is liable to spoil his specimens by too long polishing on the cloth blocks, a proceeding which will produce a very uneven surface. This is avoided by making an almost perfect polish on the very finest emery paper before finishing on the cloth blocks.

CHAPTER IV.

PRACTICAL APPLICATIONS OF METALLOGRAPHY.[1]

Introduction.—The study of the structure of metals is practically useful in two different directions:—

1. It develops the scientific instinct, when there is a trace of that instinct to be developed, by arousing inquiries as to what underlies the varied structures seen under the microscope. It stimulates research in order that an answer may be given as to why the varied structures are arranged in the order in which they are found, and to determine what conditions of heating and treatment are necessary to modify and alter them. The spirit of inquiry thus developed, and the efforts to explain the phenomena observed, are essentially highly educational, and must tend to train scientifically the mind of the student.

2. On the other hand, it has direct practical value, for, by its application, one can often judge by the structure of metals the thermal and mechanical treatment to which they have been subjected, for there is a constant relation between microstructure and the

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[1] Abridged from a lecture delivered by Dr J. E. Stead, F.R.S., before the West of Scotland Iron and Steel Institute, 12th January 1912, and reproduced here by permission of the Council.

previous treatment. Many instances of what has just been stated will be given presently.

Selection of Specimens.—In the case of metals which have failed during use, it is necessary that the specimens should be cut from the metal close to where the fracture initiated, for it is possible that every part of the material may be good excepting that which actually gave way. The importance of this is not always recognised, and specimens taken from positions far removed from the seat of failure are occasionally sent to the expert for examination and report as to cause of failure—a proceeding which is equivalent to asking a medical practitioner to examine one's perfectly sound toe with the expectation that he will be able to tell why there is a tumour on one's neck.

Except in case of local failure in steel, it is not so important to select the position from which the specimen is taken.

Macrostructure. — In order to understand the structure of metals, it is first necessary to study the macrostructure—that is, the structure visible to the naked eye, unaided by optical instruments of any kind. This study may correctly be compared to the exploration of a country. The general contour, the rivers, lakes, forests, mountains, are first of all mapped out; then follows a closer study of the individual rocks, trees, flora, and other objects which require closer investigation. The primary exploration of the greater area is analogous to the study of the macrostructure, whilst the closer examination corresponds to the study of the microstructure. If the specimen be that of a broken axle, the first thing to do is to make a general survey of the fracture itself with a pocket lens, and note whether breakage has been sudden or in detail. This is easily determined, for, if the former, the surface will have a more or less granular appearance throughout, readily seen, even if the surface is rusty. If the fracture has been one partly in detail, that is to say, one in which the primary rupture has been gradual, evidence of this will usually be present. Detail fractures always terminate in sudden breakages, and the difference between the two is most marked. The fractures in axles which have grown gradually are much smoother than those which occur suddenly, the smoothness being the result of the partially separated surfaces, originally granular, repeatedly opening slightly and coming together again during the alternating stress applied during rotation of the axles. This produces the same effect as is obtained by hammering a granular fracture till the surface is smooth.

It often happens in the case of broken axles that well-defined zones are noticed, probably indicating different speeds of growth, and that at some periods the stresses have been greater than at others when the fracture has travelled rapidly, and that it has ceased to grow for a time or not grown so rapidly when the stresses have been reduced. The appearance of these zonal lines helps to locate exactly where the initial fracture started. This is the point which it is all-important to find. Having found it, search must be made to discover whether there has been any flaw or indent in the metal, or the presence of particles of cinder near to or below the surface. Should any of these be present, one may be justified in concluding that they would lead to the concentration of stresses at these points during the time the steel was in use, and to the initiation of the fracture.

I have usually found that the greater the area of the slow-growing fracture to that of the complete section, before sudden snap occurs, the better and more reliable is the steel. This observation, however, must not be accepted as a law, for one can conceive many exceptional conditions which interfere with such a conclusion.

Having failed to detect any local defect, sections must be sawn out for microscopic examination. In general cases it is advisable first to obtain a fractured surface and examine it with great care. If it is steel, and is too hard to cut or machine, note whether the fractured surface is finely or coarsely crystalline. If exceedingly fine, the steel has probably been hardened by quenching from a little above the critical point; if coarse, the heating has been higher. If glazed and coarse, it has been heated to far too high a temperature. If the steels or metals can be machined, note whether finely or coarsely crystalline or fibrous. If a bronze, note whether traces of fir-tree crystallites are visible in the fracture, or if some of the separate crystals are coated with films of a lighter colour than the bronze itself. If steel, note if there are any points indicative of unsoundness. Note any and every peculiarity.

Grinding and Polishing.—Having obtained the specimens, they must be cut in two directions, one at right angles to the other. A suitable size for polishing is a face not more than one inch square and a quarter of an inch in thickness. They should be stamped on the back, so that they can be identified.

The surfaces are made smooth by filing or grinding on coarse emery cloth, and afterwards on progressively finer emery paper, until the finest French paper 000 is reached. Fine polishing is then conducted on a wheel either having horizontal or vertical motion, and covered with two layers of thick khaki cloth between which a layer of diamantine powder or other specially prepared polishing powder is placed. The cloths are secured in position by a tight-fitting flat ring, which is pressed over the double cloth covering and the periphery of the wheel. Water is run on to the prepared surface of the polishing block, and the specimen, held between the thumb and fingers, is made to traverse across the face of the disc, which must revolve rapidly at at least 1000 revolutions per minute. Pressure must be applied strongly at first, and then be gradually reduced until finally little more than the weight of the specimen and the fingers holding it press on the polishing surface. With practice a specimen can be prepared in ten minutes. It requires some little experience before a satisfactory polish is obtained, and the softer the metal the greater the difficulty of obtaining a good result. For those who have no mechanically driven machinery, it is quite possible to do excellent work by hand polishing; indeed, the original metal objects used by the father of metallography—Dr Sorby of Sheffield—were hand polished, and many were prepared by his devoted mother, who was intensely interested in the researches of her highly gifted son.

Dr Sorby allowed me to examine many of his specimens, and I can testify that the preparations were perfection, and were examples of what can be done with the simplest means and the least possible cost. Hand polishing is eminently suitable for ladies. The noble example set by Mrs Sorby might well be followed by the wives, sisters, mothers, and the fiancées who wish to help their masculine relations and friends and lovers in that most instructive and interesting of studies—the structure of metals and alloys.

The specimens having been polished, they should be examined under the microscope to detect slag inclusions, porosities, sulphide of manganese, or differently coloured portions of metal. More detailed directions as to polishing will be found in Chapters I. and II. of the present Part.

Etching the Specimens.—After having made sketches or photographs of the appearance of the unetched surface, the specimens are treated with dilute etching fluids suitable for the particular metal, or are heated till they assume oxidation colour films. They are then again examined.

Etching Reagents Used.—A 10 per cent. solution of copper ammonium chloride for revealing the presence of phosphorus segregation in steel. 5 per cent. solution of picric acid in alcohol. The same solution as the foregoing plus 2 per cent. nitric acid for the rapid development of the structure of carbon steels. Ferric chloride, with or without hydrochloric acid, for the development of the structure of brasses and bronzes. 3 per cent. solution of strong sulphuric acid in water for use when taking sulphur autoprints. A 1 per cent. solution of nitric acid in iso-amyl-alcohol. A 4 per cent. solution of nitric acid in iso-amyl-alcohol.

Etching Reagents recommended by Kourbatoff.[1]—The most delicate reagents to differentiate the constituents of steel are:—

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[1] *Revue de Metallurgie*, mars 1905, p. 186.

Reagent A.—4 per cent. solution of nitric acid in iso-amyl-alcohol.
Reagent B.—20 per cent. solution of hydrochloric acid in iso-amyl-alcohol, with the addition of one-third of its volume of a saturated solution of nitraniline or of nitrophenol in ordinary alcohol.

The former of these reagents, which is the most delicate, assists in establishing a difference between brittle and non-brittle steels, and in recognising the lamellar structure of "fers de lance" in nickel steels and also troostite.

The best reagents for colouring the sorbitic material and troostite without acting on the other constituents are:—

Reagent C.—1 part of a 4 per cent. solution of nitric acid in acetic anhydride.
1 part methyl alcohol.
1 part ethyl alcohol.
1 part iso-amyl-alcohol.
Reagent D.—3 parts of saturated solution of nitrophenol.
1 part of 4 per cent. solution of nitric acid in ordinary alcohol.

Tempered Hardened Steel.—The microscope is of little use in determining the proportion of substances in steels which have been tempered after hardening. The only method which approximately gives any useful result is based on the fact that the colour they assume on etching is proportional to the degree "let down" after hardening. In a given time, polished specimens on etching become darkened proportionally to the heat of tempering (fig. 95).

The figure represents a piece of steel containing 0·90 per cent. carbon. It was heated to 900° C. and quenched in cold water; it was then polished, after which one end was held in a cold vice, whilst the other end was heated till the temper tints—yellow, blue, steel-grey—appeared in sequential order. The piece was cooled, repolished, and immersed in a 1 per cent. solution of iso-amyl-alcohol for twenty seconds. The hardened untempered end remained white, and the tempered parts darkened steadily from the end which had been heated. It was washed with hot water and alcohol, and dried in a current of hot air. The results show a gradual merging in the depth of colour from bottom to top.

Fig. 95.—A short bar of 0·90 per cent. carbon steel quenched in cold water and reheated to colour tints described on figure, one end being kept quite cold. It was etched with 1 per cent. nitric acid in iso-amyl-alcohol. Note the gradation of the darkening. Traces of the needle arrangement of the martensite could be detected as far down as where the steel was tempered to steel-grey. × 2.

A standard method might be arranged on this basis to determine the relative degree of tempering. Of course the standard for comparison would have to be a hardened piece of the same steel as the one tested.

Distortion of Metals when in the Cold State.—It is well known that when steel is crushed severely its tenacity, whilst being decreased in the direction of the previously applied crushing stress, is increased at right angles to the direction of crushing. Drawn wire is an excellent example of this. When drawing a steel wire rod it is elongated by being crushed on all its sides, and increases enormously in longitudinal tenacity; but at right angles, that is to say, through the wire from wall to wall, the tenacity is feeble, and by continuing the crushing by drawing too far, it is sometimes possible to tear the wire into fibre or threads, just as though it were a piece of cane. Even well-drawn wire, on being repeatedly hammered round its circumference, can be made to split up into separate threads.

Again, when bars of steel are bent, the concave sides are crushed whilst the convex sides are extended. If the bending be continued until the convexity of the crushed side has a very small radius compared with the thickness of the bar, attempts to bend the steel back again invariably lead to breakage through the crushed part, and the fracture, having started, travels through the whole piece. Fractures of the compressed and extended portions are always quite different, for whilst that of the compressed part has a flat schistose appearance, the fracture of the extended steel is granular. It is for this reason that steel bars or plates which have been bent close or nearly close always break on attempting to straighten them (fig. 96).

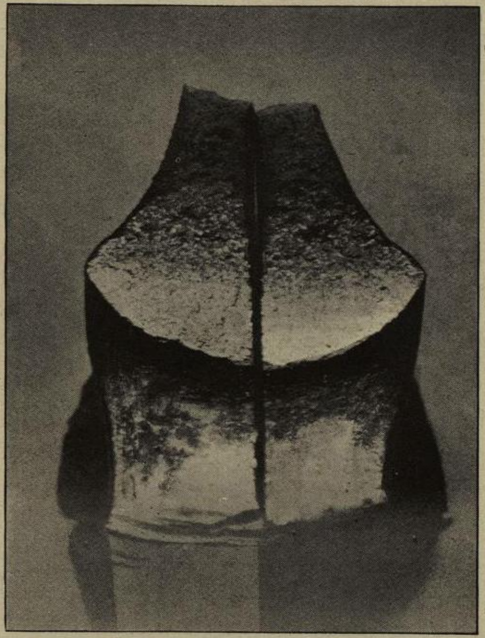

Fig. 96.—Fractured surface of a quarter-inch square, soft steel bar which had been bent over close and broke at once on attempting to bend back. The wide whiter part is smooth and schistose in character. The contracted dark part at top broke with a granular fracture. × 2½.

The crushed edges of steel plates which have been cut by shears are always more or less tender, and are liable to give way under stress.

The illustration (fig. 97) shows the characteristic appearance of a crushed edge of a steel plate which was just at the point of being cut through by shearing. The crystals have been elongated, suggesting a schistose structure.

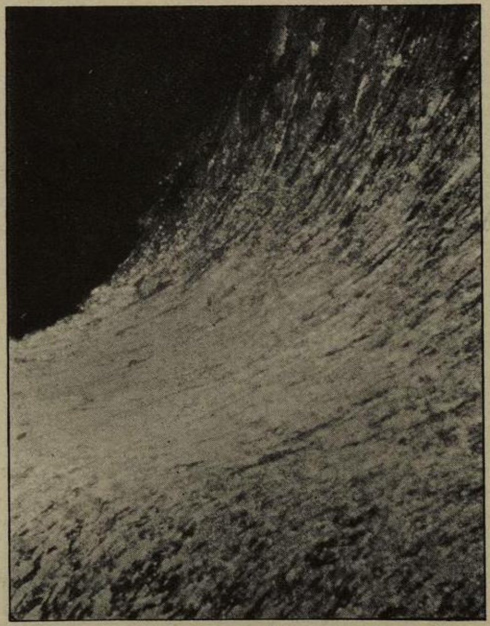

Fig. 97.—Boiler plate at the point of being cut completely through by shearing. It was illuminated by light falling obliquely on the surface. When the specimen was rotated, the bright, crushed portion appeared dark. × 50.

Crushing in this, and in all steels which have been subjected to severe cold distortion and made treacherous, can be most readily detected after etching the polished sections with copper ammonium chloride and rotating them when illuminated by rays of light which fall on the surface at an angle of about 45°.

The crushed area becomes alternately bright and dark according to whether the light falls across or at right angles to the direction of crushing (fig. 98).

Steel plates are variable in their susceptibility to crushing. Some boiler plates I have met with could be sheared and then bent nearly double and then back again without snapping, and the fracture when it eventually started tore with a fibrous, not a granular appearance. Other plates equally good in every other respect, chemical analysis, tenacity, ductility, etc., broke with a snap, yielding a granular fracture which

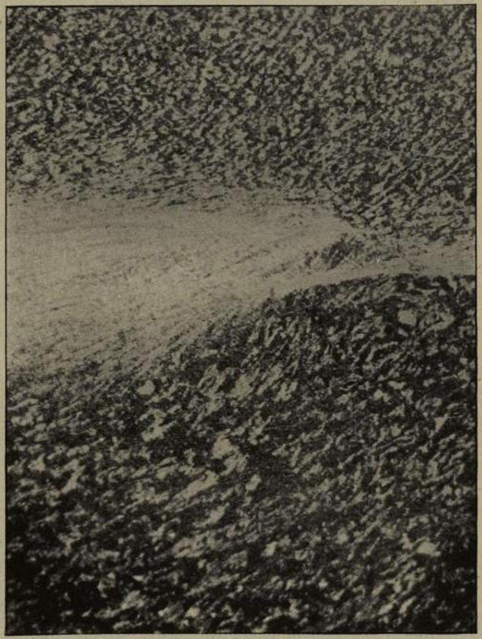

Fig. 98.—Same as fig. 97, but illuminated by light falling on the specimen at an angle. Note the very light crushed portion. On rotating the specimen 90°, the light portion became darker than the rest of the specimen. × 50.

started at the shorn edge, whilst the same material, after planing away the crushed edges, stood nearly as much punishment as the one first described. I have met with many failures of boiler plates, the causes of which were traced by the aid of the microscope to cold distortion (fig. 99).

Fig. 99.—Section of a boiler plate cut from near a rivet hole distorted and crushed. The hole was enlarged by chiselling. The plate gave way when being tested under water pressure at a point close to where the section was cut. Note the cracks represented by continuous black lines in the figure. × 50.

It is possible also to crush the walls of a drill hole by the use of a blunt drill, and I have met with several cases in which cracking in boiler fire-boxes and in boiler plates has been coincident with surface distortion, produced in the boiler shop (figs. 100–102).

It is, however, probably only in the cases where the steel is very susceptible to crushing that such slight surface distortion will lead to fracture of the material when in use.

The reduced power of steel rails to resist the shock test after they have been in use is due entirely to the crushing of the surface layers, by the rolling stock which passes over them; but here, again, one finds variation in the ability of steel to resist the effect of crushing. It is sufficient to point out that the microscope is able to reveal all cases in which the steel has been dangerously crushed.

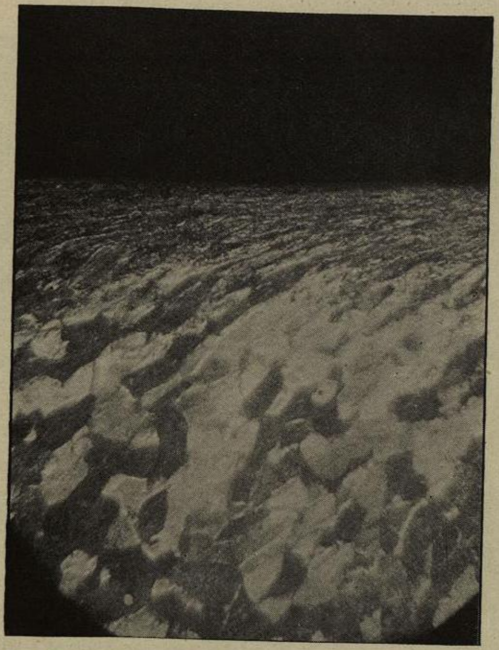

Fig. 100.—Side of drill hole in a boiler plate, crushed by using a blunt drill. × 250.

Heat Treatment of Steel.—If there is one thing more than another that the microscope can detect,

it is the last treatment to which steel has been subjected.

If a large steel casting has been submitted to proper annealing, the outside layers are always more or less decarburised, a clear evidence that the steel has been heated in a furnace after it left the mould. The structure of the steel itself enables one to judge of the temperature at which the annealing has been conducted (figs. 103 and 104). If there is a decarburised outer layer and a coarse crystalline structure, it is evidence of excessive heating in annealing, or, on the other hand, of annealing at a low temperature

Fig. 101.—Side of a drill hole in a boiler plate which cracked when in use. Note that the line of fracture follows the laminations produced by the drill. × 250.

(fig. 103). If the constituents of the pearlite are segregated into large independent masses it is an indication of prolonged heating, just below the critical point Ac, 1–2–3, 700°–729° C.

If the polished sections rapidly become brown on etching with picric acid solution the steel contains sorbite, and possibly some troostite, an indication of relatively rapid cooling.

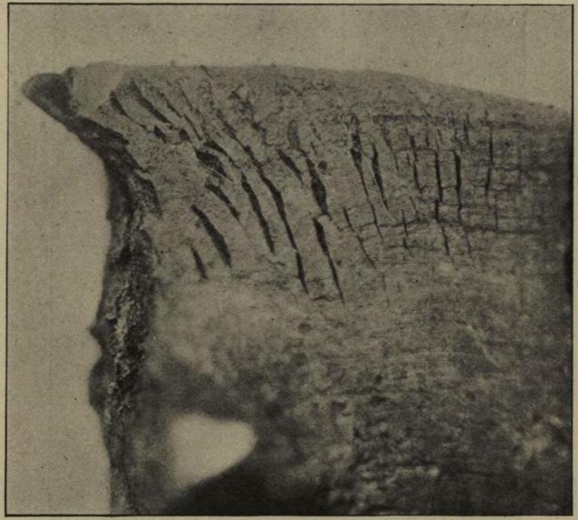

Fig. 102.—The same as fig. 101, showing cracks on surface of drill hole after slight straining.

Overheated steel is readily detected by its coarse crystalline structure, and also the triangular arrangement of the ferrite and pearlite in steels containing between 0·2 per cent. and 0·5 per cent. of carbon, and the large ferrite cell walls with offshoots of ferrite which penetrate the pearlite of the pearlite cells, in steels containing between 0·5 and 0·7 per cent. carbon. Such steel is more liable to break down in service than the same material if properly heated.

Burnt Steel.—Steel which has been heated to near the point of fusion sometimes contains intercrystalline substances and porosities, which are readily detected under the microscope. Such material is dangerous and should be rejected, as it can only be restored by remelting.

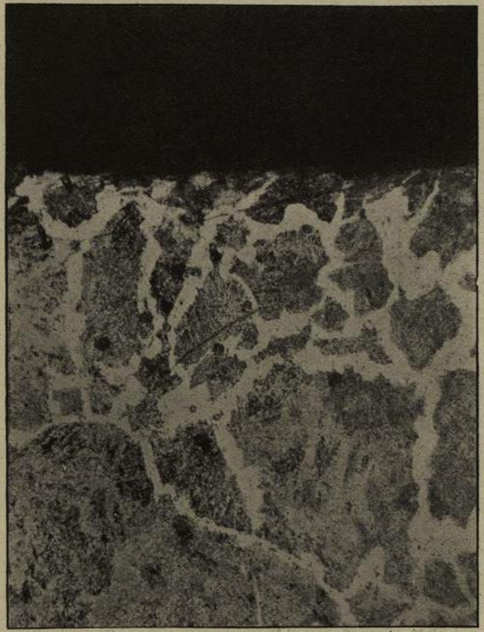

Fig. 103.—Steel casting free from any decarburised envelope. It had evidently not been properly annealed. × 50.

The excellent work of Professor Campion[1] gives a good idea of the effect of heating, at different temperatures, on the microstructure of steel, and this should be consulted by all workers of steel. Much

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[1] *Journal of the West of Scotland Iron and Steel Institute.*

has been written on the subject by authorities in America as well as in Europe. Quite recently Mr H. Brearley of Sheffield has published an excellent treatise on the heat treatment of tool steel, a work which should be in the hands of every steel worker and metallurgical student. The most excellent book on metallography by Dr Desch also demands attention.

Fig. 104.—Large steel casting with thick decarburised envelope and coarse crystalline structure. It had probably been annealed at a low temperature. × 50.

Steel Wire for Rope.—The microscope is exceedingly useful in the examination of steel wire. By its aid one can detect whether there is segregation as the prime cause of what is called cuppy fractures, and

whether internal axial fractures are the result of overdrawing or segregation. Imperfect patenting can also be detected, at least in cases where the wire rods after leaving the patenting furnace have been subjected to too rapid chilling and in which martensite and troostite are present instead of pearlite and sorbite. Experience has shown that the more sorbite that can be obtained in patented wire rods the tougher and stronger will be the wire; but in attempting to get this, there is always a danger of obtaining troostite and martensite, causing the wire to break during drawing.

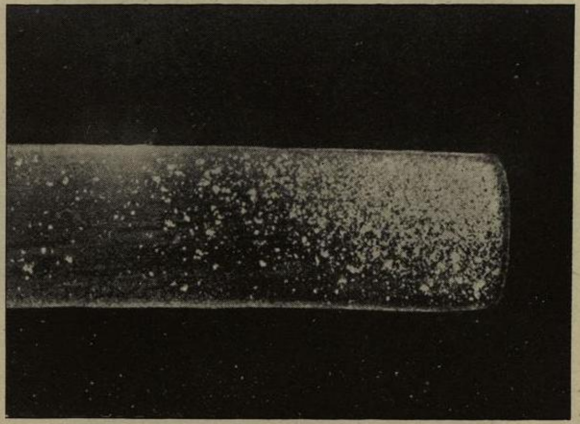

Fig. 105.—Wire rod improperly treated during the patenting process. The white areas are martensite, the dark ground-mass troostite passing into sorbite.

The microscope is useful also in determining the kind of treatment wire ropes have received during service. It not infrequently happens that the crown wires are crushed owing to the pulleys over which they travel being unsuited for the diameter or