

fit in with the picture of the nervous system then held. They have now been restored on the grounds that they are physiologically respectable. Behaviour is as real and as regular as the physiological events underlying it, and reduction from the one realm of discourse to the other is unnecessary.

Mr. Reid concluded by hoping that zoological research will continue to provide empirical studies of learning in a wide variety of animals, and to examine

the effects of hitherto neglected variables, rather than indulge in speculative theorizing.

In his concluding remarks, Dr. Thorpe directed the attention of those present to the growth of liaison between psychologists and zoologists studying behaviour. Five years previously they would barely have understood each other's problems, whereas now each has a broad knowledge of the other's work and they are aiming at similar goals.

R. A. HINDE

THE PHYSICAL PROPERTIES OF METALS

ALTHOUGH the British Association has no section dealing specifically with metallurgy, it was to be expected that the recent meeting in Sheffield should give prominence to the subject. Thus the morning session of Section A (Physics) on September 3 was devoted to physical metallurgy, and Sir George Thomson, president of the Section, presided. The first paper, "The Physical Approach to Metallurgy", was presented by Prof. A. G. Quarrell (Sheffield) and served as an introductory lecture to the morning's proceedings. It emphasized the complexity of the technology of metals to-day and described how physics has provided not only the techniques for studying metals but also the necessary mental approach to the ultimate nature of metals which is leading to an understanding of their strength and behaviour.

Metallurgy as a science dates from the application of the microscope by Sorby to metal specimens at Sheffield in 1863, and a unique series of ferrous metallographic specimens laboriously prepared by Sorby in 1864 was on view at the meeting. Fortunately, these have been preserved by a cover-glass cemented on each prepared surface, and many may still be examined at high magnification. Sorby realized that the structure visible in polished and etched specimens is characteristic of the metal and the way it has been produced, and some time later it was shown that the appearance is also related to the mechanical properties of the metal.

The maximum magnification with the optical microscope is about $\times 2,000$, but about fifteen years ago the development of the electron microscope led to an increase in the useful magnification up to $\times 100,000$. Unfortunately, direct observation of the metal surface is normally impracticable, and a replica which is transparent to electrons must be examined. The initial unreliability of replica techniques prevented the general acceptance by metallurgists of electron microscopy, but the use of vacuum-deposited carbon replicas during the past two years has completely revolutionized the situation, and the electron microscope is now a most powerful metallurgical tool.

The early optical microscopic examination of metals was soon supplemented by thermal and dilatometric studies, enabling the composition limits of the various metallic phase fields to be determined and constitution diagrams to be constructed. The understanding of the alloy formation, however, had to wait for the technique of X-ray diffraction and for the concept of a metal as an assembly of charged ions surrounded a cloud of the conducting electrons. Hume-Rothery then showed in 1926 that the limiting solubility in monovalent metals such as copper and gold depends on the relative atomic diameters of the metals concerned, and that the structure of the

intermediate alloy phases depends on the ratio of valency electrons to atoms in the alloy. These rules unfortunately fail to explain the alloying behaviour of the more complex alloys which are important in modern technology, and the approach to these alloys is still largely empirical.

The appreciation of the crystalline structure of metals has also made possible the study of the factors influencing the strength of metals. However, the theoretical strength of metals calculated from their atomic properties is 100–1,000 times greater than the measured stress required to produce permanent plastic deformation. This weakness is due to imperfections in the lattice, known as dislocations, and since the 'edge' dislocation was introduced in 1934 a complex theory of dislocations and their behaviour in crystal lattices has been developed. It has been calculated that the stress necessary to move a dislocation, if the interactions between the dislocation and the stress fields due to alloying atoms and precipitates are taken into account, is similar to the stress required to initiate slip in practice.

The dislocation theory of plasticity has been developed by theoretical physicists such as Mott and physical metallurgists such as Cottrell, and while strain-hardening, yield-points and crystal growth have been explained satisfactorily, only a beginning has been made towards the understanding of creep, fatigue and brittle fracture.

Creep is an example of a phenomenon of interest to both physicist and metallurgist; it was studied by Andrade in 1910 as a purely scientific phenomenon, but in 1920 Dickinson, in Sheffield, appreciated the importance of creep in steels at high temperatures and carried out the first long-time creep tests. These showed that at high temperatures much lower stresses would cause stretching and failure in the long-time creep test than in the short-time tensile test. The importance of creep in modern engineering has grown enormously in recent years with the trends towards high operating temperatures and pressures, and a large proportion of our metallurgical man-power is concerned with the development of new creep-resistant alloys which, for example, would be expected to last for many years at 570° C. in a modern power station.

Although complex metallurgical problems such as the mechanism of creep and its relationship to structure have not been solved completely by the physical approach, and resort must be made to semi-empirical methods, the major contribution of physics to metallurgy has been to give metallurgists a new mental attitude. Metallurgists are no longer satisfied with *ad hoc* solutions of immediate problems and have become increasingly anxious to provide fundamental explanations of important phenomena.

This truly scientific approach will undoubtedly result in rapid advance of the science of metallurgy.

"The Microstructure of Metals and Alloys" was the subject of a paper by Prof. C. S. Smith (Chicago). At the time of Sorby, the grains visible in metallographic micro-sections were not recognized as single crystals, because the single crystals of minerals in Nature were always expected to be regular polyhedra. However, it is now realized that the requirements of space filling prevent metal crystals in a polycrystalline aggregate from exhibiting regular crystallographic faces, and the geometry of the grains is governed by the condition that the interfaces contribute minimum energy to the system.

The interfaces themselves are of considerable interest as the interface atoms belong to both adjacent crystals. They have abnormal co-ordination with their neighbours, and abnormal spacing from them, making the interface a high-energy region which may be regarded as constituting a thin layer of liquid between the grains. A micro-section is essentially a random two-dimensional section through an aggregate of grains, and in a section the relationship between the number of polygons (P), the number of edges (E) and the number of corners (C) is given by the two-dimensional form of Euler's Law:

$$P - E + C = 1$$

This shows that a grain can have any number of sides greater than two, but that hexagonal polygons are the most common.

Although polygons of other than six sides are possible and do occur, the condition of minimum energy in the boundaries invariably results in the grain boundaries meeting in threes at angles of 120° , and such junctions can only be accommodated by curved boundaries. In three dimensions the grain edges meet each other in fours at angles of $109\frac{1}{2}^\circ$ to each other at each junction. These four crystal junctions are the only constant unit of structure and may be connected in innumerable ways. A three-dimensional array is thus made up of irregular grains each with approximately fourteen faces, and each face having an average of $5\frac{1}{7}$ faces.

The arrangement of the grains in beta brass can be revealed by fracturing in the hot-short range and is analogous to that of the bubbles in a soap froth or the cells in human fat, as they are all controlled by the requirement that the interface energy, and hence the area, must tend to a minimum.

Such grains show curved faces, and if a metal is heated to the temperature at which diffusion can occur, the boundaries move towards their centres of curvature and the smaller, convex, cells disappear while their concave neighbours grow. The final minimum-energy state would consist of a single crystal.

In two-phase alloys the same relations between the grains apply, but the dihedral angle between the grains usually differs from 120° as the interfacial tensions are usually different. This angle is often zero for a liquid between two crystals which breaks all coherence, as in brass in contact with mercury or molten solder. In solid two-phase alloys the angle is often between 90° and 100° , showing that the chemically different interface is of lower energy than that between the two crystals of the same phase.

In this treatment it has been assumed that the energy of the interface is independent of the orientation between the grains forming the grain boundary; but this generally correct assumption breaks down

at certain critical orientations. Thus the twins and plate-like precipitates which are due to a nucleation and growth processes, orientate themselves to give the lowest possible energy, and this outweighs the spatial improbability of such relationships. The majority of precipitates within the grains of heat-treated structures are of this type, exhibiting an orientated, polyhedral habit.

These general principles of space filling by polyhedra to give the minimum area, and hence minimum energy, of the interface, apply not only to metals but also to other microcrystalline materials such as ceramics and rocks, and all structures and transformations can be classified in terms of the structure of the boundary and the kind of adjustments in composition and position which occur as the boundary moves.

Dr. N. J. Petch (Leeds) spoke next on "Brittle Fracture", a subject he has made peculiarly his own. A fracture is defined as brittle if it is associated purely with elastic deformation and the fractured metal thus shows no evidence of deformation.

The difference between a brittle and a ductile crack is in its method of propagation. In the former case the applied stress required to spread the crack decreases as the crack grows; hence the maximum stress is required initially and catastrophic propagation occurs once the crack is initiated. If the crack is ductile, some energy is expended in deforming the ends of the crack, and continued straining is necessary to spread the crack.

Although a mild steel may be quite ductile in a tensile test, it may behave in a brittle manner when incorporated into a structure. This difference has become more obvious with the use of all-welded structures, in which a crack, once started, can often travel a very large distance before being arrested by a physical discontinuity. More than one-fifth of the 5,000 ships built under the American emergency shipbuilding programme during the Second World War suffered serious cracking within three years, and eleven had broken completely in half by 1951. Other serious fractures have occurred in bridges and oil-storage tanks, and outstanding fractures a mile long have been reported in 30-in. diameter natural gas pipe-lines in the United States. These fractures travel with speeds approaching the speed of sound in the metal and a mile-long fracture would thus occur in about one second.

It is found that brittle materials exhibit a strength which is approximately one-thousandth of that calculated for a perfect solid, and Griffith laid the foundation of our present understanding of brittle fracture by showing that in glass and silica this weakness is due to minute cracks acting as stress concentrators. The current ideas of metallic fracture regard these stress concentrators as dislocation pile-ups on slip planes blocked by grain boundaries, and the stress concentration of $\times 1,000$ necessary to account for the difference between the observed and theoretical strengths would require a thousand piled-up dislocations, which is not unreasonable. The difference between brittle and ductile materials is in the behaviour at the pile-up; in ductile metals crack formation is accompanied by plastic deformation, so that energy is lost in initiating the new dislocation movements, and the resulting crack is too small to propagate itself; many small cracks are thus formed which eventually join up and cause failure. In brittle failure, the propagation is elastic and no plastic deformation occurs, so that all the

energy of the dislocation pile-up goes into the production of the crack and the initial crack is sufficiently long for spontaneous propagation.

Metals are most prone to brittle failure if movement of the dislocations, that is, plastic deformation, is difficult; for example, mild steel shows more brittleness than, say, copper because the dislocations become locked by carbon atoms, and this effect becomes more pronounced the lower the temperature.

The dislocation model also explains why brittle cracking is often observed in structures when a test piece of the same steel is ductile. Notches in the structure cause stress concentrations at their roots at which the rate of strain is high and dislocation movements are not rapid enough to avoid brittle fracture.

In general, the physical explanation of brittle fracture in polycrystalline metals is satisfactory, but the mechanism of the fracture in single crystals is still obscure.

In his paper on "The Metallurgy of Nuclear Energy", Mr. L. Rotherham (United Kingdom Atomic Energy Authority) outlined the metallurgical problems in the design of nuclear reactors. A thermal reactor consists essentially of a lattice of uranium rods surrounded by a moderator, usually of graphite. When a chain reaction is allowed to take place in the uranium, heat is generated and the pile must be continuously cooled. This is accomplished in the Harwell and Windscale piles by the use of air as a coolant and at the Calder Hall power station by carbon dioxide under pressure.

The problems encountered may be divided into those of a conventional nature which might be encountered in general chemical engineering, and those in which radiation effects are important. A typical conventional problem was the construction of the steel pressure vessels at Calder Hall, which are 40 ft. in diameter and 60 ft. long, containing carbon dioxide under pressure to increase its efficiency as a coolant. These vessels were fabricated by welding two-inch thick steel, and to avoid the brittle fracture dangers discussed by Dr. Petch, they were made of special steels.

The fuel elements consist of uranium rods protected by aluminium or magnesium 'cans' to prevent attack by the coolant. Unfortunately, uranium has low crystal symmetry with three markedly differing coefficients of thermal expansion along the three orthogonal crystal axes, and on heating and cooling considerable thermal distortion can occur in polycrystalline material. The effect of irradiation is similar, and considerable dimensional changes can

also occur due to the internal strains produced by the fission products, which occupy more space than the parent uranium atoms. This effect is aggravated if atoms of rare gas are produced, which afterwards diffuse into voids and set up a considerable pressure. At 200° C. a single crystal of uranium would approximately double its length after the fission of one in a thousand uranium atoms. Irradiation of cast polycrystalline material produces an orange-peel surface wrinkling, while rolled material may increase its length and decrease its width, or vice versa, according to the rolling temperature. A further complication arises from the phase change in uranium at 650° C., as repeated heating and cooling through this transformation leads to severe distortion and surface roughening. The metallurgists' problem is to minimize these effects by heat-treatment to produce smaller grain-size, to avoid any preferred orientation due to fabrication and to study the effects of alloying which might stiffen the rods and thus help to resist the effects of internal pressure.

It is also possible to prevent distortion of the fuel elements by enclosing them in a rigid can. The Harwell and Windscale reactors employ aluminium cans; but as the fuel elements are discharged for plutonium extraction after relatively short periods in the pile, the distortion problems are not severe. In the Calder Hall reactors, power and not plutonium production is the main objective, and to withstand the severe distortion and growth consequent on a high burn-up of uranium, magnesium was chosen for the canning material. Magnesium has a higher creep strength than aluminium, and as it has a lower neutron absorption cross-section, a thicker and more rigid sheet can be used for the can.

In the future, the higher temperatures of fast reactors as envisaged at Dounreay will preclude the use of aluminium and magnesium as canning materials, and new metals will have to be employed. The choice is limited by the requirement that the metal must have a low neutron absorption, and use must be made of the rarer metals beryllium, zirconium, niobium, vanadium, tungsten and molybdenum. Of these metals niobium perhaps offers the most advantages, in that it is the most resistant to attack by uranium and liquid sodium, it has good high-temperature strength and it is extremely ductile and therefore readily fabricated into cans.

Up to the present, the extraction and properties of the rarer metals have been explored, and future developments will lie in the direction of enhancing the usefulness of these metals by alloying.

R. G. WARD

THE ELECTRICAL CONDUCTIVITY OF THE HEAD-WATERS OF THE WHITE NILE

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FOR many years records have been kept of the levels of the lakes that form the head waters of the White Nile, and estimates have been made of the amount of water discharged from these lakes. Yet some uncertainty still exists regarding the relative contributions made by these various sources. This is not surprising when one considers the extent and complexity of this lake and river system, and the

fact that the whole area is subject to high and irregular rates of evaporation and precipitation. The purpose of this article is to indicate the value of keeping, in addition to records of lake-levels and rates of discharge, records of the electrical conductivity of the water at particular points in the system. The electrical conductivities of these lakes and rivers cover a wide range of values. A study of