

a tensile strength of about 24 tons per square inch (Fig. 7). This steel shows a number of black specks of slag, elongated in the direction of rolling, and these are largely due to the fact that the steel is made by the basic open-hearth process. Apart from the structure consists entirely of *ferrite*.

The presence of some *pearlite* is clearly seen in a specimen of Lithgow mild steel, containing 0.19 per cent. of carbon (Fig. 8), whilst a still larger quantity is found in a section of an old railway axle, containing 0.25 per cent. of carbon (Fig. 9). This sample of steel is of very high quality, and it was thought possible that it might have been used for the manufacture of shells, but was found to be a little too soft for the purpose.

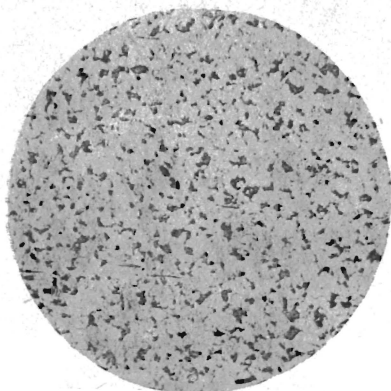


Fig. 8 (x 60).

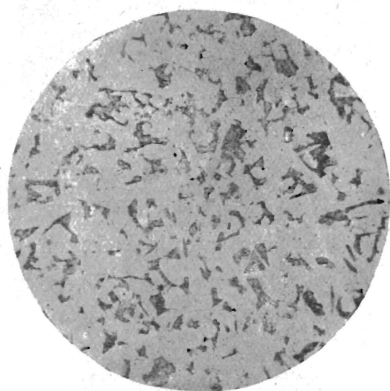


Fig. 9 (x 60).

It may be stated here that the proportion of the dark constituent, *pearlite*, is, to some extent, modified by the amount of manganese which the steel contains. Thus, with the same carbon, the presence of much manganese will give rise to more *pearlite*, and vice versa. This will be seen clearly in the slides now following, the next being taken from a special steel made at Lithgow for manufacture of nuts, and containing 0.58 per cent. of carbon, with a low proportion of manganese (Fig. 10). Compare this speci-

men with the appearance of a section of steel rail manufactured at Newcastle, containing 0.60 per cent. carbon, with a somewhat high proportion of manganese (Fig. 11).

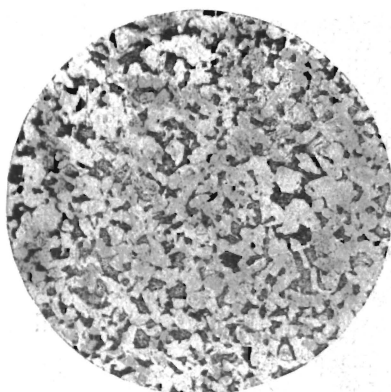


Fig. 10 (x 60)

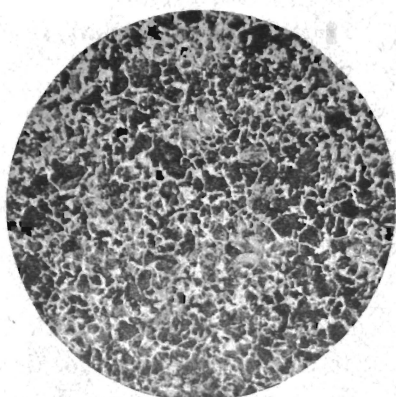


Fig. 11 (x 60)

The great increase in the proportion of *pearlite*, with increasing carbon, will have already been observed, and when we get to a carbon content of 0.89, the whole of the structure is seen to be made up of *pearlite*, as seen in Fig. 12. This sample is taken from a hard steel bit used for boring purposes.

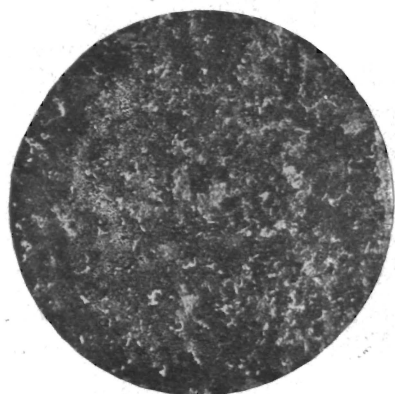


Fig. 12 (x 60).

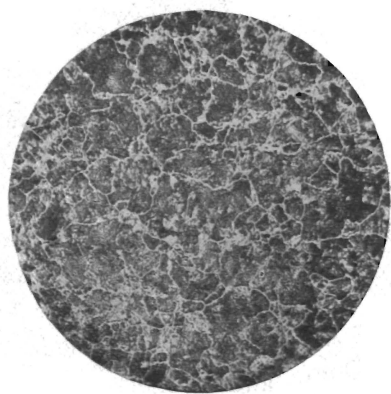


Fig. 14 (x 60).

When the percentage of carbon is increased beyond 0.89, the *ferrite* is no longer seen, but a new constituent, *cementite*, makes its appearance as a clear white network surrounding the *pearlite* (Fig. 14). An experienced eye can identify *cementite* by its appearance; but in order to distinguish it from *ferrite*, the specimen may be etched in a special reagent—hot picrate of soda—which gives the *cementite* a dark colour, and leaves the *pearlite* light. The specimen last seen was treated in this manner, with the result shown in Fig. 15.



Fig. 13 (x 500)

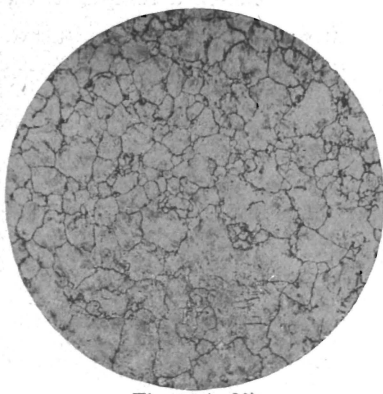


Fig. 15 (x 60)

The whole of the slides so far examined have been viewed under a low power of the microscope, but if a higher power is used it is found that *pearlite* has a peculiar structure of its own, consisting of fine layers, alternately dark and light in colour, as seen in Fig. 13, something very like a thumb print in appearance. This structure causes the specimens to have the appearance of mother of pearl, the light being diffracted at its surface, and from this appearance its name is derived. When *pearlite* appears in this form it is generally called *lamellar pearlite*.

Structure at High Temperature.—Up to the present we have examined only steels which have been allowed to cool down steadily to ordinary temperatures, and in which

the *pearlite* has been allowed to separate, and we have seen that the proportion of this constituent gives an indication of the percentage of carbon in the steel.

If we refer once more to the equilibrium diagram we shall see that at high temperatures, say at 1000 deg. C. (Fig. 5), the whole of the steels with which we have been dealing exist in the condition of γ -iron, from which the carbon has not separated as *pearlite*. Now there are some practical difficulties in the way of applying the microscope at such a temperature, but by special means Baykoff succeeded in observing the structure under these conditions; and his methods have been repeated in my own laboratory.

The sections are first polished and placed in a tube, which passes through a furnace, which can be heated electrically to any desired temperature. A current of hydrogen is then passed through the tube until all air is removed, the current switched on, and the metal heated. After sufficient time has elapsed to bring the mass of metal to 1000 deg. C., a small quantity of dry hydrochloric acid gas is introduced into the hydrogen, and this at once attacks the surface of the iron and etches a pattern.

More hydrogen is then passed through until the acid is completely removed, and the specimen is allowed to cool down. Now, although the internal structure of the metal again changes during the process of cooling, the pattern obtained at 1000 deg. C. still remains, and it is seen that no matter whether the carbon is 0.64 (Fig. 16), or 1.25 (Fig. 17), the structure of γ -iron is the same. The constituent of γ -iron is called *austenite*, and at the temperatures at which it exists the carbon remains completely dissolved in the iron.

It might be thought possible to retain the steel in the form of *austenite* by rapid quenching in cold water. This constituent, however, undergoes transformation very rapidly; but the presence of carbon does tend to slow up the change to some extent, and specimens may be obtained by quenching from steels containing 1 per cent. of carbon. With a large quantity of manganese or nickel, however, the steel can readily be prepared in the austenitic condition.

Before leaving *austenite*, a peculiar feature called "twinning" may be noticed, since this occurs very commonly in this constituent. Parallel markings are seen across the



Fig. 16 (x 120)

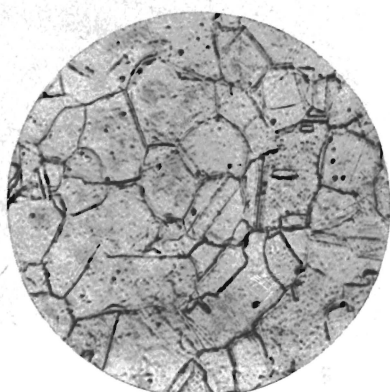


Fig. 17 (x 120)

grains caused by the crystals of one system forming twin crystals with those of the next. These twinning marks are seen also in most metals having a grain structure, which have been subjected to cold work and have then been heated to an annealing temperature, and are particularly to be observed in brass which has been rolled cold and annealed.

Hardening and Tempering—Heat Treatment.—We may now proceed to examine the structures which are obtained in the processes of hardening and tempering of steel.

When a steel containing more than about 0.3 per cent. of carbon is quenched from a high temperature, the cooling takes place so rapidly that the separation of *ferrite* and *pearlite* is prevented, and a hard constituent is formed having a characteristic appearance, and named *martensite* (Fig. 18). This constituent, *martensite*, appears to be a form intermediate between the separation of *ferrite* and *pearlite* from *austenite*, though it must be stated that much discussion is still taking place as to whether this is the correct explanation of its formation. In the specimen shown, a section from a Lithgow fishplate quenched in



Fig. 18 (x 320)



Fig. 19 (x 320)

water, the *martensite* is seen as straw-like needles, which take up a triangular arrangement. This constituent *martensite*, is characterised by the fact that it etches very slowly, and on again heating it undergoes decomposition, passing through a series of transition stages as the temperature rises, until, at about 650 deg. C., it is transformed into *ferrite* and *pearlite*. During the change the steel gradually loses its hardness, the process being that commonly known as tempering.

Several constituents have been described as representing the stages of decomposition of *martensite*, but they may be reduced to the principal ones, namely, *troostite* and

sorbite. *Troostite* is formed when *martensite* is heated to about 450 deg. C. When seen under the microscope this constituent is known by the fact that, whereas the *martensite* only etches slowly, *troostite* readily darkens, and becomes almost black. *Troostite* is also obtained together with *martensite* if the process of quenching is not sufficiently rapid, as seen in Fig. 19.

On heating *martensite* to 550 deg. C. it is converted into *sorbite*, a constituent which is principally characterised by the fact that it cannot be resolved even under the highest



Fig. 20 (x 320)

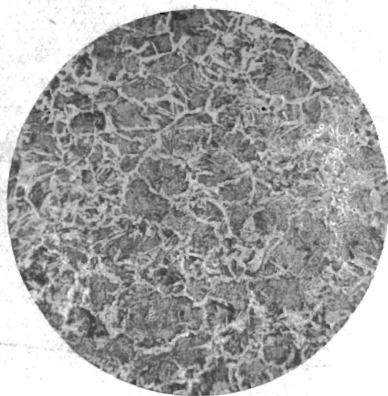


Fig. 22 (x 45)

powers. In Fig. 20 the ground mass is *sorbite*, but the markings are due to the martensitic structure not being heated sufficiently long to be entirely removed.

Sorbite is also obtained in place of *pearlite* when steels are subjected to rolling at the temperature at which the *pearlite* would separate, and it is then seen in conjunction with *ferrite* (Fig. 22).

Sorbite generally confers on steel a little greater hardness, and considerably greater toughness than the metal would possess in the *pearlite-ferrite* condition, and it is to obtain *sorbite* that processes of heat treatment are resorted to in the manufacture of high-grade steel products. Fur-

ther heating beyond the *sorbite* stage transforms the metal into *pearlite* and *ferrite*, and if the heating is not continued too far, such metal will have a fine structure superior to that formed in the direct process of cooling. In the slide shown under a high power (Fig. 21) it is seen that the *sorbite* is just beginning to break up into *pearlite*.

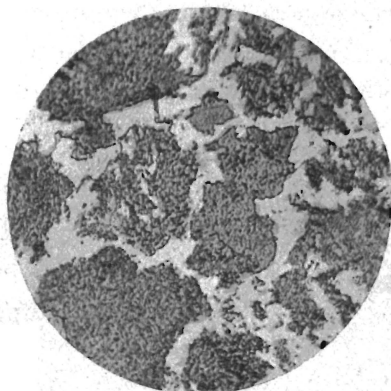


Fig. 21 (x 320)

Size of Grain.—In the foregoing remarks it has been inferred in several places that the size of the grain exerts an important influence on the strength and ductility of the steel. There is no doubt that the grain boundaries represent the strongest portion of the structure, and many theories have been advanced to account for this. Some think that the grains are cemented together by a cement composed of the metal itself in a very thin, amorphous condition. Others are inclined to believe that the strength of the grain boundaries follows directly from the laws of surface tension. The process of rolling breaks down the metal into fine grains, whilst if the same are again subjected to heat, the structure grows, the grains gradually running into one another.

I have prepared a series of specimens showing a section of a fishplate just as it came from the rolls (Fig. 26), and

the effect of heating the same to various temperatures. Each of the photographs is taken under the same magnification, so that comparison may be made.

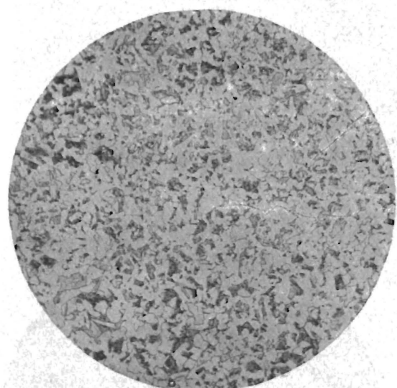


Fig. 26 (x 60)

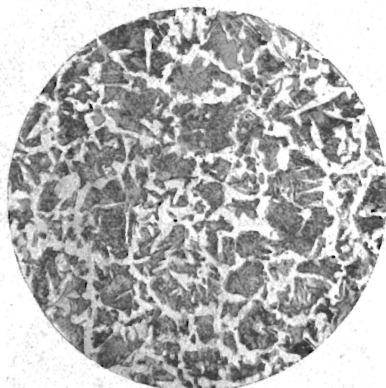


Fig. 27 (x 60)

Re-heating for four hours at 900 deg. C. causes the grains to grow about 6 or 7 times (Fig. 27). A further heating for four hours at a temperature of 1100 deg. C. (Fig. 28) shows a great increase in size of grain, and, in addition, the *pearlite* becomes pierced in all directions by wedged-shaped areas of *ferrite*.



Fig. 28 (x 60)

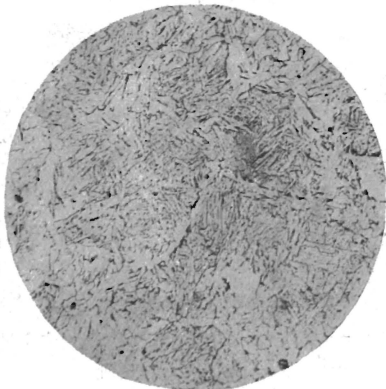


Fig. 29 (x 60)

In the next photo. (Fig. 29) the steel has been heated for a further four hours at 1400 deg. C., and it will be seen that the *pearlite* has largely disappeared, the carbon having been burned out.

These photos. were prepared from small sections, which will naturally be affected by burning more rapidly than large masses of steel. When actual burning takes place it cannot be cured, but a bar which has merely been overheated could be refined by quenching and re-heating. The next photo. (Fig. 23) shows the structure of a bayonet

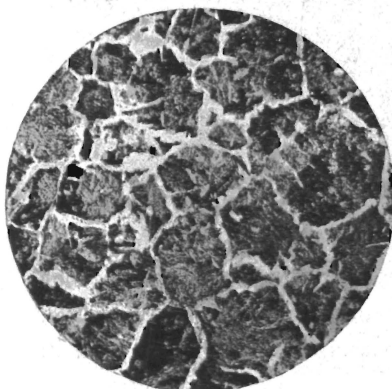


Fig. 23 (x 60).

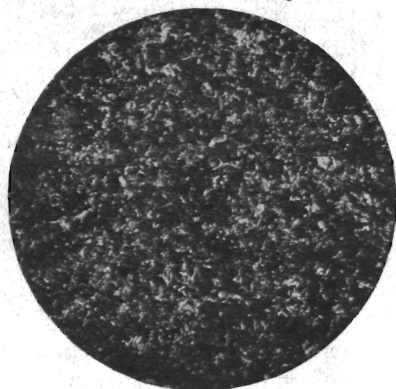


Fig. 24 (x 60.)

picked up on the scrap heap at the Lithgow Ironworks. This bayonet had probably been rejected owing to overheating, and from the structure there is no doubt that it could be refined by the method above mentioned.

Irregularity in Composition.—As an example of the irregularity which may exist in one bar of the same steel, I have two photos. of the structure at each end of a bar of tool steel. Fig. 24 shows the *pearlite* structure that this steel should have; whilst Fig. 25 shows the other end—*ferrite* and *pearlite*—corresponding to about 0.5 per cent. of carbon. Such a bar as this might be expected to give very irregular results if put into use.

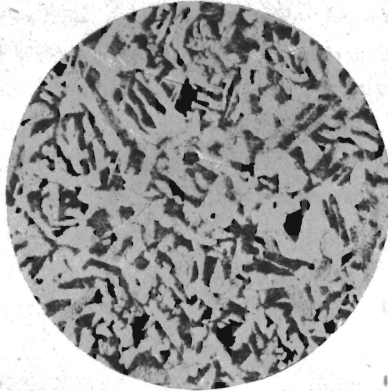


Fig 25 (x 60)

Segregation—Ghosts.—Segregation can, as a rule, be seen without the aid of the microscope by what is often called macroscopic examination. A section of the bar is polished and etched with a suitable reagent, such as picric acid, and the segregated area may then be seen readily. As an example of this, I have two sections of steel rail, one of which was segregated (Fig. 30). The latter, on being subjected to the drop test, split longitudinally, a crack running right down from the head to the base of the flange. In the photo. the top radius of the head was inadvertently taken off in mounting the slide.

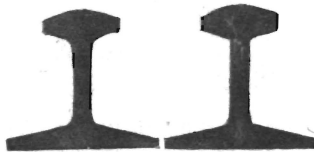


Fig. 30

The segregation of phosphorus in steel behaves sometimes in a peculiar manner. Instead of separating to the centre of the ingot, it often occurs through the metal in irregular patches, which appear to have some relation to the original crystallisation of the mass. When rolled, these areas become elongated into streaks running longitudinally

through the metal. They show themselves on etching by the fact that areas high in phosphorus are etched less rapidly than those free from this element, and a peculiar appearance, known as "ghost" lines, is the result (Fig. 31). A moderately high percentage of phosphorus in steel is not in itself such an objection, but the danger lies in the fact that, by segregation, bands of material may exist in the finished product very much higher in phosphorus content than the average for the whole of the metal.

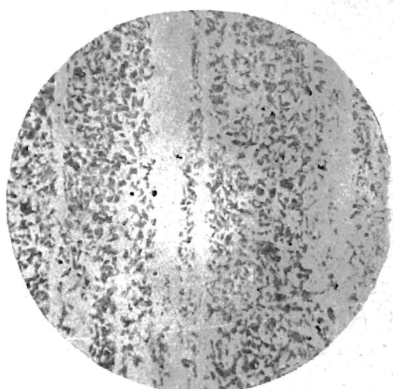


Fig. 31 (x 60).

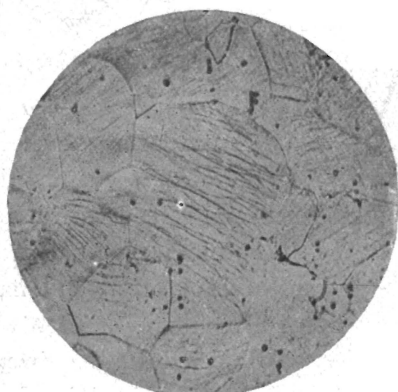


Fig. 32 (120)

Effect of Strain.—The next photo. (Fig. 32) has been prepared to show the effect of straining a bar of iron beyond its elastic limit. This bar of iron was arranged in the testing machine, one of its sides having previously been polished. It was then carefully strained until the metal began to yield, and then photographed. The fine lines across the grains thus rendered visible show the process of deformation. They are called slip bands, and they show that when the metal is strained the crystals within the grains glide over one another, slipping along the gliding planes just like a pack of cards being pushed aside. Further strain causes the grains to become elongated until, just prior to fracture, they exist as long fibres.

My last photograph (Fig. 33) shows the appearance of a fracture caused by "fatigue." In order to obtain this photograph the fractured surface was first cleaned free from grease by immersion in soda. It was then coated with a thin layer of copper by electro-deposition in a cyanide bath, this being used to prevent the face of the fracture from chemical attack. It was then removed to an acid bath, and a thick coating of nickel deposited on the copper. The section was then cut through, polished, and etched.

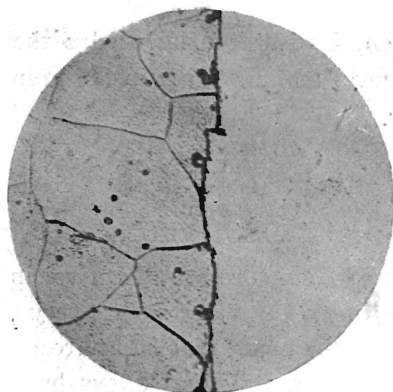


Fig. 33 (x 320)

You will notice that the fracture passed across the grains of the *ferrite*, never around them. The path of the fracture is along the planes of cleavage of the crystals within the grains; and it is this fact that gives to such fractures a crystalline appearance. The idea that metals, when subjected to fatigue or stresses, change their structure and become crystalline is entirely erroneous.

With this photo. I must draw my remarks to a close. I trust that the somewhat scrappy and hurried treatment of this inexhaustible subject may have served to interest you, and to show how the microscope can be brought to

use to trace the causes of failure in steels, and to account for observations which are not explainable until the internal structure of the metal is seen.

The study of this science is still in its infancy, and much remains to be discovered before it can be said that the microscope will elucidate any problem. Nevertheless, the discoveries which have already been made are capable of very direct application in the work of testing steel, and when utilised together with the remainder of a metallurgist's stock in trade, the microscope now serves as a most valuable adjunct.

In conclusion, I wish to acknowledge the assistance of Messrs. P. Pecover and E. Curry in the preparation of the lantern slides.

DISCUSSION

Mr. HARRICKS: I am sure that I am voicing the opinion of this meeting when I say that we are very much indebted to Mr. Smart for the paper that he has read to us to-night. The examination of metals and alloys by the aid of the microscope has assumed so much importance during the last few years that every engineer whose business it is to design or to run machinery must feel that, to some extent at least, he should devote attention to this scientific aspect of the question. Of course, we must at the same time realise that research work must be left very largely to the specially trained physical chemist or the metallurgical engineer; but microscopical examination and its interpretation is within the capacity of every intelligent engineer. The quality and behaviour of metals can be so minutely followed by examination of their structure, that we must all be very keenly interested in what Mr. Smart has told us to-night.