Increase of physical and mechanical properties of low-alloy bronze of the Cu-Cr system by radial swaging

R N Asfandiyarov¹,², D A Aksenov¹,² and G I Raab¹
¹Ufa State Aviation Technical University, 12 K. Marx str., Ufa 450008 Russia
²Institute of Molecule and Crystal Physics - Subdivision of the Ufa Federal Research Centre of the Russian Academy of Sciences, Prospekt Oktyabrya 151, Ufa, Russia, 450075

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

Abstract. Conventional methods for producing wires for high-speed railways include continuous casting, rolling and/or subsequent drawing and do not always allow achieving the required level of operation properties. In the presented work, as an alternative, under the conditions of continuous processing, a combined method is proposed, including radial swaging (two cycles) and subsequent deformation by the ECAP-Conform method combined with forming the shaped profile of a low-alloy bronze wire of the Cu-Cr system. The stress-strain state and thermal conditions of plastic processing operations were investigated using computer simulation. It is established that the combined treatment by radial swaging with subsequent ECAP-Conform and the forming operation of the shaped profile allows achieving a total true deformation up to the value $e \sim 7$. A comparative physical experiment showed that the relative ductility of bronze after rotational reduction is 1.5 times greater than after rolling, and is 23% and 15%, respectively.

1. Introduction

An important direction in the development of rail transport is increasing the speed of trains. However, with the increase in speed, the loads on the contact networks of high-speed railroads also increase. One of the features of the operation of high-speed railway contact wires is that the tension of the wire is increased by 2.5-2.7 times, in comparison with the traditional conditions, which is a consequence of an increase in the speed of propagation of a mechanical wave at speeds of 300-400 km per hour [1]. In addition, the cross-section of the wires decreases due to mechanical wear in the permissible range up to 20%. Thus, there is a need to increase the strength of the contact wires while maintaining other operation characteristics.

Known traditional methods - rolling and subsequent drawing, have some drawbacks and do not always allow achieving the required level of operational properties. As a rule, the quasimonotonous character of the deformation at high drawing coefficients leads to high anisotropy of properties and a critical decrease in ductility in the longitudinal direction. In addition, a large fracture of deformation entails increased energy consumption and requires large production areas.

In this paper, as an alternative, the method of radial swaging is studied. Radial swaging under certain regimes can be considered as one of the methods of severe plastic deformation (SPD) [2]. Currently, SPD is widely used to improve the physical and mechanical properties of metals and alloys and is of great scientific and practical interest [3]. The traditional scheme of radial swaging has a number of
advantages, including relatively high productivity, high metal utilization, increased strength characteristics, comparatively low power consumption, high precision and product quality, the ability to process long products, simplicity and speed of tool change-over, relative versatility of the tool. It is also important that during radial swaging a low level of tensile stress is observed, which reduces the defectiveness of the surface layers of the billets and promotes an increase in technological ductility [4,5].

As indicated the quasimonotonic nature of the deformation of the traditional scheme of radial swaging (RS), usually leads to the drawing-down of the billet mainly in one direction - along the longitudinal axis. For this case, the rotations of the principal axis of the strain tensor relative to this direction are rather small, which leads to the formation of an axial texture [2,6,8]. Although it is known, that the degree of monotonicity of deformation is an important factor that has a decisive influence on the formation of more isotropic properties [9], moreover an extremely nonmonotonic deformation is most preferable. To increase the factor of nonmonotonicity of deformation under radial swaging, a new geometry of the deforming tool was proposed and the effect from its use was investigated in the present paper.

The main goal of the paper is to investigate the influence of the geometry of the deforming tool, which provides conditions for an increased nonmonotonic deformation, on the structure and properties of low-alloy bronze of the Cu-Cr system under conditions of combined thermomechanical processing; as well as to study the stress-strain state of the billet in the process of sequential processing by the radial swaging method and the subsequent ECAP with the forming of the shaped profile of the wire.

In connection with the goal, the following tasks are defined:
- characterization of the billet’s structure by the SEM method after treatment with RS and rolling with the same degree of drawing;
- study of physical and mechanical properties of billets after treatment by RS and rolling with the same degree of drawing;
- analysis using finite-element computer simulation of the stress train state of a full-scale industrial billet in the process of radial swaging and subsequent ECAP according to the "conform" scheme with the formation of a shaped wire profile.

2. Materials

The Cu-0.6Cr alloy is a thermally strengthened alloy, after thermo-mechanical treatment it has a good combination of physical, mechanical and operational properties [10], and is suitable for the manufacture of electrical products. The initial state of the material was obtained by heat treatment, including holding for one hour in a Nabertherm furnace at a temperature of 1050° C with further quenching into water. As a result, an equiaxed grain structure is obtained. The average grain size was 120 ± 3 μm. In the initial state, the Cu-0.6Cr alloy has the following physical and mechanical characteristics: tensile strength ~ 240 MPa, electrical conductivity 45% IACS, ductility 40%.

3. Methods

During the experiment, the samples were produced by three methods of deformation.

3.1. Radial swaging

Radial swaging was performed on a rotary forging machine of model B.2129. The initial rod 350 mm in length, 14 mm in diameter, was processed in 3 passes with a single degree of deformation equal to e ~ 0.3-0.4 to the final cross-sectional dimension 6.8 mm, the treatment was carried out at room temperature, preheating of the billet during one the pass was about 50° C.

The billet was fed manually. Two sets of anvils were used, with traditional and special geometry. The special shape of the anvils makes it possible to increase the degree of accumulated strain in comparison with the classical tool, as well as to increase the degree of nonmonotonicity [11]. The
difference is illustrated in figures 1 and 2, which present 3D models of classical and with a special form of anvils.

After deformation treatment, the samples for tensile tests were cut from a rod; some of them were subjected to heat treatment - aging. Aging was carried out at 450° C for 1 hour.

![Figure 1. Application of anvils of classical shape.](image1)

![Figure 2. Application of anvils with a special shape.](image2)

3.2. Rolling

The rolling mill of “YUMO” brand (Russian origin) was used for rolling. The initial rod with a diameter of 14 mm and a length of 350 mm was rolled at room temperature, with reduction of 0.2-0.3 mm per pass to the cross-sectional dimension of 6.8 mm. After deformation treatment, samples for tensile tests were cut from a rod, some of them were subjected to heat treatment - aging. Aging was carried out at 450° C for 1 hour.

4. Results

4.1. Microstructural analysis

After deformation by rolling with a degree of $e = 1.2$, a coarse-grained structure elongated in the direction of the longitudinal axis with a coefficient of elongation of the grain shape $k \sim 15..17$ is formed. A grain-subgrain type of structure with an average grain size of $42 \pm 2 \mu m$ is formed in the cross section of the sample, the grains having a shape close to equiaxial with the presence of twin boundaries of deformation origin. With rotary forging in special shaped anvils, with the same degree of deformation $e = 1.2$, a smaller band-like structure with an average strip size of about $6-10 \mu m$ is formed and also with a coefficient of elongation of the grain shape $k = 13 \ldots 15$. Inside the bands, a high density of secondary slip bands is observed, which indicates the inhomogeneity of the deformation. A strongly deformed structure with a high misorientation of the boundaries of predominantly equiaxed grains $6-10 \mu m$ in size is observed in the cross section of the sample.

Microstructure images taken from a scanning electron microscope are shown in figure 3.
Figure 3. Microstructure images in a scanning electron microscope after rolling (a, b) and rotary forging in special anvils (c, d) in the longitudinal and cross sections of the sample, respectively.

4.2. Physical and mechanical properties

In the course of the study, the main attention was paid to three parameters: strength, electrical conductivity and ductility. Strength and electrical conductivity are one of the main characteristics of contact wires, technological ductility affects the quality of the product, and increased residual ductility positively affects the operational reliability of the product. The obtained results are summarized in the table.

Table. Physical and mechanical properties of Cu-0.6Cr alloy after radial swaging and rolling.

| Method                  | Stain degree | UTS, MPa  | Elong.% | Electrical conductivity, %IACS |
|-------------------------|--------------|-----------|---------|-------------------------------|
| Radial swaging          | 1.202        | 390±10    | 14      | 33±2                          |
| Radial swaging +aging   | 515±15       | 23        |         | 73±2                          |
| Rolling                 | 1.202        | 375±10    | 11      | 83±2                          |
| Rolling + aging         | 480±15       | 15        |         | 76±2                          |
The obtained positive information from the use of rotary forging to achieve the enhanced properties in the Cu-0.6Cr alloy allowed us to proceed to the design of a pilot-experimental process for producing a contact wire using radial swaging elements and traditional SPD methods. A virtual analysis of one of the variants of such a process is presented below.

5. Computer simulation of the combined process of producing shaped wires for high-speed railways

It is known that in order to obtain the ultrafine grained (UFG) and nanostructured (NS) states in metals and, accordingly, the increased strength characteristics, a combination of high intensity and essential nonmonotonicity of deformation is necessary, and the temperature of the deformation process should not exceed the recrystallization temperature [7]. The combined process proposed for computer research, including the sequential radial swaging of the billet and its subsequent deformation by ECAP-Conform with the formation of the shaped profile of the wire, fully corresponds to the mentioned above information (Figure 4), where radial swaging is carried out for two cycles under conditions of large single deformation of more than 50% with the change of the force application axis, similar to comprehensive forging, and ECAP for one cycle, with a single accumulated deformation to \( e = 1.18 \).

![Figure 4](image)

**Figure 4.** The proposed technological scheme for producing a contact wire using SPD methods: the initial billet after the first RS, after the second RS, after the ECAP and the formation of a shaped profile.

Finite-element computer modeling was carried out in the Deform-3D software package. For the preparation of geometric models of the tool and billet, a 3D Compass three-dimensional modeling system was used (figures 5-7).

In modeling the process of radial swaging, a number of tasks were set by, namely:
- analysis of the temperature regime of treatment;
- stress analysis;
- analysis of the deformed state;
- analysis of the power parameters of the process.
Figure 5. The scheme of the developed model of the first forging unit: 1 - the first anvil; 2 - second anvil; 3 - billet; 4 - imitation of feed.

Figure 6. Scheme of the developed model of the second forging unit: 1 - vertical anvils; 2 - horizontal anvils; 3 - billet; 4 – support.

Figure 7. ECAP-Conform scheme with formation of the contact wire profile: 1 – working wheel; 2 - matrix; 3 - a clamp; 4 – billet.

5.1. The conditions and assumptions used in modeling

The material of the initial billet is low-alloy bronze Cu-0.65Cr. In the modeling, the hardening curves taken from the Deform 3D database were used. The billet is a plastic body. The stamp tool is an absolutely rigid body. The dimensions of the rectangular cross-section of the initial billet are 37.2x74 mm, length - 300 mm. The option of compensating the volume of the billet model was activated. A finite element mesh was created, consisting of tetrahedrons, the number of which was 32,000. The minimum element size is 3.2 mm, the maximum size is 6.5 mm. For the tool model the finite element mesh was not made. The speed of movement of the anvils was chosen to be constant for all simulation variants and was 200 mm / s. The angular velocity of rotation of the working wheel was 1 rad / sec, which corresponds to 10 rpm. The cross-section of the billet after the first forging block is 33x65 mm.
On the contact surfaces of the die-set, the condition of impermeability is specified. The coefficient of friction for Zibel was assumed as: during forging as \( f = 0.2 \); during ECAP-Conform \( f = 0.4 \) between the wheel and the billet, \( f = 0.2 \) between the billet, the clamp and the matrix.

The simulation was performed for the process of room temperature deformation, taking into account the increase in the metal temperature due to the thermal deformation effect. The coefficient of heat exchange between the anvils and the billet was taken as 5 N/sec/mm°C (5000 W/m²°C).

5.2. Analysis of the data received in the postprocessor

The study of stress strain state and thermal conditions for processing the combined treatment scheme is presented in figures 8-10.

**Figure 8.** Patterns of distribution of the accumulated strain of the billet: a - the 1st forging block, b - the second forging block, c – ECAP-Conform.

From the analysis of patterns of distribution of accumulated strain (figure 8) it follows that in the longitudinal section of the billet the accumulated deformation after the first forging block averages \( e = 1 \ldots 1.1 \), with the maximum values prevailing in the center of the billet, which corresponds to the simple upsetting scheme, with the formation of a deformation cross (shear deformation). After the second forging block, the level of accumulated strain increases to \( e = 2.5 \ldots 3.5 \). After the second block, a high homogeneity of the strain distribution is observed. After the ECAP-Conform process at the steady-state stage of the flow in the exit part of the channel, the level of accumulated strain is \( e = 5.5 \ldots 6.5 \) and the degree of homogeneity of the deformation distribution is also high, which implies homogeneity of the properties obtained. Thus, the shear character in the deformation centers and the high level of accumulated strain are a significant prerequisite for the formation of the UFG structure.
Figure 9. Main stresses in the longitudinal section of the billet: a - 1st forging block, b - 2nd forging block, c – ECAP-Conform.

Figure 10. Billet’s temperature: a - 1st forging block, b - 2nd forging block, c - ECAP-Conform.
Analysis of the results of computer simulation showed that in the region of the deformation zone of the billet, compressive stresses predominate in all three stages of plastic processing (Figure 9). Such loading schemes are "soft" and, as a rule, promote the production of items without defects. The torque moment on the wheel during ECAP-Conform in the steady-state flow is 300 kN • m and does not exceed the capabilities of the existing technological equipment, for example, extruder of the Conform 550i brand. The thermal effect of deformation along transitions is quite high and the temperature at the final stage of the process (ECAP-Conform) can reach 550 °C (Figure 10).

6. Conclusions

1. It was found that at the same reduction ratio (~ 1.2), the size of structural fragments in the cross section after rotary forging is much less than after rolling. On average, after rotary forging, the size of structural fragments is ~ 6.5 ± 0.5 μm, and after rolling 42 ± 3 μm.

2. Subsequent aging of the samples of the RS produced at 450° C, (1 hour) leads to an increase in their strength to ~ 515 MPa, relative to ~ 480 MPa after rolling and similar heat treatment.

3. The relative ductility of the samples obtained by the RS method and aging is 23%, which is much higher than this index equal to 15%, after rolling and aging.

4. The electrical conductivity after the thermal processing of billets produced by the rolling mill and rolling is 73-76% IACS.

5. Computer simulation of the combined process for producing a shaped wire from Cu-0.6Cr alloy for high-speed railroad applications showed the following:
   - the total level of accumulated strain was $e = 5.5 \ldots 6.5$
   - average stresses at all three stages of plastic processing are mainly compressing
   - the torque moment at the ECAP-Conform at the established stage of the flow do not exceed the capability of the technological equipment available in the market in the form of an extruder of the Conform 550i brand.
   - deformation heating of billets at the final stage of the process (ECAP-Conform) can reach 550 °C.

Acknowledgments

The authors are grateful for their support to the Ministry of Science and Education of the Russian Federation under Grant agreement No. 14.586.21.0025 (UIN: RFMEFI58616X0025).

7. References

[1] Gershman I S and Mironos N V 2011 Requirements for contact wires for high-speed rail transport Vestnik of All-Russia R&D Institute of Railway Transport 3 13-17 (in Russian)
[2] Valiev R Z and Aleksandrov I V 2000 Nanostructured materials produced by severe plastic deformation (Moscow: Pegas) p 272 (in Russian)
[3] Gunderov D V, Nizamutdinova A M, Valeev K A and Stolyarov V V 1998 RFeB alloys in the initial state and subjected to severe plastic deformation by torsion Bulletin of the Bashkir University 2 28-32 (in Russian)
[4] Sosenushkin E N 2013 Technologies of constructional nanomaterials from the position of synergic approach News of National Technical University “Kharkov polytechnical institute” 42 156-166 (in Russian)
[5] Dedyulina O K, Salishchev G A 2013 Fundamental research Formation of ultrafine-grained structure in medium-carbon steel 40Cr-Mn-Ni-Mo by rotary forging and its influence on mechanical properties I 701-706 (in Russian).
[6] Utyashev F Z 2008 Modern methods of severe plastic deformation (Ufa: USATU) p 313 (in Russian)
[7] Kaybyshev O L and Utyashev F Z 2002 Superplasticity, refinement of structure and processing
of hard-to-deform alloys (Moscow: Science) p 438 (in Russian)

[8] Tyurin V A 1990 Forging on radial swaging machines (Moscow: Mechanical engineering) p 256 (in Russian)

[9] Zherebtsov S V 2013 Structural changes in the course of large plastic deformation and the development of methods for producing an ultrafine-grained structure in semi-finished products of titanium-based alloys: Abstract of. dis. Dr. of Tech. sciences (Ekaterinburg: Ural Federal University named after the first President of Russia B.N. Yeltsin) p 43 (in Russian)

[10] Osintsev O and Fedorov V 2004 Copper and copper alloys. Domestic and foreign brands (Moscow: Mechanical engineering) p 336 (in Russian)

[11] Asfandiyarov R, Raab G and Aksenov D 2018 Solid State Phenomena Analysis of the stress-strained state of billets processed by rotary forging with special shape of the tool, in press