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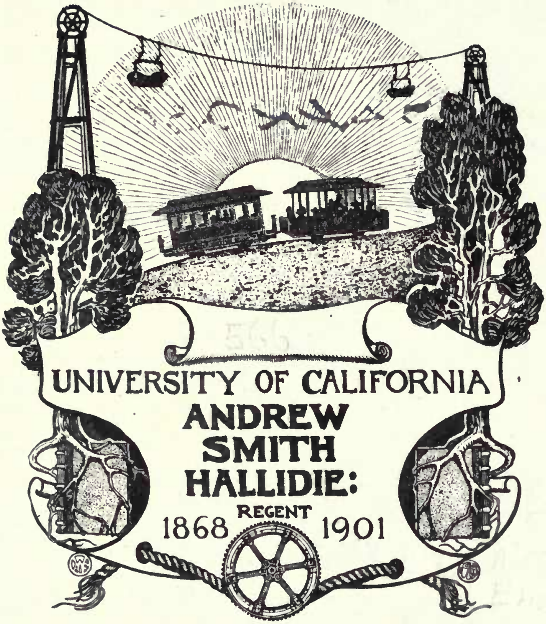
THE HARDENING AND TEMPERING OF STEEL

F. REISER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THE HARDENING AND TEMPERING OF STEEL

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In Theory and Practice

BY

FRIDOLIN REISER

MINING COUNCILLOR, DIRECTOR OF THE CAST STEEL FOUNDRY
KAPFENBERG

*TRANSLATED FROM THE GERMAN OF THE
THIRD AND ENLARGED EDITION*

BY

ARTHUR MORRIS AND HERBERT ROBSON, B.Sc.

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> "There is a very great difference, when it [red-hot iron] is immersed glowing in water. . . . It is usual to extinguish thin pieces of iron in oil, for water would make them so hard as to be brittle." PLINY, Bk. xxxiv. Chap. 14.

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PREFACE TO THE FIRST GERMAN EDITION.

THE manufacture of steel is making rapid progress, and improvements and inventions follow one another without intermission. The union of science and practice has produced results scarcely dreamt of thirty years ago. The progress in metallurgy and the revolutions it has lately undergone, which have stirred up every section of it, have become so important, that the iron and steel industries would seem to have exchanged the symbol of Mars for that of Saturn, who swallowed his own children.

This progress we owe to science, which is represented by an excellent technical literature of the subject.

This literature becomes very scanty, however, where manufacture ceases and the working up of the manufactured product begins. But this branch also requires the support of theory. It is scarcely necessary to point out that the trades which have made the most progress are those which have most sought the advice of science.

In particular, the preparation of tool steel offers great practical difficulties, which may easily lead to failure. This is still more specially the case with tempering, which in making good tools is quite as important as the quality of the steel.

This matter is treated in most scientific works with encyclopædic brevity, and, besides, these works are inaccessible to the

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majority of the public. It has hence occurred to me that a work was needed which should deal exclusively and thoroughly with all matters which are of influence on the quality of finished steel tools.

As proper treatment of a material presupposes an exact knowledge of its properties, I have undertaken a concise but nevertheless complete description of those properties of steel which are connected with its preparation. The changes of strength undergone by steel by various methods of heating and tempering have been investigated with the testing machine, and are illustrated by numerous examples.

With the attempt to find scientific reasons for the idiosyncrasies of steel, hypothesis comes in whether we will or no. This is hardly to be avoided in a field in which much remains to be explained, and which has only been trodden by a few in its entirety.

I wish in this connection to call special attention to my views on spoilt, overheated, and burnt steel, as well as on weldability and temperability.

I considered that I ought to overcome my disinclination to combine theoretical deductions with the description of practical work, in deference to those thoughtful and rational craftsmen who are in the habit of seeking reasons for what they do. And as these theories not only do not contradict experience, but are supported by it, their position will always appear, in this little work, to be justified in the eyes of those who prefer a scientific explanation of a physical phenomenon to the more convenient acceptation of it without inquiry.

The authorities used have been Schafhaute's article on "Steel" in Prechtl's *Cyclopædia* (1847); Hartmann's *Manufacture and Preparation of Steel* (1856); Wedding's *Handbook of Iron Manufacture*; Ledebur's *Mechanico-Metallurgical Technology*; the technical dictionary of Karmarsch and Heeren; an article on "Tempering" by Jarolimek, published in 1876, in the

Oesterreichische Zeitschrift fur Berg- und Huttenwesen ; another on the same subject published by P. von Tunner in the September 1879 number of the *Berg- und Hutten-Männischer Verein far Steiermark und Karnten,* and several others.

I now publish this unpretentious work, with the hope that it may receive a friendly yet critical judgment.

KAPFENBERG, STEIERMARK,
September 1880.

PREFACE TO THE SECOND GERMAN EDITION.

SINCE the appearance of the First Edition, important work has been done with the various forms of carbon and their influence, and microscopic investigation of polished surfaces of iron has furnished valuable information, unattainable by chemical analysis, on the conditions and arrangement of the contained carbon produced by various processes of cooling.

I have paid careful attention to these results in revising the theoretical part of the book.

The work has been translated into Hungarian by Alfred von Probstner, an ironworks engineer, and the translation was published in Schemnitz.

KAPFENBERG, *End of* 1895.

PREFACE TO THE THIRD GERMAN EDITION.

THE present Edition has been increased by a chapter on "Heating Arrangements for Tempering Steel and Methods of Measuring High Temperatures." The second part of this chapter is intended to create a wider interest in the pyrometer, which has lately been brought to great perfection. For tempering purposes it is of great value, and it is to be earnestly hoped that it will be recognised as an indispensable assistant in tempering shops as soon as possible.

Barbary de Langlade, an engineer and ironworks owner, has translated the second edition into French. The translation was published by Baudry & Co., Paris, in 1897.

KAPFENBERG, *April* 1900.

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THE HARDENING AND TEMPERING OF STEEL

CHAPTER I.

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STEEL.

DEFINITION AND CLASSIFICATION.

IRON which is forgable and temperable when heated to particular temperature and then suddenly cooled, becomes harder, and is called steel. These properties depend chiefly on the amount of carbon in the iron, and this varies very gradually. There is no hard and fast line between steel and iron. If the carbon is less than ·45 per cent., the hardening becomes barely noticeable, and the iron is no longer steel but wrought iron.[1] When the percentage of carbon exceeds 2·3, the iron is no longer forgable.

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But steel contains other elements, partly accidently,—for the impurities of the raw materials pass more or less into the steel according to the process of manufacture; and partly purposely, —for substances are added to the steel, partly to neutralise the

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[1] Moreover, tempering is not without effect even on wrought iron. It acquires, although it is not perceptibly hardened, a higher limit of elasticity and absolute fixedness with diminished tension, and usually shows greater toughness under bending strain.

bad effects of the inevitable impurities, and partly to improve the properties of the steel. As a rule, the less carbon there is in the steel the less the injurious effect of the accidental impurities, and the greater the good effect of the intentional additions.

Those steels with smaller amounts of carbon and more of the intentional addition may be classed as "special steels."

The Committee constituted on the occasion of the Philadelphia Exhibition of 1877 for the purpose of getting uniformity of nomenclature for iron and steel has recommended :—

1. That all forgable combinations of iron with the usual ingredients which have been produced from softened masses or faggots, but not in a liquid state, and can be annealed and tempered, so that they are analogous to what has been so far called puddled steel, shall henceforth be called "welding steel."

2. All such combinations of iron which have been cast into forgable masses from the liquid state, and can be tempered or annealed, shall in future be called "ingot steel."

While this terminology divides steel into two great classes according to its manufacture, it does not touch the further division of welding steel into refined, puddled, cementation, and shear steel, and of ingot steel into Bessemer, Siemens-Martin, and crucible steel.

As in this work my special object is to deal with the tempering of steel, the difficulties of which are most marked in the manufacture of fine tools, and as cast steel is almost exclusively used for them, I shall give this the most prominent place.

As regards the classification of cast steel, its carbon usually varies between ·5 and 1·5 per cent. For a long time some of the Austrian iron works have classed it under 6 to 8 degrees of hardness: No. 0 or No. 1 being generally the hardest, and No. 6 or No. 7 the softest. This system made its way later into other countries, without, however, any definite degree of hardness being signified by any particular number. This classification of cast steel according to hardness is very proper, as this property forms its most important qualification for its use for any given purpose. Naturally the hardness should be associated with as much toughness as possible.

Considering the enormous importance which a proper choice of hardness has for successful tool-making, it is greatly to be regretted that there is no uniform and accepted scale of hardness. Such a classification would unquestionably help the buyer of tools, and protect him from making wrong selections. The most easy way to secure this desirable object would be to take the carbon-percentage as an expression of the hardness, as is done with Bessemer and Siemens-Martin steel.

The classification of Bessemer steel introduced by Tunner is unsuitable for cast steel, as Bessemer and Siemens-Martin steel are always much softer than cast steel. Besides, the intervals between the amounts of carbon (·25 per cent.) are much too wide for numbering cast steel. It might be advisable to number so that the highest numbers contained the most carbon, and to make the intervals between the numbers correspond to ·1 per cent. of carbon, as Kupelwieser proposed for Bessemer steel, were it not that it would be very unsafe to base the hardness scale on the carbon-percentage only, for manganese, silicon, and other elements have an influence on the hardness of the steel, and may be present in very different proportions.

As there is no absolute measure of hardness, and as it is very difficult, on account of the minute variations in hardness, to make any reliable comparative scale, such as Mohs made for minerals, all researches must be welcomed which may lead us to a practicable and easy method of determining the hardness, and give us reliable data which can be expressed numerically, so as to be understood by all.

Professor Kirsch has paid special attention to the literature of this part of our subject, and has compared concisely all the known methods of measuring hardness in the *Mittheilungen des K. K. technologischen Gewerbemuseums in Wien* (p. 79, 1891). These methods may be classified as gradual pressure, hammering, and scratching. Most of these methods are tantamount to regarding hardness as the degree of resistance opposed to the penetration of a foreign body, and presuppose that the hardness is uniform throughout the mass, which is not exactly the case with wire or with cold-worked steel or iron. Kirsch, however, defines hardness as the power of maintaining shape unchanged, and arrives at the result that the general hardness must be measured by the welding power, but the surface hardness by the pressure exerted by a standard mass at the moment that it begins to make a permanent impression.

For determining the surface hardness, Kirsch recommends a stamp of exactly known surface (5 mm. in diameter), pressed with sufficient force upon the planed surface to produce a permanent depression ·01 mm. deep.

Professor Kick's proposal to use the resistance to cutting as a measure of hardness, approaches this method very closely, as resistance to cutting is closely connected with welding power.

The scratching method of Martens depends on the use of a diamond. The hardness is measured by the pressure required to make the diamond produce a scratch ·005 mm. wide. This method has the advantage that it can be applied to the hardest substances, but it has the disadvantage of giving discordant results.

Just lately, attempts have been made to compare very hard steels by exposing rods of exactly the same diameter to an emery wheel. The rods are mounted horizontally in a frame, and kept pressed against the wheel with a uniform pressure.

The wear undergone in a given time can be used as a measure of the hardness.

This process seems rather rough and ready, but its very simplicity might make it important in practice, if it were possible always to get an emery wheel of exactly the same abrading power. Possibly the material for such a standard wheel might be found in carborundum.

CHAPTER II.

CHEMICAL AND PHYSICAL PROPERTIES OF STEEL, AND THEIR CAUSAL CONNECTION.

I. PROPERTIES OF UNTEMPERED STEEL.

THE natural hardness of steel, *i.e.* that which it possesses when slowly cooled in the air after fusion or after working at a red heat, depends first upon the amount and kind of carbon it contains. We usually distinguish four kinds of carbon in iron :—

1. *Graphite.*—When fused, the iron holds all its carbon in solution. During solidification, a segregation from the solution of carbon in iron takes place, in which the graphite separates out in the form of hexagonal plates nearly uniformly distributed through the mass. This, however, only happens when the fused iron contains more carbon than it can retain in combination when cold. Hence graphite never appears except in cast iron.

2. *Annealing Carbon.*—This results from a prolonged white heat, and is so called because it usually makes its appearance in annealed iron. Like graphite, its form is not affected by quenching in water.

3. *Carbide Carbon.*—This form does not occur in a free state, but chemically combined with the iron. This compound,[1] richer

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[1] Mrazek says, with respect to the chemical constitution of steel, in his *Experimentellen Untersuchungen uber Silicium und Mangan im Stahle*: "In chemical affinity silicium, like carbon, is an electro-negative element. Phosphorus and sulphur are also, and such elements stand in sharp con-

in carbon than the liquid iron, and of almost invariable composition, segregates during cooling from a bright red heat, and traverses it in veins or network, as can be seen on microscopical examination of a polished surface.

This compound is called carbide, and its composition corresponds roughly to the formula Fe_3C, as it contains about 6·67 per cent. of carbon to 93·33 per cent. of iron.

Like graphite, carbide is the result of a segregating process, a separation on cooling from solution. The temperature at which this happens is about 700° C., and usually higher the poorer the iron is in carbon. The formation of carbide, like that of graphite, and almost every other refining process, is accompanied by an evolution of heat which can be seen with the eye if a red-hot iron rod is allowed to cool in the dark. At the moment of the formation of the carbon, a recalescence of the rod is plainly visible.

On heating the iron above the temperature above given as that of the formation of the carbide, the carbon again enters into solution in the iron.

4. *Hardening Carbon.*—This forms with the iron a completely uniform mass. When liquid, iron contains its carbon in this form only. On solidification, graphite first forms, then the carbide, and on long heating the hardening carbon, which has received its name from the fact that the hardness depends materially upon its amount. Carbide and hardening carbon are often collectively known as combined carbon.

Slow cooling and the presence of large percentages of silicon

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trast to iron, which is electro-positive, and hence form with it true chemical compounds in certain simple proportions. When there is a great excess of the metal, as is always the case in commercial iron, only as much iron as corresponds to the maximum saturating capacity of silicon and carbon is in combination, so that more or less of the iron is in the free state. Steel and iron, therefore, always consist of free iron, together with comparatively small amounts of carbide, phosphide, sulphide, etc., of iron."

favour the production of graphite and carbide, while quick cooling and a large percentage of manganese check or prevent it.

Graphite and annealing carbon are not attacked by hydrochloric acid, while carbide dissolves in the hot acid, but not in the cold, and the hardening carbon dissolves either in the hot or cold acid.

In unignited steel there is only hardening carbon and carbide, and its hardness increases if it contains more of either of them. Hardening carbon, however, acts less equally than carbide, and although carbide of iron is distinctly harder than pure iron, it traverses the mass in fine veins, and its influence on the average hardness is thus not so clear as that of the hardening carbon.

Manganese, chromium, and tungsten, also, increase the natural hardness, as, to a less extent, do silicon and phosphorus. The last element, however, never occurs in cast steel in sufficient quantity to be considered as affecting the hardness.

We may here remark that by alloying a low-carbon steel with tungsten, chromium, manganese, or nickel, steels may be produced which cannot be used for turning tools, as they are too hard to have any cutting power. These alloys only acquire that power when they contain much more carbon, so that we may distinguish an active or cutting hardness and a passive or abrading hardness.

The appearance of a fracture enables us to judge of the natural hardness of rolled or forged steel, but not of its quality. In soft steel the grain is coarse and the colour grey. As the hardness increases, the grain gets finer and the colour darker. The fineness of the grain also increases the more the steel has been worked and the thinner it has been hammered or rolled. But the way in which the steel is broken, and the temperature at which it left the rolls or the hammer, influence the nature of the fracture materially.

If the steel is notched cold with a chisel and thus broken, the grain is coarser than if the steel had been notched and broken at a red heat. In that case there is a displacement of the section which has its effect upon its appearance. As regards the temperature-influence the hotter the steel comes from rolls or hammer, the coarser the grain, and *vice versâ*. This circumstance often produces different fracture-appearances in the same rod. For example, let us consider the case of a small ingot, forged into a rod in two heats. At first the whole of the ingot is heated in the furnace, and it is then held by one end in the tongs while the other end is forged. The unhammered end is then put back in the furnace, while the forged part projects from it. In spite of this the forged part also undergoes more or less of a second heating, but does not get any more hammering. Where the two parts meet the steel will always show a somewhat coarser grain than the rest.

As regards the connection between the percentage of carbon and the strength of the steel, the extensibility becomes less as that percentage increases, but the elastic limit and absolute strength increase. The absolute strength reaches its maximum with from 1 to 1·25 per cent. of carbon.

Other ingredients besides the carbon affect the strength of the steel. The following account may be given of the effect of the commonest ones.

Phosphorus increases the absolute strength and still more the elastic limit, but it greatly diminishes the resistance of the steel to blows at the ordinary temperature, so that phosphorus steel is "cold-short." The brittleness of phosphorus steel is caused by its tendency to a coarse-grained structure with a consequent diminished cohesion between the crystals. This effect increases with the percentage of carbon.

Cold-shortness may vary for the same content of phosphorus, as it also depends upon the degree to which the steel is stretched during its working when hot. The more the steel is extended, the less the danger that the crystallisation which began on heating will assume dangerous proportions. Tin and antimony make steel cold-short.

Sulphur makes iron weaker at a dull red heat, but not above or below that temperature. Hence sulphur steel is said to be red-short.

Silicon lessens the resistance of steel to blows, and lessens its extensibility (ductility).

Manganese diminishes the deleterious action of silicon and sulphur. An increase in the amount of manganese raises the limit of elasticity and the breaking load, and lessens the extensibility, so that it behaves like an increase in the carbon. Too much manganese makes the steel brittle.

Chromium and tungsten favour the formation of a fine grain, increase the hardness, the elastic limit, and the breaking strain, without lessening extensibility so much as carbon does. Hence chrome and tungsten steels are less brittle than purely carbon steels of the same hardness.

The resistance of steel to blows and jolts varies with the temperature. Below zero C. steel is comparatively brittle, but when warm it is stronger than at normal temperatures. This can be observed even at the warmth of the hand, and from it an unusual mobility of the molecules may be inferred.

In testing tensile strength we generally find that the absolute strength of the steel does not vary between $-30°$ and $+200°$ C., but diminishes rapidly above 300°. The extension remains unchanged between $-20°$ and $+20°$, but above that it lessens, and reaches a minimum at from 200° to 300°. It then again increases up to 600°, above which it rapidly lessens again.

Forging, rolling, and pressing increase the specific gravity of steel, and, as the coarsely crystalline structure always present in the ingot is made finer, the strength and, up to a certain amount of working, the extensibility also is increased.

Langley found that the specific gravity of a steel containing 1 per cent. of carbon was 7·807 in the ingot and 7·826 rolled into a bar.

The changes produced by working cast steel at high temperatures are illustrated by the following table of Kirkaldy's results.

The tests were carried out with Bessemer ingots of Fagersta, which were forged down from 152 mm. to 51 mm. :—

	Percentage of Carbon.	Elastic Limit per sq. mm. in kilos.	Tensile Strength per sq. mm. in kilos.	Extension in Percentage of Original Length.	Lessening of Cross-Section Percentage.
Unforged . .	·2	15·6	37·2	11·6	11·9
Forged . . .	·2	24·7	42·1	22·5	61·3
Unforged . .	·4	19·9	38·8	3·4	4·2
Forged . . .	·4	27·6	52·7	17·9	52·5
Unforged . .	·6	27·3	46·8	1·7	2·3
Forged . . .	·6	33·5	68·8	10·2	28·4
Unforged . .	·8	33·5	47·2	1·1	1·5
Forged . . .	·8	46·8	69·3	2·2	3·2

The specific gravity of the steel increases as the percentage of carbon falls. The Reschitzka ironworks has published the following table of its Bessemer steel :—

Percentage of Carbon.	Specific Gravity.
1·00	7·826
·75	7·84
·50	7·853
·28	7·865
·12	7·879

Karmarsch gives the specific gravity of forged steel at 7·826–8·029.

The fusion point of steel also falls as the percentage of carbon rises, and ranges between 1350° and 1480° C., and at the same time its forgability is decreased. When the carbon-percentage reaches 2·3, forging is no longer possible, and the steel becomes cast iron. Forgability is affected in very different degrees by other constituents in the steel. Sulphur, as already mentioned, is specially injurious to forgability. Arsenic, copper, tin, zinc, bismuth, and antimony behave like it, as does silicon, but less powerfully. When several of these bodies are present together, very little of each of them will make the steel red-short. Steel is made more susceptible than wrought iron to the effect of impurities, on account of the larger percentage of carbon it contains.

The presence of ferrous oxide in ingot steel has the same effect as that of sulphur. It cannot, however, occur in crucible steel, for the atmosphere of the crucible is a reducing one. Phosphorus, to the extent that it is possible for it to exist in usable steel, has no injurious effect upon the forgability.

The influence of chromium, nickel, and tungsten, which are very infusible, is far less than that of carbon, for steel containing several per cent. of those metals is still malleable, while the forgability ceases when the carbon exceeds 2·3 per cent. All these remarks apply to metal which has been properly heated with as little access of air as possible. We proceed now to describe the results of improper heating.

Steel which has been heated to too high a temperature is almost invariably called burnt steel, without regard to the degree of excess to which the heating was carried. Nevertheless, overheated and burnt steel are really very different, resulting from different causes, and showing very different properties.

A steel is overheated when, without having undergone any detectable chemical change, it has been made brittle and coarse grained by excess of temperature, not extending, however, to the fusion point. The alteration is due to mechanical causes. Now as the fusion point of the steel sinks with increase of carbon, so does its proper working temperature, and the more it is liable to be overheated. This effect is still more marked with steel containing phosphorus.

The definitions of burnt and perished steel must be prefaced with the remark that steel at high temperatures can take up

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carbon from an atmosphere capable of yielding that element, but in air will take up oxygen, and give off oxides of carbon.

Burnt steel is steel which, through overheating in the air till it emits sparks, has had its carbon burnt out of it to a certain depth, and has been oxidised. The oxide near the surface fuses and destroys the cohesion of the steel. This explains the property of burnt steel to crack or break up when forged or rolled.

Perished steel, which has become soft and lost its steely nature more or less, is steel which has been heated too often in the air to the ordinary forging temperature, or kept at this temperature too long. It, too, has lost carbon, and become oxidised.

Both perished and burnt steel have a coarsely crystalline grain. Burnt steel is very brittle, and very much burnt steel is easily powdered. In perished steel the brittleness caused by crystallisation impairs the extensibility and toughness of the iron.

The tendency to get perished or burnt is different with different steels. The latter tendency is increased by the presence of easily fusible and oxidisable bodies. The tendency to perish depends only on the presence of oxidisable bodies. Hence ingot steel perishes more easily than refined or cast steel. Tungsten and chrome steel show the tendency to perish particularly, and frequent heatings alter their properties materially, and the more so the more chromium or tungsten they contain. Here, then, the ready oxidisability of the chromium or tungsten plays the chief part, as it is converted into chromic or tungstic acid by heating in the air.

The chemical difference between cast steel and ingot steel is chiefly that the former contains less manganese and silicon than the latter. Hence from the analogy of chromium and tungsten steel I consider that those two elements are the cause of the steel readily perishing, as they have a great affinity for oxygen at high temperatures, manganese a greater one than silicon.

In cast steel, according to St. Claire and Deville, diffusion pores open in the metal, and permit the escape of the carbonic acid formed by the oxygen of the air, so that the cohesion of the steel is not impaired.

It is different with the infused oxides of silicon and manganese, which are readily formed even at comparatively low temperatures, and remain in the steel. It is these unfused oxides which do the mischief in perished steel, but they reach the highest point of injuriousness when they become fused, and this, in all probability, is the case with burnt steel.

Reference must here be made to the property of burnt steel to be harder than it was before it went wrong, although it now contains less carbon. This increased hardness occurs particularly in patches formed on the surface of the steel, which from their nature and shape are called hard grains. The explanation of this phenomenon is that a silicate of manganese has been formed in those places, and makes itself evident by the great hardness characteristic of it.

Now that we have considered overheated, burnt, and perished steel, we come to the question of weldability. It is inevitable that great heat should be used for welding, and it is very easy for the welder to end by burning the steel.

Welding is extremely closely connected with malleability, for a steel which will not forge at a comparatively high temperature will not weld, and just as the forgability diminishes as the percentage of carbon and other bodies than iron increases, so does the power of the steel to weld. In general, steel is therefore the easier to weld the softer and the milder it is, and the less it contains of such easily fusible constituents which lower the fusion point of the whole, and hinder more or less the assumption by the steel of the necessary plastic condition. But the degree of oxidability of the various constituents of the steel, and hence its tendency to become perished, has also doubtless great influence on the weldability. This connection between that property and chemical constitution is well shown by the fact that a steel containing ferrous oxide is difficult or impossible to weld. The oxides make difficult the production of the clean metallic surfaces necessary for welding, for although the fluxes remove the surface oxides, they at the same time lay bare fresh oxide. This must happen in the presence of readily oxidisable bodies, which occur both on the surface and in the mass of the steel.

A reference to what has been already said as to the influence of foreign bodies on the iron in steel is shown by the same foreign bodies having very different effects, for the higher the temperature or the more oxygen can act, the more their fusibility or affinity for oxygen becomes important. Thus, for example, the presence of manganese, chromium, or tungsten is favourable to forging, although they incline the steel to perish. That this latter property makes those metals adverse to welding we know by experience. Thus pig iron with a rather high percentage of manganese gives on puddling or refining a product difficult to weld. The cause of this is, no doubt, that a part of the manganese, although that metal is more oxidable than the iron, remains obstinately in it.

In an experiment at a puddling works in Styria white pig iron, with about 3 per cent. of chromium, gave an entirely unweldable product. It was very difficult to form the blooms, and they fell to pieces between the rolls or under the hammer. They contained about ·2 per cent. of chromium.

These examples confirm the above expressed opinions about weldability very well, for the manufacture of wrought iron depends upon the weldability of the product. With ingot steel the weldability is without importance in the manufacture, but is a very material circumstance for its usability, especially with soft steels. Welding is a property rarely required in hard tool steel, so that chromium and manganese, in spite of their bad effect on welding, are not only not avoided, but purposely added.

Silicon is unfavourable to forgability, and lessens the resistance of the steel to repeated heats. As both silicon and manganese are almost always more abundant in ingot than in finery steel, this difference in composition must be considered as the cause of the fact that Styrian finery steel keeps its welding power with larger percentages of carbon than ingot steel generally does. There is, however, another reason for the difference between the two steels. Ingot steel is free from slag, while the other is not. The silicate slag in shear steel increases the weldability from its fusibility and its dissolving power for ferrous oxide.

The most important property of cast steel is its homogeneity of structure and of chemical composition. With well-forged or rolled cast steel this homogeneity is absolute, for neither chemical nor physical tests can detect any difference between one part and another, so that tools made out of such steel, when properly tempered, are equally hard and tough all over. It is by virtue of its strength, hardness, and toughness that cast steel is becoming more and more used in the manufacture of tools.

To make the best use of this property, in which cast steel far surpasses both finery and shear steel, it is necessary to bear in mind that it perishes more easily, and to treat it accordingly. Hence it should be put in the hands of skilled smiths only, who are able to bring it to the desired shape in a few heats. To protect the surface of the steel as far as possible from oxidation, a fusible pottery clay, made still more so by the addition of soda, should be used for complicated work. For this purpose a solution is made of the following proportions:—Clay, 20 lb.; soda (carbonate), 2 lb.; water, 2 gals. The iron is dipped cold into this, dried over the fire, and then treated as usual.

Although overheating is bad for steel, the forging heat should not sink below a red heat, or the steel will not be malleable enough for the sudden changes of shape induced by hammering, and may split. Another occurrence may take place at too low a temperature with high carbon steel. If the harder kinds of steel are forged with heavy hammers at a temperature only enough to produce a brownish red, and so forcibly that the steel increases in luminosity under the blows, the outside of the mass shows a black colour, which penetrates to a greater or less depth, and is caused by the separation of annealing carbon. Ledebur investigated a steel with a black fracture, which contained nearly half its carbon in the form of annealing carbon, and found that after hardening it contained the same quantity of annealing carbon as before, and could be filed as easily hardened as unhardened. Annealing carbon can, by hardening, be converted into hardening carbon or carbide.

Iron is most affected by mechanical working at temperatures between 220° and 300° C. These are the temperatures at which a section of a rod or a filed surface shows a tempering colour. This appearance is known as blue-short, and the temperature at which it occurs the critical temperature.

Hence we have the important practical rule that the working of iron must cease when it is no longer hot enough to show any colour. As already stated, the extensibility of forgable iron is comparatively small between 200° and 300° C., and it is probable that blue-shortness may be referred to this circumstance.

In the closest connection with the blue-shortness is the blue-short test. If an ingot containing flaws is rolled or forged into a rod and then broken cold, it may seem quite faultless. But if the same rod is broken at about 300° C., the broken surface is not smooth, but jagged, and the jags show the partitions between the flaws. Such flaws never occur in well-fused and cast-hard crucible steel, and very seldom in soft crucible steel, and then only in the upper half of the ingot. They are only occasionally of importance to the steel-buyer. Flaws are much more common in ingot steel, so that this kind of steel is much more liable to blue-shortness than cast steel.

In special cases, when a tool has to combine great hardness with great elasticity, cold hammering of the steel may be resorted to, which, as a rule, does not alter the shape, but simply increases the hardness and the elasticity.

This may be done either to untempered or to hardened and annealed steel. It goes without saying, however, that it can only be done with very thin steel, and even then with the greatest regularity. If the steel gets warmer than the hand by the hammering, the work must be stopped till it is cold again, or the heat would destroy the effect of the hammering. Watch-springs and fine chisels for splitting steel pens are cold hammered after tempering.

As one of the rarer examples, in which a change of shape as well as an increase in hardness and elasticity is sought by cold-hammering, we may mention the forging of scythe blades.

Unequal density in a steel or heavy hammering at too low a temperature causes brittleness, which can only be got rid of entirely by heating the steel red hot and then very slowly cooling it. But such steel, if quenched instead of being cooled slowly, is very liable to split. The same kind of brittleness is very largely caused in wire-drawing. The wire loses it, however, of its own accord to some extent if left to itself, when the particles displaced by the drawing return more or less to their original positions. This same thing happens after stretching and bending, and is called "secondary action."

This spontaneous recovery is not, however, sufficiently complete to permit the omission of annealing after wire-drawing, but it is important to be aware of it, as it makes a wire give different results to tests when fresh drawn than it would later on.

Wire-drawing and cold-hammering both increase the absolute strength and still more the elastic limit, at the same time lessening the extensibility. These effects are further increased if the wire is gently hardened and annealed, and the absolute strength of a good steel can be increased from 75 kilos. per square mm. in its forged state to 175–200 kilos., as is seen in the strings of musical instruments.

A steel heated red hot and then slowly cooled retains a permanent expansion, has its grain made coarser, and becomes softer. The tempering carbon becomes converted into carbide, or even, if the temperature is high and long maintained, into annealing carbon. The heating lowers the limit of elasticity and the absolute strength, and increases the extensibility.

The practical details of the heating will be considered in chapter v. Here we will merely remark that if it lasts too long, even if air is completely excluded and the temperature is not too high, it produces a coarsely crystalline fracture, and brings down the absolute strength and the elastic limit very much, and also gets rid of part of the increase in extensibility. These important changes also occur to some extent in hardened steel, and hence it is injurious to heat too much before tempering, forging, or rolling.

A special phenomenon is the shortness of iron and steel caused by pickling. In making wire, it is freed from oxide with dilute acid, and when it passes out of the acid it is brittle, but loses that property in time spontaneously. This effect depends upon the fact that forgable iron, when acted upon by acid with the consequent formation of hydrogen, occludes some of that gas, which, however, gradually escapes with time or on gentle heating.

Steel, like every other form of iron, rusts. This obvious property would not need to be mentioned here, were it not that certain steels, of different origin but with the same percentage of carbon, are differently susceptible to rust, as scythe manufacturers in particular can testify, who have used both shear and ingot steel. Silicon appears to have no influence on rusting, as ferro-silicon is not easily attacked by acids. Sulphur is said to increase the tendency to rust and phosphorus to lessen it, but both elements are rare in crucible steel. Ingot steel usually rusts more easily than shear steel, probably because it contains more manganese.

To close this section of the book we may make a few remarks on the nature of ingots, as this is connected with certain failures often observed in the manufacture of rods, which are noticed in our section on smithy tests.

An unworked ingot of crucible steel has a funnel-shaped depression at the top of it, lined with acicular crystals. It is not visible externally, as it is closed by a concave layer of steel. This layer contains openings which are very small, but are visible to the naked eye, and give the funnel communication with the outer air. This funnel is caused by the contraction of the steel on cooling. If the ingot has been cast from steel not sufficiently liquid, its top is flat, has a badly developed funnel, and contains flaws or bubbles in its upper part.[1] A still less liquid steel shows no funnel, and rises instead of sinking in the middle, and is pervaded with bubbles throughout.[2]

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[1] As in this case the temperature of the steel on casting is too low, and it flows too thickly to enable the contraction to be uniform throughout, we have formed, not a single big funnel, but a large number of small ones, which are probably occupied by a vacuum, and may be called contraction pores. In the casting of metals, it is a rule not to cast too hot, but this, however, depends upon the fact that we prefer to have a great many minute hollows than one big one. The result is called a close casting, although the numerous small hollows can be seen with a lens.

[2] Such flaws as these are not vacua, but contain gases, the expansion of which causes the convexity of the upper part of the ingot. Ingots of Bessemer or Martin steel do not usually show a distinct funnel, but, unless they have been compressed during cooling, flaws. The reason of this is the presence of entangled gas in these steels. Fused iron absorbs

Such ingots are different in hardness in different parts, and are treated as scrap. Hence the presence of the funnel, if it is not too big, shows that the steel has been properly fused and cast. If left when the ingot is rolled into a rod it appears as a crop end, which must be removed.

Bessemer and Siemens-Martin steels in the ingot have a coarsely crystalline structure, the axes of the crystals being perpendicular to the outer surface. Within the carbon-percentage limits of crucible steel, the crystallisation is more pronounced the softer the steel is. We have already seen that the coarsely crystalline structure becomes grainy when the ingot is rolled or forged. But the crystals are not destroyed by those processes, but only when the ingot has been brought to a bright red heat and allowed to cool in the air. This improves the strength and ductility of the steel, but not so much as forging or rolling does.

In a special investigation published by Tunner, the increase in strength and extensibility by reheating an original steel casting, and then allowing it to cool slowly, was from 30 to 60 per cent., while the increase in the same two properties obtained by the same reheating, followed, however, by hammering, was as much as 100 to 120 per cent.

It must be specially noticed that heating and cooling are indispensable for the destruction of the crystalline structure. The alteration of textures goes on during the cooling. An

gases, especially hydrogen, and more than it can retain on cooling, so that the bubble-formation is due to the escape of the excess gas. The expansion of this gas acts against the contraction of the metal on cooling. According to Dr. F. Müller, the funnel disappears with a small excess of gas amounting to about 2 per cent. The ingot then has a level top, and contains minute flaws throughout. The absorption of gases will naturally be greater the more facilities have been afforded for it in the smelting processes. The gaseous pressure in the furnace, and whether the furnace gases do or do not come into direct contact with the ore, are, of course, great factors in the result.

ingot heated up and then thrown at once into water shows no alteration of fracture. Herein lies a proof of what has been already said about the brittleness produced by uneven texture or with heavy hammering at a low temperature.

II. BEHAVIOUR OF STEEL DURING TEMPERING AND THE PROPERTIES OF TEMPERED STEEL.

It is well known that steel is hardened by being heated to a definite temperature and then suddenly cooled. The extreme degree of hardness is dead-hard or glass-hard. This does not, however, mean any definite degree of hardness, and is simply used to distinguish the steel from untempered steel, and that which has been annealed, or of which the temper has been drawn.

Under the hardening steel scales, *i.e.* the thin layers of smithy scale peel off by reason of contracting at a different rate from the metal. This occurs most completely when the steel is quenched in water, being probably helped by the development of steam between the scale and the metal. Chromium and tungsten steel do not scale off completely. If the iron is cooled in oil, fat, or mercury, the scale is merely loosened, so that it can be rubbed off, leaving a bright metallic surface, and a very fine-grained velvety grain appears on fracture.

Soft steel scales off less perfectly than hard, because, as we shall see, there is less contraction with soft than with hard steel.

The hardening power of the steel increases with its percentage of carbon, and reaches a maximum at about 2 per cent.

Steel begins to glow at a temperature between 500° and 600° C. The colour is then a dark brownish red. As the heat increases, the colour passes through a dark cherry and a bright red heat to a yellowish red at 1000° C. It becomes pure yellow at 1100–1200°, a dull white at 1200–1300°, and finally into a bright white at 1500–1600°.]

The hardening temperature of the steel, that at which the steel receives on quenching, the proper relationship between hardness and toughness lies somewhat deeper than the forging temperature, and is between a dark and a light cherry red, and, according to the carbon-percentage of the steel, varies from 800° to 900° C. The more carbon there is, the lower the hardening temperature must be taken.

When the hardening is effected by means of a proper temperature, the absolute strength and the elastic limit of the steel are raised, and its ductility lessened.

Hardened steel, then, shows brittleness on stretching, for the outer parts shrink on the inner in the cooling. This evokes a reaction pressure of the inside on the outside, which is greater in proportion as the change of temperature is greater on the outside as compared with the inside, *i.e.* the thicker the steel is. If the steel also differs in thickness in different places, this effect is further increased, for the places of least section cool first, and are unable to yield to the later contraction of the thicker parts.

The lower the elastic limit, the more the steel particles yield to the pressure, so that with soft steels there is very little danger of splitting. In hard steel, however, the reaction of the inside may cause the steel to split during hardening or shortly after. For similar reasons, rings, and especially hollow castings, are less liable to crack in hardening.

If the hardening temperature has been somewhat too high, its strength is diminished, it acquires a crystalline fracture, and is "overheated." We have already described this, and have remarked that it is usually wrongly called "burnt." If the steel is quenched when below a red heat, it becomes softer instead of harder. Hence in France the expression "negative hardness" is used. Practical use is sometimes made of this fact for working hard steels. In this case, however, the steel must not be heated above the point at which it appears somewhat reddish in the dark. At this temperature a piece of wood rubbed forcibly over the steel is superficially charred.

The steel, which has been expanded by the heating, cannot contract on sudden cooling as quickly as it loses its heat. Hence its volume remains permanently larger and its specific gravity less. This increase of volume is the greater the more carbon the steel contains, and the higher the temperature to which it was heated for hardening. The following table, compiled by Metcalfe and Langley, will illustrate this point, as it gives the specific gravity of the ingot, and also that of rolled steels quenched at different temperatures. A few small irregularities in the figures are explained by supposing that in those cases the heating was not quite uniform.

Percentage of Carbon.	Specific Gravity						
	of the Ingot.	of the rolled but unhardened Steel.	of Steel hardened at a dark red.	of Steel hardened at a full red heat.	of Steel hardened at a bright red heat.	of Steel hardened at a yellow heat.	of Steel hardened at nearly a white heat.
·529	7·841	7·844	7·831	7·826	7·823	7·814	7·818
·649	7·829	7·824	7·806	7·849	7·830	7·811	7·791
·841	7·824	7·829	7·812	7·808	7·780	7·784	7·789
·871	7·818	7·825	7·790	7·773	7·758	7·755	7·752
1·005	7·807	7·826	7·812	7·789	7·755	7·749	7·744
1·079	7·805	7·825	7·811	7·798	7·769	7·741	7·690

That the expansion per degree of temperature rises rapidly and in direct proportion to the percentage of carbon is the result of the greater resistance of hard steel to compression.

From the great alterability of steel by heat and cooling, it follows that steel during its cooling should always be laid on a completely dry surface of uniform temperature.

We can also gather from the above table that the increase in specific gravity caused by mechanical treatment (in this case rolling) is the greater the more carbon the steel contains, and the greater the carbon-percentage the more force is required to produce any given change in shape.

After the carbon-percentage and the hardening temperature the alteration of volume depends upon the rapidity of the cooling. The quicker this is, the greater is the change in volume. This increases with every fresh hardening, until at last the steel splits. To prevent this, when a tool has to be repeatedly heated, it is a rule to give it a preliminary heating, whereby the volume is brought back to its original amount.

The loss of specific gravity and the increase of volume in hardening is easily shown. For instance, a hardened wire will no longer pass through a hole which it would traverse before being hardened.

The extension remaining after hardness is only in thickness in round and square or closely allied forms, the length becoming smaller. In the manufacture of twist drills a shortening of 1 mm. in 500 mm. has been observed. A proof of this remarkable peculiarity is that a ring becomes of less diameter by hardening. If the extension took place in all directions the ring would have all its dimensions increased by hardening, including the internal diameter. Among other uses of this circumstance it is taken advantage of in connection with binding rings for machines for making cartridge cases. When these get stretched with use they are restored to their original size by hardening. This can be done as often as twenty times in succession, but it will be easily understood that no preliminary heating before the hardening must alter the volume of the mass. The narrowing of the steel rings gets greater with the carbon-percentage, *i.e.* with the hardening power of the steel.

According to Metcalfe and Langley, who investigated the effect of seven hardenings of a ring ¾ of an inch in internal diameter, the total contraction was for

·848	per cent.	carbon	·02752	inch.
·649	,,	,,	·00771	,,
·529	,,	,,	*nil.*	

The last ring behaved rather irregularly. It underwent a contraction on the first two hardenings, no change on the next, an expansion with each on the next three, and a contraction on the last hardening.

The shortening of steel on hardening may be very simply proved by heating a rod uniformly and then half immersing it in water in a horizontal position. Repetition of this treatment made a rod of tungsten steel 30 square mm. in section and 260 mm. long perceptibly bend, with the concave side underneath, the height of the arch being 18 mm. If a square or round bar is heated more on one side than the other, and then dipped vertically into water, the bar is warped and becomes concave on the side that had been most heated. While a round or square bar is shortened and thickened by hardening, a plate gets narrower, shorter, and thicker. This seems to argue that forces producing contraction in different directions are different, those tending to shorten the large dimensions being together greater than those tending to reduce the thickness. The result is a deformation as above explained, consisting of contraction and expansion, and which is made possible by the plastic condition of the heated steel, the net result being at the same time an increase of volume.

This increase of volume is the immediate cause of hardening-cracks. In refined steel they occur typically as transverse cracks. This steel is forged into a square bar, and then while still red hot is flung into water. The bars are sorted according to the fracture after hardening, according to the appearance of soft places, which show themselves by a paler and coarser structure. Hard refined steel of some size usually shows several fine transverse cracks after hardening. On the surfaces bounding the crack, the steel shows tempering colours in concentric rings, called roses, whence the steel is called rose steel. The formation of these transverse cracks is explained by the fact that the surface of the bar, and especially its edges, cool more during forging than the inside. Hence the edges shorten by hardening more than the hotter interior. Besides, on quenching they are much more quickly cooled than the inside. Hence when the inside does begin to shorten, its tendency to do so is resisted by the already rigid edges, so that the steel cracks transversely.

A hard-cast steel treated in the same way also receives transverse cracks, whence it follows that a tool must be allowed to cool after forging, and must have an entirely new heat to harden it. Forging and hardening must not be done in the same heat.

As fully hardened steel is too brittle for use, the temper must be drawn, *i.e.* the steel must be tempered by subsequent annealing. This second process consists in gently heating the steel, *i.e.* to a temperature varying according to circumstances from 220° to 330° C. The temperature is judged by the tempering colours which appear on the smooth surface. The tempering increases the ductility of the steel and diminishes its hardness the more the higher the tempering temperature. The loss of brittleness is greater than the loss of hardness. The tempering of hardened steel increases the specific gravity, and therefore lessens the volume. If the tempering colour was grey, the iron is left with a specific gravity nearly the same as it had in the unworked state.

C. Fromme has determined the specific gravity of a number of rods from 2·55 to 7 mm. thick in the unworked state and tempered at various temperatures. Taking the volume of the unhardened steel as unity, he has compiled the following table from the results of his experiments.

Condition of the Rod.	Vol. of Rod 7 mm. thick.	Vol. of Rod 4·2 mm. thick.	Vol. of Rod 2·65 mm. thick.	Vol. of Rod 2·55 mm. thick.
Unhardened . . .	1·00000	1·00000	1·00000	1·00000
Dead hard . . .	1·00772	1·01000	1·01285	1·01210
Tempered at yellow . .	1·00347	1·00495	1·00660	1·00620
,, ,, blue . .	1·00217	1·00425	1·00370	1·00205
,, ,, grey . .	0·99957	1·00060	1·00055	0·99930
,, ,, very high temperature	...	1·00175	1·00215	1·00340

These figures show that the thicker the rod the less it increases in volume on hardening. The table also shows us something we knew before, namely, that the high temperature and slow cooling to which the unhardened steel has been subjected lowers its specific gravity. Hence heating has an opposite action on hardened and on unhardened steel, because hardened steel is in the condition of being stretched to an extent artificially determined, and its particles tend to return to their natural arrangement. But after hardened steel has been tempered, repeated heats increase its volume and lessen its specific gravity.

As an illustration of the already described changes in strength which steel undergoes by different treatments in the furnace and in hardening, a table of tensile tests is given on page opposite. The rods broken were made of medium hard Kapfenberg crucible steel, and were all made from the same ingot. They were 150 mm. long and 15 mm. in diameter.

No. 2, compared with No. 1, shows the effect of the hardening heat, and No. 3 shows the difference produced by the hardening. No. 4, compared with No. 3, shows the effect of a preliminary heat before the hardening heat. No. 5, compared with No. 2, shows this effect is much greater with steel that has been hardened before.

No. of Rod.	Condition of Rod.	Kilos. per square mm.		Percentage of Original Length.	
		Elastic Limit.	Breaking Load.	Extension.	Contraction.
1	Unhardened forged bar .	42·63	90·81	4·17	1·4
2	Heated red hot and allowed to cool in the air	49·61	86·98	10·6	31·7
3	Hardened in oil . .	62·4	123·08	2·16	0·17
4	Heated red hot, cooled in wood ashes and then hardened in oil . .	48·47	108·03	3·3	6·3
5	Hardened in oil, and then heated red hot and allowed to cool in the air	35·49	82·3	13·3	41·0
6	Hardened in oil, then heated red hot and allowed to cool in the air, and then again hardened in oil . .	53·89	118·7	5·56	13·4
7	Hardened in oil, after overheating to a bright red	68·0	131·09	1·21	0·94
8	Heated bright red, allowed to cool in the air, and then hardened at a cherry red in oil .	54·96	112·8	3·9	2·8
9	Heated bright red, allowed to cool in the air, and then thrice brought to a dark cherry red and twice quenched in hot water, and left in the water after the third heating . .	52·8	100·08	8·4	6·2
10	Heated to a brown red and quenched in oil .	48·47	106·23	7·9	25·8

While No. 4 shows the result of the preliminary heat when compared with No. 3, No. 6, which is simply No. 5 rehardened,

	Unhardened.					Hardened in Oil.					Hardened in Water.				
	Elastic Limit.	Breaking Load for Original Section.	Difference.	Breaking Load for Fractured Section.	Percentage of Lengthening.	Elastic Limit.	Breaking Load for Original Section.	Difference.	Breaking Load for Fractured Section.	Percentage of Lengthening.	Elastic Limit.	Breaking Load for Original Section.	Difference.	Breaking Load for Fractured Section	Percentage of Lengthening.
	Kilos. per sq. mm.					Kilos. per sq. mm.					Kilos. per sq. mm.				
·15 per cent. Carbon—															
Rod 14 mm. diam., 100 mm. long	22·0	35·7	13·7	104·2	34·0	32·8	46·8	14·0	140·0	28·6	30·8	48·8	18·0	151·0	19·0
,, 20 ,, 200 ,,	18·2	36·4	18·2	160·0	32·3	31·4	46·8	15·4	138·0	23·7	33·1	50·4	17·3	157·0	18·25
·496 per cent. Carbon—															
Rod 14 mm. diam., 100 mm. long	26·2	48·4	22·2	73·4	24·0	44·6	70·5	25·9	139·0	12·0	45·4	78·5	33·1	80·9	2·5
,, 20 ,, 200 ,,	23·0	48·0	25·0	80·4	24·8	46·4	71·0	24·6	97·0	12·5	49·3	78·2	28·9	121·5	7·0
·709 per cent. Carbon—															
Rod 14 mm. diam., 100 mm. long	31·6	68·0	36·4	83·1	15·0	68·8	107·1	38·3	115·5	4·0	Broke in the hardening				
,, 20 ,, 200 ,,	30·8	68·2	37·4	76·5	10·0	67·8	97·0	29·2	100·3	1·25					
·875 per cent. Carbon—															
Rod 14 mm. diam., 100 mm. long	34·2	74·1	39·9	90·5	9·5	90·5	106·0	15·5	107·5	1·0	Broke in the hardening				
,, 20 ,, 200 ,,	32·8	73·2	40·4	78·5	8·4	77·8	104·6	26·8	106·7	0·8					
1·05 per cent. Carbon—															
Rod 14 mm. diam., 100 mm. long	39·2	86·1	46·9	98·5	4·5	Broke in the hardening									
,, 20 ,, 200 ,,	39·5	86·0	46·5	90·0	5·2	92·6	130·8	38·2	133·5	1·0	Broke in the hardening				

shows it still more clearly. No. 7 shows the influence of slight overheating, when compared with the normal effect shown by No. 3. While Nos. 3, 4, 5, and 6 were quenched at a cherry red, No. 7 was heated to a bright red heat, which for steel of its degree of hardness is overheating. No. 8 shows that the effect of this overheating can be cured by a subsequent hardening without overheating. As we shall see later, overheated steel can be regenerated by repeated quenching in hot water, which naturally does not harden so much as cold. No. 9 shows the effects of this. No. 10 shows that quenching at a brownish red, of which we have already spoken, increases the extensibility of the steel.

To show the influence which the carbon-percentage has on the strength during hardening, the table of tensile strains on the previous page will serve. The tests were carried out at Terre-noire with Martin steel.

The table shows that the breaking load of unhardened steel increases much faster with a rise in carbon than the elastic limit does, so that the difference between the two numbers, and which is given in the table, increases with the percentage of carbon. This influence of carbon-percentage remains in the hardened steel, but only up to about 0·8 per cent. of carbon. With steels containing more than this amount of carbon, especially when they have been much hardened, the influence is reversed, and the elastic limit rises faster than the tensile strength, so that the difference begins to lessen after increasing up to a certain point.

As the carbon increases the ductility lessens, and faster in hardened than in unhardened steel.

The table shows well how much more powerful the hardening action of water is than that of oil.

We close this chapter with another table showing the results of experiments at Terre-noire on unforged and flawless cast steel. As will be seen, the table shows that hardening and a subsequent heat have the same effect upon the cast steel as forging would have.

Rods 100 mm. long, 14 mm. in diameter, and containing 0·75 per cent. of Carbon.	Elastic Limit.	Breaking Load for Original Section.	Breaking Load for Fractured Section.	Lengthening.
	Kilos. per sq. mm.			Per cent.
Unhardened	30·5	64·2	67·2	3·5
Hardened in oil and tempered	35·8	74·2	82·5	14·3

CHAPTER III.

CLASSIFICATION OF STEEL ACCORDING TO USE.

GOOD steel is frequently considered synonymous with hard steel, the hardest being reckoned the best. This is wrong, for that steel is the best which is most suited to the particular use to be made of it. Very hard and fine grained steel is unsuitable for sledge-hammers, and a very good steel for springs is unfitted for turning in a lathe. Hence various uses necessitate a large amount of choice among hard steels, and a special tool requires steel of a particular degree of hardness, or—so far as the percentage of carbon is in general the chief factor in the hardness—a definite amount of that element, only very narrow limits of variation being allowable, if the steel is to answer its purpose properly.

Now it is above all things convenient, both for seller and buyer, for there to be in stock only one sort of steel in the usual sizes, a medium hard kind, which is to respond to all demands. But from what we have said it is clear that this convenience may sometimes be very dearly bought, for tools for which a harder steel would be better, as conducing to the keeping of an edge, in this case do not do their duty properly, while other tools, which ought to have been made with softer steel, will go wrong in use or in the hardening, through want of toughness.

Hence one of the most important conditions of the successful manufacture of steel articles is choosing steel of the right hardness.

The connection between the use of a steel and its carbon-percentage is shown in the following table, which shows the Kapfenberg steel-classification.

Quality.	Hardness Number.	Approximate Percentage of Carbon.	Use.	Proper Hardening Temperature.
Tungsten steel.	—	Tungsten, 3 per cent.	Excessively hard. For turning and planing tools, for working chilled cast iron, magnets, and hard iron generally.	Dark cherry red.
Extra quality tool steel.	I	1·5	Very hard. For turning and planing tools, callipers, tools for working millstones, engraving tools, and for unhardened shears for cutting hot plates.	Do.
,,	II	1·4		
,,	III	1·3		
,,	IV	1·2	Hard to medium and tough. For drills, punches, milling tools, rimers, shear-backs, file-cutters, chisels, stamps, and short shears for cutting cold plates, as well as stone-masons' tools.	Cherry red.
,,	V	1·1		
Ordinary tool steel.	1	1·4	Very hard. For turning and planing tools, and unhardened shears.	
,,	2	1·3		
,,	3	1·2	Hard. For drills for steel and hard stone callipers, punches, hammer heads, milling tools, knife-blades, etc.	Cherry red.
,,	4	1·1	Tough and medium hard. For stamps, cold chisels, shears for cold plates, polishing hammers and iron-drills.	Do.

Quality.	Hardness Number.	Approximate Percentage of Carbon.	Use.	Proper Hardening Temperature.
Ordinary tool steel.	5	0·9	Tough and weldable. For dies, swages, hearths and plugs, springs, borers for soft stone, large plate-shears, stamps and chisels for hot metal, joiners' chisels, tobacco knives, wood-working tools; also for covering fine tools.	Bright cherry red.
,,	6	0·75	Soft and easily welded. For sledge hammers, awls, surgical instruments, etc., and for steeling over large surfaces.	Do.

It is of course impossible in such a table to name more than a very small number of tools. In cases of doubt, it is best to trust the choice of the steel to the tool-maker, or, if that course is objected to, to err on the side of softness rather than on that of hardness, until trial has shown what is wanted.

A steel is better the more easily it hardens without splitting, and the tougher it is for any given degree of hardness. These properties are to some extent contradictory, for, as is well known, the elastic limit and the strength of naturally hard steel are, after a hardening process, very near together. But here, too, different grades of steel vary. As it is no use having a tool so hard that it gives way after being used for a short time, it is necessary, when the customer decides on choosing from among inferior steels, that some of the hardness should be given up for the sake of getting more toughness.

When it is a question of uniting in a tool the greatest hardness with the greatest possible toughness, or when the shape and size of a tool makes its hardening difficult, and in short, in all cases where the cost of labour on a tool greatly exceeds that of the material, a finer steel will always be preferred, in spite of its high price, to an inferior quality. We are also led to this conclusion by the fact that the better steel lasts very much longer, and also by the consideration that good tools increase the output of the workman. This is often overlooked, because it cannot easily be expressed in figures, and is not so evident as the wear of a tool. As the hardening becomes more and more difficult with the size of the tool, as we shall soon see, it is advisable in difficult cases to use different steels for different sizes of the same tool, a harder steel for a large size than for a small size. Besides the steels in the above table, there are steels for milling wheels, scythes, large files, and gun barrels, as well as magnet steel and a steel with a large percentage of tungsten used unhardened for turning tools.

CHAPTER IV.

Testing the Quality of Steel.

I. CHEMICAL ANALYSIS AND THE TESTING MACHINE.

AS steel contains varying amounts of other bodies than carbon, which are of influence on the quality of the steel, it would seem at first sight quite right to resort to chemical analysis to determine its quality. But at present our knowledge of the action of these bodies on one another and on the steel cannot be regarded as quite satisfactory, and has undergone great modification of late with the progress of quantitative analysis, together with very exact tests of quality. This modification was inaugurated by the publications of Professor Mzarek on the influence of silicon and manganese on iron. His researches were continued and completed by Akerman, Müller, and others.

While according to Karsten even the smallest quantity of silicon in iron is injurious, certain Sheffield steels have been proved to contain as much as 0·5 per cent. of silicon, together with considerable amounts of manganese. The effect of a fair amount of manganese in neutralising the injurious action of silicon makes the presence of that metal necessary for getting flawless ingots of silicon steel. This is now generally recognised, and the manufacturers are trying to determine what percentage of manganese is best for any particular kind of steel. Further researches are required to fix the amount of manganese according to the various amounts of carbon, silicon, phospherous, etc., in the steel, so as to get the best result, and to obtain a proper scientific estimation of the effects produced by the interaction of the various constituents of the steel among one another.

We see, then, that this part of the subject is as yet not fully understood, so that chemical analysis, indispensable as it is for controlling the work of the iron manufacturer, does not yet enable us, by itself, always to form a proper estimation of the quality of a steel, and that independently of the fact that the quality depends not on the chemical composition alone, but also on the molecular condition of the steel, that is to say, its homogeneity, which for its part depends on the way in which the steel has been worked, and the temperatures to which it has been subjected. The presence of absorbed gases is also of importance, and so far analysis has taken no note of them.

Tests of strength are of even less use than analysis in the case of tool steel, which has to be used in a hardened condition, and hence has to be considered in a totally different manner from construction steel. With this, the tensile strength is of great importance, for all such steels which have to be exposed to tensile strains. Several precautions must, however, be taken in judging from testing machine results, or wrong conclusions will be drawn. In comparing materials from different factories, it must be remembered that differences in the build of testing machines in the time during which the steel has been subject to the various loads, and the way in which the strain has increased, and especially in the shape and size of the test-bars, may cause considerable variations in the results of the tests.

It would seem so far that the form of the section of a rod has no effect on its strength, although Barba and Goedicke found that square bars were more extensible than round ones. The extension before fracture lessens as the sectional area diminishes. The length, too, of the test bar is of great influence on the extension, which is greatest just before the bar breaks, gradually increasing up to that point. The permanent set, compared with the original length as unity, therefore becomes a greater percentage the smaller the unit of length taken.

Unfortunately, tensile tests give no exact determination of the toughness, a very important property, for the lengthening and diminution of section only stand approximately in connection with the toughness. For example, a casting of close, flawless, crucible steel, always shows, *ceteris paribus*, a smaller extension than ingot steel, but can be shown by bending and hammer tests to be tougher than it. These two classes of test should therefore have the first place in testing steel to be used for construction, where it will be exposed to bending strain or shocks.

We have yet another important circumstance to consider, that is, the effect of the working temperatures on the strength.

If the steel is rolled or forged at a low temperature, it has a higher elastic limit and strength with less extensibility than if it came at a good red heat from hammer or rolls, and small differences in the heat show clearer and clearer effects the harder the steel is.

If, then, a construction steel is to be used as delivered, forging or rolling of the sample piece is to be avoided. But if the steel has to be further worked with the aid of heat, whereby its strength will become of a different nature, it is advisable to heat the test-rod before testing, so as to get at what the properties of the steel will be after the further working.

But in all cases the surest judgment of the steel is obtained by testing a finished tool or other object whenever that is permissible.

II. SMITHY TESTS.

A. *Testing Soft Steel* (·55 to ·8 per cent. carbon).

This includes the examination of steel readily forgable at a yellow heat, and such as is used for saw and scythe blades, springs, sledge hammers, milling wheels, etc. We shall describe the whole process in its practically approved form. It can be quickly done with sufficient accuracy. We shall add some remarks anent the fracture-appearances. We have already mentioned that the appearance of the fracture of unhardened steel shows rather its hardness than its quality, unless it reveals flaws or other obvious faults. The case is so far different with hardened steel that the fracture will show any want of uniformity in the hardness of different parts. The softer parts harden less than the harder parts, and so show, after hardening, a coarser grain than the latter. This is, however, of rare occurrence, and the fracture of hardened steel serves a much more important purpose, *i.e.*, to indicate the temperature at which the steel was hardened. But no verbal description of fracture-appearances will enable an unpractised person to judge from them with any approach to certainty. The only way to acquire the power of forming reliable conclusions is to constantly see and compare the fractures themselves.

A process mentioned by Schafhaütl, and lately described very thoroughly by Metcalfe, is highly to be recommended, with the modification here given to it, and enables us quickly to infer the influence of the hardening temperature on the grain, the toughness, and the hardness of the steel. It is as follows:—Take a rolled or forged piece of steel of any section (from 15 to 20 mm. square is a good size), and while it is cold or red hot make about nine notches round it at intervals of 15 mm. Then heat the first notched part in a clean forge fire so as to heat the rest of the iron as much as possible by conduction from the part in the fire, and as little as possible by the direct action of the fire itself. When the first piece is burnt (sparking) and the rest of the bar shows nearest the fire a dark brownish red, fading entirely away as the distance from the fire increases, the bar is plunged into water and carefully dried. Testing with the file shows that the directly heated piece is the hardest (see chap. ii.), and that the hardness diminishes from it up to a point usually near the middle of the rod, where the hardness again rises, and becomes nearly as great as that of the part which has been in the fire. This is the part of the steel which has been hardened at the proper temperature, and on receding from it we find the hardness again lessening till we come to a part of the bar which has not been hardened by the quenching at all. The first piece will show the coarsely crystalline white-shining fracture, characteristic of burnt steel. From it the fracture gets finer and finer till we get to the piece near the middle which has been hardened at the right temperature. The fracture of this is perfectly uniform, of a velvety lustre, and without any special grain.

If a steel of larger section is treated as above described, its edges and surfaces will show to a certain depth the same velvety dull lustre as just mentioned, but, farther in, the grain will be coarser, the hardening not having penetrated right through. This is just the most desirable degree of hardening. The steel has its full hardness on the surface, but possesses a softer and tougher inside, which guarantees the tool from breaking with proper use.

Returning to our original rod, we find the fractures, after we have passed the properly hardened section, becoming coarser and coarser, and the fractured surfaces rougher. This shows that differences of hardening temperature barely appreciable by the eye cause distinct differences in the grain and strength of the steel. If the hardening makes the grain coarser than in the unhardened steel, the hardened steel is overheated or burnt, brittle, and inclined to split. A similar but less injurious effect is produced if the steel is first overheated, and then allowed to cool to the proper hardening temperature.

From this test of Metcalfe's we also conclude that the best combination of hardness and toughness requires a hardening temperature kept within somewhat narrow limits, and that the results are less favourable beyond those limits. Hard and soft steel behave differently to the test, in so far as the proper hardening temperature for soft steel is rather higher than for hard steel, that is, a bright cherry red instead of a dark cherry red. Hence no part of the bar tested can be relied on as showing absolutely where exactly the right hardening temperature had prevailed.

As already said, the permanent set caused by hardening increases with the carbon-percentage and with the hardening temperature. In other words, the permanent set is the greater the more the steel was expanded by the heat before quenching, and there is a certain degree of extension corresponding to every perceptible alteration of the grain caused by the hardening. Hence when the rod is tested by Metcalfe's test the density of it diminishes regularly from the cold end to the burnt end. This extension, whereby, if the expression be allowable, the particles of the steel are disturbed from their natural positions, causes stresses which may easily result in a cracking of the steel. These stresses are worst when the steel has been unequally heated, not in different parts of its length, as in our test, but in different parts of its cross-section, so that parts under different stress lie side by side instead of end on. Such a steel must warp, and it is instructive to note that it very often cracks as well. This method of Metcalfe's for finding the right hardening temperature by noting the appearances of the various parts of the rod is very instructive, and will be of service even to skilled workmen.

We now proceed to special tests for quality, supposing throughout that we have to do with a bar 30 mm. square. If it shows no recent fracture, it is notched with a chisel near the end and a piece broken off. We can then see if we have a soft or a hard steel. In the former case the fracture will be rather coarse grained and grey with white-shining points. If the fracture shows no grain on the side of the bar opposite to the notch, and if it looks at the edges like that of a cold-cut iron, the steel is particularly soft, and approaches the lower limit of ·55 per cent. of carbon. But if the grain is uniform over the whole surface of the break, the hardness is greater. The surface of the bar must be quite free from cracks. We now cut off a piece of the bar from 120 to 150 mm. long, heat it to a bright red heat and forge it out under the hammer by about 15 mm. The piece is then again uniformly heated, but this time to a bright cherry red, and hardened in water. As soon as the steel is quite cold it is taken from the water and dried. The less the steel has scaled, the softer it is as a rule. Even now the steel must show no longitudinal or transverse cracks.

Next comes the file-test. Under this the edges always prove harder than the sides of the bar, because inevitably they have been heated more quickly, and to a higher temperature than the rest. Steel with from ·55 to ·65 per cent. of carbon is bitten somewhat by a good file, but not steel with a higher percentage of carbon.

The surfaces should be uniformly hard. Next, the hardened steel is broken with the hammer on the edge of an anvil. Soft steel stands several moderate blows, but hard steel breaks at the first stroke. This last test, which may appear very rough, is nevertheless of great practical value, if it is always conducted under the same circumstances, and especially with steels of the same dimension. With practice such a knowledge of the feel of the steel under the hand-hammer is obtained that steel can be sorted according to hardness and toughness with very great precision by this test. Steel which bends under blows before it breaks, is also easily attacked by the file, and contains less than ·55 per cent. of carbon.

To any one that possesses a steel whose hardness and suitability for some particular use is already known, the determination of the hardness of a test-rod is facilitated, for it is subjected to the same treatment as another rod made of the steel whose properties are known, and its properties are compared at every stage of the investigation. Before breaking off pieces of the two pieces of steel to be compared, the edges of both are beaten together at first gently and afterwards more strongly. The impression of the edges gives an idea of the difference in hardness. Finally, the structure of the steel is tested. This, if the hardening is properly done, must be uniform if the cross-section of the rod does not exceed 15 mm. square. The same section must show no lighter and cross grained (*i.e.* softer) parts, which not only detract from the keeping of an edge by the tool, but may also cause it to warp in the hardening.

An etching test will show the least want of uniformity in the steel. To carry this out a smooth polished surface of the steel is acted upon by a mixture of concentrated hydrochloric acid with one-third of its volume of fuming nitric acid for a few hours. The harder parts of the steel then appear darker and less attacked than the softer parts.

To test steel as to its forgability, it is hammered out thin at a yellow red heat. It must then not crack, and the edges must remain unbroken. At the same temperature, too, the steel must double and weld together, without showing the place where it was bent. If the steel does not stand this test it is red-short. This fault, if serious, shows itself by edge-cracks under ordinary forging, and such steels are usually carefully kept off the market.

If a piece of steel-plate, measuring about 30 × 3 mm. is split off a length of 50 to 60 mm. with a chisel, and the ends are worked together over the beak of an anvil, they must show no cracks at the place of bending, or the steel is red-short. This brittleness is absent at higher temperatures, and the sulphur which causes it does not affect the strength of the steel at low temperatures.

If the steel is subjected to the same test at or below a brown-red heat, and gets thereby longitudinal cracks in the fold, or splits between the two parts, the ingot contained flaws. This is the appearance which has been already described under unhardened steel (chap. ii). Flaws or bubbles in ingot steel can always be known by the production of longitudinal cracks in the rod forged from it. The surface-flaws, drawn out by the rolling, appear as these cracks. The test alluded to is thus unnecessary for any ordinary purpose if the surface is free from longitudinal cracks.

With regard to the absence of longitudinal cracks, rolled steel, especially if not rolled quite smooth, can be even less well judged of from its appearance than forged steel. Forging distorts the steel more than rolling, and reopens all the surface cracks as the surfaces are forcibly expanded under the blows of the hammer. This method of working, which may serve as a test of quality, not only in connection with longitudinal cracks, but as regards malleability, is avoided to a large extent when the steel is rolled. The deforming force then only acts in one direction, and is fairly uniformly distributed over the whole of the cross-section of the bar.

A rolled and very pure steel, when forged into smaller dimensions, may easily show longitudinal cracks.

Cold-shortness depends upon a crystalline structure of the iron mostly caused by the presence of phosphorus. The simplest way to test for it is by bending. The test-bar is bent cold, and the extent to which it will bend without beginning to break, as compared with another bar of the same hardness and of approved quality, will give a very good indication, provided that both bars are of the same size, and have both been made in the same way, and not one rolled and the other forged. The bending test must also be conducted in the same way with both.

It may here be remarked that the expensive manufacture of crucible steel can only be remunerative when carried out with good materials, so that such rough tests as cold- and red-shortness are rarely resorted to, and only under exceptional circumstances. At the same time, the bending test is always of interest, as it is a test of the toughness of a steel, as well as for cold-shortness. This test gains in value when executed with hardened and not with unhardened steel, as tool steel is never used unhardened, and because the alterations of strength produced by hardening may be very different even in steels which behave in the same way before hardening, according to their chemical composition. The bending test is confined, for hardened steel, to soft steels of small thickness, for which hardening in oil is intended.

We now proceed to the investigation of the weldability of a steel. This has evidently a special value only when the steel will have to be welded in making articles of it. Even medium and hard steels may be welded more or less successfully by skilled men with the aid of fluxes. But, nevertheless, we understand by a weldable steel, properly so called, a steel which can be welded easily to a reliable joint without any extraneous help than that of ordinary welding sand. In this sense, steel with over ·75 per cent. of carbon can only very rarely be reckoned among the weldable steels.

The welding test is carried out at a dull white heat as usual, and the welded steel is hardened at a bright red heat in water. It is then broken on the anvil at the weld. It must then show a smooth fracture and one without any want of uniformity. The harder steels can rarely be so perfectly welded as to show a perfectly healthy fracture at every part.

A low degree of weldability may be quite sufficient in certain cases if the welded place is subjected only to longitudinal strains, as in stone-boring machines, where the end of the boring rod is forked, and the wedge-shaped base of the boring tool is welded into the fork.

A very practical and delicate test for soft steel is to forge a plate of it, $\frac{1}{2}$ to $\frac{3}{4}$ mm. thick and 50 to 60 mm. wide. The edges must not split in the process. The plate is then oil-hardened and cut across. When the edges of the cut crumble for about 10 mm. from the edge of the plate, and then remain sharp and whole, the steel has about the hardness of No. 6 of the Kapfenberg catalogue, and contains about ·75 per cent. of carbon.

B. *Testing Medium and Hard Steels* (·8 *per cent. of carbon and upwards*).

The harder the steel is the lower its fusion point, and the more liable it is to overheating the smaller its extensibility and toughness, and the more easily it will crack on hardening. In a word, the harder it is the more difficult it is to work. This is the result, not only of the carbon in the steel, but of other bodies, which in no steel are entirely absent. As these substances which determine the character of the steel vary in quantity in steels of different origin, it follows that such steels have often to be treated in very different ways. This explains the often occurring fact that a steel known elsewhere as a good one, often appears at the first trial worthless in the hands of a stranger, though he may be a very highly skilled workman. In investigating the quality of an unknown steel, it is therefore impossible to pronounce from the outcome of a single test. The tests must be repeated under varying circumstances, *e.g.* with different hardening temperatures and liquids, and with different tempering colours. Then only will it become possible to form a reliable opinion of the quality of the steel.

The Metcalfe method of determining the right hardening temperature is specially to be recommended for medium and hard steels. Very hard steel will often split in the process, but no opinion of its quality can be formed from that circumstance.

When we are sure as to the best hardening temperature, which is generally at or near a dark cherry red, we test the fracture, so as to form an opinion of the hardness, and having satisfied ourselves of the proper condition of the surface, we carefully harden a piece 20 to 25 mm. square, and about 50 mm. long, in water at 20° C. A not very hard steel of good quality will take this hardening without cracking. This is a severe test, for it is practically impossible to get a square bar which is perfectly uniform and so to heat it that the edges do not get hotter than the rest of the steel. For these reasons a round rod of the same cross-section stands hardening better.

The steel is next tried with the file, which ought not to affect it.

If the steel has cracked in the hardening, it is broken and its fracture examined. An ununiform fracture in hard steel is very rarely due to ununiform quality, but generally results from irregular heating for hardening, because hard steel fuses at a lower temperature than soft, so that such a fault of manufacture as want of uniformity is very unlikely in a hard steel. If, however, the grain is unequal, and especially if it is not of that fineness that should be shown after hardening at the right temperature, the cause is probably in the way the steel has been treated, and the test must be repeated.

It may happen that the fracture shows in its middle a flaw which favours cracking on hardening. Such flaws may appear in that end of a rod which corresponds to the upper end of the ingot, and show that the funnel therein was not completely removed. If they occur in the middle of a bar, they usually indicate that the bar has been bruised there. This may take place when rather thin octagonal, round, or flat steel, which has been worked with too heavy a hammer after it has got too cool. These flaws escape notice with octagonal and round bars, as they do not reach the surface.

This occurrence, although troublesome, is rare, and it must not be laid to the account of the quality of the steel, with which it has no relation. A second or third piece from the same bar would in most cases show a totally different state of affairs. If we cannot gather the cause of cracking or hardening from the fracture, and if the steel proves, at least in the form of a square bar, not to stand hardening in water, the hardening is tried again with a round rod of the steel. Oil-hardening should also be tried, so as to find out what hardening liquid is best, whether for complicated or for simple articles made of the steel which have to be fully hardened, or whether the steel should be used for tools in which only the part near the cutting edge is hardened.

The difficulty of uniformly heating the steel increases with its dimensions, and if these exceed a certain limit the internal stresses produced by the hardening will crack the best steel. No steel manufacturer, for example, can give a full guarantee for large sizes of roller steel. When rollers are hardened, a considerable percentage of them always burst, a fact which explains the high prices charged for rollers of all kinds. In these prices, the risk of failure in the hardening counts for more than the labour bestowed on making them. This fact must be remembered when large masses of steel are being tested by being hardened.

To get an idea of the hardness and quality of a steel quickly, the best plan is to try a chisel made of it. Great demands are made on the resistance of a chisel to shocks, on its power of keeping an edge, and on its toughness. Hence a steel which has made a good chisel may be depended upon for the majority of cutting tools.

A good chisel should show no considerable wear even after long use on cast or wrought iron or soft steel, and should not become cracked or brittle. The usual tempering colour for such chisels is violet. If the chisel is spoilt in use, it should be hardened again at a purple red. If this does not remedy matters, the steel contains less than ·75 per cent. of carbon, and is not hard enough. If a violet or blue tempering colour answers, however, the carbon-percentage is ·8 to ·9. Most hand chisels require a steel of the qualities described under No. 5 of the Kapfenberg catalogue on p. 35.

If the sample chisel cracks in use, after hardening at a blue tempering colour, the steel is either too brittle or is too hard to be fit for the purpose, and contains more than ·9 per cent. of carbon. Such a steel tempered yellow must, in the form of a turning tool, keep a good edge when used on wrought iron, and must neither upset nor crack with prolonged use.

These tests are sufficient for forming a pretty safe judgment of the essential properties of a steel, and of its suitability for any given purpose. But in all cases, the safest of all tests is the behaviour in use of the finished tool, made with the steel the suitability of which for making that tool is in question.

CHAPTER V.

Hardening Steel.

I. THEORY OF THE HARDENING PROCESS.

FROM what has been already said with reference to the effect on the hardness of iron of various forms of carbon, and the change of one form into another, we may sum up the explanation of the internal changes on hardening briefly as follows:—By heating to the hardening temperature all the carbon becomes hardening carbon, and it is kept from changing back again by the sudden cooling. The other non-iron constituents of the steel are not able to make it harden, although some of them appear to help matters and to make the steel more resistant to the softening effect of the necessary after-tempering, probably by assisting the sudden change of temperature to keep the carbon as hardening carbon, and to prevent the formation of carbide. Among bodies which do this, manganese and chromium play a very predominant part, while tungsten and silicon seem to act the other way. The investigation of this question is difficult, and must not be looked upon as concluded. On quenching, the outer layers of the steel, which are cooled first, undergo strong contraction, whereby unequally strong reaction of the interior against the pressure of the outside is evoked. This compression helps the action of the rapid cooling, and expresses itself in hardened steel in its brittleness as well as in hardness.[1]

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[1] There is some analogy between the effect here with steel and the case of hardened glass, although there are wide differences between the molecular stresses in the two cases. Karmarsch says that hardened glass

The brittleness is greater the higher the elastic limit of the steel lies, and the greater is the difference between the effect of the temperature change on the outer part and that of the same change on the interior, *i.e.* the higher the hardening temperature and the colder the quenching bath.

By the tempering of the hardened steel, the hardness is lessened more or less according to the height and duration of the tempering temperature, for, according to those circumstances, more or less of the hardening carbon becomes carbide carbon. This change requires a lower temperature than that of carbide into hardening carbon. The tempering also lessens the stresses between the inside and the outside of the mass, and therefore also the brittleness. The following analyses of Le Debur show the proportions in different steels between hardening carbon and carbide carbon. All the figures denote percentages :—

	Graphite and Annealing Carbon.	Carbide Carbon.	Hardening Carbon.	Total.
Forged steel (tool steel) with ·11 per cent. silicon and ·11 per cent. manganese—				
1. Unhardened . . .	None	·71	·22	·93
2. Hardened in water .	None	·38	·65	1·03
3. Tempered after hardening, and from a blue (about 290° C.) . .	None	·67	·36	1·03

Analogous to that in steel-hardening is the course of events in making chilled cast iron, except that there we have graphite

cannot be cut with a diamond, and has a greater resistance to blows and changes of temperature than ordinary glass. The process of De la Bastie, the inventor of hardened glass, consists in heating the manufactured glass article to a dull red heat, and then plunging it into a bath previously heated to 200° to 300° C., where it is allowed to get quite cold. The bath may consist of many different substances. Oils, resins, fusible alloys, are all instead of carbide carbon. The rapid cooling resulting from the casting of the iron in metal moulds can make pig, which would separate out graphite on slow cooling, contain nearly all its carbon when cold as carbide and hardening carbon. Another table of Le Debur's shows the proportions between the different sorts of carbon in grey and white pig.

	Graphite and Annealing Carbon.	Hardening Carbon.	Carbide Carbon.	Total.	Silicon.	Manganese.	Phosphorus.	Iron.
White pig . . .	·19	·58	2·43	3.2	·83	·15	·88	94·94
Light grey charcoal iron .	2·4	·17	·73	3·3	1·02	·28	·59	94·81

All the above numbers are percentages.

Just lately a new theory of hardening has been broached, according to which the effect is not due to a change of form in the carbon, but to allotropic modification of the iron (according to Osmond, of alpha-iron into beta-iron). We must wait to see whether this theory can be established indisputably. I think for the present that circumstances, such as the increase of strength and elasticity got by heating and quenching iron very poor in carbon, or low carbon nickel, tungsten, and chrome steels, cannot be referred simply to metamorphoses of the carbon, and can be very satisfactorily explained by molecular stress, and to the alteration of texture always occurring after hardening.

used. Leger has shown that the process increases the specific gravity of the glass. But the specific gravity varies with different parts of the glass, as is shown by its behaviour to polarised light. The more uniform the hardening is the better, and the greater the increased resistance to external influences bestowed upon the glass. Any glass can be hardened, but some sorts harden better than others, especially glass of good composition which has been manufactured at a proper temperature.

II. FURNACES FOR HEATING IRON FOR HARDENING, AND THE MENSURATION OF HIGH TEMPERATURES.

Before we describe the operations of, and preliminary to, hardening, we must describe the furnaces briefly, for their construction and management have a large influence on the result. The simplest arrangement is the ordinary forge-fire, a walled-in hearth with a twyer from the side or from below. The fuel used should be charcoal, whenever possible, as it burns well with a low air-pressure in the blast. Hence the danger of exposing the steel to the direct action of the blast is less with charcoal than with coal or coke, which, being less combustible, require a stronger air-current. They also have a higher combustion temperature, which makes it more likely that the steel may be overheated or burnt. Another advantage of charcoal over coal or coke is that it forms no clinker and gives more carbonic acid. The fuel should be used in pieces of, as nearly as possible, uniform size, so that it should lie close over the twyer and keep the blast from impinging upon the steel. When the steel is put in, the fire must be at full heat; but the blast must be lowered for hardening purposes, especially with thick steel, and only raised again towards the end of the heat. If coal is used, it must be half burnt out when the steel is put in the fire, so that the pyrites in it may have been fully decomposed. If the sulphur gets into the steel, it will hinder the hardening and make soft places in the steel.

The forge-fire is very suitable when it is a question of heating single pieces, whether for forging on the anvil or for hardening. The form and size of the hearth must be suited to the piece to be forged, and must, if necessary, be lengthened and be provided with several twyers. In general, the forge-fire can be used for heating any piece of steel that it is powerful enough to heat uniformly. For tool-making on a large scale, and for heating large masses, other arrangements must be used.

A file-hardening stove may serve as the simplest type of the draught-furnaces with a chimney. They consist of a square or rectangular pit, 40 to 80 cm. wide, or more, and about 120 cm. high for medium-sized masses of steel. Of this height, about a third belongs to the ashpit, a third to the fire, and a third to the working space, so that the bearers on which the objects to be heated are laid by the tongs lie about 40 cm. above the horizontal fire-bars, and they are about 40 cm. above the bottom of the ashpit. In front of the door for inserting the steel is the working table. The steel-chamber is arched, and its top is perforated with a few openings to let the combustion gases pass to the chimney. These openings are regulated with dampers for the control of the temperature of the steel-chamber. The heating can be done with charcoal, coke, or a flame-giving fuel, and with or without a special blast from below. The use of charcoal or coke facilitates the maintenance of a uniform temperature in the steel-chamber. If no blast is used, a sufficiently strong chimney draught must be secured.

To protect the heated steel from the direct action of the flame, the bearers can be covered with a strong iron plate, somewhat narrower than the hearth, so as to allow the hot gases from the fire to get past it. If coal or coke is used, this plate is essential, and then both bearers and iron-plate, which wear out very fast, can be replaced with advantage by a brick arch, with openings to allow the passage of the gases, and plastered so as to make a flat floor to the steel-chamber. If long objects, such as shear-blades, have to be heated, the stove is made of corresponding shape without altering its area. With long stoves, the fire-door and that of the steel-chamber are put one in front and one at the side, so that firing does not interrupt attention to the steel being heated.

While in the forge-fire the steel is brought into direct contact with the fuel; it here only meets the combustion gases, and in a muffle-furnace it comes into contact with neither, and this gives the muffle a distinct advantage over the other two. The furnace just described can be made into a muffle-furnace by building a muffle in the steel-chamber, and of somewhat smaller size, so that the hot gases can heat it from every side. The muffle is made of iron, or, more commonly, of firebrick, and has a door in front of the same material, to keep the air from the inside as much as possible. There is a spyhole in the door closed by a slide or by a sheet of mica. Where coal-gas is available, a gas muffle-furnace should be used, which gives clean working and ready control.

We here mention reverberatory-furnaces for the sake of being complete, as, although used for forging steel, they are rarely employed in hardening, as different temperatures prevail at different parts of the hearth. The reverberatory-furnace consists of a hearth between the fire and the stack, on which the objects to be heated are placed. The heating is effected with flame-burning fuel, such as brown or ordinary coal. The grate is horizontal for large fuel and in steps for small fuel, and there may or may not be a blast from below it. If, for any local reasons, a reverberatory-furnace is used, the hearth must not be too long, and the flame must be reverberated upon the hearth as much as possible by making the roof so as to bend the flame downwards before it can get to the flue.

As regards the management of these various furnaces, they must all be fired one or several hours before they are used, according to their size, and heated till the walls are red hot, *i.e.* possess the temperature which it is desired to give to the steel. As the temperature radiated from the fuel is greater than that from the furnace walls, it is necessary to turn the steel frequently to prevent uneven heating or overheating. This danger even exists with the muffle-furnace, for the walls of the muffle are never quite uniformly heated, and if the muffle is exposed to a temperature considerably higher than the hardening temperature, the steel may become overheated.

Hence the steel is not laid directly on the floor of the muffle, but on an iron stand in it, so as to bring the steel as nearly as may be into the centre of the muffle. The larger the muffle is, the larger becomes that zone in the middle of it where the heat radiated from the different parts equalises itself, so that the temperature of the zone may be regarded as uniform throughout. Hence the size of the muffle should not be too restricted.

For the best judgment of the glow, semi-darkness is requisite. In full daylight the temperature will probably be taken lower, in complete darkness higher, than it really is. Hence the hardening shop should be always darkened, and even then the most skilled workmen are by no means absolutely protected from error.

It must be remembered that successful hardening means the use of a definite temperature, and the one best suited to the particular sort of steel in hand, and that, as the author's researches have shown, a difference of 30° C. one way or the other may make the result altogether unsatisfactory. We shall then cease to wonder at the numerous failures, and the great differences shown by tools all made from the same kind of steel. Now even the most highly skilled eye can hardly detect a difference of 60° C. in heated steel. Hence the importance of actually measuring the temperature instead of merely guessing it, if the result of the hardening is to be made certain instead of being more or less a matter of chance.

The instruments used for measuring high temperatures are called pyrometers. They are made on very various principles. One, for example, depends on the shrinkage of strongly heated clay, another on the unequal expansion of solids, another on the known fusion points of various alloys of platinum, gold, and silver, or on specific heat, as in the water-pyrometer, or on a knowledge of coefficients of expansion, as in the air-pyrometer. Only a few of them have turned out to be of practical utility.

Those which depend on differences between the expansibility of bodies, *e.g.* between brass and iron, or between carbon and iron, have the drawback that they require constant adjustment, because the expansions do not remain constant, and the index of the instrument will not return to zero when the pyrometer is cold. The use of alloys of various fusion points depends on the same principle as Seeger's cones, which are got by adding various amounts of quartz, lime, and potash to kaolin, which by itself is infusible in our furnaces. These cones show particular temperatures by softening the alloys by their fusion. These methods permit of only one determination of the highest temperature in each experiment.

The water-pyrometer of William Siemens has proved itself very good for temperatures not exceeding 900° C. It consists of a double walled copper vessel wrapped in a bad conductor of heat, into which is placed a known weight of water. Into this water, which contains a mercury thermometer, a weighed copper or platinum cylinder is thrown after having been heated long enough in the space of which the temperature is to be determined. As such a calorimeter is graduated empirically, the temperature wanted can be read off from a sliding rule from the rise in the temperature of the water. In addition, however, to the inaccuracy arising from the fact that the immersed metal must cool during its transference from the heated space to the water, the additional disadvantage that the temperature cannot be constantly watched, only the particular temperature existing at the moment the experiment is made can be ascertained, so that a great many separate experiments are necessary to arrive at changes in temperature.

For the uninterrupted indication of temperatures which are not too high, Siemens and Braun's electric-resistance pyrometer is very good. It depends on Siemens' idea of using the increase in the resistance of a platinum wire, which is about proportional to its absolute temperature, for measuring thermometric degrees. As the temperature can be read off at any moment and at any distance from the furnace, this pyrometer has been much used for controlling gas-furnaces, and in ascertaining the temperature of the blast of blast-furnaces.

A very accurate pyrometer, even at very high temperatures, is that of Le Chatelier, of which the principle is that of the thermoelectric pile. Each couple consists of a platinum element and one of an alloy of 90 per cent. platinum and 10 per cent. rhodium, and consists of two wires about 150 cm. long and fused together at one end. They are inserted into the space of which the temperature is to be measured, so that the points of junction are exposed to the temperature to be determined, while the free ends, connected by thick insulated copper wire with the indicator, are outside the furnace and at the same temperature, which is as low as possible. The two wires are kept apart in tubes of porcelain or firebrick, which are themselves guarded from breakage by tubes of iron or nickel. The current is passed through a galvanometer, and the apparatus is designed for uninterrupted observation of changes in temperature. The galvanometer has a solenoid instead of a needle, and in some forms of the apparatus the temperature can be read off at once in Centigrade degrees, *e.g.* in those of Heraus, and Keiser and Schmidt; while in others, such as that of the Ateliers Rechenkorff, the movement of the solenoid is read off by the movement of a spot of light reflected by a mirror on to a graduated horizontal rule at a particular distance from the galvanometer, such that every graduation of the scale corresponds to a change of temperature of 14·5° C. This difference of arrangement is immaterial, for in practice it is only a question of maintaining a heat which has been previously found to be the best, and this is then determined as to temperature by means of the pyrometer, so that with the same aid it can always be obtained again under the same circumstances.

Of the furnaces above described, the only one suitable for the use of Le Chatelier's pyrometer is the muffle-furnace. The tube containing the thermoelectric couple is put into the side of the muffle from without through an opening about half-way between the door and the back of the muffle. The parts of the pyrometer outside the muffle must be protected from heat by a large and thick firebrick tube. The pyrometer reaches about 10 cm. into the muffle, and in such a position that the moving of the steel in the muffle is not impeded. If, however, on account of this the temperature is not shown exactly as it is in the middle of the muffle where the steel lies, that makes no difference, because the small differences between the temperatures of different parts of the muffle are fairly constant one as compared with another.

When once the proper pyrometer indication for the hardening temperature has been ascertained, the muffle is heated to just that temperature and no higher, and then kept at this temperature by means of continual observation of the pyrometer-readings. It has been already stated that it is easier to ensure this steadiness of temperature with charcoal or coke than with fuel which burns with a flame. Great attention to the dampers is required to keep the pyrometer indications constant. If the muffle is not allowed to get above the proper hardening temperature, any overheating of the steel is impossible, even if it stays longer in the muffle than necessary, although that should be avoided if possible. The watch permits of the proper stay in the muffle of the steel, according to its size, to be easily fixed. We have thus now in the perfection reached with the pyrometer a means, at least with the muffle-furnace, of escaping from the difficulty of hitting upon the right hardening temperature, and the universal use of the pyrometer for the purpose cannot be too earnestly recommended.

III. OPERATIONS BEFORE AND DURING HARDENING.

A. *The Preliminary and the Hardening Heat.*

The increase of volume in hardening, which increases with the hardening temperature, causes stresses, which may ultimately result in a cracking of the steel. From the relationship between hardening temperature and increase of volume we have the rule, that the hardening temperature must be as low as possible, otherwise the steel will be the less able to resist the increased stresses resulting from the increase of volume. If, moreover, the extension of heating was not at all uniform, neither can the increase of volume after hardening be uniform, and the steel will warp. But if a steel is only to be partly hardened, it will endure the alteration in the volume and texture of its parts the more the differences between them are gradual. Hence neither the heating nor the quenching of the steel must be considered as within sharp limits. Herein lie the essential reasons for the precautions to be observed in hardening. Before we go into the process in detail, we will discuss a cause of failure which may cause the steel to warp or crack in the hardening. Forged or rolled tool steel in the state in which it comes upon the market, is usually brittle, from having been worked when nearly cold, and the further shaping in making the tool from it causes internal stresses through unequal forging, and also differences in the texture of different parts of the steel. The use of chisels, punches, etc., in shaping should be avoided as much as possible, but it is impossible to prevent inequalities being produced in the steel by the forging. It is therefore necessary in the case of tools of at all complicated shape, and with very varying cross-sections at different points, to remove these inequalities by an annealing before the hardening. This is done by heating to a dull red heat, and then allowing the steel to cool slowly in the air, or, if it is very thin or has very projecting edges, buried in dry charcoal powder.

With articles of which the size and shape favours warping or cracking, such as rimers, twist drills, milling cutters, etc., the steel after rough turning to shape is laid in an iron box and closely packed with clean and rust-free iron turnings. The box is then made airtight with loam and heated in a coal-fire till the interior of it is at a dull red heat. This may be ascertained by having a bar passing right through the box, which can be removed and replaced. According to the size of the piece being annealed, and the closeness with which it is packed, the heating may take two, four, or more hours. The box is then taken from the fire and allowed to cool gradually in the air or buried in dry sand or wood ashes. This operation is very important, and is more effectual against warping and cracking during hardening than quenching in bad conductors of heat is. Care must, of course, be taken that the steel is not overheated during the annealing. If it is heated in the open, it may become perished. The temperature must never exceed a dull red heat, and must not be maintained longer than is necessary to heat the whole mass of the steel uniformly. Air should be excluded during the heating as far as possible, and the cooling must be made as gradual as it can be. The slower the cooling the better will the differences of stress in the steel be done away with. It need hardly be said that any furnace which will serve to heat steel for hardening will do for this purpose also.

It is, however, important to observe that even the most careful annealing will not always completely put right a steel which has been carelessly or ignorantly treated. If, for example, the piece to be used for making the tool has been broken off cold from the bar instead of having been cut off warm, the very act of breaking it off may produce fine cracks, particularly in hard and thick steel. In all cases, too, a bar must be chosen as thick as the thickest part of the tool, so that the steel need not be bulged. When the steel has been shaped and annealed, it is heated for hardening. We have first to deal with tools that have to be wholly hardened, *i.e.* which have to be heated all through.

We have already discussed the conditions of success in the last chapter and at the beginning of the present one, so that very little remains to be said. There is, however, a special difficulty in uniformly heating objects having prominent edges and corners, unless a muffle-furnace with pyrometer control is used. If this is not available, such steel must be slowly heated to a brown red in a space which is not at a higher temperature, and must be then first put into the hardening fire. If this is a forge-fire, and the form of the tool permits, the thinner parts of the steel should come into the fire first, and the tool must be turned about and its colour carefully watched. It should, too, not be plunged at once into the hardening liquid when it leaves the fire, but should cool a little in the air first. The thinner parts of the steel, which were unavoidably heated quicker than the rest, cool quicker also during this exposure, so that the tool soon assumes a uniform red colour, and should then be quenched at once. Another plan is to take the object from the fire repeatedly and cool the thinner parts by just dipping them for a second in water.

In heating thin objects, a gas-pipe can be put in the fire and heated to a uniform red heat, and the steel can then be heated by placing it inside the pipe, in which it is turned round and round. For pieces of very irregular section, it is often very advisable to heat them in fused lead, free from sulphur, brought to a red heat in a cast-iron crucible. If the temperature of this metallic bath is kept as accurately as possible at the hardening temperature, which can only be done with a hydrometer-control, no danger of heating the thinnest parts exists, even if they are left in the bath longer than is necessary. This method gives very uniform heating, and avoids all formation of scale. To prevent the lead from adhering to the steel, the latter is smeared with linseed oil, and then sprinkled with soot and dried. As the molten lead gives off poisonous fumes, it must be kept under a chimney with a good draught.

It is most important, if only part of the steel is heated, that there should not be any sharp boundary between the heated part and the rest. If this precaution is neglected the steel will probably crack at the boundary. With a forge-fire it is easy to make the passage from the hot part of the steel to the rest gradual. For the same purpose the steel must be given an up-and-down movement in the lead bath.

If it is a question of hardening special parts of a piece of steel only, and its shape does not admit of these parts alone being heated, the parts not to be hardened are protected from the fire by a sufficiently thick layer of loam. For example, the trunnions of small cylinders for rolling gold and silver are plastered with loam and cowhair to protect them in the hardening fire. The cowhair prevents the loam from falling off, and as a further precaution it is wrapped outside with wire. The coating must extend a few millemetres beyond the trunnion.

It follows from what has been said on the heating of objects of irregular section, that the duration of the heating is a matter of importance. If it is done too quickly, the thinner parts will reach the hardening temperature before the rest, so that it is impossible to secure uniformity of temperature throughout the steel. If, on the other hand, the heating is too slow, too much scale must almost of necessity be formed, and this is burnt into the steel so firmly that it remains in whole or in part during the hardening, and its presence prevents the hardening effect. One way of preventing the formation of scale is to strew the steel with dry common salt, which fuses in the fire and forms a crust. Soft soap or ferrocyanide of potassium may be used instead of salt. Sometimes, also, the steel is heated in an iron box closely packed with charcoal powder or the dust of

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carbonised leather, but the box is not closely shut. This is very often done with engraved steel, such as dies for coins and plates for printing banknotes, or with large masses which must be exposed for a proportionately long time to a higher temperature to heat them uniformly all through.

It is also recommended for preventing oxidation and the formation of scale that the steel should be dipped, after a preliminary warming, in a paste made by boiling together gelatine, charcoal powder, and ferrocyanide of potassium, the weight of the charcoal being double that of the ferrocyanide. The steel is dried after immersion in this paste, and again dipped and dried, and so on till it has received a coating two or three millimetres thick. It is then heated to the hardening temperature.

It must be, however, expressly mentioned that burnt leather, and still more potassium ferrocyanide, add carbon to the surface of the steel, and thereby make the steel harder and more brittle, which is disadvantageous with a steel which is already hard enough for its destined purpose. In the choice of a grade of steel this circumstance must be borne in mind when it is a question of making tools which might be injured thereby. The carbonising action of the wood-charcoal is insignificant, as the time is so short. In our chapter on surface-hardening we shall consider this matter in more detail.

The already mentioned effect of scale is of special importance when annealed steel is hardened without any further preliminary preparation, as more scale must be formed in the hardening process unless air is fully excluded.

In connection with the duration of the heat we have also the rule to heat up as quickly as is consistent with uniform heating.

B. *Quenching and Cooling.*

These processes must be as uniform and as rapid as possible. Uniformity is indispensable, for the steel, expanded with the heat, contracts somewhat with the sudden cooling, and will warp unless it is all cooled at once. The article to be hardened must be plunged into the middle of the bath and not near one of the sides. With the exception of small things, which are hardened together in large numbers, such as sewing needles, objects must not be thrown into the cooling liquid, not only because they have to be put into a particular position according to their shape, but because their surfaces which lie on the bottom of the cooling reservoir, do not come into contact with the liquid.

If a bar, square or round, or nearly so, is dipped in the hardening liquid horizontally, it warps. Hence it must be put in vertically and not too quickly. They are sometimes worked spirally in the liquid to bring them into contact with fresh parts of it. The slow immersion is designed to make the cooling take place chiefly at the surface of the liquid, so that the steam produced may readily escape.

Thin objects are plunged into the liquid partly horizontally and partly vertical, with their narrow side outwards, and unequally thick articles are dipped vertically. It is necessary that the thicker parts should be cooled first, to prevent the effect of their contraction on the thin parts. If this cannot be carried out in practice, the thinner parts should be protected by a very thin coating of loam. As a preventive to cracking and warping, Karmarsch recommends that the piece to be hardened should be pressed if it is a plate, and stretched if it is a ring.

To get a perfectly uniform hardening, the temperature of the hardening fluid must not be much altered by the quenching, so that plenty of it must be used. In long hollow pieces of steel, which have to be hardened inside, the hardening liquid must be kept in motion. This can be done by passing a stream of water through the cavity under pressure, or by having a vertical tube supplied with water under pressure, or by having a rose at its upper end. The heated steel is then placed so that the numerous fine streams of water coming from the rose cool its interior. The size of the tube must be such as to allow plenty of room between it and the inside of the hollow steel for the water to escape. This arrangement gives a very uniform heating, as every part of the hollow body continually receives fresh supplies of water.

Partially heated objects must be dipped into the cooling liquid so as just to immerse that part which has a brown-red glow. If for any reason an object is heated in parts not to be hardened, it must be moved up and down in the cooling liquid. If this is not done, it is apt to break at the water-line. The rate at which the cooling takes place depends upon the conducting power, specific gravity, boiling point, and latest heat of the liquid used. This will be considered in detail in describing the various hardening liquids. The temperature of the cooling liquids is another factor. If steel is quenched in hot water, it will be noticed that the glow does not disappear so quickly as in cold water, and the same thing happens when oils or quicksilver are used for the hardening liquid. The cause is that the development of steam is favoured by the water being hot. The opinion is thus justified that the colder the water used, the harder the steel is made. It is true that fused metals, such as lead, tin, or even zinc, which gives a bath at about 400° C., can be used for hardening, but this is only done in special cases. We know that no hardening takes place if the steel is quenched at a brown-red heat, so that by the time the steel has cooled down to that temperature, the hardening is over. The further cooling does not contribute to the hardening, but is necessary for preventing the hardening produced in the first stage of the cooling from being lost again, which would take place to a greater or less extent if the further cooling was slow. Hence the hardening may be divided into a hardening cooling and a fixing cooling, the latter started when the heat has come down from a cherry red to a brown red. Thin steel wire, for example, is hardened if dipped for a moment in molten zinc, but loses the hardness again if allowed to stop in the bath. The hardness will depend upon the rapidity with which the steel cools in the air after removal from the zinc, *i.e.* the thicker it is, and the longer, therefore, it retains its heat in the air, the more annealed and the softer it will be by the time it is quite cold. It follows that to get the greatest possible hardness the cooling must be as rapid as it can be made, so that the temperature of the cooling liquid should be low. But as the harder the steel is, the more brittle and likely to crack during the hardening it becomes, the use of very rapid cooling is confined to special cases to be considered later. Steel which is glass-hard is very seldom used in practice. It is nearly always tempered at the cost of some of its hardness, to prevent it from being too brittle. As a rule, the tempering acts from without inwards, and the tempering colour will show on the surface before the interior of the mass possesses the corresponding temperature. In this case the tool becomes softer and tougher on the surface than in the interior of the steel. This is the reverse of what should be the case, as the original toughness of the steel should be preserved in the interior as much as possible, and in any case it should not be less inside than on the surface. In this connection we have to note tempering from within and broken hardening. In both methods the tempering is combined directly with the hardening. The former consists of dipping the steel into the hardening liquid without letting it cool completely in it. It is usually removed while still hot enough to show tempering colours, and as soon as the right one appears it is fixed by sudden cooling in water. If a large number of tools have to be hardened like this, a skilled man soon gets to be able to judge the proper time for dipping, so that the internal heat of the steel still serves to produce the colour desired so accurately, that no fixing of it in water is needed.

It is a universal experience that large masses of steel are apt to crack if taken from the hardening liquid before they are quite cold. The cause is easily explained. Let us suppose a large cubical mass of steel which has been so long in the liquid as to have a hot spheroidally bounded interior. If it is then removed from the water the heat from the interior passes to the surface and causes stresses of expansion. As the cold edges and corners are set, this causes cracking. Hence this method of tempering from within can only be adopted for small objects, which are so shaped that all parts of the surface are reached at the same time by the heat coming from the still heated interior. The second method, called broken hardening by Jarolimek, consists in cooling the steel quickly down to 400° C., and then completing the cooling slowly. This is effected by dipping the steel into fused lead or tin, the temperature of which is below 400°. The fused metal being a good conductor, the steel is rapidly brought to the temperature of the bath and so hardened. If the hardness is not to be all taken out of the steel, it must be removed from the bath at the proper moment and quickly cooled. The essential difference between this method and the other is that the quenching liquid has a different temperature in the two cases. If in the broken hardening the steel is left too long in the hardening liquid, it becomes entirely softened again, but under the same circumstances with the other method it becomes glass-hard. In the interrupted hardening a tempering action is exerted both from within and from without, while in the other method, the only factor in the case is the temperature of the steel itself. In my own experiments in this matter, quenching steel at a bright red heat in fused lead gave good results for wire and saws for cutting metal. Thicker steel, however, such as half-inch drills, etc., could not be made hard enough. They received only a weak spring-hardening insufficient for cutting tools, even when they were cooled in water on removal from the lead.

In so far as in broken hardening the quenching is rapid, but the after-cooling slow, the following method has some affinity with it. It consists in quenching in a good conductor of heat, and completing the cooling in a bad one. It differs from broken hardening chiefly in necessitating a subsequent tempering. The heated steel is quenched in water, and as soon as its surface becomes dark is transferred to oil. At Terre-noire, for example, the cast-steel shells are heated red hot, and then dipped conical end first in water till the surface glow has disappeared, and then left to cool in oil. This method is also good for tools whether they are to be hardened all over or only partially, in cases where all oil-hardening would not give the necessary hardness, and where water-hardening would probably crack the steel.

IV. OPERATIONS AFTER HARDENING.

A. *Tempering.*

We have stated with regard to tempering from within that an unusual amount of skill was required for doing it successfully. As, however, the test of the tempering colour is available with it so as to show the heat, it is easier to get good results with it than when the tempering is avoided by broken hardening. Hence the practice is to give the steel the full hardness by letting it cool completely in the hardening liquid, and then temper by a subsequent gentle heating. Certain objects in which very great hardness and little toughness are needed, such as files, are not tempered.

When the hardened object has been removed from the hardening liquid and dried, it is tested accurately with eye and file. If the right hardness has been got, the tempering should not be omitted without good cause, and should follow quickly after the hardening before anything else is done. The stresses produced by hardness may otherwise eventually result in the cracking of the steel, which danger is averted if the steel is tempered.

The tempering heating should be slow. The slower it is the more the heat is distributed uniformly through the steel, and the tougher it becomes. As soon as the desired tempering colour appears, it is fixed by immediate immersion in water. If it is allowed to cool slowly, the next following colour will appear, and the steel will turn out softer than was intended. A steel which has cooled in the air is always somewhat harder and more brittle, other things being equal, than one which has been cooled in water in tempering. As the tempering colours appear far below a red heat, no hardening accompanies the plunging of the steel into water. A polished steel smeared with grease shows no tempering colours, a proof that they are due to oxidation of the surface.

If it is correct that the influence of those bodies in the steel which partly increase and partly lessen its capacity for hardening depends upon their effect in the combining of the iron and the carbon, steel must lose more or less of its hardness, when tempered under the same circumstances, in proportion to the amount of those bodies which it contains. Judgment must, however, be suspended until sufficient data has been accumulated by experiments on cast steels of varying chemical composition, but of the same glass-hardness, by means of tensile tests, and the durability of the tools made with them. The following tables give the temperatures corresponding to the various tempering colours and the classes of tools for which they are respectively suitable.

Group I.

Pale yellow (220° to 230° C.)	Turning tools and plane irons for hard steel and cast iron (O–II. 1). Gravers for steel and hard stone (II. 111). Polishing

	hammers IV. 4). Dies and stamps (IV. V. 5) and mill steps.
Dark yellow (240° C.)	Turning tools and planes (I.–III. 1, 2) and borers (IV. 3) for steel and cast iron, rimers and milling tools for metal (IV., V. 3). Saws for cutting metal, sledge-hammers (4–6), mill picks, crown hammers (II.–IV.), cutting punches (V. 5) and
Yellowish brown (255° C.)	Screw-dies (IV., V. 4), trunnions (5, 6); small hand hammers (V. 3, 4) and callipers.

GROUP II.

Brownish red (265° C.)	Twist drills and spiral borers (IV., V. 4). Bone-cutting tools and punches for leather (V. 5) and razors (V. 3).
Purple red (275° C.)	Turning, boring, and planing tools. Shears for iron and brass (V. 4, 5). Chisels for wood engravers (V. 5), punches for cold metal (IV., V. 3, 4), and file-cutters' chisels.
Violet (285° C.)	Hand chisels for steel (5), hammers, shaping knives for woodwork and milling tools for hard wood. Chisels and borers for stone (IV. 2 and V. 2–5), marking hammers for steel (V. 3), chisels for cold metal and crown borers (V. 4). Punches for hot metal, shear blades (V. 4, 5), and paper knives, penknives (V. 4), centre punches (IV. 3, V. 4), wood borers (5, 6), tobacco knives (IV., V. 4, 5).

GROUP III.

The colours of Group III. are generally given as pale blue, cornflower blue, blackish blue, and grey. This depends on a delusion, as may be easily proved by smoothing a thin steel with the file, and then laying it on a piece of red-hot iron till the grey tempering colour appears. As a matter of fact, pale blue constitutes the transaction to the grey tempering colour.

Cornflower colour (295° C.)	Hand chisels for cast iron, chisels for hot metals, plane irons for wood and matches, wood borers, wood choppers, axes, fine saws for wood, rapiers (6), daggers (V. 5), shaping and milling tools for softening wood (V. 5, 6), table-knives, setting punches for boiler smiths (V. 5), scythes.
Pale blue (315° C.)	Hand chisels for wrought iron (V. 4, 5), wood saws (5, 6), surgical implements (V. 6), shoemakers' awls (6), springs.
Sea green (330° C.)	The so-called grey Kärntner scythes.

As regards the connection between the temperatures and the colours, that can be shown by heating separate bars to temperatures from 220° to 230° C., and then notching with a sharp chisel and breaking off the piece. The fractured surface will show the tempering colour corresponding to the temperature. Every temperature has its corresponding colour, which appears at once when the steel is broken without going through the changes of colour corresponding to different temperatures. Nevertheless, the tempering colours are not entirely dependent on temperature, as the duration of any given temperature affects the colour, and they may all be made to appear in succession without changing the temperature. In one experiment at 230° C., a pale yellow appeared in 15 minutes, became red 30 minutes later, and 45 minutes later still began to pass into blue. In an hour the surface was a light blue, so that the whole colour scale was traversed in an hour at a steady temperature of 230° C. Further experiments showed that when one and the same kind of steel is tempered quickly at a high temperature or slowly at a low one to the same colour, the final hardness is almost exactly the same in each case, although very careful examination shows that the latter steel was slightly the harder.

Hence the height of the temperature and its duration may act oppositely on the steel, both as regards the colour produced and on the final hardness of the tool. Although in practice a tempering temperature below 220° C. is not employed as a rule, it must be noted if hardened steel is exposed for a long time to 100° it undergoes a perceptible loss of hardness. On the other hand, hardened steel may be heated considerably above the temperature generally considered to correspond to grey, without entirely removing the effect of the previous hardening. The spiral springs of railway buffers, if made of hard steel, are heated for tempering till they look brownish red in the dark.

As to the choice of a grade of hardness for any given purpose, opinions differ greatly, and this causes different tempering colours to be adopted by different people. As these cannot be regarded as absolute, I have put to the names of the various tools the hardness symbol denoting the steel in the catalogue on pp. 34, 35, which is connected with the particular tempering colour.

The limits of choice which can be allowed as regards the grade of steel and the tempering colour are narrow. For a given tool there is not much latitude possible. Hence good and universally applicable rules can be laid down, even if they cannot be in such a precise form as to be absolutely rigorous.

For the sake of clearness I have divided the tempering colours into three groups, dark yellow, violet, and cornflower blue, as representing the colours most commonly used.

In Group I. the hardness and brittleness of the glass-hard steel is least mitigated, and in Group III. the most. Hence it follows that in general the tempering colours of Group I. are specially suitable for tools requiring a fine hard cutting edge, but which are not subject to blows, but work under a fairly constant force. Those of Group II. are best for cutting tools worked by means of blows, or which have to resist powerful twisting action. Those of Group III. are best for tools where toughness is a desideratum, and it is not necessary to have a particularly sharp edge, *e.g.* scythes and saws which have to be set with a hammer.

If we keep the characteristic differences of these three groups in view, the choice of a tempering colour for objects not here specially mentioned will not be difficult.

Too little heating or tempering of a tool may cause it to break in use. Thus for any special purpose requiring a hard steel it is best to pick a less hard steel for making the tool, and then to give the necessary hardness with a slight tempering. This is better than picking too hard a steel and tempering it more. In choosing between the tempering colours of the same group, we are guided by the hardness of the material and the greater or less liability to break indicated by the form of the tool. When a steel has passed through the above given scale of colour, and is further heated, they appear a second time in the same order, but succeed each other more quickly, till they disappear as the steel begins to glow.

In the tempering operation, as already said, the heating should be as slow as possible, and as uniform as possible, if we are to get a tool of uniformly strong steel. For this purpose we should use a clean (not smoky) and not too luminous a flame of uniform size, the light from which will not interfere with the observation of the tempering colour. These conditions are best fulfilled by a good spirit flame. For large objects, however, the use of such a flame is too expensive, and must be replaced by a charcoal fire, or a brazier covered with a perforated iron plate to lay the steel on, as soon as the glowing coals have heated it uniformly. Instead of this plate, some use an iron muffle, and others a sand bath. The sand is heated with constant stirring, and then smoothed down and the steel laid on it. A lead bath is also sometimes resorted to. The lead is kept as nearly as possible at its fusion temperature in a cast-iron box, not too deep. An iron plate to receive the pieces of steel swims on the molten lead.

In many cases it is a very good plan to heat with pieces of red-hot iron corresponding in shape and size to the piece of steel to be tempered. The steel is laid on the hot iron and frequently turned so as to get it uniformly heated.

A special type of tempering process is adopted for gunlock springs, saw blades, self-coiling measuring rods, etc. The steel is gently warmed, smeared with oil or tallow, and then heated uniformly till the grease begins to burn. If the steel is very thin, the grease must not be allowed to burn out, or all the temper would be drawn, and the hardening completely undone. With objects of large or irregular thickness, the burning is repeated, either all over or in places, so as to get as far as possible a uniform temper. Especially with the gun springs, a somewhat different process is used according to the hardness of the steel and the strength of the spring. After hardening the springs in oil or water, they are burnt for 2 to 2½ minutes and then cooled in the air or in oil. Another way of drawing the temper is to put the springs in an iron trough and cover them with cold oil or tallow, and heat the whole gently. In this way we get great uniformity of temperature, and the thin parts do not suffer as when the grease is burnt. The temperature of the oil should be about 290° C., to correspond with the blue tempering colour. This temperature may be known by the oil readily taking fire with a match. As the oil will catch fire spontaneously at a temperature not very much higher, a closely fitting lid must be provided for the trough, so that the oil can be put out taking it from the fire. Here we have a tempering process which is independent of the observation of colours, so that the gunsprings need not be polished before tempering.

Another method, with the same end in view, is used for making railway carriage springs. They are heated till a dry piece of lime or hazel wood rubbed over it emits sparks. For softer steel, the temperature must be lower and the piece of wood smoke only.

To avoid the difficulty of getting the steel to be tempered uniformly heated, and to become independent of colour-observations, various fusible alloys can be used, with melting points determined with the pyrometer, corresponding to the different colours. The period of immersion of the steel in these baths is regulated by the watch. In practice this method is confined to very few articles. It answers very well with file-spikes, which are fully let down. By dipping the spike into a red-hot lead bath, a sharpness of demarcation between the hard and the soft parts of the file can be got that is otherwise unattainable. One of the drawbacks of the lead bath is the waste of metal and necessity of constant cleaning caused by the oxidation of the surface. This can, however, be avoided by covering the surface with coarse charcoal powder, which does not interfere with the tempering. A cast-iron crucible, about 100 mm. wide, and deep enough to take the largest file-spike, is used, and heated in a furnace which can be built like a kitchen range.

If tools hardened all over are required to show gradations of hardness in different parts, the source of heat is allowed to act directly only on those parts of the steel which are to be most strongly tempered. From these parts the heat spreads to the others the more uniformly the lower the temperature employed is. In tempering blades which must have a hard elastic edge and a tough back, a somewhat different process is sometimes adopted. When the steel has been heated to a violet or dark blue, it is placed between two pieces of iron with the back projecting. The whole is then taken with the tongs, and the back of the blade is reheated quickly to a grey, while the pieces of iron protect the blade, which retains its hardness.

Partially hardened tools, such as borers, are heated a few centimetres behind the point in a flame, and when the desired colour occurs near the point, that is at once cooled in water. With this heating proceeding towards the point or edge of the tool, the part next to it remains much tougher than if only the point or edge had been heated. Even with partially hardened tools the different parts must always be uniformly tempered.

If it is necessary to remove the tempering colour from the steel, it is done with a polishing powder or dilute acid, the latter if the colour is to remain on sharply bounded parts of the surface. These parts are covered with wax, or if they are to make a design, with an oil colour of fine-rubber bloodstone, and applied with a brush. The whole object is then dipped into a mixture of 20 parts of water and 1 of sulphuric acid, and when the colour has gone, at once removed and rinsed with water, to prevent rusting.

B. *Curing Warped Steel.*

This operation is, if permissible, usually very difficult, and must be conducted with the greatest care to be successful. It is generally done after the tempering. Objects which have only been slightly tempered or not at all, are made hand warm so as to slightly lessen their brittleness but not their hardness. They are then put between warm copper blocks in a screw press, and gradually brought to the proper shape and left to cool under the pressure. More strongly tempered objects of softer steel are quickly and gently hammered on the anvil with a hammer, with a very narrow and rounded face, which stands in the direction of the hammer handle. The blows are given on the concave side of the steel, where the contracted parts lie. These are extended by the hammering till the steel has its proper shape restored. The blows must fall exactly in the direction of the bending, and not across it. The face of the hammer must be, if necessary, so small that the whole length of it lies closely on the surface when the blow is struck. If the hammer is too heavy or used with too much force, its action extends over the whole section of the object, and the warping is made worse. Besides, the steel may then easily be broken.

Blue-tempered thin elastic objects, such as blades, may, while still warm from the tempering, be bent the other way. For this purpose two pegs are fixed about 80 mm. apart in the work bench. Dietlen, in *Dingler's Polytechnic Journal*, recommends adjusting the warped steel during tempering. "Stretch the hardened article on a piece of iron by means of iron screws, with its concave side next the iron, and heat the whole slowly over a coal-fire. When the steel begins to be yellow, it may be slowly straightened by means of the screws. As soon as it has the desired tempering colour, it is cooled with water on the side that had been convex, and will keep its shape when the screws are removed. Very slight warping may be cured by heating the concave side, and then wetting the convex side."

It hardly needs to be mentioned that only comparatively thin objects, such as files and blades, can be cured as above if warped. Compacter objects cannot be straightened, and must be rehardened, after having been brought very slowly in a slow fire to a red heat, and then allowed to cool in the air or in wood ashes. If this does not make matters right, the piece must be reforged. If the heating is too quick, the steel may easily be cracked, and if the rehardening is done without this preliminary heating, it will probably cause cracking and fresh warping.

V. HARDENING LIQUIDS.

The most usual hardening liquid is water, although its action is not thoroughly satisfactory, as the steam developed prevents proper contact between the steel and the water, so that the latter loses its heat rather by radiation than conduction. To prevent this we have already advised the slow insertion of the object into the water, and moving it about therein. The first precaution allows a rapid escape of the steam which is then formed chiefly on the surface of the water, and the other constantly brings fresh and colder water against the steel which does not get surrounded by a layer of warm water. This is most effectually done by hardening in running water. In any case, the cooling is ununiform, for these parts of the steel which press against the water or on which the running water impinges get cooled fastest. This can be avoided, however, by giving the steel a motion of rotation as well. Long pieces of steel which easily warp, cannot as a rule be hardened by either of the ways mentioned. They should be hardened in rising water, entering the hardening trough from below under high pressure. For rapid disposal of the steam, a stream of water falling from a height is also very good, as there is a constant change in the water touching the steel, and the steam is driven away by the impact of the water. A reservoir is placed near the roof of the factory, and is used through a pipe with a mouthpiece of the proper form. A modification of the same method is cooling by sprinkling, with water issuing under pressure from a rose. We have already described this form of apparatus. It has the advantage over a single stream that larger surfaces can be quenched uniformly with rapidly renewed water. The stream is thus used chiefly for small objects. According to Jarolimek, the action is the better the finer the holes in the rose and the greater the pressure of the water. The whole space between the separate streams is available for the escape of the steam, so that it escapes freely, and a very uniform hardening results. The strongest degree of hardening is said to be reached when only as much water is used as can be converted into steam, whereby much heat is made latent.

The form of the rose must naturally correspond with the shape and size of the steel to be hardened. If it has to be hardened all over several roses are made to act in different directions, or the steel is given a rapid movement of rotation when possible.

Another way of improving the action of water is to dissolve in it from 2 to 4 per cent. of its weight of common salt, sal ammoniac, or nitric or sulphuric acid. This increases the conductivity of the water. Well water which contains carbonates in the same way cools more energetically than river water. Objects hardened in acidulated water must be afterwards rinsed with pure water or lime water, to prevent rusting.

To diminish the conducting power of the water when its action is to be less energetic, it is mixed with milk of lime, soap, etc. Strong soap water hardly hardens at all. Thin flat objects are sometimes hardened in damp ashes. Wet sand is also recommended. The energy of the cooling depends upon the coarseness of the sand. The finest sand hardens the best. Admixture of gum, dextrine, or spirit, in sufficient quantity to water will prevent it from hardening. Turbid brook water in rainy weather hardens less than clean water. Other liquids hardening less intensely than water are the oils and fats. Tallow hardens rather sharper than oil, and a semi-liquid mixture of tallow with oil is sometimes used. Fish oil is largely used on account of its cheapness, but it easily evaporates and catches fire.

Mercury as a hardening liquid has the advantage that it cools the steel very rapidly, being such a good conductor of heat, and that, at least with small objects, it does not make enough vapour to prevent intimate contact with the steel, so that the cooling is very uniform. With large objects there is a perceptible amount of mercury vapour formed, and care must be taken not to inhale it.

The high price of mercury prevents it from being more largely used. Besides, its specific heat being only one thirtieth of that of water, thirty times the weight of mercury has to be used than is wanted of water, so that the temperature of the hardening liquid may not be too much raised. As mercury is a good conductor and can be used below zero C., it is very suitable for producing very great hardness.

Oils, fats, and mercury are cooled during use in hardening by having the vessels containing them cooled outside by circulating water.

Even air can be used for hardening, by passing a strong current of it over the steel, or by moving the hot steel rapidly in the air. It is said that Damascus blades are hardened in a blast of cold air, driven through a small opening, or by being fixed to a rapidly rotating wheel.

Fused metals may also be mentioned for the sake of completeness. Tin fuses at 230° C., lead at 330°, and zinc at 400°.

If we take the hardness got by cooling in water of 20° C. as the standard, we may classify hardening liquids in two divisions, the more strongly and the less strongly hardening ones. In the latter category we have water mixed with bad conductors, and also oils, fats, wax, resin, etc. The former class includes water if below 20° C., salted or acidulated water, and mercury, especially at low temperatures.

Cutting tools must above all things be hard to be of any use. Hence were it not that the possibility of cracking the steel has to be borne in mind, it would not be difficult to choose a hardening liquid, namely, one of strongly hardening nature.

We know how difficult it is to heat a large or awkwardly shaped piece of steel uniformly. When the heating is not uniform, the resulting internal stresses are powerfully assisted by energetic hardening, which causes great contraction. To this we must attribute the fact that steel hardened in water below zero C. more easily cracks, and still more easily if it was hardened in acid water, than steel hardened in fat or tallow. In this sense, then, these hardening liquids deserve the preference, and the more so as they are less likely to warp the steel. Independently of cracking and warping we must recollect that the steel is made more brittle by hardening, and that two differently hardened steels have different probabilities of breaking in use, even if they have been tempered from the same temperature.

It is therefore often preferable in making very hard tools to harden a high carbon steel in oil, rather than a low carbon steel in water, or to also use liquids hardening more strongly than water at 20° C., for the severe hardening affects within limits of toughness in a tool more than a greater natural hardness in the steel with gentler hardening.

New steel is not now made with over 1·5 per cent. of carbon, or it would not only be very brittle, but very hard to manage in the fire and to harden.

If such a hardness is insufficient for a particular tool, and if the tool must also be tough, and is large, or for other reasons difficult to heat uniformly, and if cracks are feared if a hard steel is used, we use in many cases a medium hard and tough steel, and harden it superficially, as explained later.

There has been an attempt to meet the demand for harder steels by means of alloys, especially chrome and tungsten steels. As already stated, both these metals have the property of increasing the natural hardness of a steel considerably without injuring the extensibility in proportion, as would be the result if the hardness was got with an increased percentage of carbon. These metals are not only added to steel in large percentages for the sake of the hardness, but also to get a very ductile and tough steel of medium hardness. But a very hard tungsten or chrome steel is not tough enough to be used for tool-making, except in the case of those which are not worked by blows, but with a steady force. They are used almost exclusively for planes and turning tools.

Cases in which the use of a high carbon steel with normal hardening, or in which a medium will not do after it has been superficially hardened, seldom occur, so that it is only exceptionally necessary to use very energetic hardening liquids. Acidulated water below 20° C., or mercury, will therefore be only used for very fine cutting tools with a steady force actuating them, while in ordinary cases water-hardening is indicated for ordinary tools in which only the cutting edge is hardened.

Complicated, fragile, and large-surfaced steel objects, especially if they have to be heated all over, and objects of very hard steel, even if small and of simple shape, are usually hardened in oil, tallow, lime water, or the like less energetic liquids, or at least by the method of quenching in water, and finishing the cooling in oil.

VI. SPECIAL PROCESS FOR HARDENING THE MOST USUAL TOOLS AND STEEL GOODS.

The following remarks may serve as an amplification of the general principles already enunciated, and as an explanation of the special methods. The processes to be described have justified themselves, although it cannot be said definitely that other methods might not serve as well. In considering the question I shall pass from partial to total, from the simpler to the more difficult hardening, and shall allude to the hardening of certain steel goods for the sake of completeness.

Turning and Plane Irons, Gouges, Chisels, and Borers.

These are heated to a cherry red to a little distance beyond the edge, say 15 mm., passing away to darkness gradually beyond that. The tool is then immersed vertically in water of 20° C. rather beyond where any glow is visible, and turned about, whereby scale separates from the immersed portion. When the glow has disappeared the tool is taken slowly out of the water. Then its internal heat produces the tempering colour (tempering from inside). These colours appear on the smooth surface left by the scaling, and gradually fade off towards the edge. This should take place parallel to the cutting edge. If either the heating or the cooling was ununiform, they fade off slanting or curved towards the edge. In this case, the parts in which they go farthest are to be cooled by a momentary immersion in water. When the edge shows the proper tempering colour, the tool is plunged at once into water to cool. If it is preferred to let the steel cool completely in the hardening liquid, the subsequent tempering should be done by heating not the point or the edge itself, but, for reasons already stated, a part at a little distance,—a few centimetres.

All stone-borers, stone chisels, and pointed tools have to be hardened in the same way, and the same is the case in hardening a large piece of steel.

The often practised method with large jobs of heating such stone-working tools for about 40 mm. from the edge, and then cooling by immersion of about 15 mm. from the edge, is contrary to the science of proper hardening, and, especially in the case of hard steel, wanted for hard stone, readily leads to failure. The greater care that has to be taken in the hardening is richly repaid by the durability of the tool.

Mill Picks.

One edge is hardened in water to a depth of from 15 to at most 25 mm. at a dark red heat, and when it is quite cold, the other edge is hardened in the same way. The tool is then tempered outwards from the middle at a yellow tempering colour, for getting which it is advisable to lay the tool on a cubical piece of red-hot iron about 100 mm. in size. It is quite as important to make the heating very slow and uniform, and only to a dull red heat, as to keep the hardening within 25 mm. of the edge.

File-Cutters' Chisels.

These are hardened in water to a depth of from 15 to 20 mm., according to their size, after being raised to a dull red heat, which must be uniform over the whole width of the edge, which is the only part hardened. The chisels are tempered at a purple red on red-hot iron. They can be ground down about 8 mm., after which fresh hardening is wanted.

Before this rehardening the edge must be forged thinner, as it has already become too thick by wear and grinding. At this time, too, the shank is forged out smooth again. If the shank has been hardened it might fly, to the danger of the eye or hand of the file-cutter. Hence it is a mistake to believe that a hardened shank of a file-cutter's chisel lasts longer than an unhardened shank.

Hammer Heads.

For hardening the face of a hammer head, which must be made so that its surface must be fully congruent with that of a flat anvil, the upper part of the head is heated to a depth of about 15 mm. a dark cherry red, and so that the colour disappears in the next 40 to 48 mm. The head is then laid with the face downwards transversely on two sharp-angled and thin iron supports immersed to a depth of about 15 mm. in water. The water is always being renewed from below, and the hardening trough has a waste-pipe to keep the level of the water at any desired level. The supply ought to be rapid, so as to keep the surface of the water disturbed. The hammer head is left in the water till quite cold and is not tempered. Before being wedged on to the handle, and every time the hammer is used after long standing idle, the head should be made hand-warm, so that it may not split.

For heavy hammers and anvils, sprinkling hardening is best. The possibility, not only that cracks may result from unequal heating, etc., but that also pieces may be thrown off, makes it advisable not to stand too close during the hardening.

Hammers.

If the hammer is short, so that the faces are close together, the whole head is heated and hardened in water, beginning with the flat face. Then the other face is heated, which by this time has got hot enough. During this second heating the flat face is protected by repeatedly dipping it for a moment into water. When both faces are hardened and the temperature of the iron has sunk to a dark brownish red, the whole can be cooled in water, without hardening the middle of the head. Hammers are usually made of very soft steel, and are therefore not tempered. With harder steels, the faces are hardened at dark yellow or from that to yellowish brown.

Stamping Hammers (for marking cold metal).

The forged heads are placed, about eight together, in an iron box, with smithy scale carefully packed all round them. The uppermost layer of scale is covered with about 25 mm. of damp well-kneaded loam as a lute. The box is then heated as uniformly as possible for several hours, and not above a red heat. The box is then taken from the fire and cooled as slowly as possible in a close wrapping of charcoal ashes. When cold, the heads should only show a very thin coating of scale. If it is thick, more air got to the iron than was advisable. The heads are now softened so as to be engraved, and when that is done, the part of the hammer to be hardened is raised to a cherry red in an open forge-fire over as short a length as possible, whereupon the steel is hardened in water, being taken out before it is quite cold, so that the tempering at a violet heat can still be done by the residual heat of the metal.

Sledge Hammers.

The heating is done exactly as to be presently described in the case of dies and press-stamps. It is not only necessary that the temperature should be uniform on edge and hollowed out part, but it is also essential that the hardening heat should not be sharply limited, but should reach back over the hollowed part and then gradually sink. If the edge is heated too much, in comparison with the hollow, it cracks, and in such a case the whole edge comes off as a ring. The hardening is done in water, and the tempering from within at a violet heat.

Paper and Tobacco Knives and Shears.

Long articles of these kinds are best heated in a cupola and kept there till the edge has reached the hardening temperature. These cutting tools have generally holes and slots in them whereby they are fixed into the machine. So that the thin edges of these apertures may not get hotter than the solid metal near them, they should be stopped with loam before heating. The hardening is done in water or, in difficult cases, in tallow, into which the knife is put horizontally with its back outwards.

For tempering we use a rectangular iron frame, somewhat longer than the knife. Several holes are cut below in the sides of the frame, and fire-bars rest on bearers a little way above the holes. This permits the access of air to the coal-fire which is made in the box. When a sufficient glow is got, two thin iron bars are laid across the box and the knives are laid on them with their backs downwards. There they remain till their edges appear violet. Another way is to lay the knives flat, so that only half the width of the lowest knife is over the fire. The second half covers the first, the third the second, and so on, so that only the backs of the knives are exposed to the direct heat of the fire, the edges being heated by conduction only. The reason is that the edge must be hard and the rest of the knife soft and tough.

Short knives are dipped vertically in the hardening liquid.

Short thick shear-blades are heated with the cutting side downwards in an open forge-fire, only at the edge, but not bounding the heated part too closely. The edge is then dipped horizontally into the hardening liquid, the process being similar to that used for chisels and plane irons.

Twist Drills.

These are hardened at a weak cherry-red heat in water, being immersed vertically, and then slightly withdrawn slowly, so that the head cools less quickly and remains softer. The tool is moved about in the water till the glow has gone and just enough heat is left inside to produce a brown-red tempering colour, when the drill is taken from the water.

The heating can be done in an open forge-fire. A bright charcoal fire is made, the blast cut nearly off, and the drill is then laid in the fire. If it only gets feebly red hot, the blast is somewhat increased. The tool must be continually turned about in the fire and its colour watched. If it does not seem uniformly heated, the less heated parts must be exposed to the hottest parts of the fire. If there is a large number of drills, of long sizes, to harden, they are heated in an iron box in charcoal powder and then quenched separately in water. If they are not tempered from within, the hardening should be done in oil or tallow, or in water containing lime, allowing them to cool entirely in the hardening liquid, and are afterwards tempered.

Rotary Cutters.

These are heated like twist drills, and best hardened in tallow. If much hardness is wanted, the tools should be dipped vertically into water till their surface appears dark. They are then at once immersed in oil and left to cool. The tempering colour is dark yellow to yellowish brown.

Milling.

These are heated red hot in a muffle, or packed with charcoal in an iron box, and then dipped vertically into lime water, oil, or tallow, and left there to cool. Or they can be dipped into plain water till the glow has gone, and then at once transferred to oil, and allowed to cool in it completely.

The discs should, for metal work, be dark yellow at the edge, and blue towards the centre, for tempering. This is managed by laying the disc on a piece of red-hot iron of correspondingly smaller diameter, or by putting a red-hot bar through the hole in the disc.

Stamps.

These include, in the widest sense, such a great variety of articles, differing in size, shape, and use, that it would be difficult to give either a general or an exhaustive description of their hardening. I must therefore confine myself to the chief representatives of each kind.[1]

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[1] Stamps can be classified from their chief characters as follows:— Punches used for making holes in metal. The shape and size of the

1. *Minting Dies.*—These are heated red hot in charcoal in an iron box smeared with loam, but not closely shut. The working face of the die is then hardened by allowing a stream of water to fall upon its centre, as it is difficult to get that part as hot as the edge, and yet the whole surface must have a uniform hardness. The working surface is usually not tempered, and the rest of the die only a little, so that the die may not be deformed in use by the powerful pressure.

2. *Press Tools.*—Such dies with very fine engraving are hardened like coining dies. Those for button- and ornament-making and also for rivet manufacture can, however, be heated in an open charcoal fire. They are heated up, slowly at first, till the whole mass, and particularly the working surface, appears of a uniform brown red. Then the working surface is quickly brought to a higher temperature, as uniform all over as possible, and shading off into the brown red of the rest of

flat ground surface corresponds to and determines the shape and size of the hole made and of the piece of metal punched out. Stamps are matrices worked by the hand, like a chisel. They consist of short steel rods with working faces of the proper form, and are used principally for making hollow bodies and for inscribing letters on metal, and ornamenting it by inlaying. Strictly speaking, the already described stamping hammers come into this class. In many cases, the gradual action of a large number of weak blows with the hammer may be advantageously replaced, with the aid of a machine, by a single powerful impulse or pressure, in which case the form to be given is determined by a matrix or die. Stamps include both matrices and relief dies. For stamping metal buttons, jewellery, ornaments, etc., matrices are generally used (rarely relief dies), and are called stamps most generally. The stamp has an under and an upper part. In coining, two stamps are used, the lower one being fixed, while the upper one comes down vertically above it. A ring confines the edges of the coin during the stamping, so as to prevent the deformation of them. The second stamp, made from an original stamp, is called the matrix or model-stamp, and is used for making dies by pressing. The making of minting dies is described fully in the *Report of the Imperial Mint* for 1892 and 1893, published at the State printing works at Vienna in 1894.

the tool. For this purpose the fire must be kept short. To compensate for the unavoidably unequal heating of the working surface, the hardening should be done with a stream of water falling on the middle of it. If the edge gets harder than the rest it must be tempered rather more, to prevent cracking in use. The tempering is done in a sand bath or an iron plate floating on fused lead, the working surface being upwards so as to temper the body of the tool the most. To prevent the tempering colour from getting too much into the middle, that part is cooled with drops of water.

For press tools used with heavy blows, tallow-hardening is advisable.

3. *Punches for Boilermakers.* — The heating should not be too local, for, if there is too sharp a transition between the hardened and unhardened parts, the tool is likely to break where they meet. In heating, care is taken not to overheat the edge. This is not difficult, for only the edge must be hard, and the use of the punch is not materially affected if the middle of the working surface is somewhat soft. Thus attention may be concentrated on the temperature of the edge. In quenching, the punch must be dipped vertically into the water to a depth a few centimetres greater than the heating has extended, and slowly withdrawn before it is quite cold. If, however, it has been left too long in the water and the internal heat can no longer produce a purple-red tempering colour, the tool must be reheated, taking care, however, not to heat the edge, but only the metal behind it.

The hardening of punches for reaming out holes is carried out quite similarly.

4. *Drawing Rods for Cartridge-Case-making.* — These are hardened over their whole length, and there is the danger to be encountered that from want of care they may be warped. They are best heated inside a uniformly heated tube lying in long-bedded forge-fire with several twyers, or in a muffle. The

hardening consists in a vertical dipping into water till the surface of the steel is dark, and finishing the cooling in oil or tallow. Tempering is usually dispensed with.

5. *Matrices for Rivet-making.*—These must be hard on the upper surface, on the inner edge of this surface, and also in its anterior walls, but very tough and resistant to blows in the rest of its mass. The heating has therefore to be done accordingly, which is difficult. After a preliminary gentle heating, as uniform as possible, of the whole tool, it is brought into the hot part of the fire with its working surface downwards, so as to give that the full hardening heat. The quenching is best done with a stream of water, directed not merely through the opening of the matrix but over all its upper surface. If the outer edge scales fairly completely it must be tempered yellow, which can be done with a red-hot iron ring. Matrices for cartridge-case manufacture are quenched the same way.

6. *Short Stamps with large Working Face.*—These are heated entirely and uniformly to the hardening temperature, and quickly cooled in a large vessel of water, with a constant flow through it, by dipping vertically and stirring them about. If possible the flow of water into the reservoir should be under pressure from below, in which case the stamps can be held quietly in the current. This is enough for soft steel (about ·7 per cent. of carbon), but for harder steels the quenching in water is followed by a cooling in oil. In neither case is the steel tempered. If the stamps are made of medium or of hard steel, they must only be hardened in oil or tallow, and must be slightly tempered. Soft steel should be preferred, as it is more easily engraved. In heating such steel the working surface should be sprinkled with ferrocyanide of potash, both to prevent oxidation and to get greater hardness. The residual ferrocyanide is quickly removed with a fine wire brush before the hardening temperature is reached, and renewed thinly and uniformly by means of a wire sieve.

7. *Long Stamps with large Working Surface.*—These are warmed all over, but the further heating is only at the working end, the cherry red passing into a brown red a little way up the tool. The quenching is done, like that of hammer heads, in water with a rapidly rising inflow. The overflow pipe must be so arranged that the surface of the water does not come more than about 2 cm. above the working face of the tool.

The chief difference between the hardening of short and long stamps is, that the former are hardened all over, the latter only at the face. If short stamps were only hardened partially they would warp, and this need not be feared with long stamps, as the larger mass of steel proceeding from the working face opposes a sufficient resistance to warping.

8. *Cutting Matrices for punching out Plates for Tinman's Work, etc.*—These are heated like the stamps for rivet-making, and quenched by vertical dipping in water, or for hard steel in oil or tallow. Tempering colour: yellowish brown to brown red.

In general, it may be remarked that with stamps which have to work with great accuracy, and which must therefore be of an exact size after hardening, the change of volume produced by the hardening must be allowed for. Hence a solid tool must be made somewhat too small, a hollow one somewhat too large, and just enough to compensate for the expansion in the one case and the contraction in the other. As the change in volume is different for different kinds of steel, it must be determined beforehand for each kind.

Saws.

Haswell recommends the following hardening method for saws in Karmarsch and Heeren's technical dictionary: "Circular saws are brought to a cherry red and quenched in water with a thin layer of oil on its surface. The heating must be done slowly. The saws are immersed vertically. The oil catches fire as it touches the hot steel, and covers it with a crust of carbon, which protects it from too quick cooling and makes cracking less likely. Single saws can be given the hardening heat by laying them on a cold iron plate and then heating both together, and still better by heating the saw while pressed between two wrought-iron plates. This ensures slow heating of the saw and prevents warping. For the thinnest saws only oil is used for quenching, or a mixture of oil and tallow. This gives enough hardness. Saws of medium thickness are best quenched in solid tallow. This gives a somewhat greater hardness than oil. Very thin saw blades also get hard enough if heated red hot and cooled between two iron plates smeared with tallow. Saws for metal must be tempered at a straw yellow. This is done after polishing best by laying the saw on red-hot iron."

Holzapfel describes the hardening of saw blades as follows in the *Mechanic's Magazine* :—" Saw blades are heated in special long stoves and then laid horizontally with the toothed edge, or the edge to be toothed, uppermost in the hardening liquid, which is a mixture of oil, tallow, wax, etc. Two troughs are generally used, so that when one gets too hot the other can be used while it cools again. A part of the hardening liquid is wiped from the saws to a piece of leather, and they are then heated over a bright coke fire till the grease left on them catches fire. If they have to be left rather hard, only a little fat is allowed to burn on them, but more if they are to be softer. To get spring-hardness, all the fat is allowed to burn.

" With other objects, which are thick, or of unequal section, such as many springs, two or three lots of fat are burnt off them, so as to ensure the same tempering throughout."

Thin saw blades and other small objects are sometimes brought to the hardening temperature by immersion in red-hot lead, having first, as already said, smeared them with linseed oil and soot, and dried to prevent the lead from sticking to them.

Shears.

The blades are heated uniformly to a dark cherry red reaching from the point to the rivet hole. This can be done in the open fire, first with a weak blast, until the steel begins to glow. Then the fire is left to itself, and the steel is moved about in the fire till all the parts to be hardened have received a uniform dark cherry red. Both blades are hardened together in water and tempered at a purple red or violet. It is necessary to treat the two blades together throughout, so that both may be of equal hardness, so that one will not cut the other—the well-known rule of dipping the blades vertically and slowly, points uppermost, down to over the rivet hole.

Table and Pocket Knives.

There is little special about hardening table-knives. The blade is dipped slantwise at a dark cherry red, back first, into the hardening liquid, which is usually plain water, or water covered to a depth of 10 to 15 mm. with oil. The blades are then tempered at violet or blue. Pocket-knives are taken, half a dozen at a time, in the tongs, the separate blades being kept apart in the grip of the tongs by a piece of iron. They are then heated edge uppermost over a fire or hot-iron plate. For fine knives, a fused mixture of tin and lead is used for tempering the back and a spirit flame for tempering the edge.

Scythes.

The blades are heated in a little reverberatory-furnace, a small walled flue of nearly square section, which is steeply inclined towards the chimney. The grate is in front, and in front of it is a twyer-opening. It is preferred to fire with wood rather than charcoal, as the former makes more flame and keeps out the air better. A few centimetres above the sole of the furnace iron bearers carry the scythe blades. At first one blade is put with about a third of its length in the furnace, with its back downwards and with the point foremost. When this has been somewhat heated, other blades are put in, and the first is gradually got entirely into the furnace. The number of blades being heated at once depends on the temperature of the furnace. The slow pushing in of the blades is necessary, because the greatest heat is in front, over the grate, so that the points of the scythes would get less heated than the rest if they were put at once into the fire.

The quenching is in tallow, with edge uppermost. The scythe is removed from the hardening trough when fumes cease to come from the tallow. The tallow is scraped off the still warm steel with a sharpened piece of bark. Cherry tree bark is preferred for this. The scythe is then worked about in a heap of coal ashes to clean it. It is then heated very gently and as uniformly as possible over a charcoal fire, and then immersed with a hewing movement in a trough of running water. This brings the scale partly off the front side of the blade. The rest of it is got off with an emery wheel, and the scythe is finally blue tempered. For this purpose an iron trough of proper size is lined on three sides with glowing charcoal, leaving one of the long sides free. On this side the scythe blades are put with their backs downwards on iron bearers and brought separately in turn nearer to the heat. As the tempering colour should appear uniformly over the whole blade, any defects in it are rectified over a charcoal fire with a gentle blast, heating those parts which have not been tempered enough, while the over-tempering of the rest is prevented by keeping it cool with a wet cloth applied now and then. The tempered scythes are cooled in the air. If very hard steel has been used, the scythes are tempered twice, polishing the front side of the blade before the second tempering, so that the colour can be observed. A sand bath heated by waste heat or some inferior fuel is more economical than the open charcoal trough, but does not do the tempering so well.

The subsequent operations consist principally in hammering the slightly heated blades under a very rapid but light machine-driven hammer with a very small rise. This rectifies the distortions produced by hardness, and increases the hardness and elasticity of the steel. This is followed by a final adjustment of the blade to its right form by means of hand-hammering.

Wire.

According to Tunner, piano wire is hardened in Worcester as follows:—After a lead bath in an iron pipe kept red hot, the wire is hardened in a circulating oil bath. It then passes to a second lead bath, which, however, is at a temperature only just above the fusion point, and tempers the hardened wire.

Watch Springs.

An interesting machine of Kugler of Paris for hardening watch springs is described as follows by Kohn in Karmarsch and Heeren's technical dictionary:—"After the steel wire has been rolled out to the proper thinness it is coiled up on a cylinder, from which the ribbon passes through an iron pipe surrounded outside by fireproof material and having a rectangular section of about 100 mm. wide and 12 mm. high. This pipe is in a furnace heated with charcoal. As the steel ribbon slowly passes through the pipe it becomes red hot, and is drawn through a bath of oil and hardened. The heating of this bath is prevented by a constant flow of oil, the warm oil escaping by an overflow. On leaving the oil the ribbon passes between two pairs of drying rollers, one behind the other, which are suitably loaded and from which the oil flows back into the hardening bath. The band next arrives at a cast-iron plate heated by a fire, to temper the spring. Here it is also straightened by a weight, and, finally, through a polishing apparatus consisting of six emery rollers, which polish both sides of the spring. The spring is finally wound on a reel."

A similarly acting apparatus for hardening and tempering long springs is that patented by Luttger Brothers of Solingen. Here, however, the hardening is done dry, by passing the spring as it leaves the hot pipe between two cast-iron reservoirs filled with cold water, which harden it by their pressure and coldness. The reservoirs are kept cool by a constant flow of water. The pressure of the upper reservoir on the spring can be regulated by a lever.

Hollow Steels.

The method to be followed with these has been already described, but we will here mention an apparatus patented by Lorenz of Karlsruhe. It consists essentially of the following parts:—To a vertical water pipe with a conical valve regulated by a screw, a mouthpiece is fixed below by a coupling box. The mouthpiece must exactly fit into the object to be hardened, and it is given a spheroidal shape to enable it to fit into various sizes. Below there is a vertical overflow pipe, which can be raised or lowered by a lever, and by a spring acting on this lever is pressed up against the mouthpiece. This pipe has a suitable flange to carry the hollow steel. If the hardening is to be internal only, the red-hot steel is put between the overflow pipe and the mouthpiece, from which the water then flows through it. In this it is clear that the stream of water must fit the bore of the steel, or else the supply of water must be somewhat lessened, so that the thinner stream may spread over the inside of the steel.

If the hollow steel is to be hardened first inside and then outside, the overflow pipe receives a sort of cast-iron pan, the edge of which reaches the upper edge of the steel to be hardened. In this pan a small tripod is put for the steel to stand on. With this arrangement the water flowing into the pan through the hollow of the steel ultimately immerses it altogether. The overflow from the pan is taken away through a side opening into the overflow pipe. To drive the hardening water close against the inner sides of the steel, the mouthpiece has a spindle in its centre, which spreads out outwards into a cone which directs the water outwards. The space left by the base of the cone for the water to pass out can be regulated.

If a hollow steel is to be hardened inside and out simultaneously, Lorenz uses an apparatus of which we can form an idea by supposing that a short coupling pipe is placed over the above-mentioned pan. This is connected above to the mouthpiece, which in this case does not rest upon the hollow steel. In this we get a closed chamber in which the hollow steel is placed free on all sides. The conical spindle sends the water both inside and outside at the same time, and it flows away by openings in the chamber. A detailed account of the apparatus and a drawing appeared in *Dingler's Polytechnic Journal* of February 1, 1880. Both these latter methods are employed by Lorenz in hardening matrices used in the manufacture of metallic cartridge cases.

VII. CASE-HARDENING.

A. *Theory and Practice of Case-Hardening.*

By case-hardening is meant a superficial addition of carbon to the steel. It is done in the case of such steel articles which must be very hard outside, but which, on account of irregular shape or large size, offer special difficulties in hardening. In the place of a hard and high carbon steel, which would readily crack in hardening, we take a softer and easily hardened steel, and give it a case-hardening. For this purpose water is the only quenching liquid used.

The process consists in general of sprinkling the steel at a dull red heat with carbonising substances, then heating it in a forge to the hardening temperature, and quenching it in water. Or the object to be hardened is painted over cold with a paste of carbonising substance, dried, and then heated, usually in a cupola flame, and hardened in water.

Smaller articles are kept for a long time red hot in an iron box with animal or vegetable charcoal. They are then taken out and hardened at once. Parts not to be hardened are covered with clay and dried, or else embedded in clay.

Cementation, *i.e.* the combining of wrought iron with carbon by contact without fusion, begins at a dull red heat, and goes on faster as the temperature rises. At the same temperature, too, the combination goes on at a rate proportional to the closeness of the contact between the carbon and the iron, and the longer time is given for the action the further the carbon penetrates into the iron. It gradually works its way into the metal. At first the outside of the iron is richer in carbon than the inside, but in the course of time the whole of the iron, if it is not too thick, is nearly uniformly carbonised. The carbonisation is hindered by increase of thickness, and if that exceeds a certain limit, the further taking up of carbon becomes entirely stopped.

Wedding has found that experiment proves an experience in the management of cementation furnaces, namely, that in cementation with wood charcoal at a fixed temperature, the absorption of carbon is limited, and infers that the degree in which solid carbon is taken up by iron is a function of the temperature.

In case-hardening, then, it is a question of getting as much carbon into the surface of the steel, and in as short a time as possible, at the hardening temperature. To do this is impossible if coarsely powdered carbon is used, as in the cementation process. We must use finely divided carbonising bodies, which will lie close to the surface to be hardened, and be effective even at low temperatures. Such hardening compositions often consist of many ingredients, and are by no means rationally compounded. Many of the ingredients serve no other purpose than to throw a veil of mystery over the preparation. In our consideration of the action of cementation in general and that of the most usual hardening compounds, the value or worthlessness of them will appear in the proper light.

B. *Theory of Cementation.*

The question whether the process used on a large scale for the manufacture of cementation steel consists in a combination of the solid carbon with the unfused iron, gradually spreading into the interior by molecular motion, or whether it is not rather that gases developed from the carbon produce the carbonisation, by entering the diffusion pores which open in red-hot iron, has been settled in favour of the former theory.

That hydrocarbons have a cementing action there is no doubt, and it is an old experience with cementation steel-makers that the wood charcoal almost exclusively used, loses its effect by repeated use, and that at every fresh charge the old and degassed carbon must be mixed with fresh, if the process is to be finished in a reasonable time. Hence it must be admitted that the hydrocarbons in the wood charcoal play a part, but, for all that, the chief factor in cementation is the solid carbon. This enters the iron, and travels by molecular motion, the molecule richer in carbon giving up a part of its carbon to a neighbouring molecule poorer in carbon, and this action gradually spreads into the interior of the mass.

C. *Cementing or Hardening Substances.*

These are used for case-hardening, and comprise solid carbon, especially wood charcoal and soot, and also nitrogenous and carbonaceous animal matter, such as bone, horn, and leather charcoal, and horn and hoof clippings. The cyanogen in them breaks up at low temperatures in contact with iron into carbon and nitrogen. The carbon partly combines with the iron and partly adheres to its surface.

Ferrocyanide of potassium ($FeK_4Cy_6 + 3H_2O$) has a similar action. It is also known as yellow prussiate. At a red heat, it forms volatile potassium cyanide, nitrogen, and carbide of iron. The last shares its carbon with the glowing metal in contact with it.

Resins are also used in the hardening compounds. They fuse at low temperatures, and decompose on further heating, burning with a smoky flame and leaving a residue of porous carbon. They also make the other hardening ingredients adhere better to the iron, and by developing gaseous hydrocarbons hinder the access of the air. By themselves their carbonising action is very small.

Animal fats behave similarly. With the use of them is united the object of getting the hardening compound in the form of a paste, which can be applied uniformly over the surface of the steel. Even yeast, meal stirred up in water, etc., are used for this purpose, and also help by containing carbon and nitrogen.

Finally, saltpetre, common salt, glass, etc., are used. These fuse at a red heat, destroy the coat of oxide always present in the iron, prevent the formation of another, and serve as a binding material for the other ingredients, and prevent them from falling off in the fire. The glassy flux at once dissolves off when the iron is dipped in water and allows free access to the steel.

Ferrocyanide and the above-mentioned nitrogenous animal matters, which work very energetically at comparatively low temperatures, are largely used by themselves. Other less active bodies are mixed with them, partly for economy but particularly and with good reason, to increase the bulk, whereby the uniform distribution and adhesion of the hardening mixture is very greatly facilitated, and the whole conduct of the operation.

(a) *Hardening Powders.*

1. RINMANN'S

(For use in iron boxes).

Powdered birch charcoal	40 lb.
,, leather ,,	10 ,,
Soot	30 ,,

II. KARMARSCH'S

(For use in the open fire).

Horn charcoal	48 lb.
,, filings	6 ,,
Nitrate of potash	19 ,,
Common salt	110 ,,
Glue	12 ,,

III.

Saltpetre	15 lb.
Colophony	2 ,,
Ferrocyanide of potash	7 ,,

The ingredients are well mixed and ground in a mortar. The steel to be hardened is raised to a dull red heat, and then sprinkled with enough of the powder to make a sort of glaze. A small wire sieve on a handle answers well for this. The steel is then heated to the hardening temperature, and cooled in water as usual. The common salt is roasted before use to prevent it from lumping.

(b) *Thick Liquid Hardeners.*

IV. KULICKE'S.

Tartaric acid	6 lb.
Cod oil	30 ,,
Ox tallow	10 ,,
Charcoal powder . . .	2 ,,
Bone black	8 ,,
Burnt hartshorn . . .	3 ,,
Ferrocyanide of potash . .	5 ,,

The tallow is melted and mixed with the cod oil, and the solid ingredients are then mixed in by thorough stirring. The mixture solidifies to a paste in two or three weeks. The steel to be treated is made red hot and dipped into the paste, or painted with it, then heated to the hardening temperature and cooled in water.

V.

Common salt . . .	80 lb.
Glass	5 ,,
Hoof meal	30 ,,
Rye ,, ...	10 ,,
Colophony	10 ,,
Birch charcoal . . .	10 ,,
Yellow prussiate . . .	4 ,,

The prussiate is dissolved in about 160 lb. of boiling beer-yeast, and the other ingredients are stirred into the liquid.

VI. SCHIRLITZ'S.

Roasted horn meal . .	16 lb.
Quinine bark . . .	8 ,,
Yellow prussiate . . .	4 ,,
Purified nitrate of potash .	2 ,,
Common salt . . .	4 ,,
Soft soap	30 ,,

The ingredients are kneaded together to a paste, and dried. For use, the mass is mixed with water and applied with a brush. Hardener v. is an excellent recipe for file-hardening.

Brinkmann recommends the following recipe for files:—Salt, 2 lb.; corn meal, 15 lb.; ox hoofs burnt brown, 30 lb. These are ground as fine as possible together in a mortar, and the mixture is made into a paste with water. This paste is laid on the files and allowed to dry. If some of it comes off in the heating, the file is quickly taken from the fire, and the place is strewn with dry ox-hoof meal, and the file is put back in the fire. When the suitable hardening temperature is reached, the file is slowly dipped vertically into water, without moving it left or right, or it would become bent. The cold file is cleaned with brushes in soft water, and rinsed with lime water to prevent rusting. The spikes of the dried files are tempered in fused lead, and the still warm files are then oiled.

To get a true picture of the variety in hardening mixtures as used in practice I thought I ought to give the preceding recipes unaltered, although some of them might be simplified by omitting some of their ingredients or cheapened by using cheaper ones, without impairing the efficacy of the mixture.

CHAPTER VI.

INVESTIGATION OF THE CAUSES OF FAILURE IN HARDENING.

THE causes of failure in hardening may lie in the steel or in the treatment of it. We have already discussed the signs of deficient quality in chapter iv. So far as these tests of quality consist in experiments on hardness, they of course only give a reliable indication of the quality of the steel, in case that the hardening was properly done. This is also true of finished and hardened tools.

To be able to form a judgment in this question, we must then consider some of the signs that a steel has been improperly treated.

One of the greatest difficulties in hardening is to get the steel heated uniformly, and a particular and not too high a temperature. This gives us, then, the chief cause of failure. Even the most skilled workman may make an oversight, by neglecting to take into consideration apparently trifling circumstances, such, for example, as a change in the light of the workshop, which has to be illuminated so that the colours of the hot iron can be judged properly. Now we know that different hardening temperatures are associated with different and characteristic fracture-appearances, and it is principally by these that we see whether the hardening has been properly done.

Burnt hardened steel has a coarsely crystalline fracture with a whity lustre, and is particularly hard. If burnt before forging, its surface will be covered with minute edge-cracks. If it was forged at the right temperature and then hardened, its fracture will be nearly normal, but the cracks will show that it is burnt.

Overheated hardened steel has a coarse-grained fracture, with a whity lustre, and nearly the proper hardness. In a steel which has been found overheated and has been hardened, it must be assumed that the overheating took place during the hardening, for if it had occurred during forging, proper hardening would have restored the fine grain. Overheating in forging can therefore only be detected in unhardened steel.

Perished hardened steel is coarse grained, and might pass for an unhardened steel, and is rather soft.

Normal hardened steel shows no particular grain, but a fine velvety fracture with a dull lustre.

As soon as a steel object gets a hardening crack, and the cause of the evil is not manifest, it is absolutely indispensable to break the steel and examine a fresh fracture. It should be broken so that on the one hand the thinnest, and hence those parts which got most heating in the hardening have their structure exposed, and on the other that such parts which ought to have hardened equally, show comparative sections to the eye. For instance, in a turning tool, we should cut off the point, from a hand chisel both corners of the edge, from a milling wheel single teeth, and then break the wheel in two along a diameter.

A horseshoe shaped crack in a chisel or plane iron convex towards the edge, shows that the edge is overheated at the corners, and as a rule that the edge was hardened with too purely local heating. If the bend of the crack is not symmetrical, the overheating was unequal. If the edge is now broken off, the fracture will show the justice of these conclusions.

In overheated sledge-hammers the edge cracks where it passes into the thick part with a conchoidal fracture. In bad cases the whole edge may come off as a ring. In dies with sharp edges the overheated corners easily break spheroidally from the compact part.

In larger bodies hardening carried out at the right temperature becomes less in the interior of the mass, as will be shown by the coarser fracture there. Such large pieces must, however, show a fracture which is quite uniform over the exterior, and the hard layer must penetrate the same distance all round.

Steel which has been heated too hot and too long often does not scale completely, and bits of scale remain adhering to it. But if the scale on partially hardened pieces, so far as the hardening reached, is completely removed, it forms on steel heated too hot and too long a thick layer at the part next to the hardened part, and will serve as a sign.

Too rapid heating can usually be detected by want of uniformity in the fracture, for in the short time during which the steel was exposed to a proportionately high temperature, the thinner parts were heated higher and to a greater depth than the thicker parts.

If a really homogeneous steel warps on hardening, it was either heated unequally, or it was improperly dipped into the hardening liquid, or, finally, it was brittle from internal stresses which were not removed by heating and slow cooling. It is well known, too, that water-hardening is more apt to cause warping than that in tallow or oil. So that the cause of the evil may lie in an improper choice of hardening liquid. It is often enough to harden a tool in oil instead of in water, not only to get rid of all the hardening difficulties, but to get a more durable tool.

Whether a tool with a hardening crack was hardened in water, oil, or fat, is easily found by splitting the steel in the course of the crack. Water-hardening leaves rust in the crack.

If, however, it is doubtful whether the crack was caused by hardening, or is a longitudinal crack resulting from the manufacture, the interior of the crack will clear the matter up. A hardening crack shows on the bounding surfaces, which are light, the grain of the steel. The other has black smooth walls. The colour is the result of a thin layer of scale which formed in the crack in the fire. Besides, the longitudinal cracks always run approximately parallel to the long axis of the steel, as necessarily follows from the manner of their production, namely, a drawing out in forging or rolling of flaws in the ingot. Although a hardening crack may be parallel to the long axis, it may have any other direction.

With regard to the shape of the tool, it is an extremely important rule for avoiding difficulties in hardening to never give sharp or projected edges without necessity, but wherever possible to have rounded edges, and grooves with rounded bottoms, so that the changes of section are as gradual as possible. Thus in a twist bore the ribs carrying the cutting edge should be rounded off. In stamps, those for example which have the shape of two coaxial cylinders, a large one carrying the working face, and a smaller one by which the tool is held in the machine, the upper edge of the lower cylinder should be rounded off and pass by a curve to the upper one.

In finishing tools, especially those of hard steel, violent blows with chisels, etc., should be avoided as much as may be, as they tend to produce cracks.

A further and very important cause of hardening failures is the choice of a wrong grade of steel. This causes the tool to answer its purpose badly, even if it has got through the hardening all right. Here, too, we have defective forging of chisels, planes, and turning tools. When a piece of square or flat steel is forged to a point or edge at one end, the blows of the hammer do not affect all parts of the section equally. The resulting want of uniformity, if the part is cut off with a cold chisel, will cause the tool to break when used.

In other cases a tool breaks because it has not been sufficiently tempered. If this takes place after tempering at a violet, the effect of tempering at dark blue should be tried, and it may answer perfectly. But too soft an edge may break if it has been deformed beyond a certain point.

Rapid blunting of edge tools may result from deformation or breaking. In tools acting fairly quietly and without shocks, such as milling wheels, they may break away in such fine particles that it is difficult to detect it, and the steel may be unjustly blamed as too soft. Careful observation would show that the fault is probably the other way, and more of the temper should have been drawn.

Tool-smiths' articles which are often in the fire should not be too small. The coating of scale is associated with more or less decarbonised places, which, if the finishing was insufficient, appear softer in use after hardening.

After these few remarks on failure in use I return to a few words on failure in hardening, only however to remark—as I hope I have proved—that it is not very hard to find out how a steel has been hardened and to detect any resulting weaknesses. This fact is by no means new, but it is not made proper use of in all workshops. Where it is, and where skilled workmen properly understand the hardening of steel, and are in the habit of investigating the reason for every failure, the art of hardening will, in that workshop, always be approaching a higher and higher state of perfection.

CHAPTER VII.

Regeneration of Steel spoiled in the Fire.

OVERHEATED, perished, and burnt steel are not sharply different, and may be spoiled in many different degrees, and that decides on the measure of success to be expected in regeneration.

The regeneration of overheated steel can be effected by forging or hardening it at the proper temperature. Yet it retains a coarser grain than it had originally, and never regains its former qualities completely, if the overheating was very great. The theory of this treatment is the destruction of the coarsely crystalline texture that makes the steel brittle. As strong compression of the outer layers of steel takes place in hardening, hardening acts in this matter in the same way as forging.

Instead of normal hardening in cold water, the regeneration of an overheated steel may be affected by heating it red hot and quenching it in boiling water, which only causes slight hardening. The experiments of Malberg have shown that the action of the first quenching is the most thorough, and that the effect diminishes with repetition, so that three times heating red hot and quenching in boiling water are enough for the regeneration. The same experiments proved that the water as such does not produce the generation, but that it is rather a question of temperature, so that any liquid would do for the same temperature, *i.e.* if the liquid is at the boiling point of water, or if it is a bad conductor of heat. A good regenerating liquid of the last kind is got by fusing 30 lb. of colophony and then slowly stirring in 20 lb. of boiled oil, so as to make a brown syrupy mass. The fact that the regeneration is a matter of temperature only, is the more important that secret nostrums are offered for sale, which, in any case, do not owe any effect they may have to their frequently adventurous composition. For a chemical action on the steel, even if such an action were thinkable from the composition of the nostrum, the necessary conditions are not present when the steel is merely quenched in it. Besides, a chemical action is unnecessary when the steel has only suffered mechanically, *i.e.* by the development of an undesirable texture.

For which kind of regeneration we should decide depends on the special circumstances of the case. An already shaped tool will not usually be reforged, nor will an unshaped piece of steel be hardened, for fear of the ensuing of cracks in the process.

The regeneration of perished steel consists in adding carbon to its surface by cementation and destroying its crystalline structure mechanically. If oxides of silicon, manganese, chromium, tungsten, etc., are present in perished steel, they cannot be reduced by the regeneration. The regeneration can also be done with a hardening mixture (see p. 103), and the process is nearly the same in case-hardening, differing from it only in the steel to be regenerated being not put into water but hammered until it has lost its glow. A cherry-red heat is used. Perished steel can, however, never be fully regenerated. It never recovers its original strength of elasticity entirely. This is still truer of burnt steel. If the steel is decidedly burnt, efforts to regenerate are just so much labour lost. It is unusable, and will remain so. If it is only very little burnt, it can be somewhat improved by the above process. The many secret preparations which are puffed as able to restore burnt steel by quenching it in them, are a delusion, which exists on account of the usual confusion in the trade between burnt and overheated steel.

CHAPTER VIII.

WELDING STEEL.

I. THEORY OF WELDING.

SOLIDS owe their existence to a force of cohesion which exists between their atoms. Wedding defines welding as a union of separate pieces of wrought iron into one homogeneous piece, and attributes it simply to cohesion which asserts itself when atoms first apart are brought as close together as the atoms in an undivided piece.

The same author gives as conditions for welding clean metallic surfaces and high temperature and pressure, and expresses himself about them thus: Only where the separate pieces of iron have clean metallic surfaces, and are not kept apart by other bodies, such as a film of oxide, or slag, etc., can they unite. The high temperature is necessary to get the iron into a more or less pasty state, so that, under pressure, the unevennesses of the surface can be removed, and perfect contact result. The pressure is also necessary to drive out foreign bodies, which cannot be done unless they are in a liquid state.

Hence, in welding, we must adopt such means as will get the difficultly fusible scale, the formation of which cannot be prevented, into a fluid state. Such a means is afforded by fused silicate of iron, which is formed when the surfaces to be welded are sprinkled with sand or with a quartzy clay. The silicic acid takes up a part of the scale as protoxide. The silicate thus formed will dissolve considerable quantities of the scale or magnetic oxide, without losing its fluidity.

The welding point of steel is below that of iron but above its own forging and hardening temperatures. In welding cast steel overheating always takes place, and if care is not taken, the overheating may easily become burning.

As is well known, the fusion point of hard steel is lower than that of soft, and the temperature at which hard steel acquires the necessary plasticity for welding is very near its fusion point, and hence the difficulty of the welding.

To dissolve quickly the scale which is formed even at the low welding heat of steel, we use instead of sand, or in combination with it, the so-called welding powders which contain partly other acids, and specially alkaline salts which give a very fusible slag. As the slag is the more fusible the more bases it contains, welding powders are usually composed of several ingredients, such as borax, the carbonate of potash and soda, common salt, sal ammoniac, fluorspar, oxide of manganese, and glass.

To prevent also, as far as possible, the unavoidable oxidation, the welding powders are often mixed with carbon-giving bodies, especially the yellow prussiate. Quick heating with as little access of air as possible are required for successful welding.

II. THE WELDING PROCESS.

When two pieces of steel are to be welded together at the ends, they are given a half-wedgelike form, so that the slanting sides can be welded together. The slant surfaces are notched across to prevent any slipping of one over the other under the blows of the hammer. It is still better to fork one of the ends and make the other wedge-shaped so that it can be stuck into the fork. These wedges and forks must not be too small, so as to give a sufficient welding surface. The scale formed by this preliminary shaping is removed by scraping or with a coarse file.

The ends are then put into a clean fire, a charcoal fire if possible, and heated as far as the steel can be without getting burnt. In general, the proper welding temperature for hard steel is when it begins to be yellow hot, and for medium and soft steel between a yellow heat and a dull white heat. If the steel sparks on removal from the fire, it is burnt.

During the heating, a long-handled spoon is used to apply the welding powder to the surfaces to be joined without taking them from the fire and exposing them to the air. When the pieces are at the proper temperature, they are taken out and dipped in the welding powder, which is kept in a box by the side of the fire. The parts to be welded are then quickly put together and hammered, first with a light hammer, but when the steel has become stiffer by cooling with a heavy hand-hammer or a steam-hammer, according to circumstances.

To compensate for a certain amount of decarbonisation which takes place at the outside of the weld, the place, when the forging is over and when it has sunk to a dark red heat, can be sprinkled all round with a uniform thin coating of a hardening powder.

When wrought iron and steel are welded together, it must be remembered that the welding temperature of the latter is lower than that of the former, so that the iron is put into the fire before the steel. It is a good plan to heat them in separate fires, using a charcoal fire for the steel and a coke fire for the iron, as coke develops a higher temperature than charcoal. If coal, containing sulphur, is used, sulphide of iron is formed on the surface of the iron and makes the welding imperfect.

The process of welding steel on iron is practically the same as that described for steel on steel. If two thick ends have to be joined the iron should be forked and the wedge-shaped end of the steel forged into it. This is how the edge of an axe is welded on or thin ends on hammers. If a large surface of iron is to be covered with steel, the latter is applied in several pieces. For the manipulation of these they are made with a tang which can be seized with the tongs. A medium sized anvil-top is steeled beginning with the middle. In two following heats the sides are covered. The steel plates have the edges where they meet beaten up. When they have been welded to the iron, the edges are hammered down and welded together.

If in a welding operation the two pieces have not united, a second attempt with the same pieces of steel is not likely to be more successful. If the steel has received edge-cracks and been burnt, the burnt part must be completely removed before trying to weld again.

The most usual welding powder is borax, which fuses at a bright red heat, and as it can dissolve most metallic oxides is very suitable.

As borax, when heated, swells up very much as it loses its water of crystallisation, it should be melted by itself first and allowed to cool. It then sets to an amorphous glass, which is ground up. Karmarsch gives the following recipe for an approved welding powder:—

Boric acid	83 lb.
Common salt	70 ,,
Yellow prussiate of potash	31 ,,
Calcined carbonate of soda	17 ,,

and another as follows:—

Dried loam	12 lb.
Calcined carbonate of soda	3 ,,
,, ,, potash	2 ,,

or,

Borax	16 lb.
Sal ammoniac	2 ,,
Yellow prussiate of potash	2 ,,

These ingredients are dissolved together in water and then evaporated to dryness at a gentle heat with constant stirring.

In welding the surfaces to be united are spread with a paste of this powder, or sprinkled with it dry. The outer seams are treated in the same way.

Of late, welding powders containing iron filings have been much used. They give very good results, especially in welding large surfaces. The rationale of the use of iron filings is analogous to that of soldering, in which the union of two pieces of the same or different metal is affected with a metallic cement (solder). The solder is brought into a fused state into the join between the surfaces, cools there, and by its adhesion to both of them keeps them together.

As the iron filings attain the welding temperature quickly, on account of their small size, it follows that they aid the union, especially of steel to steel. An approved welding powder of this kind is made as follows:—Mix and powder finely 6 lb. of borax and 4 lb. of yellow prussiate of potash. Then make to a paste with water and boil till the mass is stiff. Then let it harden over the fire. Then grind up the mass and mix it with 2 lb. of rust-free wrought-iron filings.

THE END.

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[*See also* "*Wood Waste Utilisation*," *p.* 33.]

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