DOI 10.1007/s11182-021-02447-7
Russian Physics Journal, Vol. 64, No. 7, November, 2021 (Russian Original No. 7, July, 2021)

EVOLUTION OF MICROSTRUCTURE AND ITS PARAMETERS AFTER DEFORMATION OF POLYCRYSTALLINE Cu-Al ALLOYS WITH DIFFERENT STACKING FAULT ENERGY

N. A. Koneva,[1] L. I. Trishkina,[1] T. V. Cherkasova,[1,2] A. N. Solov'ev,[1] and N. V. Cherkasov[1]

UDC 669.35:539.214

Transmission electron microscopy (TEM) is used to investigate the evolution of the dislocation substructure after active plastic deformation of copper-aluminum alloys with the aluminum content varying between 0.5–14 at.%. Using TEM images, the types of the dislocation substructure are determined depending on the alloying element concentration and the strain intensity. The parameters of the defect structure, such as average scalar dislocation density, bending and torsion of the crystal lattice, and microtwin density are measured. It is found that the stacking fault energy exerts an effect on the defect accumulation.

Keywords: metals, alloys, strain, grain size, bending and torsion, crystal lattice, stacking fault energy, structural defects.

INTRODUCTION

The defect formation and accumulation occur in metallic materials during their plastic strain. Such defects include dislocations, microtwins, cells, microbands, subboundaries, bending and torsion of the crystal lattice. The defect accumulation depends on several factors such as the intensity of plastic strain, strain rate, strain temperature, grain size of the polycrystal, and stacking fault energy. This parameter affects the defect accumulation in materials, the substructure formation, and mechanical properties of materials. Substructural strengthening is an important mechanism of strengthening of metals and alloys [1–3]. The influence of the stacking fault energy on the defect accumulation in polycrystals remains still unstudied, and an integrated overview of this phenomenon is thus impossible.

Dini *et al*. [4], for example, reported that at a constant strain intensity, the dislocation density ρ increased with decreasing stacking fault energy in pure Cu, Al and Ni metals and the TWIP (twinning-induced plasticity) steel. Those data on the dislocation density were, however, obtained by using nonstructural techniques. Zhao *et al*. [5], studied pure copper and zinc-containing alloys, namely: Cu 10 wt.% Zn and Cu 30 wt.% Zn, in which the stacking fault energy equaled 41, 22 and 7 mJ/m^2, respectively. An ultra-fine grain state was achieved in these alloys through the torsion of the crystal lattice induced by a hydrostatic pressure. The alloy specimens were then subjected to tensile deformation at room temperature. The dislocation density was measured by the X-ray diffraction technique, which showed that after both a hydrostatic pressure-driven torsion and tension, the dislocation density depended on the stacking fault energy. It increased with lower stacking fault energy. Steffens *et al*. [6] investigated the dislocation density in pure copper and four Cu–Al alloys with the Al content of 0.2, 2, 4 and 6 wt.%, depending on the stacking fault energy at the grain size of 50 μm and impact load conditions. It was found that the influence of the stacking fault energy on the defect accumulation depended on the impact load. Interesting results were obtained by Yuan *et al*. [7] after the modeling of

[1]Tomsk State University of Architecture and Building, Tomsk, Russia, e-mail: trishkina.53@mail.ru; tsk_san@mail.ru; cherkasov_2000@outlook.com; [2]National Research Tomsk State University, Tomsk, Russia, e-mail: cherkasova_tv@mail.ru. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika, No. 7, pp. 43–47, July, 2021. Original article submitted February 15, 2021.

ultra-fine grain copper. They studied the grain size, temperature and other parameters that affected its strengthening properties. It was shown that the stacking fault energy affected the deformation behavior of copper, i.e., strain hardening decreased with decreasing stacking fault energy. It should be noted that this effect depended on the shape of micrograins. This issue requires further investigation, since the literature in the field does not allow us to draw a final conclusion about the influence of the stacking fault energy on the defect accumulation during the deformation process of metals and alloys.

One of the main problems of using these alloys in practice, is the modeling of their optimum physical-and-mechanical properties. To solve this problem, it is necessary to investigate the changes of the dislocation substructure depending on the concentration of the alloying element and the deformation process. The alloys of the Cu–Al system are rather suitable in this case. The increase in the Al content in the Cu–Al alloys decreases the stacking fault energy [8–10]. This provides the formation of various dislocation structures and mechanical properties of the Cu–Al alloys.

The aim of this work is to study the influence of the stacking fault energy, strain intensity, and grain size on the defect accumulation and other parameters of substructures of polycrystalline alloys of the Cu–Al system.

MATERIALS AND METHODS

The copper-aluminum alloy was used to investigate the dislocation substructure. The concentration of the aluminum alloying element was varied between 0.5 and 14 at.%. The average grain size of the Cu–Al alloys was 20, 40, 60, 120 and 240 μm. The alloy plates with a 100×12×2 mm working area underwent tensile tests on an Instron testing machine at room temperature and $2 \cdot 10^{-2}$ s^{-1} strain rate. The dislocation structure was studied by using the transmission electron microscopy (TEM) at 30000× magnification and strain intensity ranging between 0.02–0.90. The dislocation structure was analyzed using electron microscopes equipped with goniometer, at a 125 kV acceleration voltage. The density of dislocations and microtwins as well as the bending and torsion of the crystal lattice were measured by using the TEM images. The bending and torsion χ of the crystal lattice is a local gradient of the crystal misorientation, *viz*. $\chi = d\varphi/dl$. The methods used in this work to determine the parameters of the dislocation substructure were described in [11].

RESULTS AND DISCUSSION

The content of the alloying element in Cu–Al alloys affects the stacking fault energy and the development of the dislocation structure. Figure 1 presents the types of nonmisoriented substructures observed in these alloys after deformation with the intensity ranging from 0.05 to 0.10, at the reduced stacking fault energy. In the copper alloys with 5 at.% Al and stacking fault energy of $\sim 4 \cdot 10^4$ J/m^2, the evolution of the dislocation substructure occurs in the following order at the 0.5 strain intensity: chaotic distribution of dislocations, dislocation pileups and cells, as shown in Fig. 1*a*, *b*, *c*. The increase in the Al content up to 14 at.% results in the formation of another chain of the dislocation substructure, which includes the dislocation agglomerates, long linear dislocations, dislocation coalescences and networks (see Fig. 1*d*, *e*, *f*).

The growth in the strain intensity is accompanied by the formation of misoriented substructures. At higher strain intensities ranging between 0.20–0.90 and aluminum concentration up to 14 at.%, the formation of misoriented dislocation substructures is observed, namely: cells, microbands, cells and networks, and microtwins. At 0.10 strain intensity, only one microtwin system is observed, while at 0.30–90 strain intensity, several microtwin systems appear. The density growth of dislocations, microbands, and microtwins enables the formation of misorientation in the material, which are characterized by the bend extinction contours observed on the TEM images, that appear in the alloys at higher strain intensities. In Fig. 2, one can see the types of the dislocation substructures formed after higher strain intensities, with the grain size of 120 μm. It should be noted that these microstructures appear with the grain sizes at issue both at low and high strain intensities. The formation of bend extinction contours at higher strain intensities indicates to the bending and torsion of the crystal lattice.

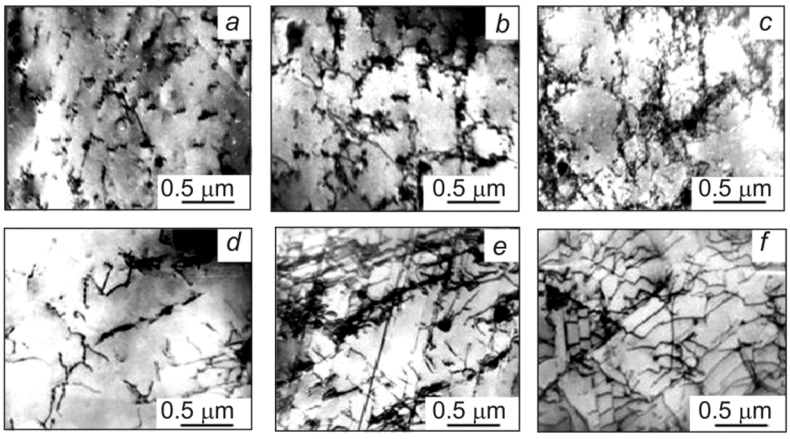

Fig. 1. TEM images of nonmisoriented substructures in Cu–Al alloys after 0.05–0.10 strain intensity: *a* – chaotic, *b* – pileups, *c* – cells, *d* – pileups, *e* – long linear and coalescences, *f* – uniform network. Alloys: *a–c* – Cu 0.5 at.% Al and Cu 5 at.% Al, *d–f* – Cu 10 at.% Al and Cu 14 at.% Al. Grain size: 120 μm.

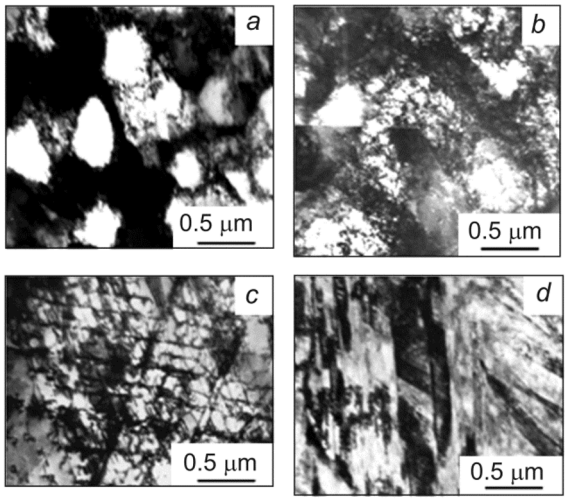

Fig. 2. TEM images of misoriented substructures in Cu 10 at.% Al and Cu 14 at.% Al alloys after 0.30–0.90 strain intensity: *a* – cells, *b* – microbands, *c* – cells and network, *d* – two and mode microtwin systems.

The average scalar dislocation density was measured for the alloys with the different stacking fault energy, grain size, and strain intensity. The dependences between the average scalar dislocation density $\langle\rho\rangle$ and stacking fault energy γ are presented in Fig. 3 for all the studied grain sizes and two values of the strain intensity, namely 0.05 and 0.40. As shown in this figure, the dislocation density reduces with increasing stacking fault energy. The grain size has an effect on the microtwin density. The dislocation density increases with lowering grain size.

With increasing concentration of the alloying element and, consequently, decreasing stacking fault energy, the microtwin formation occurs in the material (see Fig. 2*d*). Figure 4 shows the dependences between the microtwin

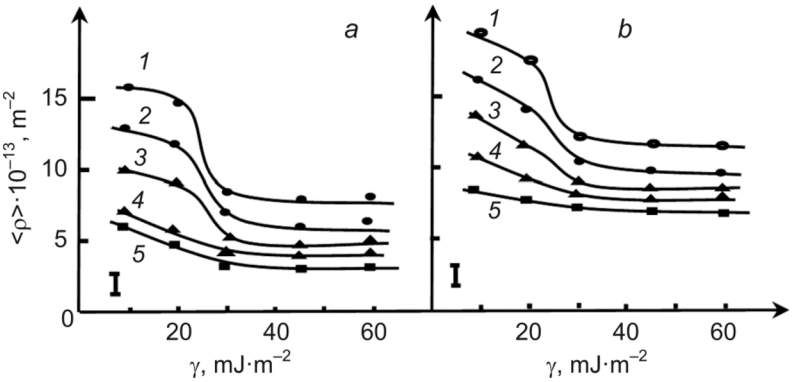

Fig. 3. Dependences between scalar dislocation density <ρ> and stacking fault energy γ at different grain sizes: *1* – 10, *2* – 40 μm, *3* – 60 μm, *4* – 120 μm, *5* – 240 μm. Strain intensity: *a* – 0.05, *b* – 0.40.

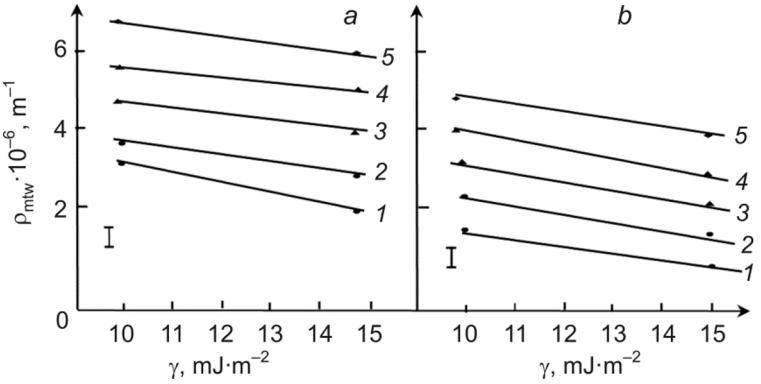

Fig. 4. Dependences between microtwin density ρ_{mtw} and stacking fault energy γ at different strain intensities: *1* – 0.10, *2* – 0.20, *3* – 0.30, *4* – 0.40, *5* – 0.50. Grain size: *a* – 10 μm, *b* – 240 μm.

density and stacking fault energy for the grain size of 10 and 240 μm. According to Fig. 4, the microtwin density grows with increasing stacking fault energy at all the strain intensities at issue. The microtwin density in alloy with 10 μm grain size is higher, than that in the alloy with 240 μm grain size.

As we mentioned above, the formation of bend extinction contours indicates to the formation of the lattice bending and torsion after the deformation of the copper-aluminum polycrystals. In Fig. 5, we present the dependences between the lattice bending and torsion and stacking fault energy. The analysis of these dependences shows that the maximum bending and torsion of the lattice occur in the alloys with the low stacking fault energy.

The dependences of the average scalar dislocation density on the grain size are presented in Fig. 6. One can see that the scalar dislocation density drastically lowers with decreasing grain size to 100–120 μm, and then changes insignificantly at 120–240 μm grain size. We assume that the grain boundaries have no serious effect on the defect accumulation in these polycrystals at the grain size of ≥100 μm. The dislocation density is higher in the alloys with the low stacking fault energy.

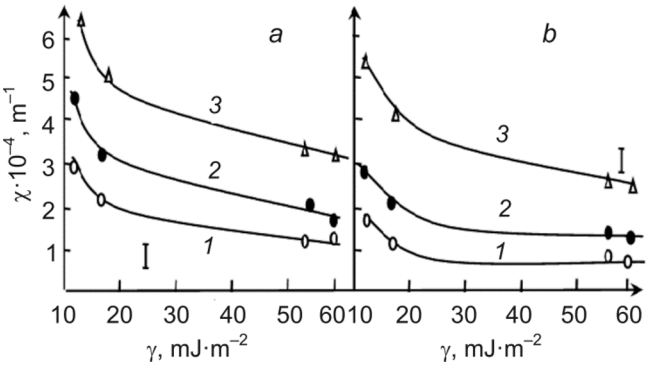

Fig. 5. Dependences between the lattice bending and torsion χ and stacking fault energy γ at different strain intensities: *1* – 0.10, *2* – 0.40, *3* – 0.60. Grain size: *a* – 10 μm, *b* – 240 μm.

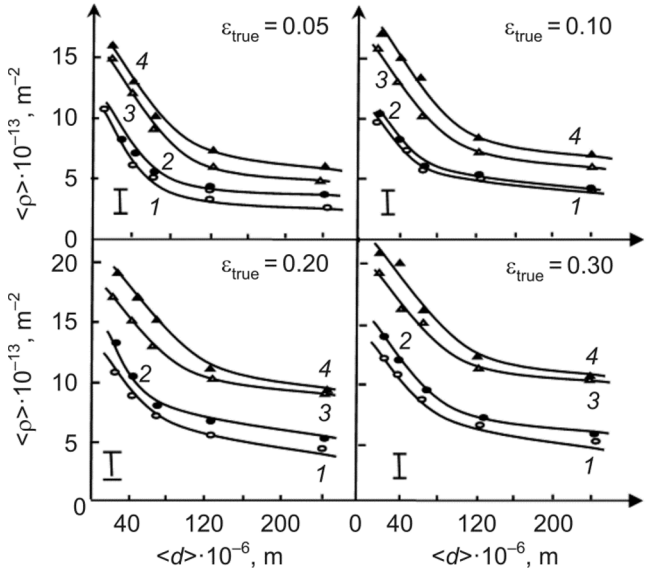

Fig. 6. Dependences of average scalar dislocation density <ρ> on grain size <*d*> at different values of strain intensity: *1* – Cu 0.5 at.% Al, *2* – Cu 5 at.% Al, *3* – Cu 10 at.% Al, *4* – Cu 14 at.% Al.

CONCLUSIONS

Using TEM observations, the evolution of the dislocation substructure was investigated in the copper-aluminum alloys with changes in the stacking fault energy and strain intensity. It was found that the stacking fault energy affected the parameters of the defect substructure. The decrease in the stacking fault energy led to the increase in the average scalar dislocation density. The microtwin density reduced with increasing stacking fault energy. The higher strain intensity resulted in bending and torsion of the crystal lattice that lowered with increasing stacking fault energy. The increase in the grain size reduced the dislocation density in all the alloys at issue.

This work was supported by the government contract N FEMN-2020-0004 from the Ministry of Science and Higher Education of the Russian Federation.

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