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# Reversible plasticity of metallic single crystals at the stage of their residual twinning

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## Abstract

The work studies regularities of the formation of wedge-shaped twins under growing concentrated load in single crystals of bismuth, zinc and bismuth-antimony alloy. It was established that the twinning, detwinning and stopping of the twin deformation near the stress concentrator can take place simultaneously with the load growth. Reversibility of plastic deformation during twinning in metals at the stage of residual twinning development was discovered. Various manifestations of spontaneous detwinning of wedge-shaped twins which emerge at stress concentrators when indenting Bi, Zn, Bi-Sb single crystals with increasing load are quantitatively studied. Depending on the value and the sign, local fields of elastic stress can encourage or discourage twinning, or cause detwinning.

*Keywords:* Twinning; Detwinning; Plastic deformation; Reversible plasticity; Bismuth; Zinc.

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## 1. Introduction

Plasticity is the property of solid bodies to be deformed irreversibly under the action of an external force. It is known that plastic deformation of real crystals occurs due to the movement of crystal lattice defects under the action of external loading. In some crystals the internal forces that appear during such movement can cause the backward motion of defects after an external load is removed. The initial shape of the crystal is restored. This process is known as reversible crystal plasticity.

Reversible plasticity is the main property of plastic deformation by twinning. It represents the first stage of the mechanical twinning of crystals, elastic twinning [1]. At this stage twinning inclusion is reversible and can completely detwin spontaneously during offloading. Under a concentrated load, a thin interlayer in the shape of a wedge appears in the crystal; it is a wedge-shaped twin and its crystal lattice is displaced at a certain angle to the matrix. The dimensions of the twin wedge grow proportionally to the external load. If the external load decreases, detwinning of the crystal takes place: the twin decreases in dimensions thus keeping the form of a thin wedge. After unloading it disappears completely, that is, leaves the crystal. Elastic twinning is observed in all twinning crystals.

The important feature of deformation twin development at the elastic twinning stage is that its dimensions

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(wedge length $L$ and its width $h$ at the base) change proportionally to the load quantity.

After some limit value of applied stress, the twin is wedged and after unloading stays in the crystal. At the stage of residual twinning, detwinning can be observed in response to the action of an external stress of the reversed sign on the crystal [2,3].

Numerous experimental investigations showed that the processes of twinning and detwinning determine the mechanical properties of many technically significant metals and alloys. This stimulates the interest in the study of this phenomenon. Detwinning in crystalline solids is a unique deformation mechanism partially responsible for the shape memory effect [4–7]. In the last years it has been revealed that twinning and detwinning are the important deformation modes in metals and alloys with various crystal structures [8–19]. The metals which have a hexagonal close-packed structure, such as Be, Mg, Zr, and Ti, have aroused great interest. Twinning-detwinning is an important deformation mode in these metals. Detwinning, a reverse twinning process, has been reported in some hexagonal close-packed metals and alloys during loading, unloading or cyclic deformation [20–27]. The detwinning characteristics in magnesium alloys obtained through a cyclic loading test have been studied in detail [28–35]. Detwinning describes the coalescence of a martensite twin into a single martensite crystallite [36,37]. It is stated both experimentally and theoretically that detwinning is a unique deformation mechanism of nanotwinned metals [38–40]. Various theoretical deformation models of crystal twinning-detwinning have been developed [41–46].

Earlier we studied the development of wedge-shaped twins in bismuth single crystals under the action of an increasing concentrated load. In Ref. [47], it was shown that an imprint had several residual wedge-shaped twins after indentation of bismuth single crystals by a diamond pyramid. Their evolution with load growth progressed in different ways. The proportional length and width changing of a wedge-shaped twin was distorted with load growth. Both twins' growing and their complete stopping while the dimensions of wedge-shaped twins under load remained unchanged were possible. We revealed the cases of a spontaneous size reduction of a twinned wedge with load growth; that was a reversible twinning under load at the stage of residual twinning.

The present paper contains studies in the regularities of the formation of a wedge-shaped twinned area under a growing concentrated load in single crystals of Zn, Bi and Bi-Sb.

## 2. Experimental technique

### 2.1. Material and sample preparation

The experiments were conducted on metal single-crystal samples with hexagonal (Zn) and rhombohedral structures (Bi and Bi-Sb alloy). The crystal-growing processes and sample preparations were quite simple. These crystals possess perfect cleavage planes. The (111) cleavages in the rhombohedral crystals and the (0001) ones in the close-packed hexagonal crystals are natural metallographic sections and do not require additional treatment for microscopic examination of the surface.

In these metals, the slipping precedes the twinning and accompanies it at all stages over a wide temperature range; besides, the development of twins in them can go with brittle fracture. The crystallography of the twinning and the slipping of the above-mentioned metals were studied thoroughly. Three slip systems are implemented in the hexagonal close-packed lattice: the easy one in the basal plane (0001) $\langle 11\bar{2}0\rangle$; the more complex one, the pyramidal slip in the system $\{11\bar{2}2\}$ $\langle \bar{1}\bar{1}23\rangle$; the prismatic slip in the system $\{10\bar{1}0\}$ $\langle 11\bar{2}0\rangle$. The twinning in the close-packed hexagonal structures is realized in the system $\{10\bar{1}2\}$ $\langle 10\bar{1}1\rangle$. Two slip systems take place simultaneously in the neighborhood of the stress concentrator during the deformation of bismuth and bismuth-antimony alloy: the easy basal slip in the system $\{111\}$ $\langle 1\bar{1}0\rangle$ and the secondary slip with a higher yield point in the system $\{11\bar{1}\}$ $\langle 110\rangle$, and the twinning in the system $\{110\}$ $\langle 001\rangle$.

All metals under study have just one twinning system ensuring the reliability of physical interpretations of the obtained research results and simplifying considerably the dislocation analysis of twinning restructuring processes.

Similar to calcite in the case of pure twinning, crystals of bismuth, bismuth-antimony and zinc provide classical samples for studying the twinning regularities in metal crystals.

The experiment was conducted with the use of zinc single crystals with initial basal dislocation density $\sim 5\times 10^4\,\mathrm{cm}^{-2}$ and pyramidal dislocation density $\sim 5\times 10^3\,\mathrm{cm}^{-2}$, as well as bismuth single crystals and bismuth-antimony alloy with dislocation density in non-basal planes $\sim 10^6\,\mathrm{cm}^{-2}$.

The working samples shaped as the right-angle prisms with the dimensions $10\times 10\times 5$ mm were made by crystal cleavage in the cleavage plane using a sharp knife at the liquid nitrogen temperature.