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METALS AND THE MICROSCOPE.

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The application of the microscope to the study of the internal structure of metals has given rise to what might almost be called a new science—certainly a new phase of science. While practically all of the work of this character has been done since the pioneering work of Sorby, in 1864, and of Osmond, in 1878, thus being comprised within a period of about sixty-five years, to date, the possibilities of the new methods now appear to be so important and far-reaching, and the results of such studies at the same time so useful and so fascinating that there is today no metallurgical industry that does not rely for its success, directly or indirectly, upon microscopic studies. And no one who has had even a glimpse of the structures that are revealed in metals by microscopic examination can fail to be interested and impressed.

The use of the microscope in this connection does not, at first thought, appear to be so revolutionary in character. For the microscope has been developed to a very high degree of refinement for a long time and it has been used in the study of materials of all sorts, and in a very wide variety of fields. But it is well to remember that ordinary methods, as familiar to every microscopist, will not apply at all in the case of metals. For the examination of biological structures, transparent minerals, etc., it is usually possible to prepare sections so thin that light will readily pass through them, thence into the optical system of the microscope and to the eye.

Such a method cannot well be applied to opaque metals. It is true that one or two of the very highly malleable metals—gold in particular—have been successfully beaten into exceedingly thin sheets, so that light will, to a certain extent, pass through these sheets. Gold, for example, has been beaten to a thickness of about $\frac{1}{180000}$ inch, and in this condition the sheets appear of green color by transmitted light.

There are at least three difficulties to be noticed in this connection if we are to attempt to apply this method to general metal examination: (1) The fact that these thin sheets appear green by transmitted light means that they are opaque to all of the other colors of the spectrum, all but a small fraction of sunlight, for instance, being stopped. (2) Only the highly malleable metals, like gold or platinum, could be beaten out to anything like this thinness. (3) And, what is more serious than either of these objections, we now know that the beating profoundly changes the original structure of the metal, so that even if a microscopic examination were possible it would tell us little or nothing

about the character of the metal as it was before beating. For this reason the value of the microscope, as a testing instrument in metallurgy, would be largely lost because one could neither study the changes of structure that accompany changes in physical properties nor form any intelligent idea as to causes of failure of metals to perform the service that was expected.

A moment's thought will convince anyone that by far the greater number of our visual observations, in general, are made by means of *reflected*, rather than transmitted, light, simply because most of the objects we see are opaque rather than transparent. What we ordinarily see is the surface of objects and we judge color, size, contour and surface outlines by means of light that has been reflected from the object to the eye. And yet it might seem, at first, almost hopeless to expect to determine anything regarding the internal structure of metals, merely by the examination of what we ordinarily see as the form of the surface of a piece of metal. This is because the surface is always so changed by wear, corrosion, oxidation or intentional modification that it does not truly represent the mass of metal underneath.

The method developed by Sorby and Osmond, and very extensively applied since their original work, was to cut through the metal and then to prepare the section so exposed by a process of progressive grinding and polishing, a brilliant and perfectly smooth surface finally being obtained. Even this would not serve for microscopic examination in most cases, simply because all that one could see, even with the aid of high magnification, would be a brilliant—usually nearly white—surface. But if this surface is dipped into a solution of some suitable reagent, which possesses the ability to attack the metal unevenly, most of the metals and alloys will be found to have developed a very remarkable—and sometimes a very beautiful—structure when viewed through the lenses of a good microscope. The development of such a structure is due to the fact that the metal is not a single, homogeneous substance. Most of the alloys consist of at least two crystalline materials and even the pure metals are found to have a structure made up of separate grains, the boundaries of which are attacked more than are the grains themselves. In the case of the alloys it nearly always happens that some of the crystals are attacked more vigorously than others, so that a relief effect is produced and the outlines of the different constituents are thus made visible.

This method of procedure opened up an extremely interesting and useful field for scientific investigation and observation, and numbers of metallurgists have followed the lead of the earlier investigators, so that we now have available a large amount of information concerning the internal structure and the properties of most of the metals and their alloys. In fact this work has become so extensive and so important that the new field has been given a name. We now speak of the microscopic study of metals and alloys as the science of "Metallography." And it is of the methods used in such study and of some of the results of the application of these methods that this discussion will treat.

Metals as Crystalline Aggregates. In the first place let us say at once that, so far as we know of them, every metal in existence is essentially crystalline in nature. This fact is not necessarily an obvious one, because ordinary experience with such soft metals as lead, or with such alloys as plumber's solder or aluminium, would lead one naturally to conclude that they are not crystalline. But this is because we are in the habit of associating *brittleness* with crystalline structure, the crystalline minerals or the crystalline compounds found in the chemical labora-
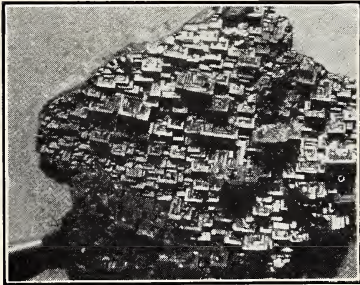

Fig. 1—Bismuth crystals grown in free space. x1.

Fig. 2—Surface of ferrosilicon. Skeleton of skin first frozen. x¼.

Fig. 3—"Galvanized" iron. x1.

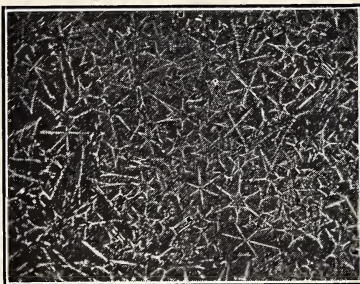Fig. 4—Cuprous oxide (cuprite) crystals from a druse of copper nugget. x130.

Fig. 5—Epsilon copper-tin crystals from lower end of cast Babbitt metal. x100.
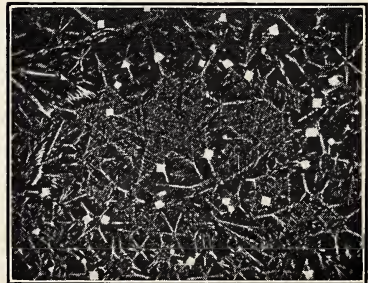

Fig. 6—Same as figure 5 but with gamma tin-antimony crystals. From top of cast. x100.

tory exhibiting this characteristic almost without exception. Such a
conclusion would be decidedly erroneous; and it might be noticed also
that glass is a common example of a transparent and brittle substance
which is not at all crystalline.

The crystals of metals are not always perfect in *outline* because of
the restrictions under which they have formed, but even then the mass
is crystalline in structure. It is only when crystallization of one con-
stituent of an alloy occurs while the remainder of the material is still
liquid, or upon the surface of a metal or alloy which has either cooled
quietly from the liquid state, or which has condensed from the vapor
state, that unmistakably crystalline outlines are seen. Some of these
are illustrated by the accompanying reproductions of photographs.

Figure 1 is from a photograph of a beautiful specimen of bismuth,
cooled upon the lining of the ladle in which it had been melted, and from
which most of the metal had been poured. Figure 2 is the upper sur-
face of a melted and cooled ferrosilicon, an alloy of iron and silicon.
Figure 3 is the surface of ordinary "galvanized" iron, so familiar to
everyone. This is simply a zinc-coated iron, prepared by dipping clean
sheets of iron into melted zinc, the latter crystallizing as it cools. Some
very beautiful figures may often be seen upon such material if it is
examined while new and before the surface has become dirty or worn
or oxidized. These figures suggest the appearance of a window pane
on a frosty winter morning; and the ice crystals there noticed have,
in fact, grown over the glass by a process quite similar to that of the
zinc crystals on the iron.

All of these are examples of crystal formation without interfer-
ence of solid matter. As another example of such crystallization in
free space, although not of a single metal or alloy, in figure 4 we have
a photomicrograph of a group of nearly perfect crystals of copper oxide,
found grown upon the walls of a small interior cavity of a piece of na-
tive copper. This particular nugget of copper weighed nearly 27 pounds.
It was brought down into northern Indiana, probably from the Lake
Superior district, as glacial drift, ages ago. And in a cavity not more
than a half inch in diameter these beautiful crystals had been hiding,
perfectly protected from mechanical injury or atmospheric corrosion, to
be revealed by the hand of man several thousand centuries later. The
tombs of the Pharaohs can give us nothing more wonderful. For here
has Nature herself built a perfect structure of the atoms of copper and
oxygen laid upon each other as no block of brick or stone can be laid
by man, and as no man-made tool may fashion—each atom itself an
invisible universe of whirling electrons but each eternally keeping its
own proper position in the crystal.

Suppose that a more careful examination is now made of a piece
of soft bearing metal, an alloy of tin, copper and antimony known as
Babbitt metal. Nearly everyone is more or less familiar with this alloy
or with an alloy somewhat similar to it in composition, as used in many
bearings of automobiles and other machinery, and it is well known that
such alloys are easily melted and poured into forms.

If a piece of genuine Babbitt metal is melted in a clay or iron crucible (at a temperature of about 400° C.) and then poured into a mould and allowed to cool slowly, one will have what corresponds to a cast bearing. Good cast bearings should be allowed to cool more rapidly, but in the present instance we should have this one cool slowly.

The cooled ingot of solid alloy is now to be cut so as to expose sections, the first one near the top and then one near the bottom. If these sections are polished, beginning with coarse emery cloth and following this, in turn, with finer emery cloth, wet emery on canvas, wet tripoli and wet rouge, finishing finally with an extremely fine abrasive, such as wet alumina (aluminium oxide), the polished sections being then immersed for a short time in a dilute solution of nitric acid in alcohol, and finally washed, dried and placed in the proper position in a microscope, one may observe a beautiful starry system of bright crystals in a darker sky of metal mass.

The section taken near the bottom of the ingot would appear something like the photomicrograph of figure 5. In this picture the dark background is nearly pure tin, while the starry clusters of crystals are composed of a sort of complex of tin and copper, designated by the metallographist as *epsilon* tin-copper—Greek letters being used to designate the various members in alloys.
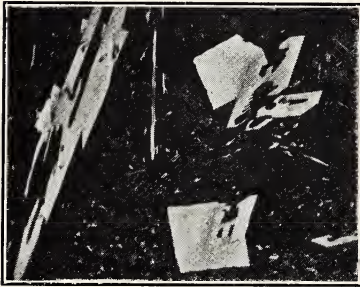

Fig. 7—Crystals in Babbitt metal. x500.   Fig. 8—Lead grains in cast lead. x150.

The picture of the section through the upper portion of the ingot, as shown in figure 6, may now be compared with this. In addition to the crystals already noticed we have here a new one of apparently cubical form. This is a complex known as *gamma* tin-antimony. Both of these crystals are very hard. And the thorough distribution of these hard particles throughout the softer and more plastic mass of more nearly pure tin is thought to be largely responsible for the excellent behavior of this alloy as an "anti-friction" bearing metal. The hard crystals by themselves would be brittle, and they would also be liable to cut and ruin a steel journal running in such a bearing, while tin alone would be too soft and yielding to be of much use. But in a conglomerate of this kind the hard crystals take the wear, while the softer matrix allows them to adjust themselves to minute irregularities of the moving journal surface, the bearing suffering no noticeable distortion.

This being true it is easy to see that a good bearing must have its hard crystals small and evenly distributed.

The formations of stars and triangles of figures 5 and 6 are clusters rather than single crystals. Figure 7 shows some of these at higher magnification. The *gamma* crystals are nearly perfect cubes, the well formed outlines being made possible because the crystals form while the principal portion of the alloy is still liquid.

Usefulness of Metals. If the average individual were asked to state, without taking much time for reflection, what is the most important and useful property of metals, in general, he might possibly mention their power to conduct electricity as of very high importance or their ability to take a fine polish, so that they may become ornamental parts of various useful articles—or even of their relative permanence when exposed to various influences that would promote decay of non-metallic things. One might think of these or of various other characteristics—but the chances are more than even that he would say that metals are of the greatest usefulness to man because of their exceptional *strength*.

And this would be quite right. All metals are conductors of electricity and some are excellent ones, thus making possible a bewildering variety of interesting and useful electrical appliances as well as serving as parts of machines for power production and utilization in modern industries. Some metals resist to a high degree the corrosive action of air and acids. All may be made to combine with certain other chemical substances in such a way as to produce many salts, oxides and other compounds, useful and nearly indispensable in our modern life. But, after all, the characteristic which separates metals, as a class, from most of the other materials which we know, and which gives them an outstanding importance to us, more fundamental and necessary than any of the properties mentioned above, is that of being able to resist pulling, bending, twisting, abrasion or compression without changing form or breaking.

This is the characteristic which makes possible all of our modern machinery of every description. If a metal could be pulled apart as easily as a stick of wood; or bent or twisted as a piece of rubber; or cut or penetrated by a point, as a lump of wax—or broken by a blow, as a mass of stone—modern life would be a very different matter from what it is, for the great bulk of modern industry and commerce, depending as it does to so great an extent upon the use of metals, would not exist. As to what would be the effect of this upon the ideals and ideas of our present civilization one may only speculate, and we may leave this to the philosophers. But certainly life would be fundamentally different from what it is; perhaps not as life in the Stone Age, for the world does change—but at least in a modified or somewhat improved Stone Age.

Pure Metals Are Not Strong. There is another thought that must be noticed in this connection. In the search of all known metals for a material that will meet our present needs in the matter of strength, *no single metal is found to serve.* Many metals are strong and at the

same time free from brittleness, as compared with most other materials of construction, but none of them will meet the needs and requirements of modern industry.

One may notice a few examples. Tungsten, formed into a wire or filament, provides a means for converting electrical energy into light energy, and with less waste in the form of heat than would be the case with most other metals, and so the incandescent light bulb is a universal convenience, and even necessity, today. But that filament is so weak and fragile that a very light blow upon the cold bulb will shatter the filament.

Platinum is a highly prized metal on account of its high fusing temperature, its remarkable resistance to corrosion by acids and other chemicals, and its ability (when in a fine state of division) to promote certain chemical reactions by "catalysis," as in the manufacture of sulphuric acid. (We may leave entirely out of consideration its appeal to the vanity of man, who—because of its present extraordinarily high cost—must have platinum in his teeth, his watch and his fianceé's engagement ring, thus crippling the chemical industries.) But platinum is so soft that it may easily be scratched or cut by a knife; so weak that very large masses would be required to withstand any important stresses. Even the platinum crucible of the chemist's laboratory has to be handled with great care if it is not to be ruined by bending or crushing.

Gold has long been used in jewelry and other ornamental articles and in coinage because of its beauty and because it is not easily oxidized or corroded. But pure gold is so soft that if jewelry or coinage were to be made of it such articles would soon wear out or become bent or scratched. Copper or other metals are always alloyed with gold in order to change this condition.

Copper is useful especially because of its high degree of conductivity for electricity. But pure copper also is quite soft and weak, and if it is to be used for other purposes in the pure state this relative weakness has to be compensated by increase of mass.

Even iron, one of the strongest of our common metals, in the pure and unalloyed condition will not do for much of our modern demands. Of course nearly pure iron is used in relatively small quantities in sheet form for tubular culverts and silos, roofing or rain gutters on buildings, and for other such purposes where a relatively high degree of resistance to weather conditions is provided by its relative purity.

Alloys Are Stronger Than the Metals of Which They Are Composed. One might go on almost indefinitely with these examples, recounting the striking characteristics and important uses of each metal. But always we should come back to the original proposition: that if a metal is to be made particularly strong something has to be done to it. Various treatments will improve the strength, but first of all it is well to notice this extremely interesting fact: *If two or more metals are alloyed with each other by melting together the solid alloy is always harder and stronger than would be expected from the general rule of averages.*

This is the first part of the principle of strengthening by the addition of another element. The second part, an extension of the first, is this: *It is usually true that the more easily one metal dissolves in (alloys with) another the less is its strengthening effect, and conversely.*

Other Indications of Crystal Structure of Metals. In the preceding discussion there have been shown some reproductions of photomicrographs and of ordinary photographs as indications of the crystalline nature of certain metals and alloys. But we have now to pass to others where the case is not so obvious. Indeed it might be said at once that in the majority of instances the microscopic examination of a section of the metal would not furnish very convincing evidence of crystal structure.

As an example of this, figure 8 represents a polished and etched section of a piece of lead. These rounded and irregular grains are not at all crystalline in appearance. Figure 9 represents a microsection of nearly pure iron—"ingot iron" it is called—and it is one of our best commercial forms of iron. Here again the irregularly formed "grains" of iron make up the entire mass. Figure 10 represents a piece of type metal, an alloy of lead and antimony. True, the bright network gives a certain suggestion of crystallinity; and yet one would be rather venturesome to predict, without further evidence, that the cell formation would prove to be of true crystals.

A great many other examples might be cited, illustrating by photomicrographs of metals or alloys that have a granular, rather than an obviously crystalline, appearance. But these are enough to lead to this point, already noticed, that *usually it is in only those cases where crystals may complete their formation in contact with liquid or free space that their outlines are obviously crystalline in form.*

Crystallinity Is Not Merely a Question of Outline. The terms "crystalline structure" and "crystalline outline" have been used in this discussion as though they represented two different ideas. And so they do. Perhaps the outline has, until recently, been regarded as the most striking feature of crystals (at least aside from certain important optical properties), but that was because we lacked evidence as to the nature of the crystal body itself. But there is no inconsistency in this. If one were to take a well formed crystal, say of alum, and grind off the external portions to form a rounded mass, the nature of what was left would not be changed any more than the grain of a piece of wood would be changed by turning it into a croquet ball.

Crystals Within Crystals. Figure 11 represents the structure of a high-carbon steel (1.1 per cent carbon). Such a steel is quite hard and strong, even without sudden cooling from high temperatures. This is because of the presence of a very hard carbide of iron, here visible as a bright network and as brilliant crystals shooting across the meshes of the network. But if the steel is examined with the aid of lenses of higher power the enmeshed grains are found also to possess a definite structure of alternating strips of dark and light. This structure is shown in figure 12.
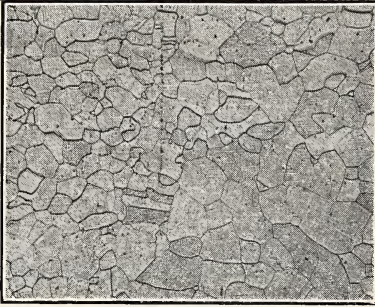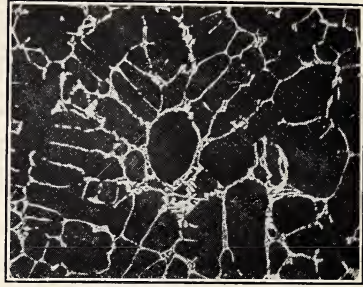
Fig. 9—Ingot iron. x100.

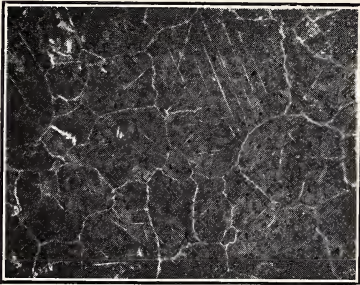Fig. 10—Type metal—alloy of lead and antimony. x50.

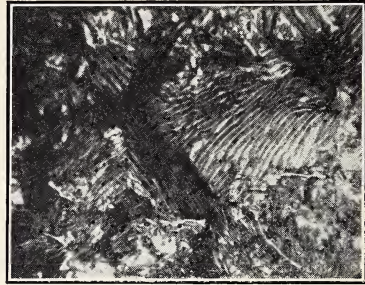

Fig. 11—High carbon steel. x100.

Fig. 12—Pearlite in steel. x750.

Figure 13 represents a section of a cast steel; that is, of a steel which has cooled slowly and without disturbance from the temperature of the liquid to that of the solid condition. Here also the arrangement of dark and light plates rather irresistibly suggests a crystal structure, although it is definitely known that this appearance is due to a crystal which has existed just after solidification and which has bequeathed its "image" to its descendants.

Fig. 13—Cast steel. x50.

Fig. 14—Slip bands in strained ingot iron. x130.

And so, here and there, it is possible to find these polyhedral (many-sided) grains which exhibit traces of a former or of a present crystalline form. Nevertheless there are too many cases where no such traces are apparent to make it possible to generalize upon the basis of such evidence alone. Consider then what happens when a granular metal, such as iron, is deformed by hammering, stretching, bending or any other means.

A piece of ingot iron similar to that represented in figure 9 was first photographed, as has been seen, then it was placed in a heavy vise and squeezed until its external form was permanently changed. This, of course, means that the iron was strained. Figure 14 shows what has been done to the iron. Each grain is crossed by one, two or three sets of fine dark lines, whose directions usually change at the grain boundary. This indicates rather unmistakably that there is some sort of order in the manner of assemblage of the ultimate particles composing the grain itself, so that when the metal was strained there was a disturbance concentrated upon certain planes—remembering again that we are seeing only one section of the metal and that these dark lines probably represent planes in section.

The X-ray in Metallurgy. It has long been known that ordinary visible light consists of pulsations or waves, in some all pervading medium, which the physicist calls the ether—that it is refracted or bent when passing from one transparent substance to another of different density, and that different colors are refracted to different degrees, so that when "white" light, for example (white light is merely a combination of all colors), is passed through a glass prism it is spread out into a strip of beautiful rainbow hues, these being the components of the original light.

Fig. 15—Conventional representation of wave length.

It is known also that the extent of refraction of a wave depends, among other things, upon its wave length, which is the distance between like phases of the wave. Thus, if we follow the conventional method for representing waves the wave length would be the distance from a to a', b to b', c to c', etc., of the line in figure 15. Violet light is of relatively short waves and red of long; the other colors lie between these in wave length.

But the light to which the human eye is sensitive covers only a very small portion of the enormous range of other radiations, many of which have been discovered within the few years just past.

Units of Measurement. In order to have some tangible method for designating the length of such radiations or waves it is necessary to use a unit of measurement much smaller than any that are employed for ordinary measurements for everyday use. For example, if the inch were to be taken as the unit there would have to be so many zeros after the decimal points that one would tire of writing and counting them.

For very short distances, such units as the *micron* (symbol μ), the millimicron (μμ), and the Ångström (Å) are used. The first is one-thousandth of a millimeter, the second one-millionth of a millimeter and the last one ten-millionth of a millimeter—or one-tenth of a millimicron. These may be related to the inch by remembering that about 25 millimeters are equivalent to an inch. If all of the figures given above are divided by 25, the following relations are found:

$$1μ = 0.001 \text{ mm} = \text{(about)}0.00004 \text{ inch}$$
$$1μμ = 0.000001 \text{ mm} = \quad 0.00000004 \text{ inch}$$
$$1Å = 0.0000001 \text{ mm} = \quad 0.000000004 \text{ inch}$$

Known waves that are very much shorter than those of visible light are the ultra-violet rays, the X-rays and the *gamma* rays of radium. Known longer waves are the infra-red or heat rays and the Hertzian waves used in radio transmission. The latter are so much longer that we drop the use of the smaller units and express the wave lengths in meters—or we might use the kilometer or the mile as a unit, although no one does this.

The following table gives the range of wave lengths of such radiations as have been mentioned. It will be noticed that there are still several unexplored gaps and it may well be that radiations will be discovered which will fit into these gaps—perhaps radiations that will prove to be as remarkable and useful as any that we now know.

TABLE I.   Wave lengths of some known radiations.

Designations	Range, Ångström units	Range, millimeters
Gamma-rays.........	0.01 to 0.1	0.000000001 to 0.00000001
X-rays.............	0.1 to 10	0.00000001 to 0.000001
Ultra-violet.........	100 to 3800	0.00001 to 0.00038
Visible light........	3800 to 7800	0.00038 to 0.00078
Infra-red...........	7800 to 313000	0.00078 to 0.00313
Hertzian............	....	2 mm to 10000 meters

It is a well known fact that X-rays will pass through a great many materials that are opaque to ordinary light and it is because of this property of such radiations that X-rays have proved to be so useful in surgery and medicine as well as in industry. We do not actually see the objects that are revealed by X-ray examination, for the human eye is not responsive to the effects of such rays. But we do see the effect of an X-ray shadow upon a special screen which becomes fluorescent where the rays strike it. Also we may see a photograph, for X-rays affect the photographic film and this makes possible a permanent record of the desired form.

If a narrow beam of such short waves as X-rays is made to pass into a crystal—which may be either an ordinary "transparent" crystal or one of an "opaque" metal—many of them will pass on through or be absorbed, but a minute amount of the radiant energy will be reflected from the atoms or molecules composing the crystal mass. Under ordinary conditions the reflection will be very faint, but if the angle of

striking is just right the radiation is reflected in separate beams of characteristic angles. A print made from a negative film recording such reflections is shown in figure 16. Here the rounded bright spot at the central point represents the position of the main portion of the original unreflected beam, while the bright spots are from the portions that are bent out of position by the reflecting atom planes of the crystal.

If a powder of such a crystal or a small mass of metal containing crystals whose axes are variously directed is used instead of a perfect crystal these separate beams form circular bands, centered about the main unreflected beam. Figure 17 shows such an effect.
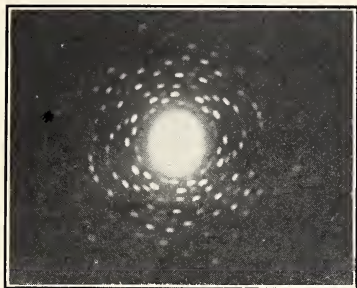

Fig. 16—Laue X-ray spectrogram of potassium nitrate. Courtesy of Professor E. D. O'Connell.
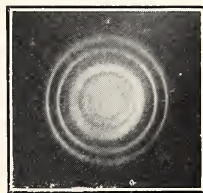
Fig. 17—Spectrum of aluminium crystal to powdered form. (After General Electric Co.)

The fact that is of the highest importance here is that the *intensity* and *spacing* of these reflected beams bear a very definite mathematical relation to the *arrangement* of the atoms within the crystal and to the *distances* between atom centers.

· Without going into details of construction of the apparatus or of the calculations themselves we may find it interesting and profitable to note several conclusions that have been reached as a result of many researches conducted with X-rays:

1. In any crystalline material, whether of an element or a chemical compound, the constituent atoms are assembled in a definite pattern in space instead of in the non-orderly plan of amorphous substances. ("Amorphous" means, literally, *without form*.)

2. Nearly all of the metals crystallize in the cubic system—a system in which the three axes of symmetrical atom grouping are equal in length and perpendicular to each other.

3. The "space lattice" (the pattern representing the arrangement of the atoms in three-dimensional space) of most metals is comparatively simple. The most common two are the *face-centered* and the *body-centered* cubic lattices.

The Crystal Space Lattice. In order to visualize the lattices, imagine that we have a stack of small cubical blocks. Arrange these in an orderly, close-packed fashion and suppose that an atom of some element (say the sodium and chlorine atoms of common salt—sodium

chloride) is situated at each point where the corners of eight blocks come together. This, of course, means that each cubical block has an atom at each of its eight corners, although each atom is a corner atom shared by eight blocks.

If now the blocks could somehow be caused to vanish, leaving the atoms suspended in space, we should then have the *simple cubic* space lattice, which might be represented diagrammatically as in figure 18,
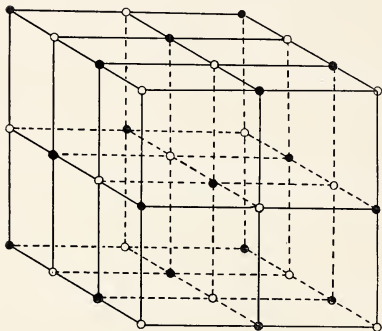

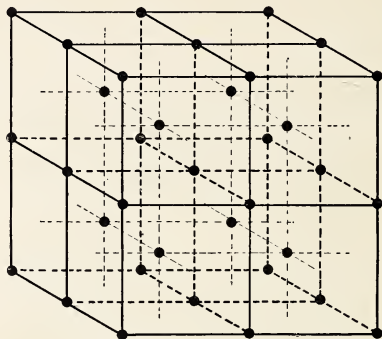Fig. 18—Simple cubic space lattice of sodium chloride.

Fig. 19—Body-centered cubic space lattice.

where the dark circles represent the positions of atoms of sodium and the open circles those of chlorine of sodium chloride. The straight lines of this diagram are used merely to assist in visualizing the space relations of the atoms within the crystal and to indicate the probable directions of the principal inter-atomic attractions.

Going back to the pile of blocks suppose, first, that iron atoms replace all of the corner atoms of sodium and chlorine, and, second, that there is an additional atom of iron at the center of each cubical block. Again let the blocks vanish, leaving the metal atoms exactly as placed. The result now is the simple *body-centered cubic* space lattice of ordinary iron (*alpha*-iron). This is depicted in figure 19, in which
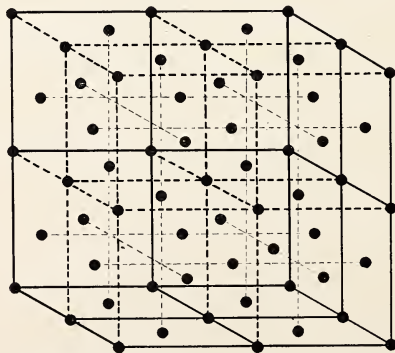

Fig. 20—Face-centered cubic space lattice.

dotted lines have been added to indicate the positions of the centered atoms, all of the atoms now being of the same element—iron. Once more, suppose that the centered atoms are absent but that, in addition to the corner atoms, one additional atom is at the center of each *face* of a given block. Of course this atom will be shared by two adjacent blocks, just as each corner atom is common to eight blocks. If now the blocks are again caused to vanish we shall have the simple *face-centered cubic* lattice, such as exists in iron when it is heated to any temperature between 900° and 1425° C., when it is known as *gamma*-iron. This space lattice is represented in figure 20.

A metal which, like iron, can thus exist in two or more different crystal forms is said to be "allotropic." Iron is one of the few allotropic metals, and this one fundamental fact is responsible, in a large degree, for the extreme usefulness of this metal in our industrial life because it makes possible the thermal treatment of steel, thus fitting it for such a great variety of uses.

How Many Atoms are in a Crystal? Any representation such as those of figures 18, 19 and 20 must be regarded as extremely inadequate to show the enormous numbers of atoms involved in the structure of a single crystal, even when the crystal is of only microscopic dimensions. For we must remember that the lattice extends in the three dimensions to the crystal boundaries and, further, that the atoms are very small and very close together, as measured by ordinary standards. While the inter-atomic distances vary somewhat with different metals, and with a single metal at different temperatures or in different allotropes, it is quite possible to form some conception of these distances by considering iron itself. It has been shown by Westgren and others that the straight side of a single cubic unit (corresponding to the straight side of the single block of the imaginary pile) of *alpha*-iron is about 2.87 Å, and of *gamma*-iron 3.61 Å. Reference to the definition of the Ångstrom unit will show that these dimensions, in terms of ordinary units, are about 0.000000011 inch and 0.000000014 inch, respectively.

The maximum diameter of the crystal grains of a good quality of steel is about 0.01 inch. Although the grains are not cubical in form, we may take some liberties with the facts and imagine them so. In this single small crystal we shall then have approximately one million lattice units, arranged regularly on a given straight line in each of the three space dimensions. This will give 1,000,000,000,000,000,000 (one quintillion) lattice units in the crystal, and this of course means the same number of atoms for the cubic unit corners. Practically speaking, we have the same number of atoms for the cube centers, for we have only to draw the lines of figure 19 somewhat differently to prove that each body-centered atom is a corner atom for eight units of a different system. The total number of atoms in this *alpha*-iron crystal is then about 2,000,000,000,000,000,000.

Of course these figures are only approximate and they are of such enormous numerical value that the mind can form little conception of their true magnitude. But a little thought given to these matters should at least cause us to appreciate the wonderful technique that has made such measurements possible. And it should bring home to us anew this

amazing truth—that the eternal *order* of the universe goes not only to the magnificent and incomprehensible distances measured by the astronomer, but also in the opposite direction to the infinitesimal structures of the physicist and the chemist.

While we are about it we might as well indulge in a bit of philosophy. We speak of going out in one direction to the "immense" sizes and distances—those of the astronomer, who deals with stars and interstellar spaces—and back in the other direction to the "small" of electrons, of atoms and of interatomic distances. But, after all, that is only because we happen to be situated "between" these conceptions. The things and sizes and distances that are easily experienced and comprehended by the unaided human senses—these we regard as normal. Very much greater or less than these we regard with a certain degree of awe.

But this absolute order of structure and composition and natural law which science is uncovering as we plod, step by step, through its maze—this order is all-pervading and eternal. This law of structure and of operation of physical and chemical forces is the very foundation of the universe. If such figures as those given above can do nothing else for us they can at least help us to realize that numbers and sizes and distances are mostly relative in their significance. Man may come to some sort of understanding of both the infinite and the infinitesimal, these terms being themselves but mathematical conceptions. But he has yet a long way to go as he strives, individual by individual, generation by generation, to push back the boundary of the unknown—to lift the dark curtain which veils the inscrutable. There is no inscrutable if we are to speak in terms of unlimited time for effort. What time shall be permitted the human race for that effort and how far we shall go in the search for other fragments of the complete truth we do not know, and we should be rash to attempt to predict. But if the man of science cannot find, in these reflections, inspiration for a continuation of his efforts he is not likely to find it elsewhere. Certainly not in the mere search for bread and butter to feed his stomach.

Straining. What happens to a piece of metal when it is strained? If the muscles or ligaments of the human body become accidentally over-stressed the result is an injury, which requires time for repair by natural physiological processes. If a piece of wood is bent or twisted or compressed so far that its form is permanently changed, as a general rule it will have been weakened. For such treatment actually begins the process of tearing apart the fibers or cells composing the biological structure. It may, therefore, be somewhat surprising to learn that exactly the opposite is true of a metal. But this is indeed a correct statement of the case if it be understood that the straining is not to be carried too far.

Straining Without Undue Heating Strengthens a Metal. If a bar of iron or brass or of any other non-brittle metal or alloy is rolled (without previous heating) into a sheet, drawn into a wire or stretched, hammered, squeezed, twisted or otherwise deformed, and if its hardness, tensile strength or elastic limit are tested, both before and after such

drastic treatment, it will be found that the numerical values express-
ing these qualities have been raised, sometimes to a remarkable degree.
Thus, a piece of commercially pure iron may have its tensile strength
raised from about 50,000 pounds to about 125,000 pounds per square
inch by cold rolling or by drawing it through dies of decreasing size,
as is done in the process of wire making. At the same time the hard-
ness is very much increased. Similar changes are noticed in copper,
brass and most other metals and alloys, providing that they are not too
brittle to permit such treatment without fracture.

Such plastic deformation of metals within ordinary temperature
ranges is known as "cold work," as distinguished from "hot work,"
which is similar deformation at higher temperatures.

The attempt to understand why cold working strengthens a metal
has provoked many conjectures and it has been the inspiration for many
researches. Without going into a historical development of the various
theories it may be well to summarize the views most favored at present.

Attention has been called to the series of criss-cross lines which
develop upon the polished section of a metal when the piece is strained.
It is also to be noted that the irregular crystalline grains composing the
mass of a metal are distorted by cold work, their new form depend-
ing upon the kind of deformation which the piece, as a whole, has suf-
fered. Thus, if a billet is rolled into a sheet the grains are flattened.
If a rod is drawn into a wire the grains are stretched into longer ones,
their longest diameter being in the axis of the wire. Such an effect is
illustrated in figure 21, which is a photomicrograph of a piece of a high-
pressure gas cylinder made from cold-rolled steel of low carbon content.
Figures 22 and 23 show similar effects of cold working of medium-carbon
steels.

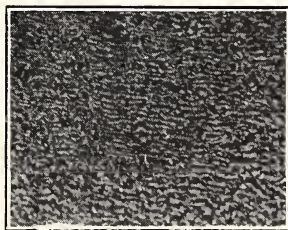Fig. 21—Cold rolled low-carbon steel. x100.

Fig. 22—Cold rolled steel. x100.

Going back for a moment to the atom lattice of the metal crystal
we may illustrate what probably happens to the metal under severe
stress by figures 24, 25, and 26. In these drawings an attempt has been
made to simplify the matter by indicating atom positions merely by in-
tersections of parallel lines, one set perpendicular to the other, thus
indicating a cross-section of a metal having a simple cubic lattice.

Suppose that the original crystal, represented by figure 24, has a
shearing stress applied, as indicated by the arrows of figure 25. If

this stress be not too great the crystal is distorted slightly, and if the stress is then removed the crystal will resume its original form. It has then been stressed within the elastic limit. While temporarily each individual atom has altered its position relative to the others, the essential inter-atomic relations have not been seriously disturbed. The condition of the lattice while under such stress is conveniently represented by figure 25.
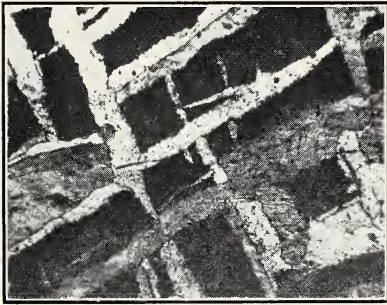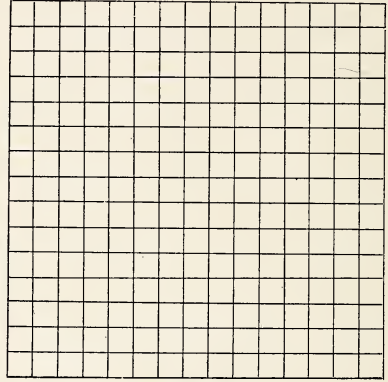

Fig. 23—Cold worked, medium carbon steel. x100.

UNSTRESSED CRYSTAL

Fig. 24—Conventional representation of a section of an unstressed crystal.
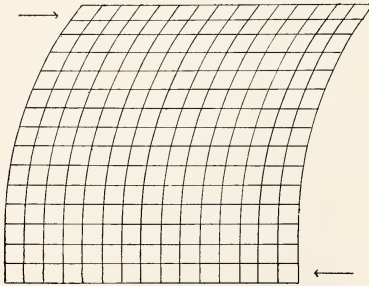

Fig. 25—Conventional representation of a section of a crystal, stressed within the elastic limit.
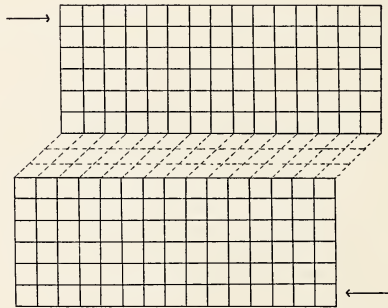

Fig. 26—Conventional representation of a section of a strained crystal.

If the stress is again applied and continuously increased, a value will presently be reached where the crystal has been deformed to a point where it will not return to its original form when the stress is removed. It has then passed the elastic limit and the metal is permanently strained. In the same conventional way the strained crystal may be represented by figure 26, where the main portion of the crystal has maintained its integrity of form but along certain atom planes a sliding or gliding has occurred, somewhat as a neatly piled pack of playing cards will slide along certain cards, if one pushes in a horizontal direction against the top of the pile. The planes along which such disturbance has taken

place are called "slip planes," and the dark lines visible in figure 14, each including enormous numbers of these slip planes grouped together, are known as "slip bands."

Just what has occurred in the regions of the slip bands we do not know for certain and we cannot represent the change by the method used in figure 26. It has been supposed that the regular lattice has been torn down along the slip planes so that the metal in these regions is no longer definitely crystalline but rather amorphous. Also it has been thought that an increased amount of amorphous metal has been formed where slip planes intersect grain boundaries, themselves probably amorphous. And because of evidence that amorphous metal is harder and stronger than crystalline metal this has been held to account, at least in part, for the improved qualities.

It has, so far, proved to be impossible experimentally to demonstrate the existence of amorphous metal, either at grain boundaries or along slip planes, so that these theories remain merely as possible explanations, but at least suggestive and interesting. What we do know is that some rather profound disturbance has taken place within the crystal lattice, *but that the. atoms have not been permanently torn apart*, as is the case when a real fracture is produced. On the contrary they continue to offer resistance to repeated deformation and the metal has been, on the whole, "stiffened up." Cold working, therefore, remains an extremely valuable method for increasing the physical strength of metals. "Cold-drawn wire," "cold-rolled sheet," and similar terms have then a peculiar significance.

Solutions. Just a remark or two concerning the ordinary use of the term "solution." People usually apply this term only to ordinary liquids. We speak of a solution of sugar or salt or soda in water, of iodine in alcohol, and so on, always keeping in mind the *liquid* character of the mixture. Lemonade is then a solution of sugar, citric acid and certain flavors in water; varnish is a solution of certain resins and oils in turpentine or alcohol. But after all, at least to the chemist, the physicist or the metallurgist, a solution is but an extremely intimate mixture of the molecules or atoms of the two or more substances which are dissolved in each other. And solutions may be either liquids, solids or gases. The atmosphere is a gaseous solution, principally of oxygen and nitrogen. And all alloys are (at least within certain temperature ranges) liquid or solid solutions of their component metals.

The idea may be extended a bit farther. We have seen that crystals are orderly structures of atoms, built together in a perfectly definite pattern. If now to a pure metal we add a second metal (or even one of several non-metals) and heat to a temperature where solution may take place (this is the melting temperature in some cases, in others not) solution occurs by the process of atoms of the dissolving element— the "solute"—either crowding solvent atoms out of their places in the crystal lattice and taking these places themselves or crowding into spaces between the solvent atoms.

This means that the interlopers try to assume the functions of the former residents, usurping their places and reaching out their combining

forces to neighboring natives. "Trying" is the proper word, for no atom of the foreign element is exactly like the one which has been displaced. It is not of exactly the same size nor has it the same characteristics in other respects. The result is that, here and there, the atom lattice of the crystal is distorted. Atom planes are no longer true planes.

If mechanical analogies are preferred suppose that a mason is constructing a house, using carefully sized bricks of specified dimensions. His courses of bricks are neatly laid, forming beautifully straight, horizontal rows. But his bricks are running short. He lacks a few, cannot obtain the right kind in a hurry but finds that others are available, almost like the proper kind but not quite. They are slightly larger or slightly smaller or certain dimensions—length, width or thickness—are slightly different. A few of these odd ones are worked in, here and there. Not in one place, of course, for that would be too obvious. With this scattering of odd formed units the result is not, perhaps, *too* obvious, but a critical eye will now see that the rows are no longer regular and straight. They are slightly distorted, just as the crystal space lattice is distorted by the entrance of foreign atoms that will not exactly fit.

Or recall the analogy of the smooth pile of playing cards and suppose that, instead of these being high-grade cards, they are of cheap pasteboard, the fibers containing a good many of those small lumps so often found in low-grade paper. These lumps are like the foreign atoms taking the places of solvent atoms in the space lattice. To use one more illustration, suppose that the cards are of the smooth variety but that small particles of some rough solid have been scattered here and there between the cards. These solid particles will now represent dissolved atoms crowding between solvent atom planes, pushing their way into the lattice by distorting the planes themselves.

In any of these cases it will be seen that a certain amount of stiffness has been imparted by the imagined changes. The brick structure has certainly not been made more beautiful by the addition of the odd shaped bricks. But if a shearing stress were to be applied to the wall in the manner illustrated by figures 25 and 26 it would probably be found that sliding of smooth and regular courses would occur before any failure upon the courses in which the lines were spoiled by the bogus bricks. In the case of the cards, if a certain definite weight were to be placed upon each of the three packs and then a horizontal shearing stress again applied surely the fine, smooth cards would slip more readily than either the cheap ones or the good ones between which sand had been scattered.

If figure 24 conventionally represents a section of a simple, perfect lattice of one metal, figure 27 may similarly represent a portion of a crystalline solid solution or alloy, where the atoms of the solute *replace* atoms of solvent, and figure 28, one where solute atoms crowd *between* atoms of the lattice. The last two drawings differ from that of figure 24 because we now find it desirable to distinguish between the position of atoms of the solute and those of the solvent. So the latter are here represented by open circles, the former by black circles.

Remembering that deformation of a metal by stress, whether this

be pressure or any other kind of stress, is really a matter of gliding of crystal planes over each other, also that strength means *resistance* to gliding under stress, and it may readily be imagined that the roughened planes of the alloy will not glide over each other as easily as the original perfect planes would have done. The alloy is, therefore, harder and stronger than the pure solvent metal since either stretching or indenting ultimately involves permanent deformation of individual grains.

One more interesting extension of this idea. A foreign metal dissolves in another pure metal, easily or with difficulty according to its similarity (or lack of it) to the first. Of course this holds only within the range of composition where the second metal is in complete solid solution.
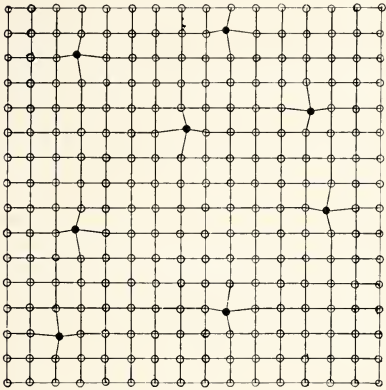

Fig. 27—Effect of dissolved foreign atoms upon crystal planes, where solute atoms displace atoms of solvent.
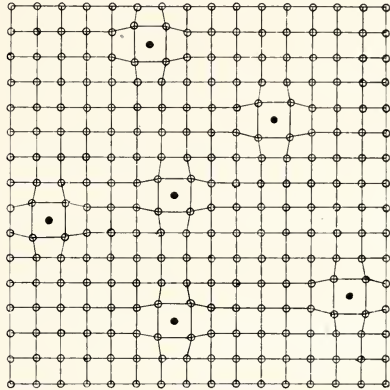
Fig. 28—Effect of foreign atoms upon crystal planes where solute atoms crowd between solvent atoms.

This is not difficult to understand. Races and communities follow similar rules. The more nearly the immigrant is like the people of the country or community, the more readily is he assimilated without undue commotion or disturbance. In the case of the metals, if the second one dissolves easily in the first this means that it takes its place in the crystal lattice with comparatively little disturbance of the perfect planes of that lattice, while if its solubility is small it is (chemically and physically) unlike its solvent and therefore it causes a correspondingly greater distortion or roughening of the atom planes.

If this be even an approximately correct view of the matter one may conclude that resistance to gliding ("slip resistance") will be, qualitatively at least, inversely as solubility, and we are therefore in possession of some sort of notion to explain the undoubted fact that *the greatest strengthening and hardening effects in alloys are produced by alloying metals whose mutual solubility is relatively small.*

A few examples may be noticed. Gold has been mentioned as being much used for ornamental and protective purposes and for coinage. But gold is quite soft and it would be relatively useless for these pur-

poses if it could not be hardened in some way. A number of metals will readily alloy with gold—some of them very easily. For practical purposes most of these are excluded because they would destroy this immunity to corrosion; and a large solubility is noticed in the case of the metals which do not themselves oxidize easily (the "noble" metals). It is, therefore, not possible to produce an extraordinary degree of hardening by the addition of such metals. However, an alloy of 90 per cent gold with 10 per cent copper is distinctly harder than gold, and it serves well enough for coinage. This is the alloy used by the government of the United States. Ordinary gold jewelry is of gold-copper composition, the proportion of gold being indicated by the number of "carats," 24 carats indicating pure gold. (Eighteen carat jewelry is therefore 18/24, or 75 per cent, gold.)

The brasses, bronzes, aluminum bronzes and Babbitt metals are other illustrations of this principle. And attention will again be called to the steels, which are essentially solid solutions of carbon in iron, especially after they have been given certain thermal treatment for hardening and strengthening. The hardening effect of carbon upon iron is very pronounced and its solubility in iron is correspondingly small. The steels are therefore very much stronger than pure iron.

The myth of "hardened copper" of the ancients is one that seems hard to dispel. It is a poor year for fakirs when at least one does not "rediscover" the "lost art." Scientific investigation invariably demonstrates that if the copper has been hardened at all, it has been either by cold work—which is not by any means a lost art—or by alloying small amounts of other metals with the copper, after which it is not copper but a copper alloy.

Lead is used in large quantities for the manufacture of the plates of ordinary storage batteries. But this metal is quite heavy and, at the same time, quite soft. Especially for use in batteries of portable nature, such as those used in automobiles, the metal would not sustain its own weight without injurious sagging. It is therefore hardened and stiffened by alloying with it a small proportion of antimony. A similar reason accounts for the use of antimony as an alloying constituent of type metal, which is otherwise largely of lead.

Grain Size. Another property vitally affecting the strength of metals is the average size of the crystalline grains composing the mass. Upon the assumption that the cellular envelopes which enclose the grains and separate them from each other are amorphous, and that amorphous metal is harder and stronger than crystalline metal, there is provided an explanation for the observed fact that when a metal is stressed to the point of fracture, the break runs normally *across* the grains and not around them. While it is not easy to prove experimentally that these grain boundaries are actually amorphous, it is certainly true that they are stronger than the grains themselves.

The particular direction in which the axes of a given grain are inclined, relatively to those of other grains, (the orientation of the grain) is more or less a random matter. On this account the "cleavage planes"—atom planes along which either slip or fracture occurs—of the

various grains will be directed, or oriented, without any regularity and again at random with relation to each other. This is seen in figure 14, where the slip bands change their direction at grain boundaries. When a piece finally breaks, the *macro*scopic appearance of the fracture is that of a multitude of bright facets, each being a section across a grain of metal. This is why a metal fracture is always more or less rough in appearance.

The Effect of Grain Size Upon Strength. The failure of a piece of wood under stress is usually a matter of splitting along planes represented by the fibrous structure of the wood. A fine, straight-grained wood splits more readily than one of twisted grain, as illustrated by oak and mahogany, respectively. If even the oak wood is full of sound knots, the wood is less susceptible to mechanical failure. The obvious reason for this is that the cleavage planes are interrupted by the knots or twisted fibers, with a corresponding change in the direction of the fracture. The dividing forces of the tool are not exerted in a way to suit this change.

This effect is still more striking when one considers a piece of two-ply or three-ply wood, with one thin board glued to another which has its grain oriented in a manner perpendicular to that of the first.
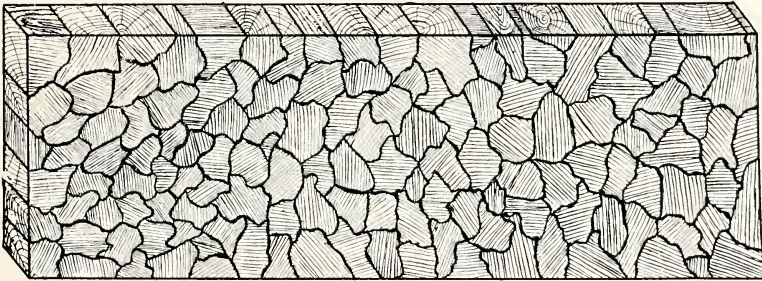

Fig. 29—Diagram of a composite block of wood, showing strengthening effects of random orientation.

Figure 29 is an imaginary representation of a piece of wood, compounded by gluing together a number of "polyhedral" blocks, each of straight-grained material, but with the grain of these blocks oriented in all sorts of directions. If the glue which has been used is as good as its manufacturers advertise, the glued joints are actually stronger than the wood itself and the analogy with the metal is complete. It will not require much debate in order to decide whether this composite specimen will be more or less easily pulled apart or crushed than would be the case with a single piece of straight-grained wood of the same dimensions.

The individual grains of the metal may be likened to the irregular blocks of figure 29. Every time a break reaches a grain boundary it has to change its direction. In addition to this, it has to run across an envelope of stronger metal. Also (and this consideration does not apply

to the piece of wood) *before* fracture a plastic deformation of the grain would have to occur to a considerable extent. As such deformation consists of slips on crystal planes, it is resisted if planes of neighboring grains are not disposed so as to continue the slip without change in direction.

It will then be seen why it is that fine-grained metal is stronger than coarse-grained; for the more frequently the inclination of slip planes is changed, the greater will be the resistance—first to slip and then to fracture.

Vibration and Crystal Growth. Most people have heard the statement that a particular piece of metal broke in service "because it had crystallized as a result of vibration." This is a mistake, for the simple reason that, with a few unimportant exceptions, metals do not crystallize or change their crystal size as a result of vibration. They are crystalline as soon as they freeze from the liquid state and they remain in that condition. Breaks of the character just mentioned are usually due to a phenomenon known as "fatigue." Sometimes they are due simply to the fact that the metal was defective in the beginning.

But this notion about metals crystallizing under vibration is as hard to dispel as the one about an ancient lost art of hardening copper. The reasoning at first seems valid. A piece of steel (say, of a bridge structure or of an automobile axle), subjected to continued vibration under intense stress, breaks. Examination of the fracture shows that it is very rough, and that the metal was therefore coarsely crystallized. The conclusion is reached that vibration has crystallized the metal, or that it has increased the average grain size.

If one should make a microscopic examination of a piece of steel, find that it is fine grained, subject it to repeated intense stresses until it breaks, and then re-examine and find coarse grains, the case would be established. But the coarse grained axle or bridge structure had not been so examined before it went into service and that bit of evidence is lacking. On the contrary, the complete experiment has been performed in the laboratory over and over again, and there is no manner of doubt now that repeated stresses have no effect whatever upon grain size or structure unless these stresses are above the elastic limit, thus causing permanent distortion before fracture.

The Structure of Eutectoids. When two metals are melted together there is usually some temperature range within which they form a homogeneous mutual solution. Upon cooling, the freezing point is usually lower than the average indicated by the percentage composition of the alloy and the freezing points of the component metals, but in many of these alloys there is some particular composition which gives an alloy having a freezing point lower than for any other composition. Such an alloy is called an "eutectic" and when the eutectic solution freezes, the metals fall out of solution and give a conglomerate of microscopic particles, this conglomerate being known as an "eutectoid."

The formation of eutectoid mixtures from eutectic solutions is a result of the simultaneous freezing of both components of the liquid

solution and this always gives rise to a very fine intermixture of these two solids. Solid eutectoids often show the structure of alternating microscopic plates of the two components; but sometimes they exhibit the characteristics of microscopic globules of one, dispersed in a matrix of the other. The patterns visible through the microscope are frequently very beautiful and a few of them will be shown here.

Figure 30 is a micro of a lead-antimony alloy. In this case the composition was "hypereutectic" (it contains more antimony than the eutectic) and the excess antimony appears as large bright crystals.
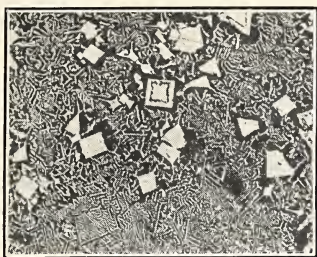

Fig. 30—Lead-antimony alloy, with eu-
tectoid and antimony crystals. x50.

Fig. 31—Lead-tin eutectoid. x100.

Figure 31 is of the eutectoid of lead and tin, containing 37 per cent of lead and 63 of tin. The eutectoid of cadmium and tin (cadmium 29 and tin 71 per cent) is easily distinguished in figure 32. The globular grains are of tin, showing that the alloy as a whole was hypoeutectoid with respect to cadmium. The dotted portion of figure 33 is the eutectoid of a "white" cast iron. The eutectoid of iron and iron carbide (pearlite) has already been shown in figure 12.

Steel. Steel is a material in which iron is the chief constituent, but which contains also small percentages of carbon. There are always present also small quantities of impurities which cannot be entirely removed in the process of manufacture, such as phosphorus, sulphur, silicon and manganese, and there are in industrial use today large numbers of special steels, to which certain amounts of other metals have been added in order to confer desirable qualities upon the steel. Such materials as the last named are known, in general, as "alloy steels." The metals most commonly added are nickel, chromium, tungsten, molybdenum, vanadium, manganese and uranium.

Steels not classed as alloy steels are often designated as "carbon steels." However it is to be remembered that carbon is an essential constituent of any steel, whether alloy or not. That is, if carbon is not present, we do not have a steel at all, but rather an alloy of iron with the added metal or metals.

Steels possess an extraordinary capacity for response to thermal treatment, the rate of heating and cooling profoundly affecting the hardness, tensile strength, elastic limit and ductility. This fact makes this class of alloys exceptionally useful in industry.

Fatigue. When a man becomes very tired he wants to quit working. If he cannot quit he goes into a state of excessive fatigue and any

physician will say that the body in such a state is an easy prey to disease-producing organisms. Possibly this is why a metal, under severe service for a long time where the stresses are repeated or alternated in direction, and finally failing, is said to have yielded to "fatigue."

Metal does not become "tired," as do living bodies, but there is a certain analogy, after all. If the severe stress, even below the elastic limit of the piece as a whole, is of an alternating or repeating character, as when a piece of machinery is subjected to intense vibration under stress, a microscopic failure may begin at one of the weaker spots. It may then spread, simply because its own proper load is thrown upon the parts immediately surrounding it and this load is more than even they can bear. The spreading of failure is so slow as to be imperceptible at first, and the piece may last for a long time. But failure gathers speed as it spreads and the piece finally breaks.

Automobile axles frequently break in this way. The stress which is applied through the drive shaft and differential is of a pulsating character and the direction of stress caused by the weight of the car is constantly changing as the wheel turns. For a long time before the break occurs, no crack of any kind could be seen. But at the last it goes rapidly and the axle finally yields suddenly.

Cast Iron. This term is more or less of a misnomer because cast irons actually contain more carbon, and usually more of the common impurities, than steel itself. But the designation sticks, as do many of the names of materials and processes of older origin.

There are three general classes of cast irons, known respectively as "white," "gray," and "malleable." As the first named class is the only one which conforms to the general principles already discussed, it should be considered first.

White Cast Iron. Although liquid iron will dissolve carbon to the extent of about 6.7 per cent of the total weight of the alloy, much of this carbon will separate in the free state unless hindered by the presence of restraining elements—of which manganese is most commonly used—or by fairly rapid cooling, or by both influences. If these steps are taken to prevent the formation of free carbon, the resulting casting is found to be exceedingly hard. If broken by the application of large stresses it will fail without any appreciable previous deformation, which proves its ductility to be practically zero. The broken surfaces are then brilliant and of light metallic luster, hence the name "white" cast iron.

The microscopic structure of white cast iron is shown in figure 33. On account of the large amount of hard iron carbide, castings of this material are so brittle and so hard, and therefore difficult to drill or machine, that they are not often made except as a first step in the production of "malleable" castings.

Gray Cast Iron. In castings of such high carbon content, a change takes place after the casting has solidified, unless precautions have been taken to prevent it. While the iron carbide of steel is quite stable—no doubt partly on account of the lower temperature at which it separates from the solid solution—the carbide of cast iron begins a chemical decomposition as soon as it has been formed from the liquid solution.

As a result of this, free carbon forms, and remains as branching masses within a matrix of ferrite grains.

Photomicrographs of this form of cast iron are shown in figure 34. The bright portion is of ferrite grains and the black masses are of free carbon, known here as "graphite." When a casting is broken the abundance of exposed graphite, intermixed with bright facets of ferrite grains, gives the fracture a gray appearance, which is responsible for the name of this class of castings. As the ferrite, ductile though it is, is so "honey-combed" with these branching masses of carbon, the castings are relatively weak and easily broken by shock.

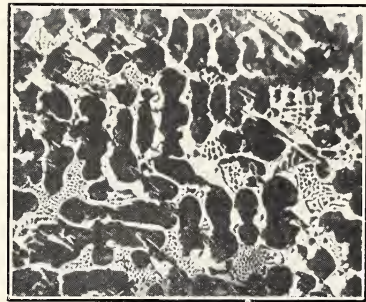
Fig. 32—Cadmium-tin eutectoid with excess of tin. x100.

Fig. 33—White cast iron. x100.

Fig. 34—Gray cast iron. x100.

Fig. 35—Malleable cast iron. x100.

One may be inclined to wonder why gray castings are ever made at all, in view of their poor strength characteristics. This is explained when we remember that such castings may be made from a moderately good grade of pig iron. As pig iron is the starting point for most of the steel making processes, the entire expense of steel making is avoided by the use of gray castings and the cost is reduced to the point where it is, in some cases, economical to provide the necessary strength by increasing the mass of the casting. The cost of the extra necessary material itself is thus more than compensated by the saving in the expense of refining.

So it happens that gray iron is used for purposes where a larger weight is not objectionable (or where it is even desirable, from the standpoint of general stability) or where much drilling or grinding is

to be done with the casting. As examples there may be mentioned the heavy bases for supporting machinery, many of the heavier parts of the machinery itself, cylinders of locomotive and automobile engines, heavy railway car wheels, and water and sewer pipe.

Malleable Castings. The carbon of gray iron has begun to separate from iron carbide as soon as the casting has become solid, continuing as cooling progresses. If the composition and cooling rate are so adjusted as to produce white iron, and if then the casting is reheated, free carbon will slowly form but the appearance of the masses will be different. Instead of the curved branches of the graphite of gray iron, extending through the mass of ductile ferrite and weakening it, the carbon forms in more compact bunches, leaving the ferrite in sounder condition.

Figure 35 indicates why this class of castings is of greater strength than gray iron and why it will withstand greater shock without breaking. As in gray iron itself, the most of the metal is ferrite grains but now the free carbon is in these smaller and more compact masses. This carbon is called "temper carbon," although the only difference between this and the graphite of gray iron is in the form of the microscopic aggregates.

"Malleable" castings are not highly malleable, as compared with pure iron. They cannot be cold-worked to any considerable extent, although bars not too thick may be bent through a considerable angle without breaking. But they will withstand both shock and slow stresses much better than gray castings. They are therefore used where the massiveness of gray castings is not permissible, but where the strength of steel is not required. The small castings of "link" belts for agricultural and other machinery, the elbows and unions used for pipe fittings, many of the small castings of automobiles, and other similar articles, are generally made of malleable castings.

CONCLUSION.

It will have become perfectly obvious to those who have listened to this address that no systematic or complete discussion of the field of metals and alloys was expected to be accomplished. A recent list published by the American Society for Testing Materials contains the names and compositions of more than fifteen hundred alloys, not even including the various irons and steels. And the list is far from being complete. A survey of such a vast field is clearly impossible in such a paper as this. Many excellent books upon these subjects are available to the student of metallurgy who may intend to devote himself to an extended study of the subject.

On the contrary, I have tried to keep in mind just what is indicated by the title to this paper. The application of the microscope to the study of metals is a subject which is so fascinating and so useful that it has seemed desirable to attempt to bring some sort of understanding and appreciation of the results of the use of this marvelous instrument to some of those who are interested in the subject, but to whom the study of metallurgy as a science may have seemed appallingly deep and intricate.