ON THE EQUILIBRIUM SHAPE OF A TWIN WHOSE GROWTH IS INHIBITED BY AN OBSTACLE

PHYSICS

1966

SovietRxiv

Abstract

Full Text

UDC 548.4

PHYSICS

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ON THE EQUILIBRIUM SHAPE OF A TWIN WHOSE GROWTH IS INHIBITED BY AN OBSTACLE

(Presented by Academician I. V. Obreimov, 10 VI 1965)

Only recently did A. M. Kosevich and L. A. Pastur bring dislocation concepts to bear on the description of the twinning process; within this framework many processes of plastic deformation are now described comparatively simply. In the theory they developed, the problem of the equilibrium distribution of twinning dislocations along a twin lamella was solved ([1,2]). Such a distribution determines one of the most important geometrical parameters of a twin—its thickness and, consequently, the shape of the twin lamella.

In ([1,2]) the equilibrium equation for twinning dislocations in a crystal was obtained and analyzed, which made it possible to determine qualitatively certain properties of the equilibrium dislocation density. Following the authors, we shall denote by $\rho(x)$ the density of dislocations along the length of the twin, coinciding with the x direction.

From ([1,2]) it follows:

1. If the end of the twin is free and, during growth into the depth of the crystal, there are no stoppers impeding its motion, then at $x = L$ (L is the length of the twin) $\rho(x) = 0$, i.e., the twin has a zero opening angle.
2. If a twin growing into the depth of the crystal is stopped at a rigid stopper, then at $x = L$, $\rho(x) = \infty$, and the opening angle of the twin is 180°. In this case the profile of the twin tip can be described by the function

$$\rho(x) \sim (L - x)^{-1/2} \quad \text{as } x \to L. \tag{1}$$

The thickness of the twin at a certain point x, according to ([1]), is related to the lattice parameter d in the direction perpendicular to the twinning plane and to the linear density of twinning dislocations by the relation

$$h(x) = d \int_x^L \rho(y)\, dy. \tag{2}$$

This makes it possible, by experimental study of the geometry of a twin, to obtain information on the distribution of twinning dislocations along the twin and thus makes possible an experimental verification of the theoretical results.

Verification and experimental confirmation of the theoretical model is especially important for metallic crystals, as proof of the dislocation nature of twin formation, since up to the present time it has not been possible to observe twinning dislocations in metals.

In the present work, a study has been carried out of the shape of a twin lamella in bismuth single crystals, growing into the depth of the crystal under the action of an external force, with the aim of detecting the effects predicted by the theory.

Fig. 1. Shape of a twin interlayer propagating into the depth of the crystal. **a** –twin far from the obstacle, 1500× (with photographic enlargement); **b** –stopping of the twin in the counter interlayer, 1500×; **c** –twin stopped by an obstacle, not resolvable with a 7000× microscope. The arrows show the direction of shear during twinning. The external force acts in the direction of shear (with photographic enlargement).

Fig. 3. **a** –formation of a secondary twin in the counter interlayer upon accumulation of twinning dislocations at the "mouth" of the stopped twin; **b** –overcoming of the obstacle by twinning dislocations in planes adjacent to the stopping plane. At the point where the dislocations were stopped, a characteristic profile of the twin "mouth" was formed.

Fig. 2. Increase in the radius of curvature in the "nose" of the twin when it is stopped, with growth of the external force P acting on the crystal: $P < P_1 < P_2$. 1500×.

Experiments were carried out on single-crystal bismuth specimens. Specimens in the form of rectangular prisms, $10 \times 5 \times 2$ in size, in which the twinning plane (110) was perpendicular to the face of the crystal (oriented during growth), were mounted on the table of a deformation machine and loaded by an external force along the twinning plane (110) and in the direction of shear during twinning $(00\bar{1})$. With this method of loading, near the steel knife by means of which the specimen was loaded by a concentrated external force, a wedge-shaped twinned interlayer readily arises in the crystal, growing into the depth of the crystal as the external load is increased. During deformation, the surface of the specimen was observed and photographed. The observation surface was an artificial shear plane $(1\bar{1}0)$.

The twinned interlayers that arise inside the crystal and emerge on the free surface differ from one another in shape. The former have the form of a thin lens, strongly elongated in the direction of shear and flattened at the ends; the latter most often resemble a thin wedge. The ratio of the thickness of the twinned interlayer to its length for very thin twins in bismuth lies in the interval $10^{-2} \div 10^{-3}$. In many cases it is possible to trace the kinetics of transformation of a lenticular twin, nucleated inside the crystal, into a wedge-shaped twinned interlayer. Under the action of external stresses, the ends of the lenticular twin move in different directions: one toward the free surface of the crystal, the other into the depth of the crystal. In this process, having reached the surface with one end, the lenticular twin turns into a wedge-shaped twinned interlayer, and a step is formed on the surface at the point of emergence.

Theoretically ([1,2]) this process is described from the viewpoint of the nucleation of twinning dislocations of different sign, which, under the action of external stresses, move in opposite directions. It is assumed in this case that the external load is such that negative dislocations emerge on the surface, creating a step on it, while positive dislocations move into the depth of the crystal and form a twin wedge. Experimental study of the geometry of twinned interlayers growing into the depth of the crystal makes it possible to draw a number of conclusions about the equilibrium shape of a twin:

1. A thin wedge-shaped twin moves freely through the crystal without encountering an obstacle. In this case the end of the twin, like the point of a needle, smoothly pierces the crystal, remaining sharp at all times (Fig. 1a). The thickness of the twin changes only weakly. The twin has the form of a wedge greatly elongated in the direction of motion, with a very thin end.

2. When moving into the depth of the crystal, the twin encounters an obstacle in the form of a twinned interlayer of another orientation (Fig. 1b). Growth in length ceases. The thickness of the twin increases rapidly, and the profile of the twin "nose" changes substantially. Its thickness becomes comparable with the thickness of the twin in the middle part, and in the "nose" of the twin there forms a characteristic rounding, resembling in shape a semicircle, to which the twin boundaries are joined. As the load is increased, the radius of curvature grows. This is apparently connected with the fact that, under the action of stresses, dislocations situated in neighboring twinning planes approach the obstacle, owing to which the number of dislocations in the pile-ups forming the characteristic profile of the twin "mouth" increases. At considerable loads the joining of impinging twins occurs not at a single point but along a section of a line. This is clearly seen from Fig. 2.

3. The twin encounters a rigid obstacle of very small dimensions, which is not resolved by the microscope (Fig. 1c). In this case as well, the "mouth" of the twin is outlined by a smooth curve, the tangent to which at the point of contact of the twin with the obstacle is perpendicular to the direction of growth of the twin in

length. The identity is evident between the shape of twin lamellae arrested by an opposing twin and by an invisible obstacle. The nature of such obstacles is still unclear. One can only suppose that they may be microscopic precipitates of foreign atoms, very small mechanical inclusions, block boundaries, etc. We were able to observe an interesting picture of growth in length of a lenticular twin that had arisen inside a crystal. Under the action of external stresses, the ends of such a twin move in opposite directions in accordance with the sign of the twinning dislocations. Cases were observed in which one end of the twin was arrested with the formation of a profile similar to Figs. 1b and 1c, while the other end was free and the length of the twin increased only through the motion of the free, pointed "nose." The photographs presented in Fig. 1 show good agreement between the theoretically predicted shape of the twin and that observed experimentally.

It should be noted that, although the fundamental possibility of an equilibrium shape of twins with an opening angle of 180° was theoretically predicted earlier in the works of M. M. Livshits ([3,4]) and has quite recently been substantiated by A. M. Kosevich and L. A. Pastur on the basis of a dislocation model of a thin twin, this effect had not previously been observed experimentally.

It is known that when complete dislocations accumulate at an obstacle, large internal stresses are produced at the head of the pile-up ([5]). In many cases the magnitude of these stresses is sufficient to cause local destruction of the crystal at the obstacle through the formation of cracks. This statement is equally valid for twinning dislocations. We were able to observe (apparently as a result of the action of a similar mechanism) the formation of a secondary twin in a thick twin lamella that served as an obstacle for an opposing twin (Fig. 3a). The formation of a pile-up of twinning dislocations in front of the twin is manifested here in the form of a "nose" profile characteristic of this case.

The elementary act of twinning is carried out by the passage of a single twinning dislocation in its own twinning plane. When twinning dislocations are arrested by an obstacle and stop in front of it, dislocations in neighboring twinning planes, having overcome the force of interaction with the arrested dislocations, can, under the action of external stresses, pass by the obstacle. Thus the obstacle can be overcome by twinning dislocations, and regions of untwinned crystal are observed in the twin lamella ([6]).

A similar phenomenon is well illustrated by Fig. 3b. It is interesting to note that in that region of the crystal where the obstacle has not been overcome by dislocations, the profile of the twin "nose" is identical to that shown in Figs. 1b and 1c.

The study of the equilibrium shape of a twin lamella makes it possible to determine experimentally the density $\rho(x)$ of twinning dislocations along the twin. Knowledge of this function is very important for determining the principal parameters of the twinning process, such as the friction force of twinning dislocations and the surface-tension force. These parameters enter into the expression for the force of nonelastic origin, which is related to the distribution function $\rho(x)$ by the integral equation (1). The profile of a twin arrested by an obstacle can be described by function (1). On the other hand, from measurements of the twin thickness $h(x)$, taking into account that, according to (2),

Fig. 4. Calculated curve of the function $\rho(x)$ taking into account the experimentally determined coefficient A. The points are the experimental values of the density of twinning dislocations in the "mouth" of a twin pinned by an obstacle. The dashed lines indicate the position of the stopper.

Figure 1: Fig. 4. Calculated curve of the function $\rho(x)$ taking into account the experimentally determined coefficient A. The points are the experimental values of the density of twinning dislocations in the "mouth" of a twin pinned by an obstacle. The dashed lines indicate the position of the stopper.

$$\rho(x) = -\frac{1}{d}\frac{dh(x)}{dx},$$

the value of the function $\rho(x)$ at each point along the twin is determined, provided the conditions under which these expressions are valid are satisfied ($d/L \sim 10^{-3}$). Figure 4 presents the dependence of the equilibrium density

of the twinning dislocations along the twin, obtained experimentally by us by means of several successive operations: first, from measurements of the twin thickness, the graph $h(x)$ was constructed for the interval ${}^{14}/_{15}L \leq x \leq L$; then, by graphical differentiation, the derivative was found at various points of the curve $h(x)$; and, finally, the numerical value of the linear density was determined by multiplying the derivative by a coefficient equal to $1/d$, the reciprocal of the interplanar distance in the direction of the normal to the twinning planes. From Fig. 4 it is seen that $\rho(x)$ increases sharply as x approaches L, and as $x \to L$, $\rho(x) \to \infty$, which agrees well with the theoretical description of the properties of the dislocation-density function.

Formula (1), describing the profile of the "nose" of the pinned twin, is valid to within a certain numerical factor. Assuming that the experimental density curve of the twinning dislocations can be exactly described by the function

$$\rho(x) = A(L - x)^{-1/2}, \tag{4}$$

one can determine the coefficient A at several points of the experimental curve and find its mean value. As a result of the calculations it was found that $A = 3{\cdot}10^7$ cm$^{-1/2}$. Taking this value of A into account, the curve $\rho(x)$ calculated from formula (4) was constructed. The experimental points lie well on the calculated curve. Thus, the totality of our observations agrees well with the theoretical conclusions developed in the dislocation theory of a thin twin—the proposed theoretical model is justified experimentally.

Fig. 4. Calculated curve of the function $\rho(x)$, taking into account the experimentally determined coefficient A. The points are the experimental values of the density of twinning dislocations in the "mouth" of a twin pinned by an obstacle. The dashed lines indicate the position of the stopper.

In conclusion, the authors express their gratitude to L. A. Pastur, V. Z. Bengus, and S. V. Lubenets for discussion of the work.

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Received
8 VII 1965

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