

## THE PHYSICS OF THE SOLID STATE

FOLLOWING the meeting of the General Assembly of the International Union of Physics in London in July, a number of scientific meetings were held to take advantage of the presence in Great Britain of the delegates to the Assembly from overseas. Of these, two were about the physics of the solid state; one at Bristol sponsored by the Union and with an attendance of about three hundred and fifty had as its subject "Defects in Crystalline Solids", and one directly afterwards in the Department of Metallurgy of the University of Birmingham was on the "Mechanical Effects of Dislocations in Crystals".

The idea of the Bristol Conference was to include two subjects which at first sight appear widely separated, but which are becoming more closely related. The first of these subjects was dislocations in their more chemical aspects. It was desired, for example, to discuss their relation to vacant lattice sites and to diffusion; their role in crystal growth and in accelerating precipitation and also their influence on semi-conductors. But questions concerned with their movement and with the mechanism of the formation of slip bands were reserved for the Birmingham Conference. The second subject was the use of electron and nuclear spin resonance in the investigation of defects in solids. On this subject an impressive series of papers was given by Kittel, Kip, Bloembergen, Slichter and others from the United States and also by representatives from Great Britain.

In addition to the X-ray camera, the optical and electron microscope, radioactive tracers and all the other techniques used in this field, microwaves have quite suddenly, in the past two or three years, become a tool of major importance. Thus, for example, the electric quadrupole moment of the nucleus makes it possible in suitable cases to determine the value of the gradient of the electric field ( $dE/dx$ ) at any lattice point where the nucleus is situated. In a pure crystalline substance of cubic symmetry this is, of course, zero, but not in an alloy. Dr. Bloembergen, of Harvard, outlined how in dilute solutions of zinc in copper it is possible to evaluate the contribution to  $dE/dx$  separately from the nearest, the next nearest neighbours and so on. Such measurements promise to be of the greatest importance for understanding the forces between atoms in alloys. It has also been possible to measure the density of dislocations in cold-worked substances by their effect on the breadth of the resonance line.

Another important effect is that described by Slichter; the broadening of the magnetic resonance line due to a nuclear spin is much reduced if the atom changes its position in a time small compared with the period of the frequency used. This is because the broadening is mainly due to the interaction with the spins of neighbouring nuclei; and it is, so to speak, averaged out by the movement of the nucleus from one lattice point to another. By this method it has proved possible to measure coefficients of self-diffusion in solids without the help of radioactive isotopes, and results were quoted for the alkali metals.

With regard to the rest of the Conference, there were many papers on the effect of irradiation by fast neutrons and other fast particles, and their effect in producing defects such as  $F$ -centres. Prof. R.

Hilsch, from Göttingen, spoke on the occurrence of a high concentration of defects in metallic and non-metallic films evaporated at the temperature of liquid helium, and the surprising amount of recovery which takes place when the temperature is raised to that of liquid hydrogen. There was much discussion of networks of dislocations in solids, which can be made visible by the formation of various types of precipitate along them. In fact, the role of dislocations in accelerating precipitation seems firmly established, though the exact mechanism by which it does so is less clear. They apparently act as centres for the nucleation of precipitates.

But perhaps one of the most important properties of dislocations which has recently been brought to light is the ease with which foreign atoms can move along them. As explained by Prof. R. Smoluchowski (Pittsburgh) and by Turnbull (General Electric Schenectady), the activation energy for diffusion along a dislocation is the same as that for diffusion in a grain boundary at which there is a large change in the orientation of the crystal planes. Boundaries at which the change of orientation is small can, as is well known, be analysed into rows of dislocations, and for these the rate of diffusion of radioactive isotopes or of impurities depends on the direction. Thus for a boundary which consists of a row of edge dislocations, the diffusion is fast in the direction in which they lie, and slow when they have to move from one dislocation to another.

It is clear that the ease with which foreign atoms diffuse along grain boundaries and dislocations, which can at the same time move about, plays a large part in allowing precipitation and age-hardening at temperatures at which normal volume diffusion would not be possible. Dr. J. H. Hollomon suggested that the formation in aluminium-copper alloys of the plates of mono-molecular thickness known as Preston-Guinier zones are due to dislocations moving through the grains and sweeping up the copper, which quickly diffuses along the dislocation to be left behind in one of these plates. Since most energy is released by this process when the plates form on the (100) planes, this is the direction in which the dislocations move.

On the subject of crystal growth, Hollomon showed a film of the growth of cadmium iodide crystals suggesting that in the early stages these crystals might well grow without the help of screw dislocations, but that the dislocations on which the well-known spirals are centred are formed when two crystals the orientations of which do not quite fit join together. Dr. J. W. Mitchell (Bristol), who was responsible for the scientific and social organization of the Conference, showed a series of slides which demonstrated that silver halide grains in emulsions owe their triangular or hexagonal shape with the (111) faces exposed to a particularly stable arrangement of three dislocations meeting in a point and lying parallel to the flat surfaces of the crystal.

The papers given at this Conference will be published by the Physical Society.

Turning now to the Conference at Birmingham, organized by Prof. A. H. Cottrell, this dealt in the main with the mechanism of work-hardening and formation of slip lines, and with the production of vacant lattice sites by moving dislocations. There

seems now to be a fair amount of agreement about many features of this process. For example, it is generally assumed that slip has its origin in Frank-Read sources; it is not now believed that the speed of moving dislocations is great enough for important dynamic effects to occur involving the kinetic energy of a dislocation, and Dr. J. D. Eshelby (Birmingham) presented a new paper on this point. Everyone was agreed on the importance of the fine slip lines (about  $10 \mu$  long and around 100 A. high) first observed on many metals by Wilsdorf (Pretoria), and that one of the main mechanisms of work-hardening is the elastic interaction between the dislocations which produce this fine slip; this is very much as envisaged in the paper which G. I. Taylor published in 1934. There was much less agreement on the cause of the slip bands which can be seen under the optical microscope and which are much longer. The case of alpha-brass, however, is particularly instructive, and was discussed by Dr. J. C. Fisher (General Electric, Schenectady). Here no fine slip was observed by Wilsdorf, and single crystals of this alloy show very little hardening, at least so long as slip is confined to one set of planes. This shows that the dislocations on neighbouring coarse slip lines are too far away from each other to interact strongly. Fisher's explanation of the absence of fine slip and the conspicuous coarse slip in this alloy is that there is a certain amount of short-range order, which has to be destroyed over a plane when a dislocation moves across it and which therefore hinders its motion. Once a dislocation has moved along a plane, however, others from the same source can follow it under the influence of a much lower stress.

Another mechanism of hardening and also of resistance to flow in annealed metals is the work which must be done to push dislocations past screw dislocations which cut the slip plane. When this occurs, a 'jog' is produced in a dislocation line, and this needs a certain energy. This mechanism of resistance to flow is expected, like the resistance due to locking by impurities, to show a strong dependence on temperature; that due to the elastic interaction of dislocations (G. I. Taylor's mechanism) is not. Cottrell showed some curves giving as a function of temperature  $\sigma/G$  for copper work-hardened at the temperature of liquid air;  $\sigma$  is here the flow stress and  $G$  is Young's modulus. This quotient except between  $200^\circ$  and  $270^\circ$  K., is quite independent of the temperature. In this narrow range, however, there is a rapid slope, and Cottrell assumes that here only is this cutting mechanism, which he calls the effect of the 'forest', the one that determines the strength. He also determines from the behaviour in this range the energy of a jog; for copper it is about 4 eV.

It was particularly emphasized by Seeger (Stuttgart) that the jog energy in aluminium is much lower, perhaps 0.5 volt. This is because in face-centred cubic lattices the dislocations split into two half dislocations separated by a stacking fault. At a jog the two halves must be brought together again, and the energy required to do this is the greatest part of the energy of a jog. Now it is characteristic of monovalent metals that the energy of a stacking fault, as of a twin boundary, is very low; there is no contribution from interaction between nearest neighbours, and little from the electrons at the surface of the Fermi distribution due to the fault in the reflecting planes. Therefore the separation between the halves of the dislocation is large, and

the work required to bring them together is large, too. For zinc and aluminium it is much less, thus providing rather convincing evidence that the behaviour of electrons near the boundary of a Brillouin zone does provide a sort of long-range force between atoms that are not nearest neighbours.

According to Seeger, many of the differences between aluminium and copper are to be associated with this large difference in the energy of a jog. Mechanical recovery and polygonization are believed to be dependent on the process known as 'climb', when a dislocation gives off or absorbs vacancies. But it can only do this at jogs, and so, if the jog energy is low, climb and recovery without recrystallization can take place at low temperatures, as is the case for aluminium.

Dr. P. L. Pratt (Birmingham) and Dr. J. C. Fisher (General Electric Company, U.S.A.) emphasized that the dislocation forest is responsible for one kind of 'river line' marking observed on cleaved crystal faces. New river lines begin at places where the advancing crack crosses a region of localized plastic deformation or a low-angle boundary. A crack must develop a step whenever it cuts through a screw dislocation, and elementary river lines thus produced run together to form large steps. The cleavage stress is increased due to the extra surface exposed on these steps. Dr. Fisher mentioned an interesting consequence of this effect. The surface area associated with the river lines increases as  $r^3$ , where  $r$  is the radius of a radially expanding crack, and not as  $r^2$ . This upsets the Griffith criterion for a critical crack size. Previous treatments have deduced a critical size by balancing an  $r^3$  elastic energy term against an  $r^2$  surface energy term; but in circumstances where the above  $r^3$  surface term predominates over the  $r^2$  one, there will not be a critical crack size, and cracks of all sizes will grow at the same critical stress.

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## INTERNATIONAL UNION OF CRYSTALLOGRAPHY THIRD CONGRESS

THE Third Congress of the International Union of Crystallography was held in Paris, at the Sorbonne, during July 21-30 and was attended by more than seven hundred members, representing some twenty different countries, including, it is gratifying to report, the U.S.S.R. This large membership raised several problems, particularly concerning the number of papers offered; these numbered about six hundred and were divided into groups of about ten, which were presented in seven parallel sessions. Since this system would normally give opportunity to members to attend only those sessions in which they were particularly interested, several survey papers were offered in addition. In this way, members were able to keep in touch with progress outside their own particular specialities. Aid in the choice of sessions was given by an 84-page booklet containing résumés of all the papers to be read.

It is naturally impossible, in this account, to deal with the whole of the Congress. Even had it been physically possible for a single person to be present at all the sessions, he could not have been expected to cope adequately with all the mathematics, physics, chemistry, mineralogy, metallurgy, biology and