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INSTITUTE OF MARINE ENGINEERS  
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SESSION



1902-1903.

*President*—DAVID J. DUNLOP, Esq.

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VOLUME XIV.

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THE INTERNAL STRUCTURE OF  
IRON AND STEEL,

WITH SPECIAL REFERENCE TO DEFECTIVE  
MATERIAL.

BY

MR. SIDNEY A. HOUGHTON,

*Assoc. Mem. Inst. C. E., Mem. I. & S. Inst.*

DELIVERED ON

MONDAY, APRIL 21st, 1902,

AT

58 ROMFORD ROAD, STRATFORD.

## PREFACE.

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58 ROMFORD ROAD,

STRATFORD, E.

*Monday, April 21st, 1902.*

A MEETING of the Institute of Marine Engineers was held here this evening, presided over by Mr. W. C. ROBERTS, Chairman of Council, when an illustrated lecture was delivered by Mr. SIDNEY A. HOUGHTON. The Lantern Slides were kindly exhibited by Mr. F. L. STURGEON, and admirably served the purpose of illustrating the lecture, which, with as many of the views as possible, is printed in the following pages. We are greatly indebted to Mr. HOUGHTON and to Mr. STURGEON for the interesting and pleasant evening.

JAS. ADAMSON,

*Hon. Secretary.*

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CHAIRMAN :

Mr. W. C. ROBERTS (CHAIRMAN OF COUNCIL).

In the first place I would call attention to the title of this lecture—"The Internal Structure of Iron and Steel." I had at first intended to have described it as the *Microstructure* of Iron and Steel, which is indeed the usual method of describing the structure of the metals, owing to the fact that a



microscope is generally required. It, however, occurred to me that some of you might imagine that there was a difference between the microstructure and the ordinary structure. There is none—there is only one structure of metals, and although as a rule it is necessary to use a microscope to examine it properly this is not invariably the case, and in fact I shall be able to show you a photograph of some iron, the general structure of which is quite visible to the naked eye. That there is some ground that a misapprehension of this nature may occur is, I think, shown by the history of this method of investigating the characteristics of metals. It is now nearly forty years since it was originated; the exact date can be stated with certainty, as, unlike many other discoveries, there is no doubt as to whom the honour is due for first using this method of examination. The first, and for a long time the only, person to do so was an Englishman—Dr. Henry Clifton Sorby, of Sheffield, who is, I believe, still alive. Dr. Sorby is a man of science and has made several discoveries and inventions, but he was not directly connected with the iron industry; indeed, he was at the time mentioned investigating the characteristics of igneous rocks, and it was in order to obtain information respecting certain of their peculiarities that he turned to examine iron, using the same methods as in petrology, i.e., he cut and polished sections so as to be quite free from scratches, afterwards etching them if necessary with acid so as to define the constituents more clearly. (I may say that I have had the pleasure of seeing some of Dr. Sorby's sections, and although the time of preparation has now been much shortened yet in respect to finish we have not appreciably advanced.) The same procedure is still employed, and the keynote of the whole science is, to use Dr. Sorby's words, that steel must be regarded as an artificial crystallised igneous rock, and to get a complete knowledge of it must be examined as such.

Well, although Dr. Sorby read several papers



about 1864, yet they excited little attention amongst those engaged in the iron and steel industry, the reason being probably that the practical men of that day considered that looking at metals through a microscope only showed a microscopic structure as different to the ordinary structure, and that it was too ultra scientific to be of any use; they had therefore to rely entirely on their chemists. Now chemistry is a great and very useful science, and I do not wish to say anything against it, but, as chemists themselves will tell you, the characteristics of metallic alloys have been and are quite unexplainable by their science. Let me take an example: by the addition of very small quantities of bismuth to copper, that metal, usually so ductile, becomes quite brittle, and, moreover, the electrical conductivity decreases. Now there is no relation between the rate at which these alterations take place and the atomic weight of bismuth, i.e., the decadence is gradual and not in steps. The reason for these peculiarities remained a mystery until the alloys were examined under the microscope by Professor Arnold, of Sheffield University, and the slides now shown are copied from some micrographs published by him. In slide No. 1a is seen a section of pure copper which consists of a number of homogeneous crystals; slide No. 2a is that of copper containing .5 per cent. of bismuth. It will be seen that the crystals are bordered by white lines, and there are also a number of dark spots, the latter containing nearly pure bismuth. The nature of the boundaries of the crystals is clearly shown in the next slide (No. 3a), from which it will be observed that each crystal is bounded by a band of what is apparently an alloy of bismuth and copper, and also that there is a distinct line between each which is, according to Professor Arnold, a line of cleavage. It will at once be seen why the strength of the metal has so diminished, and also why the electrical resistance has become greater, the current now having an increased resistance to overcome in passing from one crystal to another. You will see from this

illustration how helpless pure chemistry is for solving many of the problems which confront the metal worker. Nevertheless for about twenty years after Dr. Sorby began his work it was practically the only scientific method adopted, and even to-day there are many people who attach more importance to a chemical analysis than to an examination of the actual structure of a metal. Before leaving this question I desire to draw your attention to a very important weak point in most analyses, i.e., they give the quantities of certain elements, but take no notice of others that may be present in even large quantities; in fact, the chemist is unable as a rule to say whether an element is present unless he specially analyses for it.

The result of sole reliance on this science has been to materially delay the progress of steel manufacture, and has been indirectly the cause of much wasted material and mysterious failures. When these latter were investigated the steel maker would triumphantly produce a piece of paper on which was written that there was so much carbon, manganese, phosphorus or sulphur, all of which were within the usually accepted limits, and, although perhaps he did not directly say so, he would lead one to infer that the cause of the failure must therefore be attributed (to use the words of the old charters) "to the act of God or the Queen's enemies." This of course was not very satisfactory; unfortunately such failures still occur, and although the number is very small compared with the amount of steel made, yet so long as the causes cannot be ascertained and remedies suggested the matter is to my mind a very serious one, and every possible method of investigation should be tried to clear it up.

It must also be borne in mind that, as Professor Arnold has stated, we have got to face the fact that steel which has stood the ordinary tests satisfactorily may yet fail under normal treatment, and that on many such failures chemical analysis throws no light whatever.



As previously mentioned the method which I am bringing to your notice to-night is that which shows the structure of the material, and I think you will all agree that from the most casual consideration it is one which deserves a very high place in any investigation. It is indeed curious to think that people have been content for so long to manufacture and use in such quantities a material such as steel of whose structure they were entirely ignorant. Indeed even quite recently I read a statement that owing to vibration the *nature* of an iron shaft had changed from fibrous to crystalline! While on this point it is necessary to warn those who are beginning the study of the metallurgy of steel against accepting many of the statements in all but the most recent text-books as to the cause of the effects produced by the different elements and by heat treatment on iron and steel. In point of fact many theories previously considered as well proved have been swept away by the microscope, and at the present time the new and correct ones are not properly established. Many of the leading metallurgists in different countries are, however, working on the subject, and I think that in a few years at most our knowledge of the more common conditions will be fairly complete.

Before taking any example of defective material it will be well to describe the ideal structure of iron and steel. Slide No. 4a shows that of pure iron or ferrite, as it is called, which consists simply of crystals of the cubic system, i.e., each crystal is made up of little square bricks, which all face in the same direction in each individual crystal, but are differently pointed, or as it is technically called, orientated, in different crystals. This is very clearly shown in the next slides (Nos. 5a and 6a.) These are from photographs by Mr. Stead, of Middlesbrough, and are of iron containing about 4 per cent. of silicon. The structure is however precisely the same as that of pure iron, but the silicon enables the crystallisation to be more clearly shown. The little crystals seen must not be assumed to be the ultimate structure, as each one consists of



smaller ones, and I think it quite probable that if it were possible to go on investigating we might find that the ultimate molecules were also cubic in form, which result would, I believe, help to support Mr. Macfarlane Gray's theory of heat.

In the recent excellent lectures given here by Mr. Milton he pointed out that all metals are crystalline, but that the crystals were generally imperfect as to their boundaries, and that for this reason some people call them grains. It is undoubtedly true that the outlines of most of those found in ordinary metal are not in accordance with that of true crystals, but I think we should not judge of them any more than people by their outward appearance. Inwardly they are just as purely crystal as a diamond; for this reason I myself prefer to speak of them as crystals.

We will now pass on to steel, and the first thing that strikes us in considering this marvellous alloy is why small additions of carbon make such great differences in its strength and qualities. This remained a mystery until its structure was examined under the microscope, up to which time it was, I believe, a popular theory that it consisted of a very uniform molecular mixture of iron and carbon, the latter being possibly in combination with some of the former. Sir Frederick Abel, the eminent chemist, had certainly isolated a carbide of iron, but I believe only from pig iron. Anyhow this carbide has, as it has turned out, proved to be a very important and in fact the only one we know of as a certainty. Its formula is  $\text{Fe}_3\text{C}$ , that is to say, three atoms of iron to one of carbon, and it occurs in all steel in ordinary use. It is extremely hard when in mass—harder in fact than hardened steel—and is now known in metallurgy by the name of cementite. You will notice that the carbon has, as it were, made itself more powerful and larger by uniting with three parts of iron, but this would not be enough to give the actual strength obtained to steel, and consequently we find it in mild steel in small patches of a curious

mixture of cementite and iron, which is called pearlite. They are the dark areas of the photograph now shown (No. 1), and you will see that by getting between the iron crystals they stiffen the whole mass up and thus produce the great increase of strength of the steel. I should perhaps mention that the pearlite is not naturally dark and is only made so by the action of the agent used for etching, the object aimed at being to differentiate it from the iron crystals.

The section from which this photograph was made was taken from a boiler shell plate which failed in the working, but the defective part is not shown in this slide. In really good material, however, the pearlite would be quite evenly distributed and the size of the crystals would be smaller. This plate contained about .18 per cent. of carbon, and the tensile strength was about 28 tons. In proportion as the percentage of carbon is increased so does the area of pearlite until, as first shown by Arnold, when the carbon reaches .89 per cent. in pure carbon steel or about .8 per cent. in ordinary commercial steel, the whole of the material is composed of pearlite.

The next slide (No. 7a) is taken from steel of this description, which may be called true steel, and shows the pearlite greatly magnified so that its structure may be distinguished. It consists of plates of hard cementite (carbide of iron) alternated with plates of iron; and when viewed in the microscope in a good light this produces an appearance like mother of pearl owing to defraction of light by the thin cementite plates. The name pearlite was in fact given owing to this effect, which was first discovered by Dr. Sorby. The structure now shown is, however, seldom found in practice in mild steel with the exception of well-annealed castings, as when a fair amount of manganese is present the pearlite becomes more or less granular, the hard parts then being, I understand, a double carbide of iron and manganese corresponding to the formula  $(\text{Fe.Mn})_3\text{C}$ . This explanation will, I hope, be sufficient to show how



it is that a small quantity of carbon produces such a marked effect on iron.

There is another important modern method of investigation, which is of considerable help to the microscope, especially when considering the phenomena arising from the tempering or hardening of steel, and that is the use of cooling curves. In the recent lectures by Mr. Milton, that gentleman explained the principle of these curves, and gave some examples of those belonging to certain alloys. It will therefore only be necessary for me to mention that in the diagram No. 8a, which represents the cooling curve of pure iron, horizontal distances represent time and the vertical ones temperatures. At the extreme top a stop has occurred due to the solidification of the iron itself, and you will notice that afterwards, instead of the curve being continuous, there are two distinct breaks in it, and in the case of mild steel there would be a third. The question naturally arises, what is the cause for these breaks or arrest points, as they are technically called, and I regret to say that, with the exception of the lowest (not shown on this diagram) I cannot tell you. The lowest point is acknowledged to be that due to the formation of the cementite, and at the second iron becomes susceptible to magnetism, but in other respects the meaning of these stops has been and is the subject of fierce controversy between two opposite schools of thought—one called the "allotropists" and the other the "carbonists." The first follows the lead of M. Floris Osmond, a French engineer, and includes Sir W. C. Roberts-Austen, chemist to the Mint, and other scientific men. The leader of the carbonists is Professor Arnold, of Sheffield, who is supported by Mr. Hadfield, of the same town, and many others. A brief enunciation of the two theories may be of interest. The allotropists assert that the two upper arrest points in this diagram are due to iron changing from one allotropic state to another. Above the top one called  $Ar_3$  they call the iron gamma iron, between  $Ar_3$  and  $Ar_2$  beta iron,



and below that alpha iron. Moreover, they assert that the hardening of steel is due to the retention in its allotropic state of gamma iron, the only effect of the carbon being to assist in doing so. If this is so, it may be asked why it is not possible to harden absolutely pure iron, to which they reply that the changes then take place so rapidly that one cannot stop them in time. On the other hand, Professor Arnold and the carbonists hold that the hardening of steel is due to the presence of the carbon, and I will briefly describe his theory later on whilst some mild tempered steel is being shown.

The next curve (Slide No. 9a) is due to Sir W. Roberts-Austen, who has so modified the le Chatelier pyrometer as to make the arrest points much clearer and more evident. The curve in fact really represents the difference between the rate of cooling of a piece of very pure iron and a cylinder of platinum. The cause of the top stop in this case was unknown at the time, but has since been found to be due to the wires used in the pyrometer. The two lower arrest points were discovered by Sir W. Roberts-Austen and are due to hydrogen occluded in the metal. This may appear to be of only purely scientific interest to many of you but it has a practical bearing. Many years ago Mr. William H. Johnson found that steel wires if allowed to remain in dilute sulphuric acid became brittle, and he ascertained that the cause of this was the occlusion of nascent hydrogen gas in the metal. This fact is of some interest and importance in dealing with galvanised steel, which is usually pickled in sulphuric acid; fortunately, however, it is found that by heating the metal to between  $100^{\circ}$  and  $200^{\circ}$  C. the surplus gas is driven out and the material regains its normal quality. These pieces of steel wire, for which I am indebted to Messrs. Yarrow & Co., exemplify this peculiarity. The first is in its normal condition and can be readily bent; the second has been placed in a solution of 1 part of acid to 10 of water for half an hour and is quite brittle; and the third has been heated

to about  $100^{\circ}$  C. in a bath and has regained its ductility. Professor Arnold has also pointed out that the hydrogen arrest points occur at what is commonly called black heat when mild steel is known to lose a certain amount of ductility.

This completes what I may call the first and introductory part of my lecture; the second part, being to a great extent devoted to defects in material, as revealed by the microscope, will I hope be of more interest. I have arranged the different samples approximately according to the percentage of carbon contained in them, and accordingly begin with wrought iron.

The slide (No. 2) now shown is taken from the lower end of a wrought iron combustion chamber girder stay which broke after being overheated; in fact the chamber top came down, the cause being excessive accumulation of scale. From a cursory glance at the structure, one might be led to think that the material was defective on account of the number of flaws shown. This is not the case, and I here desire to emphatically controvert an impression that I have heard expressed to the effect that metallographists frequently regard material as defective owing to small flaws appearing big when highly magnified. Ordinary slag or sulphur flaws are as a rule negligible as far as longitudinal strength is concerned, but of course if the material is stressed at right angles to their direction a considerable diminution of strength and especially of elongation occurs. All puddled iron contains oxide of iron and slag flaws similar to those now shown, and to this cause the strength is always less across the grain as it is commonly called. You will observe, however, that this is a somewhat misleading expression, as the crystals of iron are fairly symmetrical unless the material is rolled at a very low heat, and that the so-called grain is only due to the flaws. These also frequently cause the iron to break with a fibrous fracture, but you must not on that account assume that they are a good feature. The fact is that, as previously stated, nearly all iron good or bad contains more or



less of them, but in good material the crystals of iron themselves are so ductile and the coherence between them is so good that they stretch and elongate until the flaws come so close together that fracture occurs. With bad material on the other hand the crystals are brittle and large; they do not stretch to any extent and fracture occurs through them giving a crystalline appearance. Perfectly pure iron is an extremely difficult substance to get owing to the high temperature at which it melts, at which temperature it is practically impossible to prevent it absorbing impurities. Some that has been made however at the University College, Sheffield, proved to be as soft and ductile as copper, and when broken in the testing machine it drew down to a pencil point. I hope these remarks are sufficient to make the following points clear to you—that all iron is crystalline; that absolutely pure iron is similar in ductility to copper; that commercial wrought iron contains a large number of oxide of iron and slag flaws, which when the iron itself is fairly pure cause a fibrous fracture, when impure (although the flaws are still there) the fracture passes through the crystals and the metal appears crystalline.

I will now show you an example of a very impure iron (No. 3). This is from a stay tube of a new boiler, which broke under the hydraulic test. The crystals are abnormally large and quite visible to the naked eye after being etched, many of them being quite  $\frac{3}{16}$  in. long, and this is the metal whose structure I mentioned as being easily seen without the microscope, in the early part of the lecture. The cause of these abnormal crystals is chiefly phosphorus, of which the iron contains .3 per cent., but the metal has also been worked at an improper temperature. The tubes were exceedingly brittle, and the fracture was of a coarse crystalline character. Mr. Stead has shown, as was described by Mr. Milton in his lecture, that phosphorus below 1.7 per cent. was in solution in the crystals of iron (when carbon was absent), but from the markings seen in one of the crystals it would seem as if there was some



sort of a eutectic present in this metal which contains small quantities of carbon, silicon and manganese. I have also noticed somewhat similar peculiar markings, which require further investigation, in several specimens of iron containing an unusual amount of phosphorus. I would now specially draw your attention to these lines, which are not scratches but are called slipbands, and are produced by the straining of the metal when cold; in this case by the rolling of the tube in the tube-plate. You will remember that I showed you that each crystal of iron was made up of a number of small ones symmetrically arranged. Now when a metal is strained what occurs is this. The different rows of tiny crystals begin to slide over each other, and this is how what is called the flow of metals takes place. When such metal is polished and etched the acid eats in between some of the rows and produces the lines you see, and you will notice that these lines are always parallel in each crystal but are at different angles in different crystals. Professor Ewing, of Cambridge, was, I believe, the first to discover these facts, and has given many beautiful examples of strained metals. I should, however, mention that as a rule iron and mild steel, possibly owing to their ductility, are not favourable subjects for this study.

We will now take some examples of mild steel, the most important material with which we have to do. This photograph (No. 4) is taken near the surface of a mild steel boiler plate which cracked whilst being bent in the rolls. It was over  $1\frac{3}{8}$  in. thick, and the test results gave about 30 tons, with over 20 per cent. elongation in 10 in. The dark part of the photograph is the end of a crack, which did not penetrate further, and at the top may be seen the effect produced by hammering the surface of the plate. Owing to the action of the acid and the comparatively low magnification it is not possible to see any slipbands in this part. With regard to the cause of failure in this instance I hope to give you an

explanation when taking a subsequent case, but before passing on I want you to particularly notice that the material is not very homogeneous, and also to note these bands of carbonless iron. With respect to the evil effects of cold hammering, it does not require any special knowledge to see that the crystals are so crushed and bruised that very little adhesion can be left; consequently, if the plate is bent so that these parts are on the convex side a crack is started, and this may easily spread through the whole plate. I also want you to get a rough idea of the proportion of pearlite, i.e., of the carbon to the iron, in order to compare it with that shown in this next view (No. 5), which is from near the centre of the same plate, where there is perhaps four or five times as much carbon. Now this is a very important point, as it shows us that this plate, instead of being homogeneous as one might expect, is composed of steel which may only have a strength of 24 tons per square inch on the surface, and perhaps 36 in the centre. I do not say that from a practical point of view it is any the worse for this peculiarity—indeed, it may be more ductile—but it is just as well to know the facts, and I think it would be interesting to have a series of experiments carried out with metal of this description in order to definitely ascertain its qualities as compared with homogeneous material. The reason for this variation is doubtless segregation of the carbon towards the centre of the ingot from which the plate was rolled, and it is an example of the danger of relying on a chemical analysis without examination of the structure of the material. The metal is somewhat lamellar or streaky—a point of considerable importance, and respecting which a very marked example is given in the next slide.

Slide No. 6 is also from a boiler-shell plate, the strength of which was a little over 28 tons and the elongation good. The structure very closely resembles that of a brick wall, and it is without doubt a very undesirable one, and one which is specially liable to produce failure under vibration. It was in 1899 that I



had this metal under examination, and in 1900 a paper was read at the Institution of Naval Architects by Signor Schanzer, of the Terni Steel Works, Italy, describing a similar structure in a large steel shaft which fractured. He attributed, and I think rightly, the failure of the shaft to this reason, but did not express an opinion as to the cause which produced the structure, though he mentions that possibly phosphorus, which was somewhat high in his case, may have had something to do with it. (In the boiler plate now shown the phosphorus was about .06 per cent.) I am myself inclined to think that the cause will be found in the structure of the ingot, which may be similar to that of a coarse honeycomb, the cell walls being chiefly of pearlite, and the cells themselves filled with iron crystals. I will show you later a photograph of such a structure. When therefore the metal is rolled the iron crystals are flattened out into the layers you now see. Another explanation of this form of structure, which applies in certain cases, has been given by Professor Arnold, and is as follows. If a piece of rolled metal be strongly annealed or very slowly cooled, as, for instance, in the same manner as a steel casting, the pearlite and ferrite will arrange themselves in layers parallel to the direction of rolling, and this will be the case even if previously no such a structure existed. Professor Arnold attributes this to a crystalline habit impressed on the metal by the work done on it. I shall now show you an example of this. This slide (No. 7) represents the structure of a medium steel bar 1 in. square, which a steelmaker had kindly annealed with some mild steel castings; the duration of annealing would therefore be about three days. The structure is of a very lamellar character, and although the tensile tests gave good results, yet such material would be very unreliable under vibratory stresses. In the absence of any approved mechanical tests for finding out the inferiority of this material an examination of the structure under the microscope appears to be the only method at the present time for detecting it.



The next slide (No. 8) is also from a mild steel plate which failed ; this is from near the surface. The most noticeable features are the broad carbonless bands, which are also spotted with sulphur and other flaws, and which are, in my opinion, nearly as deadly in their effects on steel as the "spotted band" described in one of the adventures of Sherlock Holmes was to human beings.

I will now deal briefly with some of the causes which result in the so-called mysterious failures of steel plates. In the first place it may be noted that such plates are frequently those of large size and great thickness ; this results in comparatively little work being done on them, and the crystals of iron are independent of each other instead of interlocking as they do in steel which has been well worked. The same cause also results in the plate leaving the rolls at a temperature much above the normal, causing the iron crystals to be of excessive size. But frequently the most important cause is, in my opinion, the following, which I have long suspected, but confirmatory proofs of which I have only lately obtained ; as far as I know it is quite a new theory. I attribute many of these failures to the presence of carbonless bands as shown in this photograph, which bands, I believe, contain a relatively large proportion of phosphorus, and are very much inferior in ductility to the remainder of the metal. They are generally near the surface, and when one actually outcrops what is called a surface defect is frequently produced. Now when a plate is bent in the rolls and one of these outcrops is reached the inferior metal cracks, and a crack once started will, as you know, go to a considerable depth. At the same time if such a plate is broken in the testing machine the ductility of the remaining metal conceals that of these veins of bad metal ; similarly, although the analysis generally shows that the phosphorus is fairly high, yet it does not indicate that a good deal of it is concentrated in one part. I do not, of course, pretend that all failures of plates can be attributed to

this cause, but it will, I think, be sufficient to explain a good many cases which have seemed mysterious.

The next slide (No. 9) shows the metal at the centre of the same plate; there is a large increase in the amount of carbon and the structure is rather lamellar. I will now show you some examples of the effect of heat treatment on steel, which of course produces a considerable difference in its properties, but of which a chemical analysis will give hardly any information.

This slide (No. 10) is taken from another boiler plate which failed, the causes being carbonless bands (not shown in this photograph) and finishing at too high a temperature, which has resulted in the iron crystals being abnormally large. In the next slide (No. 11) we have a piece of the same material which has been raised to a full red heat (above the upper arrest point) and allowed to cool quickly in the air. You will notice the enormous difference in the size of the crystals of the body, but in the carbonless bands the size is not much altered owing to the phosphorus present; it would therefore appear that a more drastic annealing was necessary in order to remove the effects of the deleterious parts. With regard to the size of the crystals shown I do not wish it to be understood that those of a boiler plate could be made so small in practice, because it would not be possible or desirable to cool it quickly enough, but there is little doubt that those seen in the preceding photograph could have been reduced in size at least one half and the material thereby increased in toughness. You will notice by comparing this and the photograph of the steel bar that whilst prolonged annealing is injurious to forged steel, raising it to a temperature above the highest arrest point and allowing to cool in air is, as a rule, of great value in making it fine grained and thereby improving the qualities of the material.

The next example (No. 12) is a piece of the same plate which has been heated above the lowest arrest point and quenched in water. This naturally brings us to the question of temper bends, in which the steel is generally required to be heated to a cherry red and



quenched in water. Well, cherry red is a somewhat vague expression, but I may point out that unless the temperature to which the steel is raised and quenched is above that of the lowest arrest point, or really the corresponding acceleration point, which is not quite identical and is about  $680^{\circ}\text{C}$  in mild steel, practically no change takes place, and the test is no more trying than if performed with the steel in the normal condition, with which, indeed, it is nearly identical. Now, it is somewhat difficult to measure temperatures exactly with the eye, but the temperature just mentioned corresponds with what careful observers have called a full cherry red. To produce any appreciable effect, therefore, on the steel it is necessary to make sure that this temperature is exceeded. I do not think that this is always the case; in fact, some time ago I received, through the courtesy of one of the leading steelmakers, some pieces of what he called typical boiler plate, which included a temper bend made at his works. The material was undoubtedly very good, but there was absolutely no difference between the tempered material and that in the normal condition.

To return to the present sample, you will notice the pearlite has somewhat extended and assumed a ropy appearance. This is called troostite by the allotropists, but according to Professor Arnold it is a form of martensite.\* Now this is usually considered to be the constituent of hardened steel, and as we do not know its composition at present I do not propose to say much on the different theories regarding it. I desire, however, to let you know what is Professor Arnold's theory respecting the hardening of steel, and which is, to a certain extent, illustrated by this and the following slides. This theory is, I believe, that at the lowest arrest point the compound constituent pearlite

\* Professor Arnold has since stated that he calls this constituent "hardenite;" this is, however, only an alteration of the name, the theory remaining the same. With regard to what is usually called martensite, he states that this is a structure and not a constituent.

changes into martensite, and that as the temperature increases this spreads out and finally permeates the whole mass. This is certainly a simple theory, and it is to be hoped, if only for that reason, that it is correct. The whole matter will, however, be probably thrashed out at the forthcoming meeting of the Iron and Steel Institute.

In the slide now shown (No. 12) it is evident that the dark etching constituent is extending, and in the next, which is the same steel quenched from a still higher temperature, it has diffused still more.

This slide (No. 14), which is at the same magnification as the previous ones, represents the metal at one end of a comparatively new thrust shaft which failed. You will notice the very coarse structure of the metal, as evidenced by the size of the pearlite areas, but owing to the method of preparation in this case the iron crystals cannot be clearly seen. Nevertheless the cause of failure was not due to this structure, and, in fact, a test made from this end of the shaft gave 31 tons tensile strength with good elongation.

The next photograph (No. 15) is taken near the point of fracture of the same shaft, and has a completely different appearance. The general structure is so coarse that it is only partly represented in the photograph, and it really consists of large cells of iron crystals surrounded by meshes of mild steel, and is the same in any plane of section. I may mention that the crossed structure shown is a characteristic of unannealed cast steel as distinguished from annealed metal. From an examination of this steel I have no hesitation in saying that this shaft was a casting and was not forged at all; in fact, only one end of it was annealed, and the cause of its fracture must be ascribed to these features.

The next slide (No. 16) represents a brittle mild steel casting, and is taken from the end of a tensile test piece. The structure shown is not unusual in imperfectly annealed castings, and, generally speaking, consists of cell walls of iron, which enclose a mixture



of pearlite and iron crystals. The cause of brittleness in this case is due to the flaws of sulphide of manganese, which you see in the middle of the cell walls. This was first pointed out by Professor Arnold, and although the flaws in this case are not continuous they probably were before annealing. It should, however, be pointed out that defects of this nature generally only occur in small castings, the big ones, such as the shaft just considered, generally containing sufficient heat to overcome this source of weakness.

The photograph now shown (No. 17) is from the same piece of steel but is taken only about  $\frac{1}{8}$  in. from the fractured end. You will see that the metal has begun to part and that the fracture passes along the cell walls, showing the weakening effect of the flaws previously mentioned. This steel gave only 9 per cent. elongation.

From some different samples of mild cast steel that I have examined it would seem that insufficient annealing is far from being infrequent, and the only perfect structure I have is, I regret to say, from steel made by a foreign firm. However, the structure shown in the next slide (No. 18) is from steel by a British maker, and is very good for cast metal. I do not wish to infer that British makers cannot make as good or better steel than anyone else, only, in some cases, sufficient care has not been taken with respect to the annealing. I am now going to show you photographs of two of the very best medium carbon steels that, I think I may say, the world can produce. They are by two Sheffield firms, and the steel was ordered by a celebrated firm of torpedo boat builders, not unknown in this neighbourhood. I understand the order was for the very best nickel steel of about forty tons strength regardless of price, which, I am told, was a very stiff one indeed.

Slide No. 19 represents the nickel steel supplied by one firm, and if one only regarded the proportion of pearlite the metal would not appear to possess such great strength. The action of nickel on the structure of steel has not been very fully investigated,

but, as far as I know, it reduces the size of the crystals and makes them pointed and interlocking.

The next photograph (No. 20) represents the steel supplied by the other firm, the structure of which is quite different. It is about that of carbon steel of the strength required, so that it is evident that this firm did not use nearly so much nickel. The area of pearlite is such that only sufficient iron is left to form cell walls. This is about the structure generally found in rail steel, and represents about .5 per cent. carbon. You may remember that I mentioned that with about .8 per cent. carbon the whole mass was pearlite.

Slide No. 21 is also metal containing a good proportion of carbon, but as will be seen from the photograph the structure is of an unusual character, part of the areas of pearlite being comparatively small and surrounded by ferrite, whilst in the remainder the areas are very large indeed. This metal is, in fact, something of a curio, as it was found loose in a cavity in a steel forging. It was about  $\frac{5}{8}$  in. thick, the finer structure being on the outside, and I wish particularly to call your attention to the flaws represented by the dark areas in this part.

The next slide (No. 22) shows some of these parts highly magnified, and you can see that a crack joins up the dark areas; this is due to an excess of sulphur. Now sulphur as a rule does not produce any serious effect on ordinary mild rolled steel, for this reason, it unites very readily with manganese, forming sulphide of manganese, and remains in isolated globules. This is dove grey in colour and some is represented by the two half-tone areas seen in this photograph. This would appear, however, that there was not enough manganese in this instance, and when this is the case sulphur is a very dangerous element, stretching itself in thin layers as sulphide of iron between the crystals and making the whole mass absolutely rotten. This discovery, like many others, is due to Professor Arnold.

We will now add more carbon to the steel and



observe the effect. This slide (No. 23) represents blister steel prepared by the cementation process, and which contains probably about 1·4 per cent. of carbon. We have now passed the saturation point when the steel is composed entirely of pearlite, and the extra carbon takes the form of massive cementite, which is brilliantly white when viewed by the microscope. Owing to the massive veins of this constituent this metal is somewhat brittle and requires further treatment before it can be used for cutlery, etc.

In the metal now represented (Slide No. 24) still more carbon is included and we have a new constituent, namely, graphite—similar to that used in lead pencils. This material is called “black heart” steel, and is getting near the border line of cast iron; in fact, some of the latter has a structure similar to this. This steel contains about ·3 per cent. of graphite, and 1·5 of combined carbon, i.e., in the state of cementite and pearlite; you will notice that the plates of cementite are very heavy. Each graphite centre is surrounded by radial iron crystals, which have a very beautiful appearance under the microscope, resembling rosettes, by which name this description of structure is generally known.

This is a view (Slide No. 25) of malleable cast iron taken near the outside. As you are aware, this is cast iron heated in closed boxes with iron ore or oxide in order to extract a certain proportion of the carbon, and by this treatment the metal is rendered sufficiently ductile to withstand a moderate amount of bending. Metal of this description is a very interesting subject to study, but time will not permit me to deal more than cursorily with the matter. The upper part of the photograph is on the outside of the casting, and the metal here consists of iron crystals, all the carbon having been extracted. You will also notice that the crystals have arranged themselves radially to the surface. As we get deeper into the metal pearlite begins to appear, and further on graphite also. Malleable iron therefore consists of a cast iron core surrounded by a more or less thick layer of wrought

iron, and chiefly to this ductile skin its property of bending is due. This teaches us that metal of this description should not be filed or machined, as otherwise we run a great risk of reducing it to the condition of ordinary cast iron, a specimen of which metal is the next slide I have to show you (Slide No. 26).

In dealing with cast iron we have to consider a material in which the quantities of metals other than iron itself are many times greater than in steel, and the structure is, as might be expected, much more varied. In the present instance we have no less than four distinct constituents, not counting sulphide of manganese. The first of these is graphite, which is in globules and plates. These plates are, as has been pointed out by Mr. Stead, generally in a form resembling shells, and are placed at all sorts of angles. If they were in a continuous line the metal would be quite rotten, but being at different angles any pulling stress placed on the metal has a certain amount of solid iron to break. Graphite can, however, resist a very great compressive stress, and it is to this cause that cast iron is so strong to resist compression as compared with tension. Round the graphite plates we find crystals of iron, and beyond them is pearlite, whilst after that we have what is called a phosphorus eutectic. I will describe the nature of this substance when dealing with the next metal, but before doing so I would call your attention to the manner in which this structure illustrates what happens when molten cast iron cools. In the first place the graphite separates out, then come the iron crystals, which group themselves round the graphite plates, and after that the combined carbon, at first in the form of martensite, which afterwards changes to the pearlite shown. Finally at about 900° C., the phosphorus eutectic solidifies, but this has by that time been forced by the other constituents to take up the vacant spaces left, and we therefore find it, as a rule, furthest from the graphite plates.



In the metal now shown (Slide No. 27), also cast iron, there are only three constituents—graphite, iron and phosphorus eutectic. The absence of pearlite is due to the fact that there is a large amount of silicon present which has the power of keeping the carbon in the graphitic state, and the metal is, of course, much softer to file or turn. The silicon appears to be dissolved in the iron, and does not, unless in great quantities, make any marked difference in the structure. In the slides, however, shown at the beginning of the lecture, where there was 4 per cent. silicon, the crystals of iron seemed to resist the action of the acid better, and there is no doubt that a fairly large proportion of silicon makes the iron crystals more brittle. Now with regard to the phosphorus eutectic. In the first place, I should say that the word eutectic is applied to those structural constituents which solidify last; they must also not be in proportions for chemical combination, and generally speaking, they consist of two constituents which may themselves be of compound character. These, as a rule, arrange themselves in parallel lines or dots. Thus pearlite is the eutectic of steel, and, as before mentioned, it consists in its simplest form of thin parallel plates of cementite separated by similar plates of iron. In the iron now shown the phosphorus amounted to 1.4 per cent., and as this eutectic happens to be of a brittle character the iron was rendered very weak in consequence. I would here address a word of warning against judging cast iron by its fracture. Apart from other characteristics, it is practically impossible to tell by this means whether the phosphorus it contains is in dangerous proportions or not. As a matter of fact, the iron now being dealt with had a most clean, close-grained and sound appearance at the fracture; yet it was most inferior as regards strength on account of the phosphorus and silicon it contained. Now phosphorus has several advantages from a founder's point of view—for instance, it increases the fluidity of the metal and assists to make sound castings.

It is, therefore, an element that requires to be carefully watched for and kept within reasonable quantities, say '3 per cent., in castings exposed to steam pressure, and particularly where any shocks due to water-hammer, etc., may occur.

Slide No. 28 shows an enlarged view of some of the same metal; the continuous line of eutectic can be seen, but the most striking feature is this diamond shaped crystal in the corner. This is, I believe, according to Mr. Stead, who has written the standard work on this subject, a rhombic crystal of phosphide of iron ( $\text{Fe}_3\text{P}$ ). This is very rare in ordinary iron and may be regarded as a curiosity.

Slide No. 29 is a more highly magnified photograph of the phosphorus eutectic. In this case the metal has not been treated with acid. Some graphite plates are to be seen.

Another photograph (No. 30) of the same subject but treated with nitric acid, which has revealed the outlines of the crystals of iron; at the same time it has more clearly marked the eutectic itself. The structure of this, which is of a characteristic nature, is very similar to that of the back bone of an animal, and considering how necessary phosphorus and iron are to our bodies, it has been suggested to me that there may be some connection between the two.

It should be mentioned that the normal composition of the eutectic is, according to Stead, about 10 per cent. of phosphorus and 90 per cent. iron, and it solidifies at about  $900^\circ \text{C}$ .

Slide No. 1b, for which I am indebted to Mr. Milton, represents some Cleveland pig iron and is of similar structure to that just dealt with, but contains rather more phosphorus, viz., 1.6 per cent. The metal consists of graphite plates and globules, iron containing silicon, etc., in solution, and the phosphorus eutectic.

Slide No. 31 is a photograph of Carron pig iron, which has the same constituents as the last example, but the phosphorus is only about 1 per cent. The



most striking feature is the size of the graphite plates which are plainly visible to the naked eye and which caused the metal to break with a coarse crystalline fracture. This is, however, merely because the iron has been very slowly cooled, and the metal itself is of better quality than the Cleveland iron, which, it may be remarked, broke with a fine grey fracture. It should also be noticed in this case that the graphite plates are very straight, which is another source of weakness. The phosphide areas are small and disconnected and although the proportion is higher than is desirable, still it would not probably greatly alter the tensile strength, though if subjected to shock, the effect might be serious.

Slide No. 32 represents pig iron used in the basic process and contains about  $3\frac{1}{2}$  per cent. of phosphorus, whilst all the carbon is in the combined form as cementite, there being no graphite present. The brilliant white parts are plates of cementite, the dark parts pearlite, and the half-tone areas a sort of compound eutectic of pearlite and phosphorus, the nature of which is not exactly known. It will be noticed that there are rows of pearlite running across the photograph at different angles. I am inclined to think that these are the borders of large crystals, and what we see is really a secondary or sub-structure. The metal is extremely hard, and sections can only be prepared with the assistance of an emery wheel.

Slide No. 33 is spiegeleisen, which, as you know, is an alloy used for adding carbon and manganese to molten steel. It contains 5 per cent. of carbon and 20 per cent. of manganese. The broad bands are probably the same double carbide of iron and manganese that forms the cementite in the pearlite of ordinary mild steel. The dotted part is a eutectic of some description.

Slide No. 34 represents the structure of silico spiegel, an alloy used for adding silicon to molten steel; it contains 11 per cent. of silicon. The markings seen are a eutectic very similar in character to that of

phosphorus in the cast irons shown, though there is much more difficulty in etching it.

This is the last slide I have to show. I am afraid the particulars I have given are of a rather cursory and superficial nature, but I trust they have been sufficient to let you see the advantages of examining the structure of metals instead of relying solely on analysis. Very much remains to be done, and we are still only on the threshold of the temple of knowledge as far as metals are concerned.

However, as before remarked, there is every probability that the next few years will result in real progress being made, which we shall not have to retract, as has been the case with so many theories propounded before the structure of metals was revealed by the microscope.

In conclusion, I have to express my indebtedness to Mr. Milton for the kind assistance he has given me in preparing many of the particulars I have been able to show you to-night, and I must also thank Mr. Sturgeon for making the very beautiful slides shown at the beginning of the lecture, and for his kindness in coming here to-night to exhibit them.

## LIST OF SLIDES.

Dis- ting- uishing number	SUBJECT	Number of diameters magnified	By whom first published
1a	Pure copper .. ..	11	Prof. Arnold
2a	Copper containing .5 per cent. of bismuth .. ..	11	"
3a	Copper containing .5 per cent. of bismuth .. ..	66	"
4a	Pure iron .. ..	..	"
5a	Silicon steel; $4\frac{1}{2}$ per cent. silicon	100	J. E. Stead
6a	" 4 per cent. "	100	"
1	Mild steel .. ..	58	Original
7a	Pearlite .. ..	700	F. Osmond
8a	Cooling curve of pure iron ..	..	"
9a	" " ..	..	W. C. Roberts- Austen
2	Wrought iron stay ..	53	Original
3	Iron stay tube (phosphoretic) ..	58	"



LIST OF SLIDES—*continued.*

Dis- tinct- gush- ing number	SUBJECT	Number of diameters magnified	By whom first published
4	Mild steel boiler plate near outside	58	Original
5	" " near centre	58	"
6	" " lamellar structure .. ..	..	"
7	Over annealed steel bar .. ..	53	"
8	Mild steel boiler plate near outside	58	"
9	" " near inside	58	"
10	" " .. ..	53	"
11	" " annealed ..	53	"
12	" " tempered ..	53	"
13	" " " ..	53	"
14	Steel thrust-shaft; flange ..	53	"
15	" " at fracture ..	58	"
16	Brittle steel casting .. ..	53	"
17	" " .. ..	58	"
18	Well-annealed steel casting ..	58	"
19	Nickel steel .. ..	53	"
20	Medium hard steel .. ..	..	"
21	Metal found inside a forging ..	24	"
22	" " " ..	236	"
23	Blister steel .. ..	58	"
24	High carbon steel .. ..	236	"
25	Malleable cast iron .. ..	53	"
26	Cast iron .. ..	58	"
27	Phosphoretic cast iron .. ..	75	"
28	" " .. ..	236	"
29	Phosphorus eutectic .. ..	188	"
30	" " " .. ..	385	"
1b	Cleveland pig iron .. ..	58	"
31	Carron pig iron .. ..	53	"
32	Basic pig iron .. ..	53	"
33	Spiegeleisen .. ..	53	"
34	Silicospiegel .. ..	31	"

NOTE.—Slides No. 1a to 9a were made by Mr. F. L. Sturgeon from engravings published in various periodicals, etc.; and Slide No. 1b is by Mr. J. T. Milton.

No. 9a Slide is reproduced by kind permission of the Council of the Institute of Mechanical Engineers, and Nos. 5a and 6a Slides by permission of the Council of the Iron and Steel Institute.

Some of the slides have been reduced in reproduction, but the figures given under each photograph represent the correct magnification.

In these descriptions the words after the number of diameters magnified explain the manner in which the structure was developed. Thus  $\text{HNO}_3$  signifies that dilute nitric acid was employed, and  $\text{NH}_4\text{NO}_3$  that Osmond's polish etching process with nitrate of ammonia or liquorice root was used.

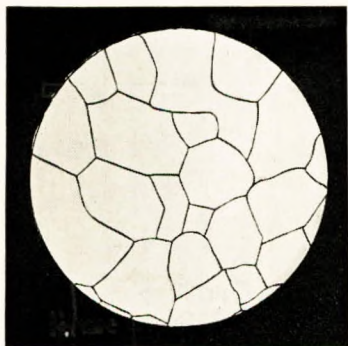




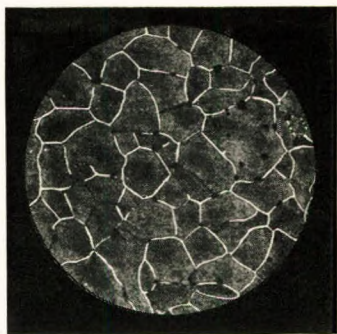




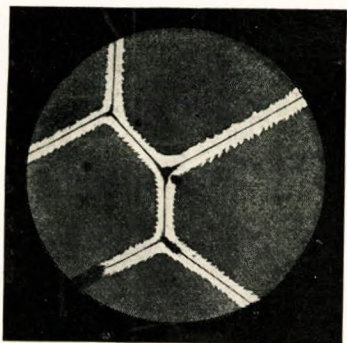




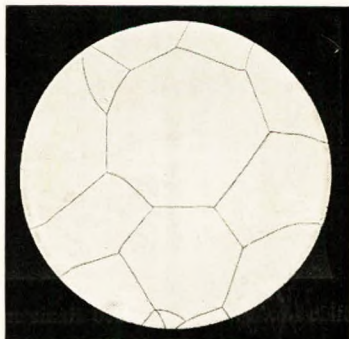
Slide No. 1a. Pure Copper. 8 diameters.



Slide No. 2a. Copper containing .5 per cent. bismuth. 8 diameters.



Slide No. 3a. Copper containing .5 per cent. bismuth. 48 diameters.



Slide No. 4a. Pure Swedish Iron.



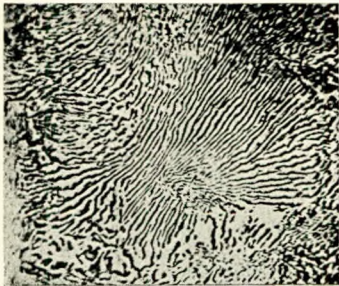
Slide No. 5a. Silicon Steel. 60 diameters.



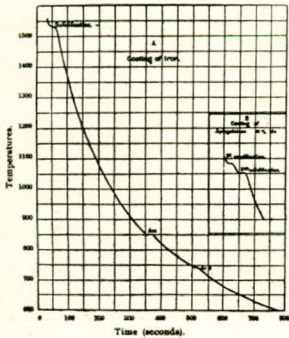
Slide No. 6a. Silicon Steel. 60 diameters.



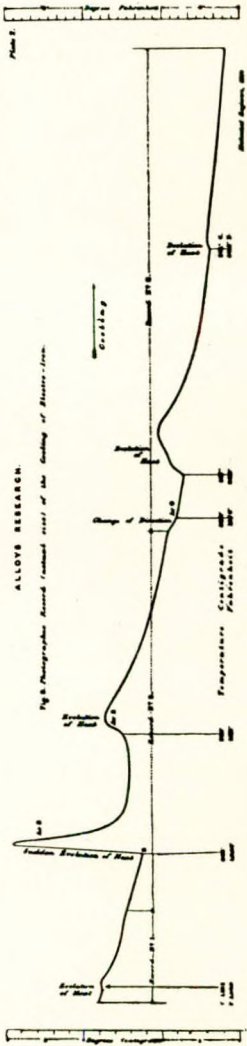
Slide No. 1. Mild Steel.  
58 diameters.  $\text{HNO}_3$ .



Slide No. 7a. Pearlite. 500 diameters.



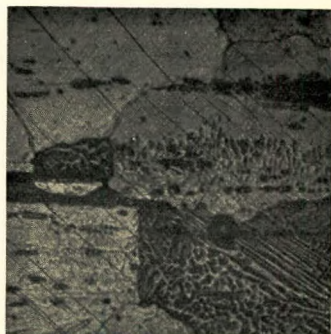
Slide No. 8a.  
Cooling Curve of Pure Iron.



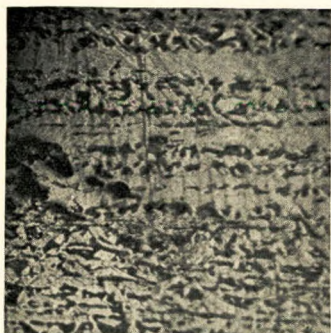




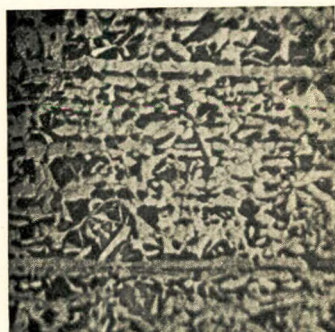
Slide No. 2. Wrought Iron Stay.  
53 diameters.  $\text{HNO}_3$ .



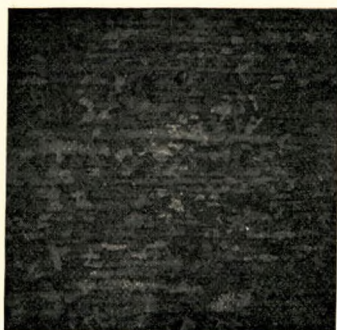
Slide No. 3. Phosphoretic Iron Stay  
Tube. 58 diameters.  $\text{HNO}_3$ .



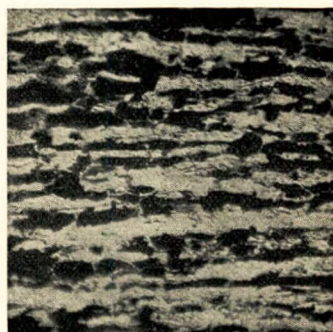
Slide No. 4. Mild Steel Boiler Plate,  
near outside. 58 diameters.  $\text{HNO}_3$ .



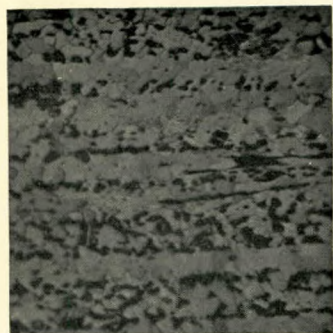
Slide No. 5. Mild Steel Boiler Plate,  
near centre. 58 diameters.  $\text{HNO}_3$ .



Slide No. 6. Mild Steel Boiler Plate.  
 $\text{HNO}_3$ .



Slide No. 7. Over annealed Steel Bar.  
53 diameters.  $\text{NH}_4\text{NO}_3$ .



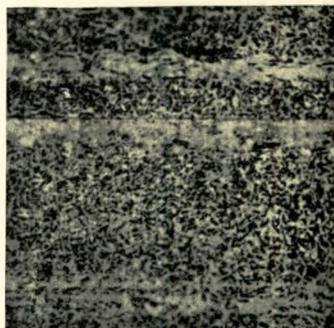
Slide No. 8. Mild Steel Boiler Plate,  
near outside. 58 diameters.  $\text{HNO}_3$ .



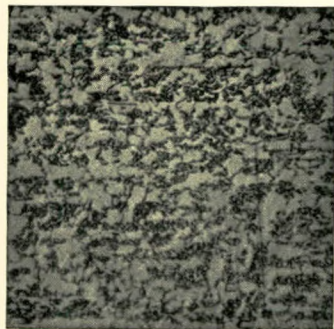
Slide No. 9. Mild Steel Boiler Plate,  
near centre. 58 diameters.  $\text{HNO}_3$ .



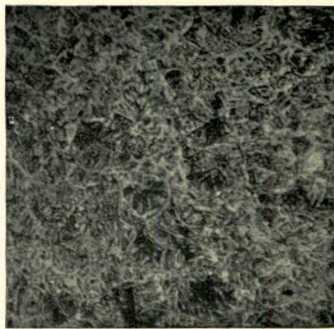
Slide No. 10. Mild Steel Boiler Plate,  
normal. 53 diameters.  $\text{NH}_4\text{NO}_3$ .



Slide No. 11. Mild Steel Boiler Plate,  
annealed. 53 diameters.  $\text{NH}_4\text{NO}_3$ .

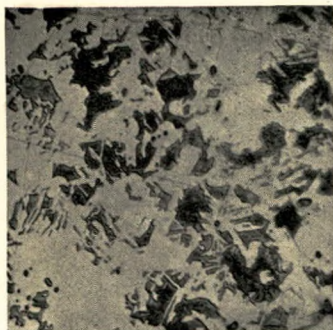


Slide No. 12. Mild Steel Boiler Plate,  
tempered. 53 diameters.  $\text{NH}_4\text{NO}_3$ .



Slide No. 13. Mild Steel Boiler Plate,  
tempered. 53 diameters.  $\text{NH}_4\text{NO}_3$ .

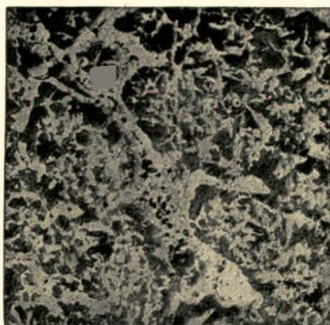




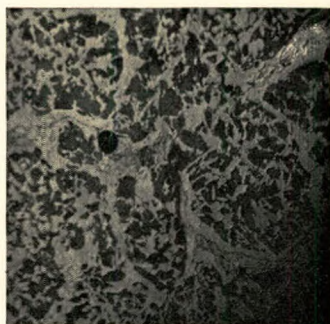
Slide No. 14. Mild Steel Thrust Shaft,  
Flange. 53 diameters.  $\text{NH}_4\text{NO}_3$ .



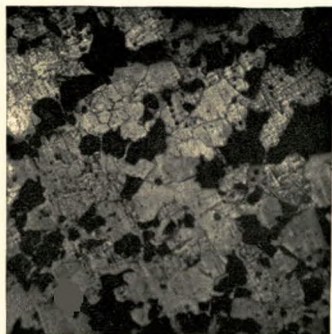
Slide No. 15. Mild Steel Thrust Shaft  
at fracture. 58 diameters.  $\text{NH}_4\text{NO}_3$ .



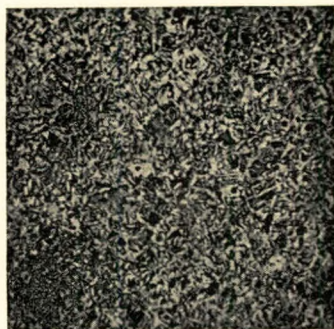
Slide No. 16. Brittle Mild Steel Cast-  
ing. 53 diameters.  $\text{NH}_4\text{NO}_3$ .



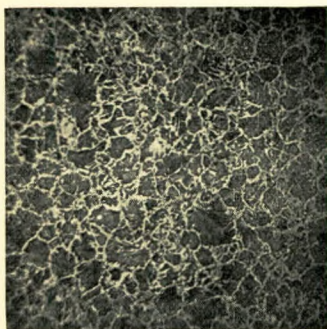
Slide No. 17. Brittle Mild Steel Cast-  
ing. 58 diameters.  $\text{NH}_4\text{NO}_3$ .



Slide No. 18. Well annealed Mild Steel  
Casting. 58 diameters.  $\text{HNO}_3$ .



Slide No. 19. Nickel Steel.  
53 diameters.  $\text{NH}_4\text{NO}_3$ .



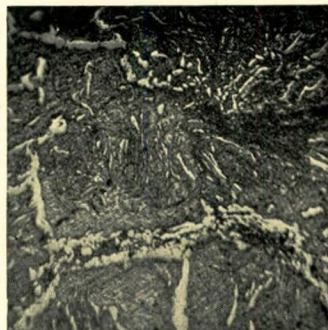
Slide No. 20. Medium Steel.  
 $\text{NH}_4\text{NO}_3$ .



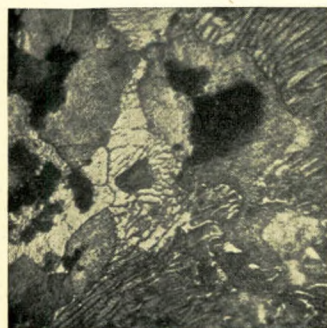
Slide No. 21. Metal found inside a  
forging. 24 diameters.  $\text{NH}_4\text{NO}_3$ .



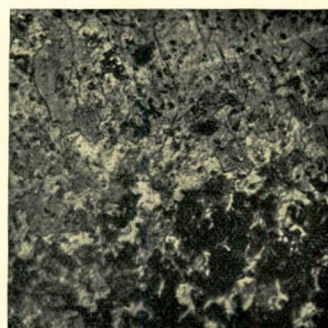
Slide No. 22. Metal found inside a  
forging. 236 diameters.  $\text{NH}_4\text{NO}_3$ .



Slide No. 23. Blister Steel.  
58 diameters.  $\text{HNO}_3$ .

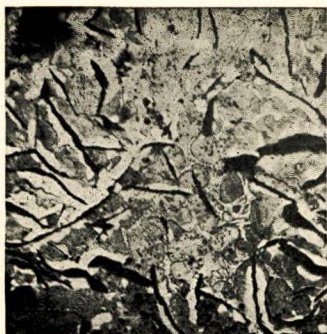


Slide No. 24. High Carbon Steel.  
236 diameters.  $\text{HNO}_3$ .



Slide No. 25. Malleable Cast Iron.  
53 diameters.  $\text{NH}_4\text{NO}_3$ .





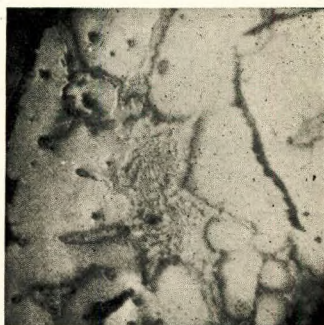
Slide No. 26. Cast Iron.  
58 diameters.  $\text{HNO}_3$ .



Slide No. 27. Phosphoretic Cast Iron.  
75 diameters. Heat tinted.



Slide No. 28. Phosphoretic Cast Iron.  
236 diameters.  $\text{HNO}_3$ .



Slide No. 29. Phosphorus Eutectic.  
188 diameters. Heat tinted.



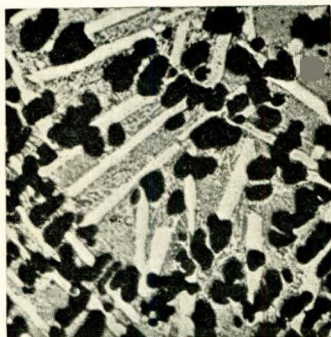
Slide No. 30. Phosphorus Eutectic.  
385 diameters.  $\text{HNO}_3$ .



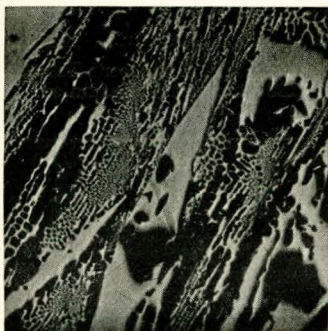
Slide No. 1b. Cleveland Pig-iron.  
58 diameters. Heat tinted.



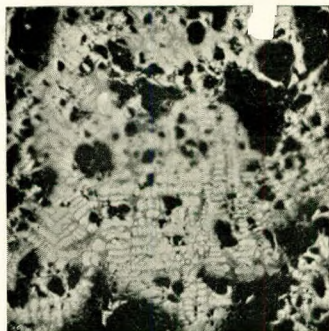
Slide No. 31. Carron Pig-iron.  
53 diameters. Heat tinted.



Slide No. 32. Basic Pig-iron.  
53 diameters.  $\text{HNO}_3$ .



Slide No. 33. Spiegeleisen.  
53 diameters.  $\text{HNO}_3$ .



Slide No. 34. Silicospiegel.  
31 diameters.  $\text{HNO}_3$ .