

THE
STRENGTH AND STRUCTURE OF ALLOYS.

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THE INCORPORATED INSTITUTION OF AUTOMOBILE ENGINEERS.

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THERE is no branch of engineering in which the correct scientific choice of materials specially suitable for the purpose which the various parts have to fulfil is more essential than in the design and construction of motor cars. That is a point that I need not emphasize to this audience.

In order to obtain a thorough knowledge of the materials it is not, I think, sufficient merely to know the numerical data of the ordinary tests, such as the tensile test, the elongation, the more modern forms of shock tests, and so on, but I think an intimate knowledge of the detailed structure of the materials is of the utmost value and importance to the man who has to use those materials under extreme conditions. For that reason I think I may be pardoned for bringing before you something which may possibly be alien to your ordinary lines of thought. As a matter of fact, the connection between motor engineering and metallurgy is fairly intimate, as will be recognized by the fact that one very eminent metallurgist, Dr. Guillet, has for a long time been connected with the firm of De Dion-Bouton.

The aspect of metallurgy that I am dealing with, and the point of view from which the engineer is chiefly interested, in the structure of metals, is the question of their strength. I do not mean by that merely the ultimate breaking strength of the metal, but the whole of the mechanical properties of the material which affect its usefulness.

The strength of a metal depends upon a number of factors, which may, however, be divided into two classes. The ultimate factor is, perhaps, to be summed up in the somewhat vague term "molecular

cohesion." This aspect of the question I do not propose to discuss to-night; it is too vague and speculative for practical purposes. Further, I know nothing about it, and I do not think anyone knows very much about it. There is, however, something of a more tangible nature that we can discuss, and that is the microscopic internal structure of metals. The modern method of examining metals by means of the microscope has thrown a flood of light upon the internal nature and structure of metals and their behaviour under stress, both when that stress is sufficient to break them and when it is only sufficient to cause deformation.

In order to give you some idea of the manner in which metals are examined under the microscope, I must briefly outline the method which is followed for that purpose.

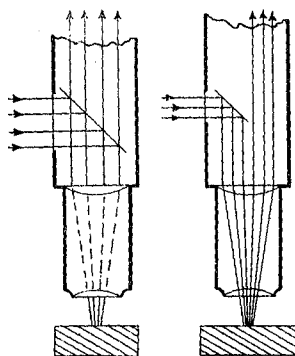


FIG. 1.

The piece of metal to be examined is cut and made smooth by ordinary mechanical means, and is finally polished in such a manner as to remove all scratches from its surface. The specimen is then attacked by some chemical re-agent, such as a weak acid, which acts differently upon the different constituents. It is found that chemical re-agents do not attack metals uniformly, but that after being subjected to this treatment inequalities are revealed on the surface, and this surface pattern represents the internal structure of the metal. These patterns are examined by looking at the specimen under the microscope by means of reflected light.

One of the instruments used for the purpose represents a form of microscope specially designed for metallurgical work. Two examples of this instrument are on the table in the ante-

room. The main point is that the instrument is specially arranged for lighting opaque objects. The way the lighting is done is made more clear by Fig. 1, which is a simple diagram of the path of the light that is employed for the purpose. It is important to notice that for most purposes the light falls on the specimen vertically downwards through the objective lens of the microscope.

Let us consider first the structure of a pure metal as seen under the microscope. The next figure (2) is a photograph of a specimen of very pure iron which has been polished, etched and illuminated in the manner shown. The whole area is occupied by a number of irregular polygons. These polygons are irregular crystals which have not had room to develop to their full extent,

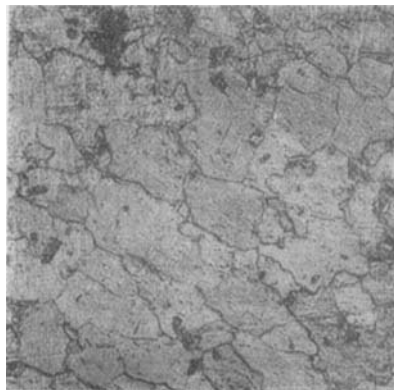


FIG. 2.

and which have assumed accidental irregular shapes owing to the fact that the growth of each has limited the growth of its neighbours. The evidence shown in this and the following slides proves conclusively that each of these areas is a section of a true crystal. The crystals have grown in the liquid until they encountered one another, so that their bounding shapes are not regular or geometrical, in the sense in which crystals which grow freely are geometrical, but their structure is nevertheless truly crystalline.

The next figure (3) shows the same object under a different kind of illumination; here the light falls obliquely on the object. We see again the polygonal areas of the previous figure, but instead of being uniformly white some of the polygons appear bright, while

others appear dark. This is due to the fact that the surfaces of these polygons are made up of numerous minute facets, all the facets on one polygon having a common orientation. When a polygon is so placed that its facets catch the light and reflect it into the microscope, then that polygon appears bright, while other neighbouring polygons, whose facets have a different direction, and therefore fail to catch the light, remain dark.

The next figure shows the same appearance in a specimen of lead.

In the next figure a view similar to the first is again seen, but it is on a specimen of another metal (Cadmium), which has been neither polished nor etched, but which has been allowed to solidify

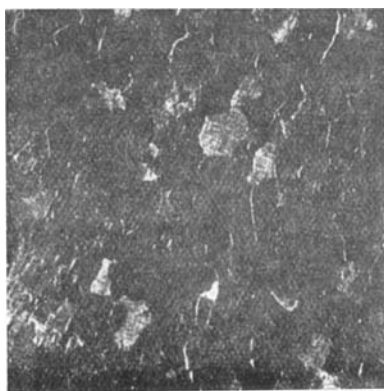


FIG. 3.

in contact with glass, and on cooling the contraction of the metal has thrown into relief the natural outlines of the crystals.

The next figures illustrate the prevalence of this polygonal, crystalline structure in all kinds of pure or nearly pure metals, such as electro-deposited copper, sheet zinc, and even sheet lead. An ordinary piece of sheet lead, which has not been polished, but simply etched, shows the crystals on a large and well-developed scale.

The next figure shows on a larger scale a view of a few crystals seen by oblique light, and the lines visible on their surfaces mark the edges of the facets. In this specimen they are not regular in appearance, but the next figure shows these facets in a more perfectly developed manner on the surface of tinplate. The facets are seen as small geometrical figures that have a common orienta-

tion on one crystal, but are different in shape and position on other crystals. These can also be seen in iron; the particular example shown (Fig. 4) was taken from a piece of iron reduced cold from one inch to half inch diameter, and the display of crystalline structure in metal that has undergone extreme deformation is certainly striking.

The crystalline structure of metal is sometimes rendered visible in another way, which is illustrated by the next figure; this shows a surface of metal (Cadmium) which has cooled in contact with a smooth polished surface. Apparently some air was included between the metal and this surface, and the bubbles were left in the solid metal occupying the place of some of the minute elements

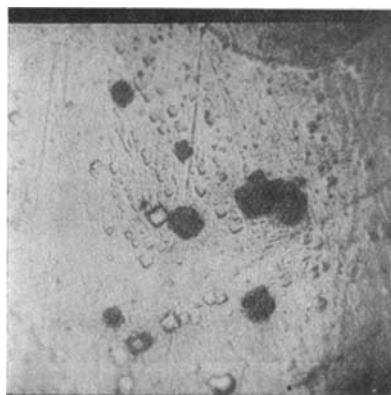


FIG. 4.

or "bricks" of which the crystals are built up. The hole left by each bubble has thus a geometrical shape, and all those that lie within the same crystal are similar in shape and position, but differ markedly in both respects from those on neighbouring crystals.

Let us now consider for a moment the manner in which these crystals grow. In a solidifying metal crystallization begins at a great number of points. Each crystal grows outwards, not by an accretion of concentric coats, but by the formation of arms or branches somewhat like the branches of a fir tree in shape. These branches shoot out in all directions, each pursuing its own direct course until it meets a branch of some other crystal shooting out from another centre in an opposite direction. Each of these skeleton crystals continues to grow, covering as large a volume of

the mass of metal as possible, until its progress is arrested by contact with the arms of another skeleton. Then when it cannot proceed any further in that particular direction the filling up process begins in the interstices left by the branches as they first shot out in all directions. These spaces between the arms are eventually filled and the complete crystal is formed of polygonal shape, its outline being determined by the points where the branches of adjacent crystals met in the early stages of crystallization.

The next figure shows a very beautiful fir tree crystal taken from the core of a large hollow ingot of steel; in that case the molten metal drained away and left the skeleton unfinished. In the next

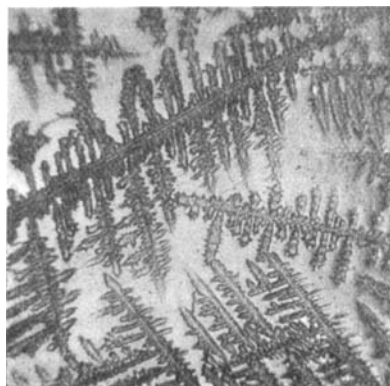


FIG. 5.

figure (5) we see, not a metal, but the crystallization of an ordinary salt (ammonium chloride) arrested at a point where the fir tree or "dendritic" structure is very evident, and the extent to which the arms of adjacent skeletons interpenetrate is clearly shown. This is exactly analogous to the process of crystallization in a metal, and it is evident that the strength of the metal will depend upon the manner in which these dendritic arms have interpenetrated and interlocked with one another. To further illustrate the process of dendritic crystallization, the next figure shows the structure of an alloy in which, after the formation of the skeleton, the remaining liquid was of a different chemical composition; this other substance appears dark on the slide, and allows us to see the white skeleton as it existed at that early stage in the solidification of the metal.

I have now shown you some of the evidence upon which is based the view that metals are aggregates of a large number of minute crystals; I have by no means touched upon all the available evidence, but it may be taken as an accepted fact that, at any rate in the ordinary condition, metals are truly crystalline. We may now consider upon what factors the strength of such an aggregate of crystals will depend. It must depend first of all upon the power of the crystals to resist separation from one another, and I have already pointed out how this power will depend upon the manner in which the dendritic or skeleton crystals first formed have interpenetrated and interlocked with one another. In practice the extent to which this happens depends upon a number of factors, such as the casting temperature, the rate of cooling, and the purity of the metal, while in many metals the whole arrangement of the crystals can be modified by both mechanical and heat treatment applied subsequently to the first solidification of the metal. Present methods of microscopic examination do not very readily show small difference in this respect, but the grosser cases in which the crystals have failed to interlock adequately are readily detected.

The other great factor that determines the strength of a metal is obviously the strength of individual crystals to resist deformation or fracture. When we come to study the behaviour of such crystals under the action of deforming stresses we meet a phenomenon that is at first surprising. The crystals are incapable of undergoing ordinary plastic deformation, in the sense in which putty or wax undergoes change of shape—*i.e.*, by continuous flow—yet, in the aggregate, they form a mass that behaves very like wax or putty. What actually happens is, that the crystals adjust themselves to the new shapes, which the deforming forces impose upon them by a process of slipping, which occurs within each crystal.

We have seen that each crystal is built up of a great number of minute crystalline elements, or “bricks,” and these bricks are capable of sliding past one another in layers. In order to observe this phenomenon, or rather to observe its surface effects, it is only necessary to deform a specimen of some ductile metal upon which a polished surface had previously been prepared. Before deformation the metal—taking iron as an example—shows the usual polygonal structure; the areas of the polygons themselves—apart from accidental markings due to other causes—are white and featureless; but after the specimen has been bent, twisted, stretched, or otherwise permanently altered in shape, if it be again examined in the

microscope, the polygons are seen to be cross-hatched by numerous dark lines. These have been called slip-bands, because they are really minute steps formed upon the surface by the sliding action that has gone on among the layers of each crystal. The figures

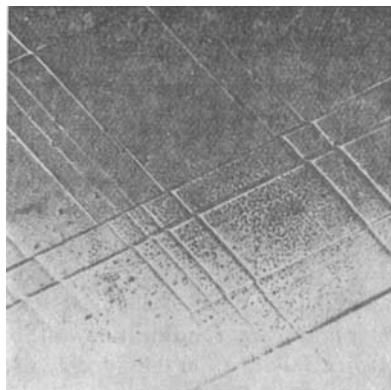


FIG. 6.

shown illustrate the appearance of iron before and after tensile deformation, one of the figures representing the first photomicrograph ever taken of this appearance. The appearance of slip-bands in other metals, especially in lead and copper, is shown

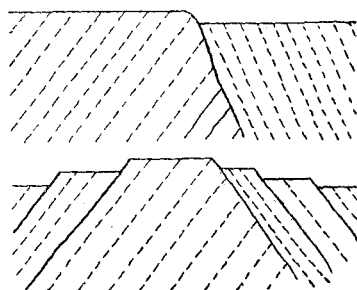


FIG. 7.

on the following slides, those on lead being particularly striking (Fig. 6). When highly magnified they show the fact that these lines are really due to steps very clearly. But this fundamental fact that these lines are really steps, and neither ridges nor grooves

in the surface, rests upon much firmer ground than the mere appearance of the lines in favourable specimens. The rough diagram in the next figure (7) shows the arrangement of the layers of crystalline elements in two adjacent crystals, as seen in an imaginary section, before and after deformation. If we look at the surface of the deformed metal, it will be seen that when such a surface is illuminated by light falling vertically down upon it, then the flat spaces will reflect the light back into the microscope, and will appear white; while the short slopes will reflect the light outwards, away from the microscope, and will therefore appear as narrow black bands or lines—and that is the ordinary appearance of such a specimen. But if the light fall upon such a surface obliquely from

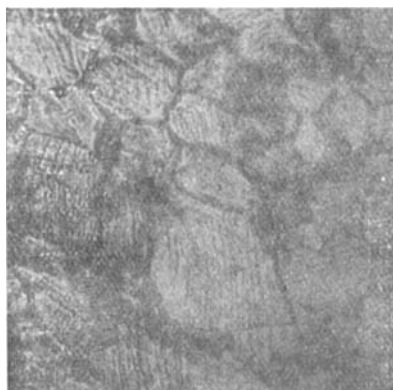


FIG. 8.

outside the microscope, only certain favourably situated sloped surfaces will catch the light, and throw it up into the microscope. The flat spaces will, in this case, throw the light away from the microscope, and the resulting appearance will be that of bright lines or bands on a black background. The appearance of the same field of view in a specimen of strained iron is shown in the next two figures (8 and 9), which give good examples of the bright and dark appearance of the same lines under the two modes of illumination. Another interesting way of studying these lines is to illuminate them by oblique light from two opposite directions, using, for instance, a red light from one side and a blue light from the opposite side. A photograph of the appearance of the bands in lead when thus illuminated is shown in natural colours in the next

diagram. The bands are evidently due to two different sets of slopes, some facing the blue and others the red light. Now, it has been suggested that these lines are not due to steps such as I have indicated on the diagram, but are merely opposite slopes of furrow or ridges. The diagram disproves that view, since, in furrows or ridges, there must always be an equal number of slopes facing each way; while, in reality, we see that there is a much smaller number of bands facing one side than the other.

To still further clinch this matter, I have been able to show actual sectional views of these steps produced in the surface of polished metal by the process of plastic deformation. For this purpose a method was devised, which has also proved of use in the study of



FIG. 9.

fractures—viz., that of embedding metal specimens in an electro-deposit of copper, and subsequently cutting sections through the combined mass. By that means it is possible to secure an absolutely sharp section of the original surface of the metal, whether that surface be that of metal showing slip-bands, or the fracture of a test-piece, or of a part that has broken in practice. The next diagrams show sections of strained surfaces of metal—*i.e.*, of surfaces which were covered with slip-bands before the copper was deposited upon them. The sections are very highly magnified, but they show the steps of the original surface very clearly, and the striking resemblance of these actual sectional views with the sectional diagram, which has already been shown, is strong proof of the essential truth of the whole theory of deformation by slip.

Having now considered in brief outline the manner in which a pure, or nearly pure, metal yields to stresses that are great enough to cause a permanent change of shape, we come to consider what takes place when the stresses are still further increased, until finally fracture occurs. If the process be watched directly under the microscope, as can be readily done in the case of a tensile specimen up to a certain point, one can see the slip-bands increasing, both in number and in width or thickness; but as these lines are crossing each other in numberless places, each line becomes greatly stepped, and the crystals themselves become more and more elongated in general outline. What the final step is we can only arrive at by examining the sections of actual fractures, prepared by

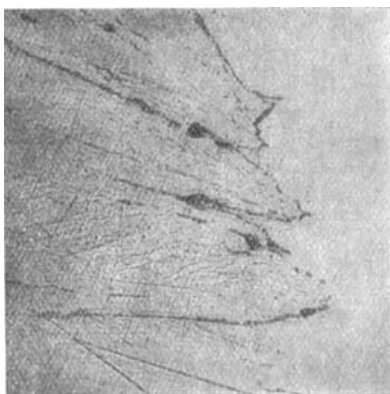


FIG. 10.

the aid of an electro-deposit of copper, as already described. The next figure (10) shows the section through the fracture of a piece of very soft, pure sheet-iron. It shows the crystals drawn out into narrow and relatively long bodies, more or less suggestive of fibres, while the fracture itself follows the direction of the numerous surfaces on which slip has taken place, stepping across numberless minute cleavages from one surface of slip to another within each of the crystals. It is this minutely-stepped nature of the tensile fracture of ductile metals that gives to the fracture their characteristic dull, fibrous appearance. But there is, in reality, no such thing as a "fibrous" metal. The iron was perfectly crystalline before the tensile stresses drew the crystals out into elongated shapes; and even the apparently fibrous fracture is, in its details, really crystal-

line in character. If the same material be broken by a sharp blow applied to a notched bar, a very different type of fracture results. Here there has been no prolonged deformation, and its accompanying slipping and stepping. The blow simply starts slips on a number of the cleavage or gliding planes of the crystals, and, if the energy of the blow is sufficient, each of these slips continues unchecked, until the two parts that are slipping over each other are entirely separated, and fracture—essentially by cleavage—results. The fracture produced in this manner shows large, brilliant facets, and is commonly called “crystalline,” although the term “cleavage fracture” would be more appropriate. The sectional appearance of such a fracture is shown in the next figure (11).

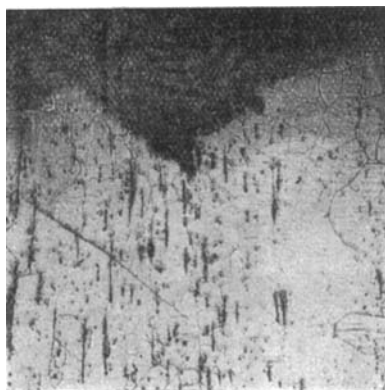


FIG. 11.

Another mode of fracture of a pure metal, which is taken from the work of Ewing and Humfrey, is the mechanism of failure under alternating stresses, and is a mode of failure which is of special importance in connection with many parts of motor vehicles. It has been shown that the process of failure begins by the occurrence of slip in a few isolated crystals. The surfaces that have slipped upon one another are not, however, allowed to rest, and to “heal up,” as they would do under other conditions, but are forced to undergo repeated slipping backward and forward under the continued action of the alternating stresses, until finally the two surfaces have ground each other away sufficiently to form an actual crack or fissure. Such a crack, once formed, will spread rapidly across adjacent crystals; and since there

is no great amount of deformation going on, the crack will propagate itself unchecked along the cleavage or gliding planes of the metal, until fracture results. The resulting fracture will thus have the appearance of a "cleavage" or "crystalline" fracture, and it is this appearance which has led to the idea that the failure of metal by "fatigue"—*i.e.*, under alternating stresses—arose from "crystallization" of the metal under the influence of vibration or stress. It is almost certain that no real change in the general crystalline structure of iron or steel can take place at ordinary temperatures under such conditions. The broken piece is no more crystalline, and no less crystalline, than it was originally, but the special mode of fracture has developed a display of cleavage facets on the surface of the break. Frequently, in the case of such failures, where the "crystallization" of the metal is blamed, the true cause has been the fact that the metal was exposed to a greater range of alternating stresses than it could permanently resist, or, what comes to the same thing, that a metal of too low an elastic limit has been employed.

Having now rapidly surveyed the behaviour of pure or nearly pure metals under the action of deforming and breaking stresses, we are prepared for the study of alloys. These are industrially of much greater importance than pure metals, and it is probably no exaggeration to say that if we had been compelled to confine ourselves to the use of pure or nearly pure metals, no such thing as a motor car could ever have been built. Fortunately alloys are really much more easily made than pure metals, and at the present time we have a very considerable power of control over their manufacture and resulting properties.

If we examine the micro-structure of a metal with which increasing amounts of another element have been alloyed, what changes do we observe? That will depend entirely upon the particular substance which has been introduced, or rather whether the substance belongs to one or other of two great classes or groups. If the other substance belongs to the first of these groups, or rather if the alloy formed belongs to the first of the two great classes of alloys, no very obvious change of structure will be observable in consequence of the change of composition; the structure of such an alloy remains very similar to that of a pure metal, although there are some very characteristic minor differences. But the mechanical properties of the alloy will frequently be very different from those of the pure metal. It is interesting to consider how this

effect on the mechanical properties arises, since it is difficult to suppose that the mere presence, in a state of solution or suspension, of so low a percentage as 0.1 (one part in a thousand) should be able to directly produce the striking effects which arise in certain cases. The explanation which I would suggest is based upon an analogy taken from the behaviour of certain substances, such as alum, when allowed to crystallize out from either a pure solution of the substance in water, or when the solution is contaminated by the presence of a small quantity of another substance, such as common salt or alcohol. When crystallizing from the pure solution, the crystals of such a substance ordinarily assume one of a particular group of crystalline forms, and this form is called the crystalline "habit" of the substance; but the presence of the foreign substance in some cases completely alters this crystalline habit, and the substance persistently develops forms that it never develops in pure solutions. Now in a metal we cannot observe the crystalline form or habit that the substance is assuming, but it is at all events likely that both the arrangement of the cleavage and gliding planes, and the interlocking of the dendritic skeletons formed during solidification, would differ very materially in crystals of the same substance formed in a different "habit."

Briefly expressed, my view is that the effect of the presence in solution in a metal of even very small proportions of another substance in some cases very materially affects the whole mechanism of crystallization, and consequently also the mechanism by which the crystals yield under stress.

Examples of this class of alloy are found in the alloys of copper and aluminium, and of copper and tin; so long as the percentage of aluminium or of tin does not exceed a certain amount (about 7 per cent. in the case of aluminium), there is no visible change of structure, but the mechanical properties are profoundly affected—in the direction of greater stiffness and reduced ductility—by the presence of the other element. Ordinary carbon steel belongs to the other great group of alloys, but when this alloy of two substances is converted into an alloy of three substances, by the addition of such elements as nickel, manganese and vanadium, very remarkable results follow (slides giving diagrams of the mechanical properties of nickel and manganese steels were shown). When the proportion of nickel or manganese present exceeds a certain definite amount, depending somewhat upon the amount of carbon also present, this triple alloy has a structure closely resembling that of a pure metal,

but the mechanical properties, as you have seen, are wonderfully different from those of pure or nearly pure iron. Perhaps the most astonishing results of all, however, follow the introduction of minute quantities of the rare element vanadium into either carbon steels or into nickel or chrome steels. The quantity of vanadium used—from 0.1 to 0.2 per cent.—does not produce any decided change of micro-structure in either case, but it produces most marked changes in the physical properties of the steels. For example, there is one variety of nickel-vanadium steel which Mr. Kent-Smith rightly describes as a “marvellous metal.” It contains only 3 per cent. nickel and 0.2 per cent. vanadium, and has an elastic limit of 80

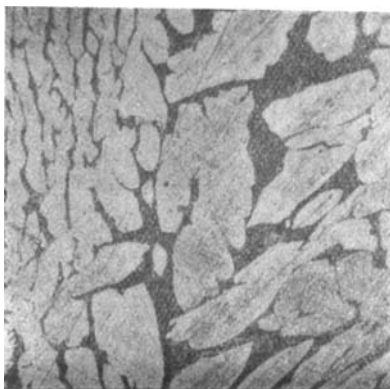


FIG. 12.

tons per square inch, and a breaking stress of 84 tons, while it still shows a contraction of area of 52 per cent.

We turn now to the second group of alloys, viz., those in which the introduction of the second element results in the formation of a new constituent in the alloy. The structure of such an alloy is illustrated in the next figure (12); in place of the polygonal areas of the crystals of the pure metal we have here a light and a dark constituent—the next figure (13) shows the dark constituent in greater detail at a much higher magnification. The darker appearance of this new constituent is, of course, only due to the etching process which the specimen has undergone, and the actual colour of the two constituents may be quite similar, or the one that appears dark in these figures may actually have the lighter colour apart from the etching. This other constituent is known to metallurgists as the “eutectic,” since

it is the most fusible part of the alloy. As you see in the figures, this eutectic is itself a duplex body having a minute structure of its own, and this very characteristic laminated structure is seen very plainly in the two following slides. As to the intimate physical structure of these eutectic bodies not very much is known, but there is some ground for thinking that they consist of a mass of very minute crystals or layers of crystals. Now from what we have already seen as to the manner in which aggregates of crystals yield to plastic deformation, we can infer that a mass of minute crystals will behave as a much stiffer and stronger body than a mass of large crystals of the same general kind—in the mass of minute crystals, slip has to propagate itself from one crystal to another with

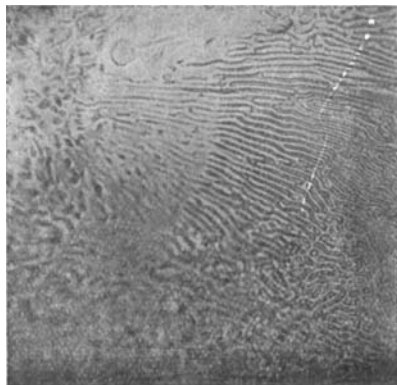


FIG. 13.

frequent changes of direction every time a boundary is crossed, and this process will require the exertion of a greater amount of force. Thus on account of their mere physical arrangement, eutectic bodies are stiffer and stronger than pure metals. In the class of alloys we are now dealing with, the proportion of eutectic contained in a given alloy increases up to a certain point as the alloy becomes richer in the added element, until ultimately the entire mass is composed of the eutectic body and we have the "eutectic alloy" of the series, which is always a stiffer, harder and less ductile body than the pure metal. In addition to this, we have seen that the eutectic is itself duplex, and very frequently one of the constituents is itself a hard, brittle body—in fact when one of the constituents of such a eutectic is a definite chemical compound between two

metals, or between a metal and a metalloid, then that compound is always an exceedingly hard and brittle body—the well-known carbide of iron, called “cementite,” is an example of this; but the rule applies with striking uniformity even to compounds between two ductile metals, as for example tin and copper or gold-aluminium. In such a case the eutectic will consist of minute particles—probably crystals—of a hard body embedded in a relatively soft matrix. One would perhaps suppose that the moment such a brittle substance made its appearance in a series of alloys the entire metal would become weaker and more brittle. But this is only very partially true. The fact is that when a hard and strong but brittle body is embedded in a soft matrix, it is really under the best possible conditions for

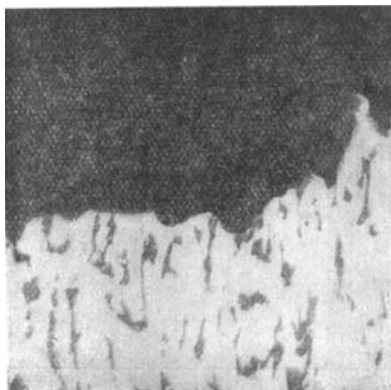


FIG. 14.

exhibiting its strength rather than its weakness, and only when the amount of soft matrix is reduced below a certain limit does the brittleness of the hard body come into play. Thus the first effect of the presence of small quantities of eutectics of this kind is to increase the strength of the alloy very greatly without seriously diminishing the ductility. The figure shows the correlation between micro-structure of carbon steels and their tensile strength, hardness and ductility. In carbon steels we have a body, generally known as “pearlite,” which is essentially of the nature of a eutectic, although it is formed from a solid and not from a liquid solution of its two constituents. One of the constituents of this eutectic is the compound cementite, which is hard and brittle. Steel contains a rapidly increasing proportion of pearlite as the

carbon contents increase, until at about 0.9 per cent. of carbon the metal is entirely composed of the "eutectoid," as it is called. The tenacity increases regularly up to this point, but the ductility falls rapidly as the proportion of pearlite increases.

In order to understand more fully the part played by the two constituents of a duplex alloy containing a eutectic constituent in determining the strength of the metal, we will now consider the behaviour of such an alloy when it is broken in various ways. For this purpose I have a series of figures illustrating by means of sections the modes of fracture of a carbon steel containing about 0.2 per cent. of carbon, but the conclusions arrived at from the



FIG. 15.

study of this metal are probably applicable, with slight modification, to most duplex alloys of this class.

The first of these figures (14) shows a section through the fracture of an ordinary tensile test-piece. All these sections have again been obtained by first embedding the fracture in copper and then cutting the section through the steel and copper together. This first view is taken at a low magnification and shows the general nature of the fracture, and we can see at a glance that the path of the fracture does not greatly favour either the light (ferrite) or the dark (pearlite) constituent, but runs indifferently through both. Seeing that the tensile strength of a steel consisting entirely of pearlite is so very much higher than that of pure ferrite, this result is somewhat surprising; but when we come to look at these fractures under higher magnification, we soon see that the very strength and

stiffness of the eutectic are the cause of its ultimate fracture. The next figure (15) shows sections of tensile fractures of steel under very high magnifications; it shows first of all that the fracture frequently leaves small shreds of pearlite adhering to the edge at points where a shorter path entirely through ferrite was obviously available. Further, we see frequent fissures in the pearlite at points near the fracture, but not actually communicating with the main break. This I interpret to mean that when the metal was drawn out in tension the two constituents, ferrite and pearlite, were forced to elongate together by their close adhesion to one another; but since the ferrite is capable of undergoing much greater extension than pearlite, the latter would reach the limit of its extensibility



FIG. 16.

first, and the next step of the drawing-out process would result in the fissuring of the pearlite at many places. The entire load would then be thrown on the ferrite, which would draw out a little further and would then tear, the fracture naturally running through the fissures already formed in the pearlite.

The next figure (16) shows a section through a fracture of the same material produced by shock—a notched bar being broken by a single blow with a heavy hammer. Here the fracture is seen to run as nearly as possible entirely through the ferrite areas, and internal fissures are found in the ferrite and not in the pearlite. Evidently under this treatment the greatly superior strength of the pearlite has asserted itself, and the ferrite has simply cleaved under the blow, much in the manner that has been described in dealing

with the fractures of pure metals. The fissuring of the ferrite is always seen to a greater or less extent in shock fractures of iron and steel, so that this feature can serve as a means of differentiating fractures caused by sudden shocks from those produced by gradual stretching or other forms of deformation.

There are other modes of fracture, such as bending of a notched bar and alternate bending of a plain bar. The features in these cases are of an intermediate kind, and they serve to illustrate the general rule that where there is much plastic deformation before fracture occurs, the path of the fracture will lie indifferently through both constituents; but where fracture occurs without previous deformation of the metal, the break will be of the nature of a cleavage which tends to avoid the pearlite or eutectic constituent. This rule must not, of course, be applied too rigidly, but it expresses the normal tendency of such fractures. Other observers, such as Stanton and Bairstow, who have observed the fracture of steel under alternating stresses in direct tension, and Seaton and Jude, who have observed the paths of cracks formed during impact tests on notched bars, obtain results which are in accordance with this rule, although in the case of Messrs. Seaton and Jude the preference for ferrite which they attribute to their fractures does not appear to be marked.

In examining such fractures in commercial mild steel, an interesting question arises in connection with the presence in all commercial steels of enclosures of foreign substances which, strictly, should not be present in the steel. These slag-like bodies are probably little globules of a compound of manganese and silicon, and they become elongated and often flattened by the processes of rolling and forging which the metal undergoes. When the metal is stressed and broken in the direction of the greatest length of these enclosures, its strength is very little affected by their presence; but a study of these fractures shows very plainly that in bending fractures, and in fact in all forms of fracture which involve serious shearing stresses along the length of the bars, the presence of such enclosures weakens the metal by facilitating longitudinal splitting. This deleterious influence of these impurities appears to be particularly prominent where the metal is exposed to shock and vibration, so that the study of steel from this point of view may be commended to the attention of automobile engineers.

Finally, I would direct your attention to the fact that the method of examining fractures which I have brought to your notice is of

considerable interest from a practical point of view, and has great possibilities in that direction. It is possible in the case of fractures of a metal whose normal behaviour has once been studied to decide by examination of the fracture by what kind of force the breakage has been caused, whether it has been done after considerable deformation of the part, or whether it has happened under a sudden impact, and it may frequently be instructive, especially in the case of failure of motor car parts, to know whether the failure has been sudden or whether it has been gradual.

Another point of importance is this: it is sometimes possible, by examining a broken piece in this way, to decide whether the cause of the breakage lies with the manner in which the steel was used, or with the steel itself. By the ordinary methods of microscopic examination, it would be impossible to tell whether the broken part has been used in an unfair manner, that is to say, in such a way that the metal could not be expected to resist the strains put upon it, or whether the breakage was the result of some local defect which made the steel weak.

The study of mysterious failures by means of the microscope in the ordinary way is exceedingly difficult, and may not reveal anything amiss with the metal, so that one would in such a case naturally conclude that the steel was what it ought to be. But it may be that there are enclosures of foreign bodies, or defects of structure due to wrong casting of the ingot, to inadequate welding of the joints, or to something of that kind, that will escape detection by the usual methods of examination. But if a section is taken right through the actual fracture it is fairly certain that any such accidental defect will be detected, and that is very often of considerable value. For success, it is, however, necessary that the fracture should be examined in the condition in which it broke, not three, four, five or six weeks afterwards when it has been much handled and has become oily or rusty. Almost the only way of preserving fractures is to wrap the pieces in tinfoil and keep them so covered until an electro-deposit of copper can be put on. If the specimen is only sent for examination several weeks afterwards, after it has been allowed to corrode or become dirty, the method of examination which I have set forth is no longer applicable.

I hope I have said and shown enough to illustrate the possibilities of applying the microscope to the study of metals. The new knowledge which this microscopic study of metals has opened up is bound to prove of the utmost importance to all branches of the

engineering industry, and not least among them to the manufacture of motor cars.

I have kept you a long time over these matters, but if you think over the questions of the structure of alloys, and the relation of their structure to their strength, you will see that a thorough understanding of these matters will lead to a clearer insight into, and a better appreciation of the qualities of metals and alloys, and their uses in engineering manufacture.

THE DISCUSSION.

THE PRESIDENT (Colonel R. E. Crompton) : I have during the whole time been learning, and have had many matters cleared up which I have been studying for some time past, and of which I had just learned enough to enable me to thoroughly appreciate the very clear and able manner in which Mr. Rosenhain has dealt with many of the difficulties which present themselves to everybody who is studying metals microscopically, which is at present the only way of studying them. I will now call on Mr. Tucker to open the discussion on this paper.

MR. A. E. TUCKER : I have often had the advantage of listening to Mr. Rosenhain's lectures, and have always congratulated myself on having been present. The extremely happy and charming way in which he puts these most technical matters before us is in itself admirable, because it is clearly a matter of difficulty to adapt such extremely high class and abstract physical considerations to everyday practical use. Dealing with one point of very special importance to all of us, I may say at once that I am disposed to disagree with Mr. Rosenhain in attributing a very heavy percentage of failures in steel work to the presence of slag in the interior of the metal. If we recollect the conditions under which steel is cast, it seems to me clear that in the majority of cases slag can hardly possibly be present. You have, in the majority of cases where steel is made for motor car work, a large quantity, consisting of very many tons—sometimes ten tons—of metal in a state of perfect liquid. It goes from a clean nozzle into a fairly clean mould, and the only conditions under which slag can get into the metal is through the exercise of gross carelessness on the part of the workman in lining, or whitewashing, or it may be "slobbering," his bottom plate on which the mould rests. If any foreign matter gets in at all, it would probably be clay of some description. But even if that were present, I think the intense heat under which the metal is cast would liquify the slag, and it would rapidly free itself.

Those who are familiar, like myself, with steel works practice will be aware of the great beauty of a fractured ingot when it is of considerable size. I have had the advantage of seeing several ingots broken across which have become hollow, and in them you see a most perfect crystalline formation such as Mr. Rosenhain has

illustrated. Dealing with other metals than steel, the lecturer alluded to the effect of aluminium on copper alloys. Now, the effect of aluminium on such alloys is somewhat analogous to that of phosphorus and arsenic, and I may tell you—especially those gentlemen who are interested in brass castings as applied to motor car or similar work where high-grade quality is required—that I know of a firm in Birmingham who in their commonest work invariably use phosphorus with the object of obtaining a similar result to that which is obtained with aluminium or arsenic, namely (to use the happy expression which Mr. Rosenhain adopted), because it affects the mechanism of crystallization of the metal itself when the cleavage planes to which he alluded are very much reduced; and I take it that the mechanical strength of the crystals themselves is enhanced. Therefore you get not only a very much stronger metal, but from a practical point of view you get fewer defects; and further than that, your sectional area for constructional work can be correspondingly reduced. With regard to vanadium steel, I have been particularly interested in this matter. In fact, I read a paper before the Institute in Birmingham on my experiences in vanadium steel, in association with Mr. Kent Smith. An interesting point arises from that. In spite of the extraordinary properties of this vanadium steel, in spite of its elongation, it is found in actual practice that this elongation works rather seriously against the machining of the articles. It unites this characteristic with the toughness of copper, and it has been found necessary to alter the angles of the cutting tools to meet that point. In connection with the mechanism of crystallization it may interest you to know that I had recently brought before me an alloy of zinc containing only something like 9 per cent of aluminium, which has a tensile strength of 22 tons per square inch. That is a most extraordinary result—an alloy of zinc showing a tensile strength equal to that of steel. That has been produced by what is practically a squirting process such as that by which lead pipes are made in the ordinary way. The result is such a reduction, I suppose it is, of the cleavage planes that Mr. Rosenhain has alluded to, and such an interlocking of the crystalline formation, that the tensile strength goes up to the point that I named. The material in question, I am aware, is being used in motor car work, but principally in connection with electrical fittings and for making screws to replace ordinary brass screws where great strength is required. I mention that as showing what can be done by the subsequent treatment of

metals. I thank Mr. Rosenhain personally for the enjoyment I have received from his lecture.

DR. H. S. HELE-SHAW: I should like to ask the lecturer three questions. First, I am not clear about the beautiful microscope which I saw in the other room, and which I believe is Mr. Rosenhain's own invention. What I am not clear about is the arrangement of the reflectors. Which is the one used for illuminating the object—the one which lets the light go down over half of the lens, or the one which is a thin sheet of glass?

MR. ROSENHAIN: You can use either.

DR. H. S. HELE-SHAW: I commend to everyone here the advisability of examining this excellent instrument. In an ordinary microscope, every time you examine anything you have to re-set your light, but this one remains perfectly constant, and I have never seen one so conveniently arranged as this. The second question is concerning one of the earliest slides shown. It was the first enlargement in which a metal was shown under strain. I noticed that the striations had gone over the border line of the crystal. Now the striations usually end at the border line, and I wish to ask if it is exceptional for these striations going beyond the border line? The third point is in regard to the way in which the lecturer put the copper on the specimens. Mr. Rosenhain was good enough to explain it to me at the last meeting of the British Association, but it did not seem quite clear this evening how he produces the coppered surface above the fracture, and a clear line below it. I remember when I was a student I was very much fascinated with a book—a French book—"The Infinitely Great and the Infinitely Little," a study in Astronomy and Biology, and I used to wonder whether the microscope would ever reveal to us what was going on in the structure of metals, about which practically nothing was then known, and to-day those working in the direction Mr. Rosenhain is doing are adding enormously to our knowledge on the subject. As an example of what still lies before us to be discovered, in order to see the movement of the ultimate particles of matter, I may remark that if you let a million of these particles fall per second and try to fill a glass with them it would take between seven millions and forty-seven millions of years to fill the glass. Largely through the labours of J. J. Thompson, of Cambridge, we have been able to split that "ultimate particle" into 500 parts, so that you must multiply that number of years by 500. We need not, therefore, be afraid that Mr. Rosenhain

has exhausted nature and has got down to the ultimate elements. What he is doing is to show us by means of diagrams the movement of groups of particles. He has got down to groups which it was never thought we should see. The extraordinary thing to me has been this, that although the theories upon which the stresses and strains are calculated—mathematical theories—suppose the materials to be homogeneous, while in fact the metals are crystalline, and stresses and strains in them give rise to crystalline movements, yet these results agree fairly well with the mathematical calculations.

I feel, coming to the practical side of the matter, that as automobile engineers we are very much indebted to the author to-night for his valuable contribution to the proceedings of this Institution. When I was in Paris at the recent Motor Car Show, what struck me more than anything else was the way in which the French had gone into the question of details of the material of which their cars were constructed. I there had a catalogue put into my hands in which every part of a motor car—the teeth of the gearing, the shafts, the frame work—was specified as being constructed of specific kinds of material. I think there were about twenty different parts all specified of different steels—nickel steel, chrome steel, and so on—even the percentages of the nickel and chrome being stated. These parts are very much specialized in France. The French realize that if they are to keep ahead they must go into details of this kind and adopt this kind of specialization. British manufacturers are looking more closely than ever into this matter. For that reason I think we have done well to have had a paper of this sort, not only one of great scientific interest, but also one of great practical importance to all automobile engineers, showing, as it does, that we can and must understand thoroughly the materials we are using. By such methods as those that Mr. Rosenhain is using we may, if we will, learn very much more. Mr. Rosenhain is a student of Prof. Ewing, who has brought him out, and should be very proud of him. I also have had two brilliant students who have distinguished themselves in a similar direction, and are engaged in steel works solely in pursuing investigations into steel products such as Mr. Rosenhain has been showing us to-night. We ought to see whether we cannot out of this Institution get some research work done, so that the materials used in automobile manufacture may be treated specially for our particular needs in some such way as we have had outlined to us this evening. I

must again thank Mr. Rosenhain for his instructive and valuable lecture.

Professor J. A. EWING: I am glad to have the opportunity of congratulating this Institution on having heard so extremely lucid, interesting and comprehensive an address, and Mr. Rosenhain himself on the manner in which he has put before us an immense collection of what is essentially original work. If it had a fault at all it is that there was too much of it. There was so much that he said that was suggestive—I speak from my own experience—that one could not help letting one's attention wander in chewing the cud, as it were, of one sentence, and when one awoke from that state, the lecturer had passed on to another point. There was really too much for one address. There was enough for a course of lectures. I feel, as no doubt you all do, that there were many points on which the lecturer touched which we could have wished to hear more fully developed. I would like, for example, to hear a good deal more about vanadium steel, with its very extraordinary properties which Mr. Rosenhain just mentioned. I do not know whether this meeting quite realizes the extent to which the work which Mr. Rosenhain has put before us has been original research work. He came to me a good many years ago as a student in Cambridge, before I had suffered what Shakespeare calls a sea change, and he showed before he had been with me long that he possessed a genius for original research such as I have not seen in any other student, and I have had a good deal of experience of scientific and engineering students. We soon became engaged jointly in research regarding the crystalline structure of metals, and although Mr. Rosenhain was too modest to say it to-night, I will say it for him, that the first half or so of his lecture was an account of discoveries which we made jointly. The whole business of "slip" lines; the manner in which crystals yield under strain; the relation between an elastic and non-elastic strain as determined by these "slips"—all that was original work which was first of all described in our Bakerian lecture, a joint production, before the Royal Society. But as Mr. Rosenhain went on he passed the limits of our joint production, and in the latter part of his lecture to-night he dealt with work which was entirely and absolutely his own—work of great value and of the utmost originality. The discovery of slip lines was one which, in our judgment, was sufficiently proved by our original experimental work; but some Continental workers, whose opinions are certainly entitled to the fullest respect, questioned the validity of these results,

and Mr. Rosenhain accordingly set himself to "slay the slain," to prove what we had already proved, and to prove it in a way which would convince the most sceptical. It was with that view that he devised the methods of getting actual sections through the strained crystal which he has shown you to-night. This demonstration, and other points on which he also touched more lightly, have succeeded in placing beyond the shadow or possibility of any doubt at all the fact that "slips" occur in the crystals just as you might slip cards in a pack, and it is owing to such slips that the crystals possess the property of plasticity and are capable of altering their shape to a very great degree before fracture. There is one point upon which Mr. Rosenhain touched where I think a little speculation might, perhaps, be added to what he said—the point, namely, about the structure of the eutectic alloy. He showed you some beautiful figures in which that curiously stratified structure was visible, which all of those who have worked at the subject know is the characteristic structure of all eutectic alloys. It seems to me that this stratified structure may be explained. Mr. Rosenhain said, and truly, that we know very little about it, but here is a suggestion which I throw out for your consideration. It seems to me that that curious stratification of structure arises from the fact that the process of solidification is always an unstable process. It is difficult to start, but, once started, it goes on with a rush. Now, what is a eutectic solution before it begins to solidify? If you call the two constituents for shortness A and B, the eutectic solution may be regarded as a saturated solution of A dissolved in B; or a saturated solution of B dissolved in A. You may look at it both ways and both are clearly valid. Before the alloy which has solidified has reached the stage at which only the eutectic remains to solidify; one of the constituents has been in excess and has been crystallizing out. Let us call it A which has been in excess. It has been rapidly crystallizing out, and instead of finishing the process of crystallization at the proper moment, so to speak, it oversteps the mark, and leaves a super-saturated solution of B in A, and when that has gone far enough the super-saturation becomes so excessive that a layer of B crystallizes out, and this occurs again in such a manner as to leave a super-saturated solution of A in B. And so, in turn, the process oscillates between the two. The whole process is an oscillatory one, and it is for that reason you get that remarkable stratification of structure, which I think is due to a deposit from the super-saturated solution of each

constituent in turn. I will not attempt at this late hour to take up any other points, but I might be allowed to say that Professor Hele-Shaw, when he speaks of me as feeling a justifiable pride in listening to Mr. Rosenhain, describes my feelings exactly. It is perhaps the greatest satisfaction that an old Professor can have, to sit at the feet of one who was formerly his student. I have enjoyed to the very full that satisfaction to-night.

Mr. J. S. CRITCHLEY : I have listened to Mr. Rosenhain's interesting lecture with very great pleasure, and the only thing I am sorry for is that it has come to an end. So many interesting points in connection with steels have been brought before us, and have been dealt with in such an interesting manner, that one does not like to find fault ; but to us, as motor engineers, there are a great many points that he has not touched upon in the lecture this evening. When one listens to such an able man as Mr. Rosenhain, one cannot go away without having a great deal to think about. I only wish he had been able to give us this lecture ten years ago. It was my misfortune to be in the trade ten years ago, when the structure of steels was certainly not so well understood as it is to-day. The Institution of Mechanical Engineers eleven years ago started research into alloys. I have listened to many of these papers, and have gleaned a good deal of information. I can remember, in 1897 and 1898, trying to obtain suitable steels for motor car construction. In many cases we had costly failures, but the reasons for these failures we could not find out. We got what steel makers recommended, and the parts either broke or wore away very rapidly. I very well remember going to France in 1899, and visiting some of the large steel works there. I put the matter before them, and they said : " Oh, yes ; we can help you out." And they recommended in those days nickel chrome steel. I brought some steel back to England, and submitted it to steel-makers here. I was told it was impossible to make such steel, except at an enormous price. I struggled on for twelve months, until I finally got that steel matched by one steel manufacturer. To-day it is being largely sold by that maker for gear-wheels of motor cars. There is nothing more interesting in connection with motor cars than the question of case-hardening. It has been the bugbear of motor engineers for many years, but possibly now we are getting to the end of our troubles, as far as case-hardening is concerned. Steel makers undoubtedly have during this last four or five years given motor car manufacturers a tremendous amount of assistance. Two

years ago, I think it was, I was bold enough to bring the question before the members of the Automobile Club. I read a paper there, and it was surprising, after that paper had been read, the number of steel makers who wrote to me for further information. It seemed to come to them as a revelation that such things were wanted as steels to stand up to the work that we required. I can give you another instance. I was specifying some crank-shafts, and was specifying about 45-ton steel—reasonable steel, such as we understand it to-day. I was told it was impossible to make such steel, and that the steel-makers would simply laugh at it if it was put before them. I had to go and tell the firm that if they would go to Krupp, in Germany, they would get such steel. That is only about three years ago. Coming to the question of nickel steel for gears, it does seem that the term nickel steel is often misunderstood. Speaking of nickel steel, you often hear it described as 3, 4, 5, or 6 per cent. nickel. Such description does not mean anything. You have always to take into account the carbon element. In case-hardening ordinary mild steel, I think it is generally found that the best results are obtained by double-quenching, or cooling it, and repeating the quenching. With nickel steels, it is found that the results, so far as the strength of the steel is concerned, are better than with ordinary mild steels—that is, with only one quenching. That is a very great point in favour of nickel steel. Another point in connection with nickel steel is this: that, after a certain amount of cementation, or case-hardening, a certain proportion of carbon is added, and we get a martensite structure, which is really hardened steel. So, by a mixture of 2 per cent. of carbon with 7 per cent. of nickel, and cooling gradually without any quenching, we get case-hardened steel. That is a wonderful steel. There is no doubt about it; and I think De Dions have largely used it. By such combination we get case-hardening steel, without any quenching whatever. I think if Mr. Rosenhain could have given us a few instances of case-hardened steel such figures would have been of interest to motor car manufacturers. I should like to see such slides. Illustrations would convey an idea of what is the actual structure of case-hardened steel. I could hope that Mr. Rosenhain will at some future time give us a further lecture on this most important matter of case-hardened steel.

Mr. F. W. HARBORD: I most heartily congratulate the lecturer on the successful preparation of the beautiful photo-micrographs with which he has illustrated his lecture. All metallurgists owe a

debt of gratitude to Mr. Rosenhain for the ingenious way in which he succeeded in obtaining photo-micrographs of the actual fractures by depositing copper on the specimens previous to polishing. I have made endless attempts to make microscopic examination of fractures, especially under high powers, but I have never succeeded in overcoming the rounding off the edges. By Mr. Rosenhain's method of embedding the fracture in copper you can polish the section, and get an extremely good edge, so that you can see how the fracture has taken place, whether through the pearlite or ferrite, and it also enables you to form a good opinion as to the conditions under which the fracture took place. I would emphasize the importance of having the specimens intended for examination sent in a condition with the fracture well preserved. I am constantly having specimens sent to me which it is most difficult to deal with owing to a tarnished fracture, and without any history attached to the piece, so that it is impossible to form an opinion upon the cause of failure. In regard to Mr. Tucker's remark with respect to slag in steel, I assume Mr. Rosenhain did not mean slag in the ordinary sense, but silicide of manganese. I do not myself think that this is likely to be the cause of serious fractures. You rarely find it running in parallel lines in the substance of the steel. It would not form a lamination in the same way that slag might do in wrought iron. In some few cases I have found it that way, but it has been the exception. Generally speaking, it is in masses. Although they may be in the direction of the rolling, and are to some extent a source of weakness, yet I do not think they seriously affect the strength of the material. I congratulate Mr. Rosenhain again on his interesting lecture.

Mr. P. L. RENOUF: Mr. Rosenhain has shown us some figures illustrating the effect of the reversal of stresses: perhaps he can tell me whether he has made investigations to show whether after a certain number of such stresses, if the metal remains dormant, there is any tendency for the metal to re-constitute itself. I will illustrate the point by reference to my own experiences. In the old days of cycling we used to have twenty-four hours' rides. There is no question that we have had bicycles which did good service in training. They would stand up well on roughish roads for week-end rides, but on going for long-distance rides for twenty-four hours at a stretch the machines would break down. I myself am convinced that there is a great difference in the behaviour of metal in which the reversal of stresses is continued beyond a certain

point from that which has a chance of a long rest in between. I do not think we have been able to establish that in any other way than by facts that we can speculate on ; but I think the microscope may reveal to us probably facts which we have not known before. When we come to consider motor car work it is extremely important, because we have vibration of a certain kind going on which may be continued for several hours without serious effects, but which, if continued all day long, may mean a great deal. I should like to know whether the lecturer's microscopic investigations have thrown any light on this question of the fatigue and resuscitation of metals.

MR. RUSSELL CLARKE: May I also be permitted to give my congratulations to Mr. Rosenhain? I was a fellow student of his in Professor Ewing's laboratory. It strikes me that if we have a few more papers like this the Institution of Automobile Engineers will be a very great success indeed. This is the sort of paper we want to enable us to hold up our heads. If we maintain this high level we need not consider our papers less interesting than those of other learned societies or institutions which regard themselves as the scientific societies of England. There is one question I should like to ask about the microscope. A great authority on microscopes told me that he found a very useful way of looking at small objects by reflected light was to cut the object down to the smallest possible dimension and really not light it except by the light reflected from the object glass. This authority, Mr. Gordon, told me that the light you get in that way was ample to see by. The microscopes on the table have the light going through a hole in the tube on to the object. In this other case you illuminate round the object. I should like to ask whether Mr. Rosenhain has tried that way.

THE PRESIDENT: There are one or two points that I should like to refer to. It is a thousand pities that we let the French take the lead of us in the choice of materials for the construction of things where great strength and elasticity are required. It is nearly ten years ago since I began this study. I think I read a paper before the old parent Institute on Long Crank Bicycles. One great difficulty I had was to get any material to stand the great stresses put upon such cranks. I was an electrical engineer carrying out the lighting of Cammell's Works in Sheffield, and I heard mention of a wonderful metal used for armour plates. This was really kept a profound secret, but it turned out to be 5 per

cent. nickel and $\frac{1}{8}$ th per cent. carbon. I persuaded them to let me try the metal on a small scale. It was an unheard-of thing to have it in bars. However, I had some bars drawn and had my bicycle cranks made of it, and they are working still. The necessity was forced on me of lightening the 9-inch cranks I was using, and that really drew me so strongly to study the nickel steel and other alloys of that kind that it has furnished the last ten years of my life with an additional source of pleasure and study. I am sure that has been the case with many other engineers. One of the points upon which we latter-day engineers are differentiating ourselves from those of the previous decade is this, that we are really beginning to know something about alloys. The Alloys Research Committee of the Institution of Mechanical Engineers has done a great work, and not the least has been that it has directed attention to this microscopic structure of metals. It is a new revelation to us, but it is astounding how it has been followed up, and the rate of progress of scientific knowledge on this subject not only in England but in other countries also, notably in France, is remarkable. There need be no international jealousy in this matter. It is an honourable race between these countries as to who will add most to our stock of knowledge on this most important question to us as engineers of the mechanical strength and efficiency of materials. One of the points in which we may advance very greatly in motor car construction is in getting materials of very high elastic limit. We can do wonderful things not only in springs, but, when we come to commercial vehicles, in the wheels themselves. Probably one of the ways in which road shocks can be reduced, and the working expenses of commercial vehicles correspondingly reduced, will be by the study of steel rims of a comparatively simple form, but of a material suitable for the work; and I believe that material is very nearly being obtained. Not only are we near to the attainment of the proper material, but also to the heat treatment of that material—the method of arresting the segregating process which takes place by quenching it at certain times. I am one of those who are studying under Mr. Rosenhain. I have already benefited a great deal by the knowledge and hints he has given. My state of knowledge is such that a hint from him now will enable me to go ahead. Not one of the least things he has called attention to is that beautiful arrangement, the central or axial way of throwing the light down on the object. We engineers are only just beginning to use the microscope as a tool. Where we have to make ball

bearings it is of importance that we should study the nature of those surfaces before they leave our shops, and the advantage of being able to do that with microscopes of the best kind, which were only made a few years ago for transparent objects, is of infinite importance. This beautiful microscope was new to me, and when I first saw it I said, "I must have one to look at my surfaces." I think a great many gentlemen here will feel as I do, that the whole time we have been in this room we have been benefiting, drinking in knowledge of the utmost use to us all, and I thoroughly agree with what Mr. Russell Clarke has just said, that this is a very proud moment for us to feel that we have had such a splendid paper—one that will attract further audiences. We have got together a young society anxious to learn, and we have got the men who can teach us.

Mr. ROSENHAIN, in replying on the discussion, said: I can hardly tell you the pleasure it gives me to find that I have succeeded in interesting you in a subject which is of such very great interest to myself, and to which I have devoted so much time during the last eight years. I must say that I had some misgiving in responding to Colonel Crompton's kind invitation to come here to give this paper to you, because I felt that what I was saying was not very new, and its bearings upon motor engineering were not of that immediate practical kind which so many practical men look for; but I am all the more pleased to find that what is after all a somewhat abstruse disquisition should have been so kindly received by you. I can hardly find words to express the feelings raised by Professor Ewing's remarks and those of one or two others—but perhaps I can leave that to your imagination. With regard to the points raised by the various speakers, they are very numerous, and it would take me at least an hour and a half to answer them in detail. In regard to the point as to the inclusion of "slag," Mr. Harbord was right in correcting me. I should not have used the word as I did. When one finds silicide of manganese one expects it to incorporate itself with the slag, but I do not think that under any conditions the separation of these compounds from liquid steel is really complete. I have had a great deal of experience of molten materials, and I find that, particularly if the operations are very rapid, the enclosure of these bodies cannot be prevented. It is not always a matter of carelessness. Mr. Harbord, like Mr. Tucker, seems rather to underrate the danger arising from these things, especially where the metal has to resist alternating stresses.

Mr. TUCKER : I do not at all underrate them.

Mr. ROSENHAIN : My figures show some fissures starting from these enclosures. They are very often flattened out in certain directions, and I have frequently observed them as direct sources of fracture. With regard to the zinc and aluminium alloy which Mr. Tucker mentioned, that alloy has a very marvellous tensile strength, but it must not be compared with steel. It is a material which has been extruded. It is really like hard-drawn wire, and there is no ductility left. It is not fair to compare it with the tensile strength of mild steel bars ; the proper comparison is with hard-drawn wire. With regard to the electrical deposition of copper, I shall have to refer Dr. Hele-Shaw to my published papers ; it will be too long a matter to go into to-night.

Dr. HELE-SHAW : What I wanted to know was whether you put it on to the end and take it off again.

Mr. ROSENHAIN : I put the copper on the fractured end, and then cut through copper and steel together.

Dr. HELE-SHAW : It is a longitudinal section of the fracture ?

Mr. ROSENHAIN : Yes. With regard to the example, mentioned by Dr. Hele-Shaw, of slip-bands that appeared to run on across a crystal boundary, it must be noted that the mere fact of a slip occurring in one crystal will tend to start a slip in as nearly as possible the same direction in the next adjoining crystal ; as a rule, there is at least a slight but visible change of direction on passing from one crystal to another, but it occasionally happens that two adjacent crystals have one direction of a set of cleavage planes in common, and in that case the bands might cross a boundary unbroken. The example given of the case-hardening of nickel steel without quenching is quite one of those achievements which the microscopic study of metals has made possible. I think that without the work of Guillet and others no one would ever have dreamed that the mere cementation of nickel steel would have been sufficient to produce really hardened steel surfaces. When a steel is hardened by quenching the change at the critical temperature is suppressed. When nickel is added in increasing quantities the temperature at which this change occurs is gradually lowered, and finally falls below the ordinary temperature, so that the change does not occur even on slow cooling and the steel retains the full hardness of martensite. Mr. Renouf has raised the question of the fatigue and rest of metals. I think metals are capable of fatigue and are amenable to the rest cure, provided the fatigue has not gone too

far, somewhat in the same way as the human machine. If you take it in time and rest it before the damage is done it will repair itself. That is a large subject. There is some experimental evidence in support of the theory, and there is also a good deal of theoretical reasoning which leads to the conclusion that it is so. I am glad to hear the example of the racing cycle brought forward. If you dip the fatigued metal in hot water that accelerates the rest cure. This is well known in the case of razors; I do not know whether it would apply to a bicycle. I may say that I have tried the mode of illuminating the object to be examined by reflected light as described by Mr. Russell Clarke, but owing to the small size of specimen required I fear it is not available for the study of metals. Several gentlemen appear to have a wrong impression about that microscope. The idea of axial or vertical illumination is not original with me, but goes back a long time. What is original about the microscope is the general design and arrangement of the mechanical parts. I claim for it that it is a tool adapted to a specific purpose. The capabilities of the microscope in the engineering workshop are very great indeed, and I think they are hardly yet sufficiently realized. I must thank you again for the attention you have given to what I have had to say.