

Effect of the stacking fault energy on the mechanical properties of pure Cu and Cu-Al alloys subjected to severe plastic deformation

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Abstract. The effect of stacking fault energy (SFE) on the mechanical properties of pure Cu and alloys of Cu-2.2%Al and Cu-4.5%Al subjected to severe plastic deformation (SPD) was investigated. SPD was performed by equal channel angular pressing (ECAP) at room and cryogenic temperatures. It is established that the increase in the weight concentration of Al in the Cu matrix (a reduction of SFE) and decreasing the ECAP temperature leads to an increase of the strength characteristics. The observed tendency is caused by increasing of the role of deformation twinning.

1 Introduction

The stacking fault energy (SFE) and temperature are important parameters determining the mechanisms and peculiarities of the microstructure refinement during the deformation of metallic materials [1]. In general, lowering of SFE in the result of the alloying metal materials, and reducing the deformation temperature, promotes the processes of deformation twinning. While deformation twinning and dislocation slip are two main competing mechanisms of plastic deformation in metals and alloys under relatively low temperatures [2].

It is known that in face-centered cubic (FCC) metals and alloys the possibility of twinning is higher in the materials with lower SFE values [3 - 5]. Twinning often observed in FCC materials, such as Cu-Zn alloys [4] with a low SFE, while in alloys with high SFE, such as Al twins are rare [6].

In recent years, among researchers a growing interest in twinning in metals at the nanoscale is observed [7,8]. The main reason for this interest is the experimental evidence that the strength of the materials increases with increasing density of twin boundaries. Twin boundaries affect the strength as well as the conventional grain boundaries, even at nanoscale thicknesses of twins. In addition, the grain refinement to the nano regime may occur by fragmentation of nanoscale twins [9, 10]. It was shown that the dynamic plastic deformation at low temperatures in alloys with a low SFE promotes the formation of high density of nanoscale twins [11, 12].

Recent studies have demonstrated the fact that the methods of severe plastic deformation (SPD) are promising methods of forming ultrafine-grained (UFG) and nanostructured (NS) states, including metallic materials with the various SFE [13, 14]. The contribution

of the previously listed mechanisms in the deformation of these materials varies with their microstructure refinement. It also depends on the SFE and deformation temperature.

In [15] it was shown that in the Cu-Al alloys subjected to SPD by high pressure torsion, implemented at room temperature (RT), SFE plays an important role in the deformation process, since the strength of the alloy increases with decreasing SFE, and uniform elongation is also increased, with the exception of the alloys containing the lowest SFE (16 wt.% Al), where the uniform elongation is reduced. It was concluded that there is an optimum SFE (5 wt.% Al) to achieve the maximum uniform elongation in the Cu-Al alloys after HPT processing.

The analysis of these experimental results by the method of numerical modeling showed that the nonmonotonic change of ductility with SFE of the considered materials is due to the fact that in alloys with 5 wt.% Al work hardening is the main mechanism of hardening in tension and it increases due to the accumulation of dislocations in the inner areas of grains at the twin boundaries [16]. At the same time, the increase of Al concentration up to 16 wt.% retards the annihilation processes. As a result, the possibility of further accumulation of dislocations inside small grains is limited, which leads to the decrease of the degree of homogeneous deformation. This significantly increased concentration of deformation vacancies contributes to the destruction of the sample.

Studies of mechanical properties of Cu-Al alloys subjected to ECAP and further cold rolling at the liquid nitrogen temperature showed an increase in strength and ductility due to increasing contribution of twinning with decreasing SFE [17, 18].

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The aim of the present research is the analysis of the influence of SFE on the microhardness and mechanical properties of pure Cu and Cu-Al alloys with 2.2 and 4.5 wt.% Al subjected to ECAP at room temperature and the liquid nitrogen temperature.

2 Experimental

The materials used in this work are Cu and Cu-Al alloys with 2.2 and 4.5 wt.% Al. The SFEs of these alloys are approximately 78 mJ/m², 25 mJ/m², 12 mJ/m², respectively. The square rods with a size of 12.0 mm × 12.0 mm × 80 mm were annealed in vacuum at 1073 K for 2 h, slowly cooled to 773 K and then quenched in water with the aim to avoid the possible short-range ordering (SRO) in Cu-Al alloys which could lead to inhomogeneous plastic deformation during a metal forming process [19]. These states are marked as SS states. ECAP was conducted in air at room and liquid nitrogen cryogenic temperature with a pressing speed of 0.25 mm×s⁻¹ using a die with the inner and outer channel intersection angles $\phi = 120^\circ$ and $\psi = 0^\circ$ correspondingly. All samples were pressed by one ECAP pass with the equivalent strain 0.7. Some samples before ECAP were immersed in liquid nitrogen for more than 5 min until no bubbling. The ECAP die was cooled by liquid nitrogen during plastic deformation [18].

Microhardness measurements were conducted on Struers Duramin hardness testing machine by Vickers method under the applied load of 100 grams for 10 seconds. The measurements were performed at points located at a distance of 25 μm from each other. The results of measurements were averaged for at least 10 points.

Mechanical tensile tests were carried out on a tensile testing machine Instron 8801 at room temperature with a strain rate of 0.24 mm/min. For tests flat samples cut along the direction of deformation with an initial working part 4 mm were used.

The optical micrographs were obtained from the ECAP flow plane characterization. Thin foils to prepare samples for transmission electron microscope (TEM) investigations were cut from the mentioned plane. Viewing and photography of samples were carried out on optical microscope Olympus GX51 at magnifications ×100. Thin foils were examined using a TEM JEM-2100 in dark and light fields at an accelerating voltage of 160-200 kV. Final thinning of the foils was performed by the method of ink-jet electrolytic polishing in a special unit Tenupol-5 using the electrolyte of the following composition: 33% nitric acid and 67% methanol at -25°C with a current of 180-200 mA.

3 Results and analysis

3.1 Microhardness and tensile properties

Fig. 1 contains a chart representing the results of the microhardness measurement of for pure Cu and Cu-Al alloys in the studied conditions. As it follows from the analysis of the diagram, there are two obvious patterns of

change in microhardness. The first trend consists in the increase of microhardness with decreasing SFE (increasing Al content in the investigated Cu-Al alloys). This trend is typical for all similar conditions of the investigated materials, including SS states, and the states after ECAP at RT and ECAP at LNT. The second trend is the increase of microhardness with decreasing temperature ECAP for all relevant states of the investigated materials.

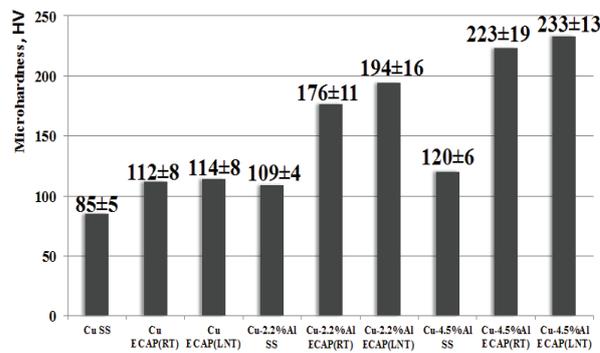


Fig. 1. Microhardness diagram for Cu, Cu-2.2%Al, Cu-4.5%Al in SS states and states after ECAP at RT and LNT.

In the SS condition, the microhardness of samples of pure copper is 85±5 Hv, alloys Cu-2.2%Al and Cu-4.5%Al - 109±4 Hv, 120±6 Hv, respectively. After conducting ECAP there is a significant increase in the hardness of the material relative to the hardness of the SS state. Microhardness of Cu after ECAP at room temperature is 112±8 Hv, and after ECAP at cryogenic temperature - 114±8 Hv. The microhardness of the alloys Cu-2.2%Al and Cu-4.5%Al after ECAP at room temperature is 176±11 Hv and 223±19 Hv, respectively, while after ECAP at cryogenic temperature of 194±16 Hv and 233±13 Hv respectively.

The results of experimental studies of the engineering tensile curves of samples of the investigated states are presented in Fig. 2.

The values of tensile strength, calculated on the basis of the engineering tensile curves for SS states are equal to 130 MPa for pure Cu, 155 MPa for Cu-2.2%Al alloy and 176 MPa for Cu-4.5%Al alloy, respectively. After ECAP at RT tensile strength is 150 MPa for pure Cu, 282 MPa for Cu-2.2%Al alloy and 478 MPa for Cu-4.5%Al alloy. After ECAP at LNT tensile strength equal to 276 MPa for pure Cu, 302 MPa for Cu-2.2%Al alloy and 533 MPa for Cu-4.5%Al alloy. As can be seen, both the decrease in SFE and decrease of ECAP temperature lead to higher tensile strength of the investigated materials. Thus, there is a full correlation of the detected tendencies related to tensile strength with the tendencies related to microhardness for the studied states.

The obtained values of the elongation for SS states are 70% for pure Cu, 32% for Cu-2.2%Al alloy and 44% for Cu-4.5%Al alloy, respectively. After ECAP at RT elongation is equal to 39% for pure Cu, 15% for Cu-2.2%Al alloy and 11% for Cu-4.5%Al alloy. After ECAP at LNT elongation is 14% for pure Cu, 19% for Cu-2.2%Al alloy and 8% for Cu-4.5%Al alloy.

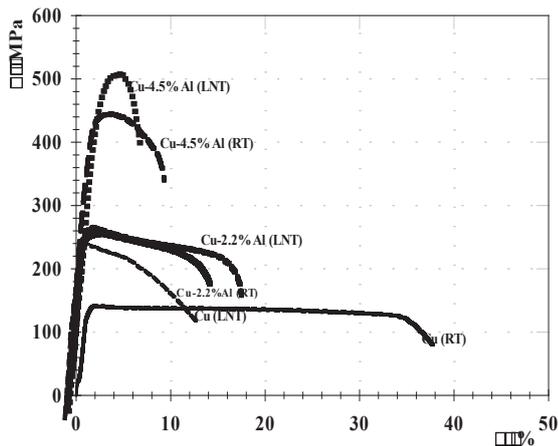


Fig. 2. Tensile engineering stress-strain curves of Cu, Cu-2.2%Al, Cu-4.5%Al after ECAP at RT and ECAP at LNT.

Thus, according to the obtained results it can be concluded that for the selected alloys with low and high SFE after ECAP at LNT there is an increase in strength, however the ductility decreases. However, for the Cu-2.2 wt.% Al alloy with an intermediate value of SFE after ECAP at LNT there is an increase in strength and elongation. In [20] the optimum SFE at which there is increased ductility of the alloy Cu-Al is reported. This can be explained by low dislocation density revealed in the observed fine structure (Fig. 4 a). As is known [21], the elongation can be improved in materials with lower density of dislocations, since there is more space for further accumulation of dislocations. Based on these results one can assume that a low dislocation density in the microstructure of the Cu-2.2%Al alloy led to further accumulation of dislocations during tensile testing, which led to hardening and increased ductility.

3.2 Microstructure characterization

Optical microstructure of Cu and Cu-Al alloys with 2.2, 4.5%Al show significant changes as a result of ECAP at room and cryogenic temperatures (Fig. 3 a - f).

After conducting ECAP at room temperature in the Cu, Cu-2.2%Al, Cu-4.5%Al alloys the boundaries of the former grains are seen. Shear bands are observed as well. The direction of the shear bands depends on grain orientation (Fig. 3 a - c). The shear occurs in three directions.

When the temperature of the ECAP is decreased, the shear bands become thinner, the distance between them

decreases (Fig. 3 b, d). With increasing Al content, namely, in the alloy Cu-4.5%Al, there steps on shear bands are observed (Fig. 3 d).

TEM images indicate the presence of deformation twins and dislocations in Cu-2.2%Al, Cu-4.5%Al alloys after ECAP at cryotemperature (Fig. 4 a, b). The number of deformation twins increases with decreasing the processing temperature.

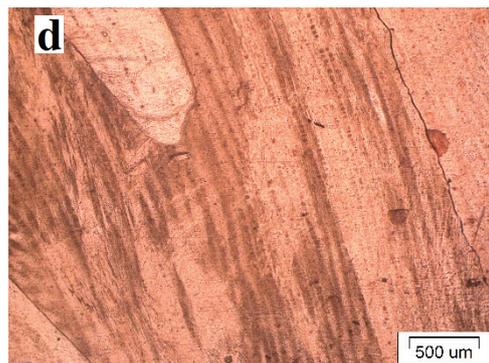
Thus, one can conclude that deformation twinning plays an increasingly crucial role in grain refinement and microstructural evolution during SPD [22 - 24]. Since the thickness of twins decreases with decreasing SFE, the twin can easily be converted into nanoscale grains with uniform distribution through the complex interaction of twins, dislocations and shear bands [25].

In addition to the development of the increased microstructural homogeneity, the average grain size is also decreasing with decreasing SFE and lower processing temperature due to the limited dynamic recovery and change of the dominant refinement mechanism from the dislocation one to twin fragmentation mechanism [26].

4 Conclusions

- (1) Two obvious tendencies in the microhardness evolution depending on the SFE for the analogous states of pure Cu and Cu-Al alloys are observed. One is that the increase of the microhardness with decreasing SFE (increasing of the Al content) in the investigated Cu-Al. The other is the increase of the microhardness with decreasing ECAP temperature for all the investigated states of the mentioned materials.
- (2) The decrease of SFE and ECAP temperature promotes the increase of the tensile strength of the investigated metallic materials.
- (3) The microstructural investigations revealed the increased twinning activities with lowering of SFE and ECAP temperature.
- (4) For a Cu-2.2%Al lowering the ECAP temperature helped to improve both strength and ductility. It seems that the reason for that is the balance achieved between the dislocation and twinning deformation mechanisms.

The work is executed by the financial support of the Ministry of education and science within the framework of the project No. 16.1969.2017/PCh and the Science and Technology Bureau of Jiangsu Province, P.R. China under grant No. BY2016029-19.



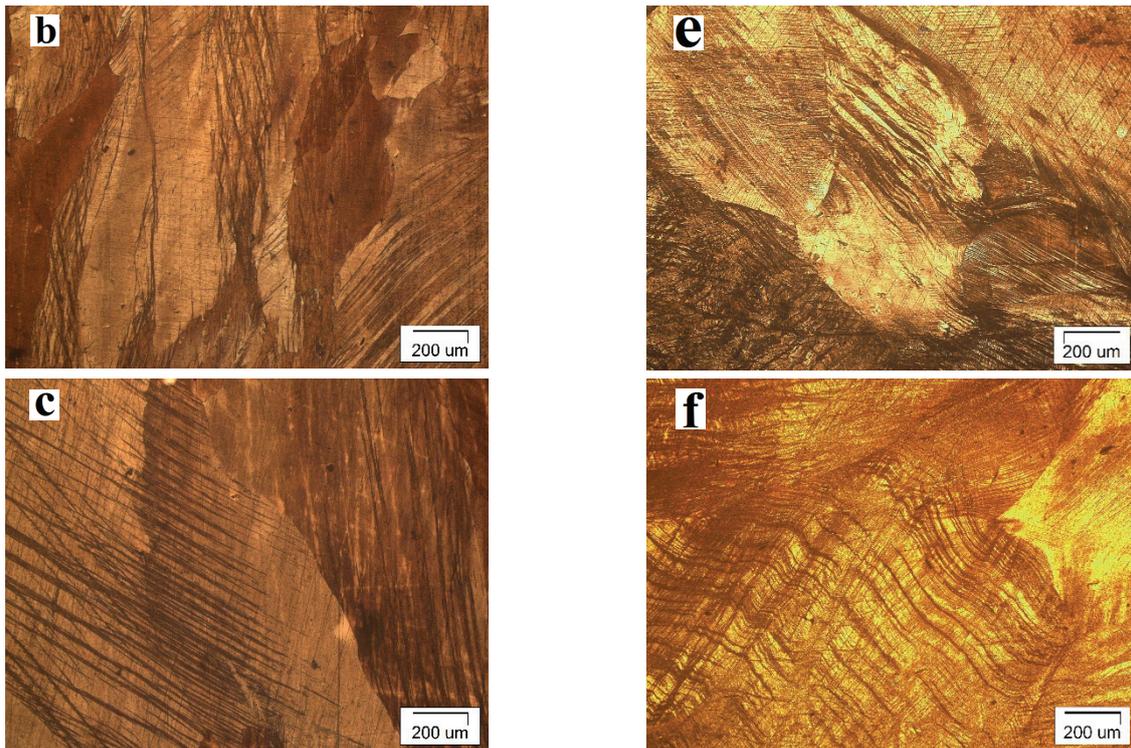


Fig. 3. Optical microscopy: a - Cu, b - Cu-2.2%Al, c - Cu-4.5%Al after ECAP at RT and d - Cu, e – Cu-2.2%Al, f - Cu-4.5%Al after cryoECAP.

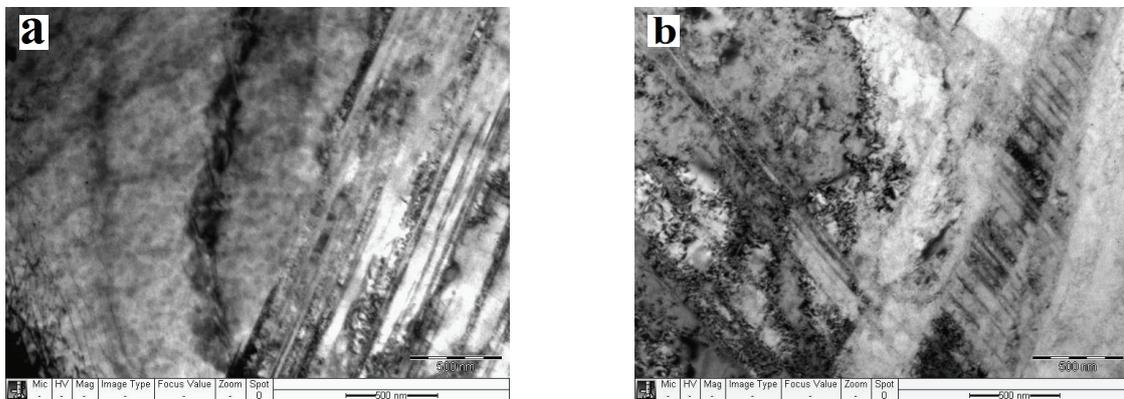


Fig. 4. TEM images: a-Cu-2.2%Al, b-Cu-4.5%Al after cryoECAP.

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