V.

GENERAL PROPERTIES OF STEEL.

STEEL is very sensitive to heat. In general it may be stated that, starting with cold steel, every degree of heat added causes a change in size and in structure, until the limit is reached where disintegration begins. The changes are not continuous; there are one or two breaks in the line, notably at the point where we have what is called recalescence; this is a marked phenomenon and it will be considered later.

The effects of heat are permanent, so that it is a fact that every variation of temperature which is marked enough to be visible to the naked eye will leave a structure, due to that variation, when the steel is cold, which will be observable by the naked eye, and such structure, when not influenced by external force, such as by hammering or rolling, is as invariable and certain as is the structure of an ingot due to the quantity of carbon present.

This property furnishes what may be called the steel-maker's and the steel-user's thermometer. By its means the steel-maker can discover every irregularity in heating that may have been perpetrated by the operatives; so also the steel-user can decide whether the steel furnished him has been heated and worked uniformly and properly, and later he can tell whether those who have shaped this steel to its final forms have done their work properly. A thorough knowledge of this property is essential to a steel-maker; until he possesses it he is not fit to conduct his business. It is of great importance to the steel-user, and every engineer should try to acquire a knowledge of it in order that he may not be fooled by the carelessness or rascality of those who have preceded him. The steel-maker acquires this knowledge by daily contact with the facts; the engineer does not have it forced upon him in this way, but he should seek opportunities of observation, which will be abundant in his earlier practice when he is sent upon inspection duty. Like the structure of ingots, this heat-structure cannot be illustrated on paper, and an attempt to do so would be misleading; attempts at description will be made in the hope that by their means the engineer will have a pretty good idea what to look for, and to know when his suspicions should be aroused.

In addition to the ocular observations mentioned it has been shown by specific-gravity determinations, and by delicate electrical tests through small ranges of temperature, that steel is as truly thermometrical as mercury.

Steel passes through or into four general conditions due to heat. First, in the cold state, it is a crystalline solid of no uniform structure, for its structure is influenced by every element that enters into it, and by every irregularity of heat to which it has been subjected.

Good steel may be described as having a bluish-gray color, uniform grain as seen by the naked eye, and little lustre. But it should have some lustre and a silky appearance. When it is right, a steel-worker will say it is "sappy," and that name, absurd as it may sound when applied to a metal, really expresses an appearance, and implies an excellence that it would be hard to find a better word for. If the structure be dull and sandy-looking, the steel-worker will say it is "dry," and that term is as suggestive and appropriate as the word "sappy."

If the fracture be granular with bright, flashing lustre, the steel-worker will say it is "fiery," and again his term is expressive and proper.

It is perfectly safe to say that steel of a "sappy" appearance is good steel; but in order to know what it is it must be learned by observation, it cannot be described in exact terms.

It is equally certain that a "dry" fracture indicates a mean steel, a steel inherently mean,—too much phosphorus, or silicon, or oxides, or all combined,—and such a steel is incurable.

A "fiery" fracture indicates too much heat. It may be found in the best steel and in the poorest; it may be corrected by simply heating to a proper temperature. It shows that some one needs to be reprimanded for careless work.

If now an inquirer will take a piece of good steel of "sappy" fracture, and of "dry" steel of dull, sandy fracture of the same carbon, and will heat them say first to dark orange, then to bright orange, dark lemon, and so on, and examine the fractures after each heating, he will find a "fiery" fracture in the "dry" steel at a heat much below that which is necessary to make the "sappy" steel "fiery." This is one proof that good steel will endure more punishment than poor steel.

Cold steel is not plastic in the common acceptance of the word; strictly speaking it has some plasticity, as shown in the extension noted in pulling it; this is its measure of ductility.

Also it may be drawn cold to fine wire of only a few

thousandths of an inch in diameter, and it has been rolled cold to one five thousandth of an inch thick. But this work must be done with great care; the steel soon becomes brittle, and a little overdrawing or overrolling will crush the grain and ruin the steel; therefore the work must be done a little at a time, and be followed by a careful annealing.

To reduce a No. 5 wire rod to .005 inch diameter will require with high steel suitable for hair-springs about fourteen annealings.

A skilful hammerman will take a piece of mild cold steel, and by means of light, rapid blows he will heat it up to a bright lemon heat without fracturing it; then he will have it thoroughly plastic and malleable.

This has no practical commercial value; it is a beautiful scientific experiment exhibiting high manual skill, and showing that there is no hard and fast line between non-plasticity and plasticity.

The first condition, then, is cold steel, not plastic, not malleable.

When steel is heated, it begins to show color at about 700° to 800° F.; the first color is known as dark cherry red, or, better, orange red; above this color it turns to a distinct, rather dark, or medium orange color; this is the heat of recalescence, a good forging-heat, and the best annealing- and quenching-heat. At this heat and above it good steel is truly plastic and malleable; a roller or hammerman will say, "It works like wax," and so it does.

This is the second or *plastic* condition.

Heated above this plastic condition to a bright lemon in high steel, or to a creamy, almost scintillating, heat in mild steel, steel will go to pieces under the hammer or in the rolls; the workman will probably say it is burned, but it is not burned necessarily; it is simply heated up to the third or granular condition; it is the beginning of disintegration and the end of plasticity.

This granular condition is important in several ways. It is made use of in Sweden, and has been demonstrated in the United States, to determine the quantity of carbon in steel. An intelligent blacksmith is given a set of rods of predetermined carbon, ranging from 100 carbon to zero, or through any range that may be necessary; each rod is marked to indicate its carbon. He takes the rods one by one and heats them until they scintillate, well up into the granular condition, then lays them on his anvil and hammers them, observing carefully the color at which each one becomes plastic as it cools slowly. After a little practice he is given rods that are not marked, and by treating them in the same way he will give them their proper numbers, rarely missing the carbon by as much as 10 points, or one temper.

It is a beautiful and useful illustration of the effect of carbon. The rule is, the higher the carbon the lower the granulating-point; or, as is well known, high steel will melt at a lower temperature than low steel.

This shows that every temper of steel has its disintegration temperature where it passes from plastic to granular, as fixed as its fusion-point or its point of recalescence.

Steel passes from the granular condition to the *liquid* or fourth form.

There is little of interest in the liquid condition of steel to any but the steel-maker; what there is to be said will be mentioned later.

Steel in cooling from the liquid passes through the granular and the plastic conditions to the cold state.

The granular form is of special interest to the steel-maker for the reason that in this condition the steel has more of adhesion than cohesion; it will stick to anything it touches, and so cannot be made to flow. This is the cause of "bears," "stickers," and many of the troubles of the melter. Therefore steel must be put into the moulds while it is still molten, and moulds should be well smoked or lime-washed to prevent stickers. This condition is of great interest to engineers, because the failure to roll or shape molten steel by pouring it directly between the rolls is doubtless due to this adhesive, non-cohesive condition.

To produce sheets, bars, and all sorts of shapes from molten steel direct, without the expense of making, handling, and re-heating ingots, is an enticing idea which has occupied the minds and efforts of many able mechanics and engineers.

If steel passed directly from the liquid to the plastic condition as glass does, hammers and rolls would soon be replaced by dies at a great saving of cost and labor. It is no wonder that such a desirable end has led to many persistent and costly efforts, but until some way can be devised to eliminate this granular form in cooling it would seem that all such efforts must end in failure.

As steel cools down through the plastic condition the cooling is not continuous; there are two or three points where it is arrested for a time, and at one notable point the cooling is not only arrested, but after a few moments of stop the operation is reversed, the steel becomes visibly hotter, and then the cooling goes on regularly; there may be other slight pauses, but they are of little importance compared to this one, which is known as the point of *recalescence.* There are many theories of the cause of this recalescence; the ablest scientists are still working at it; and until some definite conclusion is reached it is not worth while to write pages of discussion which may be found fully stated and illustrated over and over again in the various technical journals, and transactions of different engineering societies.

There are some properties of steel of great interest which seem to cluster around this recalescence-point; they will be noted as they are reached.

We have seen that there is a marked, definite structure of the grain of ingots due to every quantity of carbon, and also that there is a fixed limit of malleability for every quantity of carbon. It is known also that the recalescence-point shifts slightly with a change of carbon, and that it is much more marked and brighter in high-carbon steel than in low.

There are no other sure indications of the quantity of carbon present. As soon as an ingot is heated up to orange color, or the recalescent-point, it loses its distinctive structure and its fracture no longer furnishes a sure guide.

If three ingots of say, 20, 80, and 120 carbon respectively be heated to orange and then cooled slowly, their fractures will be so different as to enable an expert to place them properly in their order of carbon, and to classify them as mild, hard, and harder; beyond that he could not go; if he attempted to give them their temper numbers, he would be likely to miss by four or five numbers either way, and a correct mark would be only a lucky guess.

Hammering and rolling heated steel affect the grain or structure profoundly; a high steel may be worked so that the grain will look mild, and a mild steel may be so worked that the grain will look hard. It is common to see a bar of steel with a fine grain at one end and a coarse grain at the other, and this state of things often frightens a consumer, who imagines that he has received a very irregular, uneven article, and he is as often astonished when it is shown to him that at the same proper heat the two ends will refine and harden equally well, and be exactly alike. In such a bar one end has been finished a little hotter than the other, and the grain is due to the heat in each case. This uneven heating may have been incidental or careless; with skilful workers it is rare.

One end might have been finished so cold as to crush the grain, and the other end so hot as to cause incipient disintegration, but a competent inspector would discover either condition at once and reject the bar.

There is, then, a specific structure due to temperature; it is modified by carbon and by treatment under the hammer or in the rolls. If a bar of steel be heated up to the highest plastic limit, just so that it will not fall to pieces, and then cooled slowly without disturbance, and a fracture be taken, it will be found to be coarse and with an exceedingly brilliant lustre. Now let it be heated again to a bright lemon color, but still plastic, and cooled as before; it will be found to be coarse, with bright lustre, but neither so coarse nor so bright as the first piece. Then let it be treated in this way to lemon color, light orange, medium orange, dark orange, and orange red; as the heats go down the grain will be finer and the lustre will be less, until at about medium orange the lustre will be absent.

If any number of bars of even composition be heated in this way, the fractures will all be alike for each temperature.

If a series of bars of the different full tempers, about seven in all, be treated in this way, the structures due to a given temperature will all be similar, but there will be no two exactly alike, because high steel is much more profoundly affected by heat than low steel.

Seven tempers are mentioned here, because that is the number of full tempers in common use. Steel is graded out into fifteen tempers ordinarily by the interpolation of half numbers; this is easy and sure in the ingot inspection. In the above experiment the differences due to carbon are not quite so delicate, and the work is hampered in the heating by the personal equation, so that the use of seven full tempers is refinement enough. There is a difference due to every separable quantity of carbon, which could be shown if all of the operations of the experiment were exact.

If when a bar is broken cold the fracture is uneven, with coarse grain in one part and fine grain in another, it shows that there has been uneven heating. If one side has large grain and the other side is fine, the bar has been a great deal hotter on the side having coarse grain than on the other: the heater has let the bar lie in the furnace with one side exposed to a hot flame and the other protected from the flame in some way; he has neglected to turn the bar over and heat it evenly.

If the outside of the bar is fine and the centre is coarse, the bar has been very hot all through and has been finished by light blows of the hammer or by light passes in the rolls; it has been worked superficially and not thoroughly.

If the outside of the bar is coarse and the centre is fine, the steel has been heated on the surface too hot and too quickly; it has not had time to get hot through, and it has had too little work in the finishing.

If the grain is dark, with the appearance of a rather heavy india-ink tint, the steel has been finished too cold, and it will be found to be brittle.

If the grain is very dark, especially about the middle, looking almost black, then it has been finished altogether too cold: the grain is disintegrated, and the bar is fit only for the scrap-heap.

A bar of this kind containing enough carbon to harden will harden thoroughly, and often appear to be sound and fine, but it is not sound and will not do good work; if it be brought up to a proper heat and forged to a point, it will almost certainly burst, showing that the integrity of the steel has heen destroyed.

If a bar, or plate, or beam shows cracks on the surface or at the corners, with rough, torn surfaces, the steel has either been superficially burned or it is red-short. In either case it should be rejected, for the cracks, although small, will provide starting-points for ultimate fractures, whether it be tool-steel that is to be hardened, or structural steel that is to be strained without hardening. If the steel is to be machined, so that all of the cracks can be cut out, then in machinery-steel the removal of these surface defects might leave the finished piece sufficiently sound and good. If, however the steel is to be hardened, and the defects should be due to red-shortness, the piece would almost certainly break in the hardening; and if it were not red-short, then unless the cracks were cut away entirely, if the least trace of the crack is there, although it may not be visible, that trace will be sufficient to start a crack when the piece is hardened.

EFFECTS OF COOLING.

Increase of heat causes increase of softness up to the liquid condition.

Decrease of heat—cooling—increases hardness up to the hardness of glass.

As an invariable rule the rate of cooling fixes the degree of hardness to be had in the cold piece within the limits of obtainable hardness or softness.

Slow cooling retains softness, so that when annealing is to be done the slower the cooling the better. Cooling is always a hardening process, but when it is carried on slowly more softness, will be retained than when the cooling is quick.

Rapid cooling produces hardness, and the more nearly instantaneous it is the greater the hardness will be. This property of hardening is of such extreme importance that it will be treated fully in a separate chapter.

There is an apparent exception to this rule shown in the operation called water-annealing. It is common, when work is hurried, to heat a piece of steel carefully and uniformly up to the first color, that is, until it just begins to show color, and then to quench it in water.

This is called water-annealing; and many believe that because a piece so treated is left softer than it was before treatment, the water-cooling had something to do with it. The fact is that hammering and rolling are hardening processes. When the increment of heat due to the work is less than the decrement of heat due to radiation, the compacting of the grain increases hardness.

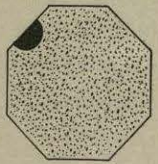
This process leaves the piece harder than does the quenching in water-annealing; the decrease in hardness due to water-annealing is the difference between the effects of the two operations. Let two pieces of the same bar be heated exactly the same for water-annealing; let one be quenched in water, and the other be allowed to cool in the air in a dry place. Then the superior softness of the air-cooled piece will show that the so-called water-annealing furnishes no exception to the rule.

There is one extremely important matter connected with cooling that should be noted carefully.

It is a common practice among steel-workers when they get a part of a piece of steel too hot to partially quench that part, and then go on with their heating; or if they are in a hurry to get out a big day's work, or if the weather is hot, and a pile of red-hot bars is uncomfortable, to dash water over the pile and hurry the cooling.

This practice means checks in the steel, hundreds of them.

A bar breaks and has this appearance. The dark spot is



the check; it did not show in the bar, no inspector could see it, but it broke the bar. Any one can prove this to his own satisfaction in a few minutes. Take a bar of convenient size, about one inch by one eighth; heat it carefully to an even medium orange color and quench it completely; then snip it with a hand-hammer over the edge of an anvil, snipping away until satisfied that it is sound steel. There are no checks.

Now heat a similar length of the same bar in the same way, and pass it through the stream from the bosh-pipe, or submerge it for a moment in the bosh, not long enough to produce more than the slightest trace of a change in the color; then put it back in the fire and bring it gently to the uniform color used before, and quench it completely. Now when it is snipped over the anvil it will show numerous checks, dozens of them.

In this experiment the complete submersion for a moment may not produce checks at every trial, because the complete submersion permits practically uniform cooling, which if continued to complete cooling would be simply the ordinary hardening process. Still it will produce checks in the majority of cases, indicating that starting the changes, strains, or whatever they are of the quenching process and then stopping them suddenly while the steel is in the plastic condition does cause disintegration, so that the operation is dangerous and should not be tolerated. Passing the hot steel through a stream of water or dashing water over it must cause different rates of cooling, and necessarily produce local strains resulting in checks. These latter ways of injuring, therefore, rarely fail to produce the ruinous checks.

If this positive destruction is produced in this way, in steel containing enough carbon to harden it is clear that similar, although not so pronounced, results will be produced in the mildest steels when they are treated in the same manner.

The rule, then, should be: Never allow water to come in contact with hot steel, and never allow hot steel to be laid down upon a damp floor.

Even the spray from water which is run upon roll-necks may cause these checks in steel that is passing through the rolls, so that it is better to put up a guard to deflect such water away from the body of the roll.

A hammerman may sweep a bar with a damp broom to cause the vapor to explode with violence when the hammer comes down, and so tear away all rough scale and produce a beautiful finish. A careful, skilful man may be permitted to do this, but as surely as he gets his broom too wet, so that drops of water will fall on the steel and whirl around in the spheroidal condition, just so surely will he check the steel.

The best way is to have the broom not wet enough to drip, and then to strike it up against the top die when it is ready to descend; sufficient moisture will be caught upon the die to cause a loud explosion when it strikes the hot steel; it is a violent explosion and will drive off every particle of detachable scale, leaving as beautiful a surface as that which is peculiar to Russia sheet iron.

It is common in rolling tires to run jets of water over the tire to break up the scale and produce a clean surface. Tire-makers assert that experience shows that the water does no harm. There are two reasons for this if it be true: first, the steel is of medium carbon and more inert than high steel, and it has been hammered and compacted before rolling; second, the tires are usually turned, and this would cut away any little checks that might occur on the surface.

The magnetic properties of steel are well known. Soft steel, like soft wrought iron, cannot be magnetized permanently; higher carbon steel will retain magnetism a long time, and hardened steel will retain it still longer. Hardened-steel magnets are the most permanent.

The permanency and the efficiency of a magnet increase with the quantity of carbon up to about 85 carbon; steel of higher carbon than this will not make magnets of so good permanency. The efficiency of a magnet of 85 carbon is increased largely by the addition of a little tungsten; a little less than .05% is sufficient.

It has been shown that tungsten has the property of retaining the hardness of steel up to a relatively high temperature; this additional power of retaining magnetism may indicate a close relation between the conditions set up by magnetism and by hardening.

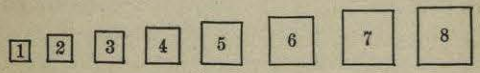
It has been stated that maximum physical properties, except as to compression, are found at from 90 to 100 carbon; now we find maximum magnetic properties in the same region. Prof. Arnold has found by microscopic tests the same point of saturation; he fixes it at 89 carbon and deduces from it an unstable carbide of $Fe_{24}C$.

The magnetic maximum was found by magnet-makers by actual use in large numbers of magnets. Prof. J. W. Langley found the same maximum in a series of careful and delicate experiments undertaken to determine the best composition and the best treatment for the production of permanent magnets. Magnetism is affected by temperature, and it is found that steel becomes non-magnetic at or about the point of recalescence. This is important to electricians, as it marks the limit of temperature that is available to them. It is of interest to the scientists, as it is another indication of the importance of the changes that

take place at this temperature. Later, recalescence will be found to be an equally important point to the steel-worker, especially to the temperer

It has been stated that if a bar of steel be heated to any visible temperature and then be cooled without disturbance there will be a resulting grain or structure that is due to the highest temperature to which the bar was subjected. As a rule the highest temperature leaves a grain that appears to the eye to be the largest, or coarsest, whether the microscope shows it to be composed of larger crystals or not.

Let the following squares represent the apparent sizes of the grains:



1. The natural bar, untreated
2. Grain due to dark orange or orange red.
3. “ “ “ medium orange
4. “ “ “ bright orange
5. “ “ “ dark lemon
6. “ “ “ medium lemon
7. “ “ “ bright lemon
8. “ “ “ very bright lemon, or creamy.

These designations are used because steel in cooling down, or in heating up, runs through a series of yellow tints, not reds. It is common to see the expression “glowing white” applied to steel that is not even melted, when as a matter of fact melted wrought iron is not quite white. An occasional heat of steel may be seen that could fairly be called white, and then the melter knows that it is altogether too hot, and that he must cool the steel or make bad ingots.

"Glowing white," like "cherry red," will do for ordinary talk, but not for accurate description, although "cherry red" comes nearer to describing the dying color than "glowing white" comes to describing the highest heat.

An arc light may be "glowing white," and sunlight is "glowing white," and when either light falls upon melted steel it shows how far the steel is from being "glowing white."

Referring to the squares: If a bar that has been heated to No. 8 be re-heated to No. 2 and be kept at that color a few minutes to allow the steel to arrange itself, in other words, to provide for lag, and then be cooled, it will be found to have grain No. 2. Sometimes in performing this experiment the fracture will be interspersed with brilliant spots as if it were set with gems; this shows that not quite enough time was allowed for lag. Another trial with a little more time will bring it to a complete No. 2 fracture. If now it be heated to No. 4, or 5, or 6 in the same way, it will be found to have when cold the grain due to No. 4, or 5, or 6 temperature.

This may be repeated any number of times, and the changes may be rung on all of the numbers, until the disintegrating effect of numerous heatings begins to destroy the steel. This property of registering temperature, this steel thermometer, is of great value, and it will be referred to frequently.

EFFECTS OF MECHANICAL WORK.

When an ingot is heated and then hammered, rolled, or pressed hot, its density will be increased, as well as its strength when cold under all strains.

If it be hammered carefully, with heavy blows at first, and with lighter and quicker blows at the last, the grain will become very close and fine; it is called "hammer-refined."

When down to the so-called cherry red, orange red, great care is needed, and when black begins to show through the red much caution must be used; any heavy blows will crush the grain and produce the dark or black color mentioned before.

Fine-tool makers attach great importance to this hammer-refining; some of the most expert will not have a rolled bar if a well-hammered one can be had. At first thought this would seem to be a mere notion, but the testimony in favor of hammering is so universal among those who know their business that it would seem as if it must be based upon some reason. If it have any scientific basis of fact, it is that the shocks or vibrations of the hammer keep the carbon in more intimate union with the iron, whether it be combination or solution, than either rolling or pressing will do. After considering the phenomena of hardening, tempering, annealing, etc., it may be concluded that there is something in this. It is easy to laugh at and to deride shop prejudices, and there are enough of them that deserve ridicule; again, there are some that will not down, and they compel the scientist to hunt for explanations. But after all, ridicule is dangerous; it is possible that a careful comparison of some of the laws laid down by the highest scientists would tend to excite the risibles. If the hand-worker sometimes flounders in the mud, the scientist is sometimes enveloped and groping in mist.

Hot-rolling produces results similar to those of hot-hammering; it makes the grain finer, increases density, and adds to the strength.

The same precautions are needed in rolling as in hammering. Heavy passes with rapid reduction may be used to advantage while the steel is hot and thoroughly plastic; as the heat falls the passes should be lighter to avoid crushing the grain.

Overrolling, like too much hammering, may be more injurious than too little work; a coarse, irregular structure due to too little work may be rectified and made fine and even by annealing, while if the grain be crushed by overwork the damage cannot be cured by annealing; the annealed grain may appear to be all right, but on testing, the strength will be found impaired.

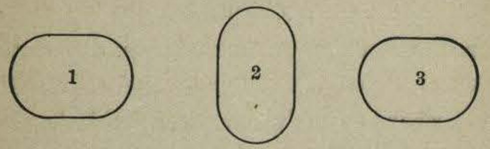
By care and light passes steel may be rolled safely down to a black heat and be made elastic and springy. It is common to roll spring-steel in this way so that it may be formed into a spring and have all of the properties of a tempered spring without going through the operations of hardening and tempering. This is often desirable for spring-makers, as it saves them considerable expense; but it is hazardous work, because it is so difficult to heat every piece exactly to the same temperature, and secure every time the same number of passes and the same pressure in each. The best roller will get some pieces too hard and brittle, and some too soft and ductile. A careful steel-maker will shun such work.

Cold-hammering, cold-rolling, and cold-drawing reduce specific gravity and increase tensile, transverse, compressive, and torsional strength. They increase hardness and brittleness, reducing ductility. The hardness due to cold-working is different from that due to hot-work or quenching; the latter operations produce great elasticity as well as hardness.

The hardness due to cold-working might be described as harshness; the steel is not truly springy; of course it will bend farther without permanent set than an annealed piece, but it never has the true spring elasticity. If it be worked far enough to be really springy, it will bear the same relation to a hot-worked spring that a piece of cross-grained, brashy oak bears to a piece of well-seasoned, straight-grained hickory.

The hammering of round sections between flat dies tends to burst the bars in the centre; great care must be used to avoid this, and the most skilful and careful hammermen will often turn out bursted bars. The bursts do not show on the surface; the bars are true to size, round, smooth, and sound on the outside. The safest plan is to hammer in a V-die, or in rounded swedges.

Radial rolling will produce the same results, and it is on this principle that the celebrated Mansmann tubes are made. The explanation seems to be simple, as the following exaggerated sketches will show:



No. 1 has been struck; it is then turned up to position No. 2 and knocked into shape No. 3. The rapid hammering of a bar, turning it a little at a time, must burst it if the blows are heavy enough to deform the whole section. Heavy radial rolling produces the same results.

The concluding pages of this chapter will be devoted to a few examples showing by tests the effects of heat and work upon specific gravity, tensile strength, elasticity, and ductility; they are not to be taken as fixing exact limits in any case; they are given merely to illustrate the truth of the general properties stated, and to show the wide ranges of strength that are attainable by varying carbon and work.

TABLE I.

Crucible Steel.	Ingot Numbers.											
	1	2	3	4	5	6	7	8	9	10	11	12
Carbon.......	.302	.490	.529	.649	.801	.841	.867	.871	.955	1.005	1.058	1.079
Silicon. ..	.019	.034	.043	.039	.029	.039	.057	.053	.059	.088	.120	.039
Phosphorus..	.047	.005	.047	.030	.035	.024	.014	.024	.070	.034	.064	.044
Sulphur......	.018	.016	.018	.012	.016	.010	.018	.012	.016	.012	.006	.004
Sp.gr. ingots.	7.855	7.836	7.841	7.829	7.838	7.824	7.819	7.818	7.813	7.807	7.803	7.805
Sp. gr. bars, burned, 1..	.. .	.....	7.818	7.791	... .	7.789	.....	7.752	.....	7.744	....	7.690
2..	....	... .	7.814	7.811	.....	7.784	....	7.755	.....	7.749	....	7.741
3..	.....	.....	7.823	7.830	....	7.780	... .	7.758	.....	7.755	.....	7.769
4..	....	.....	7.826	7.849	.....	7.808	.....	7.773	.....	7.789	....	7.798
5..	....	.....	7.831	7.806	....	7.812	. ..	7.790	.....	7.812	.....	7.811
cold, 6......	.....	.....	7.844	7.824	....	7.829	.....	7.825	.....	7.826	.....	7.825
Diff. 6-1......	.. .	.....	.025	.034	.....	.040	....	.073	.....	.082	.....	.135
Mean diff. of carbon	.071	....	..	....	....	.....	.....	... .	.....	.....	.....	......

The twelve ingots treated here were first selected by ocular inspection for carbons; the carbons were then determined by combustion analyses.

It will be seen that the inspection was correct, and that the mean difference in carbon between consecutive numbers is .007. Between Nos. 7 and 8 there is a difference of only .004 ; when the analyst discovered this, he asked for a reinspection, not giving any reason for his request. The inspectors made new fractures, examined the ingots carefully in good light, and reported that they erred the first time, that both ingots belonged in the same temper number, but that if there were any difference No. 8 was the harder. It is not claimed that a difference of .004 is really observable.

The contents of silicon, phosphorus, and sulphur show clearly that the controlling element is carbon. This experiment has been repeated a number of times, and always with the same result, showing that there is no uncertainty in this method of separating tempers.

Parts of these ingots were reduced to ¾-inch round bars. The specific gravities of the ingots were taken, showing generally a reduction of sp. gr. for an increase of carbon. No. 3 and 5 are anomalous; an explanation of this could doubtless have been found if a careful investigation had been made, but there was no re-examination.

The sp. gr. No. 6 are of the ¾-inch bars as they came from the rolls; they are all heavier than the ingots except No. 4, and they are of nearly uniform sp. gr.; this is due doubtless to the fact that the higher carbon steels are so much harder than the low-carbon steels that it required much more work to reduce them to the bars, and as hot-working increases density, the densities of the higher carbons were increased more than those of the lower.

The bars were nicked six times at intervals of about ¾ inch and then heated so that the ends were scintillating, ready to pass into the granular condition, and the heat was so regulated as to have each piece less hot than the piece next nearer to the end, the last piece, No. 6, being black and as nearly cold as possible.

It is manifest that this operation is subject to the error of accidentally getting No. 2, for instance, hotter than No. 1, and so on, so that perfect regularity is not to be expected; to obtain a true rule of expansion it would be necessary to make hundreds of such experiments and use the mean of all.

It will be noticed that No. 4 is abnormal in the ingot series, and that the No. 6 piece of No. 4 is abnormal in being lighter than the ingot; probably this No. 6 of No. 4

was hot when it was intended to be cold. Also No. 2 of ingot No. 3 is lighter than its No. 1, showing another irregularity in heating.

Taking the whole list of No. 1 pieces, they are all lighter than their respective No. 6 pieces; the differences of sp. gr. 6–1 are progressive, being only .025 for the No. 3 ingot and .135 for the No. 12 ingot. This shows clearly that expansion due to a given difference in temperature is much greater in high steel than in low steel.

This clears away the mystery of the so-called treachery of high steel, its tendency to crack when hardened. There is no treachery about it; it is very sensitive to temperature, and it must be treated accordingly.

A few examples will now be given to show the changes of tensile strength, ductility, etc., that may be had by differences of carbon, and by differences of treatment, annealing, hardening, and tempering.

TABLE II.

Character of Steel.	O. H.	Crucible Sheet	O. H.	O. H.	O. H.	Crucible Eye-bar, 2″×1″.	Crucible Eye-bar, 2″×1″.	Crucible Eye-bar, 2″×1 .	Crucible ½-in. Drawn Wire.
Carbon……	.09 to .12	.435	.50	.60	.70	.96	1.35	1.40	1.15
Silicon………	.008	.014	.025	…..	……	.156	……..	………..	<.02
Phosphorus.. .	.007	.050	.016	……	.. …	.008	…….	……. ..	<.02
Sulphur…….	.026	.023	.028	…	……	.015	……..	………..	trace
Manganese …	.055	.204	.325	.. …	……	.24	…….	……….	<.30
Tensile str'gth, lbs. per sq.in.	46800	73142	84220	108800	117400	124800	100733	117710	141500
Elastic limit…	30900	…..	63560	71500	69980	65000	85078	69850	92420
Elongation…	in 2 in.41%	in 1 in.42%	25%	14.5%	11.5%	4.75%	.5%	7.28 at 2.85 in 2½	2%
Reduction of area……..	75.85%	62.3%	29.91%	13.55%	8.59%	…….	…….	13.03%	2.42%
Fracture…..	silky ½cup	……	….	……	….	broke in neck slight flaw, fine grain	broke in head close grain	……….	broke in grip

O. H. is the abbreviation for open hearth.

Second column is mean of 24 analyses and 24 tests of boiler-sheets.

TABLE III.

Cold-drawn Wire, ½-inch Diam.	Tensile Strength, lbs. per sq. in.	Elastic Limit, lbs. per sq. in.	Elongation.		Reduction of Area, per ct.
			In 3 in.	Per cent.	
Cold-drawn, broke in grip………….	141,500	92,400	.06	2.00	2.42
Same bar drawn black …… ……..	138,400	114,700	.18	6.00	12.45
" " annealed….. …………	98,410	68,110	.30	10.00	11.69
" " hardened and then drawn black ……. ……………….	248,700	152,800	.25	8.33	19.7

Analysis of this bar is given in Table II in the last column.

A test of ½-inch wire to show effect of cold-drawing, tempering, annealing, and hardening and tempering. Four pieces were cut from the same bar. It is probable that the first piece would have given a little higher tensile if it had not broken in the grip; it was clamped too tight. The second piece was heated until it passed through all of the temper colors and turned black, technically called "drawing black," or drawing out all of the temper. It is not quite annealing; the idea was to find the effect of temper-drawing upon a cold-hardened drawn wire.

The effect of this operation was to lower the ultimate and raise the elastic strength, increasing also the ductility.

The third piece was heated carefully to the recalescence-point, and cooled slowly, thus annealing it completely, and giving the normal strength of a bar of this composition.

The fourth piece was heated to recalescence and quenched, hardening and refining it thoroughly; it was then tempered through all of the colors until it turned black; the result shows the enormous potencies there are in the hardening and tempering operations.

The cases given in Table II were selected indiscriminately, so as to show better the effect of carbon, as we here 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,