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Macrosegmentation and strain hardening stages in copper single crystals under compression

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ABSTRACT

The surface deformation-induced pattern (relief) of copper single crystals with the orientation of the compression axis along $[1\bar{1}\bar{1}]$ has been investigated by means of optical, scanning electron and atomic force microscopy. The misorientations between both macroscopic and mesoscopic areas in $[1\bar{1}\bar{1}]$-single crystals have been determined using the electron back scattering diffraction (EBSD) technique. The macroscopic reorientation has been revealed to rotate the crystalline lattice around the [110] axis. The single crystal has been divided into five macrosegments with their misorientations distributed along the compression axis in a manner that the deformation axis sequentially coincided with the crystallographic directions in the order $[1\bar{1}\bar{1}]$-$[2\bar{2}\bar{1}]$-$[7\bar{7}\bar{3}]$-$[1\bar{1}0]$. Shear by unloaded plane $(1\bar{1}\bar{1})$ has been observed. The macrolevel deformation up to 25% has been developing as follows: shear by octahedral planes – development of macrobands – reorientation of the central zones – shear by unloaded octahedral plane in the reoriented zones. The steps of this sequence corresponded to the stages of the stress-strain curves.

1. Introduction

To study texturing in polycrystalline materials we need to define more accurately the already known strain patterns in order to apply them to an isolated grain. Earlier such researchers as Taylor (1938), Lebensohn and Tome (1993), van Houtte et al. (1999), and Mahesh (2009, 2010) treated each grain of the polycrystalline material as a homogeneously deformed solid. Nevertheless, the results of numerous experimental works showed that the grains deformed inhomogeneously. Therefore, we have to separate macroscopically induced strain gradients from the micromechanical effect of plastic inhomogeneity within the grain scale (Raabe et al., 2001). The important thing in this case is not only the crystallographic orientation of an isolated grain with respect to the deformation axis but also an interaction between the neighboring grains. This interaction may add complexity to the macroscopically simple strain-stress state. One of the approaches to find a solution to this problem has been offered by Raabe and Zhao et al. (2002a), (2002b) in the form of a theory of orientation gradients where these reorientation gradients arise both by internal and external reasons such as the crystallite orientation and effect of neighboring grains,

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respectively. Such an approach allowed establishing a crystallographic orientation which is prone to increasing the reorientation gradient both in fcc and bcc lattices (Raabe et al., 2002a). Moreover, some important points concerning an interaction between the neighboring grains have also been established by Raabe et al. (2002b). In particular, the essential influence of both the grain topology and microtexturing on the strain inhomogeneity has been demonstrated by Raabe et al. (2003) and Zhao et al. (2008). Also the practically important effect of the rolled sheet roughness has been taken into account.

It appears to be important to consider both the surface roughness and complexity of the subsurface stress-strain state when performing the compression test. The inhomogeneous triaxial compression primary stress pattern is created in the subsurface of a sample below the testing machine's platen according to Lychagin (2006). Both vertexes and edges of the tetragonal prism-shaped sample serve as stress concentrators so that stresses damp with the distance away from them. These stresses may create not only the compression strain local zones in accordance with the axial loading but also the small local zones of the tensile strain. The irregularities on both sample's and platens' surfaces add even more complexity to the subsurface stress pattern at the microscale level and therefore sample's surface has to be polished or coated. The friction force influence is more clearly observed in tribological testing by intense grain subdivision (Tarasov et al., 2012) and development of rotational plasticity in the subsurface of real contact area with final generation of submicro – and nanocrystalline structures (Tarasov et al., 2013).

There is a point to be made concerning the boundaries between the zones having different primary stress patterns. The availability of these zones and boundaries will facilitate the development of rotational plasticity, cross slip and hindered shear. Conceptual models describing such situations have been presented elsewhere (Lychagin et al., 2006). Even if special precautions were made to provide free displacement of samples in machine's grips the strain pattern in the subsurface of contact areas differs from that of the sample's bulk. That such is true has been shown both by the results of our experiments reported by Lychagin, (2006), Lychagin et al. (2006, 2011) and by the results of other researchers who studied strain in single crystals using a digital image correlation technique (Raabe et al., 2001, 2003; Zhao et al., 2008; Roters et al., 2010; Magid et al., 2009; Ha and Kim, 2011; Florando et al., 2007).

The issue of the single crystal reorientation in deformation is closely intertwined with the initial orientation of its faces as shown by Franciosi, Zaoui (1982), Roters et al. (2010), Havner (2007), (2011), Paul et al. (2010). When studying the compression of high-symmetry orientation single crystals it is reasonable to provide consistency between the symmetry of equally-loaded slip planes positions and lateral faces. Franciosi and Zaoui (1982) took that into account when they carried out compression testing of copper single crystals and used trigonal prism-shaped samples with two sets of faces {110}, {112} for orientation [111] and tetragonal prism-shaped ones for all orientations other than [111]. Our own investigations show that deformation-induced surface pattern as well as the development of strain inhomogeneity on the sample faces is influenced not only by differences in the primary stress patterns between the subsurface and the central part of the sample but also by the orientation of the lateral faces (Lychagin, 2006; Lychagin et al., 2011). Geometrical positions of slip planes in the bulk of the sample may differ depending on it. Analogously, the slip plane positions are changed with respect to basic stress concentrators so that single crystal is subdivided into zones within which definite shear systems or shear domains are working. We call such a process as fragmentation or segmentation. The strain inconsistency between these shear domains will result in intense strain localization at the domain boundary (Lychagin et al., 2011).

It is especially important to take the lateral face orientation into account when carrying out a channel die test. Havner (1992, 2007, 2011) gives a review of works done on single crystals in this field. Also he analyzed in details the [110] orientation of single crystals (Havner, 2007, 2011, 2014) and stressed the importance of these works by citing Fares et al. (2002) as follows: “The channel die test occupies an important position within single crystal deformation studies and has been viewed as representing a first approximation to the constraint and loading condition for metal poly-crystals”.

It seems interesting to study these results in connection with a stress-strain hardening curve. The orientation dependence of lateral faces has been studied by Paul et al. (2010). Copper single crystals having the Goss {110}<001> orientation have been channel die tested up to reaching the preliminary strain corresponding to the stage IV. For further testing they used both prestrained samples and those having their orientations changed for Brass {110}<112>, M{110}<111> and Hard {110}<011> ones. The result was that the stress level reduced in the order Hard → M → Goss → Brass orientations and in accordance with the Taylor factor changed. However, the higher is the stress level achieved, the higher is the effect of softening in the subsequent test. Such a specificity can not be explained without extra experimenting. Paul et al. (2010) studied surface deformation pattern and slip band structures at macro- and microscale level, respectively. It was shown then that the rate of softening is related both to the macroband generation intensity and the slip band density in them. Accumulation of misorientations between the macrobands is determined by accumulation of misorientations in the microband structures. So these results dictate the necessity of studying the deformation at different scale levels to enable description of the stress-strain curve behavior. This study should involve not only the analysis of general orientation changes with respect to either a whole single crystal or its parts, but also the detailed examination of the deformation-induced surface pattern in connection with the rotations observed. Such an approach would allow us to reveal mechanisms responsible for hardening and softening in the single crystals under consideration.

Classification of structural elements generated and observed in metallic materials under deformation is given elsewhere (Honeycombe, 1984; Jasienski, Piatkowski, 1980; Dillamore, 1980; Hatherly, 1982; Laird, 1996). Those elements include kink bands, secondary shear or slip bands, accommodation bands, shear bands, persistent slip and deformation bands. The sample's areas occupied by persistent slip bands generated by fatigue mechanism contain both extrusions and intrusions (Laird, 1996; Man et al., 2009a,b; Mughrabi, 2009). Kumar and Mahesh (2012, 2013) focused on generation and evolution of