, but do not enter it. Thus the metal is protected from any injurious effects from the gases of combustion while they are being heated.

Any of the above liquid fuel furnaces can be used for the gaseous fuels by merely changing the burners.

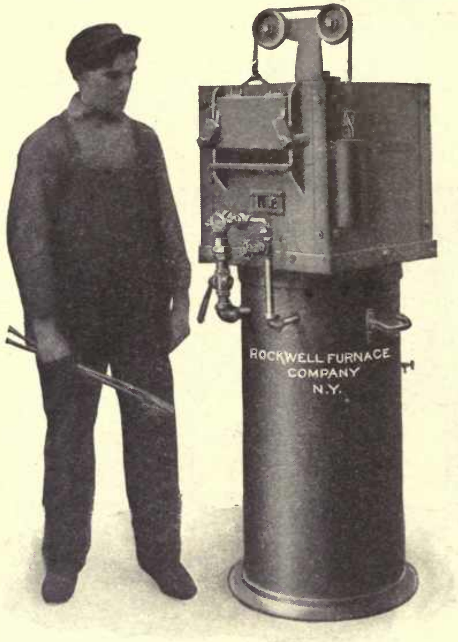


FIG. 85. — Portable oil furnace with self-contained outfit.

GASEOUS FUEL

Furnaces using gaseous fuel are growing in favor, and are constructed so they can use either natural gas, artificial gas, or producer gas. They are very easy to regulate, and if well built are capable of maintaining a constant temperature within a wide range. Their first cost is greater than that of solid fuel furnaces. The cost of installation, however, is soon paid for where natural gas, or possibly producer gas, is used for fuel, as then it is the cheapest furnace to operate. Artificial or city gas is more expensive than oil for fuel, but is much cleaner and easier to operate, as it is not necessary to install tanks or apparatus in which to store the supply. If the cost of the upkeep of these be figured in, there might not be such a great difference in the cost of furnace fuel, providing the city gas be obtained at a reasonable price. Where high-grade steels are used, and the best work is demanded, doubtless gas is the best fuel.

Producer gas is continually increasing in use for furnaces, but unless a number of furnaces are operated, or a few large ones, a separate producer plant to supply the furnaces is not economical. Where a producer plant can be utilized for other things, such as furnishing power, it is probably a very cheap fuel to pipe from the central power plant and burn in the furnaces. With this, or any of the gas fuels, a large part of the heat that goes up the chimney, when other fuels are used, can be utilized in heating the air of combustion that enters the furnace. This can be done with very little special construction.

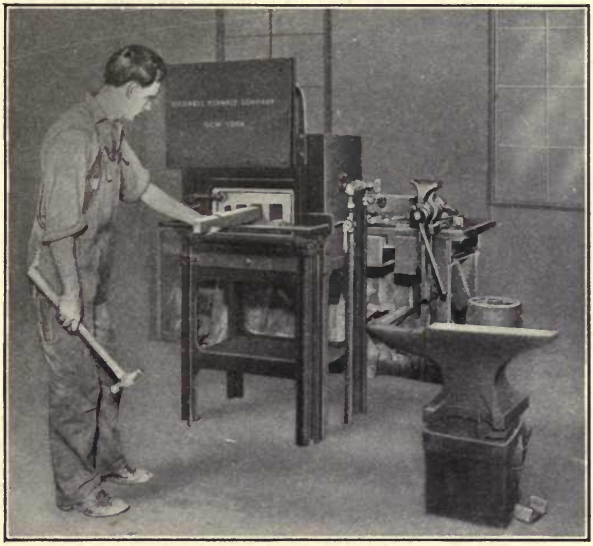


Fig. 86. — Oil furnace with water jacketed front.

Results which are very uniform are obtained with the gas furnaces, and it is much easier to maintain a constant temperature for liquid baths than in a solid fuel furnace, or a metal retort may be used to place the work in for the purpose of keeping it away from the gases of combustion, with a greater assurance that the work in it will be raised to the proper temperature and maintained evenly for a given length of time.

One of the muffle or oven style of furnaces that uses gas for fuel is shown in Fig. 87. In this the blast connects at *C* with the end of the drum *D*, and goes through the pipe *A*, where it picks up the gas at *G* and carries it to the burners *B*. In placing a cutter like *X*, in the furnace, it should be supported by a fire-brick similar to *Y*, so the teeth will not touch the bottom slab *Z*. The door *E* has a counterweight above *H*, so it can be opened and closed quickly, and it slides in the guides *S*. At *P* is a peep-hole, and at *V* is a vent to allow the gases to escape from the furnace. This principle has been carried farther by revolving the oven, or work holder, and sending the heating gases around it, as shown in Fig. 88.

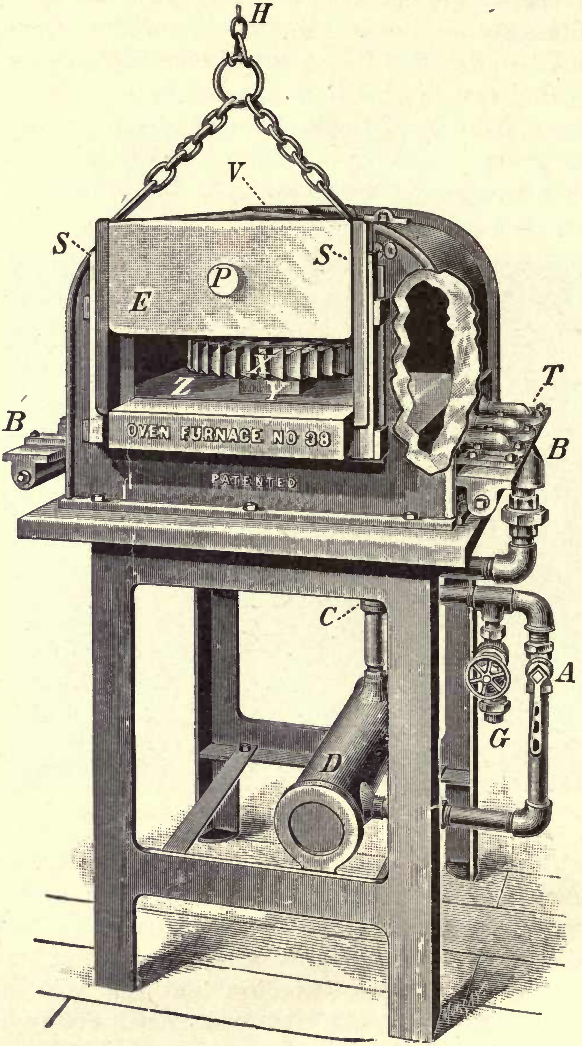


FIG. 87. — Gas furnace with oven.

Pyrometers can be used very easily to measure the heat with this style of furnace. Thus definite results may be obtained in the degree of temperature without depending on the skill or knowledge of the workman to as great an extent as with the furnaces using coal, coke, or charcoal for fuel. Furnaces using liquid and gaseous fuels differ very little in their construction, and are made in many different styles and sizes to suit the various materials they are to handle, or the kind of heat-treatment.

An instance of this is shown by the upright furnace in Fig. 89, which is for heating long bars or steel pieces. The heat is evenly distributed in the heating chamber by regulating burners *F*, which enter the furnace from four sides and on a tangent, so as to give the flames a swirling motion. They are controlled by the gas and air valves, *A* and *G*. For short lengths the upper burners *E* are shut off, and the section *Y* can be removed and cover *Z* lowered. The large opening at *I* will give the necessary draft, and vents *H* can be used for peep-holes, while vent *P* allows the used gases to escape.

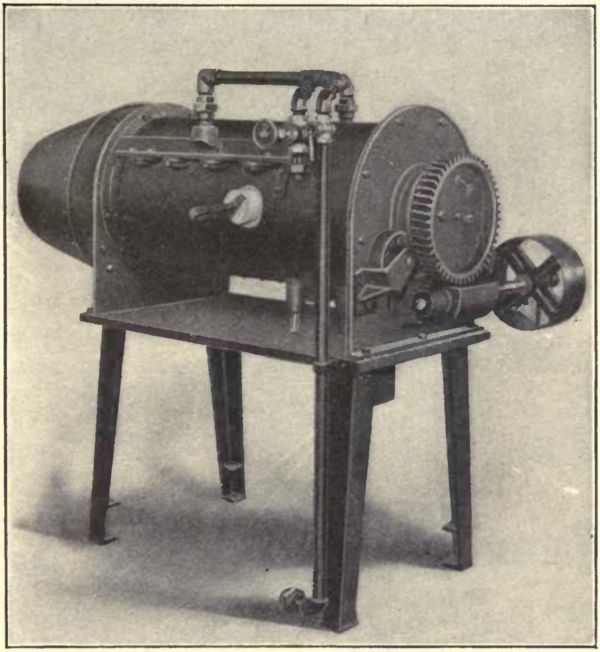


Fig. 88. — Gas furnace with revolving retort.

Special designs of furnaces have been made for all of the various operations of heat-treating, such as annealing, tempering, hardening, coloring, etc. Some of these have been made continuous operating and automatic as shown in Figs. 90 to 93 inclusive. In Figs. 90 and 91 is shown the furnace combined with a quenching bath, into which the work drops directly from the furnace. This quenching tank contains an automatic conveyer that lifts the work out of the tank and dumps it into a wheelbarrow shown in Fig. 91. Fig. 91 shows the details of the furnace as supplied with a smooth lining, and Fig. 92 shows the helical or worm lining that can be used with the same furnace if desired. The furnace is mounted in such a manner that its axis may be tilted at an angle, giving the revolving hearth an incline, with the discharge end lower than the entrance or feed end. The gradual incline causes the material to feed forward, and by means of a hand-wheel the degree of pitch may be adjusted so as to regulate the progression of the material through the furnace, and consequently the time of heating.

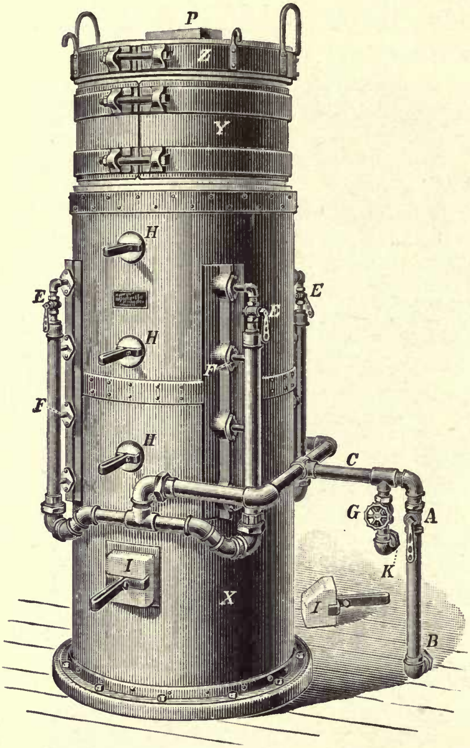


Fig. 89. — Upright gas furnace.

The advantages of this method of automatic continuous heating are many: The material is charged in a hopper in bulk at one end of the furnace and fed automatically into the chamber. It comes continually in contact with the newly heated interior surface, which is revolving, thereby absorbing the heat from the lining as well as from the heated gases. In a stationary furnace the heat from the sides and roof are not utilized, as the material remains in a fixed position; that farthest removed from the heat requires a much longer period to be brought to the desired temperature and the more exposed pieces are liable to overheating, while others are insufficiently heated. To prevent oxidation, the end of the discharge spout may be carried beneath the level of the bath, thereby sealing it and excluding the air.

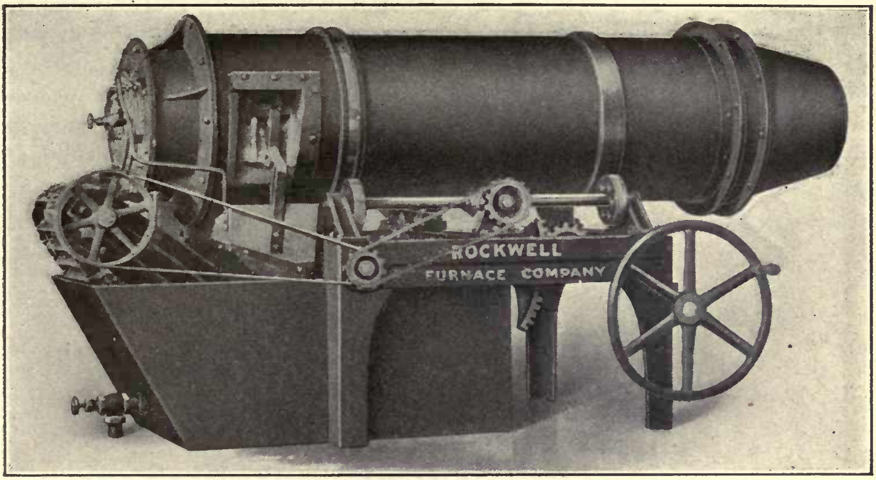


FIG. 90. — Automatic and continuous hardening furnace, with tilting mechanism.

In operation, the pieces are fed continuously into one end of the cylinder. The furnace is fired internally from the opposite end, with the zone of highest temperature at the discharge end. The cylinder revolves slowly (1 to 4 revolutions per minute), and owing to the slight inclina-

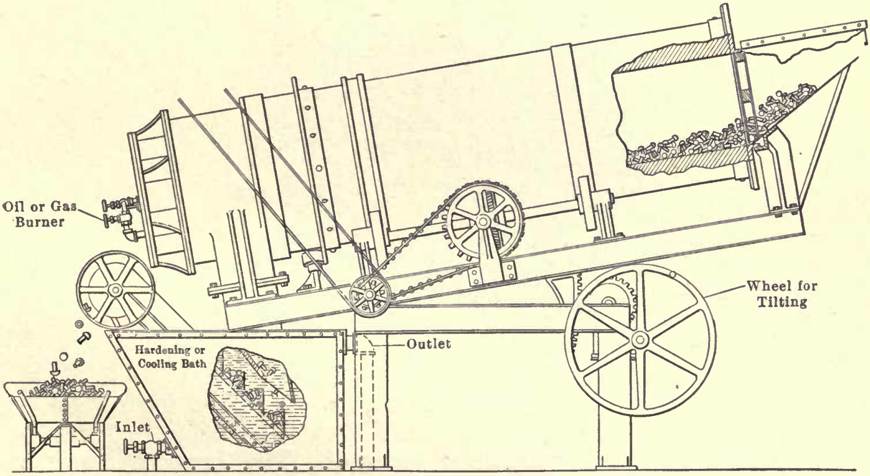


FIG. 91. — Details of continous hardening furnace, showing smooth interior.

tion of the furnace, the pieces treated fall slightly forward at each revolution, gradually progressing toward the discharge end, where they enter a proper receptacle or bath upon reaching the desired temperature.

In certain classes of work, such as balls, nuts, and uniform shapes, the helical or worm type, as shown in Figs. 92 and 93, is used, but for irregular shapes, where the smooth lining can be used, the cost is less and a greater life is insured. Fig. 93 shows the details of construction of a furnace built on the same principle, with the exception that the work is held in a revolving retort, and the heating gases surround this in such a way that they do not come in contact with the work.

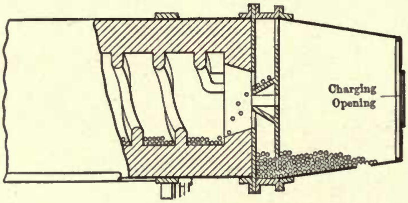


FIG. 92. — Section of same furnace with helical or worm interior.

Oil or gas fuel may be used and perfectly uniform results obtained, as the work treated is heated gradually with every portion of its surface exposed to the direct action of the hot gases and lining, and both temperature and time are maintained constant. The furnaces are built to suit a wide range of requirements, and in sizes that will handle up to 2000 pounds of stock per hour. While they were designed principally for hardening steel pieces, they are also useful for annealing non-ferrous metals, such as brass cartridge shells, etc.

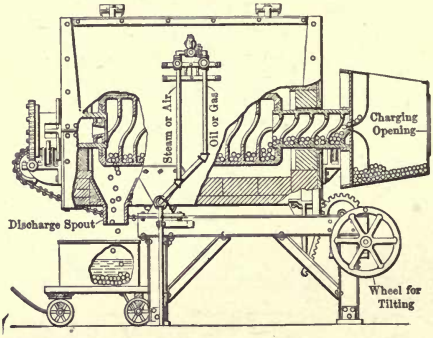


FIG. 93. — Sectional view of furnace with closed retort for work.

Automatic apparatus has also been added to furnaces to carry the work through quenching and cleansing baths of various kinds. In one case an automatic gas-heating furnace discharges its work into a tank for quenching. The quenching tank contains a conveyer for removing it from the tank into receptacles with which it can be carried away. Two tanks can also be coupled together; into the first one of which the work is dumped from the furnace for quenching. From there it is conveyed to the second tank, in which the work is cleaned, and from there conveyed to pans, trays, or other containers in which it can be easily handled. The work drops from the furnace into the quenching bath in a continuous stream, and from the hopper it is fed through a perforated barrel, that inclines down to the other end of the tank, where it is picked up by the conveyer and discharged from the tank. The perforated barrel revolves slowly to agitate the articles, thus bringing them in contact with the quenching liquid on all sides. The barrel end next to the hopper is movable, so it can be raised or lowered to make the work travel fast or slow. The liquid is admitted to the tank beneath the receiving end of the barrel, and as it becomes heated, by contact with the articles, it rises and is drained off, from the top of the tank, near the discharge end of the barrel. At the lower end of the barrel the pieces are picked up by the lower loops of an endless chain that is formed of buckets open on the inner side. They are elevated by this and dumped into a fixed hopper within the upper loop of the chain, and from there the discharge chute

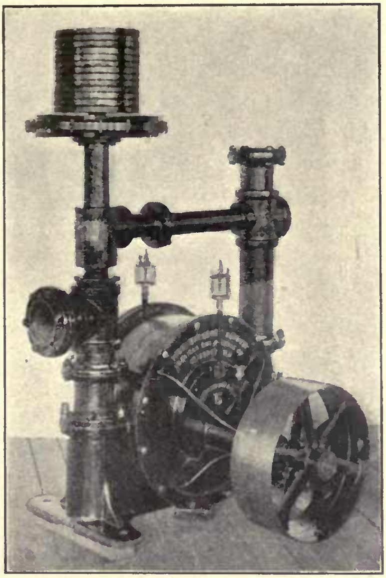


FIG. 94. — Gas booster to supply furnaces.

leads them away from the tank. The buckets are perforated so as to strain the liquid from the pieces hardened.

The double tanks may be used to quench work in the one, and then send it through a cleaning compound in the other. For instance, work that is quenched in oil may be sent through a second tank containing some liquid that will cut the oil from the work and leave it clean, or a liquid containing chemicals that act as a rust preventative may be used in the second tank. In fact there are many combinations for the double tank.

The gas pipes from the street or the main in the street are sometimes found to be too small to supply the necessary gas to the furnaces when installing them. In this case a gas booster, similar to that shown in Fig. 94, is used. This sucks the gas from the main faster than it would naturally flow, and delivers it to the furnaces as required.

With gaseous fuels, it is probably as easy to control the temperature of furnaces to within a few degrees of a given point as with any fuel used. The latest invention along this line is the automatic apparatus, for controlling the temperature of gas furnaces. It was put on the market by the American Gas Furnace Company in December, 1909, and controls the temperature to within 5 degrees of a given point. Pyrometers being required to measure these high heats, the pointer on the pyrometer indicator was used as a starting point. The pointer was left free to oscillate back and forth as the temperature rises or falls in the furnace, as anything that would retard the action of this pointer would throw the pyrometer out of true and ruin it for accurate temperature readings. At the same time it was necessary to have power enough to instantaneously open and close the gas and air valves that admit the fuel to the furnace. The mechanism also had to be positive in its action.

In Fig. 95 is shown a muffle gas furnace with the complete automatic temperature controlling apparatus attached thereto; Fig. 96 shows, on a much larger scale, the apparatus connected to the indicator; Figs. 97 and 98 show the operating mechanism of the apparatus connected to the indicator, and Fig. 99 shows the apparatus connected to the furnace. The instrument operates as follows:

In Fig. 95 the thermo-couple or hot end of the pyrometer is inserted into the furnace at *A*, and connected to the indicator at *B*. Underneath *B* is the mechanism shown in Fig. 96, while at *C* is that shown in Fig. 99. At *D*, in Fig. 96, is located a thumb screw that revolves the disk *E* and moves the pointer *F* with its arms, *G*, to the temperature at which it is desired to maintain the furnace. The arms *G*, as well as the rest of the mechanism, are operated by power supplied from a fan located in the case *J*. This is revolved by a current of air that is sent through a $\frac{1}{4}$-inch pipe, and blows against the blades of the fan.

How the arms *G* operate is best shown by the drawing, Fig. 97, which is a view that looks down on their top. When the temperature rises in the furnace, the indicator pointer *I* travels to the right until it passes under the left-hand arm *G*, which is now stationary, and comes in contact with the right-hand arm *G*, which is constantly oscillating in and out of slot *H*. When it arrives at the position shown, right-hand arm *G* grips it for an instant, and this trips the arm and throws it back to the position shown by left-hand arm *G*, so that the indicator pointer *I* will pass it and register any rise in temperature which may occur after this, due to the lag. When right-hand arm *G* is thrown back to the stationary

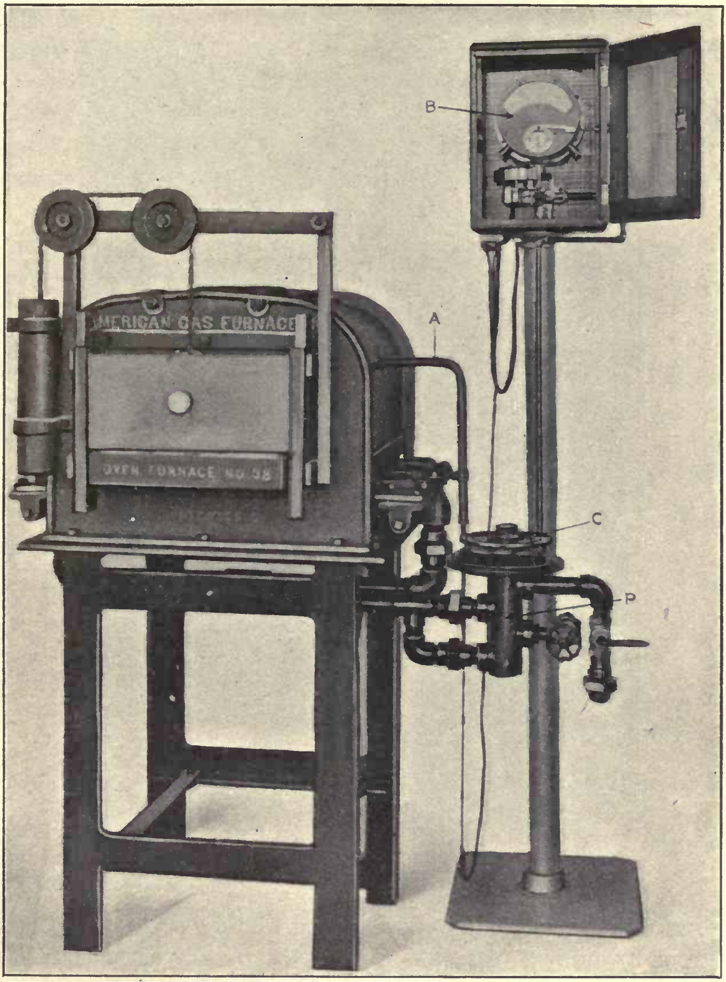


FIG. 95.—Instrument for automatically controlling temperature of furnaces.

position, left-hand arm *G* is started oscillating in and out of slot *H*, by means of a cam. The valves that admit the gas and air into the furnace for fuel are then shut off, thereby stopping the heat. Then as the furnace cools and the indicator pointer *I* travels back to the left to record the lowering temperature, left-hand arm *G* catches it, trips, turns on the gas and air, and the right-hand arm *G* starts operating.

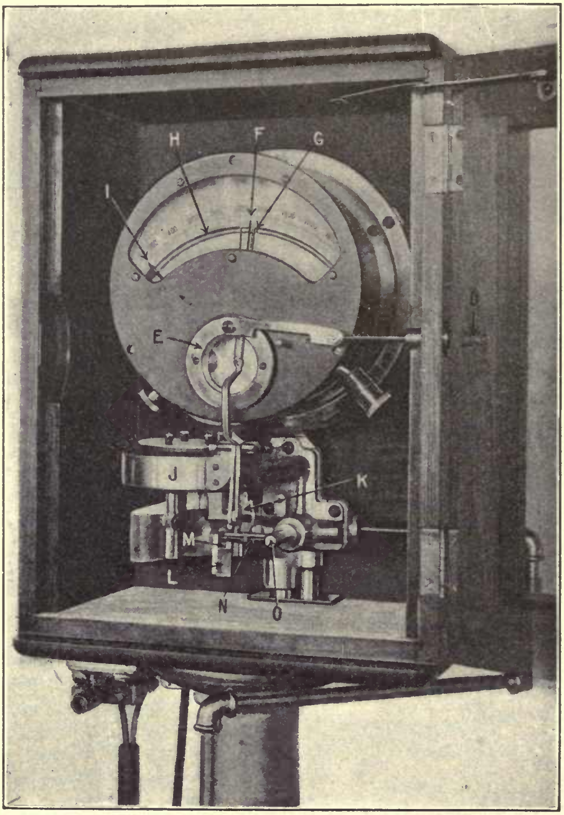


Fig. 96. — Apparatus connected to the indicator.

The arms *G* are given their oscillating motion or held stationary by the lower end riding on two disks *K*, that alternately act as cams and are fastened together, as shown in Figs. 96 and 98. The disks *K* are moved back and forth on their centers by piece *L*, which is moved back and forth the distance of the opening *M*. Piece *L* rides on bar *N* for one-half of this distance, and for the other half, the half round in the top in the opening *M* drops over the bar *N* and moves it back and forth to oscillate the disks *K*. While doing so, the end of bar *N* rides on a flat spot in the valve rod *O*, but when one of the arms *G* is tripped and the other starts operating, the end of bar *N* pushes in or out the valve end *O*, and opens or closes an air valve that sends a current of air into a diaphragm that is located in the lower part of the apparatus shown in Fig. 99. As will be seen in Fig. 98, one of the *G* arms is riding on the cam of the disk *K* and is therefore in motion, while the other *G* arm is riding on the outer circle and is therefore stationary.

In the lower part of the apparatus two square holes are provided in the cylinder *P*, Fig. 95, to act as openings for the air and gas to pass through, and over these is a plate that raises and lowers to open and close them. The amount that these can be opened and closed is regulated by moving the arms *R* and *S*, in Fig. 99. These move the center rings up or down on the screw, and they can be clamped to it by the set screws back of the arms, when the proper amount of motion for the valve slide is decided upon. The pin *T* is connected to the slide and allows it to be moved from the top to the bottom ring by the air that is admitted to or shut off from the diaphragm through the pipe *U*.

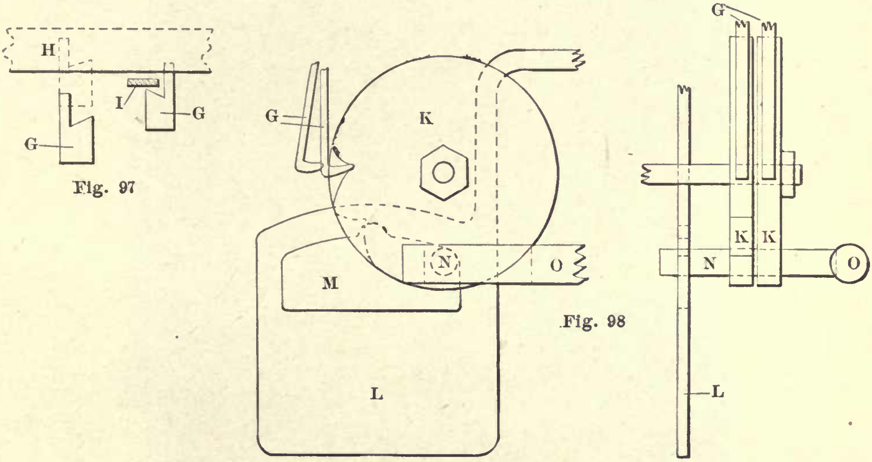


Fig. 97

Fig. 98

FIGS. 97 and 98. — Operating mechanism connected to indicator.

One point on the arbitrary scale on the disk *S* means a motion of $\frac{1}{64}$ of an inch for the valve slide, and when the arm *R* is placed at the "open" mark, and the arm *S* at the "shut" mark, the air and gas passages can be opened or closed by the slides traveling their full distance. This is seldom done, however, as the furnace can usually be regulated by turning on or shutting off a part of the heat.

This apparatus promises to fill a long-felt want in furnaces for heat-treating metals, as any one who operates them knows how difficult it is to keep the temperature at a certain given point by hand-operated valves.

HEATING IN LIQUIDS

Furnaces using liquid for heating consist of a receptacle to hold the liquid, and a chamber underneath and around its sides that is heated by coal, oil, gas, or electricity; the liquid being kept at the highest temperature to which the piece should be heated. The piece should be heated slowly in an ordinary furnace to about 800° F., after which it should be immersed in the liquid bath and kept there long enough to attain the temperature of the bath and then removed to be annealed or hardened.

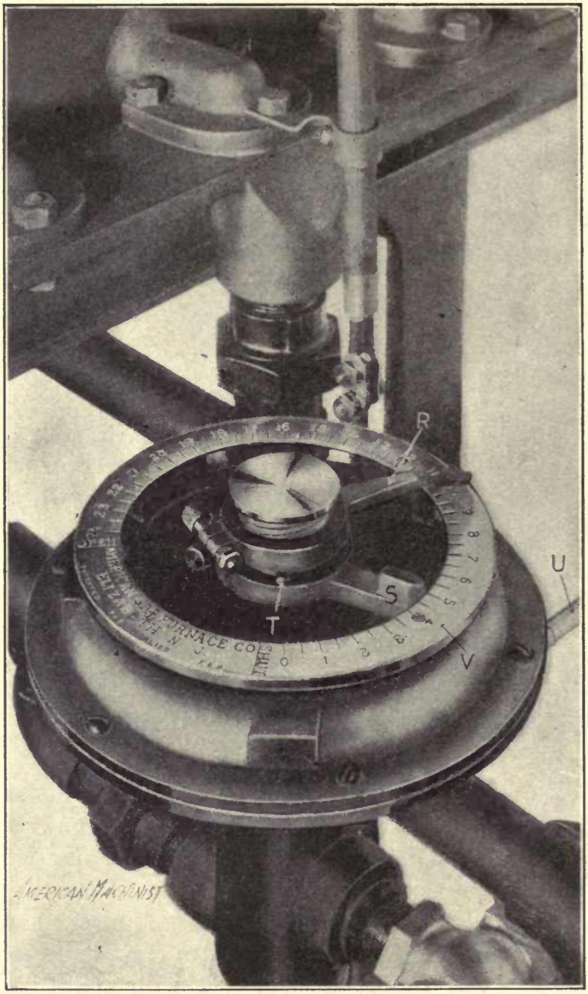


Fig. 99. — Apparatus connected to the furnace.

The bath usually consists of lead, although antimony, cyanide of potassium, chloride of barium, a mixture of chloride of barium and chloride of potassium in different proportions, mercury, common salt, and metallic salts have been used successfully.

This method gives good results, as no portion of the piece to be treated can reach a temperature above that of the liquid bath; a pyrometer attachment will indicate exactly when the piece has arrived at that temperature, and its surface cannot be acted upon chemically. The bath can be maintained easily at the proper temperature, and the entire process is under perfect control.

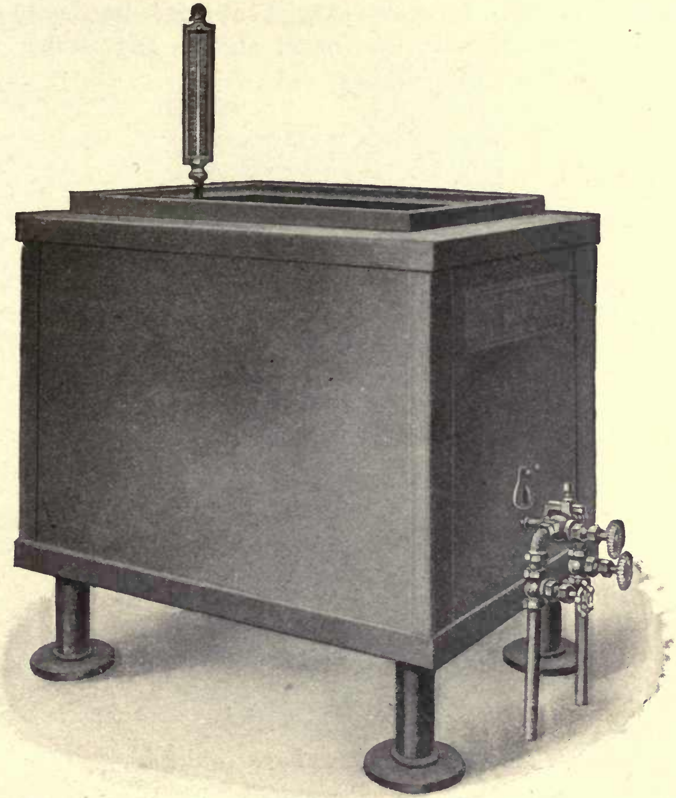


FIG. 100. — Oil or gas lead (or oil) bath furnace.

When lead is used it is liable to stick to the steel and retard the cooling of the spots where it adheres. This can be overcome to a large extent by using a wire brush to clean the work with. A better method, however, is to heat the piece to a blue color, which is about 600° F., then dip it quickly in a strong salt water, and then heat it in the lead bath to the hardening temperature. By dipping in and out of the brine quickly the piece is completely coated with salt and this prevents the lead from sticking to the piece when heating it for hardening.

The greatest objection to the lead bath is that impurities such as sulphur, etc., are liable to be absorbed by the steel, and thus alter its chemical composition. This is especially so if the lead bath is used for the hardening heats, as at these high temperatures steel has a great affinity for certain impurities. A notable example of this is its greatly increased attraction for oxygen, which the metal absorbs and retains as oxides and occluded gases. With high temperatures lead and cyanide of potassium throw off poisonous vapors which make them prohibitive, and even at comparatively low temperatures these vapors are detrimental to the health of the workmen in the hardening room. The metallic salts, however, do not give off these posionous vapors, hence are much better to use for this purpose; but in many cases the fumes are unbearable.

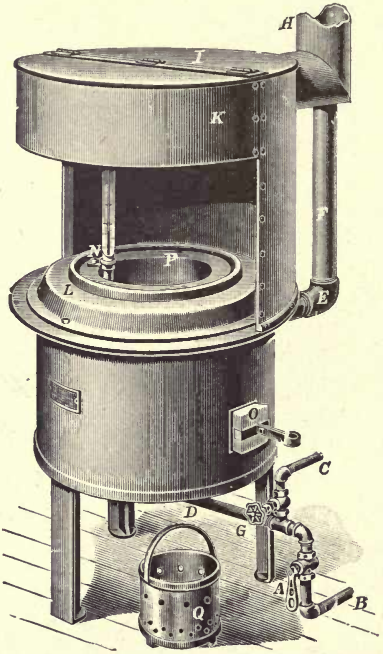


Fig. 101.—Lead bath furnace with hood.

When the lead bath is only used for the lower tempering heats the furnace shown in Fig. 100 is a good design. It can use either gas or oil for fuel, and is supplied with a high-temperature thermometer to measure the heat of the bath. This should never be higher than is desired for drawing the temper. It is a great improvement, even with this furnace, to place a hood over it that is piped to the outside of the building, and has a good draft, to carry away any fumes that may arise from the bath. This is an absolute necessity, however, when the lead bath is used for the hardening heats, and for that reason a furnace, with its own hood, similar to that shown in Fig. 101, is much better. These of course can be obtained or made with any size or shape of lead pot that is required for the work to be heat-treated.

Cyanide of potassium when applied to steel that has been heated to a red heat reduces the oxides and causes any scale that may have formed on the metal to peel off. Thus soft spots that may be caused by scale or blisters when hardening steel can be abolished by dusting cyanide on the piece before quenching it. It, however, has another use in heat-treating steel, as when the metal is heated to a red heat, in a cyanide bath, it is slightly carbonized on the surface and is thus used quite extensively for case-hardening. It should be kept at the boiling point and the metal submerged in it for about 5 minutes and then quenched. This has resulted in the building of a special furnace for heating cyanide, as shown in Fig.

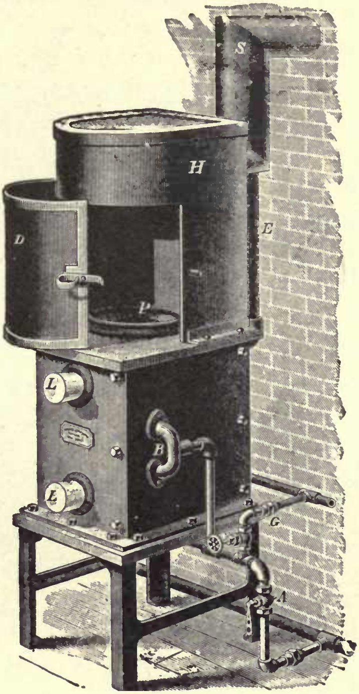


Fig. 102. — Gas furnace for pot of cyanide.

102. Here the cyanide pot *P* is suspended by its flange over a chamber filled with gas flames, and hood *H* gathers the flames and carries them out through pipe *S*.

Molten cyanide sputters and drops fly, like red-hot bullets, and consequently many bad burns are caused by its use. The fumes arising from the pot are also very poisonous, and the cyanide of potassium itself is a rank poison. It is therefore a dangerous product to use. Tools dipped in powdered cyanide and quenched in a bath causes the bath to become very poisonous, and the hand should never be put in the bath to take pieces out, as running sores that are hard to heal may be the result. Cyanide is also injurious to high-carbon or high-speed steels, and as there are many other chemicals coming into use that will do everything that cyanide will do, and some things that it will not do, this material is fast going out of use in heat-treating steel. The metallic salts are taking its place and doing much better work, and they are not poisonous.

A barium-chloride bath offers all the advantages obtained from a lead bath, or cyanide, and to this is added the advantage of the barium chloride forming a coating on the steel while it is being transferred from the heating bath to the quenching bath. This prevents the metal from becoming oxidized, by keeping it from coming in contact with the oxygen in the air. It also volatilizes at a much higher temperature than lead, or any of the other materials, used for heating baths, and therefore is successfully used for the high temperatures that are needed to harden high-speed steeels.

As pieces heated in this bath have the temperature raised evenly, and at the same time, on all sides or exposed parts, it overcomes, to a very great extent, the tendency to warping or distortion which all steels have.

While barium chloride forms a coating on the steel heated in it, this coating usually peels off when suddenly cooled in the quenching bath, and any which might cling to the metal is easily brushed off, or it can be jarred off by hitting the tool a sharp rap. This is also considerable of an advantage over the lead, used for heating steel, as frequently spots of lead adhere to the steel and are difficult to remove.

In Fig. 103 is shown a gas or oil burning furnace that was designed especially for barium chloride. It is composed of a sheet-metal shell that is lined with a special fire-brick to withstand the high temperatures that are required. A graphite crucible is used to hold the chloride. After the crucible is set in the furnace, the top, which fits close to the crucible, is placed on. This top is made of the same special fire-brick that forms the lining of the furnace, and it is held toegther by a sheet-metal band with two lugs and a clamping nut. This band is provided with two handles to make it easily movable when the crucible burns out and it is necessary to take this out and insert a new one. The opening between the furnace top and the crucible should be sealed with fire-clay to prevent the gas flames from attacking the barium chloride in the crucible, as this causes unnecessary fumes, that are almost unbearable, to come from the bath. Two per cent. of soda ash (carbonate of soda) is sometimes added to prevent these fumes.

The gas is sent into the furnace at an angle, as this gives the flame a rotary motion that will create an even heat on all sides of the crucible.

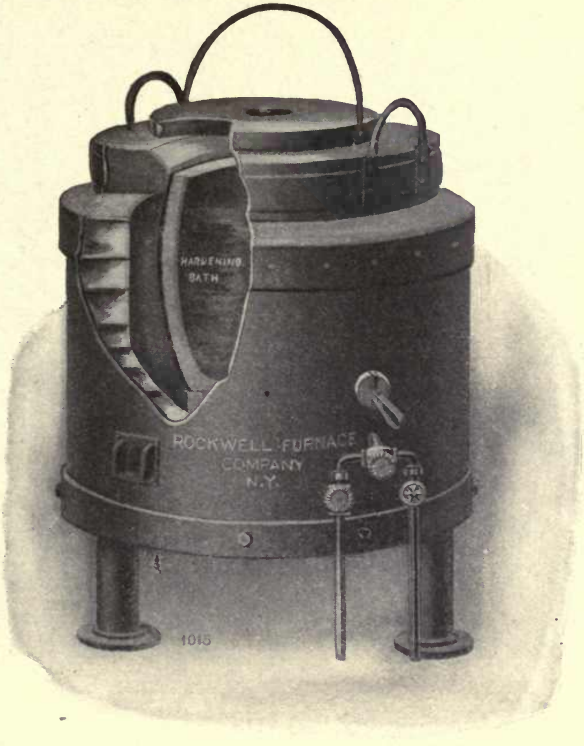


Fig. 103. — Gas or oil heated barium chloride furnace.

The exhaust opening is placed at the side of the gas inlet, and as close to it as possible, so the gas will make the complete circuit of the furnace chamber.

In Fig. 104 is shown a line drawing of the same furnace, supplied with an enclosed hood permanently fitted to it; entrance being obtained by means of a large door. Through this hood the fumes of the chloride are carried away and the burned gases are taken from the furnace through a pipe up into the top of the hood and thence out the chimney.

In heating steels for hardening that do not require a temperature of over 1650° F., a mixture of chloride of barium and chloride of potassium, in equal parts, gives the best results. As the required temperature increases the chloride of potassium should be reduced, until when 2000° F. is reached it should be left out altogether and only the pure chloride of barium used. In all cases the steel should be heated slowly to from 600° to 800° F. before it is immersed in the chloride bath, and if slowly heated to a higher temperature it will do no harm.

With the furnaces shown above, steel cannot be heated to over 2100° F. without its becoming pitted, and with many high-speed steels it is desirous to heat them to nearly 2500°. This is doubtless due to the fact that a graphite crucible is used and particles of it separate from the crucible and float in the chloride bath until the metal is inserted, when they attack it and cause pits to form. With an electric furnace, such as is shown in Fig. 108, this is entirely overcome, as the chloride holder can be made of fire-brick and electrodes inserted in the bath. Owing to the heat being generated inside of the bath, instead of surrounding the pot, a thin-walled crucible is not required, hence the chloride pot can be built up of fire-brick of any thickness that will give it the needed strength.

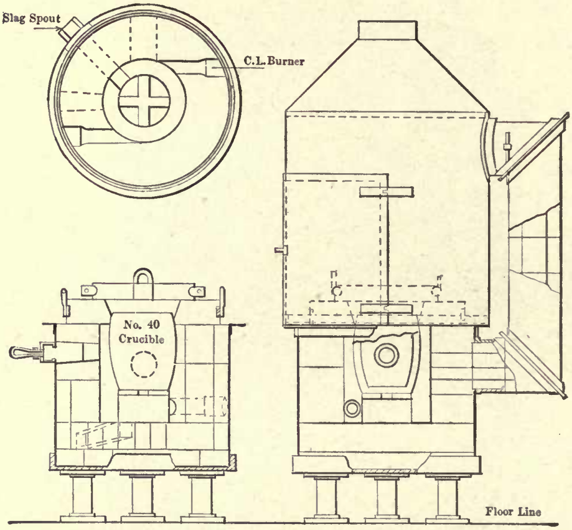


Fig. 104. — Barium chloride furnace with hood.

In starting up for the first time the crucible should be filled with the barium-chloride that can be bought in 1000-pound casks, at about 3 cents per pound, and this heated slowly until it melts down. After this more mixture should be added until the crucible is nearly full. After the bath is melted, tests should be made with a pyrometer until it is found hot enough for hardening. When through for the day the bath should be allowed to cool with the furnace, and when started again it should be heated up slowly.

After the bath is thoroughly liquid, take a piece of steel with a ground or machined surface, heat it to the temperature of the barium chloride and dip it in the cooling bath, then brush it off, and if there are no "bubbles" or "blisters" on the piece, heat the bath to a higher temperature and repeat the operation until they do appear, and then note the temperature shown by the pyrometer. For regular use a temperature about 50° below the point at which bubbles appear is the best; the test being made with a new clean bath. These bubbles are the indication of the pitting that occurs at temperatures of 2100° F. or over when the gas or oil furnace is used for heating the barium chloride. As the bath becomes old or dirty, and sluggish from steel scale, etc., bubbles will sometimes appear at a lower temperature than they should, in which case the remedy is a fresh bath in the crucible.

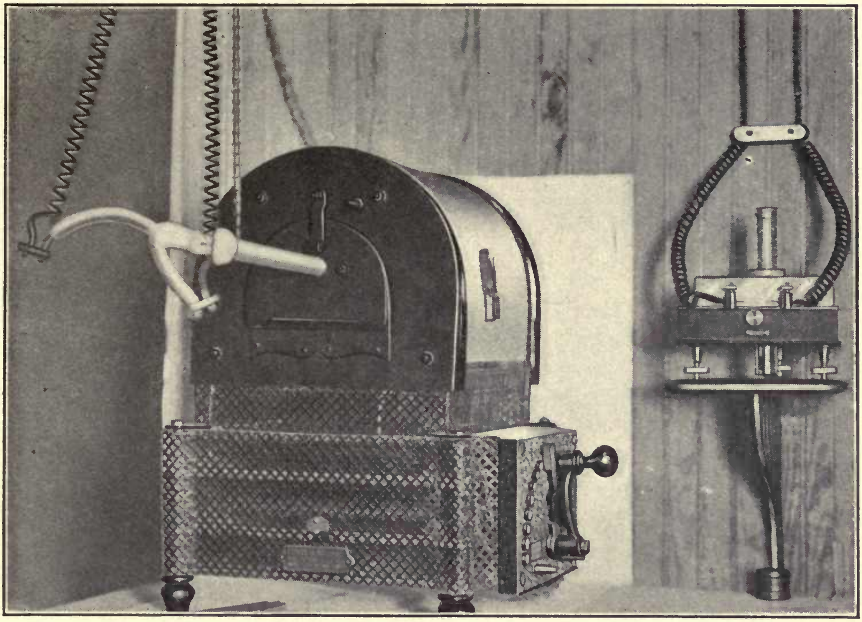


FIG. 105. — Experimental electric furnace for heat-treating steel.

ELECTRIC FURNACES

While the cost of electricity for heating furnaces is probably greater than any of the fuels, the results obtained by its use in heat-treating steel are better than by any other method.

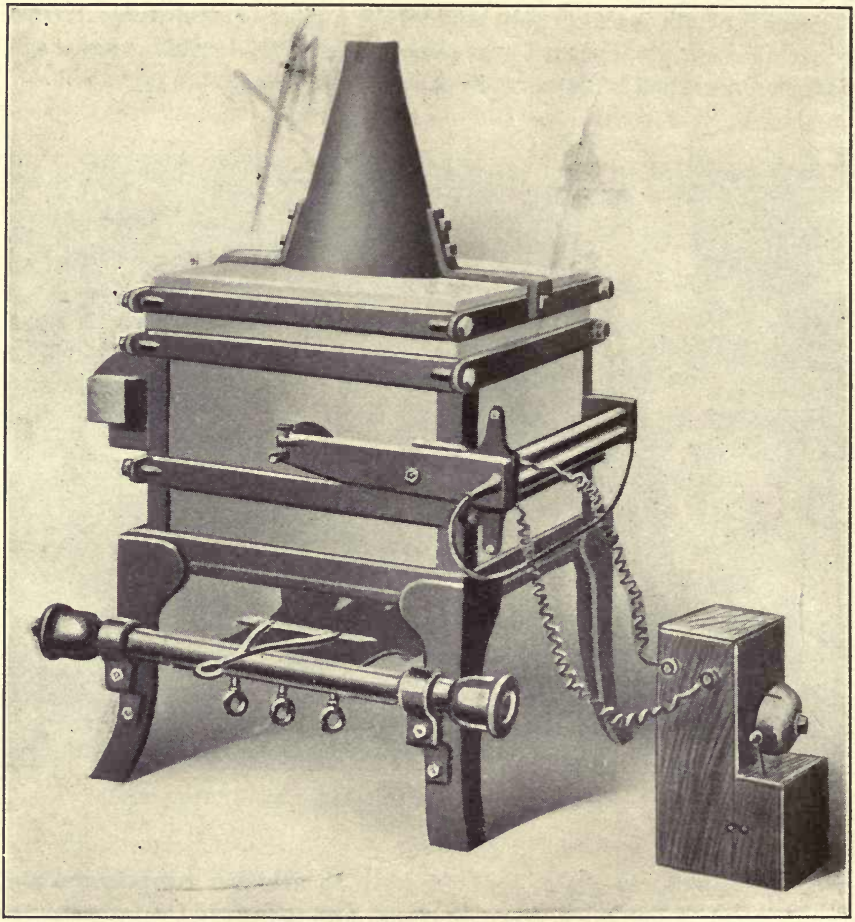


FIG. 106. — Magnetic furnace for hardening steel.

Electric furnaces may be placed in two classes; namely, those which use electrodes and those which have the heating chamber wound with platinum, nickel, or ferro-nickel wire, this being covered with some product, such as calcium aluminate, to protect it from the action of the silicates of the lining. Both of these furnaces are lined with some refractory material, but the latter is not practical for large furnaces, and is used only for very small work or for experimental purposes. This style of furnace is shown in Fig. 105.

In Figs. 106 and 107 is shown an electric furnace in which a magnet is used to hold the work until it reaches the point of recalescence, where it becomes non-magnetic. The magnetic attraction is then broken and the work can drop into a bath for quenching. This will give it the greatest hardness it is possible to give the steel, and at the same time make the grain as fine and the molecules as cohesive as they can be made by heat treatment.

Electric furnaces similar to that shown in Fig. 108 are used to heat the liquid baths described above. In this furnace the metallic salt baths seem to be the most appropriate. These salts completely prevent contact between the white hot steel and the air during the heating, as well as during the passage to the quenching bath; the steel being uniformly covered with a protective coat of the salts during the passage of the steel from the furnace to the quenching bath. On immersion in the cooling liquid this coating immediately leaves it and the surface of the steel always appears smooth. The formation of scale is entirely prevented even after tempering.

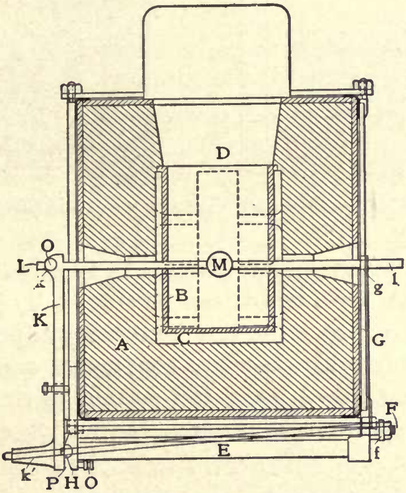


Fig. 107. — Section through muffle of magnetic furnace.

The source of heat being inside the bath in this furnace the heat is evenly distributed and the temperature of the bath is uniform throughout every part of it. High temperatures are as readily obtained, and with as little watchfulness, as relatively low ones, which makes it easy to determine the temperatures desired in heat-treating the steel.

The pyrometer can be used successfully in measuring the temperature of the bath. The temperature of the bath is proportional to the current, and one careful determination with the pyrometer is enough to afterward judge the temperature of the bath entirely by the current.

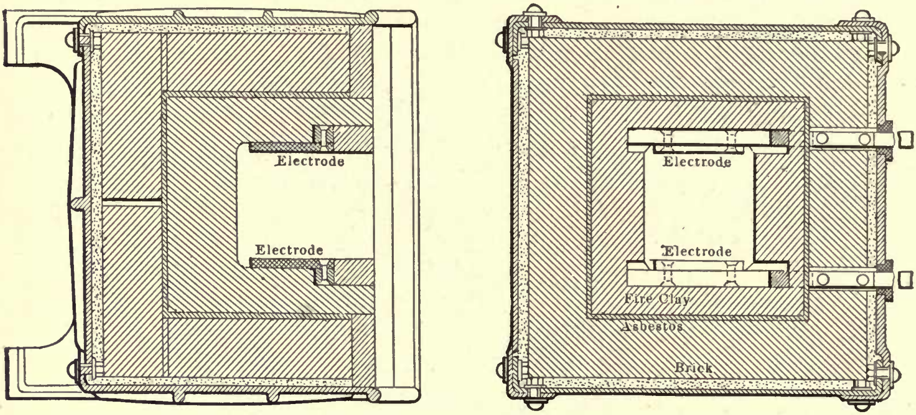


FIG. 108. — Sectional views of electrode furnace.

This style of furnace requires from 15 to 40 minutes to start, according to the size. The cold furnace can be started by passing the current through a piece of carbon until this becomes white hot and melts the surrounding salt, which then becomes conductive and in turn melts the whole mass. When finished using the current is shut off and the salt bath can be kept molten for a long time by putting a cover over it.

CHAPTER IX

Annealing Steel

THEORY, METHODS, MATERIALS USED AND APPLICATION

If the best results are desired from steel, after it has been rolled, forged, pressed, cast, or put into workable shapes in any other way, it should be annealed before any other work is done upon it. This removes the internal strains that are set up in the metal, when working it into the desired shape for future operation, and also softens the steel. It can then be more economically machined with any kind of cutting tools, can be heat-treated in various ways without the danger of cracks forming, and will have greater strength and endurance when put to its intended use.

The annealing of steel consists in carrying it above the temperature at which its highest point of transformation occurs, and then allowing it to cool gradually. This point of transformation is that at which the steel becomes non-magnetic and its physical structure changes. If a pyrometer is used to indicate the temperature of the steel in heating or cooling, it will show a point at which the rapid change in temperature ceases for a time, and the recording chart will show a line nearly at right angles to that of the rise or fall curve. At this point all the molecules have become non-magnetic and a new crystal-size of grain is born. This refines any large or coarse crystals that may have been produced in the steel by former methods of heating or working. This change in structure releases any strains which may have been set up in the metal, and allows them to readjust themselves so that they are equalized throughout all parts of the piece.

This temperature of the point of transformation varies considerably in different steels. This is partly shown by Fig. 109, which was plotted from two recording pyrometer charts. Steels vary more widely than this, however, in their highest recalescent point; it being affected by the various ingredients that are alloyed with the metal.

Another operation, sometimes called annealing, is that of partially destroying the effects of sudden cooling or quenching. In this the annealing temperature is kept below the highest point of transformation. This operation is more properly named tempering, and will be dealt with under that title.

As a general rule all steel should be annealed after every process in manufacturing that tends to throw it out of its equilibrium, such as forging, rolling, and rough machining, in order to return it to its natural state of repose.

When a steel ingot has been poured and subjected to the hammering process, that is often its first mechanical working, there is a tendency of the crystals to crush. This will bring the particles of the metal closer together, but there is a limit to the increase in the density which can be attained in this manner as a great deformation is eventually given the metal. This metal is called "hammer-hard," and some metals will show about twice the tensile strength after being hammered to the limit of compression that they will when in the normal state.

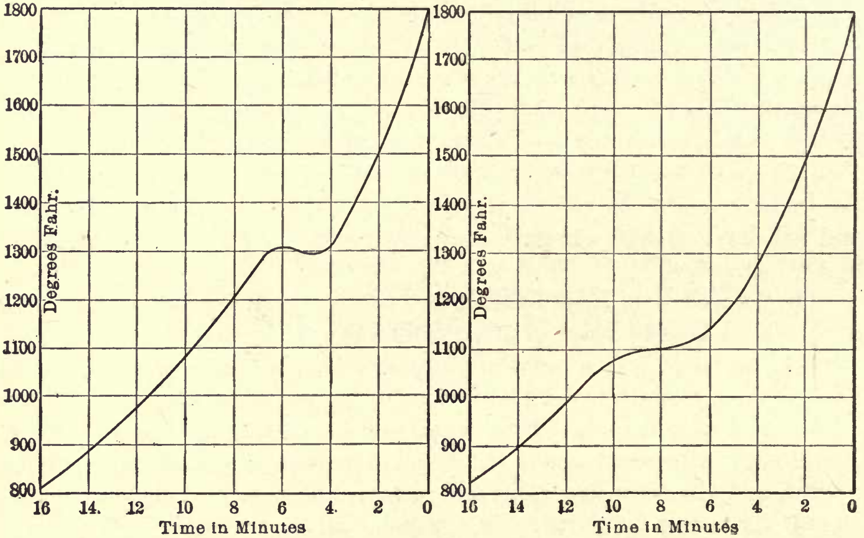


FIG. 109. — Recalescent point curves, plotted from two pyrometer charts.

The limit of compression is difficult to gage, and if passed, as it usually is in practice, the hammering is liable to cause coarser crystals to form where it has squeezed out from under the hammer blows. To remove this crystallization and refine the grain, annealing has to be resorted to, and certain laws have been formulated which hold good on annealing hammered metal, as follows:

First. — Annealing cannot be done instantaneously, but its effects are the greater in proportion to the time consumed. A rapid change takes place at the start, but this is slower and slower as the time progresses, and there is a tendency toward a fixed limit for the decrease in hammer-hardness at each degree of temperature.

Second. — The higher the annealing temperature, the lower will be the limit toward which hammer-hardness tends; in practice the more rapidly will this limit be attained.

Third. — The annealing effects are practically completed when a certain temperature has been reached, and any increase above that does not further reduce the tensile strength as this has reached the lowest point possible for the steel operated on.

The effect called "crystallization of annealing" may start at this temperature and become more pronounced as the annealing process continues. It causes the reduction of area to decrease, and if very pronounced this may become *nil*, together with the elongation, while the tensile strength is much reduced. Another phenomenon might be mentioned here, and that is spontaneous annealing. Thus, if hardened steel be left to itself it will anneal of itself, the only factor entering into this phenomenon being time. As this time, however, covers such a long period and the annealing process is such a slow one the principle is of no importance from a practical standpoint.

From the above may be deduced three practical rules to adopt in annealing steel, these being:

First. — A quenched or hammered piece must be heated to a temperature above its highest point of transformation, but as close to this point as possible.

Second. — This temperature must be retained long enough to allow the entire piece to reach an even temperature, but it must not be prolonged beyond it.

Third. — The rate of cooling must be sufficiently slow to prevent any hardening taking place, not even superficial hardening.

In applying these rules we find that extra low-carbon steel should be annealed at 1650° F., and extra high-carbon steel at 1375°. The time of annealing varies with the size and shape of the piece as well as with the work which it has to perform. The more important this work is, the more prolonged should be the annealing process. Intricate pieces with thin and thick sections have to be handled with extra care, and sometimes materials are brought into use to retard the cooling of the thin section, as ordinarily a thin section will cool quickly in comparison with the thick one, and consequently be that much harder.

To insure slow cooling, when a slow-cooling furnace is not obtainable, the work should be packed in some non-carbonizing material, in an iron box lined with fire-brick similar to the one shown in Fig. 110. The whole can then be heated in a furnace and set out on the floor to cool as the thickness of the materials prevents rapid cooling. This will also tend to prevent the pieces from scaling as they do not come in contact with the oxidizing influences of the atmosphere. When the temperature of the pieces has dropped to 550° F. they may be removed from the box as the annealing process has ceased, and there will be no danger of their air-hardening.

As it is generally agreed upon that steel should not be heated much above the point of transformation in the annealing process it would be well to give the reasons. The nine laws formulated by Prof. H. M. Howe, after many tests by himself and others, cover the ground so thoroughly that they are here given.

First Law. — When a given steel is heated to a temperature above the highest point of transformation the grain assumes a definite size, characteristic of the temperature. We call this the normal size.

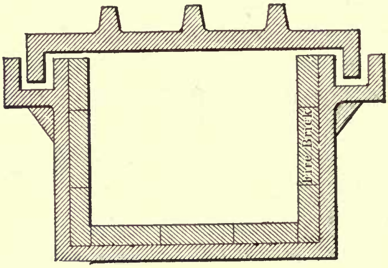


FIG. 110. — Cast-iron box for annealing.

Second Law. — The size of the grain increases in proportion to the temperature, counted from the highest point of transformation.

Third Law. — The influence of the temperature is the more pronounced the greater the carbon content of the steel. In other words, for the same annealing temperature the normal grain of the steel is coarser the greater the carbon content.

Fourth Law. — If a steel is raised to a temperature above its highest point of transformation, and if in consequence of previous treatment the steel possesses a finer grain than the normal, the grain of the metal becomes coarser until it is equal to the normal grain.

Fifth Law. — In order to attain the normal grain for any temperature, the metal must be maintained at this temperature for some time.

Sixth Law. — If the metal is heated to a certain temperature and has assumed the normal grain for this temperature, and if it is then maintained at a somewhat lower temperature, but still above the point of transformation, the size of the grain is not reduced, provided the metal is not reduced below the point of transformation.

To illustrate this, if a steel is carried to 2200° F.; the grain then becomes of the size characteristic of this temperature; if the temperature is then lowered to 1650° there will be no change in the size of the grain. It would be quite different, however, if instead of cooling the metal directly to 1650°, it had been cooled down to 925°, which is much below the point of transformation, and then reheated to 1650°.

Seventh Law. — If the temperature of a steel remains below the point of transformation its grain does not change.

Eighth Law. — If a steel is cooled slowly after having been heated to above its point of transformation, it possesses substantially the same grain as that which it possessed at the maximum temperature.

Ninth Law. — From this it may be deduced that the grain of a metal, after annealing, is the coarser the higher the temperature to which it has been raised above the point of transformation.

While the relation existing between the annealing temperature and the mechanical properties has not been fully determined, enough is known to establish certain rules that are beneficial in a practical way. A coarse-grained metal is more brittle than a fine-grained, and therefore any change in the size of the grain will affect the strength of the steel. As the annealing temperature affects the size of the grain, a steel that is heated to a variable temperature and slowly cooled will alter its mechanical properties about as follows:

First. — The tensile strength slightly increases with the increase in temperature up to 2375° F., after which it rapidly decreases.

Second. — The elastic limit passes through a minimum at the highest point of transformation, but increases slightly when the temperature passes this point, and then decreases as this point is exceeded by 175° F. The slower it is cooled from the point to which it has been heated the lower will be the elastic limit.

Third. — The elongation decreases as the annealing temperature increases, and this decrease is very important when the temperature attains 2375° F. This makes it necessary to keep the annealing temperature a little above, but as close to the point of transformation as possible.

With these points taken into consideration it will be seen that the annealing of steels cannot be too carefully done if the best results are to be obtained, and especially is this so of the high-grade alloy steels which are being used more and more every day. It has been shown that if the heat treatment is carried out in a manner that will produce sorbite, the tensile strength is much higher and the elongation is slightly greater than when the metal is simply annealed. To obtain sorbite it is necessary to quench above the point of transformation and then reheat to from 575° to 1300° F., according to the composition of the metal and the hardness desired, then cool in air or in water.

APPARATUS FOR ANNEALING

The furnaces used for annealing are the same as those used for other heat-treating operations, unless enough pieces are annealed to install a slow-cooling furnace, and then it is only the accessories that are different. The materials in which to pack the metal are nearly as numerous as the baths for quenching, and where a few years ago the ashes from the forge were all that were considered necessary for properly annealing a piece of steel, to-day many special preparations are being manufactured and sold for this purpose.

The more common materials used for annealing are powdered charcoal, charred bone, charred leather, mica, slacked lime, sawdust, sand, fire-clay, magnesia, and refractory earth. The piece to be annealed is usually packed in a cast-iron box, similar to Fig. 110; using some of these materials or combinations of them for the packing, the whole is then heated in a furnace to the proper temperature and set aside, with the cover left on, to cool gradually to the atmospheric temperature.

For certain kinds of steel these materials give good results; but for all kinds of steels and for all grades of annealing, the slow-cooling furnace no doubt gives the best satisfaction, as the temperature can be easily raised to the right point, kept there as long as necessary, and then regulated to cool down automatically and as slowly as is desired. The gas, oil, and electric furnaces are the easiest to handle and regulate.

As an example of this a maker of high-grade files uses a gas furnace in which to anneal the files, and they are packed in this with the tangs outward. The furnace is heated up and kept at a temperature of 1500° F. for 4 hours, and then allowed to slowly cool during two nights and one day. The flame is from a vaporized naphtha preparation that is free from injurious elements, such as sulphur, and is supplied with a slight undersupply of oxygen, so there will be no danger of its oxidizing the metal. The files are submitted to the direct action of this flame, which fills every part of the heating chamber, so that the end and sides, as well as the center, can be maintained at the same even temperature. By having a constant pressure and volume for the air and gas the flame is easily controlled and is non-oxidizing, therefore there is no pitting or blistering of the files. They do, however, have a very thin scale, that is caused by the air that leaks into the furnace while it is cooling, but this is not enough to do any practical damage.

There is one notable exception to these annealing rules, and that is in the case of Hatfield's manganese steel, which is so brittle when cast as to be useless. It is toughened, or tempered, by heating and quenching, and is hardened by slow cooling.

While high-speed steel has heretofore been annealed in practically the same way as the carbon steels, and therefore subject to the above rules, it is hardened by rules altogether different from those governing the carbon steels.

A new method of annealing high-speed steel that is a great improvement over this old one has been discovered and perfected by C. U. Scott of Davenport, Iowa, at the Rock Island arsenal. He places the high-speed steel in a furnace that is heated to not over 750 °F., and raises the temperature slowly to 1300° F. He then shuts off the heat and allows both the steel and the furnace to cool to not over 750° F., or to atmospheric temperature if desired. The steel is then reheated to a temperature of 1300° F., and held there for 30 minutes and then cooled in the air.

In this way any high-speed steel that is not over 1 inch square can be annealed in 40 minutes, and it does not take over one hour for large stock. The metal is made as soft and it machines as readily as steel annealed by any other method. Whether the steel is entirely cooled after the first heating or whether the temperature varies a few degrees from the 1300 is immaterial.

Another hardener on trying out this method got his data mixed and obtained the same degree of softness in another way. He heated the steel to a low red, and held the temperature at that point for 30 minutes. He then let it cool down and afterward reheated it and immediately let it cool down until it was at the correct temperature for water annealing and then laid it in the ashes until it was cold enough to handle.

CHAPTER X

Hardening Steel

ALTERATIONS IN STRUCTURE, INFLUENCE OF COMPOSITION, AND RESULTS OBTAINED

Hardening, when applied to steel, is generally understood to mean the heating of the metal to a high temperature and then plunging it into a bath for the purpose of suddenly cooling it. While this definition holds good on most steels, a few alloying materials now used reverse this and make the metals air-hardening, that is, their hardest and toughest state is obtained by a slow-cooling process rather than a sudden one.

Two reasons might be assigned for the desirability of hardening steel, and these are: First, to give the steel a cutting edge such as is required for all cutting tools, and, second, to alter the static strength and dynamic qualities of the metal so it will give the best results for the moving parts of machinery.

In this second case steels may be altered by quenching from a high temperature and tempering, to an extent that will greatly improve their wearing qualities, tensile strength, elastic limit, magnetic qualities, or resistance to shock, and yet not be capable of attaining a hardness that will not allow a file to cut it; this being the usual test of hardness applied in the shop. Thus, generally speaking, all steels may be hardened, although some may have a low carbon content.

To harden steel, therefore, it is necessary for the heating to produce a change in the structure, and the quenching, which follows the heating, retains a whole or a part of the changes produced by this change of structure. It is therefore necessary, as in annealing, that the temperature of the steel be raised to a point slightly above the point of transformation or recalescent point.

As the point of transformation varies with different ingredients which are alloyed with steel, it is necessary to find out where it is in the steel to be hardened. A steel may be heated to 1300° F. — which is above the point of transformation in some steels — and no change in structure will take place, and therefore no results in hardness will be obtained. If the same piece is heated to 1650° — which we will consider the point of transformation in this piece — the intermolecular transformation, which consists of the passage of the carbon from the combined into the dissolved state, will take place and the steel will assume the hardest state it is capable of, if properly cooled.

Thus the factors that have an influence on the results of hardening are: First, the nature and composition of the metal; second, the temperature of the metal when quenched, and, third, the nature, volume, and temperature of the quenching bath.

MICROSCOPICAL EXAMINATION

The nature of these different factors is shown to a large extent by quenching the metal at different temperatures, polishing the surface, attacking it with picric acid, tincture of iodine, hydrofluoric acid, or any other etching materials and examining it under a microscope.

Ferrite. — Steel containing less than 0.85% carbon will show small dark masses, if etched with picric acid, which are the more numerous the closer the carbon content is to 0.85%. At this percentage they cover the entire surface. These masses show alternate layers which are ferrite — pure iron — and an iron carbide called cementite. The ferrite being the softest constituent of steel, it will indent when polished and the cementite will stand out in relief.

Ferrite is the carrier for all of the alloying elements in the high-grade steels. It is the principal constituent of all steels and the predominating one in low-carbon steels. It has one peculiarity which is very important, and that is, that when heated to about 1400° F. it undergoes a sudden change which is shown by its absorption of heat. It then loses its power to attract a magnet as well as changing its specific heat and several other properties. No alteration, however, takes place in its chemical composition.

At 1550° F. it again shows changes by absorbing heat and its properties are again changed. (See chart 1, page 67.) Its electrical conductivity has changed and also its crystalline form. These changes occur both in the rise and fall of the temperature, and have been called by different metallurgists the points of transformation, the recalescence points, and the critical temperatures; all of which mean the same.

Ferrite is shown in Figs. 111, 112, 113, 114, and 117.

Cementite is the carbide of iron, and is expressed by the following formula: Fe_3C, which means ferrite — which is pure iron — 3 atoms for every one atom of carbon. It is the second constituent in importance in steel — ferrite being first — and is very hard and brittle. Practically all of the carbon is present in this form, and it usually crystallizes in thin flat plates. Cementite does not exist in pure iron, which contains no carbon, and of itself contains about 6.6% of carbon, which is about one-fifteenth of it. Two extremes of cementite formation are shown in Figs. 111 and 112.

Pearlite. — Pearlite is an intimate mixture of ferrite and cementite in the definite proportions of 32 parts ferrite to 5 of cementite, equivalent to .85% carbon. It has the appearance of mother of pearl, from which it derives its name. It exists in a lamellar formation, which is alternate plates of ferrite and cementite, or in a granular formation, which is inter-

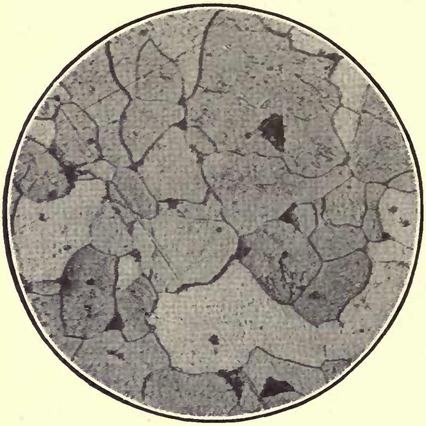


Fig. 111. — Ferrite with very thin continuous cementite skeleton. Low carbon. Magnified 250 diameters.

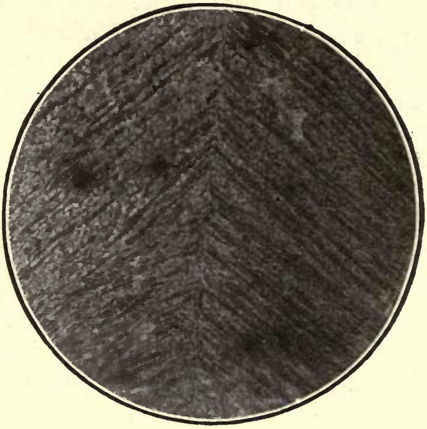


Fig. 112.—Ferrite, white. Cementite, black. Magnified 250 diameters.

Fig. 113. — Ferrite matrix with separated pearlite islands. Magnified 250 diameters.

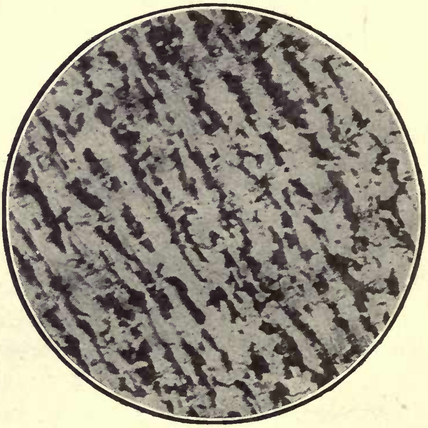


Fig. 114. — Ferrite, white. Pearlite, black. Magnified 250 diameters.

mingling grains of ferrite and cementite. A normal steel, containing 0.85% carbon, consists of 100% pearlite; below this carbon content it contains pearlite and excess ferrite; while if the total carbon exceeds 0.85% the constituent excess would be cementite instead of ferrite. Pearlite is shown in Figs. 113 and 114.

Martensite and Hardenite. — Leaving the steels that have been cooled slowly, and taking up those which have been quenched from a given temperature, and hardened, we find that a steel containing about 0.85% carbon, if heated to about 1400° F. and quenched, will show under the microscope extremely fine lines intersecting each other in the direction of the sides of an equilateral triangle. This constituent has been named martensite in honor of Professor Martens. It is the principal constituent of all ordinary hardened steels that have a carbon content above 0.16%, and tempered steels owe their quality of hardness to it. It is so hard that a needle will not scratch it after the metal has been polished.

In steels containing over 0.85% carbon the martensite is said to be saturated and shows slightly different under the microscope. This has been called hardenite by some, which word is often used in French and German books.

Martensite is shown in Figs. 115 and 116.

Sorbite is a constituent between martensite and pearlite, and chiefly differs from pearlite by the constituents not quite perfectly developing. This is drawing the line pretty fine, but the sorbitic structure is finer than the pearlitic, and it is considered the extreme opposite of the crystalline structure. The sorbitic structure is considered necessary in metals that have to resist wear and erosion, and the natural formation of this structure is rendered possible by the addition of certain alloying elements. In hardened steel, sorbite is considered as the transition from martensite to pearlite.

The sorbitic structure may be obtained when the cooling is not as rapid as that of quenching, but still much faster than the slow cooling for annealing; by quenching immediately below, or just at the end of cooling through the critical range; by cooling pretty fast through the critical range without actual quenching; or by rapidly cooling the steel and then reheating to about 1100° F. Sorbite is not clearly defined in micro-photographs, but Fig. 117 shows it fairly well, with ferrite.

Austenite. —High-carbon steels that contain over 1.10% of carbon and are suddenly cooled from a temperature of 2000° F. will show a constituent, in addition to martensite, which may be distinguished from it by a different color. If etched with nitrate of ammonia, or with a 10% solution of hydrochloric acid, it will show white. This constituent is softer than martensite, and is easily scratched with a needle. It is essentially a solid solution of carbon in gamma iron. It has been named austenite after Prof. Robert Austen.

FIG. 115. — Martensite formation. Magnified 250 diameters.

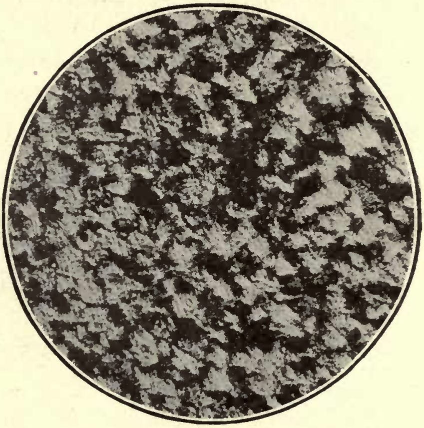


FIG. 116.—Martensite. Magnified 200 diameters.

Austenite is difficult to preserve throughout the whole structure of the steel. Quenching in a bath that has a temperature below the freezing point, or any other means which will cool it rapidly, will aid in preserving it. Tempering the metal afterward, however, loses the austenite, and it is not of much practical use owing to the high temperature at which it is obtained. Fig. 118 shows the austenite formation.

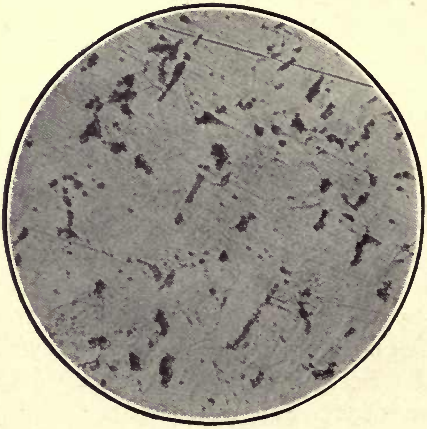


FIG. 117. — Ferrite and sorbite. Magnified 250 diameters.

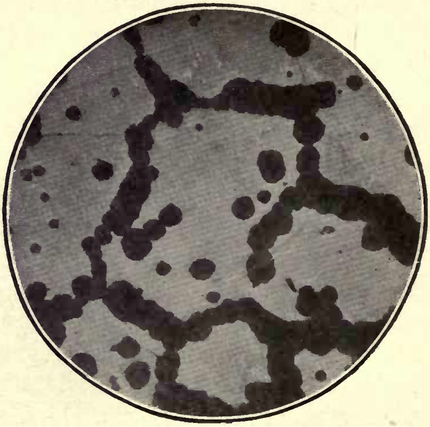


FIG. 118. — Austenite, white. Troostite, black. Magnified 50 diameters.

Troostite. — If the steel is quenched during or just above its transformation in a bath of little activity, such as oil, or if it is hardened in the usual way, and then tempered, we obtain a constituent which will show jet black if polished and etched with picric acid, or if etched with a tincture of iodine it will show white. This has been named troostite in honor of Prof. M. Troost.

Troostite is also softer than martensite, as it can be scratched with a needle. It is a transition product between martensite and sorbite, and is found plentifully in tempered steels as it is a product of the usual tempering operations. It shades gradually into the sorbite, but is very sharp in its divisions from martensite. Troostite is shown black in Fig. 118 and white in Fig. 119.

Fig. 119. — Martensite, black. Troostite, white. Magnified 350 diameters.

In subjecting steel to different heat treatments we can change the constituents from pearlite to martensite or hardenite, sorbite, austenite, and troostite, and back again through these different stages, and by examining them with the microscope we can judge very closely the treatment they have been subjected to.

By making these changes we also change its constitution, its static strengths, and its dynamic properties. This is where the practical application of this knowledge aids the engineer or designer in designing the moving as well as other parts of machinery so as to get the best results from the smallest quantity of material.

EFFECT OF COMPOSITION AND HARDENING

The constitution of a given steel is not the same in the hardened as in the normal state, owing to the carbon not being in the same state. In the annealed or normal steel it is as cementite, while in a hardened steel it is in a state of solution, which we may call martensite; and this contains more or less carbon according to the original carbon content of the steel. The composition, and therefore the mechanical properties, depend principally upon the carbon content, the mechanical properties being changed slowly and gradually by an increase in carbon.

TABLE 1. COMPOSITION

	Carbonizing Steel	Very Low Carbon	Low Carbon	Medium Carbon	High Carbon	Very High Carbon
Carbon	0.10	0.14	0.23	0.52	0.60	0.72
Silicon	0.09	0.05	0.15	0.18	0.10	0.17
Manganese	0.19	0.33	0.45	0.35	0.40	0.38
Phosphorus	0.016	0.023	0.091	0.021	0.035	0.03
Sulphur	0.025	0.052	0.062	0.043	0.025	0.06
MECHANICAL PROPERTIES WHEN ANNEALED						
Tensile Strength (in pounds per square inch)	60,300	61,500	66,500	97,800	116,400	130,700
Elastic Limit (in pounds per square inch)	36,300	35,200	41,200	52,600	66,500	75,800
Elongation (percentage in 2 inches)	29	27	26	20	14	9
MECHANICAL PROPERTIES WHEN HARDENED						
Tensile Strength (in pounds per square inch)	66,400	73,100	99,400	132,100	153,400	180,100
Elastic Limit (in pounds per square inch)	40,300	39,600	54,000	81,400	102,100	105,500
Elongation (percentage in 2 inches)	24	22	14	9	4	0

EFFECT OF COMPOSITION AND HARDENING ON THE STRENGTH OF CARBON STEEL

This is best shown by the above table , in which it will be seen that the tensile strength and elastic limit gradually increased with the increase in the percentage of carbon, both in the annealed and hardened state, while the elongation gradually decreased. These tests were made with a bar $\frac{1}{2}$ inch in diameter and 4 inches in length. It will also be seen that there was considerable change in the steels that were too low in carbon to be made so hard that they could not be filed. The reduction in elongation when the test bars were heated and quenched showed that the metal was harder than when in the annealed state.

A hardening process that will produce a steel that is as homogeneous as possible is always sought for in practice. This is easily obtained in a high-carbon steel, and especially if it contains 0.85% carbon, by passing the upper recalescent point before quenching. The desired homogeneity is not so easily obtained, however, in the low-carbon steels as they have several points of transformation. If these are quenched at a point a little above the lowest point of transformation, the carbon will be in solution, but the solution is not homogeneous. To obtain this result it is necessary that the quenching be done from a little above the highest point of transformation. This is higher in low- than in high-carbon steels. In practice this calls for a quenching of the low-carbon steels at about 1650° F., while a high-carbon steel should be quenched at about 1450°.

The degree of temperature, above the critical point, to which steel can be heated in practical commercial work and still give good results is also quite important. If a piece of steel be quenched from different temperatures above the point of transformation and examined under a microscope we find that the higher we go the coarser will be the martensite, and the lines will be more visible. If we raise this temperature a few hundred degrees above the critical point and quench in a very cold bath, austenite makes its appearance. In regard to the mechanical properties the higher the temperature above the critical point the lower will be the tensile strength and the less will be the hardness of the steel. The elongation will also show a decrease and this will mean that the steel becomes more brittle with each increase in the temperature.

This coarsening of the martensite, the reduction of both the tensile strength and elongation and the crystallization spoken of some few paragraphs back, have led to the conclusion that, in practice, 40° F. above the highest point of transformation is the extreme limit that steel should be raised to obtain the best results in hardening. The same figure also holds good for annealing.

The following results are obtained in hardening steel: All steels may be hardened, but if the carbon content is over 0.30% the effect is more pronounced. Hardening increases the tensile strength and elastic limit and reduces the elongation, the effect being greater the greater the carbon content. Quenching at the proper temperature gives the metal a greater homogeneity and this aids the resistance to shock, especially in low-carbon steels; steel should not have the hardening temperature raised more than 40 degrees above the highest point of transformation, as beyond that it no longer has the same qualities.

BATHS FOR HARDENING

As it is necessary to maintain the metal in the state it was at the moment quenching begins, the quenching bath is a very important part of the process of hardening. The rate of cooling is never swift enough to secure perfection, and the intermolecular transformation will be more or less complete according to the rate of cooling. The better the bath the nearer to perfection we will be able to arrive.

The baths for quenching are composed of a large variety of materials. Some of the more commonly used are as follows; they being arranged according to their intensity on 0.85% carbon steel: Mercury; water with sulphuric acid added; nitrate of potassium; sal ammoniac; common salt; carbonate of lime; carbonate of magnesia; pure water; water containing soap, sugar, dextrine, or alcohol; sweet milk; various oils; beef suet; tallow; wax. These baths, however, do not act under all conditions with the same relative intensity, as their conductivity and viscosity vary greatly with the temperature, and their curves of intensity are therefore very irregular and cross each other frequently. Notwithstanding the many special compounds that have been exploited for hardening, there are no virtues, or hardening and toughening properties, in any quenching bath beyond the degree of rapidity with which it conducts the heat out of the piece being quenched.

With the exception of the oils and some of the greases, the quenching effect increases as the temperature of the bath lowers. Thus water at 60° will make steel harder than water at 160°. Sperm and linseed oils, however, at all temperatures between 32° and 250° F., act about the same as distilled water at 160°. The influence of the bath depends upon its nature, its temperature, and its volume; or, in other words, on its specific heat, conductivity, volatility, and viscosity. When the bath is in constant use, the first piece quenched will be harder than the tenth or twentieth, owing to the rise in temperature of the bath. Therefore, if uniform results are to be obtained in using a water bath, it must either be of a very large volume or kept cool by some mechanical means. In other words, the bath must be maintained at a constant temperature.

In Fig. 120 is shown the effect of different hardening temperatures on the tensile strength and elongation when quenching in different baths. These tests were made at the Watertown arsenal.

The mass of the bath can be made large, so that no great rise in temperature occurs by the continuous cooling of pieces, or it can be made small, and its rise in temperature used for hardening tools that are to remain fairly soft. If this temperature is properly regulated, the tool will not have to be reheated and tempered later, and cracks and fissures are not as liable to occur. A lead bath, heated to the proper temperature, is sometimes used for the first quenching. Another way of arriving at the same results would be to use the double bath for quenching, that is, to have one bath of some product similar to salt, which fuses at 575° F. Quench the piece in that until it has reached its temperature, after which it can be quenched in a cold bath or cooled in the air.

The specific heat of the bath is an important factor, as the more rapid the cooling from 1650° to 200° F., the more effective will be the hardening process. A bath that consists of a liquid which volatilizes easily at the highest temperature it reaches, from plunging the metal into it, forms a space around the steel that is filled with vapor, and this retards the further cooling action of the liquid. The motion of the bath will throw off these vapors as it brings the liquid in contact with the metal and tends to equalize the temperature. The agitation of the piece to be hardened will give better results than trusting to the motion of the bath, as it is more energetic in distributing the vapors.

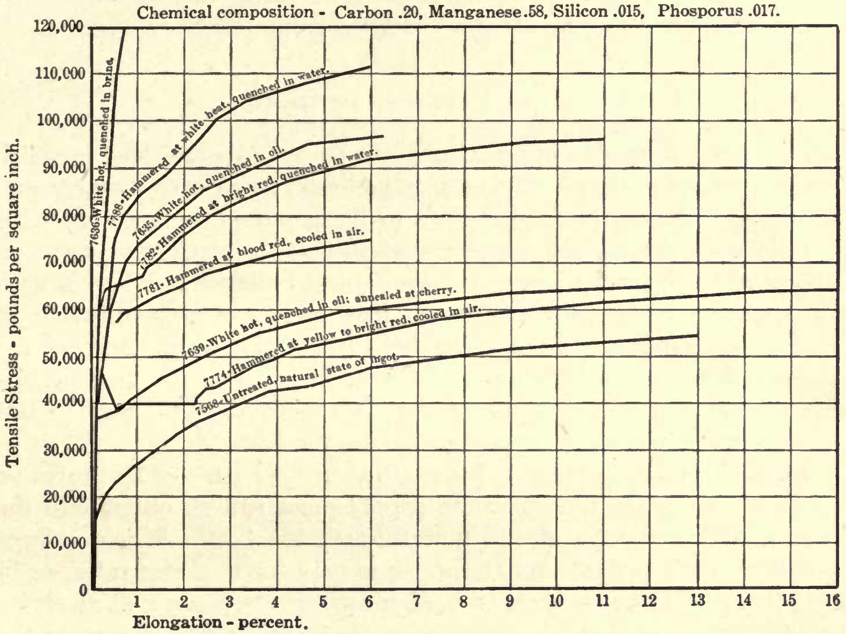


FIG. 120. — Effect of heat and mechanical treatment on the tensile stress and elongation.

The viscosity of the bath has an influence on the phenomenon of convection, which is the principal means of the exchange of heat; the higher the viscosity the less its hardening effect.

The conductivity of the bath has its effect on the exchange of heat between the piece to be hardened and the bath; therefore the greater the conductivity the more quickly the metal cools.

As a rule little account is taken of the specific heat of the bath, but it is an important factor. As soon as the heated metal is plunged into the bath, the liquid begins to heat. The number of calories necessary for raising the temperature of the liquid a certain number of degrees will be the greater the higher the specific heat. Thus the cooling of the metal will heat the bath less the higher the specific heat of the latter, and consequently a bath is the more active the higher its specific heat. The less rapidly the equilibrium is established between the hardening bath and the metal quenched in it, the more active will be the bath.

The specific heat of mercury is much less than that of water, and the cooling of quenched steel is three times as rapid in water as in mercury. The hardening effect is therefore much lower than that of water, but surface cracks and fissures are not nearly as liable to occur.

METHODS OF KEEPING BATHS COOL

The baths, for hardening, that give the best results are those in which some means are provided for keeping the liquid at an even temperature. Of course, where but few pieces are to be quenched, or a considerable time elapses between the quenching of pieces, the bath will retain an atmospheric temperature from its own natural radiation. Where a bath is in continuous use, for quenching a large number of pieces throughout the day, some means must be provided to keep the temperature of the bath at a low, even temperature. The hot pieces from the heating furnace will raise the temperature of the bath many degrees, and the last piece quenched will not be nearly as hard as the first.

When plain water is used it is easy to keep the bath cool by providing it with a pipe connecting it to the supply main and an outlet into the drain, and thus have a steady flow through the bath. Where a large amount of work is done and the water is paid for at meter rates, as in cities, this might be more expensive than having a large tank at an elevation above the bath and a pump to force the water into it, thus using the water over and over again. This flowing of the liquid would do away with the necessity of agitating the steel in the bath, as when it is of the ordinary stationary kind, owing to the flowing liquid carrying away the coating of vapor which forms around the piece and prevents its cooling rapidly.

A hole in the center of the bottom with an outlet on top is not a very good arrangement, as the cool current, striking the bottom side of the piece, is liable to cause it to warp. If the cool liquid is taken in at the bottom it should be taken in through several openings. A good method is to have the inlet covered with a spherical piece of sheet metal punched full of small holes that would deliver the liquid in fine streams similar to that of a sprinkling can. This would send the cool liquid to all parts of the bath.

A still better arrangement would be to have an extra inner wall with a large number of fine holes punched in the sides and solid at the bottom. This would cause the cool liquid to flow in from all sides, which would give the bath a complete agitation and subject the pieces to less irregularity of temperature, and would therefore reduce the tendency of the pieces to spring or warp from not cooling equally on all sides. A variation of this is shown in the spray bath in Fig. 121. In this *A* is a circular gas pipe, into which is screwed the perforated upright pipes *C*, *C*, and *B* is the intake pipe. The water comes through the fine holes in pipes *C*, *C*, and forms a spray on the lines *D*, *D*.

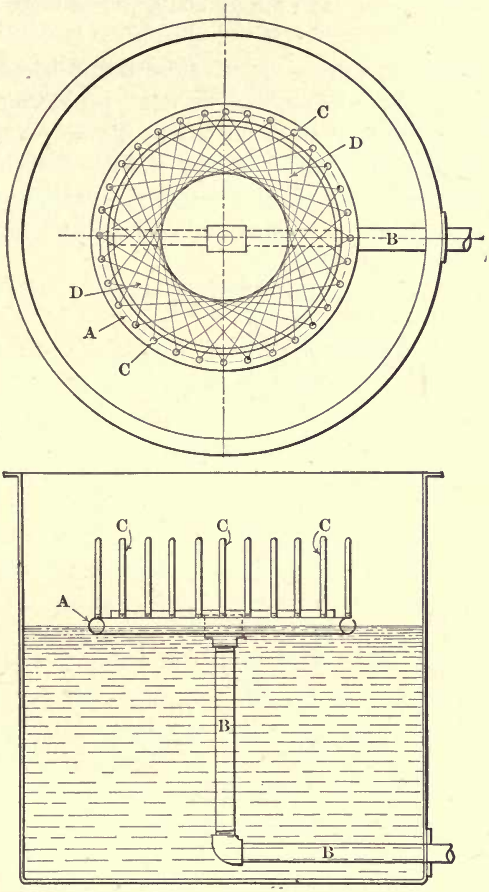


FIG. 121. — Water spray quenching bath.

With liquids, other than water, this method is not practical owing to the large volume of liquid needed for the bath, and its consequent high cost. Then again the losses from evaporation might be too great. For this kind of bath a water-jacketed receptacle could be used and a steady current of cold water kept flowing through it, or the bath could be fitted with a coil of rope, over the bottom and around the sides, through which a circulation of cold water could be maintained, and thus keep the bath cool. Another method that has been used successfully is to blow fine sprays of air through the bath from the bottom similar to the method used in the Bessemer converter on molten steel. One way of doing this is shown in Fig. 122.

With many classes of work a bath whose liquid is stationary and has no mechanical means of cooling can be used by having the volume of the bath large enough so that the heat left by the quenching of the pieces is negligible in proportion. Baths of this character are sometimes fitted with conveyors that carry the work through the bath, and out after cooling sufficiently. Some of these also carry the work through a pickling bath after it has been quenched.

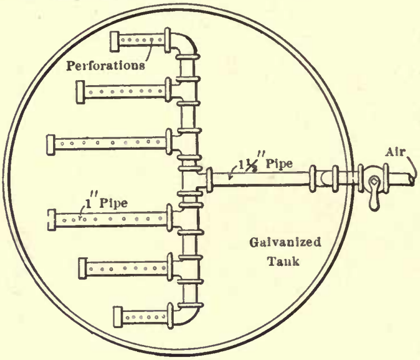


Fig. 122. — Pipes for cooling a quenching bath.

ELECTRICAL HARDENING

There is another method of hardening that is coming into use, and promises some interesting developments in the future. It consists of connecting the piece of steel to the positive and negative wires of an electrical circuit, and inserting it into a quenching bath. The current is then turned on and controlled by a rheostat, so that the metal can be heated to the proper temperature. This takes but a few seconds, and when the correct temperature is reached, the current is turned off and the steel is suddenly cooled or quenched in the bath in which it was heated, without being removed. In one case the bath was made of a solution of carbonate of potash and water. The piece is heated so quickly that is does not raise the temperature of the bath to a degree that retards the hardening effects.

This process prevents the scaling or blistering of the steel, as it is not brought into contact with the air when hot, and hence oxidization cannot take place. It also is capable of many variations, as a piece can be locally heated and hardened in the bath, or annealed in spots by heating it outside of the bath. The piece can also be placed on a copper plate and an electric arc used to heat any desired portion of it. It can then be quenched to harden, or annealed, as desired. In drawing the temper on the inside of a hollow object, a rod can be inserted in the hole and this heated up until the desired color of the steel has been reached and the current then turned off. By noting the amount of current consumed on a few test pieces, it can be regulated, by means of the rheostat, so that uniform results can be obtained on any number of pieces. The possibilities that this method suggests may make it an important factor in the future in heat-treating steels.

CRACKING AND WARPING

Much serious trouble has been caused by cracks and fissures that have been produced by the abrupt cooling of steel. Many times a piece separates abruptly from the part quenched. The reason for this is easily given, as during the cooling different parts of the steel are at different temperatures. This is many times caused by thick and thin sections in the same piece, but it also occurs in pieces of an even thickness, owing to the change in temperature not taking place everywhere at the same time. This causes internal strains, which many times attain enormous value and result in the lessening of the cohesive force that holds the molecules of the metal together. This causes brittleness and rupture at the places so affected.

In practical work the main thing to keep in mind is that these fissures only occur in high-carbon steel or some of the special alloys. There are several ways of overcoming this, and the three which are the easiest to use and most certain in their results are as follows:

First. — When a water-quenching bath is used it may be covered with from $\frac{1}{2}$ to 1 inch of oil, which will reduce the rate of cooling.

Second. — A quenching bath of comparatively small size may be used, in which case the sudden cooling will be followed by a slight tempering effect, caused by the rise in temperature of the bath.

Third. — The piece may be withdrawn from the bath before it is completely cooled. Uniform results are hard to obtain by this last method, owing to the difficulty of judging the temperature of the metal when withdrawn.

Warping may be caused by several factors, the two most important of which are, not having the steel in a proper condition of repose before it is hardened, and not putting the piece in the quenching bath properly. As any operation of working steel is liable to set up internal strains it is always best after rolling, forging, or machining steel to thoroughly anneal the piece before hardening it. This allows the metal to assume its natural state of repose. In the machining operations the roughing cuts could be taken off, the piece annealed, then the finishing cuts could be given it and the piece hardened. This would also make the steel easier to machine, as the metal is more uniform and in its softest state.

There are several rules that can be followed in hardening a piece of steel to prevent warping, and these rules always assume that the piece has been properly annealed before starting the hardening operations.

First. — A piece should never be thrown into the bath, as by laying on the bottom it would be liable to cool faster on one side than the other and thus cause warping.

Second. — The piece should be agitated, so the bath will convey its acquired heat to the atmosphere, and also destroy the coating of vapor that is liable to form on certain portions, and thus prevent its cooling as rapidly here as in the balance of the piece.

Third. — The liquid of the bath should instantaneously cover the largest possible amount of the surface of the piece when plunged into it.

Fourth. — Hollow pieces, such as spindles, should have the ends plugged, as they could not otherwise be quenched vertically on account of the steam that would be produced in the hole and cause it to throw hot water.

Fifth. — Pieces with thin and thick sections, or of intricate shapes, should be immersed so the most bulky parts would enter the bath first.

Sixth. — To harden one part of a piece only, it should be immersed so that it hardens well beneath the heated part.

Seventh. — Pieces which are very complicated should be rigged up with hoops, clamps, or supports to prevent their warping.

The hardening of large pieces gives somewhat different results as the transformation is not always complete, in which case there is a partial return to the normal stable state, that is, toward pearlite. Thus a small piece quenched from a high temperature in cold water is very hard and quite brittle, while a large piece quenched at the same temperature and under the same conditions is not quite as hard and only slightly brittle. If the large piece is examined with the microscope it would indicate martensite to be present in the surface layer, while at a certain distance below the surface would be seen troostite and sorbite. This would show that the transformation was not as complete as in the small piece and would account for the lower degree of hardness and brittleness.

This might lead one to suspect that the constituents in the center of a large piece were the same as in annealed steel, as the coefficient of expansion and the electrical resistance seem to be the same. From this might be drawn the conclusion that the mechanical properties of the two steels were not the same. These, however, are not the facts as the strengths and hardness are but little different from those of the small pieces that showed martensite.

On all steels, it is a very good rule that insists on a slow preheating of the metal before it is submitted to the high temperature of the hardening furnace. If followed, this will prevent, to a large extent, the checking, cracking, warping, etc., that is met with so often in the hardening room. To get the best results, low-carbon steels should consume about one hour in being heated up to a temperature of not less than 600° F.; high-carbon steels should be preheated to about 800°, and some of the special alloy steels, especially high-speed steel, to not less than 1000°. If even a higher temperature than this is reached in the slow heating, it will benefit rather than harm the metal, although at about these temperatures a transformation in the grain of the metals takes place that enables it to be heated more rapidly without any practical injury to the steel.

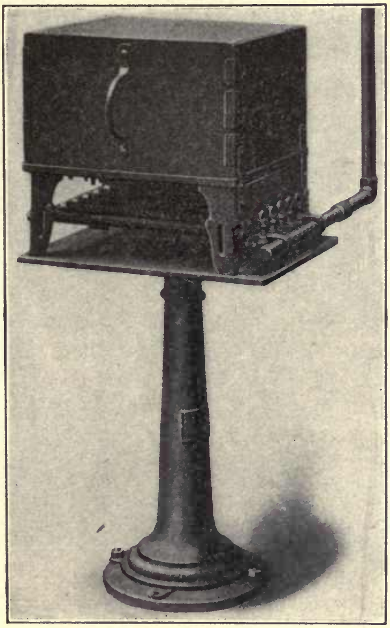


FIG. 123. — Tempering plate with sheet iron oven.

The preheating need not be made a matter of much expense to a hardening room, as low heat tempering furnaces are nearly always available, or if not ovens could be placed over the high heat furnaces. One of the simplest arrangements for slowly preheating is the hot plate that is 16 × 24 inches and covered with a sheet-iron oven, as shown in Fig. 123. It has 6 rows of 30 small gas jets underneath the plate, and any desired temperature can be attained in the oven. A small muffle furnace, similar to that shown in Fig. 124, is also very useful for preheating, and this can be used for reheating carbonized work. Both of these furnaces can be easily and successfully used for tempering, and thus the preheating not made an item of expense.

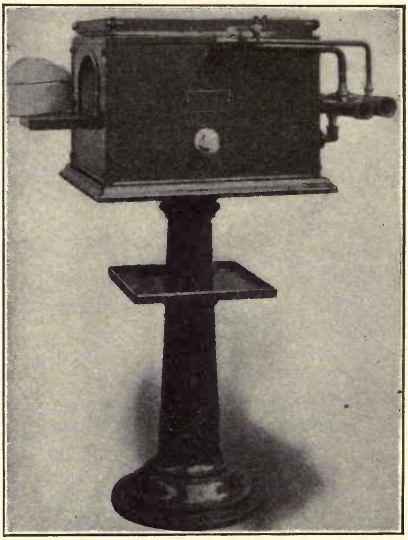


Fig. 124. — Muffle gas furnace.

The principles and practices of hardening are practically the same for the special alloyed steels as for the ordinary carbon steels, except that some of the alloying materials alter the point of transformation.

HIGH-SPEED STEELS

There is one notable exception to this, however, and that is in the case of high-speed or self-hardening steels. These are made by alloying with the steel, tungsten, and chromium, or molybdenum and chromium, or all three. These compositions completely revolutionize the points of transformation. Chromium, which has a tendency to raise the critical temperature, when added to a tungsten steel, in the proportions of 1 or 2%, reduces the critical temperature to below that of the atmosphere. Tungsten and molybdenum prolong the critical range of temperatures of the steel on slow cooling so that it begins at about 1300° F. and spreads out all the way down to 600°.

These steels are heated to from 1850° to 2450°, and cooled moderately fast, to give them the property known as "red-hardness." Sometimes they are cooled in an air blast, and sometimes they are quenched in various liquids. This treatment prevents the critical changes altogether, and preserves the steel in the austenitic condition. The austenitic condition is one of hardness and toughness, and it is peculiar that under this heat treatment the steel is not transformed into the pearlitic condition.

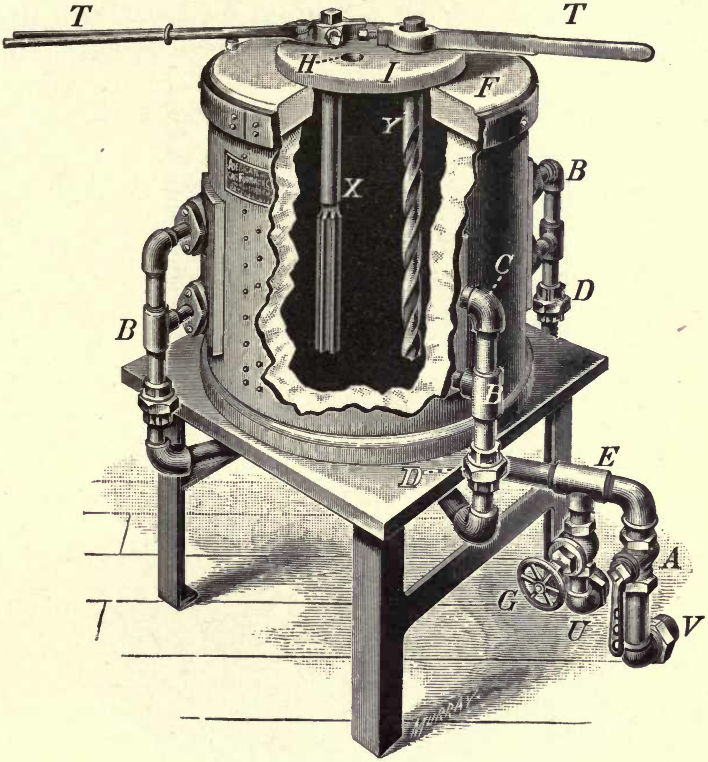


FIG. 125. — Cylindrical gas, hardening furnace.

One rule that has given good results in heat-treating some high-speed steels is to heat slowly to 1500° F., then heat fast to from 1850° to 2450°; after which cool rapidly in an air blast to 1550°; then cool either rapidly or slowly to the temperature of the air.

HARDENING FURNACES

The furnaces used for heating steel up to the necessary temperatures for hardening should be so arranged that the oxygen of the air will not attack the metal when it is hot, as then oxygen has its greatest affinity for iron, and will combine with it to form oxides that result in scale blisters, etc. The flame must therefore be a reducing one, that is, contain a deficiency of oxygen so it will not attack the metal, or a retort for holding the work must be used, and this heated from the outside by flames that are not permitted to enter the retort.

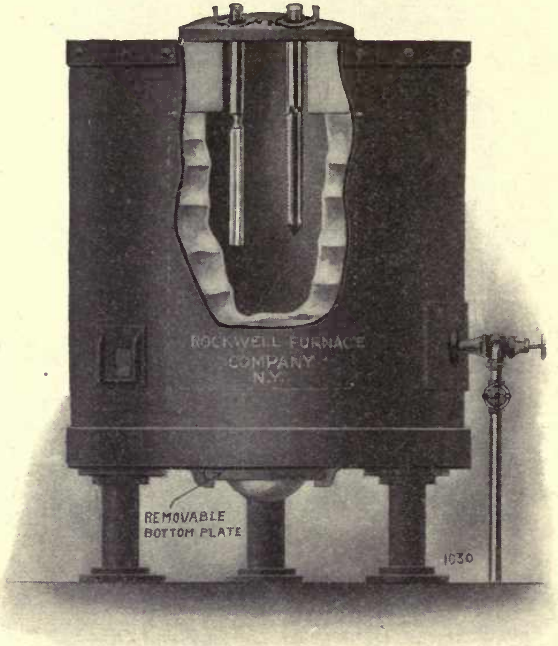


FIG. 126. — Cylindrical oil, hardening furnace.

Many furnaces that are suitable for hardening steel are shown in Chapter VIII, but there are various other styles. On long slender work it is often necessary to heat them, in a liquid or otherwise, with the ends hanging down, and for that reason furnaces of the style shown in Figs. 125 and 126 are the most suitable. These can be made to use either gas or oil for fuel.

When it comes to the high temperatures that are needed for high-speed steel, specially designed furnaces are the most economical. The furnace shown in Fig. 127 is one of these, and the details of its construction are shown in Fig. 128. A temperature of 2500° F. can be attained in 20 minutes, and maintained at that figure. The blast pressure generally used is about 2 pounds per square inch. Though usually confined to small work, the furnace can be used for long articles, as an opening at the back allows for the introduction of long bars, or drills. Two horizontal burners, each conveying air and gas in concentric tubes, enter the furnace on opposite sides and at different levels. By an arrangement of channels in the lining of the furnace, the flame is given a rotary motion, with the result that the whole of the interior of the heating chamber is filled with flame, which passes round the circular walls of the chamber, at a high speed, and out through the flues at the back. Hence the products of combustion pass to the exhaust box, that is located under the actual furnace. Through this box pass the pipes conveying the incoming gas and air, so that a regenerative action is set up, and as soon as the furnace is in blast, both the gas and air are preheated.

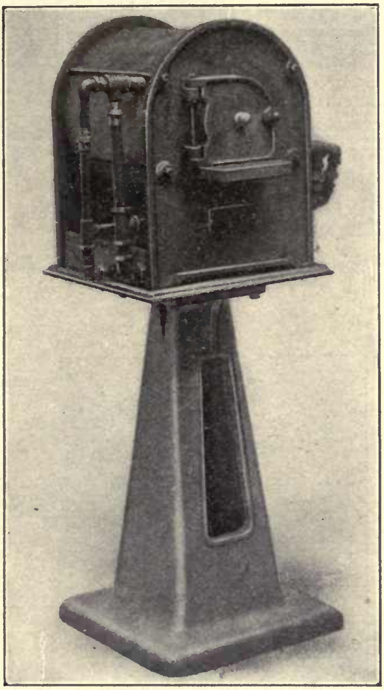


Fig. 127. — Wizard high-speed steel furnace.

Another style of high-speed steel furnace is shown by the vertical type in Fig. 129. A movable fire-clay plate, which can be raised or low-

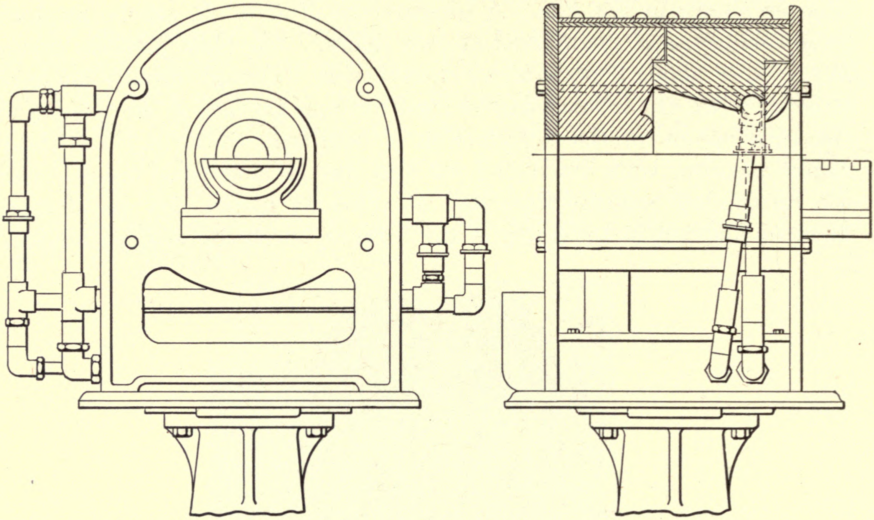


FIG. 128. — Sectional view of wizard high-speed steel furnace.

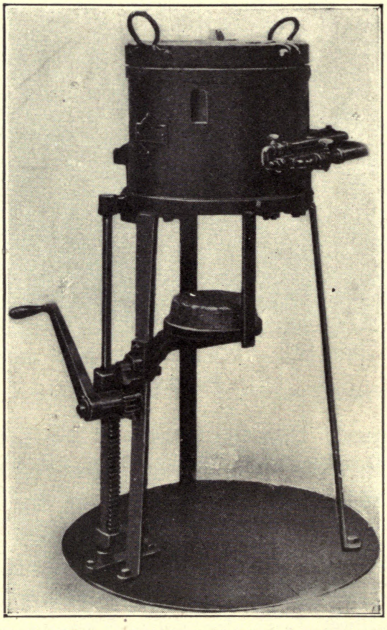


FIG. 129. — Vertical high-speed steel furnace.

ered by means of a rack and pinion, is used for inserting the work in the furnace. When raised, it forms the bottom of the furnace, by fitting into a circular cavity, and the hardener need not stand in the full glare of the opened furnace while he extracts the tool. It has the flame injected into the heating chamber at an angle so it will be given a rotating motion and thereby heat all parts of the chamber uniformly. As hot gases rise and cold gases descend the temperature of the furnace is not reduced as much when it is opened at the bottom to insert the tools as would be the case with a side or top-opened furnace. For this reason, also, the flame is inserted near the bottom of the furnace. The entire top is a cover that is made of fire-clay and held together by a steel band, with handles for lifting it off. In its center is a small peep-hole with a cover fitted in.

CHAPTER XI

TEMPERING STEEL

METHODS, MATERIALS USED, AND RESULTS OBTAINED

NEGATIVE quenching consists of cooling the metal through the critical zone at a rate equal to or below that which will give to the metal the greatest elongation when cold. This rate of cooling separates the mechanical results of quenching into the two distinct divisions mentioned farther back, namely, that for giving a cutting edge to tools, and that for increasing the static strengths and dynamic qualities. It varies as an inverse function of the carbon content unless the elements used in the special alloys influence it.

Negative quenching gives a tensile strength and elastic limit about equal to that obtained in annealed steel, and produces the highest possible elongation and a high reduction of area. This usually gives the steel the highest obtainable resistance to shocks.

As positive quenching becomes more and more pronounced it increases the tensile strength and elastic limit; at first slowly, then more and more rapidly, and reduces the elongation and resistance to shock in the same ratio. Thus, by variations in the factors governing the activity of the quenching bath, any steel may be given its most suitable state for any given purpose. In fact, all possible methods of quenching are but means of varying the rate of cooling, and the selection of the cooling mediums which will give the desired rate of cooling through each of the critical temperature zones of the metal in order to give it the desired properties is the real art of heat treatment.

Tempering steel, therefore, is to return it in part to a state of molecular equilibrium at atmospheric temperature by relieving any strains in the metal which have been caused by sudden quenching, and to correct any exaggeration of certain properties which have been caused by the hardening process.

The temperature to which a piece should be raised for tempering depends on the use to which it is to be put, the condition in which it has been left by quenching, and the composition of the metal. The maximum temperature desired should only be maintained long enough to be sure that the piece is evenly heated. The martensite which is retained in steel by the sudden cooling has a natural impulse to change into pearlite. By reheating slightly after hardening a certain amount of molecular freedom is given and changes take place that lessen the molecular rigidity set up by the hardening process. The higher the temperature is carried in reheating, the more it will lessen this molecular rigidity, and the more will the martensite give way to a pearlitic formation.

Steels heated to 150° F. will be slightly tempered, but if heated to the temperature at which the straw color is formed on a brightened surface by the appearance of an iron oxide, namely 450°, a greater tempering will result, and the temperature at which this oxide assumes a permanent blue color, namely 575°, will effect a still greater tempering. Each increase in this temperature of reheating reduces the hardness and brittleness, reduces the tensile strength and elastic limit, and increases the elongation as well as the resistance to shocks.

Steels that are not exposed to shock, and require a great hardness so that a fine cutting edge can be given them, such as razors, can have a marked degree of brittleness. A reheating to 450° F. for tempering will be the best condition that such steel can be given. Tools which have to withstand violent shocks such as cold-chisels and still retain a good cutting edge should be reheated to 575° to further remove some of the brittleness. This will lessen the hardness, and consequently the cutting powers, but is the lesser of the two evils. These two cases might be taken as the two extremes of temper desired in cutting tools.

The temperature to which it is best to draw or temper tools is about as follows:

430° F., or a Faint Straw Color:

- Tools for Metal Planers.
- Small Turning Tools.
- Hammer Faces.
- Steel-engraving Tools.
- Wood-engraving Tools.
- Ivory-cutting Tools.
- Bone-cutting Tools.
- Paper Cutters.
- Scrapers for Brass.

460° F., or a Dark Straw:

- Punches and Dies.
- Screw-cutting Dies.
- Leather-cutting Dies.
- Wire-drawing Dies.
- Taps.
- Milling Cutters.
- Metal-boring Cutters.
- Reamers.
- Tools for Wood Planers.
- Inserted Saw Teeth.
- Knife Blades.
- Wood-molding Cutters.
- Tools for Cutting Stone.
- Rock Drills.
- Half-round Bits.
- Chasers.

500° F., or a Dark Brown:
Wood-boring Cutters.
Edging Cutters.
Hand-plane Cutters.
Coopers' Tools.
Flat Drills.
Twist Drills.
Drifts.
Wood Gouges.

530° F., or a Light Purple:
Hack Saws.
Axes.
Wood Bits and Augers.
Dental Instruments.
Surgical Instruments.
Springs.

550° F., or a Dark Purple:
Cold-chisels for Steel.
Chisels for Wood.
Circular Saws for Metal.
Needles.
Gimlets.
Screw-drivers.

570° F., or a Light Blue:
Cold-chisels for Iron.
Saws for Wood.
Molding Cutters to be filed.
Planer Cutters to be filed.

The temperatures of the different colors used for tempering are about as follows:

Faint Straw, 430° F.
Straw, 460° F.
Light Brown, 490° F.
Dark Brown, 500° F.
Purple and Brown, 510° F.
Light Purple, 530° F.
Dark Purple, 550° F.
Light Blue, 570° F.
Dark Blue, 600° F.
Blue Green, 630° F.

These colors of steel, at a given temperature, cannot always be depended upon, however, as the various ingredients that enter into the composition of different grades of metal are liable to influence the color. That the carbon contents of steel has an influence on the colors is shown by the samples in Fig. 130. These pieces were carbonized and hardened, then tempered at various temperatures, as measured by a pyrometer, and it is to be regretted that the colors cannot be shown, although the contrast between the low-carbon center and the high-carbon outer shell can be seen. Some of these pieces were left rough, as they were broken and others were ground and polished before hardening.

The pieces *A* and *B* are $\frac{1}{2} \times 1\frac{3}{4}$ inches, and *A* is untreated, while *B* was hardened and then drawn until the high-carbon outer shell was a greenish-blue color. The difference between the two colors showed a decided contrast; *C* and *D* were ground and polished and then hardened and drawn until the outer shell was a dark blue. This left the low-carbon center a dark brown. These pieces were ¾ inch diameter. *E* was hardened and not drawn. This left the shell a bright steel color, while the center was almost a black; *F* was drawn to a dark blue, and this left the center a dark brown, similar to the pieces *C* and D; piece *G* was drawn to a purple, and this left the center a yellow brown or dark straw color; the *H* piece was drawn to a dark brown in the shell, which left the center a light straw color; *L* was drawn to a full purple, which left the center a spotted red brown; *M* was drawn to a full blue in the shell, and this left the center a brown purple; *J* was drawn to a dark blue, which left the center a dark brown, while piece *K* was hardened and drawn to a purplish blue, and this left the center a light brown. Pieces *I*, *N*, *P*, and *O* were drawn to a dark blue on the high-carbon outer shell, and this left the low-carbon center a dark brown.

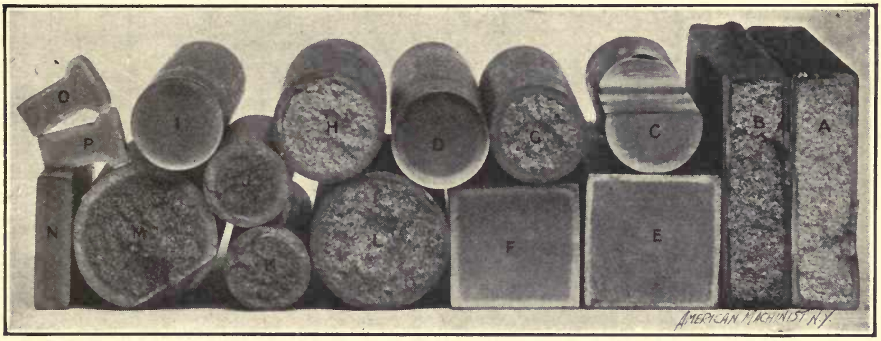


Fig. 130. — Carbonized steel after being hardened and drawn to color.

While the hardening of steel by colors has been successfully done in the past, and will be done many times in the future, these pieces would seem to make it imperative for the hardener to test a sample piece from each lot of steel before attempting to harden it by color. A much better way, however, would be to use a pyrometer for measuring the temperatures as, if the pyrometer is kept in order, a positive knowledge of the temperature at which the metal is treated can be instantly obtained, and the differences in the light in the shop or even in color-blindness will not affect the hardener.

Steels that are used in the building of machinery, as a rule, have the temper drawn much more than this, and the variation in temper is only limited by the work that the parts have to do, the composition of the metal, and the different degrees of temper which steel can be given. Leaf springs, such as carriage springs, are usually reheated to about 800° F.

Gears which are in constant mesh without any undue pressure will give the best results as to wear, strengths, and resistance to shocks if reheated to about 675°. Crank-shafts on internal-combustion engines have to withstand considerable torsion, vibrational strains, and impact stresses and seem to stand the work best when reheated to about 1000°.

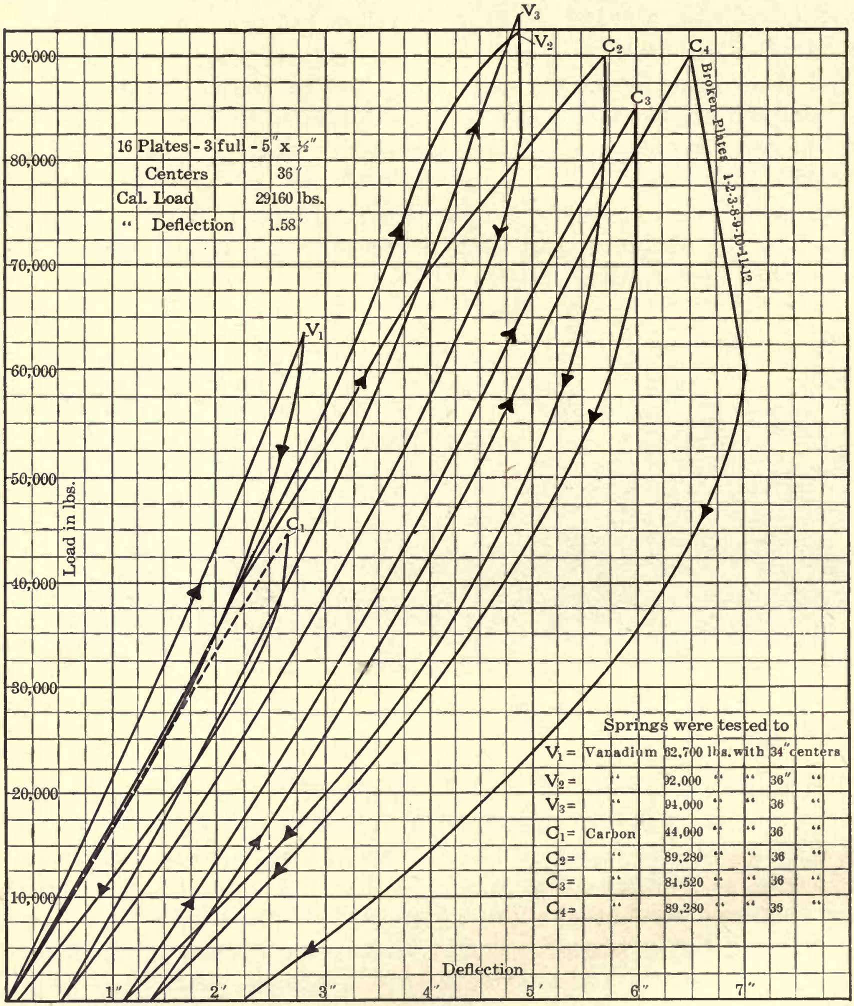


FIG. 131. — Spring deflections. Comparative tests.

Fig. 131 and 132 show the effect of the above heat treatment for springs on two kinds of steel which might be said to show the two extremes in deflection, fiber stress, and their resultant permanent set. In Fig. 131 the elastic limit was reached on the second test. This for the vanadium steels was 85,000 pounds, or 234,500 pounds fiber stress with a permanent set of 0.48 inch. In the carbon steels it was 65,000, or 180,000 pounds fiber stress with a permanent set of 1.12 inches. The carbon steel took an additional set of 0.26 inch on the third test and broke on the fourth in the center. The third test was repeated three times on the vanadium steel without any change in recorded hights. The tests were made by the American Vanadium Company.

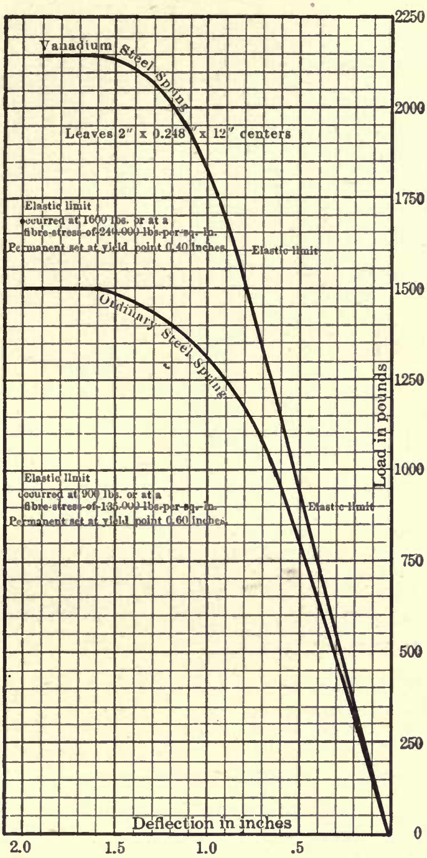


FIG. 132. — Comparative tranverse tests.

The changes that can be made in the strengths of steel are very forcibly shown in the following Table No. 2, which explains itself:

TABLE NO. 2

	Tensile Strength Lb. per Sq. In.	Elastic Limit Lb. per Sq. In.	Elongation in 2 In., Per Cent.	Reduction of Area, Per Cent
Annealed at 1475 degrees.....	87,640	64,400	29	59
Hardened at 1650 degrees, oil tempered at varying temperatures.....................	125,000	103,000	21	56
	127,800	110,100	20	58
	130,500	124,000	17	62
	138,000	127,500	18	65
	147,000	140,750	17	57
	212,000	200,000	12	51
	232,750	224,000	11	39

TEMPERING EQUIPMENT

The furnaces used are sometimes the same as those used in hardening. But furnaces that will permit of maintaining a constant temperature with appliances for measuring the heat so the correct temperature can be attained are the best kind. Thus, wherever possible it is best to have furnaces that are designed especially for tempering. These can be built cheaper than hardening and annealing furnaces, as it is not necessary to construct them so they will withstand the high heats used in hardening, and special appliances can be attached that are not needed on the hardenening or annealing furnaces.

The oven gas furnace shown in Fig. 133 is a very handy one in which to temper work, and oil fuel can be used on this style of furnace if desired. The hot plate with a sheet metal oven, that is shown in Fig. 123, is also very useful for tempering. Another type of the gas furnace for tempering is shown in Fig. 134. This is very useful for small work which is inserted through the opening *S* into the drum *D*, and the door *E* closed. The drum is then rotated by a gear and worm on shaft *N*, and the work tumbled so all the pieces will be uniform in temper and heated on all sides. Drum *D* can be pulled out of the furnace by handle *H*, to empty out the work when it is finished. The heat can be accurately controlled at the desired temperature by gas valve *G*, and air valve *A*, and reference to the thermometer *T*.

Lead baths are used a great deal, as it is easy to heat these to a certain temperature and hold them at a constant temperature for any length of time. With this the bath is heated to the temperature at which the steel needs to be tempered or drawn, the piece is placed in the bath and allowed to remain until it has attained the temperature of the bath, and it is then taken out and cooled. One of the simpler gas-heated lead baths is shown in Fig. 135. These, however, can be heated with coal, coke, oil, or any other fuel as well, and they should be supplied with a hood that is piped to the outside, as any fumes that may arise from the molten lead are injurious.

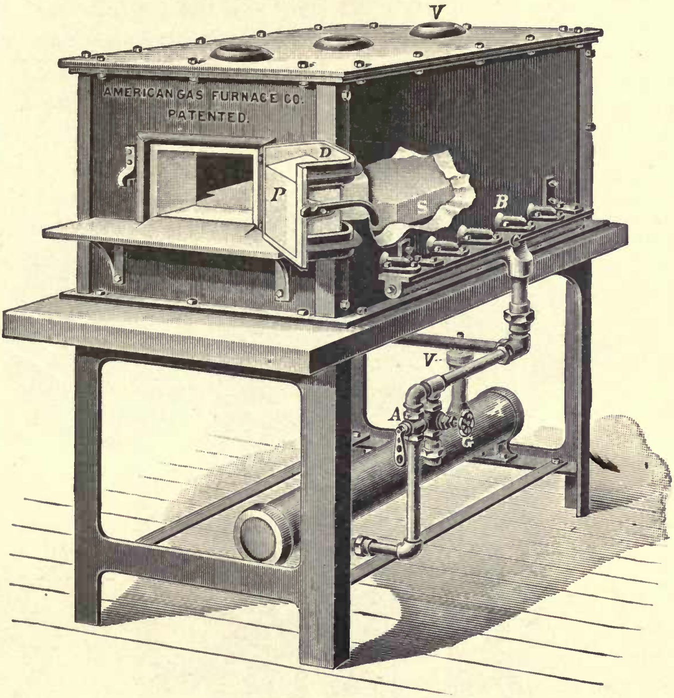


Fig. 133. — Oven furnace with gas for fuel.

As the pure lead melts at about 620° F., it is necessary to mix it with some other metal to get the lower tempering temperatures. Tin is the most often used for this purpose, as it lowers the melting temperature sufficiently, and is a comparatively cheap metal. As low as 360° F. for the melting point can be obtained by combining these two metals. The alloys that will melt at given temperatures are as follows:

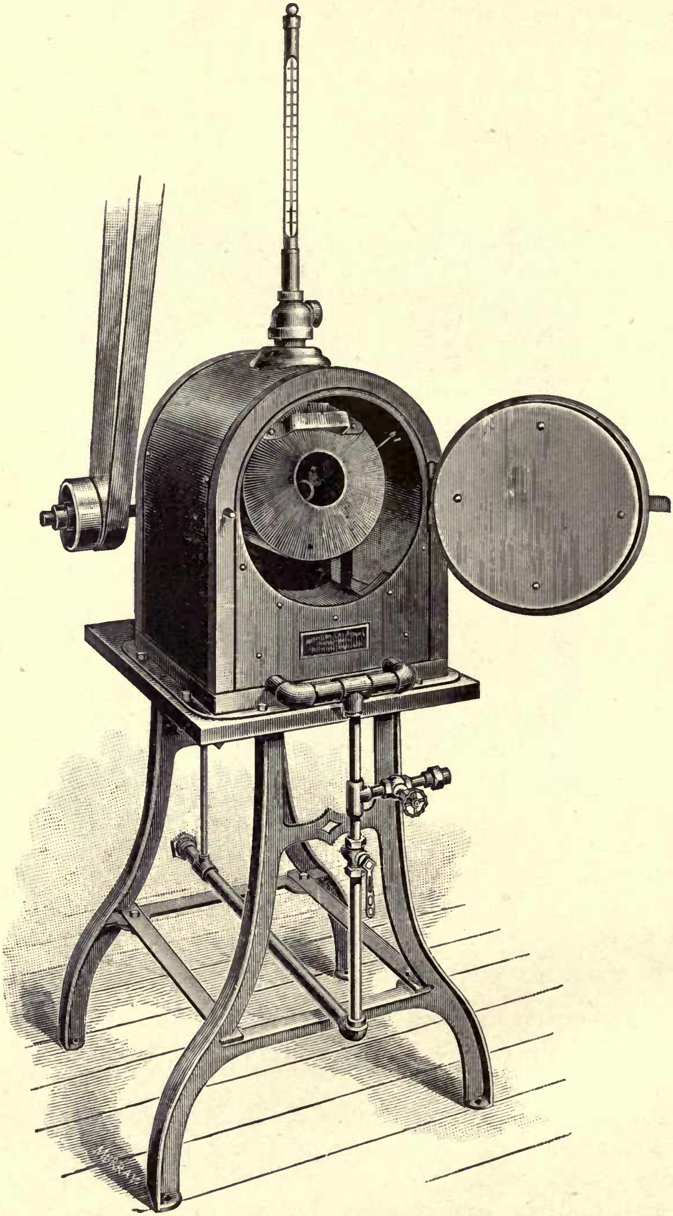


Fig. 134. — Revolving drum tempering furnace.

Pure Lead melts at 619° F.

200 parts Lead and 8 parts Tin melt at	560° F.
100 parts Lead and 8 parts Tin melt at	550° F.
75 parts Lead and 8 parts Tin melt at	540° F.
60 parts Lead and 8 parts Tin melt at	530° F.
48 parts Lead and 8 parts Tin melt at	520° F.
39 parts Lead and 8 parts Tin melt at	510° F.
33 parts Lead and 8 parts Tin melt at	500° F.
28 parts Lead and 8 parts Tin melt at	490° F.
24 parts Lead and 8 parts Tin melt at	480° F.
21 parts Lead and 8 parts Tin melt at	470° F.
19 parts Lead and 8 parts Tin melt at	460° F.
17 parts Lead and 8 parts Tin melt at	450° F.
16 parts Lead and 8 parts Tin melt at	440° F.
15 parts Lead and 8 parts Tin melt at	430° F.
14 parts Lead and 8 parts Tin melt at	420° F.

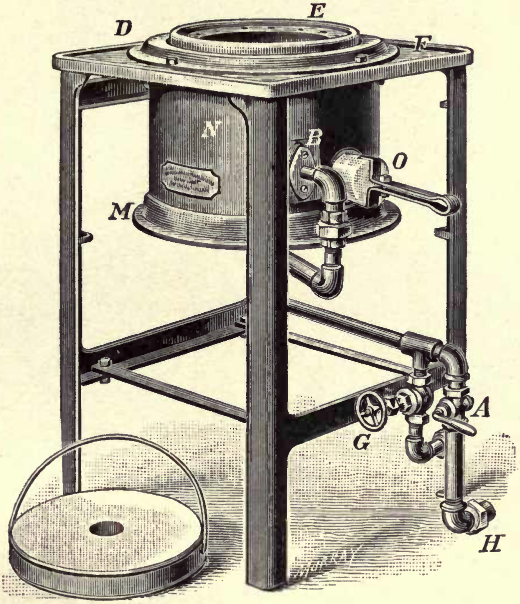


Fig. 135. — Gas-heated lead bath.

Oil baths are also used quite extensively for tempering, and like the others the bath should be maintained at the temperatures to which it is desired to draw the temper, and the work immersed until it has attained the temperature of the bath and then taken out to cool in the air. One of the best oil bath furnaces is that shown in Fig. 136, but equally good results are obtained with oil-fired or electrically heated baths. The temperature can be easily controlled by means of the gas and air valves, as in the other furnaces shown, by using the high temperature thermometer for a guide. The wire basket shown in front of the furnace is to hold the work so it can be easily removed from the oil.

Temperatures of 600° F. can be easily obtained and maintained in the oil baths with the ordinary oils, but for temperatures that are much higher than this other materials should be used. Some of the tallows can be successfully worked at temperatures as high as 800°. Steel is not injured by soaking in the oil for an indefinite time, provided the desired temperature for tempering has not been exceeded. This makes it possible to temper large and small pieces at the same time, as while the large pieces are lying in the bath to thoroughly absorb the heat in all their parts, the smaller pieces can be tempered. It is always best to slowly preheat the work to from 300° to 400° before submitting it to the tempering bath, as this allows the molecules of the metal to readjust themselves more thoroughly than if the piece is plunged immediately into the tempering bath.

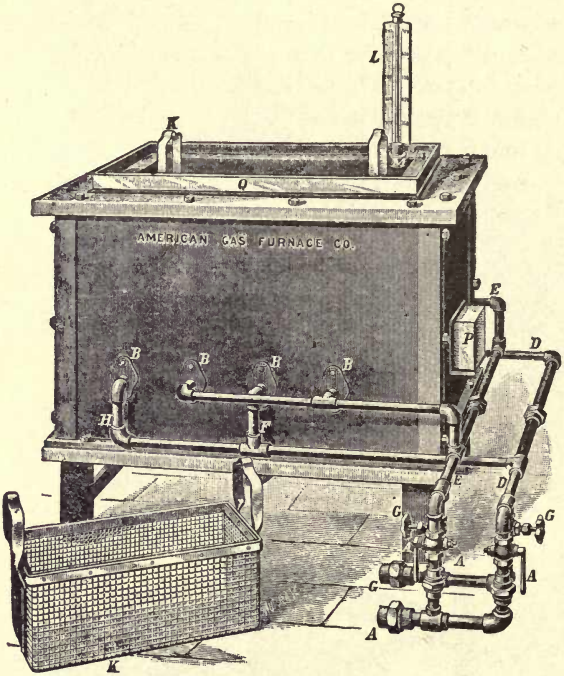


FIG. 136. — Gas heated oil bath.

The electrically heated oil bath is doubtless the best, as by means of the rheostat the temperature is very easily controlled. When the exact amount of current that is required to heat a given oil up to a given temperature is known, the rheostat can be set at this and no further attention paid to it until the work is ready to be taken out of the bath. When starting with a cold bath no preheating of the work is required, as the rheostat can be set and the work heated up with the oil. To maintain a temperature of 600° F. in one style of electrical oil bath, it required 6 kilowatts per hour for 9 gallons of oil, 7.2 kilowatts for 11 gallons, and 12 kilowatts for 20 gallons.

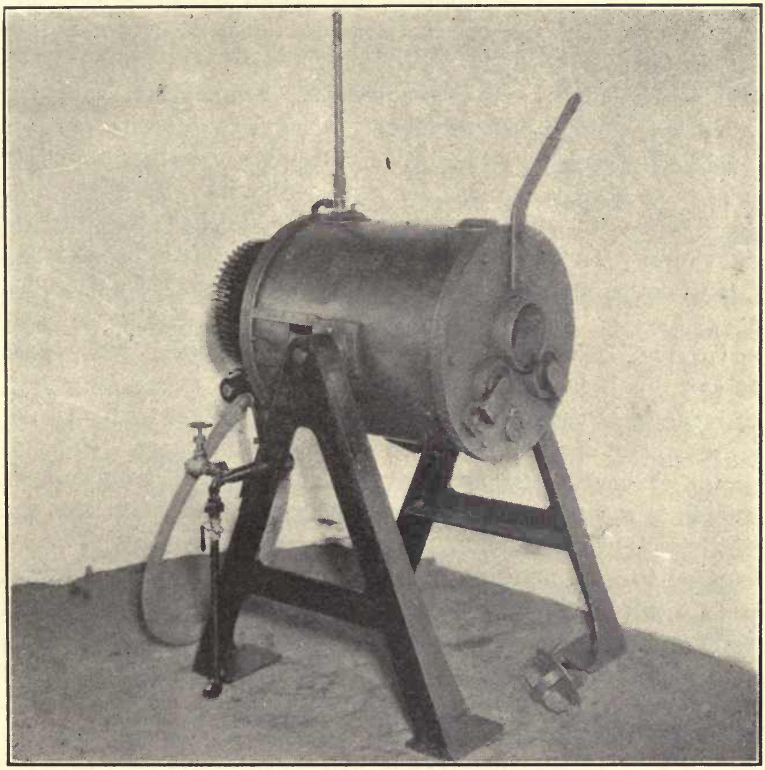


FIG. 137. — Tempering furnace with revolving retort.

Salt baths are sometimes used where the drawing temperature desired is 575° F. Salt fuses at this point, and a certainty of obtaining this temperature in the steel is assured. In using this the salt is heated to 700° or 750°, and the steel placed in the bath. When this is done the cold metal will cause the salt which surrounds it to solidify and plainly show a white crust around it. When the steel has attained a temperature of 575° the white crust will disappear as the salt which made it has melted and mixed with the rest of the bath. This clearly shows that it is time to take the piece out of the bath and allow it to cool. This method can be used for tempering above 575° and below 900°, but is not practical for higher or lower temperatures owing to the alteration in the salt of which it is composed.

Another method that is used considerably on some classes of work is sand tempering. This consists of covering the work with sand, and heating both up at the same time. Clean and well-dried sand is sometimes used in a pan, and the metal heated up in it over a fire. Some special gas furnaces have also been built for sand tempering in which the sand is permanently kept at the required temperature. The work is placed in this until it has thoroughly attained the temperature of the sand, and then cooled in the air. Continuous operating automatic gas furnaces have also been made for sand tempering. In these the work and sand travels through the furnace, from one end to the other, by the aid of a worm. The work is then dumped out, while the sand is brought back to the other end, inside of the furnace, by means of a second worm.

A gas furnace, with a revolving retort, that is used for tempering is shown in Fig. 137. The outer shell of the furnace is lined with fire-brick, and this is heated by the gas. The round retort, the opening of which is shown at the end, is placed inside of the outer shell, and revolves on 4 wheels, two of which are at each end of the furnace. It is revolved by means of bevel gears, sprockets and chains, and a pulley and belt. The whole is mounted on trunnions, and can be tilted to any angle so the work will travel through the furnace automatically. This furnace is also used to give metal parts a gun-metal finish. This color can only be given to pieces that will stand tempering to 600° F., as it takes that temperature to put the color on the metal; this being done by means of charred bone and chemicals.

CHAPTER XII

Carbonizing

METHODS AND MATERIALS USED — EFFECT OF ALLOYING MATERIALS AND HEAT TREATMENT

Many of the steels that give very high figures in their strength tests are made hard enough to resist wear for such parts of machinery as gears, cams, ball races, etc., by hardening and tempering; but when the proper degree of hardness is obtained to reduce wear to a minimum, they are too brittle to withstand shock strains.

For this reason case-hardening, carbonizing, or, as it is called in Europe, "cementation," is resorted to, as by this process the outer shell can be made hard enough to resist wear, and the core of the piece can be left soft enough to withstand the shock strains to which it is subjected. By this method gears can be made from some of the special alloy steels that will reduce the wear to a point that would have been considered impossible a few years ago, and at the same time resist shock to such an extent that it is very difficult to break out a tooth with a sledge hammer.

Several methods different from the old established one of packing the metal in a box filled with some carbonizing material, and then subjecting it to heat, have been devised in the last few years. Among them might be mentioned the Harveyizing process which is especially applicable to armor plate. This in turn has been followed by an electrical and a gas process, which claim to be great improvements over the Harveyizing process. Very recently another process has been invented which uses gas for carbonizing in a specially constructed furnace. This is very useful for carbonizing small work.

The Harveyizing process uses a layer of charcoal between two plates which are heated in a pit furnace by producer gas. The weight of the upper plate brings the charcoal in close contact with the surfaces and facilitates the soaking in of the carbon.

This process has been a great success, but it also has its faults, as the carbon soaks in to a good depth in some places, while at other places, sometimes only a foot away, the carbon will not be so deep, so that when tested a shot will glance off from one spot, and when it hits a short distance from this will tear a great hole in the plate. Then again the Harveyizing process is not suitable for small work.

Electricity has also been used in a like manner to gas in the Harveyizing process. That is, armor plate has been covered with a layer of ground bone, the whole enclosed and a current of electricity turned on to heat the bone and metal so that the carbon will combine with the steel in a surface layer of desired depth, and it is claimed for this process that the depth can be regulated, and the carbonization is even over the entire surface.

As these two processes are only used on armor plate or other large work of a similar character, and are too expensive in their installation to be made applicable to parts of machinery, or tools, they will not be gone into in detail here.

The Krupp process is similar to the above two in the kind of work it operates on, and differs from Harveyizing in that it uses a gaseous hydrocarbon to replace the bed of charcoal. This also is foreign to the subject, but the gas it uses is practically the same as that used in the furnace for carbonizing with gas, which will be described later.

FACTORS GOVERNING CARBONIZING

The result of the carbonizing operation is determined by five factors, which are as follows: First, the nature of the steel; second, the nature of the carbonizing material; third, the temperature of the carbonizing furnace; fourth, the time the piece is submitted to the carbonizing process; fifth, the heat treatment which follows carbonizing.

The nature of the steel has no influence on the speed of penetration of the carbon, but has an influence on the final result of the operation. If steel is used that has a carbon content up to 0.56%, the rate of penetration in carbonizing is constant; but the higher the carbon content, in the core, the more brittle it becomes by prolonged annealing after carbonizing. Therefore it is necessary that the carbon content should be low in the core, and for this reason a preference is given to steels containing from 0.12 to 0.15% of carbon for carbonizing or case-hardening purposes. Some, however, prefer a steel containing from 0.20 to 0.22% carbon, owing to its being more easily worked with machine tools; but the results will not be as good as with a steel containing a maximum of 0.15% carbon. Greater strength and easier working qualities can be obtained by the addition of such alloys as chromium, vanadium, titanium, nickel, etc.

Manganese. — It is also very important that the manganese content of carbonizing steels be kept low. This should never exceed 0.35%, as manganese has a tendency to render the hardened and carbonized surface brittle, thus making it liable to chip and break at the least shock. Thus manganese is usually kept down to 0.20%, and seldom exceeds 0.25%.

CHROMIUM. — While chromium has a tendency to produce a mineral hardness in steel, it prevents the development of the crystalline structure under heat treatment, thus refining the grain and making it better able to withstand shocks. Therefore chromium added in small percentages makes steels for carbonizing more homogeneous, and imparts to them greater strengths and wearing qualities. Chromium, however, produces steels that are very difficult to machine; it is therefore combined with other ingredients which offset this, except for such uses as armor plate.

VANADIUM, used in homeopathic doses, overcomes this difficulty of machining chrome steels to such an extent that it is claimed that a steel containing 1% chromium and from 0.16 to 0.18% vanadium, can be forged and machined as easily as a 0.40% carbon steel. Vanadium also produces high dynamic strengths, which gives the core of carbonized steels a high resistance to shocks.

TITANIUM produces practically the same results as vanadium in steels for carbonizing, and is usually used in percentages of from 0.40 to 0.50.

NICKEL, added to ordinary carbonizing steel in comparatively small percentages, obviates the brittleness which is usually produced by carbonizing, and makes it more homogeneous, the pearlite being distributed much better. With 2% of nickel, the steel is increased in strength; in some cases this strength is nearly double that of the ordinary carbonizing steel, but 2% nickel steel means nothing unless the carbon is of the proper percentages. When it is, it makes one of the best of steels, when carbonized and tempered, for such parts as shafts, ball races, gears, etc. It should therefore be used wherever the 2½ cents difference in price does not make it prohibitive, except where the higher price alloy steels are demanded, owing to their greater strength and wearing qualities.

A 2% nickel steel carbonized so that the surface layer contains about 1% of carbon will be pearlitic, but a 7% nickel steel will show a surface layer that is martensitic, with a pearlitic core. Martensite being a constituent of quenched steel, a 7% nickel steel carbonized so the surface layer contains 1% of carbon has the came constitution as an ordinary carbonizing steel that has been carbonized and hardened, that is, a pearlitic core and a martensitic outer shell. This martensite should become denser and denser as it approaches the outer surface. This will give high strengths, and the outer layer will readily polish without wear, thus giving it valuable wearing qualities.

This simplifies the processes of carbonizing, owing to its doing away with the hardening processes afterward, but the carbonizing and the cooling afterward must be carefully done in order to get good results from this process. If, however, the proper carbonizing materials are used, the heat of the furnace regulated so that it remains steady and at the proper temperature, and the piece not cooled too quickly, a saving in time and expense can be made with this process of carbonizing, when this grade of steel is suitable.

The influence of the different elements on the speed of penetration of the carbon, when carbonizing steels containing the same amount of carbon and different percentages of manganese, chromium, nickel, tungsten, silicon, titanium, molybdenum, and aluminum, is shown by Table 3.

TABLE 3.—PENETRATION OF CARBON PER HOUR

Component of Alloys	Speed of Penetration Per Hr. in Inches	Component of Alloys	Speed of Penetration Per Hr. in Inches
0.5 per cent. manganese.....	0.043	1.0 per cent. silicon.......	0.020
1.0 per cent. manganese.....	0.047	2.0 per cent. silicon.......	0.016
1.0 per cent. chromium	0.039	5.0 per cent. silicon.......	0.000
2.0 per cent. chromium	0.043	1.0 per cent. titanium.....	0.032
2.0 per cent. nickel.........	0.028	2.0 per cent. titanium.....	0.028
5.0 per cent. nickel.........	0.020	1.0 per cent. molybdenum.	0.036
0.5 per cent. tungsten.......	0.035	2.0 per cent. molybdenum.	0.043
1.0 per cent. tungsten.......	0.036	1.0 per cent. aluminum....	0.016
2.0 per cent. tungsten.......	0.047	3.0 per cent. aluminum....	0.008
0.5 per cent. silicon.........	0.024		

The rate of penetration for ordinary carbonizing steel under the same conditions would have been 0.035 inch. Thus it will be seen that manganese, chromium, tungsten, and molybdenum increase the rate of penetration. These seem to exist in the state of a double carbide and release a part of the cementite iron.

Nickel, silicon, titanium, and aluminum retard the rate of penetration — 5% of silicon reducing it to zero — and these exist in the state of solution in the iron. The titanium steel, however, has more titanium in it than should be present in carbonizing steel, and if this were reduced to 0.50% the results might be different. As it is, the 1% of titanium only very slightly retarded the penetration.

As a general rule the alloyed steels that give the best results in annealing, hardening, and tempering are not the best for carbonizing; for this reason most of these alloyed steels are made in a special grade for carbonizing. As an illustration of this, vanadium steel that gives the best results for crank-shafts, transmission shafts, connecting rods, and other moving engine parts is composed of 0.25 to 0.30% carbon, 0.40 to 0.50% manganese, 1% chromium, and 0.16 to 0.18% vanadium, while the best carbonizing steel has from 0.12 to 0.15% carbon, 0.20% manganese, 0.30% chromium, and 0.12% vanadium.

CARBONIZING MATERIALS

The nature of the carbonizing materials has an influence on the speed of penetration, and it is very essential that the materials be of a known chemical composition, as this is the only way to obtain like results on the same steel at all times.

These materials or cements are manufactured in many special and patented preparations. The following materials are used for carbonizing purposes: Powdered bone, wood charcoal, charred sugar, charred leather, cyanide of potassium, ferrocyanide of potassium, acid cleaned animal black, anthracite, graphite, horn, acetylene, petroleum gas, naphtha, carbon monoxide, illuminating gas, and gasoline. In addition such materials as black oxide of manganese, barium carbonate, ammonia, and others are used in mixture with the preceding substances.

Such materials as bone and leather should not be used alone as it is impossible to obtain definite results from them, owing to the changeability of their chemical composition when subjected to a temperature high enough for carbonizing.

Wood charcoal is very largely used in carbonizing steels, but the value of this material varies with the wood used, the method employed in making the charcoal, and other factors. Used alone it gives the normal rate of penetration for the first hour, but after that the rate gradually decreases until at eight hours it gives the lowest rate of penetration of any of the carbonizing materials.

The best wood charcoal is that made from hickory. This is due to the fact that this charcoal contains a relatively high percentage of carbonate of potassium, and this, in conjunction with the charcoal and the nitrogen of the air, in the carbonizing box, is capable of giving cyanide of potassium. Thus, by combining wood charcoal and carbonate of potassium, an increase in the rate of penetration can be obtained; but this speed decreases with time, due to the volatilization of the alkaline cyanides. If a current of ammonia is used, the rate of penetration becomes constant, as cyanide of ammonium is formed. Therefore some consider the best carbonizing materials to be the ones that produce the most of this substance.

Powdered charcoal and bone give good results as a carbonizing material and are successfully used in carbonizing nickel-chrome steel, by packing it in a cast-iron pot and keeping this at a temperature of about 2000° F. for four hours, and then cooling slowly before taking the metal out of the pot or removing the cover.

Pure carbon, such as that of sugar, does not carbonize in vacuum; therefore a carbonizing material that is simply composed of carbon can only act directly by solution of the carbon, starting with the iron in contact with it. Thus sugar should be mixed with some other material in order to obtain the best results from carbonization. Carbonic oxide, giving $2CO = C + CO_2$, which is formed by the action of the air, in the carbonizing box, on a carbonizing material that is composed simply of carbon, may act; but its action is slow, and the carbonic acid, CO_2, has a decarbonizing action.

Materials containing a cyanide act by means of the cyanogen radical $(CN)_2$. This compound is decomposed, giving up its carbon to the steel. In some cases a small amount of cyanide appears to act as a carrier of carbon from some other substance to the steel. Ferro-cyanide of potassium heated gives cyanide, cyanate of potassium, and oxide of iron. A mixture of ferro-cyanide and bichromate of potash gives rise to a new mixture of cyanide and cyanate diluted in a mass of iron and chromium oxide. Carbonate of barium, under certain conditions and in the presence of the nitrogen of the air, gives rise to cyanide of barium according to the following equation: $2N + 4C + CO_3Ba = (CN)_2Ba + 3CO$. Therefore it acts by means of cyanide and carbonic oxide.

Certain carbonizing materials contain carbonates that are dissociable at the temperature of carbonization, especially calcium carbonate. In the presence of carbon there is formed carbonic oxide, which carbonizes very slowly.

Therefore the carbonizing materials might be classed as follows: First, cements which act by means of carbonic oxide; second, cements which act by means of a cyanide, such as potassium, barium, or ammonium; third, cements which act by means of hydrocarbons. To carbonize with the hydrocarbons, it is necessary to generate the gases and conduct these to the receptacle in which the work has been placed in such a manner that they may carbonize the pieces before passing out of the vent.

J. C. Olson and J. S. Weissenback, at the Polytechnic Institute in Brooklyn, made some tests on carbonizing, with gases. They used $\frac{3}{8}$

inch soft Norwegian iron that contained 0.08% of carbon, and the results are best shown in Table 4.

Table 4.—Result of Experiment of Carbonizing Steel with Gases

Test Number	Gas Used	Time in Hours	Hardness	Depth of Case, Inches	Carbon Content, Per Cent.
1	Illuminating and ammonia (*a*)......	4	glass	0.004	0.57
2	Illuminating and ammonia (*b*)......	4	glass	0.008	0.66
3	Illuminating and ammonia (*c*)......	4	glass	0.008	0.91
4	Illuminating......................	4	none	none	none
5	Illuminating and ammonia (*a*)......	8	glass	0.012	1.12
6	Illuminating and ammonia (*b*)......	8	glass	0.012	1.16
7	Illuminating and ammonia (*c*)......	8	glass	0.012	1.15
8	Carbon monoxide and ammonia (*c*)..	4	glass	0.016	1.45
9	Carbon monoxide..................	4	glass	0.016	1.36
10	Acetylene and ammonia (*c*).........	4	glass	0.012	0.98
11	Acetylene........................	4	little	not well defined	0.41
12	Methane and ammonia (*c*).........	4	little	not well defined	0.32
13	Methane.........................	4	little	not well defined	0.26

The ammonia was used in different strengths *a* being the weakest with *b* twice the strength of *a* and *c* twice the strength of *b*.

From the results shown in this table the conclusions were drawn that ammonia gas facilitates the case-hardening in all cases except that of carbon monoxide, which seems to act almost as well without as with ammonia. Of the three pure gases studied, the carbonizing ability is in the following order: Carbon monoxide, acetylene, methane. The illuminating gas not being a pure gas and varying in composition with the different gas companies, it cannot be given a fair comparison with the other gases. With illuminating gas and the strongest ammonia the 4-hour test showed a very good percentage of carbon, and in the 8-hour test the percentages of carbon ran about equal in all of the three different strengths of ammonia.

The results obtained from carbon monoxide show it to be by far the best gas for this purpose, and the difference in the carbon percentage between carbon monoxide alone and carbon monoxide combined with the strongest ammonia was so slight that it does not seem necessary to use ammonia with it. In the case of carbon monoxide the gas was freed from carbon dioxide by bubbling through strong caustic potash solution before entering the case-hardening tube. Roughly speaking, the hardening depth is for the four hours proportional to the time.

Nitrogen. — The commonly used carbonizing materials all contain nitrogen in some form or other, and as the non-nitrogenous materials cost from one tenth to one-twentieth of those containing nitrogen, some experiments have been made with anthracite and coke. After carbonizing the same sized test pieces with these for four hours at 1650° F., the penetration for the anthracite was 0.006 inch, and with the best grade of hard coke it was 0.0064 inch. Charred leather under the same conditions gave a penetration of 0.062 inch. As this was in the proportions of 10 to 1 it would lead to the conclusion that nitrogen performs an important part in carbonizing.

The effect of ammonia was also tried by carbonizing in a gas pipe, and packing the work in sugar charcoal as the non-nitrogenous material. Dry ammonia was passed into one end of the gas pipe, and allowed to flow out through a small vent hole in the other end. The results obtained by carbonizing for four hours at 1650° were 0.058 inch for the charred sugar alone, and 0.070 inch for the charred sugar which had ammonia passing through it. The non-ammonia specimen was bluish-black in color, and when sawed appeared soft, while the ammonia-treated specimen was of a distinct whitish luster, and appeared to have a tough outer skin when sawed.

Thus all the evidence goes to prove that nitrogen aids carbonizing in practical work, and whether present in organic form or as ammonia it acts as a carrier of carbon, probably through the formation of small traces of cyanides.

The speed of penetration caused by the action of different cements at different temperatures for the same time, *i.e.*, eight hours, is best shown by Table 5.

TABLE 5

Temperature in Degrees Fahrenheit	MATERIALS USED AND RATE OF PENETRATION IN INCHES			
	Charcoal 60 per cent. + 40 per cent. of Carbonate of Barium	Ferro-cyanide 66 per cent. + 34 per cent. of Bichromate	Ferro-cyanide Alone	Powdered Wood Charcoal Alone
1300	.....	.....	.....	.....
1475	0.020	0.033	0.020	0.020
1650	0.088	0.069	0.079	0.048
1825	0.128	0.128	0.128	0.098
2000	0.177	0.177	0.198	0.138

The nature of the carbonizing materials has a very pronounced effect on the rate of carbonization, or the percentage of the carbon content in the surface layer of the piece, or both.

At the same temperature, *i.e.*, 1825° F., for different lengths of time and with different cements, the rate of penetration obtained was according to Table 6.

TABLE 6

Length of Time in Hours	Materials Used and Rate of Penetration in Inches				
	Carbon 60 per cent. + 40 per cent. of Carbonate	Ferro-cyanide 66 per cent. + 34 per cent. of Bichromate	Powdered Wood Charcoal Alone	Charcoal and Carbonate of Potassium	Unwashed Animal Black
1	0.031	0.033	0.028	0.059	0.035
2	0.039	0.037	0.053	0.078	0.059
4	0.047	0.049	0.063	0.094	0.088
6	0.078	0.074	0.072	0.011	0.106
8	0.118	0.128	0.098	0.138	0.128

Eighty per cent. charcoal + 20% carbonate of barium, 40% charcoal + 60% carbonate of barium, ferro-cyanide alone and 66% ferro-cyanide + 34% bichromate were used with practically the same results for eight hours' time.

Another set of tests was carried out for a longer period of time, with other materials and at a uniform temperature of 1650° F., with the results given in Table 7.

TABLE 7

Length of Time in Hours	Materials Used and Rate of Penetration in Inches		
	Charred Leather	Ground Wood Charcoal	Barium Carbonate and Wood Charcoal
2	0.045	0.028	0.055
4	0.062	0.042	0.087
8	0.080	0.062	0.111
12	0.110	0.070	0.125

The test bars in this table were 3 inches long and $\frac{1}{4}$ of an inch square. The chemical composition of the steel was as follows: Carbon, 0.14%; manganese, 0.58%; silicon, 0.01%; sulphur, 0.08%, and phosphorus, 0.03%.

These tables show that charcoal when used alone gives the slowest rate of penetration, but when combined with other materials the rate of penetration is the highest of any of the tests made. In some cases the rate of penetration of the combined materials nearly doubles that of the wood charcoal alone.

EFFECT OF TEMPERATURE

The degree of carburization of the skin depends largely on the degree of temperature maintained during the carbonizing process; therefore it is necessary that the temperature be kept at a definite point in the carbonizing of steels. This can best be done by attaching to the furnace something to gage the heat, such as a pyrometer. If the temperature is too high, the metal is liable to crystallize and the core will rapidly become brittle. And if too low the rate of penetration will be low. The temperature to which the metal can be safely raised in carbonizing varies with the kind of steel used. As a general rule the ordinary carbonizing steel cannot be raised to a temperature in excess of 1800° F. If the original carbon content is high, even this temperature cannot be safely reached, while with some of the alloy steels, such, for instance, as nickel-chrome steel, a carbonizing temperature of 2000° can be retained for four hours without the core crystallizing, and the rate of penetration will be reasonably high, providing, of course, that the original carbon content is low.

The temperature, however, must be kept above 1300° F., as ordinarily carbonization cannot take place below that point, although in an experimental way steel has been carbonized at about 850° by using a mixture of cyanide of potassium, chlorides of the alkalies, and the alkaline earths, the latter being used to lower the fusion point of the cyanide.

The percentage of carbon which is absorbed by the steel is also affected by the temperature as well as by the materials used. With a given depth of penetration and a given amount of carbon in the carbonizing material, steel will absorb a greater percentage of carbon at a high temperature than at a low one.

HEAT TREATMENT AFTER CARBONIZING

The heat treatment following carbonizing should be very carefully done owing to the fact that the piece must have a very hard outer surface to resist wear, and a non-brittle core that will resist strains; also, some methods of heat-treating have a decarbonizing effect, and some of the steels have a tendency to produce cracks or fissures and to warp. Thus crank-shafts for internal-combustion engines were formerly carbonized and hardened, but owing to the difficulty of preventing cracks and warping this practice has been abandoned.

As a general rule the piece should be annealed after carburizing. This can best be done by leaving it packed in the carbonizing case, with the cover fastened on, and allowing it to cool gradually; but if the carbonizing temperature is not over 1600° F., it can be allowed to cool to 750°, then reheated to 1400°, and quenched with good results. If the carbonizing temperature is a high one, *i.e.*, above 1800°, the piece should be allowed to cool, then reheated to 1650°, and quenched and reheated again to 1400° and quenched.

The reason for the double quenching is that the piece must be heated to above its point of transformation, *i.e.*, 1650°, to destroy the crystallization and consequent brittleness, which is liable to be in the core when it is carbonized at a high temperature; but this leaves the carbonized surface layer not hard enough to resist wear, therefore it must be quenched again at 1400°. This point of transformation varies with the different components of the high-grade alloy steels, and this should be ascertained before hardening the piece.

By quenching directly from the carbonizing retort a distinct line is formed between the high-carbon outer shell and the low-carbon cone, and this is liable to cause the metal to crack on this line when the work is used for parts similar to rollers in roller bearings, owing to the wearing and crushing strains to which they are submitted, but if the work is properly heat-treated after carbonizing, this distinct line is made to disappear, and the danger of the steels cracking there is removed.

Aside from the above rules, the general rules should be followed that are laid down for annealing, hardening, and tempering, in their respective chapters.

TIME OF EXPOSURE

The time that the work is submitted to carbonizing is an important factor, as the regulation of this under a given constant temperature is what gives the depth of carbon desired, and by the proper depth of the carbon is obtained the percentage of carbon desired in the surface layer. The percentage of carbon in a carbonized piece of steel gradually reduces from the outer shell to the core. The lower the carbonizing temperature, the less the time of submission to the carbonizing temperature, and the smaller the percentage of carbon in the carbonizing material the greater will be this reduction.

A round bar of steel that was carbonized to the depth of $\frac{3}{16}$ of an inch was examined by turning off $\frac{1}{16}$ of an inch, and analyzing the turnings for carbon, then another sixteenth was turned off and analyzed, and the third and fourth sixteenth treated in a like manner. This gave a carbon content of 1.24% for the $\frac{1}{16}$ of an inch taken from the outside, the second sixteenth gave 0.85% carbon, the third sixteenth showed 0.24% carbon, and the fourth or core contained 0.13%.

The time of submission required for a certain depth varies with the kind of carbonizing materials as well as with the process used. The carbonizing materials, such as powdered bone, charcoal, etc., which require that the work be packed in an iron box or other receptacle, take considerable more time to carbonize the work than when gases are used to furnish the carbon, owing to the necessity of the heat penetrating the box and carbonizing materials before it can affect the work. In case a deep penetration of the carbon is required, and the carbon in the carbonizing materials is nearly or entirely absorbed, it is a difficult operation to insert fresh materials in the packing box.

Another point might be mentioned here, and that is that all steels do not retain their carbonization. One specimen was examined by taking a very thin cut from the outer surface for a part of its length, which on analysis showed 1.25% of carbon. The piece was then laid aside for six months, and a similar cut taken from the rest of its length, which on analyzing showed only 0.92% of carbon. This showed that the carbon dissolved little by little into the mass.

CARBONIZING WITH GAS

In the use of hydrocarbons, or gases, a fresh supply can be kept flowing into the carbonizing receptacle, and the time greatly reduced for deep penetration with an appreciable reduction of time for the shallow penetrations.

A very important factor in carbonizing with gas is the furnace, as on the design and operation of this to a large extent depends the success or failure of the process. They are designed specially for this purpose, and are, therefore, not practical for use as hardening, annealing, or tempering furnaces, although they might be made useful for annealing or hardening large quantities of work by being fitted with appliances for handling the same.

This makes the cost of installation higher than for the appliances used for carbonizing in the old way. The cost of carbonizing, however, is about one-half of that of the old method, which makes the furnace soon pay for itself by the saving in materials and labor. Where the cost of carbonizing is reduced to this extent it makes it commercially practical to carbonize steel parts that were considered prohibitive by the high cost and non-uniform results of the old method. Owing to the nature of the process of carbonizing by the old methods it is very difficult to obtain uniform results with pieces packed in the same box, or to repeat these results in other boxes.

In order to judge the temperature of the pieces packed in a box it is necessary to insert test wires through the cover. After a certain time a test wire near the outer edge of the box is withdrawn and the temperature is found to be just right for carbonizing, but if one is drawn out of the center of the box at the same time it will be seen that the temperature here has not risen high enough, as it takes a much longer time for the pieces in the center of the box to be raised to the proper temperature than for those near the outer surfaces of the box.

As the carbonizing material must be packed in the box with the pieces, this means that the pieces near the sides of the box will begin to absorb the carbon before those in the center, and, therefore, the penetration will be greater. As the percentage of carbon in the outer surface of the pieces being carbonized is greater the greater the depth of penetration, it also means that the pieces near the outside of the box will have a greater carbon content on their surface than the pieces in the center, and this also means that they will be harder.

Carbonizing with gas overcomes this to a large extent, if not entirely, as the carbonizing gas is not turned on until all of the pieces in the retort of the furnace have arrived at the proper carbonizing temperature, and it is shut off the minute the proper depth of carbonization has been obtained. The furnace can also be so regulated that the same results can be obtained with the next lot of pieces put in the retort. The carbon in the retort is also held constant by the steady flow of the gas, and the work can be inspected for temperature by shutting off the carbonizing gas and looking through the outlet pipe, where the work can be seen and its color noted.

A special furnace for the gas carbonizing process is built and patented by the American Gas Furnace Company, and is shown in Figs. 138 and 139. In Fig. 139, *A* is the retort in which the work is placed. This is made out of extra heavy 8-inch pipe, for the size of furnace shown, and is made to revolve on the rollers *B*, by the gear wheel *C*, and the worm *D*, which in turn is propelled by the sprocket wheel shown in Fig. 138. *E E* are air compartments to prevent the heat and work from getting into that part of the retort which extends beyond the heating furnace; *F* is the heating-gas chamber, the gas coming in through 5 openings or burners similar to the one shown at *G*, and exhausting out through others; *H* is the cover for the end of the retort, and is fastened on with hinged bolts and thumb screws. This is taken off in order to put the work in the retort, the partition *I* and carbonizing gas outlet *J* coming with it.

The heating gas is fed through pipes and burners on the side, and the carbonizing gas passes through the hose shown above the sprocket wheel in Fig. 138, and then into that part of the retort where the work is held. After the carbon has penetrated the metal the gas escapes through the outlet *J*.

In this process the carbonizing gas was vaporized from the liquids, naphtha and ammonia, and as the work is made to revolve in the furnace, similar to the action obtained by a tumbling barrel, an even depth of carbon is obtained on all sides of the work, and this overcomes, to a large extent, the tendency of carbonized pieces to have hard and soft spots, as the soft spots are usually caused by the piece coming in contact with something that would not allow the carbon to act on that spot.

Pyrometers can be attached to the furnace to gage the heat for the correct temperatures, and when this has been attained the valves and cocks can be set so that the work can be duplicated for any number of times and the furnace run for a long period with an assurance of the quality of the work turned out, as the temperature is held constant. Starting with a cold furnace in the morning, an hour and a half is usually required to get the work hot enough to absorb the carbon.

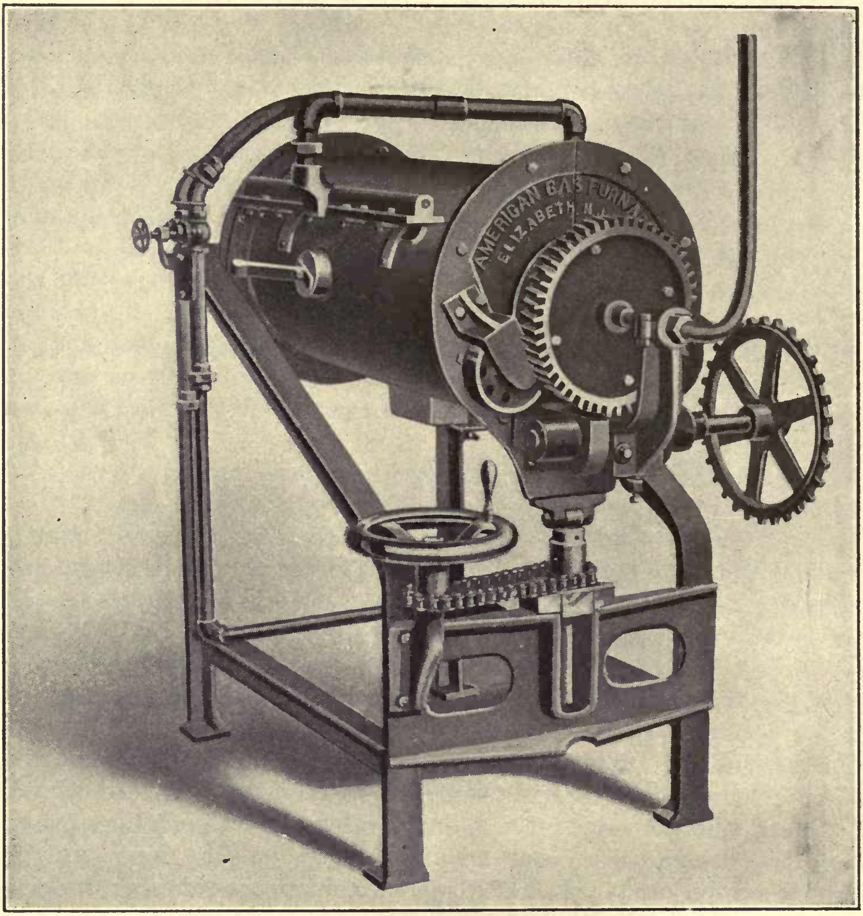


FIG. 138. — Revolving retort furnace for carbonizing with gas.

Odd-shaped and intricate pieces can be carbonized by this method

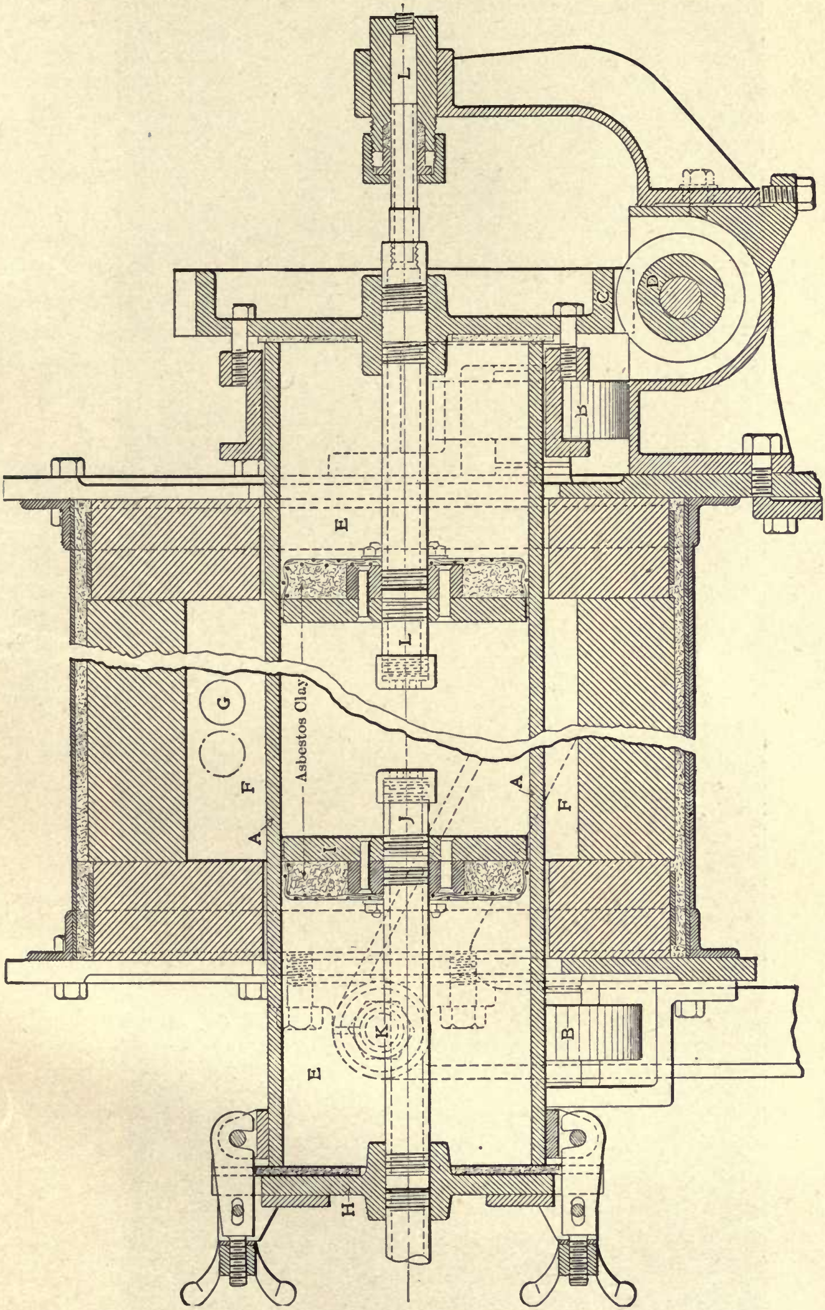


FIG. 139. — Sectional view of furnace for carbonizing with gas.

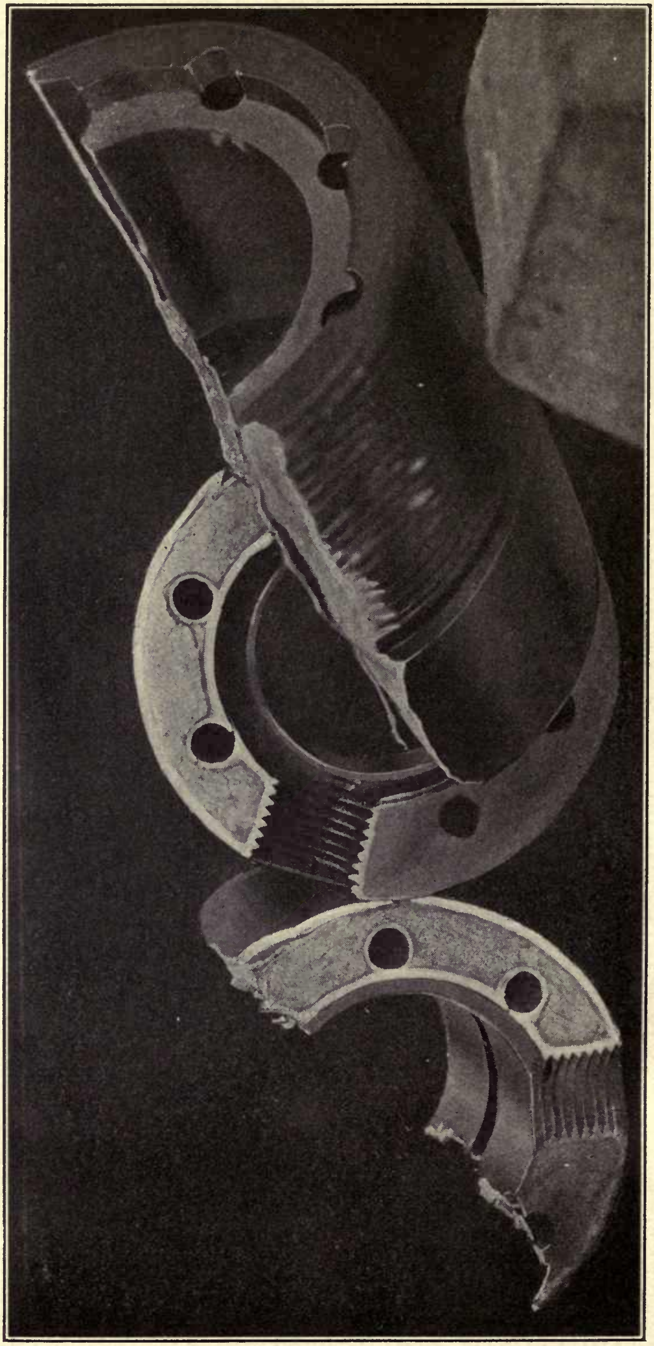


Fig. 140. — Difficult piece carbonized with gas.

that it would be difficult to do by packing in an iron box in such materials as bone and charcoal. This is best illustrated by the piece shown in Fig. 140 that has been broken open to show the action of the carbonizing gas on the seven small holes around its rim, and it will be seen by a glance at the half-tone that the carbon penetrated to a good depth all around these holes. The piece to the left shows the surface that was broken at a distance of about 4 inches from the end to the right. It also showed that the carbon had a good even penetration as to depth on all of its exposed surfaces both inside and outside.

The results of different lengths of time that the work is submitted to carbonization in this gas furnace is shown in Figs. 140 and 141. The distinct line between the carbonized shell and the core is obtained by plunging the metal directly from the carbonizing furnace into a quenching bath. By Fig. 141 is shown the depth of carbon that is obtained in this furnace by carbonizing for 4, 8, 10, 12, 14, and 16 hours, and then quenching in a lard-oil bath directly from the furnace. The test bars were $\frac{5}{8}$ inch in diameter, and are reproduced here at about their actual size. The results as to depths for this set of pieces is as follows:

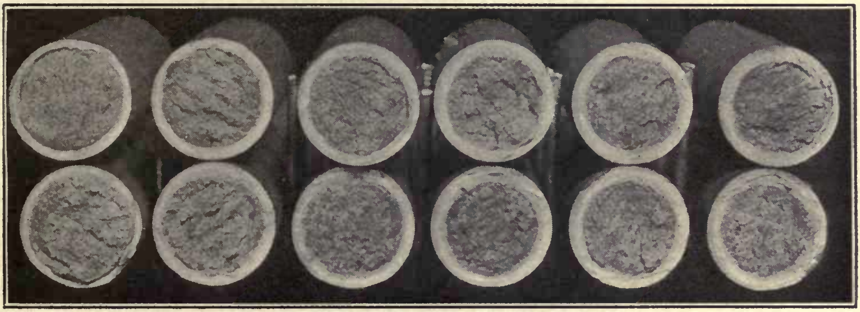


FIG. 141. — Quenched directly from the carbonizing furnace.

Time for Carbonizing in Hours	Depth of Penetration in Inches
4	0.040
8	0.062
10	0.071
12	0.079
14	0.085
16	0.090

The set of test pieces in Fig. 142 shows the depth of penetration for

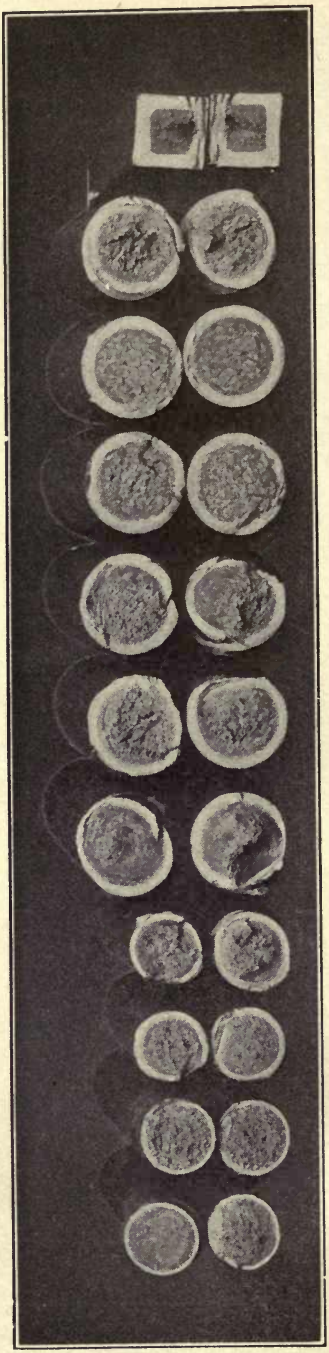


FIG 142. — Penetration of carbon each hour from one to nine.

each hour, from 1 to 9 inclusive, as follows, as well as the size and shape of the piece:

Time, Hours	Size of Test Piece	Depth in Inches
1	$\frac{3}{8}$ in. round	.015
2	$\frac{3}{8}$ in. round	.020
3	$\frac{3}{8}$ in. round	.030
4	$\frac{3}{8}$ in. round	.038
5	$\frac{1}{2}$ in. round	.046
6	$\frac{1}{2}$ in. round	.053
7	$\frac{1}{2}$ in. round	.056
8	$\frac{1}{2}$ in. round	.058
9	$\frac{1}{2}$ in. round	.060
9	$\frac{1}{2}$ in. round	.063
9	$\frac{3}{8}$ in. square	.075

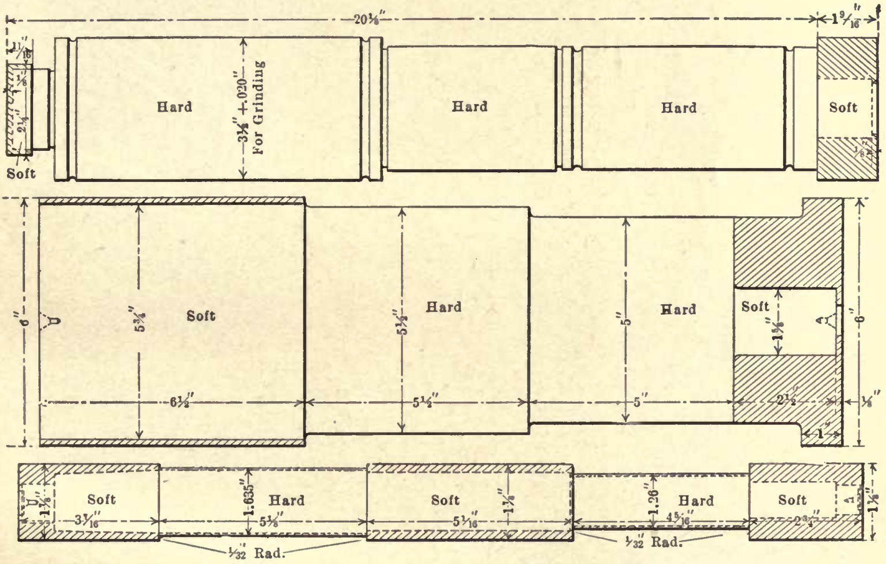


FIG. 143. — Samples of local hardening by carbonizing.

Intricate or peculiar-shaped pieces that would not turn over in the furnace, but slide around on the bottom, would have very little carbon on the side that remained in contact with the retort. For these it would be necessary to put something inside of the furnace so constructed that it would cause them to turn over. Delicate pieces that would be liable to break would also have to have some special apparatus inside of the retort to protect them.

LOCAL HARDENING

The carbonizing process is often used for hardening certain parts of a piece, and leaving the rest soft, as illustrated by the pieces shown in Fig. 143. The three pieces are turned from machinery steel to the lines shown by the outside line of each piece. After this they are carbonized to the proper depth, then annealed, and then the parts shown by the sectional lines are turned off, after which they are hardened.

By turning off the parts shown by the sectional lines, the outside layer that has been carbonized is turned off, and this leaves these parts with the machinery steel exposed. When hardening, therefore, the machinery steel does not harden, and consequently remains soft, while the balance of the pieces, which have a carbonized outer shell, do harden, and this makes the pieces hard in the parts desired and soft in the other places.

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