Features of the physico-mechanical behavior of UFG low-alloyed bronze Cu-1Cr-0.08Zr produced by severe plastic deformation

D A Aksenov¹², R Asfandiyarov¹², G I Raab¹ and G B Isyandavletova¹

¹Ufa State Aviation Technical University, 12 K. Marx str., Ufa 450008 Russia
²Institute of Molecule and Crystal Physics, Ufa Research Center RAS, 71 pr. Oktyabrya, Ufa 450054 Russia

E-mail: a.r.n@list.ru

Abstract. The authors analyze the effect of the accumulated strain during severe plastic deformation as well as the temperature and aging time on the physico-mechanical properties of low-alloyed chromium-zirconium bronze Cu-1Cr-0.08Zr. The following SPD processing techniques were employed in the work: high-pressure torsion (HPT) and equal-channel angular pressing (ECAP). As a result of the investigation there have been revealed the most reasonable regimes of thermomechanical treatment, leading to the maximum increment in mechanical properties, while preserving a high level of electrical conductivity.

1 Introduction

Low-alloyed bronzes with high electrical and thermal conductivity are the most important group of Cu-based conductor alloys. The total content of alloying elements in alloys of this type is within a range of 0.1 to 3...5% [1, 2, 3]. These alloys possess a combination of such properties as high electrical conductivity and high-temperature strength, which cannot be attained in materials based on other metals [1]. The level of properties is influenced by both the total content of alloying elements in the alloy and the method of its thermomechanical treatment. Traditionally, properties in such alloys are formed by a three-stage treatment, including high-temperature heating and quenching (to fix the supersaturated solid solution with the alloying elements of the solid solution), deformation processing at room temperature (rolling, drawing) and aging (precipitation of fine-dispersed phases from the solid solution).

The decomposition kinetics of the supersaturated solid solution depends on the type and regimes of preliminary treatments [1, 2, 3]. In recent time, severe plastic deformation (SPD) has become greatly developed. This type of processing drastically transforms a material's structure to the ultrafine-grained one or even to the nanostructured state [4, 5]. A number of papers have demonstrated the positive effect of such structural states on the decomposition kinetics of the supersaturated solid solution and the formation of enhanced physico-mechanical properties [3, 6]. In this connection, in the present investigation SPD with different accumulated strains during the processing was used at the stage of cold deformation. This approach enables revealing the efficiency of SPD processing and, consequently, the effect of the accumulated strain level and the regime of subsequent aging on the formation of physico-mechanical properties. The following SPD processing techniques were employed in the study: high-pressure torsion (HPT) and equal-channel angular pressing (ECAP).
2 Material and experimental procedure

As the material for the investigation, the low-alloyed Cu-1Cr-0.08Zr (wt%) was used. This alloy is used in production of electrodes for resistance spot welding and seam welding, railway contact wires, as well as other parts which must combine high electrical conductivity and high–temperature strength [1, 7, 8]. The samples used in the study were in the shape of rods with a diameter of 10 mm, length of 60, and in the shape of disks with a diameter of 10 mm, thickness of 6 mm. In the course of the investigation, the samples were subjected to thermomechanical treatment comprising three stages.

At the first stage, high-temperature treatment was performed – holding the samples for 1 hour at a temperature of 1050°C, with subsequent water quenching. At the second stage, the samples were subjected to two different types of SPD processing:

- equal-channel angular pressing (ECAP) – with the channels’ intersection angle 90°, route Bc, 1 and 4 passes;
- high pressure torsion (HPT), at the pressure of 6 GPa, 1 and 5 revolutions.

At the third stage, for the sake of comparison, search for reasonable regimes of aging was conducted for the samples with a coarse-grained (CG) and ultrafine-grained (UFG) structure at different temperatures and different holding times. The range of aging temperatures of 400°C, 450°C, 500°C was selected on the basis of previous studies, which demonstrated that temperatures below such a range provide a very insignificant increment in mechanical properties, as compared to the initial ones [1, 3, 6, 9]. The aging time was 10, 20, 30 min, and subsequently 1 hour – 10 hours, with an interval of 1 hour. This interval of time was selected in order to show the decomposition kinetics of the solid solution.

The Vickers microhardness tests (under a load of 0.1 kg, holding time - 10 s) were performed using the EMCO-Test DuraJet 10 microhardness tester. Electrical conductivity was measured using the VE27-NTs eddy-current conductivity meter (with an accuracy of measurement 0.5 MS/m).

3 Results and discussion

As a result of the performed studies, graphs and diagrams have been produced, which demonstrate the tendency in variation of microhardness and electrical conductivity depending on different processing parameters (time, temperature) and the accumulated strain level during ECAP and HPT processing (figure 1, figure 2). Analysis of the obtained data has revealed that SPD processing leads to a noticeable enhancement in strength, and this process runs especially actively when HPT processing is employed. This is connected with the fact that during HPT the hydrostatic pressure increased up to 6 GPa is applied, which provides accumulation of high strain values without the samples’ damage as well as formation of an ultra-disperse structure with high homogeneity with an average size of structural elements 220±25 nm. For instance, after one revolution (e=30) and five revolutions (e=270) hardness reaches 1840 MPa, in contrast to the initial hardness of 860 MPa, and the increment in hardness is 980 MPa. A similar situation, showing an increase in hardness, is observed after ECAP processing, but the increment in hardness is much lower (figure 1). Subsequent heat treatment (aging) leads to a further growth in hardness, and this process runs most actively after HPT processing under both e=30 (1 revolution) and e=270 (5 revolutions). It has been established that after 10 minutes of annealing at 500°C there is observed an intensive hardness growth, then hardness declines, and for the sample with e=30 this decline in hardness is more active and in 10 hours hardness reaches the initial material’s level. The hardness values attained after 10 minutes of aging are superior and are 1.4 times higher than the hardness values after the conventional treatment. Such an active growth of microhardness is the regular one as the HPT process leads to the refinement of initial grains and to the increase of dislocation density. At the stage of thermal treatment the process of dissolution of the solid solution with precipitation of nanostructured particles in the ultrafine grained matrix takes place, which leads to strengthening. High non-equilibrium character of grains of such structures and high temperature most probably contributes to the accelerated dissolution of the solid solution and active coagulation of these particles and, accordingly to the sudden increase, and then decrease of hardness, which has been experimentally proved. For other aging temperatures, the hardness values attained after HPT processing are lower, but still rather high, for example after 5 HPT revolutions followed by aging of the alloy at 450°C for 2 hours, the alloy’s microhardness is 2650 MPa.

After ECAP+HT, the best values of hardness (max. 2320 MPa) are exhibited by the samples produced by 4 processing cycles and at the aging temperature of 450°C (figure 1). The distinctive
feature of this processing regime is the high thermal stability of the hardness value, as the decrease
in hardness during 10 hours of holding time at the aging temperature was only 60 MPa. Strains at
ECAP are considerably lower as compared to the HPT strains. The scheme of deformation is
different in case of ECAP as well, which leads to formation of a considerably elongated structure
towards the shear direction. The average cross plane size of structural elements in this case makes
up 250±25 nm, but structural elements up to 1 µm are also observed. That is why the hardness
increment due to the structure refinement is lower than after HPT. Strengthening due to the
dissolution of the solid solution at a temperature of 450°С occurs slower, the overaging is not
observed even after 10 hours of holding time, the contribution of such dissolution to strengthening
is larger.
After one cycle of ECAP followed by aging at 450°С, the hardness values do not exceed
2000 MPa and exhibit thermal stability for only up to 5 hours of holding time (figure 1).

![Figure 1](image1.png)

**Figure 1.** Variation in microhardness depending on the time of aging.

Figure 2 shows the most characteristic graphs of variation in electrical conductivity depending on
the time of aging. It has been established that after 3 hours of treatment stabilization of this
parameter is observed, while after 10 hours of treatment the electrical conductivity value is close
for all processing regimes, but slightly higher as compared with the conventional treatment. A
similar situation is observed for the aging temperature of 450°С, but the electrical conductivity
value stabilizes after 5-6 hours of holding time.

![Figure 2](image2.png)

**Figure 2.** Variation in electrical conductivity depending on the time of aging.
The performed studies have revealed several most reasonable regimes demonstrating a combination of strength and electrical conductivity that is noticeably better than the traditional one. The most reasonable regime of ECAP processing is 4 passes with subsequent aging at a temperature of 500°C with a holding time of 1 hour. In this case, it is possible to attain a combination of microhardness of 2320 MPa and electrical conductivity of 80% IACS. The reasonable regime of HPT processing, including 5 HPT revolutions with subsequent aging of the alloy at 450°C for 2 hours, leads to an increase in hardness to 2650 MPa and an increase in electrical conductivity to 80% IACS. These regimes, in comparison with the conventional ones, are shown in figure 2.

When comparing the characteristics (figure 3) of the strain-hardenable Cu-1Cr-0.08Zr alloy, it may be noted that the microhardness after deformation processing by ECAP and HPT is higher than the microhardness after the commercial (industrial) treatment. Besides, the increment in microhardness after aging of the alloy is much higher in case of processing by SPD techniques. The material’s electrical conductivity after ECAP and HPT processing reaches values of about 30% IACS. The solid solution decomposition at the stage of aging leads to the restoration of electrical conductivity to 80% IACS.

![Figure 3](image-url)  
**Figure 3.** Variation in microhardness and electrical conductivity, depending on the type of processing.

In the course of the investigation, the contributions of the deformation component (work hardening) and of the thermally-activated component (fine-dispersed precipitation of second phases from the solid solution) into strength were analyzed. The results of this analysis are presented in figure 4.

![Figure 4](image-url)  
**Figure 4.** Diagram showing the contributions into strength after SPD processing and aging, where: 1 – quenching + 450°C 1 h (ε=0); 2 – quenching + commercial treatment (CT) (ε<1) + 450°C
1 h; 3 – quenching + ECAP 4 passes (ε=4.4) 500° C 30 min; 4 – quenching + HPT 5 revolutions (ε=350) 450° C 2 h.

Note should be made that the maximum increment in strength due to the thermal activation (aging) is observed after ECAP processing (955 MPa), while the maximum increment in strength due to the deformation action is observed after HPT processing (980 MPa).

4 Conclusions
1. The study has revealed that the use of SPD processing leads to a noticeable enhancement of physico-mechanical properties of the Cu-1Cr-0.08Zr alloy. The regimes have been experimentally established that enables producing the best combination of strength and electrical conductivity in the Cu-1Cr-0.08Zr alloy. For ECAP processing, such a regime is deformation processing through 4 passes and aging at 500° C for 1 hour (strength 2320 MPa and electrical conductivity 80% IACS). For HPT processing, such a regime is 5 revolutions with subsequent aging at 450° C for 2 hours (strength 2650 MPa and electrical conductivity 80% IACS).

2. The best thermal stability under the aging temperature of 450° C is ensured by the SPD processing regime including 4 cycles of ECAP processing at room temperature via route Bc and with the channels’ intersection angle of 90 degrees.

3. The largest contribution into the increment of strength due to the thermal activation (aging) is observed after ECAP processing (955 MPa), while the maximum increment of strength due to the deformation action (work hardening) is observed after HPT processing (980 MPa).

4. An increase in accumulated strain during SPD contributes to attaining higher strength values after both ECAP processing and HPT processing.

Acknowledgements
The authors acknowledge the financial support by the Ministry of Education and Science of Russian Federation under Grant agreement No. 14.586.21.0025 (unique identification number RFMEFI58616X0025).

References
[1] Osintsev O E 2004 Copper and Copper Alloys. Domestic and Foreign Grades: Reference Book (Moscow: Mashinostroenie) p 336 (in Russian)
[2] Batra I S, Dey G K and Kulkarni U D 2001 Microstructure and properties of a Cu–Cr–Zr alloy Journal of Nuclear Materials 299 pp 91–100
[3] Faizov I A, Raab G I, Faizova S N, Aksenov D A, Zaripov M G, Gunderov D V, Golubev O V 2016 Dissolution of the second particles in Cu-Cr-Zr alloy upon the equal channel angular pressing Tambov University Reports. Series: Natural and Technical Sciences 21 pp 1387–91 (in Russian)
[4] Valiev R Z, Zhilyaev A P and Langdon T G 2014 Bulk Nanostructured Materials: Fundamentals and Applications (Hoboken, New Jersey: John Wiley & Sons, Inc.) p 456
[5] Utyashev F Z and Raab G I 2006 The model of structure refinement in metals at large deformations and factors effecting grain sizes Rev. Adv. Mater. Sci. 11 pp 137–151
[6] Vinogradov A, Patlan V, Suzuki Y, Kitagawa K and Kopylov V 2005 Structure and properties of ultra-fine grain Cu-Cr-Zr alloy produced by equal-channel angular pressing Acta Mater. 50 pp 1639–51
[7] Nikolaev A K 2001 Low-alloyed copper alloys. Features of the compositions and production technology Tsvetnye Metally 5 pp 84–88 (in Russian)
[8] Nikolaev A K 1978 Alloys for Contact Welding Electrodes (Moscow: Metallurgiya) p 96 (in Russian)
[9] Wang Z, Zhong Y, Rao X, Wang C, Wang J, Zhang Z, Ren W and Ren Z 2012 Electrical and mechanical properties of Cu–Cr–Zr alloy aged under imposed direct continuous current Trans. Nonferrous Met. Soc. China 22 pp 1106–1111