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Abstract

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V. N. Rozhanskii

On the Mechanism of Development of Embryonic Cracks in Crystals during Their Plastic Deformation

(Presented by Academician P. A. Rebinder, 14 VII 1958)

During plastic deformation in solids, processes of development and healing of a large number of embryonic microcracks take place; under appropriate conditions these may initiate the occurrence of a fracture crack. The most general form of such lens-shaped microcracks was described by P. A. Rebinder in connection with the theory he developed of the action of a surface-active medium on the mechanical properties of solids ([1]).

Fig. 1. Scheme of the development of an embryonic crack at the head of a pile-up of dislocations (Mott, Stroh)

One of the mechanisms of development of embryonic cracks, proposed by Mott ([2,3]) and further developed in the works of Stroh ([4]), consists in the formation of a crack at the head of a pile-up of dislocations. The greatest normal stresses at the head of such a pile-up are located along a straight line making an angle $\theta \sim 70^\circ$ with the direction of slip, in connection with which development of the crack is assumed precisely in this direction (Fig. 1).

Another mechanism of crack development in the slip plane, with partial annihilation of dislocations of opposite signs ($n^+ \neq n^-$) moving in closely spaced parallel slip planes, was proposed by Fujita ([5,6]). In a number of works ([7,8]), ideas are developed concerning the possibility of formation of a crack in the slip plane on the basis of the coalescence of vacancies arising in the crystal upon intersection of dislocations; this, however, cannot be connected with the decrease in jumps of electrical resistance observed by us during stepwise deformation ([9,10]).

Fig. 2. Scheme of the development of an embryonic crack in the slip plane

Apparently, another mechanism of crack development in the slip plane is more probable; it plays an especially important role in the case where the slip planes and cleavage coincide. In describing the arrangement of atoms in the region of the core of an edge dislocation, one usually considers mainly the curvature of planes perpendicular to the Burgers vector and does not take into account the curvature of atomic planes parallel to the slip plane. Meanwhile, especially during the formation of pile-ups of edge dislocations, the bending of these planes

Fig. 3. Cracks developing in slip planes in an amalgamated zinc single crystal. A—crystal surface, B—section. 100× (after N. V. Pertsov).

Figure 1: Fig. 3. Cracks developing in slip planes in an amalgamated zinc single crystal. A—crystal surface, B—section. 100× (after N. V. Pertsov).

is quite substantial and may lead to the development of a free surface in the slip plane. In this case a cavity is formed (see Fig. 2),

possessing a large Burgers vector. Such a cavity, on the one hand, may serve as the beginning of the development of a fracture crack as a result of the concentration of stresses on it, and, on the other hand, may increase through coalescence with unit dislocations moving in the plane of development of the cavity.

This effect is manifested especially clearly in amalgamated zinc single crystals ([11]), in which cracks always develop in the basal plane. The sharp decrease in the free surface energy of the developing separation surfaces in this case promotes the formation of fracture cracks intersecting the entire cross section of the crystal (Fig. 3).

Fig. 3. Cracks developing in slip planes in an amalgamated zinc single crystal. **A**—crystal surface, **B**—section. 100× (after N. V. Pertsov).

Such a mechanism for the development of embryonic cracks is very reminiscent of the mode of development of shear formation in anisotropic bodies according to A. V. Stepanov ([12]), and also corresponds to the form of curvature of slip planes investigated by S. T. Konobeevskii and A. N. El' nikov ([13]).

Stroh ([4]) showed in a linear approximation that an embryonic crack arising as a result of the accumulation of n dislocations with Burgers vector b forms a stable cavity of size

$$c \approx n^2 b. \tag{1}$$

It is easy to see that the size of the equilibrium crack in the direction of the Burgers vector is considerably greater than the size of the crack arising according to Mott' s scheme (a wedge with base nb in the slip plane).

According to Neuber' s calculations ([14]), when a shear stress τ_0 is applied, the maximum normal stresses develop at the ends of the crack and are equal to

$$\sigma_{\max} = \frac{3}{2}\tau_0 \left(\sqrt{\frac{c}{\rho}} + 2 + \frac{1}{\sqrt{c/\rho}} \right), \tag{2}$$

where the radius of curvature at the crack tips is $\rho \sim b/2$. Thus:

$$\sigma_{\max} = \frac{3}{2}\tau_0\left(n\sqrt{2} + 2 + \frac{1}{n\sqrt{2}}\right) \approx \tau_0(2n+3). \tag{3}$$

For $n \sim 500$, stresses of the order of the theoretical values of the strength of interatomic bonds develop on the crack surface at the yield point. In this case the critical size of the embryonic crack is determined from $c \sim n^2 b \sim 5 \cdot 10^{-3}$ cm (for Zn), which is in satisfactory agreement with the value determined from experimental results (15).

The most essential circumstance is the relation between the magnitude of the deformation jump arising when such a crack closes and the size of the crack. If one adopts Stroh' s formula (16) for the change in electrical resistance as a result of crack formation,

$$\frac{\Delta\rho}{\rho} = \frac{1}{4}\pi c^2 N, \tag{4}$$

where N is the number of microcracks intersecting a unit area parallel to the direction of the current, then the dependence of $\Delta\rho/\rho$ on δl can be expressed in the form

$$-\frac{\Delta\rho}{\rho} = -\frac{\Delta R}{R} = \frac{k^4\pi\delta l^4 N\sin\chi_0}{4b^2\cos^4\chi_0},$$

where k is the ratio of the number of dislocations that formed the cavity to the total number of dislocations in the pile-up, and the dependence on the orientation of the crystal (χ_0) is conditional in character.

For the quantity q, calculated from experimental values, there should then be observed a decrease caused by the healing of embryonic cracks:

$$-\Delta q = -\frac{\Delta\delta R\, l}{2\delta l\, R} = \frac{k^4\pi l\delta l^3\sin\chi_0}{8b^2\cos^4\chi_0\, S}. \tag{5}$$

It is precisely such a dependence that corresponds to the decrease in specific electrical resistance observed by us for elementary deformation jumps (17) (Fig. 3). For large composite jumps, a constancy of Δq is observed, which is determined by the constancy of the mean value of δl for the jumps of which the composite deformation jump is made up.

Table 1

Fig. 4. Dependence of the experimental values of the quantity q on the size of the deformation jump. 1 —region of elementary jumps, 2 —region of composite jumps

Figure 2: Fig. 4. Dependence of the experimental values of the quantity q on the size of the deformation jump. 1 —region of elementary jumps, 2 —region of composite jumps

Magnitude of the jump $\delta l = \frac{nb}{k}$ in Å	Crack size $c = \frac{n^2 6 b^2}{8\pi(1-\nu)\sigma} \approx n^2 b$ at $k \sim 0.2$, in μ	Experimental value of c, calculated by the formula $c = \sqrt{\frac{-4\Delta\rho}{\rho\pi \sin\chi_0 N}}$, in μ
1000	8	8
750	5	6
500	2	–
375	1	–

In the region of elementary jumps a dependence $q \sim \delta l^3$ is observed. The maximum elementary jump can be determined from formula (5). From the value $-\Delta q = 0.25$, $\delta l \simeq 800$ Å is determined for $k = 0.2$–this value corresponds to the beginning of the bend in the values of q. At $\delta l = 500$ Å, $-\Delta q \simeq 0.02$, if k still remains equal to 0.2. These values correspond to the end of the bend. Thus, the general course of the observed dependence $q(\delta l)$ is in full agreement with the idea of the development in single crystals of microcracks lying in the slip plane. A certain increase in the values of q in the region of small δl is apparently connected with the fact that this region includes jumps associated with the formation, and not with the closing, of embryonic cracks.

The estimate of the sizes of microcracks closing during the corresponding deformation jumps, from theoretical considerations and also from experimental data, is given in Table 1.

Fig. 4. Dependence of the experimental values of the quantity q on the size of the deformation jump. 1 —region of elementary jumps, 2 —region of composite jumps.

The experimental results for the quantity c and the entire course of the values of q agree very satisfactorily with the theoretical calculations; in this case the bend in the curve of the values of the quantity q is apparently explained not by the fact that, for a small magnitude of the pile-up, a microcrack is incapable of forming at its head, but mainly by the dependence between the number dislocations forming the hollow core (nb), and the magnitude of this core ($n^2 b$) (Fig. 4).

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Moscow State University
named after M. V. Lomonosov

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