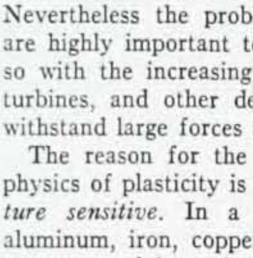
Small and exceedingly rare defects in the structure of solids are the "weak links" that determine the strength of materials. The article reviews some fundamental concepts concerning plastic deformation in certain ductile metals.

Dislocations and

By W. T. Read, Jr.

OUR UNDERSTANDING of the plastic behavior of solids has lagged well behind the knowledge gained in other branches of solid state physics. Electrical, thermal, elastic, magnetic, and optical properties are explained in terms of a few basic concepts such as the vibrations of atoms and the motion and spin of electrons. We understand fairly well what happens to the atoms and electrons when, for example, a metal absorbs heat or light or carries current in an electric or magnetic field. It is considerably more difficult, however, to discover what basic atomic mechanisms operate when a metal fractures or deforms plastically. Nevertheless the problems of strength and plasticity are highly important technologically and become more so with the increasing importance of jet engines, gas turbines, and other devices that require materials to withstand large forces at high temperatures.

The reason for the relatively slow progress in the physics of plasticity is that plastic properties are *structure sensitive*. In a crystalline solid—for example, aluminum, iron, copper, or brass—most of the atoms are arranged in a simple, regular geometrical pattern. In one of the common patterns atoms are arranged as one would arrange golf balls in a regular pattern so as to pack the greatest possible number into a given space. In good metal crystals no more than one atom in every billion or so is *not* surrounded by neighbors in the characteristic pattern. To understand most of the electrical, magnetic, elastic, and thermal properties of solids, we can ignore the one exceptional atom in a billion; that is, the exceptions, or so-called defects in the structure, contribute in proportion to their relative number and therefore have a negligible effect. Not so, however, in plasticity; the small number of structural defects are the "weak links" that determine the strength of the whole specimen. Because the defects are so small both in number and size, they are difficult to detect by even the most powerful techniques.



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For many years the physics of plastic deformation consisted of a few simple and ingenious theories based more on theoretical arguments than on direct experiment and accepted only by a handful of theorists. In the past five years, however, advances have been made that can only be described as a decisive break-through. Now a considerable body of theory is established on a sound experimental footing; predictions that can be checked experimentally are rapidly replacing ingenious guesses and speculations. This sudden progress has been so recent and rapid that it is still not widely known except to active researchers in the field, despite the fact that most of the basic ideas can be expressed in simple, physical, nonmathematical terms. This article presents some of the fundamental concepts concerning the mechanism of plastic deformation as observed in ductile metals such as aluminum, iron, tin, and copper.

Crystalline solids deform plastically by a process known as slip, in which planes of atoms slide over one another. The process is roughly similar to the shearing of a deck of cards. In general, slip occurs between those planes of atoms which are the most closely packed, and in all cases the direction of slip is the direction of closest spacing between atoms. We say that a unit of slip has occurred if the adjoining planes of atoms have been displaced by one interatomic spacing. Unit slip leaves the atoms in register; each atom simply moves into a position previously occupied by one of its neighbors. In most cases deformation proceeds by a large number (perhaps a thousand) unit slips on each of a relatively small number of active *slip planes*.

The puzzle that originally led to the idea of dislocations was the mysteriously small deformation at which slip begins. When a load is gradually applied to a specimen (as in hanging a weight on a bar), the specimen deforms at first elastically; that is, if the load is removed, the atoms return to their original positions. This is to be expected if the load is small enough that adjoining planes of atoms are displaced by a very small fraction of an interatomic spacing. When the load is increased beyond a critical value, slip starts. We would expect slip to begin in a perfect crystal when adjoining

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planes of atoms have been displaced by a large fraction of an interatomic spacing; at the critical displacement the forces between atoms (which hold the crystal together in a regular pattern) can no longer balance the applied force and planes of atoms begin to slide over one another—like the cards in a deck. In ductile materials it is easier to make planes of atoms slide over one another than to make them separate; in other words the specimen deforms plastically by slip but does not fracture (unless the deformation is continued until the "cards in the deck" actually slide off one another). We would not be surprised if slip began when the atoms on one side of a slip plane had been displaced one-half or one-quarter of the distance to the next equivalent position. In fact if we make a careful analysis and allow for the asymmetry of the interatomic force-displacement law, we find that slip should begin when the relative displacement of adjoining atomic planes is 1 to 10 percent of an interatomic spacing. However in pure single crystals of metals (for example in tin crystals), slip begins at a relative displacement of about 1/100 000 of an atomic spacing. Thus the resistance of a crystal to slip is about 1000 times smaller than we would expect for a crystal in which the atoms form a regular pattern. In the early 1930's, G. I. Taylor (now Sir Geoffrey Taylor) and E. Orowan introduced the idea

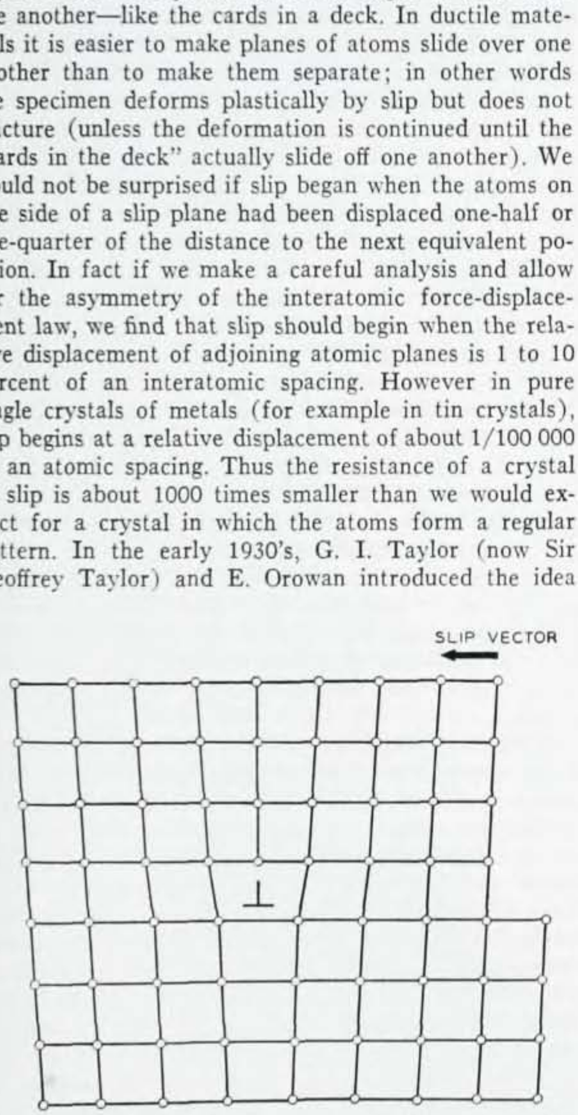

Fig 1. Edge dislocation in a cubic crystal. (Note: Figures from author's book *Dislocations in Crystals* reproduced by permission of McGraw-Hill Book Company.)

of dislocations into physics to explain this discrepancy.

The first type of dislocation to be discussed in metal physics was the Taylor-Orowan or *edge* dislocation, which is illustrated in Fig. 1; the figure shows a cross section of a three-dimensional crystal. The atoms in the figure form a square array except at the defect, or dislocation, the center of which is denoted by the symbol ⊥. The same defect runs through all planes parallel to the plane of the figure. The defect (or imperfection) is called a line defect since it lies along a line, which in Fig. 1 runs normal to the figure. The defect illustrated in Fig. 1 is one of a few simple types that are believed to exist in solids having a definite crystal structure. Perhaps the simplest defect to visualize is a lattice vacancy, which can be formed by removing an atom from an initially perfect crystal. The defect in Fig. 1 can be visualized as the result of removing part of a plane of atoms and closing the gap; the missing atoms in the plane of the figure are a vertical row just below the symbol ⊥. The same defect could be formed by inserting an extra plane of atoms above the symbol ⊥. The name *edge* dislocation comes from the fact that the dislocation forms the edge of an atomic plane which does not extend all the way through the crystal. Still another way of visualizing the dislocation is to imagine that unit slip has taken place over an area extending from the symbol ⊥ to the extreme right hand edge of the crystal. This way of thinking about the dislocation brings out the connection between dislocations and slip. A general pictorial definition of a dislocation, which applies not only to Fig. 1 but to any dislocation, is the following: *A dislocation is a line imperfection forming the boundary within the crystal of a slipped area.* Thus as a slipped area grows, its advancing front (the dislocation) moves through the crystal. Conversely, when a dislocation has swept over a plane or part of a plane, unit slip has occurred in the area swept out.

The motion of a dislocation is a type of wave motion: that is, a configuration, or disturbance in the structure, rather than actual matter, moves through the crystal. As in the motion of a hole, or vacancy, each atom moves only one interatomic spacing or less as the configuration moves through macroscopic dimensions.

We can now see how dislocations explain the low resistance to plastic deformation. If we forget about the few dislocations in a specimen, then slip must take place by whole planes of atoms sliding over one another—exactly like cards in a deck. Before unit slip can occur the adjoining planes have to pass through a halfway position of maximum misfit in which the normal crystal structure is badly distorted, and the atoms adjoining the slip plane no longer have neighbors at the proper positions. To move a dislocation through the crystal, however, it is not necessary to distort the crystal structure; rather, we simply move an already distorted configuration through the crystal. Thus there should be a large difference between the force required to cause slip by moving a dislocation and the force required to produce slip in a crystal with no dislocations. In other words, no matter how few dislocations there are, we cannot ignore their effect on plastic deformation. It is only necessary to assume that there are a few dislocations in a specimen to account for its low resistance to slip.

For many years, dislocations were taken seriously only by a few theorists and only because no other hypothesis seemed to explain the ease of slip in metal crystal. Recently, however, several developments have put the theory on a sound experimental footing. One of the most fundamental experiments was suggested by C. Herring of the Bell Telephone Laboratories. Herring reasoned that, since dislocations probably form by accidents of growth, there should be fewer accidents and fewer dislocations in a small crystal than in a large one. Therefore, if a crystal were small enough perhaps it would contain no dislocations and would behave like the hypothetical perfect crystal. Fortunately for metal physics (but unfortunately for the Bell Telephone Company) some very fine tin wires, or whiskers, had just been discovered growing spontaneously on tin plated condensers in the telephone plant (where they caused short circuits after a period of about 9 months during which they grew to a length of several millimeters). The diameters varied considerably, the smallest being about 0.001 millimeter. J. K. Galt, also of the Bell Telephone Laboratories, carried out carefully controlled mechanical tests on the microscopic whiskers. Using a microscope and micromanipulator, Galt verified Herring's prediction: the whiskers were about 1000 times stronger than normal-size specimens of the same material.

The dislocation illustrated in Fig. 1 is only one type—or, more exactly, one special orientation. By definition, any dislocation, however it may have originated, can be visualized as the boundary within the crystal of a slipped area. Thus associated with every dislocation is a vector which represents the direction and magnitude of the slip that formed the dislocation, or could have formed it. In Fig. 1 the dislocation (which runs normal to the figure) is perpendicular to the direction of slip (which lies in the plane of the figure). Actually, the boundary of the slipped area can make any angle with the slip direction.

Figure 2 shows the special case where the dislocation and slip direction are parallel. We can imagine the dislocation to be formed by slip in the area *ABCD* where the point *D* is on the bottom surface directly below *A* and does not show. The line *AD* running vertically through the crystal forms the boundary of the slipped area and is therefore a dislocation; it is called a screw dislocation. If the dislocation were not there, the crystal could be imagined as a stack of atomic planes one on top of the other like the stories of a building. With the dislocation, however, the crystal consists of one single atomic plane in the form of a helicoid or spiral ramp—hence the name screw dislocation. The screw dislocation plays an important role in some recent studies of crystal growth which have formed the most dramatic chapter in the success story of dislocation theory. The growth of a crystal from the vapor or dilute solution was first treated theoretically by ignoring the few defects that might be present in the structure of the growing crystal. W. K. Burton and N. Cabrera at the University of Bristol, England, worked out the kinetics of growth on a crystal surface in contact with its vapor. They found that at low vapor pressures it would be impossible to form new layers of crystal (that is, new atomic planes) fast enough to explain the relatively rapid growth of actual crystals. However, if new layers could somehow get started, or nucleated, they could easily grow fast enough to explain the observed growth rate. The problem was therefore to explain how growth can proceed on a crystal face without starting (nucleating) new layers.

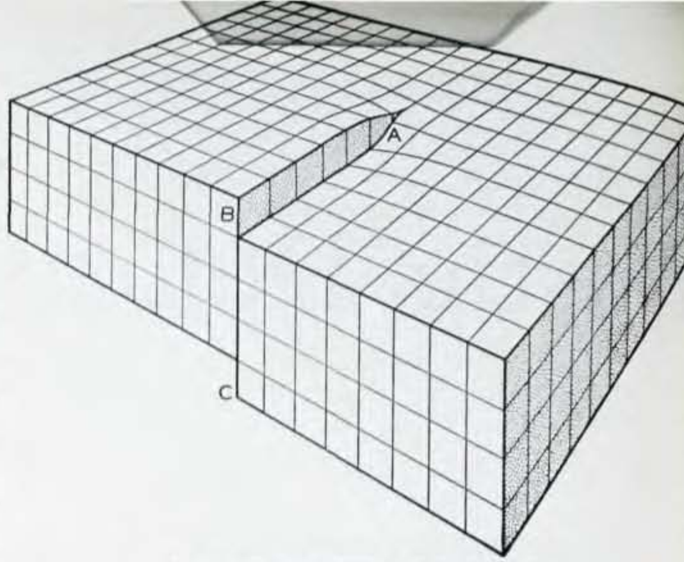

Fig. 2. Screw dislocation in a cubic crystal.

The answer was given by F. C. Frank, also of Bristol. Frank pointed out that even one defect of the type shown in Fig. 2 could completely change the growth pattern and make it unnecessary to form new layers of atoms in order for growth to proceed. As Fig. 2 illustrates, a crystal containing a screw dislocation is not a stack of atomic planes but rather a single atomic plane in the form of a spiral ramp. Thus growth proceeds, not by nucleation of every new layer, but by continued growth of the ramp. Frank showed that the step *AB* on the upper surface of the crystal in Fig. 2 would not remain straight as atoms were added on to it. Rather, the step would wind around and finally assume the form of a spiral centered on the terminal point *A*. Several years after Frank proposed his theory, L. J. Griffin, A. R. Verma, A. J. Forty, and others developed methods of observing steps one atom high on growth surfaces. The steps had exactly the form that Frank had predicted. Later, Forty used the same techniques to observe the paths over which individual dislocations had moved in crystals of silver. Thus dislocations—like electrons, charged ions, and magnetic domain walls—have ceased being only elements in a theoretical picture and have become laboratory observables.

Next to the studies of crystal growth, the most direct evidence for dislocations and their behavior has come from research on crystal grain boundaries, in particular, boundaries between grains or subgrains that have only a small difference in orientation. Experiments have verified the dislocation theory of the structure, energy, and motion of grain boundaries.

There are other results of dislocation theory which (like the theory itself in its early stages) have as yet no direct experimental verification but are nevertheless widely used because of their simplicity and the absence of conceivable alternatives. One of the most important such concepts is the so-called Frank-Read mechanism which explains how a single dislocation initially present a solid can (1) produce a large amount of slip on a single slip plane and (2) multiply and produce the substantial number of additional dislocations that accumulate inside a crystal during deformation.

Of practical metallurgical problems, probably the most successful experimental-theoretical attack has been made on the interaction of dislocations and impurity atoms as illustrated, for example, by the hardening effect of carbon in iron. A. H. Cottrell and his co-workers at the University of Birmingham, England, have led dislocation theory into this difficult but important area. It is one of the discouraging features of working on dislocations that centuries of empirical metallurgy have uncovered practical results whose discovery would otherwise have been the worldly reward of pure science. In this respect dislocation theory is less fortunate than nuclear theory and semiconductor electronics.

One of the least understood and most practical problems is the nature of work hardening (the fact that slip increases the resistance to further slip). This is known to be somehow tied up with the strong interaction between dislocations, which get tangled up with one another and thereby are immobilized. However, the details of the process remain obscure, and it is seldom possible to make definite predictions to compare with experiment.

This brief discussion has touched on only a few salient aspects of a fascinating and expanding subject where theory and experiment have just begun to bridge a long standing gap in our knowledge of solids. Not the least appealing feature of the subject is that so much can be explained with simple pictorial ideas that presuppose no more physics than is acquired in an undergraduate course.

Suggested References

W. T. Read, *Dislocations in Crystals*, McGraw-Hill Book Co., New York, 1953.

A. H. Cottrell, *Dislocations and Plastic Flow in Crystals*, Oxford, New York, 1953.

Books

Meson Physics. By Robert E. Marshak. 378 pp. McGraw-Hill Book Co., Inc., New York, 1952. $7.50.

One purpose of a book review is to help the reader make an intelligent decision concerning his purchase of the book. However, for specialists in the field of meson physics, that decision was made the instant they learned that the book was to be published; members of this group naturally sent in their orders at once. Professor Marshak's contributions to the field have been extensive, both in research and through his Rochester Conferences.

As a theoretical physicist, the author stresses the theoretical aspects of the subject, and arranges the material according to its theoretical interest. Fortunately for those who know a microsecond more intimately than they do a matrix element, the author writes as one who has spent many an hour explaining theoretical concepts to his friends in the laboratory down the hall. The book is strictly for professional physicists; there is not a single paragraph of historical introduction. The opening paragraph assumes a knowledge that π and μ mesons exist, and that the Conversi experiment gave unexpected results. It mentions photon-nucleon, and nucleon-nucleon production of π mesons, and gives an order of magnitude estimate for the unobserved production of μ meson pairs by gamma rays. Books at this level often start with an "easy chapter", but from the reviewer's personal experience, all this accomplishes is the sale of the book to some unsuspecting undergraduate students, who are pleasantly surprised that they can understand the first chapter. Marshak's approach is more candid; he implies that if you can't understand what he is talking about in the first few pages, the book should be of no interest to you. However, if you can understand, or perhaps just follow, what is discussed in the first sections, the book is a gold mine of information on all phases of meson theory and experimental results.

Meson physics differs from most other branches of physics in that the theory came before the experiments. One should rather say theories, since theoretical predictions are commonly made for mesons of various spins, parities and coupling schemes. Now that the spin and parity of the meson are known, one might at first suppose that a great theoretical simplification could take place; it should no longer be necessary to carry along all calculations for vector mesons, and mesons with even parity. But when one remembers the heavier mesons that are still so little understood, one sees the