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EFFECT OF IRRADIATION BY BORON IONS ON THE CHARACTER OF REALIZATION OF TWINNING AND SLIP UNDER PROLONGED (MORE THAN 60 SEC) LOADING OF SINGLE CRYSTALS OF BISMUTH

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The twinning of single crystals of bismuth irradiated by boron ions with an energy of 25 keV and a dose of 10^{17} ion/cm^2, in the case of prolonged (more than 60 sec) loading of a crystal is studied. It is found that prolonged exposure of a crystal to a concentrated load promotes a decrease in the number of twins in the concentrator of external stresses. An increase of temperature up to 400 K stimulates the process of slip in the realization of plastic deformation of a crystal.

Plastic deformation of metallic crystals is realized primarily by twinning and slip [1-3]; therefore, a comprehensive study of these processes is of interest not only from the viewpoint of controlling the mechanical properties of materials used in technology, but also as regards investigation of the physical phenomena observed when crystals are subjected to external loadings. At the present time, the simultaneons development of twinning and slip [3, 4], the sequence of these processes, and their relationship for a crystal system in a state of combined stress are poorly explored.

In [4] the interaction of twinning and slip was investigated as a function of temperature. The aim of the present work was to study the effect of irradiation by boron ions on the processes of twinning and slip of single crystals of bismuth deformed by concentrated loading. These investigations were inspired by the fact that ion implantation is an effective method for structural change of the near-surface layers of crystals [5], due to which it can be used as a technique for controlling the physical (including plastic) properties of solid bodies. Of interest here is the construction of the physical picture of the occurrence of twinning and slip in crystals being deformed, with the properties of the surface layer modified by an ion beam. Experimental conditions for solving this problem can be considered sufficient with the use, as is done in the preseent work, of microindentation of single crystals of bismuth irradiated by ions, in spite of the fact that the dimensions of the region deformed by the concentrated loading and the thicknesses of the implanted layer differ from each other by two or three orders of magnitude. In the study of the kinetics of twinning of ion-implanted bismuth single crystals, the possibility of deformation of the crystal surface by a diamond pyramid that penetrates the crystal by a distance of tens of microns is attributed to the fact that on application of external loading the twinning dislocations move in twinning planes that intersect with the surface of the crystal at a certain angle. This leads to a situation in which in the near-surface region of crystal irradiated by ions, the twinning dislocations actively interact with the implanted impurity, and, as was shown in [1, 3], the magnitude of this interaction is sufficient to change the character of the realization of plastic deformation by twinning.

The single crystals of bismuth were grown by the Bridgeman method from 99.999% pure raw material. The specimens were obtained by shearing the grown single crystals along the cleavage plane (111); this did not require additional processing for carrying out microscopic investigations (the dislocation density determined by the method of selective etching was equal to 10^5 cm^{-2}).

The freshly cleaved surfaces (111) of the single crystals of bismuth were irradiated by boron ions of an energy of 25 keV and dose of 10^{17} ion/cm^2. According to the state diagrams of binary systems [6] and the

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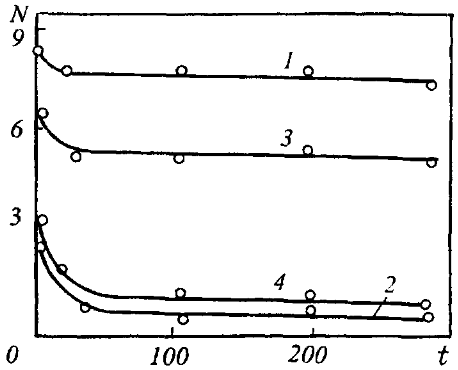


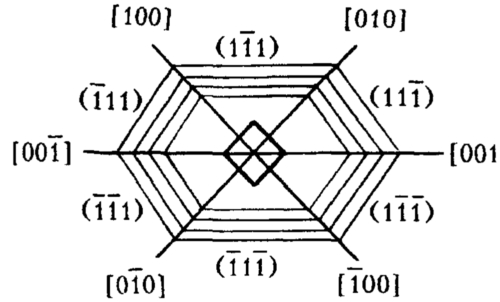


Fig. 1. Change in mean number of twins in impression of diamond indenter on cleaved surface (111) of single crystal of bismuth depending on time of action of concentrated loading of crystal: 1) unirradiated crystal at room temperature; 2) same at 400 K; 3) crystal irradiated by boron ions at room temperature; 4) same at 400 K. t, sec.

Fig. 2. Schematic representation of basic slip planes and directions of twinning observed from side of plane (111) in crystal with rhombohedral structure.

Darken–Gurri graph [7], boron is not dissolved in bismuth and tends to occupy a position in the interstitial space in its lattice.

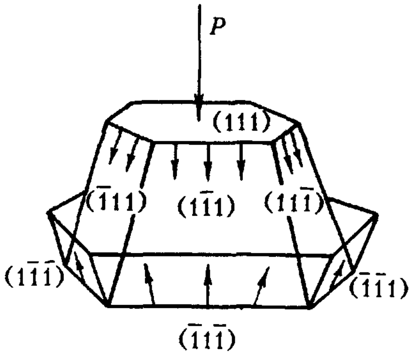
The surface (111) irradiated by ions was deformed by means of a Vickers diamond pyramid of a PMT-3 device. Observations of the evolution of the twins that appear in the impression of the diamond indenter on the cleavage plane were made using the microscope of that very device. In the course of the investigation, we recorded the number of twins in the deformed region of the crystal.

The loading of the indenter was 10 g. In the course of the experiment, the time of holding a crystal under the load was from 5 sec to 1 min or more (up to an hour). We investigated the dependence of the mean number of twins N in the impression of the pyramid on the time t of the action of the concentrated loading of the crystal. The same dependence was constructed for the case of deformation of a crystal at a temperature of 400 K.

The results of the experiment are presented in Fig. 1. An analysis of the form of the curves $N = f(t)$ indicates that an increase in the loading time of the crystal promotes a decrease in the number of twins that appear in the impression of the indenter in the PMT-3 device. In [4] this result is explained by a new kind of interaction of twinning and slip, the essence of which is that for a short time of action of a concentrated load on a crystal, the portion of the energy of external forces that cannot be spent in a short time on slip because of the inertia of the process stimulates twinning. With time, as slip develops, relaxation of stresses occurs in the crystal due to concentrated loading, and due to the plastic reversibility of twinning the distribution of deformation changes in favor of slip.

In our opinion, in [4] the processes of the realization of twinning and slip were not considered thoroughly enough to move to a deep analysis and understanding of the character of the interaction of twinning and slip. For this reason, we will consider the process of deformation of the surface of a bismuth single crystal by concentrated loading from the crystallographic point of view.

A schematic representation of the deformation picture appearing on a bismuth single crystal surface (111) deformed by concentrated loading is presented in Fig. 2. The traces of slip in different planes {111} in intersection with the cleavage plane (111) of the deformed crystral form a hexagon. This is evident if one proceeds from the fact that this slip relates to the system {111}, which incorporates eight planes: (111), ($\bar{1}$11), (1$\bar{1}$1), (11$\bar{1}$), ($\bar{1}\bar{1}$1), ($\bar{1}$1$\bar{1}$), (1$\bar{1}\bar{1}$), ($\bar{1}\bar{1}\bar{1}$). The planes (111) and ($\bar{1}\bar{1}\bar{1}$) are parallel to each other and also to the plane of the paper (Fig. 2) and to the cleavage surface (111). In these planes slip on the cleavage surface is not present. On the cleavage surface (111) one can see dislocations that extend to the surface and move over the planes intersecting with the surface: ($\bar{1}$11), (1$\bar{1}$1), (11$\bar{1}$), ($\bar{1}\bar{1}$1), ($\bar{1}$1$\bar{1}$), (1$\bar{1}\bar{1}$), of which there are six.



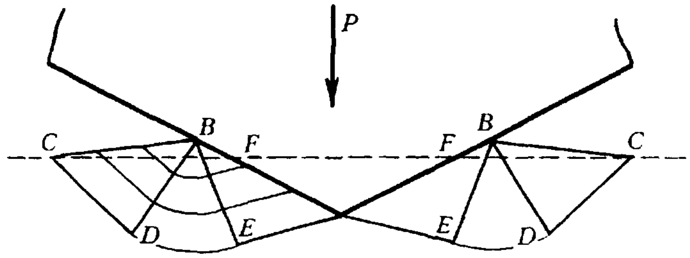


Fig. 3. Motion of basic dislocations under external loading applied to surface (111). *P* is external loading.

Fig. 4. Line of slip in impression of indenter.

Under the action of concentrated loading, the Franck–Reed sources emit full dislocations that propagate into the crystal over the planes $(\bar{1}11)$, $(1\bar{1}1)$, $(11\bar{1})$, $(\bar{1}\,\bar{1}1)$, $(\bar{1}1\bar{1})$, $(1\bar{1}\,\bar{1})$. Having traversed a certain path, these dislocations reverse direction in the same planes, but they intersect with the planes along which motion occurred originally (Fig. 3). According to the authors of [8], this change in the direction of dislocations is observed because of their "reflection" from the heteroboundary. However, in our opinion, this behavior of dislocations is attributed to the special features of the configuration of the fields of stresses around the impression of the indenter [9]. Figure 4 represents a system of slip lines in the impression of a Vickers pyramid in an approximation of a homogeneous isotropic deformed ideal rigid elastoplastic medium [9]. The region BCD (Fig. 4) contains slip lines that favor the extension of dislocations to the surface of the crystal. This also allows us to assume the presence of a situation not considered in [8], when dislocations originate not near the surface, but within the crystal in the region deformed by the indenter and move to the surface of the crystal. These dislocations do not necessarily change the direction of their motion.

The slip inertia noted in [4] at the initial stages of the deformation of the crystal is explained from the viewpoints of the notions developed in the present work by the fact that the total dislocations of the planes {111} transverse a larger path than twinning dislocations because of the change in the direction of their motion. Therefore, the process of the realization of slip develops at a later stage than the process of twinning. Moreover, for the start of generation of full dislocations in the planes {111}, a larger amount of energy is required than for the start of generation of twinning dislocations, since the critical shearing stresses needed to form the dislocation loop of critical radius at which dislocation begins its independent development are larger for full dislocations than for partial twinning ones, because of the proportionality of these stresses to the value of the Burgers vector of generated dislocations (the value of the Burgers vector of full dislocations of the planes {111} is greater than the value of this vector of Shockley partial twinning dislocations [10]).

A decrease in the number of wedge-like twins of the impression of an indenter in prolonged loading of a crystal can occur for two reasons. First, the slip that accomplished its development promotes localization of internal stresses far from the source of external stresses (see Fig. 2), with the distance from the diamond pyramid to the region of the accumulation of full dislocations being commensurable with the dimensions of the wedge-like twins of the system {110} <001>. The localization of the indicated internal stresses far from the concentrator of external stresses leads to the appearance of forces that are directed to the side of the indenter, and this causes the displacement of twinning dislocations to the diamond pyramid that deforms the crystal. These forces act most substantially on the removal of external loading. Second, under the action of external loading and stresses of the full dislocations that extend to the surface, activation of the reaction of transition of partial twinning dislocations into full ones is possible, and this also favors the disappearance of twins.

The implanted impurity prevents the extension of basic dislocations to the surface, thus increasing internal stresses due to the realized slip, as compared with an unirradiated crystal. This leads to the most clear manifestation of the effect of the disappearance of wedge-like twins when crystals are under prolonged loading in irradiated crystals than in unirradiated ones.

From a comparison of the dependences $N = f(t)$ (see Fig. 1) for crystals not irradiated by ions at room temperature (curve 1) and at a temperature of 400 K (curve 2), it is seen that an increase in temperature decreases the number of sources of twinning dislocations, which manifests itself in a decrease in the number of twins in the impression of the indenter. This fact points to a thermally stimulated predominance of slip over twinning in the process of deformation of single crystals of bismuth by concentrated loading.

In crystals irradiated by ions at 400 K the impression of the indenter has a somewhat larger number of twins than in unirradiated crystals (Fig. 1). This suggests a lower susceptibility to changes, at near-melting temperatures, in the elastic characteristics of the surface region of the crystal irradiated by ions than in an unirradiated material.

Thus, it was established that prolonged loading of a crystal promotes a decrease in the number of twins formed in a concentrator of external stresses. Irradiation by ions enhances this effect. An increase in temperature leads to the predominance of slip over twinning.

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