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ELEVATED TRIBOLOGICAL CHARACTERISTICS OF ULTRAFINE GRAINED CONDUCTIVE Cu-0.5Cr-0.2Zr ALLOY

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Abstract. For the first time, the possibility of radical reduction of the friction coefficient from 0.7 up to 0.3 with an increase in the strength from 950 MPa up to 1600 MPa was demonstrated for electrical Cu-0.5Cr-0.2Zr alloy as a result of the ultrafine-grain structure formation by equal channel angular pressing.

1. Introduction

Low alloyed bronze Cu-Cr-Zr systems have high electrical and thermal conductivity and are widely used as structural materials [1, 2]. One of the priorities of the use of this material is the production of contact wires. During operation the wires are exposed to tensile stresses and prostrate heating due to the currents passing through. Materials of the wire must have a sufficiently high durability. The main criterion for determining the increase in wear resistance is to increase hardness. In this regard, to improve the wear resistance it is necessary to increase the initial strength, while maintaining high electrical conductivity. Numerous recent studies have shown that one of the most effective ways to increase the strength and hardness of the metallic materials is to introduce the ultrafine-grained (UFG) structure by severe plastic deformation (SPD) [3-4]. In particular, equal channel angular pressing (ECAP) is one of the most effective SPD methods that allows obtaining three-dimensional UFG billets of various metals and alloys. Such UFG metallic materials possess the high potential for the successful practical application. As a rule, after 4 ECAP passes microstructure becomes UFG, with the subsequent improvement after increased number of ECAP passes [3]. At the same time SPD methods negatively affect the electrical conductivity of metallic materials [5]. The solution of this problem may be found in the aging after SPD, during which a decay of the solid solution and subsequent fallout of precipitation-hardening particles of secondary phases take place.

There is a significant number of studies aimed to find the optimum combination of strength and electrical conductivity [5-7], as well as researches to identify the nature, composition and distribution of the particles formed in the process of aging of these alloys [2, 10]. In particular the best combination of high strength (tensile strength 554 MPa) and electrical conductivity (84 % IACS of) for the Cu-0.5Cr alloy is obtained after 4 ECAP passes by route A, without rotating the billets after each pass, at room temperature, flat rolling with cumulative reduction rate of 90 %, and aging at 450 °C for 1 hour [8].

For improving durability, the hardness and strength of these alloys should be further increased without the reduction of their electrical and thermal conductivity. Wear out is quite a complex phenomenon, which includes a wide variety of mechanisms that do not always occur separately and independently. However, one can select the leading mechanism that sets the overall sort of wear out and its rate. It is generally recognized that in the case of coarse-grained (CG) metal, the higher the strength is, the less is the wear out. ECAP combined with subsequent aging resulted in a significant grain refinement in the Cu-0.8Cr-0.08Zr alloy and reduction of the wear rate as compared with the CG state [9]. It was noted that the friction coefficient decreases as hardness increases [9, 10]. However, in the case of UFG metals and alloys the situation is contradictory. There is a number of works in which the UFG alloys exhibit a reduced durability in comparison with the CG samples. Kouhanjani et al. investigated the effects of cold rolling on the tribological properties of the Cu-0.65 wt.% Cr alloy [11], it was shown that the hardness increases, but the wear resistance is decreased with an increase of deformation during cold rolling. CG Cu samples showed better wear resistance and low wear rate compared to the UFG Cu samples [12] due to the fragility of the UFG copper under the influence of the indenter that leads to the development of cracks in the surface layer.

As it follows from the above mentioned results, the study of the mechanisms of friction and wear resistance in Cu-Cr-Zr alloys is an important and topical research direction. The aim of this work was to study the effect of the SPD degree during ECAP on tribological characteristics and wear mechanism of the Cu-0.5Cr-0.2Zr alloy.

2. Methods of experimental studies

Copper alloy with chromium and zirconium Cu-0.5 Cr-0.2 Zr (wt.%) was chosen as a material for the research. The material has been studied in SS (CG) and UFG states. In order to obtain a supersaturated solid solution (SS) state a high-temperature heat treatment was carried out at 1000 °C for 0.5 hours with a following quenching in 5 % NaCl solution. Samples of a rectangular parallelepiped shape 12×12×80 mm were used. ECAP was conducted at room temperature at a rate of 0.2 mm/s with an internal angle ψ = 110° and the external angle φ = 0°. The route A, without rotating of the work piece between successive passes, was applied. The number of ECAP passes was 1, 2, 4, 8. The degree of deformation for each ECAP pass was 0.8. All studies were conducted in the longitudinal section of the sample.

To study the microstructure an optical microscope (OM) OLIMPUS GX51 and transmission electron microscope (TEM) JEOL 2100 were used. Foils for TEM studies were prepared by electrolytic thinning in solution of 30 % orthophosphoric acid and 70 % ethanol.

The “Micromet 5101” unit was used to measure microhardness of the samples under the load of 100 g and the dwelling time of 10 seconds.

Studies of the conductivity were carried out at a temperature T = 23 °C by eddy current technique on flat samples of size 12×12×1 mm^3. Surfaces of the test samples were subjected to two-stage polishing starting with the mechanical polishing followed by a final polishing with a diamond suspension.

Tribological tests were carried out on the installation Nanovea (in a "finger - plane" mode) with the indenter made of steel A473 and moving circularly at a speed of 2400 mm/min under dry friction conditions for 40 min. The load on the indenter was 2 N. Scanning electron microscope JEOL JSM-6490LV was used to investigate the nature of the tracks.

3. Results and discussion

Figure 1 shows the microstructure of the Cu-0.5Cr-0.2Zr alloy in different states. The microstructure of the alloy in the SS state is composed of equiaxed grains with an average size of about 100 ± 5 μm (see Table 1) and contains fine particles of hardening phase. The particles reach the size of 12 μm. As it has been shown in previous studies, the composition of these particles corresponds to $CrCu_2$ (Zr) [2, 10]. In addition, as shown in [13], Cu_3Zr/Cu_4Zr particles were also presented.

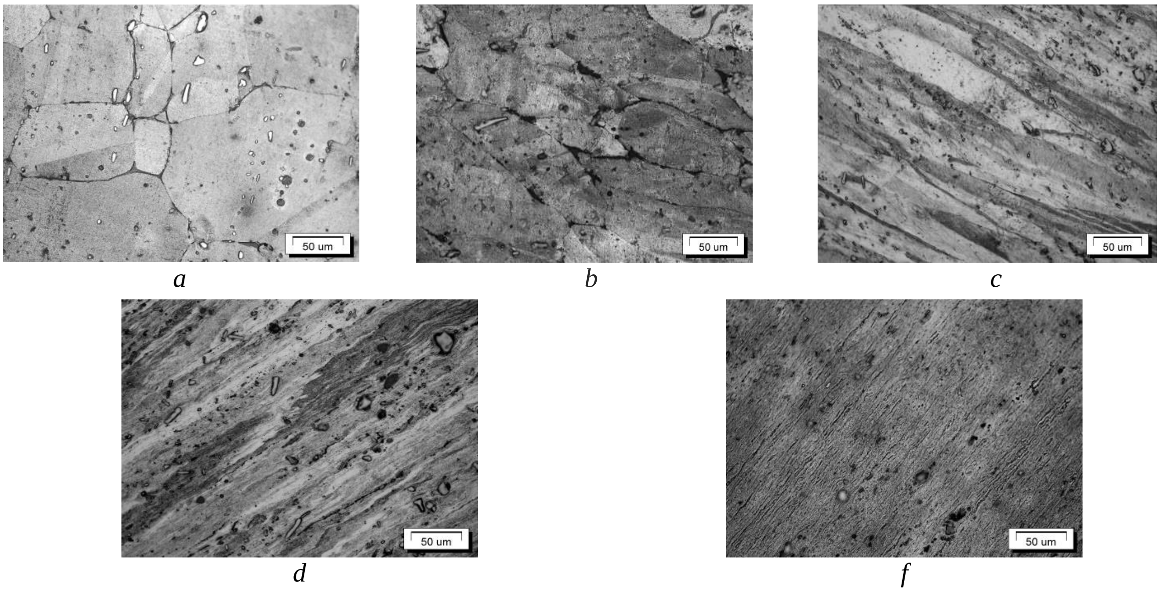


Fig. 1. Optical metallography. The microstructure of Cu-Cr-Zr alloy in different states: a – SS, b - 1 ECAP passes, c - 2 ECAP passes, d - 4 ECAP passes, f - 8 ECAP passes.

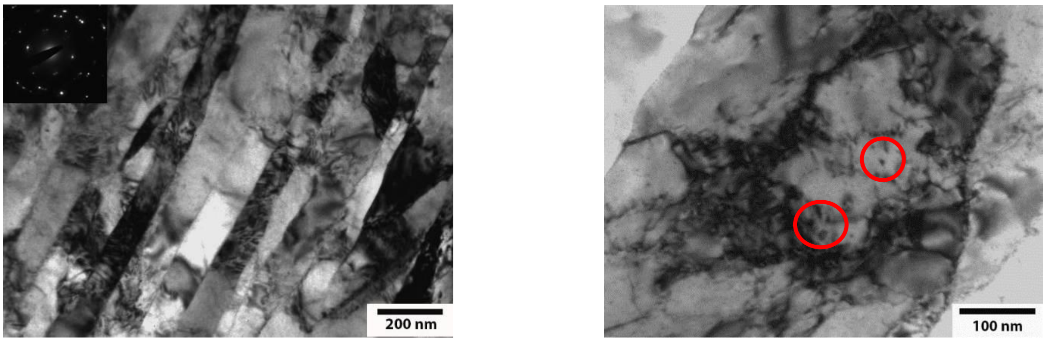
After the first ECAP pass (1ECAP) elongated grains along the deformation direction were observed. The cross dimension of the elongated grains was about 60 μm. After the second ECAP pass (2ECAP) the elongation of grains in the deformation direction is increased and subgrain structure is observed. After 4 (4ECAP) and 8 ECAP (8ECAP) passes the structure refines substantially up to 150 nm. The particles are arranged in the deformation direction (Fig. 1f).

Table 1. Grain size in different states of the Cu-0.5Cr-0.2Zr alloy.

State	d, μm
SS	100 ± 5
1ECAP	70 ± 3
2ECAP	15 ± 3
4ECAP	0.25 ± 0.01
8ECAP	0.15 ± 0.01

Analysis of the fine structure after 8 ECAP passes indicates strong grain-subgrain refinement in microstructure (Fig. 2). Because of the strong elongation of the grains it was only possible to evaluate the cross dimension, which was 150 ± 10 nm. High dislocation density was observed in the microstructure. The dislocations were present inside the grains as well as at grain boundaries. The complex diffraction contrast in the bright field image indicates the presence of of large internal stresses in the grains arising from the application of large shear strain. Small particles are visible in places where the dislocations are concentrated (Fig. 2b). Possibly, the particles serve as the obstacles for the dislocation slip, which results in further hardening of the material. The observed electron diffraction pattern is typical for the UFG structures.

Microhardness measurements showed that with the increasing deformation degree microhardness increased from 950 MPa in the SS state up to 1600 MPa after 8 ECAP passes, which is 1.7 times higher than in SS state (Table 2). The most intensive hardening takes place at the first ECAP pass. At the second ECAP pass the work hardening of the material is reduced, and further there is a monotonic increase in microhardness up to a maximum value. The obtained results are in the good agreement with the above mentioned published data.



a b

Fig. 2. TEM. The microstructure of the Cu-Cr-Zr alloy after 8 ECAP passes:
a) bright-field image, b) circles are used to mark the observed particles.

According to the results of the tribological tests the highest friction coefficient of 0.7 (Table 2) corresponds to the SS state of the alloy and reflects its low durability. The subsequent increase in the deformation degree during the ECAP leads to the reduced values of the friction coefficient. The lowest value of the friction coefficient equal to 0.3 was obtained after 8 ECAP passes. This may be due to the increased microhardness, which in turn is due to a smaller grain size of this state. Similar values of the friction coefficient in the case of the nanostructured (NS) Cu and Cu-Cr-Zr alloy were obtained in [9, 12].

Table 2. Microhardness, thickness of the tracks, friction coefficient and electroconductivity of Cu-0.5Cr-0.2Zr in the different states (Hv - microhardness and IACS - International Annealed Copper Standard).

	Microhardness Hv, MPa	Thickness of the tracks, μm	Friction coefficient	Electrical conductivity (IACS%)
SS state	950 ± 20	470 ± 20	0.7	40
1ECAP	1370 ± 30	423 ± 18	0.6	32
2ECAP	1400 ± 40	396 ± 15	0.5	35
4ECAP	1500 ± 30	361 ± 23	0.4	34
8ECAP	1600 ± 30	293 ± 21	0.3	36

However, the opposite results were obtained in [12], where the increase of the friction coefficient in the case of the UFG copper was interpreted as associated with its fragility as a result of the development of cracks in the surface layer of its ingots. In [11] the lack of dependence of the friction coefficient on the grain size is associated with oxidative mechanism of wear out, loss of the ability to deformation hardening and non-equilibrium grain boundaries.

In our case, the possibility to maintain a sufficient level of ductility and the ability to maintain sufficient strain hardening is preserved. At the same time, oxidative wear mechanism is not as important due to the rapid removal of the oxide layer by indenter during the initial sliding step.

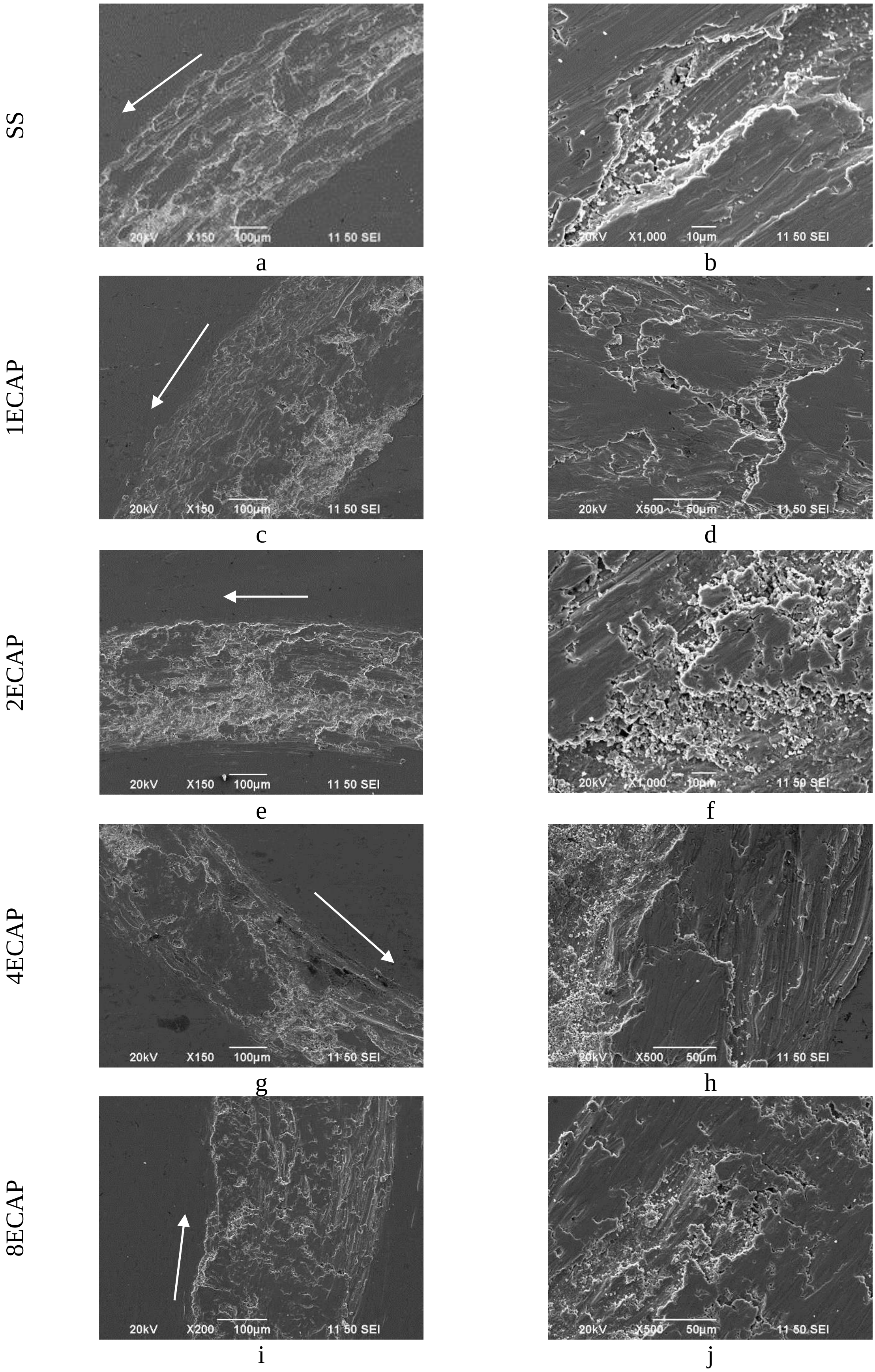


Fig. 3. SEM images of friction tracks on the surface of Cu-Cr-Zr alloy in different states: a, b) SS, c, d) 1 ECAP pass, e, f) 2 ECAP passes, g, h) 4 ECAP passes, i, j) 8 ECAP passes.

This result is also supported by studies of tracks after the test (Table 2). The width of the tracks is reduced up to 293 μm while deformation degree is increased, as compared to the SS sample where it was 470 μm. It corresponds to the greatest penetration of the indenter in the SS state, due to the lower microhardness of the material. The increase in the strength and, respectively, in hardness, makes it difficult to remove the material from the surface of friction during sliding. Thus, according to the classification given in [14], after ECAP passes the alloy can be referred to materials, which are characterized by increasing of wear resistance while the deformation degree is increased.

Important information about the process of wearout can be obtained by examining the structure of surfaces and wear particles formed by friction. Typical SEM images of wear tracks after the wear test are shown in Fig. 3, arrows indicate the direction of sliding of the ball. Overview of all SEM images shows that the types of friction tracks are very similar (Fig. 3a-f) and samples demonstrate plastically deformed material inside friction tracks. During these wear tests the material was spread over the surface.

The main type of wear in all cases was the mechanical wear, including an abrasive and fatigue wear. Multiple elastic-plastic deformation of the metal microvolumes causes fatigue failure with the separation of the particles from the surface layer. As a result of abrasive wear in the SS state deeper grooves from scratching were observed, which may be associated with a softer matrix.

The hardening of material matrix occurs as a result of ECAP and the grooves become less pronounced. After two ECAP passes (Fig. 2f) small cracks can be seen on the tracks that may indicate the oxide wear, as well as in [9] in the investigation of the Cu-Cr-Zr alloy. In this case inception of a crack occurs in the surface layer, where there are large shear deformations that result in the appearance and growth of cracks and debris particles [9]. The destruction of the oxide layer creates the potential for abrasion, where the hard oxide dust can cause abrasion and scratch of material.

SEM micrographs showed less deformation, but a higher tendency to the formation of cracks in samples after ECAP, which may be associated with lower ductility of the alloy after ECAP processing [9]. As the degree of deformation and thus microhardness is increased wear particles are transformed from flaky-shaped into the small grainy type.

Thus, as a result of ECAP processing it is possible to decrease the friction coefficient almost twice. One of the most important operating parameters - the electrical conductivity – is almost unchanged (Table 2) compared with the SS state.

Unfortunately ECAP leads to a slight decrease in the electrical conductivity of the Cu-Cr-Zr alloy (Table 2), but there is a possibility of additional artificial aging, which will improve the conductivity to a value of the value SS copper. Thereby the following studies will be aimed to analyze the effect of aging on the friction coefficient and the formation of the optimum combination of strength, wear and electroconductivity of the investigated Cu-0.5Cr-0.2Zr alloy.

4. Conclusions

The effect of severe plastic deformation conducted by ECAP on microstructure, mechanical properties and wear resistance of Cu-0.5Cr-0.2Zr alloy has been investigated. It has been revealed that the UFG microstructure resulted from ECAP is characterized by high microhardness increased by 1.5 times and friction coefficient decreased by 2 times, while the electroconductivity remains at almost the same level as for the SS counterpart.

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