Effect of cold rolling on microstructure and mechanical properties of Cu-0,5%Cr-0,2%Zr subjected to ECAP with various NUMBERS of passes

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Abstract. The paper studies the effect of the combination of ECAP and cold rolling on the structure, mechanical properties and coefficient of friction of low-alloyed bronzes. It is shown that the use of ECAP together with rolling leads to the formation of a UFG structure and an increase in strength characteristics, while the coefficient of friction is increases. Subsequent heat treatment results in additional hardening by the separation of fine particles, which also reduces the coefficient of friction.

1 Introduction

Low-alloy bronzes of the Cu-Cr-Zr system are widely used to create electrically conductive products from which enhanced strength tests are required [1, 2]. One of the priority areas of application of these bronzes is the manufacture of contact wires. The contact wire must have high strength, good electrical conductivity, and be wear-resistant.

Traditionally, scheme is used to obtain high strength in copper alloys, this treatment usually includes 3 stages. The first stage is high-temperature heat treatment followed by quenching into water to obtain a supersaturated solid solution (SS) of alloying elements in a copper matrix. The second stage is cold deformation, which leads to an increase in the strength of the matrix due to hard work. The third stage is aging, when the solid solution decomposes and, accordingly, the additional dispersion hardening of the alloy. Numerous studies have demonstrated the possibility of a significant improvement in physicomechanical properties through using of methods of severe plastic deformation (SPD). Previous studies have shown that if at the 2nd stage of deformation the traditional methods of deformation are replaced, for example by rolling, drawing, by any SPD method, a combination of high strengths of about 688 MPa can be achieved in the alloys with a conductivity of 59% IACS, or 599 MPa at 82% IACS [9-13]. If the combination of ECAP operations with subsequent cold rolling is applied at stage 2, it is possible to obtain more optimal functional properties.

The purpose of this work was to study the effect of the SPD degree in the equal-angle angular pressing (ECAP) in combination with subsequent cold rolling on the tribological characteristics of the Cu-0.5Cr-0.2Zr alloy.

2 Experimental methods

The copper alloy with chromium and zirconium Cu-0.5% Cr-0.2% Zr (weight) was chosen as the material for the studies. The material was studied in coarse-grained (CG) and UFG states. To obtain a supersaturated solid solution, a high-temperature heat treatment was carried out at 1000 °C for 0.5 hours, followed by quenching in a 5% NaCl solution. (the initial state). For the samples, 12 × 12 × 80 mm in the form of rectangular parallelepipeds were used. ECAP was carried out at room temperature at a speed of 0.2 mm / s with an internal tool angle $\psi = 110^\circ$ and an external angle $\phi = 0^\circ$ for ECAP along route A, without rotating the rods between successive passes. The number of passes was 1, 2, 4, 8. The degree of deformation for each pass was 0.8. Rolling was carried out at room temperature with a reduction of 55%.

Aging was carried out in air in an oven SUOL 45 at 450 °C for 1 hour.

All investigations were carried out in the longitudinal section of the samples.

The OLIMPUS GX51 optical microscope (OM) and the transmission electron microscope (TEM) -JEOL 2100 were used to study the microstructure. Foil for TEM studies was prepared by electrolytic thinning in a solution of 30% orthophosphoric acid and 70% ethyl alcohol.

The microhardness of the test samples was measured on a Duramin instrument under a load of 100 g and with a holding time of 10 seconds for a load. Conductivity studies were carried out at a temperature $T = 23^\circ\text{C}$ by an eddy current method on flat samples measuring 12 × 12 × 1 mm. Surfaces of the samples before the test were subjected to a two-step polishing starting with mechanical polishing followed by final polishing on a diamond suspension.

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Tribological tests were carried out on the Nanovea (finger-plane) installation when the indenter was made of 95X18 steel was moved around the circumference at a speed of 2400 mm / min under dry friction conditions for 40 minutes. The load on the indenter was 2N. To investigate the nature of the tracks, the JEOL JSM-6490LV raster microscope was used.

3 Results and discussion

Fig. 1 shows the microstructure of Cu-0.5Cr-0.2Zr alloy in initial state. The microstructure of the alloy in the initial state consists of equiaxed grains with an average size of about $100 \pm 5 \mu\text{m}$ and contains inclusions of a finely dispersed strengthening phase.

Fig. 1. Optical metallography of Cu-Cr-Zr alloy in the initial state.

The particles reach sizes up to $12 \mu\text{m}$. As already shown in previous studies, the composition of these precipitates corresponds to CrCu_2 [2, 6].

After 1-8 passages of the ECAP with subsequent rolling, the structural elements that are stretched along the deformation direction are significantly crushed. The particles line up in the direction of deformation as shown in Fig. 2a-f.

Fig. 2. Optical metallography of the Cu-Cr-Zr alloy after the ECAP with rolling: a - initial state + CR, b - 1 pass ECAP + CR, в - 2 passages ECAP + CR, г - 4 passages ECAP + CR, д - 8 passages ECAP + CR.

Analysis of the fine structure after ECAP in combination with cold rolling indicates a strong grinding with the formation of a grain-subgrain structure (Fig. 3a-f). A high density of dislocations is located in the microstructure, which are located both inside the grains and at grain boundaries. A complex diffraction contrast on the light-field image indicates the presence in the grains of large internal stresses that have arisen due to the application of large shear strains. It should be noted that with an increase in the degree of deformation, there is no significant increase in the defect density. Small particles are visible in the places of accumulation of dislocations. Probably, these particles are an obstacle to the movement of dislocations, which leads to an additional hardening of the material. Electronograms are typical for ultrafine-grained structures.

Fig. 3. TEM of Cu-Cr-Zr alloy after rolling: a - initial state + CR, b - 1 pass of ECAP + CR, c - 2 passages of ECAP + CR, d - 4 passages of ECAP + CR, f - 8 passages of ECAP + CR.

Measurements of the microhardness showed that with increasing strain, the microhardness increased from 950 MPa to 1980 MPa after 8 ECAP passes, which is 1.7 times higher than for the CG state (Table 1). The most intensive deformation hardening takes place after the rolling of the initial state. After the 1st, 2nd pass of the ECAP, microhardness does not change. Further, the microhardness increases monotonically to a maximum value of 1980 MPa. An annealing was carried out at a temperature of 450 ° C for 1 hour to determine the behavior of the samples after deformation. The states with the highest microhardness were chosen for postdeformation treatment. As a result of aging microhardness increased to 2600 MPa (Table 1), this is due to the release of dispersed particles of secondary phases. Which are clearly visible in photographs of fine structure after 8ECR and subsequent aging presented in Fig. 4. They are located non-uniformly both in the body and along the grain boundaries. Also fragments of grains are clean from defects, since annealing causes not only the release of particles, but also the return of the structure.

According to the results of tribological tests, the coefficient of friction in the initial state is 0.6 (Table 1). The subsequent increase in the degree of deformation leads to an increase in the coefficient of friction. The greatest coefficient of friction 0.9 was obtained after 4 and 8 passes of ECAP with subsequent rolling. This may be due to the brittleness of the UFG of copper and the development of cracks in the near-surface layer.

Apparently in our case it also fails to maintain a sufficient level of plasticity.

Fig. 4. TEM of the Cu-Cr-Zr alloy and rolling. The clear-field image: a) after 8 ECAP passes, typical shear bands, b) the observed particles are separated by circles.

Table 1. The mechanical properties of the alloy Cu-Cr-Zr.

States	Hv, MPa	σ_B , MPa	Friction coefficient	Electro conductivity (IACS %)
SS+CR	1650±20	520	0.6	31
1 ECR	1650±30	590	0.8	28
2 ECR	1650±40	585	0.8	28
4 ECR	1700±30	630	0.9	27
8 ECR	2000±30	660	0.9	28
8 ECR+ Aging	2600	-	0.1	69

However, subsequent aging leads to a sharp decrease in the coefficient of friction to a value of 0.1. Perhaps this is due to the fact that fine particles were formed during annealing, which led to a further increase in the strength of the material. Thus, in the process of wear, the primary larger, stronger particles are dyed from the surface of the material and then abrasive wear continues. In the case of an increase in strength due to the release of fine particles in the matrix, the extrusion of coarse particles is observed to a lesser extent, which leads to a decrease in the coefficient of friction.

Thus, as a result of ECAP in combination with rolling and subsequent aging, it is possible to reduce the coefficient of friction to 0.1. At the same time, one of the most important operational parameters - the electrical conductivity is restored to 69% IACS (Table 1)

4 Conclusions

The effect of intense plastic deformation of ECAP in combination with rolling on the microstructure, mechanical properties and wear resistance of Cu-0.5Cr-0.2Zr alloy was investigated. It was revealed that as a result of ECAP the microhardness increased to 2600MPa and the coefficient of friction decreased to 0.1. In this case, the electrical conductivity reaches 69% of IACS.

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