## NOTES ON THE HEAT TREATMENT OF STEEL.

Considerable attention has been given in recent years to the subject of the heat treatment of steels and the complex changes that proceed in the structure of the material during hardening, tempering and annealing operations, and the considerations necessary to give the best desired results in any particular case are now well understood. A great deal of investigation has, however, been necessary, and in view of the exhaustive nature of the subject it will only be possible to deal with it in this article in its broad outline with a few particular detailed references. The changes that take place and the terms used in the technology of the processes should be understood and appreciated by all engineers.

If a piece of $0 \cdot 10$ per cent. carbon steel is continuously heated from atmospheric temperature up to about 930° C. (1,706° F.), there will be three points at which, instead of rising, the temperature of the piece pauses, or may even stop. An experiment will show that $0 \cdot 25$ per cent. carbon steel also has three such critical points. The two lower points are at practically the same temperature as those of the $0 \cdot 10$ per cent. carbon steel, but the upper point will be at a lower temperature than the highest point of the $0 \cdot 10$ per cent. steel. If this experiment be repeated with $0 \cdot 50$ per cent. carbon steel, only two points will be observed. The first will be at practically the same temperature as that of the lower carbon steels, but the second point will be lower than their second point. In the case of $0 \cdot 85$ per cent. and higher carbon steels, one point only will be found, coinciding with the first point of the lower carbon steels.
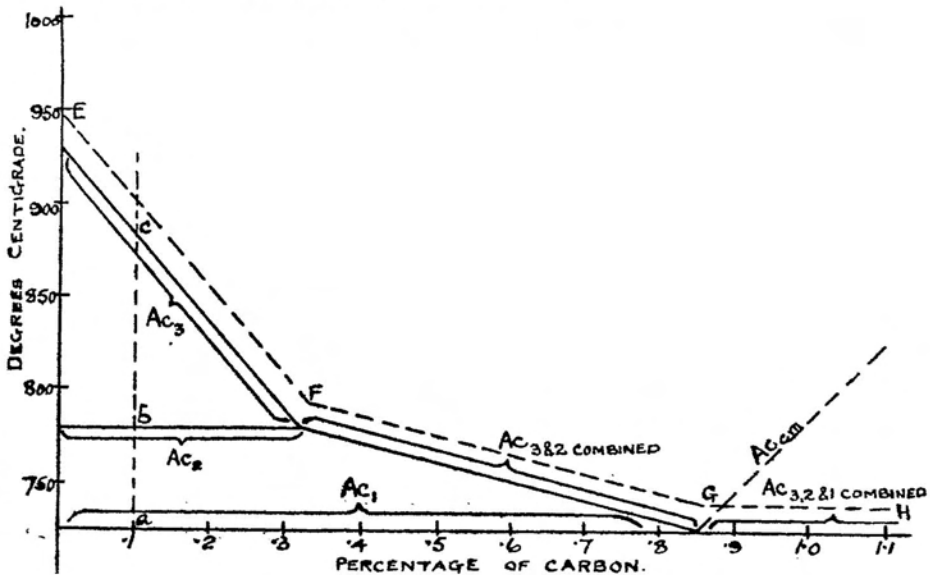
The location of these points can be seen from the diagram, which will also facilitate subsequent references to the question. On the diagram the points " a," " b," and " c " are the three critical points for the 0·10 per cent. carbon steel, and so on, determined by experiment. It should be understood that at present plain carbon steels are being referred to, the effect of additional constituents as nickel, chromium, etc., being mentioned later. It is as well to understand at once, however, that the paramount factor governing these changes is the carbon content.

The critical points that occur in the heating of a steel also occur in the cooling, but at an appreciably lower temperature. If the point occurs in heating it is called an Ac point, and in cooling an Ar point, suffixes being added to indicate the particular point referred to commencing at 1 for the lowest. The point Ar_1 that occurs in cooling is called the " recalescence point," due to the fact that the steel recaleses or actually gets hotter at that point. The term " recalescence point " is sometimes used loosely, but the only correct reference is to the Ar_1 point. The importance of knowing the location of these critical points lies in the fact that the correct hardening temperature is just above the upper Ac point for any steel or along the dotted line EFGH. Theoretically, it is just at the upper critical point, but in practice it is safer to go a little higher.

The range of temperature from the lowest to the highest critical point of any steel is called its critical range. If any piece of steel be heated to just below the foot of the range, and quenched, it will be found that there are practically no changes in its properties. If the steel be heated to a little above, and then quenched, it will be found to have been made stronger, harder and less ductile, *i.e.*, its tensile strength, elastic limit and hardness have been increased, while its elongation and reduction of area have been decreased. These effects are more marked as the temperature within the critical range increases, until at the top the maximum degree of strength and hardness and minimum of ductility are obtained. Above this point there is no gain in hardness or strength, but the grain is made coarser.

A close study of the microstructure of the steel as it passes through these points reveals the causes of the various changes. When a piece of steel is heated to a temperature below the first critical point no change takes place in the microstructure, and hence there is no change in physical properties. But if it is heated to the point Ac_1 and beyond, there is a marked change in the properties and in the microstructure. Depending on the carbon content the structure of steel in its " normalised " state consists of pearlite and ferrite in the case of what are known as hypo-eutectoid steels, *i.e.*, steel with less than about ·85 per cent. of carbon, the proportion of pearlite increasing with the carbon content till at about ·85 per cent. it is entirely pearlite and generally known as eutectoid steel. If the carbon content exceeds ·85, *i.e.*, hyper-eutectoid steel, the structure consists of

pearlite and cementite. It must be understood that ferrite is practically pure iron, cementite is a carbide of iron Fe_3C, whilst pearlite is a fine mechanical mixture of ferrite and cementite. The various structures have each their characteristic appearance under the microscope.

Just as soon as the point Ac_1 is passed the pearlite, instead of remaining as a mechanical mixture of the cementite and ferrite, becomes a solid solution of iron and carbon. As this change of the pearlite has increased the strength of the metal, it follows that the solid solution of the pearlite constituents must be stronger than pearlite in the normalised state. In this solid solution, which, as its name implies, has all the characteristics of a liquid as regards the intermingling of the constituents, it is no longer possible to distinguish the pearlite contituents from one another. As the temperature of the steel is raised above the foot of the range some of the free ferrite begins to enter the solid solution until at the top of the range all the free ferrite has entered the solution, and if the steel is then quenched it will be in the strongest possible state. If the steel contained no free ferrite or free cementite, all the pearlite would go into solution as soon as the foot of the range was passed, and the whole steel would at once be in the solid solution state. In the case of excess cementite being present this constituent does not enter the solution until the dotted line Ac_{cm} is reached.

Having reached the solid solution, if the steel is now quenched or cooled with extreme rapidity it will be retained or locked in this state, so that when cooled it is still a solid solution; this solid solution is called austenite; but as it is not possible to cool the steel instantaneously, the perfect solid solution is not retained in carbon steels, and some of the constituents separate out in the solid solution, the degree of separation or transformation for any particular steel being dependent on the rate of cooling. Microscopic examination reveals just how close the steel is to the solid solution. The first state in the decomposition from austenite is called martensite, then comes troostite, followed by sorbite, and finally pearlite. It is possible to obtain the exact decomposition product in any case by heating to the top of the range, then cooling rapidly enough to get austenite or martensite, and heating below the range. The hardening process converts the steel into a fine-grained solution (or to an approximation) and the re-heating, drawing or tempering treatment allows the steel to decompose into one of the states that experience has shown is best suited for the work desired. It should be mentioned that each of the successive decomposition products of austenite referred to above is softer than those preceding it except martensite which is harder than austenite. The hardest tool steel, for example, consists of martensite at the point of transformation into troostite.

It is not possible in the confines of this article nor is it necessary to discuss the theories underlying the transformations

referred to above during cooling, or quenching and re-heating conditions. It will suffice to point out that hardened steel is generally considered to be in an unstable condition, and therefore eager to return to a more stable form, and actually undergoing this change whenever given an opportunity, *i.e.*, on raising its temperature. If correctly treated the steel is in its finest condition, as regards structure, after quenching and on careful re-heating to the desired temperature the necessary trans-formations take place with the preservation of a fine structural condition in which the steel is again subsequently locked on cooling. Better control can be exercised by a quenching and re-heating treatment than is obtainable by cooling only to the desired temperature which may give the correct transformation product, but not necessarily in its finest form unless carried out under special conditions.

It will be understood that to anneal perfectly it is desired not only to soften the steel, but also to produce a refined grain size. It should, therefore, be heated to just above the top of the range and held there for some time, and then cooled in air away from draughts. Under these conditions the steel is given no chance to set in the solid solution state, but is decomposed through its various states to form soft, ductile sorbite or pearlite, and in a good condition to give the best results in any particular case. The steel is then said to be " normalised." The very slow cooling, *i.e.*, in the furnace or an insulating bed has been found to result in a definitely low elastic range being given to the material owing to the somewhat coarse crystallisation and segregation. In the case of steel castings it is found desirable to exceed the theoretical critical temperature by as much as 180° F., combined with long soaking at that temperature, to break up the coarse-grained structure. If a piece of steel has been worked before annealing the previous work on it has tended to break up the crystalline formation, and in such cases the subsequent annealing temperature can be kept close to the theoretical figure. In general it is not necessary to exceed a temperature of 75° F. above the upper critical point.

The necessity for knowing in any particular case the upper critical or hardening point of the steel is, therefore, sufficiently obvious if best results are to be obtained. This point, in addition to the other critical points, is now sufficiently well known in any particular case of a plain carbon steel, but in addition to the carbon content other elements are present in the alloy steels, which may have an influence on the hardening point. Nickel, for example, lowers this point about 20° C. for every per cent. of nickel in low carbon steels containing less than 5 per cent. nickel (as is usual in commercial practice); manganese also lowers it, whilst vanadium, chromium and silicon have each their modifying influences. The effect of the other rare elements as titanium, molybdenum, tungsten, uranium and zirconium have also to be considered in the special steels in which these

substances are used to produce particular properties. It is impossible, in view of the wide range of steels possessing variations in any of the foregoing constituents, to state the general effect, and each class of steel must, therefore, be treated in accordance with its properties determined by experimental investigation coupled with micrographic analysis.

When the piece of steel is heated to just above the critical range and quickly quenched, a maximum hardness is obtained, this hardness being associated with a very fine grain. If heated further above the top of the range and quenched there will be no gain in hardness; rather the steel would be overheated, and this would be seen in an increase in the size of the grains. A coarseness of grain is a distinct disadvantage, because the metal is weaker and more brittle. If the heating be carried too far the metal is burnt and may develop cracks, and no subsequent treatment, apart from re-melting, can repair such cracks in burnt steel. The alloy steels, and especially those containing chromium can, in general, be heated farther above their critical range without impairing their physical properties by enlarging the grain, than can the plain carbon steels. This fact should, however, not reduce the care required not to proceed to unnecessarily high temperatures, but may be considered as merely a point in their favour.

An important point to be considered is the time necessary to heat the piece to the correct temperature, and the length of time it should be held at this temperature. Too rapid heating may result in cracking the metal or impairing its qualities. No fixed rule can be given for the rate of heating, experience in any case being the principal guide. When heated to the proper temperature it should, however, be held at this point until sufficient time has been allowed for the complete grain transformation to take place throughout the whole piece.

The choice of a quenching medium is governed chiefly by the hardness desired, but the quenching medium employed not only has an effect on the immediate hardness obtained, but also exerts an effect on the properties subsequently obtained by tempering. It should be borne in mind that internal stresses are set up in the steel by quenching as the transformation products occupy a greater volume than the austenite itself. These stresses have to be relieved by tempering. The proper drawing or tempering temperature depends on the use for which the steel is intended. If it must be very hard, it should be tempered at a low temperature or the operation omitted altogether. If a certain amount of toughness or ductility is desired, the steel must be tempered unless it is a steel of such analysis, as, for instance, a very low carbon steel, that it possesses sufficient ductility after being hardened only.

On the introduction of one of the special elements into low or medium carbon steels to form a so-called alloy steel, the structure in the normalised state remains at first pearlitic, but as the pro-

portion of special element increases with the carbon remaining constant it becomes first martensitic and then austenitic. By increasing the amounts of carbon these changes take place at smaller percentages of the special element. The special steels are often greatly superior to the plain carbon steels in possessing greater strength, a high elastic limit and ductility. They are frequently harder and are better capable of withstanding shocks. The broad reason for this is that the elements that produce these effects dissolve in the ferrite and increase the strength of this soft constituent, whilst they exert also a retarding effect in the changes from the austenitic condition.

An important application of an alloy steel for marine purposes is seen in gearing pinions. This steel contains about $3\frac{1}{2}$ per cent. nickel and is associated with a comparatively low carbon content. The effect of the nickel is to lower the critical point appreciably, such steel having a lower critical point of about 680° C. In order to obtain the best results from this alloy therefore in the way of ductility, strength, resistance to impact, and at the same time preserve it in a condition that it can be easily machined, it is necessary after a quenching in oil from about 850° C. to temper at a figure of about 600° C. Although tempering at 650° C. would still result in the production of a material possessing the necessary properties and yet capable of being more easily machined, the risk of this temperature being exceeded must be borne in mind. Moreover, the weakening in regard to tensile strength resulting from the higher tempering temperature is not compensated by any corresponding gain in the resistance to impact. It is recommended generally for large nickel steel forgings that they should be heated and quenched twice, the re-heating for the second quenching being brief, so that the inner parts of the forging do not necessarily attain the specified temperature on the second heat. This treatment will give a hard tough core, but is not perhaps so necessary for shafts and pinions where the normal maximum and impact stresses occur at the outer surfaces and where the best metal is required.

The size of the forgings limits the rate at which they can be cooled by quenching and this necessarily limits the mechanical properties which can be attained. It is therefore important to keep down the sizes of such forgings as much as possible, and in some cases it is considered best to shrink nickel steel sleeves on to a carbon steel shaft as such sleeves are simpler to efficiently heat-treat. In any case except in very small pinions, the forgings are made hollow to assist the obtaining of best results. In a series of tests made with standard nickel steels it is found that, with steel of Admiralty specification, specimens can be made to give an ultimate stress of 52 tons per sq. in. and an elongation of 25 per cent., while if tempered at 650° C. instead of 600° C. the ultimate stress will be 48 tons and 28 per cent. elongation. The specified test of 40 tons and 23 per cent. can therefore with sufficient care be easily obtained in the largest hollow forgings

required for service. In the hollow forgings it is possible to reckon upon much greater uniformity of structure and mechanical properties throughout the thickness in consequence of the more uniform rate of cooling than in the thick solid forgings.

The effects of mass on heat-treatment have to be considered in the general question, and in the case of alloy steels is at present the subject of extensive investigation. Some interesting data in this connection have already been seen and the effect of mass is considerable, even when comparatively small specimens are considered.

The analysis expressed in percentages of one of the steels tested was as follows :—

Carbon - - - - - - - -	·36
Silicon - - - - - - -	·216
Manganese - - - - - -	·54
Sulphur - - - - - - -	·037
Phosphorus - - - - - - -	·053
Nickel - - - - - - -	3·39
Chromium - - - - - - -	·08

The test results were obtained from bars rolled to $3\frac{1}{4}$ ins., $2\frac{3}{8}$ ins., $1\frac{1}{4}$ ins., and $\frac{7}{8}$ in. diameter, and machined to 3 ins., $2\frac{1}{4}$ ins., $1\frac{1}{8}$ ins. and $1\frac{1}{16}$ in. diameter respectively. The bars were heat-treated before machining to the test piece dimensions, the treatment consisting in holding them for 15 minutes at a temperature of 840° C., quenching in oil and then tempering at various temperatures and being held at these temperatures for 30 minutes before cooling off in water. Typical test figures at some of the selected temperatures are shown in the attached table :—

Diam.			Tempered at	Elastic Limit. Tons/ sq. in.	Max. Stress. Tons/ sq. in.	Elonga- tion % on 2 inches.	Brinell.	Izod Test.
Ins.			Deg. C.					
$\frac{11}{16}$	-	-		100	120	5·3	514	6
$1\frac{1}{8}$	-	-		66	86	6·0	440	11
$2\frac{1}{8}$	-	-	100	37	57	17·0	363	23
3	-	-		32	52	20	262	28
$\frac{11}{16}$	-	-		75	82	12·0	352	15
$1\frac{1}{8}$	-	-		57	73	15·5	341	25
$2\frac{1}{8}$	-	-	400	37·5	56·2	18·5	293	23
3	-	-		36	56	17·5	285	23
$\frac{11}{16}$	-	-		60	69	17·3	311	39
$1\frac{1}{8}$	-	-		50	62	21·5	293	44
$2\frac{1}{8}$	-	-	500	37·5	53	20·5	248	33
3	-	-		36·5	54	21·0	255	33

Diam.			Tempered at	Elastic Limits. Tons/ sq. in.	Max. Stress. Tons/ sq. in.	Elonga- tion % on 2 inches.	Brinell.	Izod Test.
Ins.			Deg.C.					
$\frac{11}{16}$	-	-		50	58	21·3	255	70
$1\frac{1}{8}$	-	-		45	55	24·0	262	60
$2\frac{3}{8}$	-	-	600	35	50	24·5	241	55
3	-	-		35	50	23·5	223	40
$\frac{11}{16}$	-	-		32	72	20·0	302	17
$1\frac{1}{8}$	-	-		38	74	11·0	341	35
$2\frac{3}{8}$	-	-	700	36	65	9·5	341	11
3	-	-		30	56	22·0	321	24
$\frac{11}{16}$	-	-		81	102	3·8	477	4·5
$1\frac{1}{8}$	-	-		78	103	2·0	444	6
$2\frac{3}{8}$	-	-	725	Too hard	to saw	—	555	—
3	-	-		Too hard	to saw	—	575	—

An interesting case of the effect of heat treatment on the material of a nickel steel pinion for the gearing of a warship, was revealed when the question of the failure of the teeth of this pinion was made the subject of a special laboratory investigation, and serves to accentuate the necessity for correct treatment if the best results are to be obtained from the alloy.

A tensile test specimen cut from the pinion gave the following results :—

Elastic limit - - - - -	15 tons per sq. in.
Yield point - - - - -	21 ,, ,,
Ultimate tensile strength - - -	36 ,, ,,
Elongation on 2 ins. - - -	29 per cent.
Impact figure - - - -	31 ft. lbs.
Brinell hardness number - - -	185.

The elastic limit is seen to be rather low and the ultimate tensile strength is below the 40 tons per. sq. in. specified. Apart from this the results are satisfactory, as also was the analysis of steel which contained 3·75 per cent. nickel and ·45 per cent. carbon, although these percentages were somewhat higher than usual.

A microstructural examination of the steel showed rather a large size of the crystal grains and it was arranged to heat-treat a specimen to refine the grain and to determine the corresponding change in mechanical tests. A piece was therefore treated as follows :—

The specimen was heated in a gas-fired furnace to a tempera- ture of 830° C., and maintained at that temperature for a quarter of an hour. It was then quenched in oil and subsequently reheated to a temperature of 600° C., and cooled ·in air. It should be noted that the above treatment is that recommended for such steel modified slightly owing to the size of the specimen. In the case under discussion temperature limits had not at the

time of manufacture been specified, the material being judged in the tests of samples taken on completion of the tempering treatment.   The mechanical tests now showed :—

Elastic limit - - - - -	26·5 tons per sq. in.
Yield point - - - - -	38 ,, ,,
Ultimate stress - - - -	49·2 ,, ,,
Elongation - - - - -	20 per cent.
Impact figure - - - -	39 ft. lbs.
Brinell hardness number - -	232

The above treatment left the material a little harder than desirable and a slightly higher temperature of re-heating would have given figures with some reduction of the ultimate tensile strength and hardness number.   The results of the experiment were however sufficient to show the improvement that is it possible to effect in the properties of this nickel steel in the direction of higher elastic limit and ultimate tensile strength by suitable heat-treatment.   The effect of the treatment also showed in a much finer and closer-grained structure under the microscope.

Although the actual failure of the pinion teeth was probably due to what may be termed a mechanical as distinct from a metallurgical cause, both the mechanical tests and microscopic examination revealed that the condition of the steel was not so good as should have been obtained.   It may happen that the necessary qualities of the steel are obtained on the outer surfaces even if the forging has not been correctly treated to ensure a uniform temperature throughout and hence test specimens may give results, which are not necessarily equalled by the material in other parts and which metal is brought into use after machining has been completed.   The necessity for investigations into heat-treatment of large masses is therefore seen to be justified.

The general effects of chromium when added up to a 3 per cent. content have been recently investigated and show some interesting features.   The lower-critical points are raised by the presence of increasing amounts of chromium whilst the upper points are lowered until they merge into the lower points.   Slight modifications to the treatment applied to plain carbon steels are therefore advisable when chromium has been added.   In particular the tempering temperatures of the higher chromium steels have to be higher in order to obtain the required mechanical properties since the rate at which tempering proceeds at a given temperature is greatly diminished by chromium.   Tempering may safely be carried out at temperatures higher than those permissible for carbon steels or steels containing nickel.   As regards hardening some considerable time is required to attain complete solution just above the critical range and a minimum temperature of 850° C. for hardening is recommended.   The presence of chromium tends to prevent the separation of pearlite and ferrite on cooling.   The slowest permissible rate of cooling

through the critical range to produce hardening, and to suppress the separation of ferrite is much slower than is permissible for carbon steels. The tempering of chromium steels containing ·4 per cent. carbon and 1·5 per cent. chromium should be about 650° C. for best results and slightly higher for 3 per cent. chromium.

Stainless steel which will be fully discussed in the article following, serves to illustrate the effect of a high percentage of chromium. A microsection of such steel exhibits nearly all the characteristics of a typical solid solution of the " martensitic " type, showing that the speed of cooling even when slow through the critical range, is sufficient (due to the retarding action of the chromium) to retain the whole of the ferrite in the solid solution. The austenite-martensite change in such steels occurs at comparatively low temperatures and it takes much more time to change. It can therefore be understood that this steel has air-hardening properties under suitable conditions, as previously referred to. Moreover, as chromium raises the temperature of the transition from the pearlite to austenite, it follows that the heat-treatment must, as regards the first heating, be carried out at a proportionately higher temperature to secure the best physical properties of this steel.

The well-known self-hardening manganese and tungsten alloy steels depend for their properties on generally similar effects, the material being maintained by the action of these elements in the martensitic condition. The self-hardening properties are due in the main to the manganese constituent, the tungsten substantially aiding the stability of the structure. In the case of high speed steel which retains its hardness even when at a dull red heat, this is due to the fact that even at such temperature the martensitic condition is sufficiently stable to resist transformation, this stability being due principally to tungsten while the hardness is contributed to mainly by the chromium.

The foregoing review is sufficient to show that the heat-treatment of steel is a complex question that must be treated from a scientific basis, as there are scientific reasons underlying all the changes observed, and which must be appreciated if successful results are to be obtained.