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Strain path change effect on dislocation microstructure of multicrystalline copper sheets

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Abstract

In this study, coarse-grained copper sheets were subjected to tension–rolling and rolling–tension strain path sequences. In both cases, two different types of strain path change were studied: the tensile and rolling directions were parallel and normal to each other. TEM observations of deformed samples showed the typical dislocation structures for the prestraining paths in tension and rolling. Special microband features, not observed during prestrain, were found during the second strain path, whatever the sequence and type of strain path change. The microstructure observed during reloading is discussed in terms of the sequence and type of strain path change, parallel or normal. The frequency of appearance of microbands is discussed in terms of the activity of new slip systems, i.e. not active during the prestrain path and connected with the number of the active slip systems after reloading. The results from this study, obtained for coarse-grained multicrystalline copper sheets, are compared with previous ones for fine and medium-grained copper.

Keywords: Metals; Mechanical testing; Electron microscopy; Microstructure

1. Introduction

Microstructure evolution in fine or medium-grained copper subjected to plastic deformation has been substantially investigated during recent years [1–7]. It was found that microstructure evolution leads to the formation of low-energy dislocation structures. Investigation into the dislocation structures formed during tensile straining of copper (grain size 20 and 250 μm) revealed three types of dislocation microstructures depending on the grain orientation [2,7]: (i) one set of dislocation walls parallel to the main active slip plane; (ii) two sets of extended dislocation straight walls parallel to the two main active slip planes; (iii) equiaxed cell structure, when three or more slip systems have similar activity. It has been shown that the structural morphology of the dislocation walls is similar in the fine and medium grains.

The majority of the performed studies concern monotonous strain path, although strain path change, which frequently arises during sheet metal forming, can significantly influence the microstructural evolution of the material. For this reason, a combination of several simple loading test sequences is an effective way to investigate the dislocation microstructure of sheet metals under such real forming conditions. Several studies connected with dislocation evolution during complex strain paths deal with sequences of two uniaxial tension tests or orthogonal rolling–tension [1–4,7,8]. The influence of the dislocation microstructure developed during the first strain path on the behaviour after reloading in the second path, was understood in terms of the interaction between the mobile dislocations in the new active slip systems and the dislocation microstructure previously formed during prestraining. In these studies, special microband features caused by intense glide on one slip plane were observed after strain path change, at relatively low deformation values. These microbands correspond to regions of the crystal with a misoriented crystal lattice, and have one dimension, which is smaller than the two others. They have also been observed at large strain values during monotonic plastic deformation, in a wide range of metallic materials [3,4,6,9,10]. These microbands can play an important role in the deformation process because of their ability to accumulate large shear strains. In the case of strain path change, these special microband features were detected at lower strain values than in simple rolled copper and the appearance of such microbands depends on the grain size and, consequently,

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depends on the strain accommodation processes between grains [3,7]. From this point of view, the investigation of the appearance and development of special microband features in coarse-grained copper samples is worthy of interest.

This study is devoted to the investigation of the microstructural evolution of coarse-grained multicrystal copper sheets during complex strain paths. These multicrystalline samples are only a few-grain thick. The use of multicrystalline materials to study plastic deformation mechanisms gives a better understanding of the plastic deformation behaviour of polycrystals. This is because of the absence of constraint in the direction perpendicular to the sample surface, and therefore the strain accommodation processes between grains are insignificant, which clarifies the analysis. In this study the microstructure evolution of multicrystalline copper sheets was investigated for tension–rolling and rolling–tension sequences, the second path of each sequence being such that the tensile and the rolling directions are parallel and normal to each other.

2. Experimental procedures

The material used was oxygen free high purity copper (DHP) with a purity of 99.95%. The samples were cut from a cold-rolled and annealed sheet, 1 mm thick and with an average grain size of 20 μm, and then were annealed for 20 h at $T = 925\,^{\circ}C$ in a 10^{-5} mbar vacuum in order to obtain a structure with a mean grain size in the sheet surface of about 1.5 mm, and showing between 1 and 3 grains in thickness. The samples obtained were deformed by means of four types of complex strain paths, using the sequences: tension–rolling and rolling–tension. Two different types of strain path change were studied for both sequences: the tensile and rolling directions were parallel and normal to each other, in the sheet plane. Specimens for the tension–rolling sequence were prestrained in tension up to moderate strain values (lower than 25%) and then were rolled parallel and normal to the previous tensile direction, up to strain amounts lower than 20%. For the rolling–tension sequence, the prestrained specimens measured 100 mm × 100 mm and the tensile samples had a gauge size of 60 mm × 10 mm. The samples for the rolling–tension sequence were deformed up to 5% of tensile deformation (necking occurs at this deformation value) after prestraining in rolling up to 20%. All tensile tests were performed at an initial strain rate of $10^{-4}\,s^{-1}$.

Observation of microstructure after deformation was carried out using both optical and transmission electron microscopy. The observation plane was the sheet plane, for both cases. Slip lines were observed in the tensile samples after 10% of deformation by the interferential contrast technique in the optical microscope. At first, the samples for optical observation was deformed up to 5% and then polished and deformed again up to 10% in simple tension. These samples were polished using a solution containing 250 ml orthophosphoric acid, 250 ml ethanol, 500 ml distilled water and 3 g urea and using a current density of 60 A dm^{-2}. The dislocation microstructure was studied by TEM. Samples for TEM were polished mechanically from both sides down to a thickness of about 0.15 mm and then electropolished using a double jet thinner. A dilute solution of orthophosphoric acid (2:1) at room temperature under 10 V tension was used. TEM analysis was carried out at 100 kV.

3. Results and discussion

Analyses of deformation microstructure formed in the samples were carried out on two scales: surface characterization of slip lines, by optical microscopy and dislocation microstructure, by TEM. Also the mechanical behaviour in tension parallel and normal to previous rolling was studied for comparison.

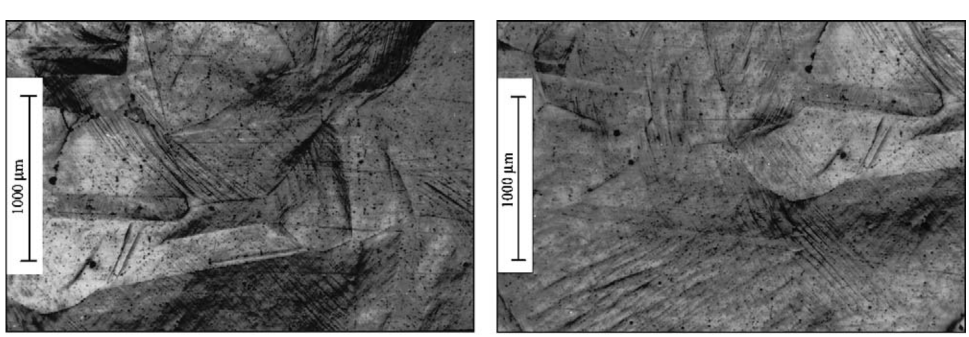
3.1. Slip lines analyses

Slip line observations were performed on the sheet plane in order to reveal the development of active slip systems during monotonic tension testing. Fig. 1 shows two examples of surface slip trace observations on the copper multicrystalline sample. Most grains present one family of parallel slip lines. In some cases, the slip lines are aligned along two main directions in the same grain. This can occur, for example, when structural twins are present: the slip line families, situated along different main directions, are separated by the twin boundary.

In conclusion, optical observations of slip line show, for copper multicrystalline sheets with coarse grain size strained in tension up to 10% of deformation, dislocation gliding mainly on one active slip system, whatever the region of the grain, which is similar with results obtained for large grain size copper polycrystals (250 μm) [2]. These results allow us to confirm on a larger scale (several grains) TEM observations of the dislocation microstructure discussed in the next paragraph. Indeed, such observations are restricted to limited regions inside each grain, taking into account the relatively large size of the grains.

3.2. Dislocation microstructure

Firstly, the dislocation microstructures developed during prestraining paths, simple tension and simple rolling, were analyzed. Depending on the grain orientation, two main types of microstructure were found in the samples prestrained in pure tension up to 25% of deformation: (i) an unorganized



(a) (b)

Fig. 1. Examples of slip line observations in the copper multicrystalline sheet, after 10% of deformation in pure tension (tensile direction: horizontal).