Localization of deformation in [$\bar{1}23$] - monocrystals of aluminum under compression

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Abstract. The study of the deformation relief of aluminum monocrystals oriented for a single slip has been carried out using methods of optical and interference microscopy. It has been established that in the volume of a single crystal several macrofragments are formed, differing in size and direction of shear. Reasons for formation of two systems macrobands of shear are identified. It has been shown that formation of the deformation relief in the investigated crystal occurs at three scale-structural levels.

1. Introduction

Monocrystals of metals and alloys with FCC lattice, oriented for a single slip, are one of the most difficult objects in revealing the laws of plastic strain and hardening. The complexity is caused by the pronounced inhomogeneity of strain behavior in such single crystals due to the anisotropy of shear stresses in slip systems [1]. It is the main reason in the fact that single crystals with orientations in the center of a standard stereographic triangle are poorly studied at all scale-structural levels, including the macro level. In recent years, for a number of single crystals of metals and alloys it has been established that the inhomogeneity of plastic strain behavior under compression is manifested, primarily, in formation of shear macrofragments [2-6]. At the same time, the laws of microfragmentation depend on the availability in a single crystal of possibilities for shear carriers to emerge onto free faces of the crystal. The volumes of the crystal in the first case became known as volumes of the lightweight shear (VLS), in the second – the volumes of the constrained shear (VCS). Usually, in single crystals with VLS the localization of the shear strain occurs in these volumes from the beginning of the plastic flow, resulting in formation of slip macrobands in single crystals [2, 5, 7]. It is natural that in single crystals oriented for a single slip there is always a volume of the lightweight shear. It occupies a large part of the crystal, and a significant localization of the shear strain with formation of a distinct slip macroband is expected, as it is observed, for example, in [1.8.12] - single crystals of Ni_3Fe [2]. The present work is devoted to the study of laws of the plastic strain macrolocalization in aluminum single crystals oriented for a single slip.

2. Materials and methods

Aluminum single crystals of commercial purity have been investigated in the work. Single crystals had the shape of a parallelepiped and were oriented for compression along the crystallographic direction $[\bar{1}23]$, i.e. for a single octahedral slip. The side faces of the crystal were parallel to the planes $(3\bar{6}5)$ and (210).

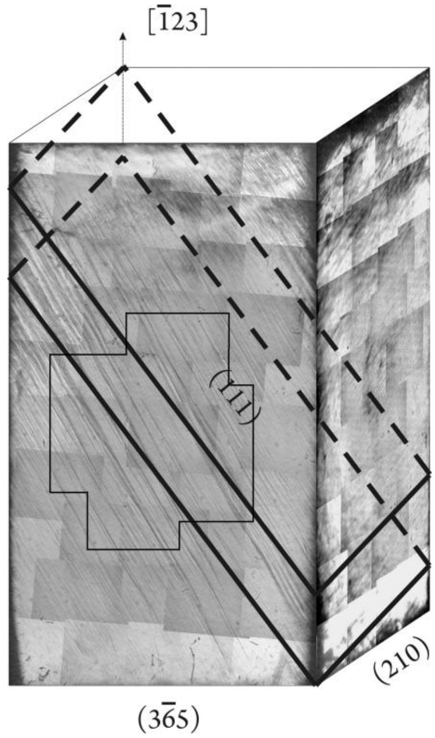

Figure 1. Strain relief of the crystal surface.

At the chosen orientation of the single crystal the primary slip system was the system (111) [110] with a Schmid factor m=0.47. The direction of the primary slip in the crystal had an orientation at which it was possible to expect an emergence of edge dislocations on the face (210), and screw dislocations on the face $(3\bar{6}5)$. In crystals with a selected crystallogeometric setting, for families of primary (111) and conjugate $(\bar{1}11)$ slip planes it is possible to allocate the volumes of the lightweight shear. For the primary plane, the volume of the lightweight shear is shown in Figure 1. Strain of the single crystal was carried out under compression at room temperature with the velocity of $1{,}5 \times 10^{-2}$ s^{-1} using the device "Instron" up to strain degree of d ε=0,06. Shooting of the strain relief was carried out using an optical microscope MIM-10 with a 250-fold magnification. With the help of special output devices the record of optical images of the strain relief was carried out directly on the computer. Along with the metallographic method, the study of the strain relief was carried out using optical (interference) profilometer Zygo New View 6000.

3. Results and Discussions

3.1. Fragmentation of shear strain at the macro-level

Figure 1 shows optical images of the strain relief formed by two mutually perpendicular lateral faces of the investigated aluminum single crystal. Although, in general, reliefs on the faces (210) and $(3\bar{6}5)$ differ considerably, the main components of the relief at the macro-level are: the system of primary slip lines and two subsystems of large-scale bands of the localized shear. Tracks of the primary slip are typical elements of the strain relief. Their average length is 320 μm. The most striking part of the

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strain relief is coarse shear bands. They can be observed on one of these faces in Figure 1. All bands are combined into two groups. Bands of the first group are concentrated in the lower bottom part of the face and begin at the left vertical edge, and the bands of the second group are localized in the upper right part of the face and begin from the right vertical edge. Most bands taper as they move away from the edge. The length of strips varies in the range of 0.5...5.0 mm; the width is 20...200 μm. The broadest bands begin in the volume of the lightweight shear of the primary system (Figure 1, for example, at the upper left and the lower right corner of the face). However, during the promotion of bands of both subsystems depthward the single crystal, they deviate from primary slip lines towards corresponding vertical edges of the single crystal at angles 4-8º. As a result, the bands that "deviated" to the opposite sides of these two systems become approximately parallel to each other. This is clearly seen in Figure 2, which is an enlarged part of the surface of the face $(3\bar{6}5)$ shown in Figure 1.

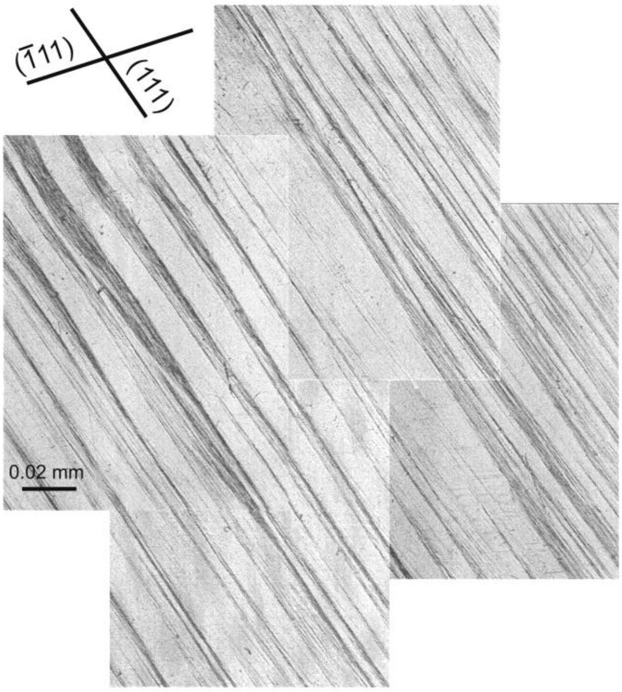

Figure 2. Enlarged images of the area highlighted in Figure 1.

As noted above, along with the optical study, the study of the strain relief for all free faces of the single crystal has been carried out in the work with the use of an interference profilometer. The corresponding photographs of two parallel faces with indicated systems of parallel bench marks are presented in Figures 3 and 4.

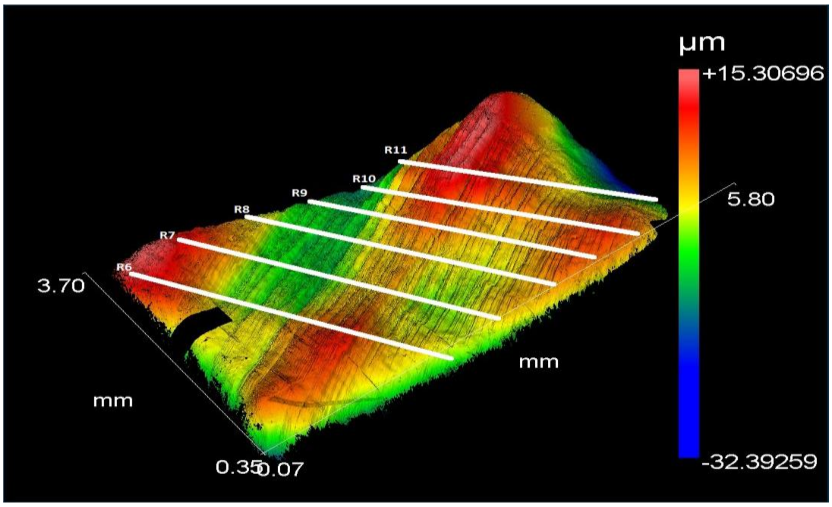

Figure 3. Surface images of faces $(3\bar{6}5)$ obtained using the interference microscopy method. The lines of bench-marks, along which the profiles of the strain relief were photographed, are indicated.

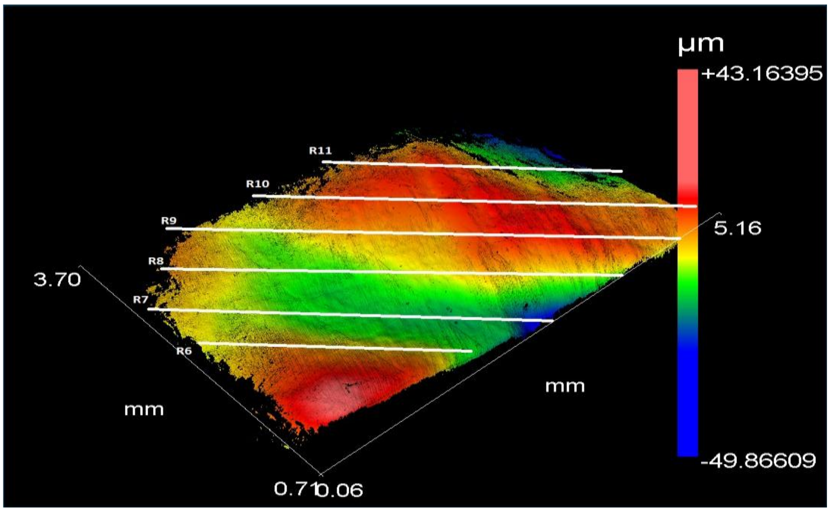

Figure 4. Surface images of faces $(\bar{3}6\bar{5})$ obtained using the interference microscopy method. The lines of bench-marks, along which the profiles of the strain relief were photographed, are indicated.

From the analysis of the relief it follows that in consequence of the plastic strain (ε = 0,06) several distinct shear macrofragments are formed in the volume of the single crystal. Their linear dimensions vary in the range of 1...6 mm. Figures 3 and 4 give an idea on the shape of macrofragments. As can be seen from the scale in Figures 3 and 4, the maximum spread of the height of the relief elements on faces $(3\bar{6}5)$ is 50...60 µm. On faces (210) – it is twice as large. On boundaries of macrofragments the difference in heights of the relief does not exceed few micrometers. At the same time, the difference in heights occurs smoothly. As a result, almost all borders of macrofragments of the shear strain at ε = 0,06 are blurred, i.e. they are boundaries with continuous (smooth) misorientation. From the comparison of Figure 1, 3 and 4 it follows that at the macro level the largest in size changes occur in VLS for primary slip planes and in areas adjacent to its vertices. At the same time, in the central part of VLS on one of the faces $(3\bar{6}5)$ a convex (red area in Figure 3) is observed, and on the opposite side – a concave (green area in Figure 4). This means that in the central part of VLS there was a shear along the primary slip system. As a result, there is a definite correlation between the shape of macrofragments and the shape of VLS for the primary plane in its central part. However, in near-end areas of VLS such correlation is absent. In general, in a single crystal the main part of shear bands is located outside VLS for the primary slip system.

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3.2. Shear bands

Figure 5 and 6, as an example, illustrate profiles of the strain relief that correspond to bench-marks R6 and R9 indicated on images of the relief (Figure 3). From the analysis of profilograms it follows that the relief, formed during plastic strain, can be characterized as a periodic, three-level. The first one, the largest scale-structural level is associated with formation of shear macrofragments. The scale of this level is millimeters, which corresponds to linear dimensions of macrofragments. The height of elements of the first level is on average few micrometers. The periodicity of the relief profile at the second scale-structural level on faces $(3\bar{6}5)$ can be easily traced for all bench-marks, including those presented in Figure 5, 6. Formation of the second scale-structural level is associated with formation of macrobands of the localized strain (Figure 1 and 2) and, of course, the scale of this level is determined by their quantitative characteristics. The period of the relief at the second level is 150-250 μm, which corresponds to the thickness of slip macrobands. The height of elements of the relief at this level varies in the range of 1-5 μm.

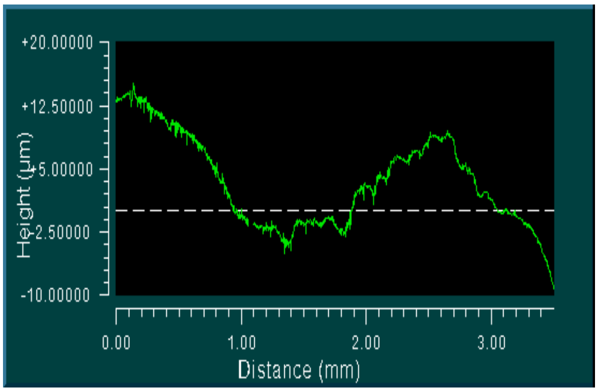

Figure 5. Profiles of strain relief, corresponding to the bench marks R6, at the surface of the face $(3\bar{6}5)$ (Figure 3*a*).

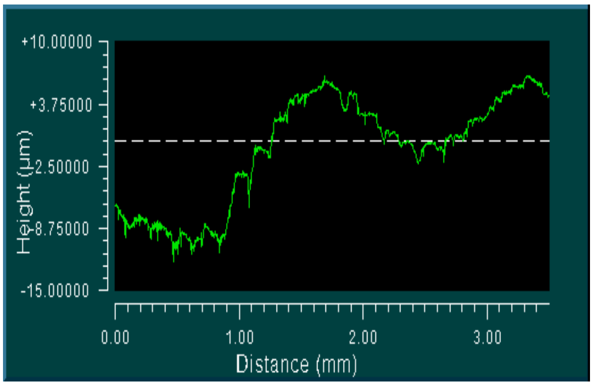

Figure 6. Profiles of strain relief, corresponding to the bench marks R9, at the surface of the face $(3\bar{6}5)$ (Figure 3*a*).

4. Conclusion

The investigated in the work $[\bar{1}23]$ - single crystal of aluminum in its crystallogeometry falls into the category of FCC single crystals with a volume of the lightweight shear. As a rule, macrolocalization of plastic strain with formation of shear macropacks in VLS takes place under uniaxial compression of such single crystals up to small degrees of strain. This mechanism of shear strain localization is characteristic of single crystals of aluminum and alloy Ni_3Fe, oriented for a symmetrical slip along close-packed planes [6, 8, 9]. A condition necessary for formation of shear macropacks is: the presence of a common edge (linear concentrator) and/or vertices (point concentrator) in the crystal and the volume of lightweight shear in it [9]. In the investigated aluminum single crystal these conditions are met. Meanwhile, even though macrolocalization of shear strain in VLS takes place the typical shear macropacks are not observed. As mentioned above, in VLS $[\bar{1}23]$ - aluminum single crystal the macrolocalization takes place, but it is achieved by a slip at the mesoscopic level rather than at the macroscopic as in the abovementioned crystals. It is to be supposed that the main reason for another mechanism of strain localization in aluminum single crystal oriented for easy slip are significant frictional force between the end faces of the sample and the testing machine punches. In crystals of the same metal but with symmetric even-numbered orientations ([110] and [001]) the mechanical stability of single-crystal samples at the macro level was achieved by two conjugate families of an active octahedral slip planes. In this case, forces of mechanical friction were compensated symmetrically. In a single crystal with an asymmetric orientation this mechanism is impossible. Due to friction at the ends, geometrically necessary dislocations gradually accumulate in the crystal (excess density of dislocations), and long-range elastic-plastic stresses appear in the volume of the crystal. Their relaxation takes place upon reaching the critical density of such dislocations and, as a consequence, high local stresses. It happens with formation of multiple shear bands in the scale of the sample. Although formation of the most representative bands begins from the areas of lateral edges located in VLS of the crystal, most of them lie outside of VLS.

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