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THE EFFECT OF CRYSTALLOGRAPHIC TEXTURE FORMATION ON THE FEATURES OF MICROSTRUCTURE EVOLUTION IN TENSILE-STRAINED COPPER

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Abstract. The microstructural evolution of a commercially pure copper specimen deformed by uniaxial tension has been studied using electron backscatter diffraction (EBSD). In the specimen deformed up to fracture, some areas (in the neck) corresponding to various strain degrees were examined. This allowed us to study the microstructure obtained for strain degrees in the range from 0,45 to 1,15 on the single sample. A texture consisting of two components with prevailing orientations of [100] and [111] directions, parallel to the tensile axis, formed concurrently with the deformation microstructure. The grains of the [111] component were shown to retain rather uniform orientation at strain degrees of about 1. At the same time, the grains of the [100] component subdivided gradually into highly disoriented fragments. The obtained results were discussed in terms of polycrystalline material micromechanics.

Keywords: plastic deformation, polycrystal, copper, microstructure, texture, fragmentation, EBSD analysis

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ОСОБЕННОСТИ ЭВОЛЮЦИИ ФРАГМЕНТИРОВАННОЙ МИКРОСТРУКТУРЫ МЕДИ ПРИ РАСТЯЖЕНИИ, ОБУСЛОВЛЕННЫЕ ФОРМИРОВАНИЕМ КРИСТАЛЛОГРАФИЧЕСКОЙ ТЕКСТУРЫ

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Аннотация. Методом дифракции обратнорассеянных электронов (ДОРЭ) изучали эволюцию микроструктуры технически чистой меди в процессе одноосного растяжения. В образце, деформированном до разрушения, в области шейки исследовали участки, соответствующие различным степеням деформации. Это позволило на одном образце изучить микроструктуру при деформациях в интервале от 0,45 до 1,15. Одновременно с деформационной микроструктурой в меди создается текстура, состоящая из двух компонент с преимущественными ориентировками направлений [100] и [111] параллельно оси растяжения. Показано, что зерна, относящиеся к компоненте [111], сохраняют относительно однородную ориентацию при деформациях около 1. В то же время, зерна, относящиеся к компоненте [100], постепенно разбиваются на сильно разориентированные фрагменты. Полученные результаты обсуждаются с точки зрения микромеханики поликристаллического материала.

Ключевые слова: пластическая деформация, поликристалл, медь, микроструктура, текстура, фрагментация, ДОРЭ анализ

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Introduction

Plastic deformation in metals triggers a microstructural evolution of the material. The most important trend in this evolution is gradual subdivision of the initial grains into misoriented micro-regions called fragments. This transformation is accompanied by a general increase in dislocation density, with a cellular dislocation substructure forming [1–3]. This phenomenon, called fragmentation [1], has been the focus of much attention in the last two decades, as novel ultra-fine grained metal materials with a unique combination of physical and mechanical properties can be produced by refining the grains [3]. On the other hand, the initial stages of fragmentation are still insufficiently understood, and many questions remain concerning both the physical mechanism of fragmentation and the dependence of structural parameters on the nature of the material and deformation conditions [3, 4].

One of the most pressing issues is the nature of the relationship between fragmentation and crystallographic texture, i.e., the orientational distribution of crystallites (grains, fragments) [5–9]. Earlier studies established that the orientation of the grain significantly affects the parameters of the deformation structure in copper under tensile strain [10, 11]. However, these studies only considered the influence of the initial grain orientation on the morphology of the dislocation structure, while the misorientations between the elements of this structure were not analyzed quantitatively. Moreover, the strain degrees detected by the authors did not exceed 0.28 [10].

In view of this situation, it is of considerable interest to analyze the orientation dependence of structural evolution at higher degrees of plastic strain, that is, during the fragmentation stage. In particular, this should allow to construct adequate mathematical models of strain hardening in polycrystals [4, 6, 11].

The goal of this study was to examine the orientation dependence of microstructural evolution and its relationship with microtexture[1] for the case of polycrystalline copper under tensile strain.

Material and methods

The specimen for the study was cut from a bar of technically pure copper M1. The specimen was pre-annealed before deformation at 700 °C for two hours to dissolve the fine precipitates of the second phase found at the grain boundaries in the as-received material. Fig. 1 shows the resulting recrystallized structure containing numerous annealing twins (the total length of the twin boundaries is approximately 65% of the total length of the grain boundaries). The specimen tested was a smooth cylinder with a length of 35 mm and an effective diameter of 5 mm. The tensile rate was 1 mm/s, which is equivalent to a deformation rate of about $3 \cdot 10^{-2}$ s^{-1}. The elongation at break was approximately 58%, and the relative narrowing in the specimen neck was 87%.

One of the halves of the fractured specimen was cut along the tensile direction to analyze the deformation microstructure in the neck (in the longitudinal section) by electron backscatter diffraction (EBSD). The true strain ε found from the magnitude of the local contraction of the specimen, was equal to 0.45, 0.70, 1.00 and 1.15 in the sites considered. The EBSD analysis was performed with a LYRA 3 XMN RL scanning electron microscope and an Oxford HKL AZtec™ system. The initial microstructure was analyzed by scanning with a step of 350 nm, and the deformation microstructure by scanning with a step of 250 nm for the case ε = 0.45 and with a step of 200 μm in other cases. The sites considered were 700×700 μm for the initial microstructure and 300×300 μm for the deformation microstructures. The experimental data obtained were processed in MTECH, an open-source toolbox from the MATLAB package [12]. The pixel colors in the orientation maps shown in the insets to Figs. 1 and 2 correspond to the local orientation of the tensile direction (TD*)*. These maps also show the boundaries with misorientations for the angles θ exceeding 2°.

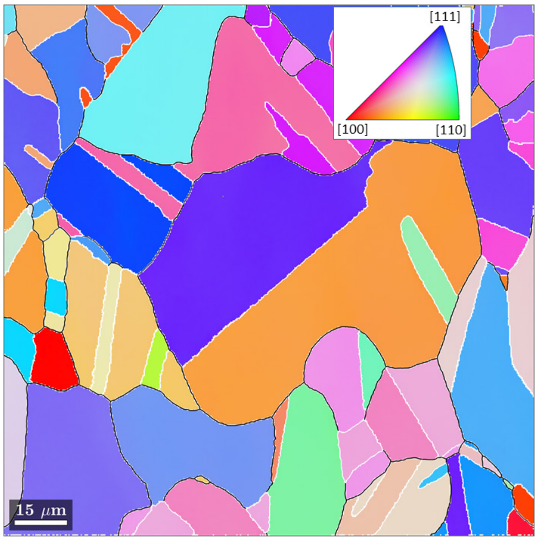

Fig. 1. Example of an orientation map for a site of the initial microstructure in the copper specimen (color coding is shown in the stereographic triangle). Arbitrary grain boundaries are colored in black, twin boundaries are colored in white

Experimental results and discussion

Fig. 2, *a*, *b* shows the orientation maps for typical sites in the microstructure of the deformed specimen for ε = 0.45 and 1.15, and Fig. 2, *c*, *d* shows the microtextures corresponding to these deformations, namely, the orientation distribution of tensile direction in stereographic projection.

[1] Microtexture is defined as the crystallographic texture observed on a microscale, i.e., on the scale of individual grains or groups of grains.

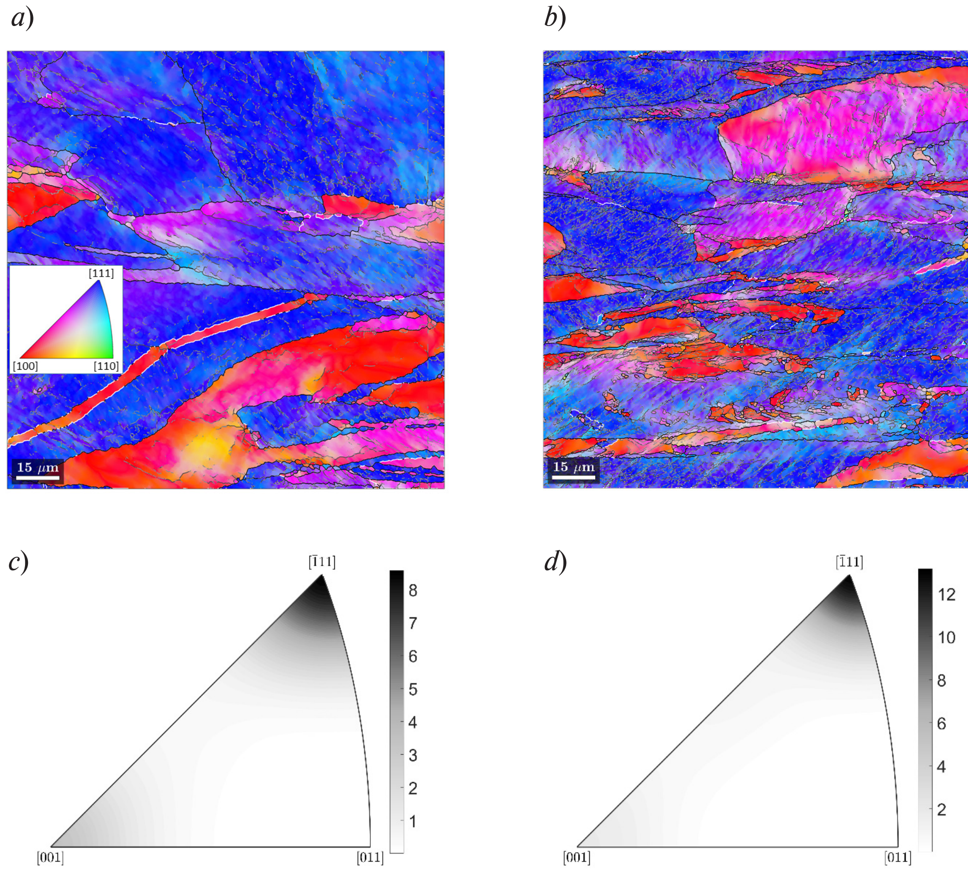

Fig. 2. Orientation maps of microstructure sites (*a*, *b*) and microtextures in these sites (*c*, *d*) corresponding to strains of 0.45 (*a*, *c*) and 1.15 (*b, d*). Arbitrary large-angle and twin boundaries are colored the same as in Fig. 1; small-angle borders are colored in gray (Fig. 2, *a*, *b*). Inverse pole figures are given for the TD (Fig. 2, *c*, *d*)

Pronounced modifications are observed in the grain structure at $\varepsilon = 0.45$ (see Fig. 2, *a*) compared to the initial state. Firstly, the misorientation of the initial grain boundaries changed; this can be assumed from the boundaries of the annealing twins, since their initial misorientation is known. The boundaries close to the twin according to Brandon's criterion (the deviation of their misorientation from the twin does not exceed the $\Delta\theta_c = 15°/\sqrt{3} = 8.66°$) are colored in white in Fig. 2, *a*, *b*. Evidently, this deviation exceeded the given value in multiple sites. Secondly, an intragranular deformation substructure appeared, in particular, numerous dislocation boundaries were formed. While these are primarily small-angle boundaries, several fragments with large-angle ($\theta > 15°$) boundaries induced by deformation are found near the initial grain boundaries. As seen from Fig. 2,*c*, a crystallographic texture appears even with this relatively small deformation: all orientations are concentrated near the side [100]–[111] of the stereographic triangle with pole density maxima near the vertices [111] and [100].

Fragmentation intensified considerably at $\varepsilon = 1.15$ (see Fig. 2,*b*), even though the texture became only slightly sharper: the maximum pole density increased by about 1.5 times (see Fig. 2,*d*). The evolution that fragmented microstructure undergoes with increasing strain degree can be quantitatively described by the distribution of misorientations at the boundaries of fragments, in terms of unit length of the boundaries $l_{DIB}(\theta)$. The quantity $l_{DIB}(\theta)$ is defined here as the total length of the boundaries with misorientations in the interval $(\theta, \theta + 1°)$. Linear graphs were constructed from the original histograms with a step of 1° so that several distributions could be conveniently presented in a single diagram (Fig. 3).

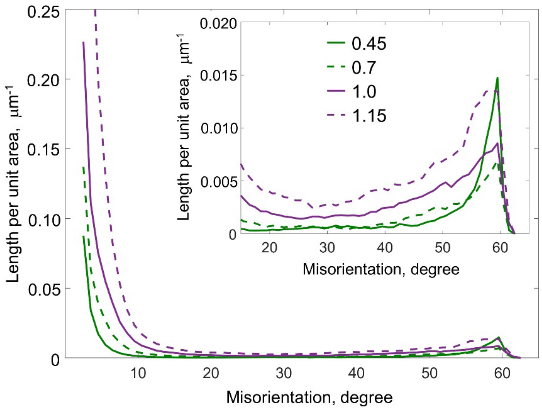

Fig. 3. Distributions of misorientations in terms of unit length of the boundaries at different strain degrees of the specimen (the values are shown in the inset)

It can be seen from Fig. 3 that the unit length of small-angle boundaries ($\theta < 5°$) is almost two orders of magnitude greater than that of the large-angle ones in the strain range considered. Nevertheless, the length of large-angle boundaries also increases continuously in the given strain range. This indicates that large-angle boundaries gradually evolve due to deformation, accompanied by grain refinement as a result of fragmentation.

At the same time, the orientation maps (see Fig. 2, *a*, *b*) indicate that the microstructure evolving is nonuniform over the volume, and the structural characteristics depend on the orientation of the site.

Let us consider the most noteworthy of these characteristics. For brevity, we refer to the grains/fragments with orientations near the vertex [100] of the stereographic triangle as [100]-grains, and grains/fragments with orientations near the vertex[111] as [111]-grains. According to the data in [11], there are almost no cell block boundaries (i.e., extended dislocation boundaries with misorientation of about 1–2° or more) in [100]-grains at $\varepsilon < 0.3$, and a low misorientation level (less than 1°) is observed between the cells. In contrast, there are two systems of intersecting cell block boundaries are always present in [111]-grains. As seen from Fig. 2,*a*, showing only the boundaries with misorientations over 2°, these features of the deformation substructure are preserved at $\varepsilon = 0.45$. Indeed, a weakly misoriented substructure is virtually absent in [100]-grains, and extended dislocation boundaries are relatively rare, primarily observed in the regions where the orientation considerably deviates from [100]‖ TD. On the contrary, numerous sites of multidirectional boundaries with misorientations over 2° are found in [111]-grains. At the same time, the behavior observed in earlier studies can be also seen in Fig. 2,*a*: [111]-grains mostly preserve a uniform orientation, while the orientation of [100]-grains turns out to be quite substantially nonuniform, even with individual fragments appearing.

The trend appearing at $\varepsilon = 0.45$ persists upon further deformation: as can be seen from Fig. 2,*b*, regions with orientations close to [100]‖ TD turn out to be significantly more fragmented at $\varepsilon = 1.15$ than regions corresponding to the second textural component. We quantified the orientation dependence of fragmentation by dividing the grains[2] into three groups depending on their size. Fig. 4 shows the distribution of orientations for each of these groups separately. Evidently, most of the small grains (less than 5 μm in size) have orientations close to the vertex [100] of the stereographic triangle. The maximum pole density in the group of grains with intermediate sizes (from 5 to 25 μm) is shifted towards the vertex [111], but the contributions of [111]- and [100]-grains remain comparable. The orientations of the largest grains (>25 μm) are concentrated near the pole [111]. Thus, [111]-grains are indeed much less prone to fragmentation than [100]-grains.

[2] In this case, grains are understood as the regions (the initial grains or their deformation-induced fragments) whose misorientation relative to the environment exceeds 15°.

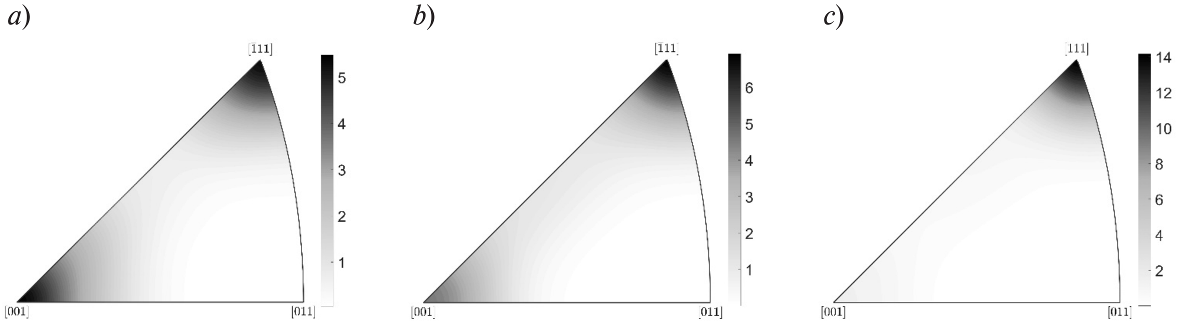

Fig. 4. Partial microtextures for 'grains' with sizes < 5 μm (*a*), from 5 to 25 μm (*b*) and > 25 μm (*c*) for a strain of 1.15. Inverse pole figures for TD are shown

Interpretation of results

The theory is that fragmentation of polycrystals is caused by plastic interaction between grains during deformation [1, 13–15]. The difference in the deformation rate of differently oriented grains produces mesoscale defects at their boundaries, which act as sources of internal stresses, stimulating in turn the heterogeneity of intragranular shifts and rotations of the crystal lattice. The fundamental characteristic determining the dependence of the grain's plastic properties on its orientation is the Taylor factor (equal in our case to the ratio of the total shear increment in active slip systems, calculated by the Taylor model), to the increment of tensile strain in the specimen [4]. The smaller the value of the Taylor factor, the easier the grain is deformed, the less dislocations it accumulates, and, accordingly, the lower is deformation hardening. For this reason, orientations with a relatively small Taylor factor are called 'soft', and those with a large Taylor factor are called 'hard'.

The Taylor factor is 2.65 for uniaxial deformation of metals with a face-centered cubic crystal lattice, and 3.67 for orientations [100] and [111] ‖ TD, respectively [11]. Thus, after a two-component texture evolves, the material consists of soft [100]-grains and hard [111]-grains. This produces a kind of composite whose 'soft' component is made up of crystallites with orientations close to [100] ‖ TD. Apparently, it is the soft, [100]-grains that tend to reorient towards the hard ones in these conditions, in particular, due to the nonuniform rotation of the crystal lattice and fragmentation, which is in agreement with our findings.

Conclusion

Our findings indicate that the microstructural evolution in copper subjected to uniaxial tensile strain depends on the orientation of the grain in which this microstructure evolves. A two-component crystallographic texture [100] + [111] starts to evolve within the specimen at an early stage of deformation. Many grains belonging to the component[111] component retain a relatively uniform orientation upon further deformation. In contrast, grains belonging to the [100] component are subdivided into highly misoriented fragments. The orientation dependence of fragmentation is likely determined by the presence of a two-component texture producing some kind of composite material where the [100] component is ductile.

Mathematical models constructed for strain hardening in metals with a face-centered cubic crystal lattice and alloys under axisymmetric plastic strain should account for this nonuniform structure.

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