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1957

Abstract

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PHYSICS

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ON THE CHANGE IN ELECTRICAL RESISTANCE DURING ELEMENTARY SHEAR FORMATION

(Presented by Academician P. A. Rebinder, 12 IV 1957)

In stretching zinc single crystals, the ratio of the increment of electrical resistance to the elongation, $\frac{\delta R}{\delta l}$, which occurs during deformation jumps of $\sim 0.5 \div 20\,\mu$, is lower than the analogous ratio $\frac{R-R_0}{l-l_0}$ for the total increment of resistance and the total elongation of the specimen; it was assumed that this decrease is connected with the emergence of avalanches of dislocations in a number of sections of the single crystal ([1]). Of greatest interest, however, was the carrying out of similar measurements for "elementary" shears of $\sim 500 \div 2000$ Å, localized in one slip zone. For this purpose the resolving power of the deformation-recording channel was brought to 50 Å, and that of the channel for recording resistance jumps—to $(3 \div 5) \cdot 10^{-9}\,\Omega$ ([2]).

The experiments were carried out on cadmium single crystals 0.75 mm in diameter and zinc single crystals 0.5 mm in diameter, 15-20 mm long, with an initial angle between the hexagonal axis and the direction of stretching of 30°, at room temperature. Stretching was performed under constant load up to 3-5% elongation, at average rates $(0.03 \div 0.6) \cdot 10^{-4}$ cm/sec. Usually, stretches of 1% were followed by intervals of 1-2 hours. Both before and after stretching, the cross section was measured along the entire length of the specimens with an accuracy of up to 1%; the total increments of resistance calculated on the basis of these data agreed exactly with the results of measurement of $R - R_0$ by a precision potentiometer, i.e., for such small and slow deformations the total increments of resistance did not show a measurable excess over those due to geometrical causes.

It is not difficult to show that, for a small deformation jump δl, localized in a section where the deformation has reached the value ε, the geometrically caused increment of resistance is $\delta R \simeq \delta l \cdot 2r_0 \cdot (1+\varepsilon)$, where r_0 is the resistance per unit length of the undeformed specimen.* If the entire increment of resistance during jumps is due to purely geometrical causes, the experimental values

$$q = \frac{\delta R}{\delta l \cdot 2r_0} \cdot 100$$

must lie in the band from 100% to 100% $+\varepsilon_{\max}$.**

The results of careful measurements of about three hundred oscillograms recorded by us, of jumps from $\delta l = 350$ Å and above, with durations from 1 to 30 m/sec, for cadmium and zinc single crystals are given in Fig. 1, where the dash-dotted lines bound the indicated band (jumps in the interval from 150 to 350 Å, although still quite distinguishable on the oscillograms, as a rule could no longer be measured with sufficient accuracy).

The data presented show that the band of actual values of q (solid curves in Fig. 1) has an S-shaped form with an inflection in the region—

* For cadmium, which has appreciable anisotropy of electrical conductivity, this also includes a small correction allowing for the change in orientation.

** In our case the local deformations reached $\varepsilon_{\max} = 30 \div 40\%$ in cadmium specimens and $40 \div 45\%$ in zinc specimens.

at $\delta l \approx 500$–1000 Å and with an overall decrease of up to 30% relative to the geometrically determined values at $\delta l > 1000$ Å, which, for the given orientations, corresponds to a shear by ~ 500 interatomic spacings in the direction of slip, i.e. $500\,\mathbf{b}$, where $\mathbf{b}$ is the Burgers vector. In other words, larger jumps, i.e. shears exceeding some critical value, correspond to restoration of order, a reduction in the defectiveness of the structure in the slip zone, whereas for small jumps $\delta l < 500$ Å this is not observed (or even the opposite occurs).

Fig. 1. Experimental values of q for deformation jumps on single crystals of cadmium and zinc

Fig. 2. Oscillograms of paired jumps with a considerable decrease in q for the secondary jump: *a*—on single crystals of cadmium, *b*—zinc, *c*—tin

Of special interest are paired jumps separated by an interval of 40-80 msec. In this case, for the second jump, q very often reveals a sharp decrease compared with the mean values (Fig. 2, secondary jumps). The points corresponding to several jumps of this type are singled out in Fig. 1.

The phenomena described can be given the following explanation. A jump of $\sim 500\,\mathbf{b}$ corresponds to the largest avalanche of dislocations that can be accumulated in the region of a single slip plane, and at the same time to the greatest possible disorder for such an accumulation, which determines significant electron scattering. In the course of the jump, over several milliseconds, this accumulation is rapidly discharged. In the region of the given slip plane the normal structure is essentially restored, and the additional resistance introduced by the accumulation disappears. A jump of $\sim 500\,\mathbf{b}$ follows,

apparently, to be regarded as the maximum elementary jump. Large jumps $> 1000\,b$ may be regarded as the discharge of prepared avalanches in a number of slip zones immediately following one elementary ("initiating") jump. The decrease in the jump δR observed in this case, relative to the geometrically determined value, is additively composed of the corresponding decreases in the separate zones, and therefore for large δl the band of q values is horizontal (Fig. 1).

For elementary jumps smaller than the maximum, the associated change in the effective cross section for electron scattering decreases not linearly, but much more rapidly, producing the bend in the q-band. Such jumps correspond to the discharge of an accumulation smaller than the maximum possible in one zone, or to an incomplete discharge of the maximum. In this case, to explain the course of the q-band it is necessary to have a nonlinear dependence of the effective cross section σ for scattering of electrons by an accumulation on the number of dislocations n, for example of the type $\sigma = An^k$; in the first case $k \approx 2$, in the second $k \approx 1/2$. The considerable decrease of q for secondary jumps must in either case be interpreted differently. The first of the mechanisms named seems to us the more probable.

A certain increase of the q-band relative to the geometrically determined one for the very smallest jumps appears possible to connect only with an entirely different process—the sudden activity of dislocation sources operating, for example, according to the Frank–Read scheme, and the consequent growth of structural imperfection in the slip zone. However, the increase named lies in our experiments almost at the limit of accuracy and requires further experimental confirmation.

The currently accepted average dislocation densities and the magnitudes of the resistances introduced by dislocations ([3], [4]) do not make it possible to describe the observed phenomena quantitatively on the basis of the usual concepts of dislocation theory. The observed decreases of q require the presence of a large local density of dislocations, perhaps caused by some new type of dislocation source, which corresponds to the strongly disturbed structure of the slip zone before the jump and to its restoration during the jump.

A partial solution of the problem may be provided by the development of the views ([5]) on avalanche preparation as a result of the action of many sources in a single slip plane, together with the assumption of an overall high concentration of dislocations in this plane; their annihilation may give only a small displacement, for example $500\,b$, but a considerable decrease in the jump δR.

Finally, despite the small durations of the jumps, the role of vacancies in the increase of the resistance of a work-hardened metal and their connection with the dislocation mechanism of deformation should be taken into account. It is not excluded that precisely in connection with Mott' s propositions on "local annealing"and enhanced diffusion of vacancies in the slip zone ([6]) an explanation will be found for the sharp decrease in the value of q for secondary jumps.

Emphasizing the hypothetical character of the considerations set forth, we believe that further investigation of the form of the q-band will make it possible to refine certain propositions of the theory of dislocations in the explanation of plastic deformation.

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Received 3 IV 1957

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Note: Figure translations are in progress. See original paper for figures.