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ON THE MECHANISM OF FORMATION OF SLIP BANDS

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Over the last decade a large number of works have been published on the study of regions of plastically deformed crystals whose orientation differs noticeably from the orientation of the original crystal. These regions, observed under certain conditions of deformation, are called differently by different investigators—slip bands, kink bands, deformation bands, accommodation bands, etc. (1-4). The universality of this phenomenon, i.e., the formation of slip bands under various types of deformation in crystals of metals and ionic compounds crystallizing in different crystal systems, over a wide temperature interval of deformation, indicates that slip-band formation is a fundamental property of the process of crystal deformation. Opinions concerning the mechanism of formation of these regions differ. Most authors believe that the phenomenon is based on complicated slip and that twinning takes no part in the formation of slip bands.

However, the x-ray study that we carried out of slip bands in single crystals of CsJ and TlJ—TlBr deformed by compression showed (5) that in portions of the crystal located at the boundary of a band, near a sharply curved external surface of the crystal, twin lamellae are observed. The twinning plane in CsJ crystals is (113), and in TlJ—TlBr crystals it is $(11n)^*$.

In the present work, in order to verify the presence of twins inside slip bands, we investigated the structure of compressed single crystals of CsBr. Bars of cesium bromide ($4 \cdot 4 \cdot 25$ mm^3) were compressed along a direction deviating from the direction [100] by 15—20°. The structure of the slip bands formed in this process was studied in polarized light and by means of Laue x-ray photographs with a beam cross section of 1—0.5 mm. The bar was then cut along the plane $(1\bar{1}0)$, situated perpendicular to the active slip plane (110) and parallel to the slip direction [001]. By grinding, the thickness of the plates was brought down to 0.3—0.2 mm. The thin plates were again studied by means of Laue x-ray photographs with beams of different cross section (from 1 mm to 40 μ). In order to make it possible to compare the stress distribution obtained from optical data with the x-ray data, we used a device constructed by us that made it possible to fix the x-ray beam on a selected region of the crystal with an accuracy of up to 10 μ.

The study of the structure of slip bands in CsBr crystals in polarized light

Fig. 1 and Fig. 2

Figure 1: Fig. 1 and Fig. 2

showed that, just as in CsJ and TlJ—TlBr crystals, in portions of the crystal located near a distinct surface kink, the slip lines undergo a sharp bend along a certain line beginning at the external surface of the crystal (lines OK and $O'K'$ in Fig. 1). The distinctness of the slip band depends on the angle of the bend. The greater the angle,

* The indeterminacy of the last index follows from the fact that the angle of rotation of individual portions of the crystal is not constant inside the slip band.

···the more the slip lines deviate from their original direction, the more distinctly the fault band is delineated.

In radiographs obtained from regions adjoining the fracture line, two types of interference maxima are observed: diffuse and sharp. The position of the diffuse interferences corresponds to the orientation of the original crystal, while that of the sharp ones corresponds to the orientation of a region of the crystal that is mirror-symmetric with respect to the parent crystal; i.e., twinning takes place.

The dimensions of the twin interlayers vary depending on the object under study and on the magnitude of the applied stresses. In CsBr crystals, for example, almost the entire fault band, 3 mm wide, was a “twin” with respect to the original crystal, whereas in a CsI crystal the thickness of the twin interlayer did not exceed 0.5 mm.

Fig. 1. Schematic representation of the structure of a fault band in a cesium bromide crystal
Fig. 2. Scatter of normals to conjugate planes according to X-ray photographs of CsBr crystals

As a rule, in the cesium bromide crystals investigated, the twinned region was an entire system of separate, symmetrically rotated regions of the crystal. The planes of symmetry were crystallographic planes of the types {113}, {114}, {115}, and {150}. The mutual arrangement of the region in which twin interlayers are observed and of the original crystal is shown in Fig. 1; the regions of the fault band whose orientation is symmetric with respect to the original one are indicated by hatching. The largest twin region adjoins the line OK, along which the slip lines undergo a sharp break. In the remaining parts of the fault band (regions LKM, $L'K'M'$ in Fig. 1), in complete agreement with the optical picture, a smooth S-shaped bending of the crystal lattice around the [110] direction is observed, with a maximum angle of rotation from the original state of 45°.

Figure 3 shows radiographs obtained in the hatched region of the fault band—in the regions LKM and $L'K'M'$—and in regions adjoining the line OK. The direction of the X-ray beam is made coincident with the [110] direction, which

Fig. 3

Figure 2: Fig. 3

is the axis of the principal rotation. Accordingly, the Laue spots from the original crystal are elongated along arcs of concentric circles. The sharpness of the interference maxima in the Laue patterns from the twinned regions of the crystal (Fig. 2a) indicates that the crystal lattice in these regions is free of stresses.

A similar structure was also observed in a fault band formed at the end of a bar subjected to compression. X-ray photography of plates obtained by longitudinal sawing of a bar with a clearly expressed fault band at its end showed that, along with the formation of twin interlayers preserving their orientation throughout the entire thickness of the bar, ⋯

Fig. 3. X-ray diffraction patterns obtained from a CsBr single crystal deformed by compression within a slip band: **a**—inside the hatched region near the line OK; **b**—on the line OK; **c**—inside the region $LK'M$ (the X-ray diffraction pattern of the region $L'K'M'$ is analogous to 2 **c**)

the formation of such interlayers is observed, which grow into another twin interlayer, conjugate with the original crystal along another plane, of the type $\{11n\}$, where n lies in the range from 3 to 5. In all, in the specimen with a boundary slip band, 9 orientations were found with conjugation planes (131), $(3\bar{1}1)$, (114), (511), $(\bar{1}\bar{1}5)$, $(51\bar{1})$, (115), $(11\bar{5})$, and (015).

The relatively rich set of twinning planes of the type $\{11n\}$ may not in fact exist, but may be explained by inaccuracy in determining the position of the conjugation plane (Fig. 3). The use of a narrow beam of X-rays made it possible to show quite convincingly that the change in orientation of the original crystal, recorded from the boundaries of the band toward the center, can cause twinning to appear along different crystallographically equivalent planes. However, we were unable to show unambiguously that twinning occurs only along different planes of one and the same family, mainly because the dynamics of formation of the slip band is unclear.

A second possible explanation for the presence of different crystallographic conjugation planes is the approximately equal ease of lattice rearrangement during twinning along planes of the type $(11n)$, owing to the slight difference in the activation energy of rearrangement, as apparently occurs in Ti and $\alpha = \mathrm{U}$ (6).

To test the equivalence of these planes, we calculated and compared the values of the mean-square displacements of atoms $\bar{s}^2$ during the transition from their initial positions to positions in the twinned region of the crystal for the twinning planes $\{11n\}$, $(n = 1 \div 5)$, $\{1n0\}$ $(n = 2 \div 5)$, $\{125\}$, and $\{127\}$. The choice of planes was based mainly on the experimental data (Fig. 2). It was assumed that lattice rearrangement during twinning occurs not by simultaneous displacement of atoms parallel to the twinning plane (as in the classical case of calcite), but by separate, regularly coordinated jumps of atoms into new equilibrium positions, as occurs in martensitic-type phase transformations. In choosing the direction of displacement, it was taken into account that the energetically most favorable jumps are those corresponding to the smallest particle displacements.

According to the calculations carried out, the energetically most favorable lattice rearrangement during twinning is along planes of the type $\{120\}$ and $\{130\}$ ($\bar{s}^2 = 0.16$), followed, in order of increasing $\bar{s}^2$, by $\{150\}$ ($\bar{s}^2 = 0.17$), $\{140\}$ ($\bar{s}^2 = 0.19$), $\{112\}$ ($\bar{s}^2 = 0.22$), $\{115\}$ ($\bar{s}^2 = 0.28$), $\{114\}$ ($\bar{s}^2 = 0.29$), $\{113\}$ ($\bar{s}^2 = 0.32$), $\{127\}$ ($\bar{s}^2 = 0.39$), and $\{125\}$ ($\bar{s}^2 = 0.40$)*. It should, of course, be stipulated that the calculation was carried out under the assumption of a perfect lattice, whereas in reality, because of the presence of local defects, this series may change substantially.

On the basis of comparing the calculated and experimental data, one may think that twinning in CsCl-type crystals, observed inside the slip band, can proceed along several different crystallographic planes of the types $\{1n0\}$ and $\{11n\}$. Apparently, the method of loading the crystal and the crystallographic orientation of the specimen play an essential role in the choice of the twinning plane.

Despite some ambiguity in the choice of the twinning plane, there can be no doubt that twinning participates in the formation of slip bands, along with slip, in those cases when the stresses can reach such a magnitude as to ensure the passage of twinning; moreover, formation of a twin relieves the stresses arising in the deformation process**. This conclusion is confirm–

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* The crystal-lattice parameter is taken as unity.

** Stress relief is also promoted by the process of recrystallization, which, apparently, can occur in these crystals under the conditions of the complex stress field of slip bands even at room temperature.

is to be expected from the experimental data of M. V. Klassen-Neklyudova and A. A. Urusovskaya, according to which only the formation of sharply pronounced slip bands in crystals of this type is accompanied by sound (^{7}).

The conclusion of Barrett et al. that the mechanism underlying the formation of slip bands is complicated slip, while twinning takes no part, follows, apparently, from the fact that the objects of investigation in the published works were metallic crystals (^{1,2,8,9}).* In such metals as Al, Zn, Cd, Sn, recovery already partially takes place at room temperature and, possibly, therefore, despite the redistribution of stresses at defects of the crystal lattice, the local stresses do not provide the conditions necessary for rearrangement of the lattice by means of twinning.

Thus, the scheme proposed by Orowan (^{8}) for describing the structure of slip bands is valid both for ionic and for metallic crystals, if one assumes that the length of the segment OK (Fig. 1) and the crystallographic indices of this direction may differ in different crystals depending on the experimental conditions and the plastic properties of the substance. For metals one must take $OK = 0$, i.e. the points K and O coincide. In this case Orowan' s scheme passes into Barrett' s scheme (2).

Our experiments show that the line OK is the trace of the twinning plane. Thus, for CsBr crystals the indices of this direction $[\bar{1}31]$, determined optically, agree well with the indices of the twinning plane (114), determined from the Laue pattern. In the case when a gradual change in the direction of slip lines is observed, twinning is absent. Consequently, it may be asserted that, with a sharp break in the slip lines, the initial crystal is partially relieved of stresses by means of a lattice rearrangement of the twinning type, whereas with a smooth bending of the slip lines there occurs a gradual S-shaped rotation of portions of the crystal, restoring the orientation of the crystal outside the slip band.

It may also be thought that the known phenomena—slip-band formation, twinning along irrational planes (10), kinking in NaCl crystals (11) (described as twinning on the plane (119)), and the formation of bent regions near twin boundaries in crystals of the hexagonal system (3)—are all merely manifestations of a combination of generally known deformation mechanisms, i.e. slip with bending and twinning in the broad sense. Which will be more pronounced—slip or twinning—depends on the orientation of the specimens, their plasticity, and also on the local distribution of stress, i.e. on the quality of the specimen surface and on the external stress field acting on the crystal.

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* An exception is the work of M. V. Klassen-Neklyudova and co-workers (^{4}), in which, on the basis of optical observations of alkali-halide single crystals deformed by compression, the authors arrive at the same conclusions as Barrett.

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

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