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Strain-induced folding on $[1\bar{1}\bar{1}]$-copper single crystals under uniaxial compression

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ABSTRACT

Using uniaxial compression we studied the mechanical instability by folded structure formation on initially smooth and plain faces of copper single crystals with deformation axis orientation along $[1\bar{1}\bar{1}]$. These folded structures can be found within several zones on the crystal's faces after compression test. We classified the folds based upon their scale, localization, state of the interfold boundaries, presence and amount of the slip bands in the folds. Subsurface crystalline lattice reorientation by deformation banding has been found to be the reason for folded structures generation. We suggest that folds generated on the $[1\bar{1}\bar{1}]$-single crystals under compression are the inherent surface relief components which denote the deformation processes occurring both in the subsurface and in the bulk of the sample. In view of that, they can be used for analyzing the deformation under compression along with other surface structural components. The main specificity behind the folded structure generation mechanism which differs them from other orientations is slipping by parallel octahedral planes in some specific local areas.

1. Introduction

In a number of plastic deformation experiments it is possible to observe deformation-induced instability resulting in folded and wrinkled structures formed both on inorganic and organic materials. Inorganic materials that are capable of folding under deformation include geological minerals as well as metallic materials. More or less full classifications of geological folds by their morphology, origination mechanisms, stages and generation conditions had been given by Huddleston [1], Ramsay and Huber [2], Hansen [3], Johnson and Williams [4], There is clear and unambiguous understanding in structural geology that fold structures are formed by bending.

Nevertheless, the origination of folded structures can be determined by a number of reasons from which the basic ones are stratification and mechanical loading which provide bending without breaking the continuity of a material. Similar structures may form on metallic materials under deformation so that the above given references could be useful for understanding the mechanisms behind folding at different scales. Thin foils and films grown on different substrates often demonstrate a special type of mechanical instability called wrinkling. There are numerous examples of works done in this field devoted to studying the effects of substrate prestressing [5], evolution of wrinkling [6], measuring the strain in coating on the wrinkled substrates [7]. Hirakata et al. [8] investigated the feasibility of creating a wrinkled surface pattern by controlling the morphology of a sacrificial layer. The nanoscale wrinkling was the subject of investigations carried out by Chung et al. [9], and Ahn and Guo [10].

Numerous instances of folded and/or wrinkled structures may be found in severe shear + compression loading conditions that achieved during sliding test and this is not surprising fact that many types of both thermal and mechanical instabilities may be found there. One of the most interesting is the so-called shear instability which allows generating the subsurface layer with nanosized grain-subgrain structure. The plastic flow of such a layer shows flow patterns very similar to those observed in Kelvin-Helmholtz instability [11,12], or in explosion welding [13]. Another type of deformation-induced instability is formation of a lip by plastic flow at the periphery of the sample [14–16].

Surface fold (bulge) formation and fluid-like instabilities during plowing the copper surface by a hard indenter have been explained [17] by the strain inhomogeneity due to flow stress orientation dependence of grains. Later on similar results were independently obtained by Beckmann et al. [18].

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Experimental investigations and modeling of deformation-induced wrinkling and folding on metal materials have been investigated by Gubernatorov et al. [19,20]. It was shown that plastic deformation in rolling may produce wave-like structures even on a structurally homogeneous metal. The corrugation and band structures in the form of shear and deformation bands are formed in the metal. Also some intermediate level transition bands of specific deformation behavior have been found.

Both folding and wrinkling are the flaws obtained in metal forming processes or during mechanical testing as shown by Hamdan et al. [21]. Khoddam et al. [22] showed that wrinkling in a twinning induced plasticity (TWIP) steel under mechanical testing is developed by twinning. In particular, such a phenomenon interferes with fabricating either complex shape or small curvature radius components. It is therefore important to control the wrinkling for production of many high-quality components by plastic metal working.

Folded structures may appear not only in thin films and layered materials. Andreussi and Gurtin [23] reported their formation on the free surfaces of a bulk deformed material under condition that appropriate stress-strain state has been created. The existence of free surface and high density of vacancies and dislocations in the subsurface layer distinguishes the subsurface layer from the bulk metal as well as allows regarding it as a certain type of a deformation structural element. Many researchers point to the fact that the subsurface microplastic strain occurs below the yield stress level. We can assume that deformation in a solid is a hierarchical interaction between the elastically deformed bulk crystal and plastically deformed subsurface layer. The excess strain of the subsurface layer is manifested as corrugation and folding. These processes have their own features distinguishing them from folding in layered structures or wrinkling in thin metal sheets during metal forming. So before studying the specificity of folding in deformed metals it would be useful to establish some classification of folded structures as depended on crystalline orientation, scale and localization.

The pioneering work by Kuhlmann-Wilsdorf and Wilsdorf [24] has been devoted to studying the surface slip line pattern developed on the surfaces of ductile metals after tensile deformation and since then much has been done in this field. In particular, it is clear now that integral characteristics of the strain-induced surface pattern without relating them to the local strain conditions do not allow fundamental understanding the plastic strain inhomogeneity as well as work hardening at each stage of the stress-strain curve. When studying a deformation-induced surface pattern on FCC single crystalline samples it was found out that folded structures are the inherent part of uniaxially compressed $[1\bar{1}\bar{1}]$-oriented single crystals [25,26]. These findings were classified as micro-, meso and macrofolds by Lychagin [27,28]. For a given orientation it was shown that folding was developed preferentially on $(\bar{1}1\bar{2})$-faces. The deformation-induced folds were distributed inhomogeneously over the crystal's face area and tended to group in fold systems and bending bands. Our opinion is that these strain-induced surface pattern features originate from processes similar to folding in the bulk compressible materials. However, a detailed classification of these structural features is necessary along with studying their formation mechanisms.

The study of folding on single crystalline samples is suggested to be worthwhile due to already known exact geometry of the dislocation glide and absence of the grain boundaries. Let us note here that this approach may serve for better understanding of the stress relaxation and accommodation mechanisms in the subsurface of metals subjected to plastic working.

Assuming the above listed considerations, we can state that the objective of this work is to study the folding as a mechanism of deformation manifested on the lateral faces of single crystalline samples as well as to classify the folded structures by the local area conditions.

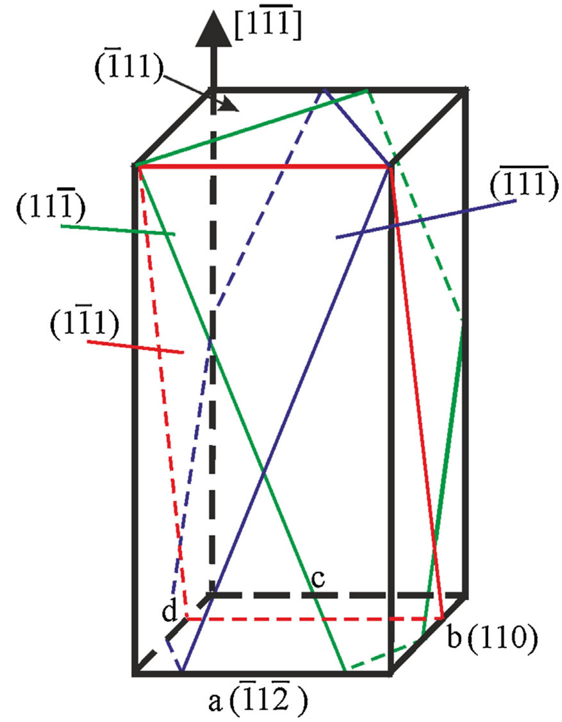

Fig. 1. Orientation of slip planes and directions in $[1\bar{1}\bar{1}]$-single crystal.

2. Materials and experimental methods

Copper is a convenient material for studying the folded structure generation under deformation by slip planes. Possessing a medium level stacking fault energy (40–60 mJ/m^2) and being mechanically loaded at room temperature and medium strain rates, copper single crystal is deformed by slip systems {111} <110>.

Single crystalline samples have been grown according to the Bridgeman method from copper with impurities as follows: 0.3–0.5 wt.% Si, 0.2 wt.% Mg, <0.1 Fe and Al and then electro-discharge machined in the shape of $3.5 \times 3.5 \times 7 \pm 0.1$ mm samples having their compression axis orientations coinciding with $[1\bar{1}\bar{1}]$. The schematics in Fig. 1 shows three equally loaded octahedral slip planes $(1\bar{1}1)$, $(\bar{1}\bar{1}\bar{1})$ and $(11\bar{1})$ marked by different colors in the tetragonal prism sample. Such a presentation helps to identify the slip planes which then form the slip bands on the sample faces a, b, c, and d during compression test.

The single crystals' orientations have been controlled using back scattering patterns to the accuracy ±0.02° obtained from DRON-3 diffractometer. The samples' surfaces have been mechanically and then electrolytically polished in 5% HF/H_3PO_4 solution to a mirror-like finish and then subjected to microstructural observations using scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD) both prior to and after compression tests. Such a sample preparation technique has been used to exclude introducing any subsurface defects. Compression tests have been carried out using Instron ElektroPuls E10000 machine operated at strain rate $3 \times 10^{-4}\,s^{-1}$ at ambient temperatures. To minimize the friction between the sample ends and tensile machine platens, we used graphite lubrication. Shear traces on the single crystal faces were obtained and then examined using optical microscope Leica DM 2500P, SEM instrument Tescan Vega II LMU with an EBSD detector and NewView 7200 interferometer. The deformation-induced