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THE MICROSCOPY OF STEEL

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Although the subject with which I propose to deal to-night is one which is purely of a metallurgical character, yet I think that I need make no apology for bringing it before a Society composed of engineers, since matters connected with the testing of steel are necessarily of vital importance in engineering practice. The study of metals under the microscope might almost be called a new science, so rapidly has it developed during the past twenty years or so, and so broad is the field for further investigation.

There was a time when the engineer pinned his faith to physical tests, such as the determination of tensile strength and elongation, and even to-day there are some people of a conservative turn of mind who think it is not the business of an engineer to concern himself with such trifles as chemical analysis, etc., which appear to them merely as stumbling blocks for the steel manufacturer. It is perhaps only natural that, where a material is used because of its strength, the user should be inclined to confine his attention to tests which will measure this property. Unfortunately, when you make a trial of strength, whether it be with steel or with men, something has to yield. The sample you test must be destroyed, and you cannot be sure that the remainder of the material from which the sample was taken would behave in a similar manner. Experience has shown that you cannot always say that one bar of steel is uniform from end to end. One end may be quite good whilst the

other may be faulty owing to segregation, piping, and similar defects. The steel from the top of an ingot will mostly differ from that at the bottom, and the ingots from a particular heat will differ from one another according to the skill with which they have been cast. Only at that moment, when the whole of a cast is in the molten state in the steel maker's ladle, is it possible to hope for uniformity; and even then the difficulties of thoroughly admixing several tons of liquid metal render it wellnigh impossible to obtain anything more than an approximately homogeneous mixture.

Now, in order to say what the average physical properties of such a mass of molten steel may be after the same has solidified, it is necessary to call in the aid of the chemist, and from the result of analysis it is possible to deduce with reasonable accuracy what sort of metal will be produced under certain conditions of cooling, forging, or rolling, as the case may be. From a knowledge of the percentage of carbon the metal contains, we can definitely say whether the steel will be hard or soft. The exact amount of hardness and strength conferred upon the metal by the carbon is modified considerably by the proportion of manganese and silicon, and, in fact, the whole of the possible constituents. When these are known and accounted for, the expert can predict within a little what tensile strength the material will acquire when suitably rolled or annealed. The effects produced by the elements sulphur and phosphorus are of an evil character, and the possible extent of such effects as red-shortness or brittleness may be inferred from the proportion in which these elements are present. Taken as a whole, the chemical analysis of a batch of steel confers upon it an identity, a sort of family name, by which its doings may be known, and an index as to its character and behaviour.

Notwithstanding the fact, however, that the ladle of molten steel may have given the proper analysis for the purpose for which the metal is intended, yet still the metal may come to grief during the subsequent operations incidental to its manufacture.

The pure, clean metal may, for instance, become contaminated with some of the slag which ought to float upon its surface, and when solid, this impurity may, in many ways, bring about the ultimate destruction of the steel. On the other hand, a change may take place during the process of cooling, whereby certain of the ingredients segregate towards the centre at the expense of the outer layers of metal. The steel may have been allowed to solidify so as to shut in bubbles of air, or to form a hollow pipe extending down through its centre, and rendering it unsound for ever afterwards. Or again, it may have been kept whilst molten in contact with furnace gases for so long that these are dissolved, so that when, afterwards, the metal solidifies, it effervesces as the gases come out of solution, and becomes porous and spongy, the tiny bubbles of gas being elongated on rolling into rokes or streaks.

Sometimes it may be spoiled at a later stage by heating it to too high a temperature, or it may be strained by subjecting it to undue punishment after it has become cold.

Finally it may be subjected to small stresses, repeatedly applied, until one day it breaks down by "fatigue," and shows an appearance which engineers speak of as crystallisation.

Until the microscope, and one might add the pyrometer, came to the aid of the metallurgist, little could be done by way of elucidating the character of such processes. It is true that many defects were readily seen, and some further knowledge was acquired from the appearance of fractures. But, in many cases, reliable conclusions could not

be drawn until, as a result of the great work of Osmond, Le Chatelier, Roberts-Austen, Stead, Rosenhain, and many others, the application of the microscope to the study of metals cast daylight where there was darkness, and opened up a new realm for the application of scientific study.

To-night I wish to explain in outline some of the principles of the microscopy of steel, and to illustrate what it is possible to learn about steel by means of the microscope, using for the purpose slides which have been prepared from specimens tested from time to time in my own laboratory, for the most part from steels manufactured in Australia. The diagrams shown in Figs. 1-5 have been drawn, with slight modifications, after Rosenhain and Goerens. A thorough acquaintance with the subject would, of course, necessitate a study of some complicated problems in physics, but I shall endeavour as far as possible to avoid such matters, and present this subject in the simplest possible form. It is, however, necessary that I should assume that all my hearers know the difference between wrought iron, cast iron, and steel—at any rate so far as their outward properties are concerned. For our purposes, cast iron may be spoken of as iron combined with over 2 per cent. of carbon. This carbon may wholly or partly be removed by various processes, and wrought iron or steel produced.

Wrought iron consists of iron containing practically no carbon, generally interspersed with layers of slag or cinder, which can easily be seen by roughly polishing and etching a section of the material, the structure thus appearing like the specimen I have on the table. Steel is composed of iron and carbon, the latter being present up to 1.5 or 2 per cent. It is practically always manufactured nowadays in the molten state from pig iron or cast iron.

Sometimes special ingredients, such as nickel or chromium, are incorporated with it, but it is not intended to deal with special steels in the present paper, nor, indeed,

with cast iron, since the subject would thereby be too extensive to do adequate justice to it within the time available.

It is proposed to describe, in the first place, how the structure of iron or steel, as revealed by the microscope, is affected by the amount of carbon contained therein, to see how this structure is modified, when the metal is heated to a high temperature, and again when it is quenched, as in the processes of hardening and tempering.

Specimens have also been prepared showing the effect of heating steel after it has been rolled, and the character of such defects as ghosts and segregation. Finally, there are one or two slides to show how the structure is modified by cold strain, the methods of studying fractures, and the character of so-called crystallisation due to fatigue.

Methods of Examining Metals.—Before coming to this, however, it is necessary to explain the method by which the structure of metals may be seen. In the case of transparent substances, a section is usually cut so thin that when illuminated from below the structure is readily seen under a microscope. Metals are, however, too opaque for this purpose, and special methods have to be applied by which a polished section of the metal is viewed by what is known as reflected light, after etching the polished surface with a suitable reagent. Great care has to be exercised in polishing the specimens, on the one hand to secure a polish free from scratches, and on the other to prevent any change in the structure owing to the operation of polishing. It is thus customary to make use of a variety of emery papers graded down to extreme fineness, the scratches from one being completely removed before the next is applied. The last minute scratches are removed by wet buffing on a piece of cloth, using fine diamantine powder.

In order to reveal the structure, the polished surface is usually etched by immersing it in a suitable reagent, and it may then be examined by means of vertical illumination in the manner you will see for yourselves with the exhibit I have on the table. Photographs of the structure may be taken by attaching a camera to the microscope, and in the case of steel, it is sometimes necessary to get a magnification of 500 or 600 diams. to resolve the structure. There are some who talk of photographs under even 2000 diameters, but even with the best apparatus there is nothing to be gained in going over 1000 magnifications—certainly no more detail is seen.

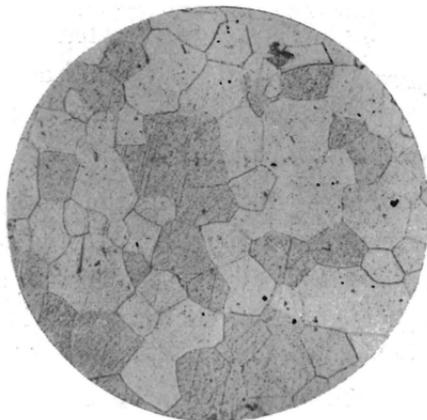


Fig. 6 (x 60).

Structure of a Pure Metal.—Proceeding in this way, we may take a section of Swedish iron, which is practically free from carbon, and in order to eliminate the complications due to any previous forging which it may have undergone, subject it to a preliminary heating to 1000 deg. C., and allow it to cool down within the furnace. When polished and etched for a few moments in nitric or picric acid solution, a specimen cut across the direction of rolling will, under a low power, say about 80 diameters, have the appearance shown in the photo. (Fig. 6).

The surface will be seen to be marked out into areas or grains surrounded by fine boundary lines. Here and there may be seen little black spots of slag, which owe their origin to the method of manufacture; whilst there are still one or two fine scratches due to the very soft character of the metal. You will notice that there is no structure within the grains, but if the latter are deeply etched, they are seen to give pits, known as etching pits, whose shape proves that within the grains the metal has a crystalline structure belonging to the cubic system.

This characteristic structure, composed simply of grains bounded by fine lines, is obtained with other metals, such as aluminium and copper, when they contain no admixture or impurity.

Mechanism of Grain Formation.—It will be of interest to consider how these peculiar boundaries are produced, since it is now known that their size and character play an important part in determining the strength of the mass, a matter on which I shall have more to say later on. In order to appreciate the manner of their formation, let us imagine a mass of the metal in the molten state, but just cooling down to the point of solidification. Freezing will commence at a number of points throughout the mass, and crystals of the metal will grow outwards from such points, each crystal developing along its axes, as I have endeavoured to show by means of squares in the diagram (Fig. 3). Finally, the various systems will meet one another at the boundary lines, when the whole of the metal has solidified.

If the metal, instead of being a pure homogeneous substance, contained some other in solution, then the two will either separate together in the crystals, forming what is known as a *solid solution*, or the foreign substance will be left behind after the crystals have separated. The resi-

dium will, therefore, congregate around the boundaries of the crystals, and perhaps remain fluid after the main bulk of the crystals have solidified. This sort of behaviour is set out in the lower portion of the figure, which represents two constituents—a white and a black, the latter having separated after the whole of the white substance had crystallised out.

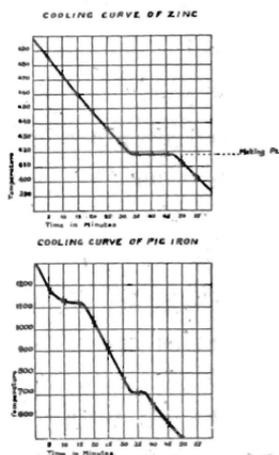


Fig. 1.

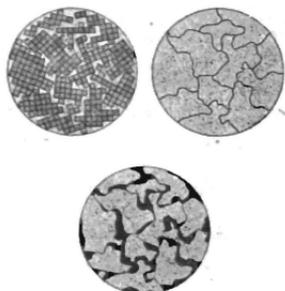


Fig. 3.

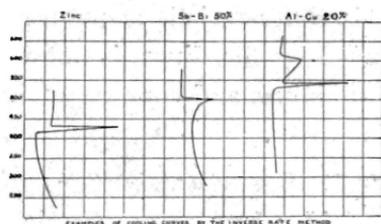


Fig. 2.

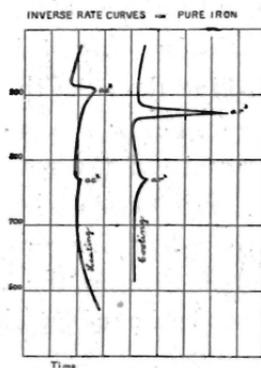


Fig. 4.

Cooling Curves.—So far we have only considered the process of formation of a structure from the point of view of its microscopic appearance, and it may be well here to call to our aid another means of studying the problem.

If we take a mass of fluid metal, and allow it to cool steadily, measuring the temperature as we go by means of a pyrometer, we shall find that at the melting point the temperature will cease to fall, and remain steady, whilst the solid metal is separating. Our observations may be rendered somewhat more precise if we take readings of the temperature at equal intervals of time, and plot a curve—known as a cooling curve—showing the rate at which cooling takes place.

Such a curve is seen in the diagram given in Fig. 1. The upper curve, containing only one sharp break, is a cooling curve of pure zinc, whilst the lower one shows that separation of two distinct constituents took place during cooling, one at a little over 1100 deg. C., the other at about 700 deg. C. This second "recalescence point," as it is called, may have marked the solidification of a small portion of the liquid left at the boundaries of the grains, or it may have indicated that the constituent which separated at 1100 deg. C. underwent a further change at 700 deg. C.

In order to detect very minute recalescence points, very refined methods have in recent years been adopted, and in some of the most up-to-date methods curves, known as "Inverse Rate Curves," are plotted, as shown in Fig. 2.

Owing to their great importance, the investigation of iron and steel has received far more attention in this respect than that of any other metals, and the phenomena which take place during the process of cooling are of a most interesting character.

In the first place, if we take a sample of pure iron, and let it cool down from the melting point, it shows recalescence points long after solidification is complete. These are best followed by reference to Fig. 4, which gives the most up-to-date results of Burgess and Crowe. The left-hand curve shows that a change takes place on heating at

about 770 degs. C., and again at 910 degs. C., whilst if the metal is then allowed to cool, the upper change does not take place until a temperature of about 875 deg. C. is reached, the lower again being observed at about 770 deg. C.

I need hardly say that these points have given rise to extensive investigation, and much controversy has arisen. It will be sufficient for me to tell you that to-day the bulk of metallurgists believe that the purest iron exists in three allotropic forms, known as α , β , or γ iron. When it freezes from the liquid state it comes out as γ -iron. This, in its turn, changes into β -iron at the upper point (ar^3), whilst β -iron is converted into α -iron at about 770 deg. C. (ar^2), the latter being the form in which iron exists at ordinary temperatures. Up to the present no difference in structure between these forms has been proved, although there are certain features which go to distinguish α -iron from γ -iron, some of which we will see later on.

Equilibrium Diagram of Iron and Carbon.—We may now pass on to consider the effect of introducing carbon into iron, but, in doing so, it will be better to deal first with the cooling curves of such combinations since, with that aid, the explanation of the microstructure is a simpler matter. In practice it has been a matter of the greatest difficulty to obtain steels consisting merely of carbon and iron, owing to the difficulty of removing the other elements, such as manganese, sulphur and phosphorus. Certain workers have, however, approached very closely to this state of affairs, the proportion of these other substances having been reduced to a minimum in carrying out their investigations. When carbon is introduced into iron, it has been proved that it forms at least one chemical compound (Fe_3C) known as *cementite*, which is dissolved in the iron.

This compound contains 6.6 per cent. of carbon, and in steels we have to deal with a solution or a mixture of this compound, *cementite*, with the iron. If a series of steels containing gradually increasing proportions of carbon are examined by means of cooling curves, it will be found that the temperatures at which recalescence takes place are greatly modified, and a very small addition of carbon gives rise to an additional point, known as ar_1 , at a temperature of 690 deg. C. The points obtained with each alloy may be plotted in the form of a curve, the proportion of carbon being measured from left to right, whilst the temperature at which recalescence points are observed are plotted as ordinates (Fig. 5). Such a diagram is known as an "Equi-

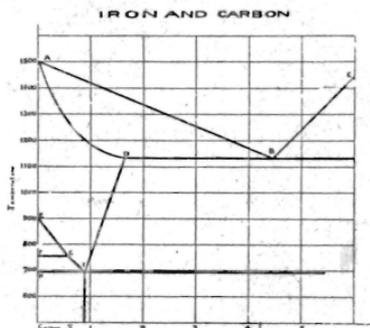


Fig. 5.

librium Diagram" or a "Freezing Point Curve." It enables the metallographer to see what the behaviour of any particular alloy will be when allowed to cool, and tells a great deal about the separation which occurs during this process.

A brief study of this curve at the present juncture will be of some service.

In the first place, if we take iron alone, we get recalescence points on cooling at E and F (called ar_3 and ar_2). The addition of carbon gives rise to a further recalescence (ar_1) at a temperature indicated by the line HI, and further it causes a lowering of the temperature at which the ar change takes place, until ar_3 and ar_2 become the same

at the point G , corresponding to a steel of about 0.6 per cent. of carbon. At the composition I , corresponding to 0.89 per cent. of carbon, the ar_3 point coincides with the new ar_1 point.

If we consider the cooling of a steel from the melting point, we may say that at all temperatures and compositions within the area above, $E G I D$, the metal exists as γ -iron. The change represented by $F G$ is not fully understood at the present time, but it is known that above this line steels are no longer magnetic. When, however, the metal cools down and α -iron has formed, a separate constituent forms, which gives a recalescence point on reaching HI .

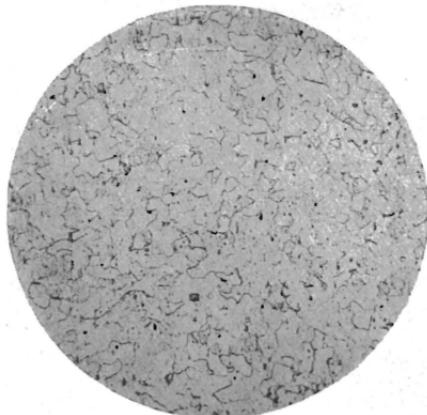


Fig. 7 (x 60).

Effect of Carbon on the Structure.—We may now proceed to examine the micro-structure of a series of steels which have been allowed to cool slowly, and we shall see that this new constituent, named *pearlite*, separates around the grains of α -iron, the latter being named *ferrite*. The *ferrite* which separates, is practically carbonless iron, almost the whole of the carbon being contained in the *pearlite*.

First, we have a very soft steel manufactured at Lithgow, containing about 0.05 per cent. of carbon, a quality which would be very suitable for welding, and which would give