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Subsurface structural evolution and wear lip formation on copper single crystals under unlubricated sliding conditions

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ABSTRACT

The crystalline lattice reorientation in copper single crystals resulted from friction-induced subsurface deformation has been studied by means of electron back scattering diffraction as well as optical microscopy. The results have been compared to those obtained earlier in uniaxial compression. The copper single crystals oriented by their normal load forces either along [110] or $[1\bar{1}\bar{1}]$ have been subjected to sliding tests during which the friction force direction was varied to assess the friction force orientation dependence on the crystalline lattice reorientation and segmentation. The results of dry sliding tests showed that the plastic deformation in copper single crystals depended on the crystal's orientation with respect to both normal and friction forces. Crystalline lattice reorientation in wear lip formation has been studied including reorientation by ridge-kink formations.

1. Introduction

The inhomogeneous character of plastic deformation can be observed already under condition of uniaxial testing schemes such as tensile and compression tests so that some special testing precautions such as for example, channel-die compression test, should be applied to provide the deformation homogeneity. An ideal condition mechanical testing may be achieved only in numerical studies of deformation, for example, when using the molecular dynamics methods. Our previous experimental studies have shown that strain inhomogeneity developed in the form of wrinkling and folding in compression tests on the copper single crystals of different orientations with respect to the compression axis. The deformation inhomogeneity in a compression test is originated from the fact that sample's ends are contacting the tensile machine platens and despite using a lubricant there are quasistatic friction forces directed from the sample's periphery to its center. These forces induce a triaxial stress state [1], local bending (folding) and lip formation [2] during compression tests. Extra loading the sample by sliding friction force adds inhomogeneity to the strain development so that the strain becomes localized mainly below the worn surface.

The subsurface plastic deformation in sliding test on a ductile material is often accompanied by formation of so-called wear lips [3] when the sample edges flow radially outwards and form projections at the sample's periphery. Depending upon the sliding speed and normal load these projections tend to form on the trailing edge of the sample, however, if thermal softening allows, they may form on all edges including the leading edge. The key factor here is the subsurface deformation under the action of normal and shear stresses distributed on the nominal contact area. Xue et al. observed this phenomenon during high-speed rubbing on a heat resistant alloy [4]. The wear (shear) lip formation has been noticed in the course of abrasive erosion on impingement of a high-speed particle into a metal surface [5].

Structural evolution of metals in sliding is a result of deformation and metal softening under frictional heating. It is a well-known fact that the resulting subsurface layer may consist of nanosized dynamically recrystallized grains, which change the subsurface layer deformation mechanism and make it flow in a quasi-viscous manner according to the grain boundary slip mechanism. The wear lip formation may often be the result of such a flow. However, there may be other reasons behind the wear lip formation. In particular, this phenomenon may be considered from the standpoint of macro crystalline lattice reorientation when local bending results in generation of macro folded structures below the worn surface. Extra loading the compressed single crystalline samples by dynamic friction force in sliding test resulted in orientation dependence of wear lip formation revealed in the form of different lip morphologies [6]. However, neither crystalline lattice reorientation nor single crystalline segmentation has been revealed in case of a sliding test to judge on the wear lip formation.

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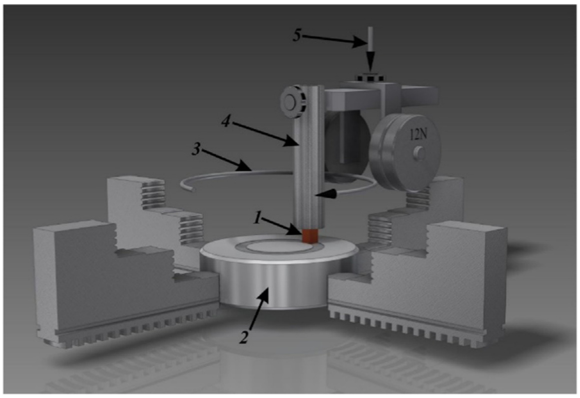

Fig. 1. Schematics of the pin-on-disk tribological test using a TRIBOtechnic tribometer. 1 – sample, 2 – soda-lime glass disk; 3 – rotation; 4 – sample holder; 5 – normal load.

The crystalline lattice reorientation by lip formation has been the subject of investigation [7] and it was shown that sample's orientation with respect to normal loading axis had its effect on it. However, it is clear that single crystal orientation with respect to both normal load and friction forces is very important taking into account the local character of folding and bending observed during wear lip (macrofold) formation. The objective of this paper is to study experimentally inhomogeneous deformation in single crystalline samples loaded by normal and friction forces and compare to the results of MD modeling as well as to assess the effect of a friction force orientation with respect to single crystal's faces on a crystalline lattice reorientation below the worn surface.

2. Materials and methods

The pin-on-disk tribological tests have been conducted on $3 \times 3 \times 6\,\text{mm}^3$ technical grade copper single crystalline samples (stacking fault energy 40–60 mJ/m^2) with their normal load axes oriented along [110] and $[1\bar{1}\bar{1}]$ and rubbed against a soda-lime glass disk using a commercial TRIBOtechnic tribometer (France) (Fig. 1). The sample edges have been rounded in order to provide better contacting conditions with the glass surface. The direction of sliding has been varied for each orientation so that normal/friction force orientations were denoted as $[110]/[1\bar{1}\bar{1}]$, $[110]/[1\bar{1}2]$, $[1\bar{1}\bar{1}]/[110]$, $[1\bar{1}\bar{1}]/[1\bar{1}2]$, $[1\bar{1}\bar{1}]/[1\bar{1}2]$, respectively. The experimental conditions were as follows: normal load 12 N, sliding speed 0.5 m/s, wear path length 200 m, air humidity 70%. Total three samples of each orientation have been electro-polished and then tested in sliding against the glass disk.

TESCAN VEGA II LMU scanning electron microscope with EBSD HKL-detector has been used to study the crystalline lattice reorientation.

Optical microscope LEICADM 2500P has been used to examine the single crystal faces and determine the origination of slip bands. The results of examination were numerous micrographs which then have been integrated into schemes.

3. Results

Sliding-induced surface patterns obtained on single crystal faces in sliding experiments are composed of several structural components such as slip bands, slip band packs and folds (wrinkles). The first part of work will be focused on studying a slip band pattern formed by slip systems on the crystal's faces as dependent on the sample orientation with respect to both compression and friction axes. Then we are going to present the results of studying a crystalline lattice evolution below the worn surface, i.e subsurface reorientation and segmentation. Finally, the crystalline lattice reorientation in wear lip formation will be discussed.

The single crystal lateral faces allow observing two main zones which could be identified (i) as a plastic deformation zone characterized by the presence of slip band structures, and (ii) a wear lip zone (macrofold) which is formed by the sample edge projection. When analyzing the crystalline lattice reorientation below the worn surface (plastic deformation zone) it is necessary to delineate between a subsurface zone characterized by the presence of high-angle boundaries and another zone with only gradient continuous misorientations. These two zones are found completely within the wear lip area.

Tribological tests have been carried out under two different sliding conditions. One part of the samples has been rubbed against an ethyl alcohol cleaned glass disk surface which allowed obtaining steady friction mode. Another part of the samples was rubbed against a copper transfer film on the glass surface formed after testing the first part samples. The latter demonstrated high friction coefficient oscillations provided due to adhesion transfer friction.

The results of tribological tests showed that coefficient of friction did not depend on the single crystal orientation irrespective of the sliding test mode (Fig. 2). The maximum coefficient of friction for

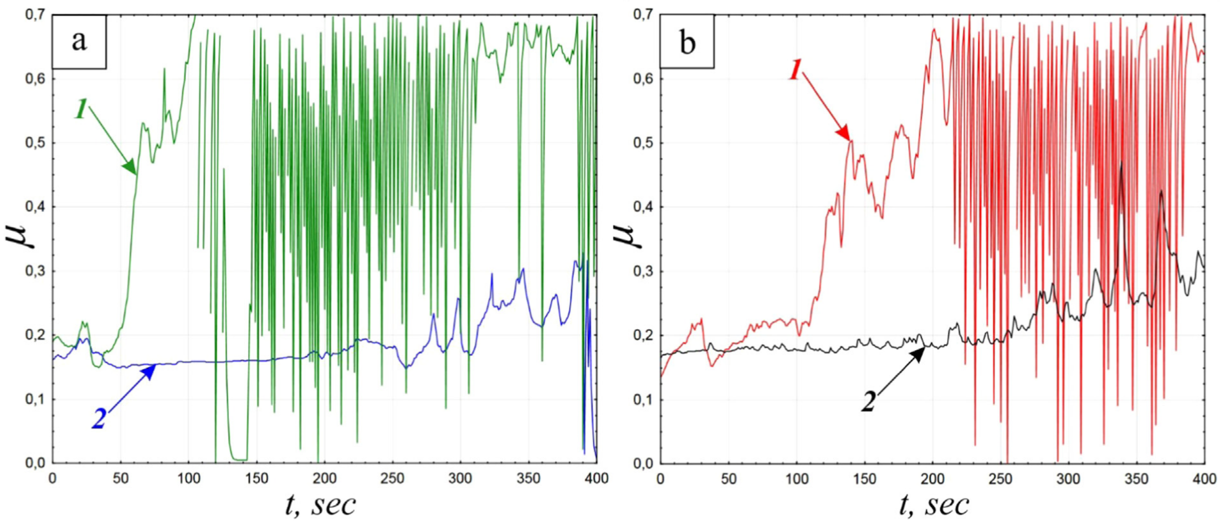

Fig. 2. The coefficient of friction vs. time dependencies for [110] (a) and $[1\bar{1}\bar{1}]$ (b) -single crystals. 1 – adhesion transfer friction; 2 – steady friction on a clean glass surface.