Rheological behavior of a Cu-Cr alloy subjected to severe plastic deformation

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Abstract. The choice of rate conditions of deformation is one of the key factors that determine the mode of thermomechanical processing of metallic materials. The aim of this work is to study the rheological behavior as well as the structural response of the Cu-0.6Cr alloy under conditions of large deformations. For this, physical modeling of upsetting of specimens on a Gleeble 3500 installation at deformation rates of 3, 30, and 300 mm/s, structural characterization of the obtained specimens and computer simulation of the equal-channel angular pressing (ECAP) process in the Deform 3D software package were carried out. It was found that with an increase in the rate of deformation, the value of deformation heating increased. If at the rate of ECAP 30 mm/s and at the initial temperature of 20°C, the temperature of the main volume of a round billet with a diameter of 20 mm reached 80-90°C, at 300 mm/s increased up to 150°C. It is shown that with an increase in the deformation rate up to 300 mm/s the necessary pressing forces increase by 1.5 times, and, accordingly, the pressures during pressing and the load on the tool increase.

1. Introduction
Chromium bronze considered in this study is a classic representative of the group of low-alloy heat-strengthened bronzes for electrical applications. The scope of its application is quite extensive, but one of the most promising areas of its use is high-speed rail transport. This material meets modern requirements, is widespread and relatively inexpensive. One of the modern methods of obtaining contact wires is the method of pressing according to the Conform scheme [1, 2]. However, this process, due to the relatively large volume of the deformation zone, is carried out at high temperatures, which reduces the characteristics of finished products. A consistent development of this approach is the ECAP-Conform method, which allows obtaining higher characteristics of finished products [3,4] including contact wires. It should be noted that the main role in the kinetics of structural and phase transformations during this process belongs to shear deformations. Therefore, the temperature regime is important during deformation of low-alloy heat-strengthened bronzes. However, direct control and, accordingly, the temperature correction in the deformation zone, is difficult to implement due to the design features of the equipment. Existing work on the analysis of deformation heating during ECAP is based either on direct observations using thermometric instruments, mainly in areas close to the
deformation zone, or on mathematical calculations performed using tabular values and coefficients found in the databases of the software systems used for modeling [5-7].

In this work, to study the rheological behavior of the Cu-0.6Cr alloy during ECAP at different rates of deformation, a combination of physical and finite element modeling was used.

2. Material and experimental procedures
As the material for the study, we selected the low-alloyed alloy Cu-0.6Cr (wt.%). The initial state of the alloy was obtained by high-temperature treatment at 1000°C for 1 hour followed by quenching in water that resulted in a supersaturated solid solution of chromium. In the initial state, the alloy had electrical conductivity equal to 35% IACS, average grain size of 130±12 µm and ultimate strength of 270±10 MPa.

Physical modeling was carried out using the Gleeble 3500 complex. Nine cylindrical samples were prepared for physical modeling with the diameter of 10 mm and length of 14 mm. Temperature control was carried out using a K type thermocouple welded to the sample by means of contact welding. After the preparation of the samples, their upsetting was carried out up to the strain value of ε = 1.1, which corresponded to the accumulated strain during one cycle of ECAP [8]. In the process of upsetting, the values of the temperature of the samples, the deformation force, and stresses during deformation were recorded.

Computer modeling was carried out in the Deform 3D software package. Based on the data obtained using the Gleeble facility, a database was prepared for the finite element computer simulation of the upsetting process and then, after verification, for the ECAP process. The heat transfer coefficient of the tool with the workpiece was taken equal to 11 N/s/mm/°C (11000 W/m²·°C). For the workpiece, a finite element mesh consisting of 15,000 tetrahedra was generated. Since a volumetric deformation pattern with high contact stresses was simulated, the Siebel friction factor was used. Based on experimental and literature data [9, 10], the Siebel friction factor for a steel-bronze pair was taken to be 0.1. The impermeability condition was set on the contact surfaces of the rig. The number of simulation steps is 300-1000. The strain rates were equal to 3, 30, and 300 mm/s. As a result of the simulation of the ECAP process of chrome bronze with different rates of deformation, data on deformation heating, power characteristics of the process, and the stress-strain state of the workpiece during deformation were obtained and studied.

3. Results

3.1. Microstructural analysis and properties after physical modeling
Characterization of the microstructure of samples after upsetting (figure 1) indicates a significant refinement of structural elements down to the range of nanometers. One can see that in all cases a predominantly elongated structure is formed. The average transverse size of the structural components, depending on the rate of deformation, is about 155 ± 10 nm at 3 mm/s, 215 ± 13 nm at 30 mm/s, and 220 ± 12 nm at 300 mm/s. At the same time, at the deformation rate of 3 mm/s, dislocation clusters are observed mainly in the grain boundary regions, while at higher deformation rates of 30 and 300

Figure 1. Microstructure of Cu-0.6Cr alloy after upsetting: a - 3 mm/s; b- 30 mm/s, c- 300 mm/s.
mm/s, dislocation networks and walls are observed in the grain body. That is, at a lower velocity, the redistribution of dislocations and their migration to the boundaries of grains and subgrains has time to occur.

In the course of the physical experiments, it was found that with an increase in the rate of deformation, stresses increase, while the electrical conductivity of the alloy also increases, which indirectly indicates an intensification of the process of deformation-stimulated decomposition of a supersaturated solid solution with an increase in the rate of deformation (Table 1).

| Deformation rate, mm/s | Stress, MPa  | δ, %IACS |
|------------------------|--------------|----------|
| 3                      | 485±15       | 61       |
| 30                     | 520±15       | 64       |
| 300                    | 690±20       | 70       |

3.2. Computer simulation results

3.2.1. Deformation heating. Analysis of the data shows that at the deformation rate of 3 mm/s (figure 2a), the temperature field in the workpiece is fairly uniform, so the difference between the maximum and minimum temperatures in the deformation zone is about 20°C. The maximum value of deformation heating is 50-55°C. At the deformation rate of 30 mm/s (figure 2b), the temperature field of the workpiece is nonuniform, so the difference between the maximum and minimum temperatures in the deformation zone is about 30-35°C. The maximum value of deformation heating is 95-100°C. Data analysis shows that at the deformation rate of 300 mm/s (figure 2c), the temperature field of the workpiece is extremely inhomogeneous, so the difference between the maximum and minimum temperatures in the deformation zone reaches up to 130°C, depending on the initial temperature. The maximum value of deformation heating is about 230°C.

Thus, under conditions of severe plastic deformation by the ECAP method, intense deformation heating occurs. The deformation rate has a significant effect on heating, so at the initial room temperature of 20°C with an increase in the deformation rate from 3 to 300 mm, deformation heating increases from 50 to 230°C.

3.2.2. Stress-strain state. Figures 3 a, b show the distribution of the accumulated strain in the longitudinal section of the workpiece. The distribution is non-uniform, the maximum values are observed in the peripheral areas and are equal to \( \varepsilon \approx 2.5 \). This can have a positive effect on the strength and wear resistance characteristics of the finished product in the form of a contact wire (in the area of the friction pair of the contact wire). The minimum values in the central region are of the order of \( \varepsilon \approx 1.4 \).

The stress state was estimated from the average stress in the deformation zone. According to the analysis of the data obtained in the deformation zone, regardless of the deformation rate, compressive
stresses prevail, which in turn contributes to the production of defect-free products. Figures 4 c, d show the distribution of average stresses at the deformation rate of 30 mm/s. One can see that the stress state is inhomogeneous, the maximum values of compressive stresses reach 230 MPa.

![Figure 3](image)

Figure 3. Stress-strain state of the workpiece during ECAP at an initial temperature of 20 °C and a deformation rate of 30 mm/s: a, b - accumulated strain distribution; c, d - distribution of average stresses

According to the simulation, as the rate of deformation increases, the required deformation force increases. For the deformation rate of 3 mm/s, the required force is about 210 kN, for 30 mm/s and 300 mm/s it amounts 220 kN and 280 kN, respectively.

Conclusions

Thus, in the course of computer modeling, a comprehensive analysis of the stress-strain state of the workpieces during processing by the ECAP method under various rate conditions was carried out.

It was found that during severe plastic deformation by the ECAP method, intense deformation heating occurs. The deformation rate has a significant effect on heating, so at the initial room temperature of 20°C with an increase in the deformation rate from 3 to 300 mm/s, the deformation heating increases from 50 to 230 °C. An increase in the rate of deformation also leads to an increase in the required force. At 20°C, an increase in the deformation rate from 3 to 300 mm/s leads to an increase in the force from 210 to 280 kN.

Based on the data obtained during the physical experiment, it was found that with an increase in the deformation rate, not only an increase in stresses and the required force will occur, but also the decomposition of a supersaturated solid solution will occur more intensively, which makes it possible to increase the electrical conductivity of the alloy to 70% IACS. The strain of \( e = 1.1 \) ensures the formation of a grain-subgrain type structure with the size of structural elements down to 150-220 nm.

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References

[1] Barcellona A, Cannizzaro L and Riccobono R 2000 Proc. of the 33rd Int. MATADOR Conf. 353-358
[2] Babcock Wire Equipment Ltd http://www.bwe.co.uk
[3] Xu C, Schroeder S, Berbon P B and Langdon T G 2010 Acta Mater. 58 4 1379-86
[4] Raab G I, Valiev R, Gunderov D, Lowe T C, Misra A and Zhu T 2008 Mater. Sci. Forum 584-586 80-5
[5] Karamia J S 2016 Mater. Res. 19 640-7
[6] Kim H S 2001 Mater. Trans. 42(3) 536-8
[7] Pei Q X, Hu B H, Lu C and Wang Y Y 2013 Scripta Mater. 49 303-8
[8] Utyashev F Z and Raab G I 2013 Deformation Methods for the Fabrication and Processing of Ultrafine-Grained and Nanostructured Materials (Ufa, Gilem) (in Russian)
[9] Loginiv Yu N 2006 Copper and Wrought Copper Alloys (Ekaterinburg, USTU) (in Russian)
[10] Male A T 1964 J. Inst. Metal. 93 38-46