have tests of ordinary test-bars, boiler-sheet, small eye-bars, and drawn wire.

The 96-carbon eye-bar and the 115-carbon ½-inch wire are the nearest to the 100-carbon saturation limit mentioned before, and they show the highest strength. The 96-carbon eye-bar had a slight flaw in the fracture, which doubtless caused it to break below its real strength.

The 135-carbon eye-bar broke in the head in a way to indicate that there was some local strain there, due to forging.

These examples are not given as establishing any general law; they are illustrations of what all experience shows to be the fact, that the strength of steel is affected profoundly by the quantity of carbon present, and also by heat and by mechanical work. From 46,800 lbs. to 248,700 lbs. tensile strength per square inch is an enormous range, and these figures probably represent pretty closely the ultimate limits at present attainable.

An inspection of the analyses makes it clear that the other elements present in addition to carbon were not there in sufficient quantity or variety to have had much effect upon the results.

VI.

HEATING FOR FORGING; FOR HARDENING; FOR WELDING.

BURNING, OVERHEATING, RESTORING.

From what has been said already about the effects of heat it follows without further argument that heating is one of the most important, or perhaps more properly the most important of all, of the operations to which steel has to be subjected.

The first and vital thing to be borne in mind is that all heating should be uniform throughout the mass. It has been shown that heat affects the grain, the structure, as surely as it moves the mercury-column, and such being the case it is plain that as perfect uniformity as it is possible to attain is the first essential for all heating, no matter what the ultimate object may be.

In heating for forging the limit lies between the point of recalescence, the beginning of true plasticity, and the granular condition, the end of plasticity; these temperatures lie between dark or medium orange for all steels and medium or light lemon on the upper limit, depending on the carbon content, or lower if it be an alloy steel.

If there is much work to be done upon a piece of steel, it is well to heat at first to as high a temperature as is safe, and then to forge or work heavily at the higher heat, reducing the blows or passes as the piece is reduced and the temperature falls. Although this high heating will raise the grain of the steel, the heavy working will bring it back to a fine, compact structure.

If little work is to be done, then it is better to heat as low as may be safe, and allow the work to be done without letting the heat down below orange red, so that the steel may not be crushed in the grain.

Below orange red, the so-called "dark cherry," steel should not be forged, except that in forging for fine tools it is well to give many light and rapid blows until black begins to show in order to hammer-refine it; this must be done with extreme care so as not to crush the steel and cause cracking in the subsequent hardening, or crumbling in the hardened tool.

HEATING FOR HARDENING.

When a piece of steel is to be hardened by quenching in water or any quick-cooling medium, it should be heated with great care to the exact temperature to produce the required hardness.

After forging, no piece of steel should be quenched without first being heated uniformly to the proper temperature. Ede in his book recommends quenching immediately after forging in some cases. The so-called Harvey patent recommends cooling from a high heat down to the required heat and then quenching.

Both practices are bad. In the Ede case this is believed to be the only bad piece of advice in his very valuable book —in every other respect the most practical and useful book upon the manipulation of steel known to the author.

The reason for objecting to the quenching after forging without re-heating is that forging always sets up uneven strains in the mass; the flow is easier from the sides than from the middle of the piece, and therefore the amount of work done upon one part is greater than upon another; also it is impossible to hammer or press a piece of steel with exact uniformity throughout, so that it follows that after forging there is never exact uniformity of texture or temperature, and such uniformity is the one essential thing to insure good and even hardening.

The practice of allowing a highly heated piece to cool down to a given color and then quenching is objectionable, because it produces a coarse and brittle grain due to the higher heat.

Referring to the illustration on page 67 of the squares representing grains due to different temperatures: Assume that square No. 3 represents the heat at which quenching is to take place, and No. 6 is the heat to which the piece has been subjected; then the piece when it has cooled to No. 3 will not have the grain due to No. 3 heat: it will have a larger, coarser grain that formed as the piece cooled from No. 6. If now it be quenched, it will have only the hardness due to No. 3, with a much coarser and more brittle grain than No. 3 heat should give. The way to manage such a case is to let the piece cool completely and assume the No. 6 grain; then re-heat carefully to exactly No. 3 and no hotter; keep the piece at that heat for a few minutes, or moments, according to its size, to allow for lag: then it will have the finer grain due to No. 3 heat, and when quenched it will be as hard as under the other method, and it will be much finer and stronger.

The same rule applies to any two temperatures.

As an expression of exactness as to evenness of heat, it may be said that the piece should be as uniform in color as if it had been dipped into a pot of paint. When such uniformity is attained, a break from quenching is rare, unless the piece has been shamefully overheated so that the strains of quenching are greater than the tenacity of the steel.

HEATING FOR WELDING.

When an ingot is to be forged or rolled, it is well to take the highest heat possible—that immediately below the heat of granulation. Such a heat may be taken safely by keeping the steel covered with a surface flux to protect it from the flame. Ordinary red clay, dried and powdered, is an excellent flux for the purpose, and the cheapest known. Melted and powdered borax is the best of known fluxes, but it is so expensive that, as a rule, it is used only on the finest tool-steel, or on some of the alloy steels where the highest heat possible is not above a bright orange color, or hardly so high.

A good flux, intermediate in cost between common red clay and powdered borax, is an earth or mineral barite, or heavy spar. This material fuses more readily than red clay and not quite so easily as borax. It forms a good protective covering on the steel, and it is nearly or quite as efficient as borax.

The object in heating so high is to make the steel as soft and plastic as it may be, so that the subsequent working will close up all porosity as far as possible. Nearly all ingots have in them a greater or less number of cavities, commonly called blow-holes, that are caused by the separation of occluded gases during cooling. If such porosities are not oxidized on the surface they will disappear under heavy working at a high heat. It is probable that under the compression of the work the gases are redisseminated in the mass and the walls of the cavities are reunited. If there be the slightest oxidation of the surface of a cavity the walls will not reunite: there will be left in the mass a little flat film of oxide which will prevent the union.

In mild steels used for machinery or structural purposes these little films may do no harm, the factor of safety being sufficient to more than cover any weakening effect. In tool-steel that is to be hardened such little films are almost certain to cause fracture. Dies as large as twelve inches square and six to eight inches thick, having been heated and quenched with the greatest care, have split fairly in two, and have revealed in the fracture a little film no larger than half an inch in diameter and of inappreciable thickness. At the same time the perfectly uniform grain and hardness showed that the highest skill had been used. This is only one illustration of the fact that every break in the continuity of the grain in steel forms a starting-point for fracture under heavy stress.

From what has been said it is plain that to weld two pieces of steel together is a difficult matter; still it can be done if great care be used. In general it is better to avoid such welding except in cases of necessity. The welding of steel tubing, and the electric welding of rails, frogs, switches, etc., is done on a large scale and satisfactorily, so that it will not do to say that steel cannot be welded. It can be welded or pasted together, and it is a good operation to avoid in all high steel. In case steel is to be hardened a weld will reveal itself almost certainly.

BURNING IN HEATING.

When a piece of steel breaks and shows a coarse, fiery fracture, it is common to say that it is burned. This is not necessarily the case. There are several degrees in the effects of heat. The first is the raising of the grain; the second, in high steel, is the decarbonizing or burning out of carbon from the surface in, the depth of the decarbonizing depending upon time and temperature; the third is oxidizing, or actual burning in the common acceptance of the term.

All of these operations go on to a slight extent every time a piece of steel is heated, but when the heating is done carefully there is only a small film of steel that is decarbonized and oxidized, and this film flies off when the piece is quenched for hardening. When the steel is forged or rolled this skin will be united firmly to the steel, and it will be thinner or thicker, according to the number of heatings and the time of exposure to the fire. In tool-making this skin must always be removed. Many an expensive tool is made perfectly worthless by not having this skin all removed, owing usually to mistaken economy. The steel is expensive, and the tool-maker does not wish to cut it up into worthless chips.

When a tool costing, say, twenty-five dollars is made useless by failure to cut away twenty-five cents' worth of useless skin, the economy of such an operation requires no discussion. It is impossible to forge a piece of steel without producing such a skin, and it is well known that decarbonized iron will not harden.

Ordinarily a cut of $\frac{1}{16}$ of an inch should remove such a skin on straight rolled or hammered bars. In the case of a shaped forging where many re-heatings have been required the forgeman will have done good work if the cutting away of $\frac{1}{8}$ of an inch will present a good surface: tool-makers should consider this and allow for it. On the other hand, if a tool-maker finds that the removal of $\frac{1}{8}$ of an inch from a bar, or $\frac{1}{4}$ of an inch from a forging will not yield him a good, hard surface, he should hold the steel-maker responsible for bad work.

Actual burning reveals itself in rough tears, and cracks at the surface and corners of the piece. Such a piece should go to the scrap heap.

Overheated steel of coarse, fiery grain has been injured, and not necessarily destroyed. Such a piece may be restored to any fineness of grain by heating to the right temperature—medium orange for the best grain—keeping it at that heat for, say, one minute for a little piece, and five to ten or fifteen minutes for a large piece. The heat should penetrate the whole mass, and it should not be allowed to run above the given color in any part, not even for a moment. It should then be allowed to cool in a dry place, without disturbance. The grain will now be fine and uniform, and the steel may be worked in the ordinary way.

This simple operation is all that is necessary to restore to a fine grain any piece of steel that has been overheated, provided that the piece has not been actually burned nor ruptured.

VII.

ANNEALING.

It has been shown that the grain or structure of steel is profoundly affected by heat, so that any difference of heat-color that is visible to the naked eye will cause a difference of grain that is also visible to the naked eye.

Specific-gravity tests and delicate magnetic tests have proved that for every variation in grain there is a difference of specific gravity, which means, of course, a difference in volume; from this it is clear that if in any one piece of steel there exists a variety of grain due to uneven heating, there must necessarily be in the mass internal destructive strains. These strains become manifest when a piece of unevenly heated steel cracks in hardening; in this case the strains are greater than the tenacity of the steel.

It is well known, also, that all working of steel, such as forging or rolling, has a hardening effect, so that ordinary bars or forgings cannot be machined readily in the condition in which they are left by these operations.

If there were no remedy for these conditions of internal stress and initial hardness, the general use of steel would be very difficult, and its application would be limited seriously.

Fortunately, there are three properties of steel which furnish an easy and efficient remedy.

First, the fact that steel will assume by mere heating a grain or structure due to any temperature, no matter what its previous structure may have been, makes it a simple matter to remove practically all irregularities of grain and stress, by heating the mass to a perfectly uniform color and allowing it to cool uniformly.

Second, as heating is a softening process always, the mere heating of any piece of steel will soften it, and the amount of this softness that can be retained when the piece is cold is a direct function of the length of time of cooling, so that by sufficiently slow cooling any steel can be left reasonably soft.

This does not apply to Hadfield's manganese steel, which cannot be made soft when cold by any of the known processes of annealing.

Third, by reference to the specific-gravity table No. I, Chap. V, it will be seen that the change in volume due to differences of temperature is much less in mild steel than in high steel. This fact does not rest upon the evidence of this table alone; it is a fact of common knowledge to all steel-makers that mild steel is much more inert than high steel; therefore differences of heat and working that produce serious results in high steel are hardly appreciable in mild steel. As a rule all structural steels are comparatively mild, therefore they are generally in a fit condition for use when they leave the rolls or forge. In cases of special forging, where one part is heated and another is left cold, as in the forging of the heads of eye-bars, it would seem to be wiser to anneal such pieces to remove the area of strain that must exist between the unheated parts and those that were heated and forged.

The operation of removing strains and hardness by careful, uniform heating and slow cooling is known as *annealing*.

Annealing should not be confused with tempering. Tempering is the partial softening of hardened steel, to remove some of the exceeding brittleness of hardened steel, and so to make it strong and highly elastic while it is still very hard.

Annealing is the complete softening of a piece of steel; that is to say, as a rule, the obtaining of the utmost softness that is possible; or in any case to have the steel softer than any tempering would leave it.

Annealing, and tempering are frequently used synonymously. Such misuse of terms in speaking of technical matters leads to confusion of ideas and misunderstandings.

As a rule, the best heat to use for annealing is that which gives a medium orange color; it is a good heat to quench from; it is a little above the heat of recalescence, about 655° Cent. This heat is that which gives the finest grain to steel when it is hardened, and is known as the refining heat.

As steel is thoroughly plastic and soft at this heat, and as it yields the best and strongest grain when cooled from this heat, it is clear that there is nothing to be gained by heating any higher for annealing.

In annealing, the steel should be brought up to the right color, medium orange, and left at that heat until it is hot through, care being taken that the heat does not run any higher in any part of the piece. If the corners or edges or any part be allowed to run up to bright orange, or to medium or bright lemon, as is often done, then there is bad work; the result will be uneven grain and internal strains.

When steel is to be hardened afterwards, there may be no harm in heating up to an even lemon color; but where is the use in applying this excess of heat merely to make a coarse grain, when the lower, medium orange color will give just as good softness and a much better grain?

The time necessary for good annealing depends upon the size of the piece; a wire may be brought up to the right heat in five minutes or less, and heated through in another minute; then it should be removed from the fire, as every additional moment of heating will only injure the steel.

A block six or eight inches cube may require three to five hours to bring it up to the color and have it heated through, and sufficient time should be given; but as soon as it is hot through it should be removed from the fire.

A six-inch block may be brought up to a medium orange color in twenty minutes or less in a hot furnace, and then if it be kept in such a furnace until it is hot all through, the surface and edges will almost certainly be brought to a bright lemon color, with bad results. To do good annealing a piece should never be hotter in one part than in another, and no part should be hotter than necessary, usually the medium orange color. Annealing, then, is a slow process comparatively, and sufficient time should be allowed.

There are many ways of annealing steel, and generally the plan used is well adapted to the result desired; it is necessary, however, to consider the end aimed at and to adopt means to accomplish it, because a plan that is excellent in one case may be entirely inefficient in another.

Probably the greatest amount of annealing is done in the manufacture of wire, where many tons must be annealed daily.

For annealing wire sunken cylindrical pits built of fire-bricks are used usually; the coils of wire are piled up in the cylinders, which are then covered tightly, and heat is applied through flues surrounding the cylinders, so that no flame comes in contact with the steel. For all ordinary uses this method of annealing wire is quick, economical, and satisfactory. The wire comes out with a heavy scale of oxide on the surface; this is pickled off in hot acid, and the steel should then be washed in limewater, then in clean water, and finally dried.

If it be desired to make drill-wire for drills, punches, graving-tools, etc., this plan will not answer, because under the removable scale there is left a thin film of decarbonized iron which cannot be pickled off without ruining the steel, and which will not harden. It is plain that this soft surface must be ruinous to steel intended for cutting-tools, for it prevents the extreme edge from hardening—the very place that must be hard if cutting is to be done.

Tools for drills, lathe-tools, reamers, punches, etc., are usually annealed in iron boxes, filled in the spaces between the tools with charcoal; the box is then looted and heated in a furnace adapted to the work. This is a satisfactory method generally, because the tools are either ground or turned after annealing, removing any decarbonized film that may be found; the charcoal usually takes up all of the oxygen and prevents the formation of heavy scale and decarbonized surfaces, but it does not do so entirely, and so for annealing drill-wire this plan is not satisfactory. It is a common practice in annealing in this way to continue the heating for many hours, sometimes as many as thirty-six hours, in the mistaken notion that long-continued heating produces greater softness, and some people adhere

to this plan in spite of remonstrances, because they find that pieces so annealed will turn as easily as soft cast iron. This last statement is true; the pieces may be turned in a lathe or cut in any way as easily as soft cast iron, for the reason that that is exactly what they are practically. When steel is made properly, the carbon is nearly all in a condition of complete solution; it is in the very best condition to harden well and to be enduring.

When steel is heated above the recalescence-point into the plastic condition, the carbon at once begins to separate out of solution and into what is known as the graphitic condition. If it be kept hot long enough, the carbon will practically all take the graphitic form, and then the steel will not harden properly, and it will not hold its temper. To illustrate: Let a piece of 90-carbon steel be hardened and drawn to a light brown temper; it will be found to be almost file hard, very strong, and capable of holding a fine, keen edge for a long time.

Next let a part of the same bar be buried in charcoal in a box and be closed up air-tight, then let it be heated to a medium orange, no hotter, and be kept at that heat for twelve hours, a common practice, and then cooled slowly. This piece will be easily cut, and it will harden very hard, but when drawn to the same light brown as the other tool a file will cut it easily; it will not hold its edge, and it will not do good work.

Clearly in this case time and money have been spent merely in spoiling good material. There is nothing to be gained, and there is everything to be lost, in long-continued heating of any piece of steel for any purpose. When it is hot enough, and hot through, get it away from the fire as quickly as possible.

This method of box-annealing is not satisfactory when applied to drill-wire, or to long thin strands intended for clock-springs, watch-springs, etc.

The coils or strands do not come out even; they will be harder in one part than in another; they will not take an even temper. When hardened and tempered, some parts will be found to be just right, and others will have a soft surface, or will not hold a good temper. The reason of this seems to be a want of uniformity in the conditions: the charcoal does not take up all of the oxygen before the steel is hot enough to be attacked, and so a decarbonized surface is formed in some parts; or it may be that some of the carbon dioxide which is formed comes in contact with the surface of the steel and takes another equivalent of carbon from it. Whatever the reaction may be, the fact is that much soft surface is formed. This soft surface may not be more than .001 of an inch thick, but that is enough to ruin a watch-spring or a fine drill.

Again, it seems to be impossible to heat such boxes evenly; it is manifest that it must take a considerable length of time to heat a mass of charcoal up to the required temperature, and if the whole be not so heated some of the steel will not be heated sufficiently; this will show itself in the subsequent drawing of the wire or rolling of the strands. On the other hand, if the whole mass be brought up to the required heat, some of the steel will have come up to the heat quickly, and will then have been subjected to that heat during the balance of the operation, and in this way the carbon will be thrown out of solution partly. This is proven by the fact that strands made in this way and hardened and tempered by the continuous process will be hard and soft at regular intervals, showing that one side

of the coil has been subjected to too much heat. This trouble is overcome by open annealing, which will be described presently.

When steel is heated in an open furnace, there is always a scale of oxide formed on the surface; this scale, being hard, and of the nature of sand or of sandstone, grinds away the edges of cutting-tools, so that, although the steel underneath may be soft and in good cutting condition, this gritty surface is very objectionable. This trouble is overcome by annealing in closed vessels; when charcoal is used, the difficulties just mentioned in connection with wire- and strand-annealing operate to some extent, although not so seriously, because the steel is to be machined, removing the surface.

The Jones method of annealing in an atmosphere of gas is a complete cure for these troubles.

Jones uses ordinary gas-pipes or welded tubes of sizes to suit the class of work. One end of the tube is welded up solid; the other end is reinforced by a band upon which a screw-thread is cut; a cap is made to screw on this end when the tube is charged. A gas-pipe of about $\frac{1}{2}$-inch diameter is screwed into the solid end, and a hole of $\frac{1}{16}$- to $\frac{1}{8}$-inch diameter is drilled in the cap.

When the tube is charged and the cap is screwed on, a hose connected with a gas-main is attached to the piece of gas-pipe in the solid end of the tube; the gas-pipe is long enough to project out of the end of the furnace a foot or so through a slot made in the end of the furnace for that purpose.

The gas is now turned on and a flame is held near the hole in the cap until the escaping gas ignites; this shows that the air is driven out and replaced by gas.

The pipe is now rolled into the furnace and the door is closed, the gas continuing to flow through the pipe. By keeping the pipe down to a proper annealing-heat it is manifest that the steel will not be any hotter than the pipe. By heating the pipe evenly by rolling it over occasionally the steel will be heated evenly. A little experience will teach the operator how long it takes to heat through a given size of pipe and its contents, so that he need not expose his steel to heat any longer than necessary.

There is not a great quantity of gas consumed in the operation, because the expanding gas in the tube makes a back pressure, the vent in the cap being small. This seems to be the perfection of annealing. A tube containing a bushel or more of bright, polished tacks will deliver them all perfectly bright and as ductile as lead, showing that there is no oxidation whatever. Experiments with drill-rods, with the use of natural gas, have shown that they can be annealed in this way, leaving the surface perfectly bright, and thoroughly hard when quenched. This Jones process is patented.

Although the Jones process is so perfect, and necessary for bright surfaces, its detail is not necessary when a tarnished surface is not objectionable.

The charcoal difficulty can be overcome also. Let a pipe be made like a Jones pipe without a hole in the cap or a gas-pipe in the end. To charge it first throw a handful of resin into the bottom of the pipe, then put in the steel, then another handful of resin near the open end, and screw on the cap. The cap is a loose fit. Now roll the whole into the furnace; the resin will be volatilized at once, fill the pipe with carbon or hydrocarbon gases, and unite with the air long before the steel is hot enough to be attacked.

The gas will cause an outward pressure, and may be seen burning as it leaks through the joint at the cap. This prevents air from coming in contact with the steel. This method is as efficient as the Jones plan as far as perfect heating and easy management are concerned. It reduces the scale on the surfaces of the pieces, leaving them a dark gray color and covered with fine carbon or soot. For annealing blocks or bars it is handier and cheaper than the Jones plan, but it will not do for polished surfaces. This method is not patented.

OPEN ANNEALING.

Open annealing, or annealing without boxes or pipes, is practised wherever there are comparatively few pieces to anneal and where a regular annealing-plant would not pay, or in a specially arranged annealing-furnace where drill-wire, clock-spring steel, etc., are to be annealed.

For ordinary work a blacksmith has near his fire a box of dry lime or of powdered charcoal. He brings his piece up to the right heat and buries it in the box, where it may cool slowly. In annealing in this way it is well not to use blast, because it is liable to force all edges up to too high a heat and to make a very heavy scale all over the surface. With a little common-sense and by the use of a little care this way of annealing is admirable.

It is a common practice where there is a furnace in use in daytime and allowed to go cold at night to charge the furnace in the evening, after the fire is drawn, with steel to be annealed, close the doors and damper, and leave the whole until morning. The furnace does not look too hot when it is closed up, but no one knows how hot it will make the steel by radiation: the steel is almost always made too hot, it is kept hot too long, and so converted into cast iron, and there is an excessively heavy scale on it.

Many thousands of dollars worth of good steel are ruined annually in this way, and it is in every way about the worst method of annealing that was ever devised.

To anneal wire or thin strands in an open furnace the furnace should be built with vertical walls about two feet high and then arched to a half circle. The inports for flame should be vertical and open into the furnace at the top of the vertical wall; the outports for the gases of combustion should be vertical and at the same level as the inports and on the opposite side of the furnace from the inports. These outflues may be carried under the floor of the furnace to keep it hot.

The bottom of the door should be at the level of the ports to keep indraught air away from the steel. The annealing-pot is then the whole size of the furnace—two feet deep—and closed all around.

The draught should be regulated so that the flame will pass around the roof, or so nearly so as to never touch the steel, not even in momentary eddies.

In such a furnace clock-spring wire not more than .01 inch in diameter, or clock spring strands not more than .006 to .008 inch thick and several hundred feet long, may be annealed perfectly. The steel is scaled of course, but the operation is so quick and so complete that there is no decarbonized surface under the scale.

This plan is better than the Jones method or any closed method, because the big boxes necessary to hold the

strands or coils cannot be heated up without in some parts overheating the steel; all of which is avoided in the open furnace, because by means of peep-holes the operator can see what he is about, and after a little practice he can anneal large quantities of steel uniformly and efficiently.