THE *Electron* MICROSCOPE

BY CHARLES S. BARRETT

THE development of the electron microscope is the most important advance in the field of microscopy in many years. It opens to view for the first time the world of things at a size of a millionth of an inch. Bacteriology, biology, chemistry and metallurgy have profited from the use of this instrument during the very few years it has been available and much more may be expected of it in the future. An attempt will be made in this article to touch upon its applications to various fields of research, but the writer himself is engaged in metallurgical research and therefore will speak of that field in greater detail.

THE INSTRUMENT

The current commercial model of the electron microscope, manufactured by the Radio Corporation of America, is truly imposing. (See *Fig. 1.*) It stands about seven feet high and, together with its auxiliary vacuum pumps and work benches, requires a room of moderate size. It is in reality a large vacuum tube containing an incandescent lamp filament that throws off electrons when heated, a source of high voltage electricity to speed the electrons down through the instrument, and a series of wire-wound magnets to bring the electrons into focus on the viewing screen and on the photographic plate. There are 53 radio tubes in it, which are fitted compactly on panels that fold down from the back of the instrument. The numerous electrical circuits and radio tubes are necessitated by the requirement that the electrical currents through some of the windings be held constant to one part in 25,000, while the voltage in the city electric lines supplying the microscopes may vary by one part in 25. The mechanical details of the device are also intricate, for they must provide for movement of the specimen and of the photographic plate inside the vacuum chamber without disturbing the high vacuum. There are more than 50 joints that must be made and maintained vacuum tight. Quite naturally, the adjustment and maintenance problems are much more numerous and varied with this instrument than with ordinary microscopes.

An instrument so complex in construction and so time-consuming in operation should give in return some results far superior to those from an ordinary light microscope, and this it does. It is a sort of "supermicroscope," with a power to magnify small particles and details of objects that is far beyond that of conventional microscopes. It has been said that the electron microscope can enlarge a human hair to the size of a giant redwood tree, or a particle of metal powder so fine as to be barely visible to the size of a room. While statements like these can be justified, the degree of magnification that can be obtained is not the important aspect of the problem. Even a child's movie projector can produce enlargements of this size, if the screen is moved to a sufficient distance from the lantern.

The importance of the electron microscope lies, rather, in the amount of detail that can be seen in the final enlargement—the sharpness of the image. Some of the accompanying reproductions of pictures taken with the electron microscope and with the conventional type microscope illustrate the fact that, at the same magnification, much more can be seen in the electron micrograph than in the light micrograph. In fact, the details that can be seen in the photographs from the electron microscope range down to a tenth and even to a hundredth the size of the smallest details that can be seen with the ordinary light microscope. Particles can be photographed that are only 10 to 15 atoms in diameter. This great increase in power (resolving power, as the microscopist calls it) could only be obtained in a light microscope by a reduction in the wave length of the light to a hundredth of the actual wave length of visible light. This is impossible with light, but in the electron microscope it is accomplished, in effect, by substituting for light a stream of

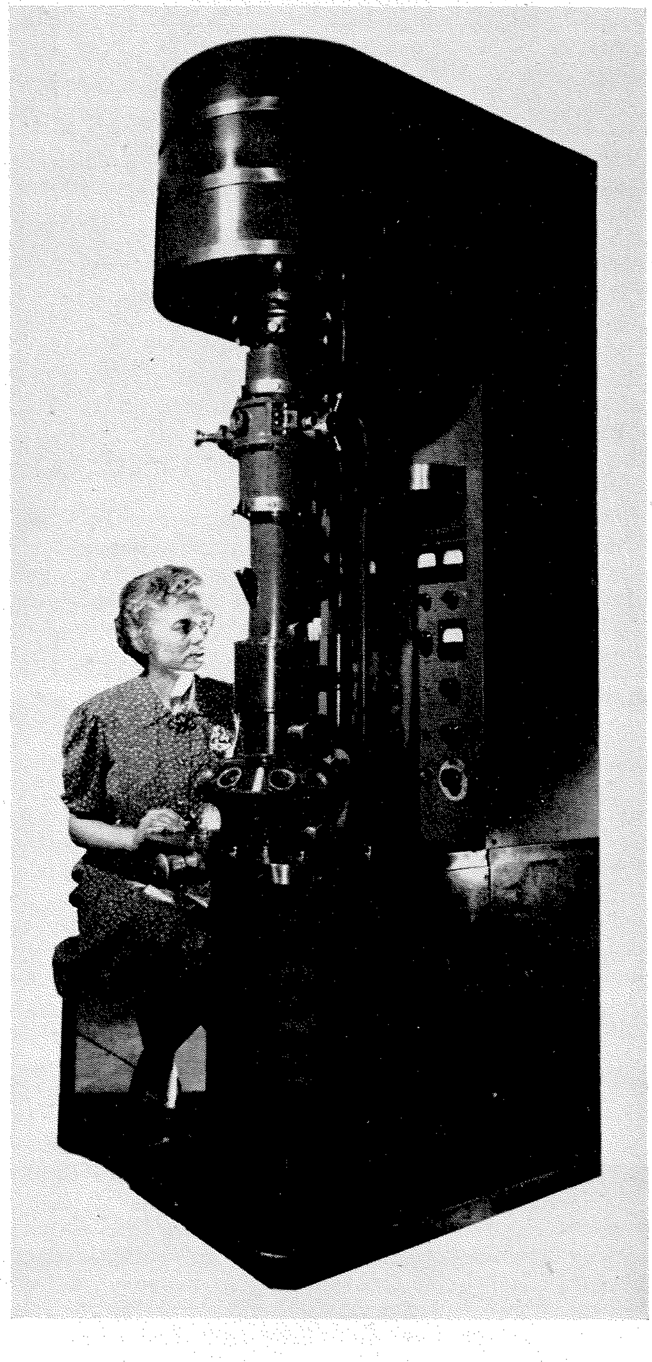


FIG. 1—The electron microscope.

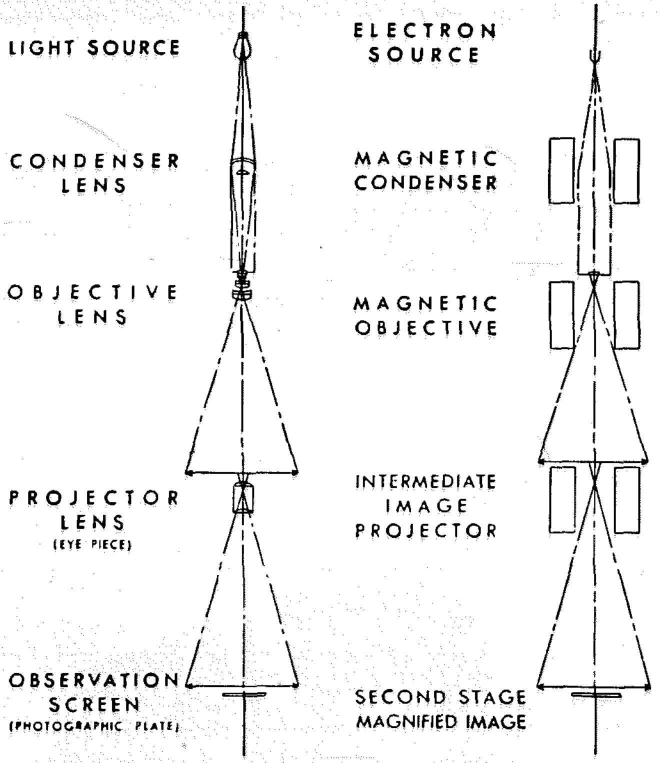


FIG. 2—The sequence of lenses in a high-power microscope is duplicated in an electron microscope.

electrons that act in the way that a beam of light of this short wave length would act. The electrons are directed by electric and magnetic means so that they are focussed as a beam of light is focussed by a lens. (See *Fig. 2.*)

The substitution of a beam of electrons for a beam of light shortens the wave length much more than a hundredfold, and if one could make full use of the principle that the resolving power increases proportionately, one might imagine that the electron microscope would permit us to see individual atoms. At the present time, however, this is not possible, and it seems likely that several factors will prevent it even if additional improvements in the apparatus are made.

It is sometimes practicable to magnify the linear dimensions of objects 100,000 times by using an electron microscope, but usually it is better to use magnifications of 5,000, 10,000 or 20,000, for it is seldom that the detail can be increased by using magnifications beyond these figures. The entire field of view at a magnification of 100,000 diameters is not large enough to show the whole of one red blood cell, or of an average-sized particle of airborne dust 0.002 millimeters in diameter. It is understandable, therefore, why it is often best to increase the field of view by reducing the magnification to about 2,000 diameters when exposing the negative and then to enlarge the negative in the dark room when making prints of it.

OPERATION

The electron microscope is operated by inserting a sample in the vacuum chamber and adjusting it in the beam of electrons. The enlarged image is brought into view and focussed on the viewing screen, which is about the size of one's hand, by turning knobs much as one tunes a radio receiver. Increasing the current through the final lens causes the image to grow from a pinpoint until it covers the entire screen, and at the same time the image rotates about its center. If the sample is powdered material, dust, colloidal particles or bacteria, the image will be a greatly enlarged shadow of these. The electrons seldom actually penetrate the particles themselves, for only particles that are less than one or two hundred atoms in thickness are transparent to the electrons; all larger particles are opaque and merely cast shadows on the viewing screen. Unfortunately, the image is in black and white and lacks the color that is such a striking and valuable attribute of an image in an ordinary microscope, but it is nevertheless excellent for measuring the size and shape of the particles or for disclosing their surface contours. It is possible to take two pictures of the same particles in such a way that they can be viewed in a stereoscope. When one looks at a pair of stereoscopic pictures the sense of depth they convey makes it easy to imagine one is in a micro-world full of strange objects.

APPLICATIONS

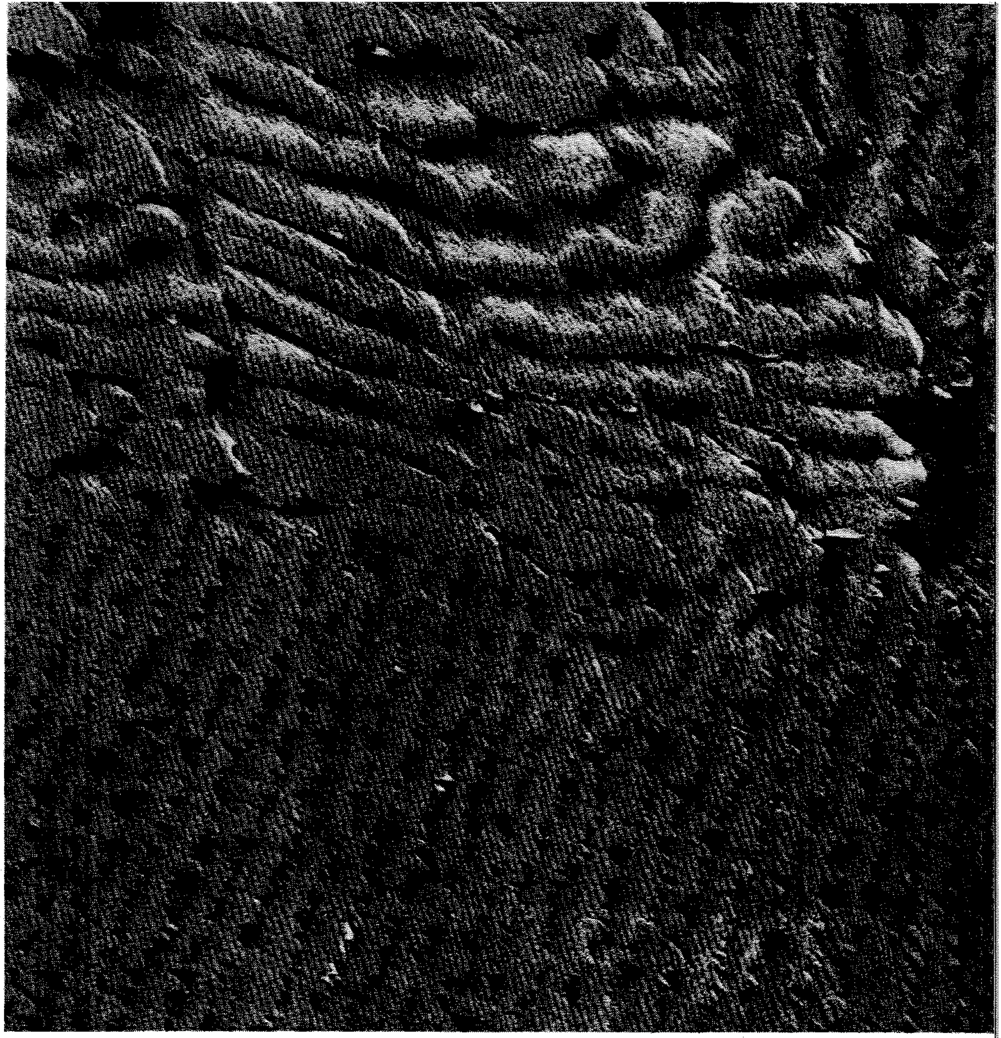
In the fields of bacteriology, biology, and chemistry, many discoveries have been made and many structures seen for the first time with the electron microscope. The study of viruses has progressed rapidly with the new instrument, for practically all of the viruses are too small to be observed directly by any other means. Their exact shape and size can now be measured, as well as their tendency to clump together. The manner in which drugs attack the viruses can be studied, as well as the way viruses are attacked by antibodies that are generated in the body. When bacteria are magnified to the size of cigarettes it becomes possible to view the much smaller organisms known as bacteriophage that attach themselves to the bacteria and bring about their destruction. One type of bacteriophage, which consists of tadpole-shaped bodies each having a head and a tail, has proved to be quickly destroyed by sound waves and by ultraviolet light. The long thread-like arms by which the bacteria move, called flagella, are now readily photographed, and protective outer shells have been found on several varieties of bacteria, including typhoid bacilli, streptococci and pneumococci.

One or two examples from the chemical field may be cited. Very fine grained carbon has many commercial

FIG. 3—Cubic particles of magnesium oxide enlarged 20,000 diameters.

AT RIGHT

FIG. 4—Pearlite in steel. A lamellar arrangement of iron and brittle iron carbide. The magnification is 20,000 diameters.



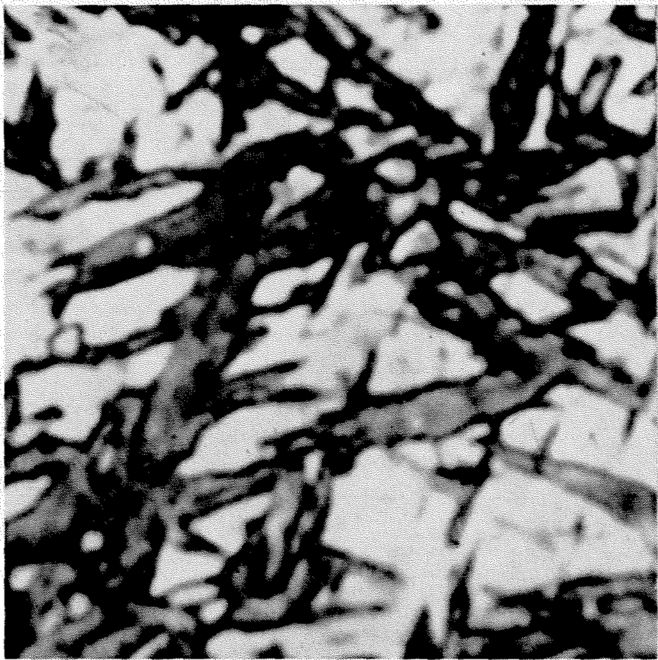
uses; it colors inks and plastics, reinforces rubber and improves its physical properties, serves as a lubricant, and is employed in the radio industry. The size and shape of the particles of colloidal carbon can be investigated very easily in the microscope, which makes it an important means for the manufacturer to inspect and control his carbon production processes. Similar applications are common in the field of paint manufacture, where the size of the particles of pigment and the way in which they cluster are of great industrial importance. The appearance of magnesium oxide particles (see *Fig. 3*) has been found to be closely related to properties of the oxide that are of importance in industrial chemistry. A bright future for electron microscopy exists in the study of high polymers, where some preliminary successes have been reported in the determination of molecular weights of polymers.

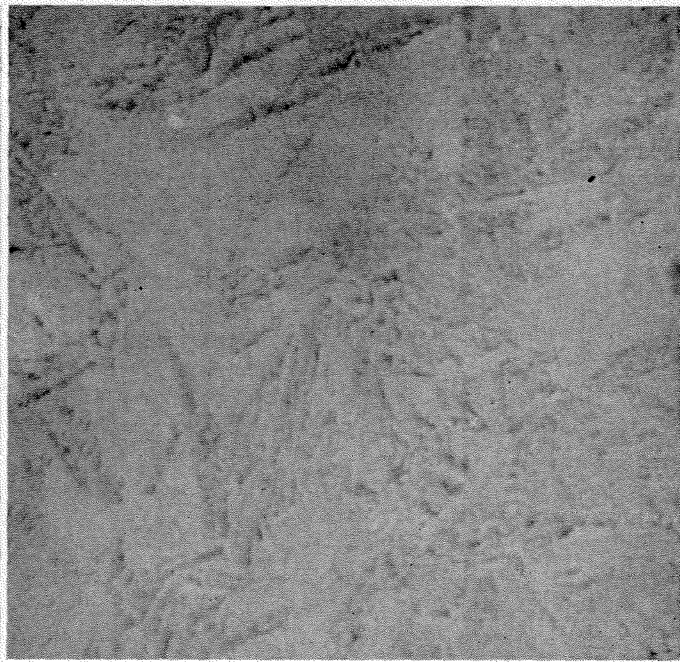
The instrument in the Metals Research Laboratory of Carnegie Institute of Technology is one of the few devoted to research in physical metallurgy. It is a real handicap to the metallurgist that he cannot look at metal specimens directly in this instrument. The electrons have so little penetrative power that they cannot pass through the thinnest metal sheet. The structure that is developed on the surface of a thick piece of metal after careful polishing and etching can be photographed easily with an optical microscope, but to make a photograph with the electron microscope it is necessary to prepare a replica of the surface thin enough to transmit electrons. One way to accomplish this is to paint the metal surface with a dilute varnish and strip off the film of varnish after it has dried. When the conditions are carefully controlled, the resultant film, transparent to the electrons, duplicates the markings seen on the surface of the metal. While this is one of the simplest techniques available, it has not given results as satisfactory as some others. A method that has been tried on the Carnegie Tech microscope recently with considerable success is being developed by metallurgists at The Aluminum Company of America. In this method, a thin oxide layer is formed on the surface of the metal (usually aluminum or an aluminum alloy in this case) and the metal is then dissolved by chemicals. The residual film serves as a replica of the surface undulations and also traps within it various particles that originally existed within the metal.

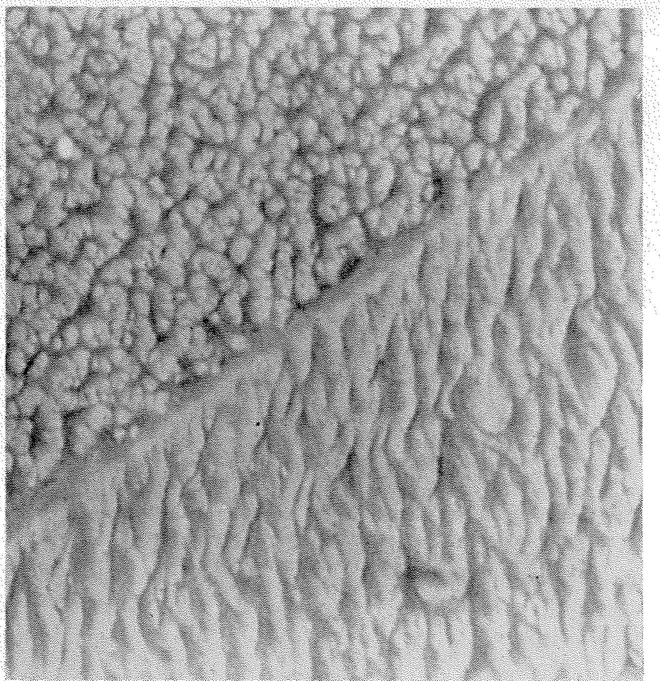
REPLICAS

The most effective of the present methods makes use of a replica that is made from a previously prepared replica—the electrons pass through a film that is two steps removed from the metal surface that is being studied. The procedure for the double replica technique is briefly as follows: A specimen is polished, etched, and examined for suitability under the optical microscope. When it passes this inspection it is mounted in a press and a thermoplastic material (polystyrene) is molded into the prepared surface. This is accomplished by applying a pressure of 3,000 pounds per square inch and a temperature of 150°C. After cooling, the plastic molding is separated from the metal and mounted in an evacuated bell-jar, where a thin layer of silica (SiO_2) is deposited upon it by evaporating a piece of quartz in a small electric furnace. When a layer 200 or 300 atoms thick has been deposited, the molding is placed in a liquid (ethyl bromide) that dissolves the plastic and leaves the thin silica film swimming in the solvent. The almost invisible film is then caught on a fine wire mesh and transferred to the microscope, where its variations in thickness provide a replica of the details on the surface of the metal specimen.

Such a series of operations naturally provides many opportunities for trouble, and the preparation is often spoiled before it reaches the final stage. The final picture may present difficulties, too, for it may be full of details that are totally unfamiliar to the metallurgist. He is faced with the questions, "Are they real or spurious? If they are spurious, how can they be avoided? If they are real, what do they mean?" Each specimen becomes







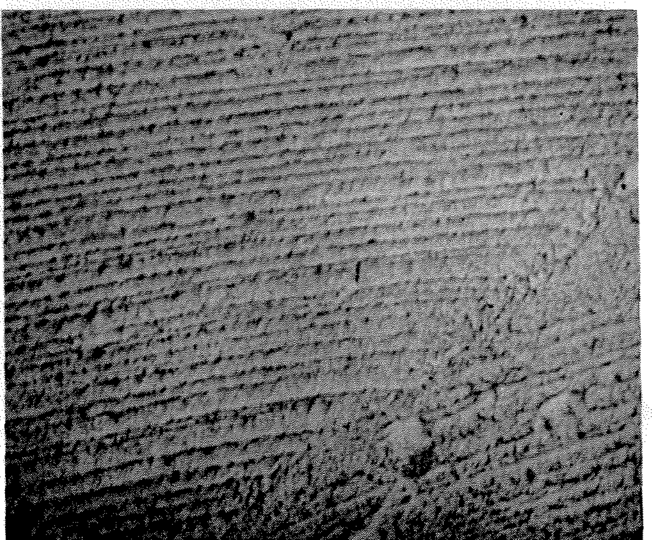


FIG. 5—(Two views at top) Hardened steel as viewed with the optical microscope (on the left) and the electron microscope (on the right) at the same magnification, 4000 diameters. Dark, roughened areas are martensite crystals.

FIG. 6—(Center, left) The surface of copper after etching. A boundary between two different crystals is shown at 10,000 diameters.

FIG. 7—(Lower, left) Markings on metal surface caused by severe deformation. The movement of layers over each other produces a stepped surface. The magnification is 15,000 diameters.

a challenge and leads to an "adventure" of some kind. After surviving a series of such adventures one realizes how the microscopist felt in the early days of the optical microscope, when he, too, saw structures never seen before, which were sometimes difficult to interpret. The correct pictures and the correct interpretations of them were gradually developed by the combined experience of many observers who used many lines of indirect evidence, and the same evolution will undoubtedly take place in this new microscopy. There are frequent exchanges of information on techniques and results among electron microscopists—in fact, in typical American fashion, a technical society has been organized for electron microscopists and various symposia have been held.

STRUCTURE OF METALS

Many of the 1500 or more photographs that have been made on the microscope at Carnegie Institute of Technology are of steel in one or another of its structural modifications, an appropriate interest for a laboratory located in Pittsburgh. Pearlite is the name given to one common structure in steel (the name originating from the mother-of-pearl appearance of the etched surface). As *Fig. 4* shows, pearlite consists of alternate dark and light lamella, which are layers of iron and iron carbide. The layers of this picture are too closely spaced to be seen clearly on a light microscope.

The structure of steel that is heat treated to great hardness is illustrated by the pair of micrographs shown in *Fig. 5*, one made with the electron microscope and the other with the optical microscope. Dark boat-shaped

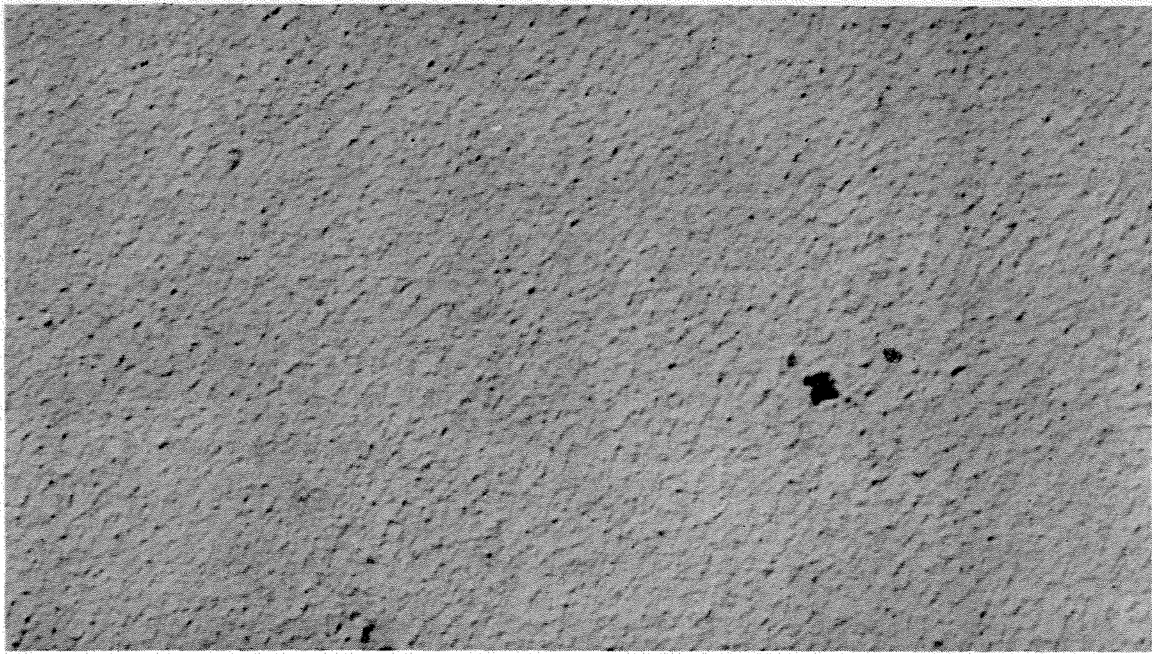


FIG. 8—Hardened Monel metal at a magnification of 20,000. The black specks are precipitated crystals 50 to 100 atoms in diameter, causing the hardening.

markings of the optical picture resolve into pitted areas on the electron picture. These pits are the individual points of attack of the acid that has etched the surface, and they mark out the crystals of the constituent known as martensite, which produces the hardness.

Pictures often resemble aerial photographs and sometimes give a remarkable appearance of depth or perspective. The photograph of etched copper reproduced in *Fig. 6* is an example of this. Why acids carve the surface of a metal into such complex but systematic patterns and what the patterns mean with regard to the internal structure of a crystal are questions that will require much more research to answer.

The markings on the surface of a metal that has been compressed or stretched are of great scientific interest, for they reveal the mechanism of plastic flow in metals. Some bands and lines can be seen on a deformed metal with the unaided eye, but a great many more appear if a low power microscope is used. The number increases so rapidly with higher magnifications that one wonders whether there are still others that could be made visible with electron pictures, and whether the lines that appear to be single lines at ordinary magnifications might not be resolved into bundles of closely spaced lines when the new microscope is employed. The photomicrograph in *Fig. 7* does show, indeed, parallel "slip lines" too closely spaced to be seen clearly with the earlier types of microscope. The lines are caused by the movement of layers of the crystals over one another much like the displacement of cards in a deck, a movement that leaves the surface crossed by a series of steps about a millionth of an inch apart. But the belief that these lines might be made up of still more closely spaced lines seems to be unfounded; in all electron microscope pictures that have been made thus far the lines occur as individuals. Physical metallurgists are giving much thought to the semi-regularity in the spacings of the slip lines, so apparent in the accompanying reproduction, for when the spacings are understood we shall be much nearer a full understanding of the strength of metals.

Fig. 8 shows the structure of Monel metal, a stainless alloy of both industrial and household uses. It is one of a class of important alloys that can be hardened by a heat treatment that consists of heating to an appropriate temperature, quenching in water, and finally "aging" at another temperature, lower than the first. The purpose of these treatments is to provide a supersaturated condition in the metal that tends to relieve itself by precipitating a galaxy of small new crystals throughout the body of the metal. Metallurgists had concluded from indirect evidence that this precipitation during the aging treatment actually occurs, but they were unable to see the precipitated crystals in this alloy after the hardening treatment. This was a tailor-made task for the new microscope, which was easily able to resolve the individual particles and to show their size and distribution. There are a great many other age-hardening alloys that provide similar opportunities for the new instrument to supplement the old, to reveal fine precipitated particles not yet seen, and to yield new information on the complex structural changes accompanying hardening.

OTHER DEVELOPMENTS

While there is much interest in electron microscopes, not many metallurgical laboratories have installed this equipment. A director of research must think several times before buying an instrument that costs about three times as much as the best optical microscope and also requires more skill and more time to operate. Consequently there is much interest in the development of a portable model that will be simpler and will cost but little more than a high power optical microscope. Both the R.C.A. Laboratories and the General Electric Company are now developing such models.

A recent improvement of the current model that is being installed on many instruments is an attachment that permits a chemical analysis to be made of the collection of minute particles viewed on the screen. The analysis is made by means of the diffraction of electrons from crystalline material in the sample, making use of the principle that every crystalline substance has its own characteristic manner of diffracting a stream of electrons. A pattern of concentric rings is produced that serves as a

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education of the prospective magnesium user to overcome his fears of magnesium fires. Many years ago both gasoline and kerosene were thought to be so dangerous that neither would ever be commonly used. Today the inflammability of gasoline has been greatly increased and yet it plays a very important part throughout the entire daily lives of all of us. Dangerous? Yes, but only under certain conditions and certainly not when one knows how to handle it.

Most people do not realize that in every magnesium incendiary bomb is some thermite, a mixture of aluminum powder and iron rust. This mixture is first ignited and it is this that sets fire to the magnesium. Magnesium will burn but only if heated to 1,250 degrees Fahrenheit in the presence of air or an oxidizing material.

As to the fields where magnesium may be expected to make its first showing after the war, the following appear most worthwhile considering:

Lightweight household appliances, vacuum cleaners, sewing machines, refrigerators, furniture, folding tables, washing machines, ironers, dish washers and driers, clothes driers, ventilating and other fans, small motors, can all be made of greater usefulness with magnesium. Window shades, screens and frames for the windows themselves are possibilities.

In the field of transportation, by airplane, by automobile and by train, magnesium undoubtedly will fill a tremendous demand. Its use in airplane construction is increasing, and the per cent of the total weight of the plane that is magnesium continues to increase in present manufacturing practice. The advantages in airplane, rail and ship transportation obtained by use of light metals and alloys are quite obvious.

In the field of automobile manufacture, with continued high gasoline taxes it seems quite probable that the need for higher gasoline mileage to guarantee economical transportation will require lightweight cars.

In commenting on various possible uses for magnesium, Dr. Colin G. Fink suggests the use of magnesium for coins. Speaking of magnesium instead of copper pennies, Dr. Fink says, "There are approximately 1,000,000,000 copper pennies in circulation equivalent to 6,600,000 pounds of copper. The peacetime production cost of copper is six cents per pound as against about 14.5 cents for magnesium. For the same sized coin, the magnesium penny weighs but one-fifth the weight of the copper penny. In other words, 1,320,000 pounds of magnesium pennies at a base cost of $191,400 would replace 6,600,000 pounds of copper pennies at a base cost of $396,000. There is only enough copper in the world to last industry 40 years as against 10,000 years for magnesium."

In considering the possible future uses for magnesium and light metal alloys, it is difficult to find applications in which they cannot serve.

The Electron Microscope

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positive means of identifying the material. The microscope combined with the diffraction attachment becomes a research tool that is particularly advantageous for pigments, dusts, and various chemical preparations. Its usefulness in varied fields of research may lead in the future to an instrument in which individual particles only 50 atoms or so in diameter can be singled out of a sample of powder, photographed and then identified by "Submicroscopic chemical analysis," either by the diffraction method or by an analysis of the velocity of the electrons that emerge from the particle.

Windowless Factory

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volt equipment is supplied through 50 kilovolt-ampere, 440-120/208 volt, three-phase, air-cooled transformers installed at regular intervals throughout the plant. In general, each serves three multibreaker panel boards from which current is extended by conduit or through the underfloor duct system which is extended throughout most factory areas. Balance is maintained as closely as possible between phases.

CONCLUSION

To evaluate a "controlled conditions" plant properly in relation to traditional factory construction requires exhaustive analysis beyond the scope of this article. Certain advantages, however, are obvious. First, product quality and uniformity have a better chance of being maintained at a high level. Second, and especially in a severe climate, employee comfort and efficiency are greatly improved. Third, inaccuracies due to expansion and contraction can be held to a minimum. This is very important as assemblies of light metals get larger and larger, and for accurate machining of large light structures. Fourth, corrosion from both atmospheric conditions and handling is reduced.

The only serious disadvantage which has become apparent is that of increased investment and operating cost. This is a disadvantage only when full production is not maintained. In this respect it may be compared with a high-production special machine tool versus a less expensive but more common type.

For mass production, the special tool and the "controlled conditions" factory both have an outstanding place in the future of industrial development.

The Month in Focus

(Continued from Page 3)

that the public may be assured of safety. Another civil engineer may be concerned with the construction of channels, involving a knowledge of hydraulics as well as features of construction. Such differences may be cited in other branches of engineering. Thus it is apparent that the complete unification of engineers into a single professional group is difficult and that there are major barriers to the realization of this ideal. Some fields of engineering have been legally professionalized by several states in requiring licensing of those who wish to practice publicly. It is probable that more extensive developments will take place along these lines which will place the various fields of engineering on a professional basis in the eyes of the public.

Those who read "Mechanical Engineering" may have noted in the May issue the article by Hans Ernst on "High-Speed Milling with Negative Rake Angles." These developments originating on the Pacific Coast have led to greatly increased rates of production in milling operations. In this work, carbide-tipped cutters have been and are being operated at cutting speeds in excess of 500 feet per minute and with unusually high feeds. Some of the advantages obtained with these methods are higher production, improved finish, and less distortion of work due to heat. Naturally, these developments present many problems which require research to establish the soundest procedures. As a part of a program of studying milling operations under these new conditions, California Institute of Technology is conducting certain studies which will be interesting to watch. In his article in "Mechanical Engineering," Hans Ernst presents some interesting data in this connection.