best steel can be made better there are many users who would gladly pay a higher price for a better service.

The results were not encouraging. The high-carbon nickel steel was not as strong as the same quality of steel without nickel; the mixture seemed to be imperfect, containing little dark specks, supposed to be carbon thrown into the graphitic state. The steel did not refine as well and was not as strong as the carbon steel.

All of this applies to high-carbon tool-steel, hardened and tempered; no tests were made of the steel unhardened, for they would have been of no practical use.

ALUMINUM STEEL.

When a heat of steel is boiling violently, is wild, and unfit to be poured, the addition of a minute quantity of aluminum will have the effect of quieting it quickly. Half an ounce to an ounce of aluminum to a ton of steel will be enough usually, and for this purpose aluminum has become useful to steel-makers. If a little too much aluminum be added, the ingots will pipe from end to end; therefore the use of aluminum is restricted to small quantities. Experiments have shown that a considerable percentage of aluminum adds no good properties to steel; therefore aluminum steel so called may be treated later under a different heading.

IV.

CARBON.

Of all of the abundant elements of nature carbon is presented in the greatest variety of forms, and admits of the greatest number of useful applications.

In the form of the diamond it is the hardest of substances, and is the base used in determining the comparative hardness of all others.

In the form of graphite it is soft and smooth, and is one of the best and most durable of lubricants.

In the form of soot it is probably the softest of solids.

In the form of coal it is the one great and abundant fuel of the world, while as graphite again it is one of the best of refractory materials.

Hard, soft, highly combustible, almost infusible, refractory, it lends itself to the greatest variety of useful applications. To the iron- and steel-maker or worker it is simply indispensable; as charcoal or coke it is the fuel of the smelter; as gas, either carbon monoxide or as a hydrocarbon, it is the cheapest and most manageable fuel for melting and for all operations requiring heat.

As graphite, plumbago, mixed with a little fire-clay as a binder, it is the best material for crucibles in which to melt metals; as soot it forms the best coating for moulds into which metals are to be cast.

Durable beyond almost any other substance, it would make the very best paint for metal structures if there were any known way to make it adhere.

CARBON IN IRON.

Carbon may be introduced into iron in any quantity from a few hundredths of one per cent as usually found in wrought iron, and in what is known as dead-soft steel, up to about four per cent as found in cast iron. By the addition of manganese as high as six or seven per cent of carbon has been introduced into iron. Carbon does not form a true alloy with iron, neither does it form any stable chemical compound. Its condition in iron seems to be as variable as it is in nature, and sometimes it has been supposed to be as capricious as it is variable. It is hoped that the reader of these pages will find that there is no caprice about it, that its action is governed by as sure laws as any in nature, and that certain results may be predicated upon any treatment to which it is subjected.

The theories of its actions are as numerous and variable as are the actions themselves, and they will be treated in a separate chapter, this chapter being confined to a statement of known facts.

As stated in Chap. I, carbon may be introduced into iron by heating carbon and iron in contact when air is excluded; and, conversely, carbon is burned out of cast iron by the Bessemer and open-hearth processes to reduce the cast iron to cast steel.

In the crucible any quantity of carbon may be obtained in steel by melting a mixture of high blister-steel and wrought iron, or cast iron and wrought iron, or by charging with wrought iron the necessary quantity of coke or charcoal. When using plumbago crucibles, the iron takes up some carbon from the crucible; also the spiegel-eisen or ferro-manganese used adds some carbon; and for these two sources of carbon the melter allows when he decides upon the quantity of charcoal needed.

Results from crucible-melting are not strictly uniform; even if every charge were weighed in a chemical balance accurately the product would not be uniform, because one crucible gives off more carbon than another; in one crucible a little more charcoal may be burned and escape as gas than in another; and most variable of all, unless the charcoal has been dried thoroughly, is the quantity of moisture in the charcoal. One charge of charcoal may be dry, and the next may contain as much as twenty-five per cent of moisture; obviously equal weights in such a case would not give equal quantities of carbon to the steel.

In crucible-steel this is no disadvantage; a skilful mixer will get from 75% to 90% of his ingots of the desired temper; the other ingots will all be in demand for other uses, and as he can separate them all with absolute certainty by ocular inspection, as described before, he labors under no fear of bad results.

In the Bessemer process it is usual to burn out all of the carbon and then to add the required amount in the spiegel; for structural steels and for rails this method is satisfactory. For high steel—from fifty to a hundred or more carbon—the spiegel method does not answer so well, because it increases the quantity of manganese to too great an amount; higher carbon is then sometimes put in by the addition of a given quantity of pure pig iron previously melted, or by putting coke in the ladle, but this is very uncertain on account of the tendency of the coke to float, and be dissipated as a gas instead of entering the steel.

The Darby method is to place in the way of the stream of steel as it is poured from the vessel to the ladle a refractory-lined, funnel-shaped vessel filled with finely divided, but not powdered, coke. As the stream rushes through the coke it absorbs carbon with great rapidity, and it is asserted that the currents and eddies formed in the ladle by the rush of the stream cause an even distribution of carbon. That carbon will be taken up in this way is certain; that a required amount, evenly distributed, can be obtained is not so certain.

In the acid open-hearth as in the Bessemer process for milder steels it is usual to burn the carbon out almost entirely, and then to add the desired amount with the spiegel. Higher carbon may be obtained by the addition of pure pig iron, or by using carbon bricks pasted together with tar and weighted with iron turnings; these bricks may be pushed under the surface in different parts of the bath, and in this way the carbon can be distributed pretty evenly. In good practice now the melt is stopped at the carbon desired with great success, thus saving time and expense. In the basic open-hearth the melter, by the use of a little care and good judgment, stops his melt at the required carbon, and so avoids any additional operations, unless his charge is excessively high in phosphorus and his steel is to be very low in the same; in that case he may have to melt clear down and re-carbonize.

Steel of 130 carbon with phosphorus <.05 may be made on the basic hearth from a charge containing 10 to 12 phosphorus without melting below 130 carbon.

If high-carbon Bessemer steel is not uniform, it is not to

be wondered at, but as a matter of fact it is usually found to be fairly uniform, sufficiently so to work well.

If open-hearth steel of high carbon is not uniform, it is clearly because the maker would not take a little trouble to have it so.

Assuming that for convenience cast steel is graded for carbon content by even tens, and that the different tempers are separated half-way between the tens, we have:

Carbon.					
.10	including	from	.05	to	.15
.20	"	"	.16	"	.25
.30	"	"	.26	"	.35
.40	"	"	.36	"	.45
.50	"	"	.46	"	.55
.60	"	"	.56	"	.65
.70	"	"	.66	"	.75
.80	"	"	.76	"	.85
.90	"	"	.86	"	.95
1.00	"	"	.96	"	1.05
1.10	"	"	1.06	"	1.15
1.20	"	"	1.16	"	1.25
1.30	"	"	1.26	"	1.35
1.40	"	"	1.36	"	1.45
1.50	"	"	1.46	"	1.55

This covers the usual commercial range from what is known as dead-soft steel up to a high, lathe-temper steel.

Higher steels are used sometimes, even up to 225 carbon, but they are so exceptional that it is not worth while to continue the list above 150.

This list allows a variation of .05 carbon above and below the datum of each temper; some margin must be had of course, and this is sufficient in the hands of a careful steel-maker; it is found in practice to be satisfactory to the user. Even in the highest lathe-steel where the strains from hardening are the greatest, because the change in volume due to a degree of temperature is the greatest, a variation of three or four points above and below the mean does not make enough difference in the results to throw a skilful temperer off from his desired conditions.

On the other hand, a difference of a full temper will throw the most skilful worker off from the track, and so that much variation is not allowable. For instance, if a man be working 130 carbon, and he should receive a lot of steel of 120 carbon, he would get his work too soft in following his regular methods; then if he doubted himself, as he would be apt to do, and raised his heat to correct his supposed aberration, he would get his work too hard, coarse-grained, and brittle; if he tried to correct this by drawing to a lower temper color, his tools would be too soft. Again, if he received a lot of steel of 140 carbon and proceeded in his regular way, he would get a lot of cracked tools. So that in either case the result would be confusion. It is probable that in almost any case either 120 or 140 carbon would make a thoroughly good tool if the temperer knew what he was working with and adapted his heats to the carbon. But he does not know of the variation, and even if he did he would say, very rightly, that he did not propose to make daily changes in his methods to suit the convenience or the carelessness of the steel-maker.

It must not be understood, however, that this narrow range for each temper limits the capacity of the steel; it merely gives the limit for regular easy working.

To illustrate: A good lathe-tool may be made of 100-carbon steel, and of 150 carbon; but no worker could use these tempers indiscriminately, nor even alternately, although he knew which was which, because he could not change all of his heats say every five minutes and turn out satisfactory work. A spring of given size, and to carry a given load, may be made equally good of 60-carbon steel or of 140 carbon, and such work is done frequently in shops that are attached to steel-works; but the spring-maker must be told beforehand what he is to work with, and he must be given enough of one kind of steel to make say a day's work, so that he can go along regularly. The springs will be good, but the one containing 140 carbon will have the highest elasticity and the most life, although both will have the same modulus of elasticity. The spring-maker who buys his steel will not submit to any such variations, and he ought not to be asked to do it, because one temper of steel costs no more than another, and the selecting out and separating the tempers is only a matter of a little care.

Is it practicable to keep steel uniform in carbon within such narrow limits?

In crucible-steel practice it is very easy to do so. All ingots of 60 carbon upwards up to four or four and one half inches square may be broken completely off at the top, and then the clean fracture will indicate the quantity of carbon invariably, and after the ingot has been glanced at and marked properly it is as easy to put it on its proper pile as to put it on any other. In a good light a competent inspector will mark thirty or forty ingots per minute and do it correctly; it is as easy to the trained eye as it is to read a printed page.

This inspection is so important that it should never be neglected. It is not costly, much less than a dollar a ton.

With larger ingots only a piece can be broken off from the edge, but if the topper does his work properly, enough can be taken off to show the temper clearly. Large ingots containing the contents of a number of crucibles are liable to unevenness of temper from having uneven mixtures in the pots and from bad teeming into the moulds; this can be detected usually in the ingot inspection, and if not it can be found later during another inspection. Such variations are often called segregations. This question of segregation will be discussed in a future chapter.

In the Bessemer and the open-hearth practice ocular inspection of ingots to determine carbon is not used.

Enough examinations have been made to show that the fractures, although differing from those of crucible-steel, are quite as characteristic, and ocular inspection could be used. The ingots are large usually and to handle and top them would be expensive; but the heats are also large,—from five tons up to thirty tons in one heat,—and as they are supposed to be homogeneous, one chemical carbon analysis is enough for each heat.

Below 50 carbon a quick color analysis is accurate enough; above 50 carbon combustion should be used, for in high carbons the color test in the best hands is only the wildest guess-work.

The ten-point range of carbon is far more difficult to attain in high-carbon open-hearth practice than in the crucible. In one case where the limit fixed in a specification was 90 to 110 carbon, two full tempers, one of the most skilful and successful concerns in the world failed to

meet the specification in twenty-ton and thirty-ton furnaces.

It was supposed at first that the trouble came from using different heats, and large lots of billets were sent out with the heat number stamped on each billet. The same variations were found in every heat, the carbon ranging from 80 to 120. The specification was met without any trouble in five-ton furnace.

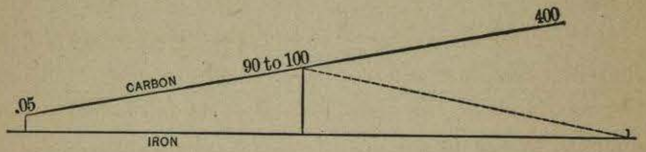
This illustration should not lead to the conclusion that practically uniform steel cannot be obtained; there is little doubt that if the 30-ton heats had been stirred thoroughly in the furnace the required limits would have been obtained.

Neither is it to be understood that the same variation would occur in mild steel under 30 carbon. A call for 20 carbon would not result in steel ranging from below 10 to above 30,—such a result would show gross carelessness on the part of the melter,—the variation would go by percentage; thus the variation in the high steel is from 15% below to 15% above the mean of 100, or even as much as 20%.

If 20-carbon steel be required, a variation of 20% would give a range from 16 to 24 carbon, or well within the limits of one temper.

This matter will be considered farther under the head of Segregation.

The appropriate applications of the different tempers of steel have been stated in a general way, with the advice that for all tool purposes it is better to leave the selection of the temper to the steel-maker; also in structural work it may prove to be better to leave the question of temper, or carbon content, to the steel-maker, who should know how to meet any specification that is within the capacity of steel. On the other hand, every engineer should know what is attainable, and an effort to give this information in more definite form will be made in later chapters. A general view will now be taken of what may be called the carbon-line.



Let the horizontal line represent iron, the inclined line iron plus carbon, and the verticals physical properties.

We do not know the physical properties of pure iron. Assuming them to be uniform, let the vertical at .05 represent the tensile, torsional, transverse, or compressional strength of steel of 5 carbon; then for every increment of carbon up to 90 to 100 there will be an increase of strength to resist any of these strains, increasing in such regular amounts as to make the resulting carbon-line practically straight, as shown in the sketch. Above 100 carbon these resistances will all decrease, except resistance to compression.

So far as it is known, compressive strength increases slightly with the carbon, until cast iron is fairly reached; then the presence of silicon, and the fact that we are dealing with a casting instead of forged or rolled metal, causes a rapid fall in all resistances until the strength is below that of 5-carbon steel.

With increase of carbon there is a reduction of ductility, so that the extension of length and reduction of area

decrease as the strength increases. In every case the engineer must decide how little ductility he can do with safely in securing the ultimate strength or the elastic limit he may require.

The highest strength and the greatest ductility cannot be had together; they are inverse functions one of the other.

If the exact resistances due to carbon were known along the whole line, it would be of great value to give them here but nearly all of the thousands of tests published are influenced by the quantities of silicon, phosphorus, sulphur, manganese, or oxides present, and an effort to determine the effects of the carbon-line exactly would be hazardous.

Kirkaldy's tests of Fagersta steel, published in 1876, furnish a valuable guide in this direction.

Webster's experiments on the effects of the different elements, phosphorus, manganese, etc., are interesting and valuable, but he has not yet tested a complete carbon-line with no other variables.

It has been stated time and again by experienced steel-makers that the best steel, the most reliable under all circumstances, is that which comes nearest to pure iron and carbon.

Some intelligent steel-makers, and engineers cast doubts upon this statement, and assert that because phosphorus up to a certain limit, or manganese, or silicon, or in fact it may be said almost any element, added to dead-soft steel will give an increase of strength, therefore the presence of one or more of these elements is not only not harmful, but beneficial.

As a matter of fact, however, every one of these elements is harmful, either in producing cold-shortness, or red-shortness, or brittleness, and not one of them will add any good quality to steel that may not be obtained better by the use of carbon. Given a uniform minimum content of these impurities, the carbon-line may be depended upon to furnish any desirable quality that is obtainable in steel; and it is certain, always sure, that that steel which is the nearest to pure carbon and iron will endure the most punishment with the least harm.

That is to say, that such a steel when overheated a little, or overworked, or subjected to any of the irregularities that are inevitable in shop practice, will suffer less permanent harm than a steel of equal strength where there is less carbon and the additional strength is given by any other known substance.

It is difficult to show this from testing-machine data, indeed it is doubtful if any such data exist, but experience in the steel-works, in the bridge- and machine-shops, and in the field proves it to be true. For further discussion of this question see Chap. X.

The effects of a small difference in phosphorus or in silicon contents are shown plainly and unmistakably in high-carbon steel, and not so plainly in low-carbon steel; but as there is no known hard and fast line that divides low steel, medium steel, and high steel, so there is no marked difference in their properties. The same rules hold all along the line, the same laws govern all of the way through.

There is no set of properties peculiar to low steel and another set peculiar to high steel; the same laws govern all, and differences are those of degree and not of law.

Given three samples of steel of the following compositions:

	No. 1.	No. 2.	No. 3.
Silicon................	.02	.20	.02
Phosphorus............	.01	.01	.02
Sulphur	.005	.005	.005
Manganese.............	.100	.100	.100
Carbon................	1.100	1.100	1.100

A skilful worker, not knowing the composition of any, will pick them out invariably by tempering them and testing them with a hand-hammer and by inspecting the fractures.

He will pronounce No. 1 to be the best and the strongest in every way; No. 2 to be not quite as strong as No. 1, and more liable to crack from a little variation in heat; No. 3 to be not so strong as No. 1, and that it will not come quite as fine as either of the others, and, like No. 2, it will not stand as much variation in heat as No. 1.

Give a ton of each to a skilful axe-maker, from which he will make one thousand axes of each, and he will be sure to report No. 1 all right; No. 2 good steel, more loss from cracked axes than in No. 1.

No. 3 good steel, some inclination to crack; it will not refine as well as No. 1 and is not as strong.

This is no guess-work, nor is it a fancy case; it is simple fact, borne out by long experience.

Give a skilful die-maker one hundred blocks of each to be made into dies. He will not break one of No. 1 in hardening them; he will probably break five to ten of No. 2; and if he breaks none of No. 3—a doubtful case—he will find in use that No. 1 will do from twice to twenty times as much work as either of the others. If he is making expensive dies,—many dies cost hundreds of dollars each for the engraving,—he will think No. 1 cheap at 25 cents a pound, and either of the others dear at 15 cents a pound.

In such steel, then, the absence of a few points of silicon, or of a point or two of phosphorus, is worth easily 10 cents a pound.

Now let the carbon in these three steels be reduced to 10, making them the mildest structural steel. The differences to be found in the testing-machine in tensile strength, elastic limit, extension, and reduction of area will be almost or altogether nothing; in forging, flanging, punching, etc., under ordinary conditions differences would not be observable; therefore there would be no practical difference in value. But let the silicon be raised to 30 or the phosphorus to 10,—the Bessemer limit,—or let both be raised together, and both the testing-machine and shop practice would show a marked difference.

This shows that in the absence of carbon the action of these elements is sluggish as compared to their effects in the presence of high carbon, or in the low-carbon steels their effects are not so observable. That their influence is there, there can be no doubt, but if it be not enough to endanger the material it is not worth while to take it into account.

Is it safe and wise, then, for steel-users to ignore composition?

Users of tool-steel may do so safely, because the smallest variations will manifest themselves so unmistakably that they give immediate warning, and the steel-maker must keep his product up to a rigid standard of excellence or lose his character and his trade. Many of the ablest users of structural steel take a similar ground, and say, We

have nothing to do with method or composition if the material meets our tests.

It is believed that if these men knew how easy it is for a skilful worker to doctor temporarily an off heat by a little manipulation, and how dangerous the same may become by a little off practice in the field, they would be convinced that some limits should be put upon composition, especially if they could realize that a reasonable specification would add nothing to cost, as competition would take care of that.

The reader is referred again to Chap. X on impurities.