Modeling of a combined process for the production of contact wires for high-speed railways

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Abstract. The development of high-speed railways (HSR) is an important task aimed at improving the transport system of today's global community. The most heavily-loaded element of HSR, governing their reliability and lifetime, is a contact wire. In this connection, the present study was focused on designing a new set of physico-mechanical properties of a wire made from the heat-treatable Cu-0.65Cr alloy with the use of a new procedure of continuous plastic processing, based on the principles of severe plastic deformation. Thus, an important difference from the common technical solutions used in the production of wires was the use of a combination of SPD processes – radial forging and ECAP-Conform, joined with the shape-forming of shaped sections of wire. In our study, we performed finite-element computer and physical modeling of the processes of plastic and heat treatment. Using computer modeling, we demonstrated that as a result of the implementation of the new procedure of continuous processing, a rather homogeneous strained state is formed in the workpiece, and the accumulated strain is in a range of $\epsilon = 6-7$. At all stages of plastic processing, compressive stresses prevail in the deformation site. As a result of physical modeling, we produced laboratory samples of contact wire from the heat-treatable Cu-0.65Cr alloy with a cross-section area of 150 mm². Metallographic studies reveal that a banded structure of a grain-subgrain type with a fragment size below 1 micron is formed in the laboratory samples of contact wire. The ultimate tensile strength of these samples after heat treatment is 550-560 MPa, the electrical conductivity is 72-75% IACS, the ductility is 16-20%.

1 Introduction

Contact wire is one of the most heavily-loaded and important parts of HSR. In today's world with the growing speeds and volume of transportation, the requirements to contact wires increase correspondingly. There emerges a need to increase a set of performance properties of this product. The current technologies for the manufacture of contact wires for railway networks, incorporating the processes of continuous casting-rolling, as well as drawing and heat treatment, have restrictions in terms of variation of processing parameters and therefore cannot influence actively the properties of final products [1]. An alternative could be the methods of plastic structure formation, such as severe plastic deformation, resulting in an active influence on the physical and mechanical properties of commonly used metallic materials [2,3]. Due to an extremely non-monotonic strain, SPD enables producing ultrafine-grained states, also in copper materials, thereby providing enhancement of their properties [4-6]. In this connection, a new technological approach for the production of contact wires, using SPD methods, was developed as an alternative for the conventional approach. To meet the
conditions of continuous production, the most technologically advanced methods were selected, namely radial forging with an alteration of the axe of force application by 90 degrees and ECAP-Conform [7-10]. The ECAP-Conform operation was joined with the shape-forming of shaped sections of wire. This approach provides a range of advantages related to the reduction of power consumption, number of operations, expenditures between operations and expenditures for a die-set, with a reduction of the required production floors. In this study, we performed computer and verification analyses of the processing parameters and physico-mechanical properties of the samples of contact wire from a Cu alloy produced using a combination of SPD methods, and evaluated the use of the combined method for industrial production.

2 Finite-element computer modeling

When analyzing the deformation processes, our research was focused on the study of the stress-strain state (SSS) of the workpieces during the processing and temperature analysis. As it is known, these factors are responsible for the adaptability of a process to manufacture, the durability and reliability of a deforming tool, the physical and mechanical properties of materials subjected to deformation.

2.1. Boundary conditions in the modeling.

The material under study is a heat-treatable Cu-Cr alloy in the initial state, quenched from 1000°C. For the modeling, we used the Deform 3D database. The processing parameter of the rate of workpiece feed was selected on the basis of the conditions provided by foundry equipment and amounted to 4, 5 and 6 meters per minute. Radial forging was implemented in two processing operations.

The dimensions of the square cross section of the initial workpiece were 37.2x74 mm, the length was 300 mm. The finite-element grid of the workpiece was generated from tetrahedra in the amount of 32 000. The rate of the anvil movement was selected as constant for all of the modeling options and amounted to 200 mm/s. The angular rate of rotation of the working wheel was 1 rad/s, which corresponds to 10 rev/min. The cross section of the workpiece after the first forging unit was 33x65 mm, and after the second forging unit – 26x26 mm.

The friction coefficient according to Siebel was accepted as: f = 0.2 for radial forging; for ECAP-C, f=0.4 between the wheel and the workpiece, f=0.3 between the workpiece, the clamp and the die.

Modeling was performed for the processing at room temperature, taking into account the increment in metal temperature due to the thermal effect of deformation. The coefficient of heat exchange between the anvils and the workpiece was accepted as equal to 5 N/s/mm/°C (5000 W/m²×°C).

2.2. Research results. Stress-strain state.

It follows from the analysis of the patterns of accumulated strain distribution that in the longitudinal section of the workpiece, the accumulated strain after the first forging unit is on average e=1-1.3, with the maximum values prevailing in the workpiece center, which corresponds to the procedure of simple upsetting with the formation of deformation cross (shear deformation). After the second forging unit, the accumulated strain grows to 2.5-3.5, and there is observed a high non-uniformity of strain distribution. After ECAP-C, in the steady-state flow, at the channel outlet the accumulated strain in the shaped wire workpiece is e = 6-7 (figure 1), i.e. the produced rather homogeneous deformed state implies also the homogeneity of the produced properties. Thus, the use of an extremely non-monotonic deformation and the revealed high level of accumulated strain are a significant prerequisite for UFG structure formation. The average stresses emerging in the deformation site are predominantly compressive.
2.3. Analysis of the thermal fields of the workpiece during the processing.

The temperature range of deformation is another highly important factor, especially for the processing of heat-treatable materials under large severe strains. An increase in the temperature reduces flow stresses and, correspondingly, the deformation forces, accelerates the diffusion processes, solid solution breakdown and the precipitation of strengthening particles, therefore it is required to analyze these processes immediately after the processing. In addition, the aging temperature of the chromium bronze lies in a range of 450-500 °C (figure 2), which is a limiting factor for its plastic treatment in the solid-solution state (after quenching) and should be monitored under the conditions of intensive deformational heating. In this connection, study of the temperature fields was also an important task in our research.

The modeling shows that during high-speed swaging, an intensive deformational heating of the material takes place. After deformation in the first forging unit, the heating of the workpiece is 100-150 °C. After the second forging unit, the temperature reaches 250-290 °C. Processing by ECAP-Conform with pressing takes place with an intensive heat generation, and in the steady state in the peripheral zone of pressing the temperature reaches 550 °C. This established fact calls for measures to cool the workpiece, for instance, by air flow, prior to the ECAP-Conform operation.

3 Material and experimental procedure

3.1. Contact wire material.

The Cu-Cr alloy refers to a special class of low-alloyed conductive chromium bronzes [11]. Unlike other systems of bronzes with a high electrical conductivity, such as Cu-Ag, Cu-Sn, Cu-Cd, Cu-Mg, or heat-resistant systems Cu-Zr, Cu-Hf, the Cu-Cr alloy has simultaneously a high electrical conductivity and a high heat resistance. Besides, it is cheaper than the ternary system Cu-Cr-Zr.
It is also known that chromium affects electrical conductivity less than other alloying elements. The material in the initial state was produced by heat treatment, including holding in a Nabertherm furnace at a temperature 1000°C for 1 hour, followed by water quenching. As a result, an equiaxed grain structure was obtained. The average grain size was 120±3 µm. In the initial state, the Cu-0.65Cr alloy had the following physico-mechanical characteristics: ultimate tensile strength ~240 MPa, electrical conductivity 45% IACS, ductility 40%.

3.2. Physical modeling.
Physical modeling was performed following the principle of similarity to the processing. The processing is similar in terms of the following criteria – the pattern of forces applications, the speed parameters of processing, the temperature range of processing, as well as the geometrical similarity with consideration of true strain. The operation of radial swaging was conducted using a pneumatic hammer, turning the workpieces during the processing. The frequency of strokes of this hammer is 210 min\(^{-1}\) (the frequency of strokes of the anvils on the radial-forging machine is about 300 min\(^{-1}\)). The temperature of the workpiece in the beginning of the process was room temperature, 20°C. The heating of the workpiece during the processing was 300°C. The direction of drawing was maintained during the processing. The proposed procedure of plastic processing is displayed in figure 3.

![Figure 3. The proposed procedure for producing contact wire using SPD methods – the initial workpiece, after the first radial swaging, after the second radial swaging, after ECAP-C and shape-forming of shaped sections.](image)

The next operation of the proposed technology is ECAP-Conform joined with the extrusion of shaped sections of contact wire. In order to observe the principle of similarity, the die-set and the workpiece during the processing were heated to a temperature of 450°C. The laboratory sample produced as a result of pilot studies are shown in figure 4. The wire samples were subjected to heat treatment (aging) at a temperature of 450°C for 1 hour.

**Experiment results**

![Figure 4. General view of the workpiece after ECAP.](image)
Structural studies demonstrate that as a result of plastic processing via the proposed procedure, a homogeneous banded structure is formed (figure 5), with particle precipitation predominantly at boundaries. Finer studies (TEM) (figure 5) show that the size of fragments inside the bands is below 500 nm.

Studies of the physical and mechanical properties provided the following results:

- electrical conductivity: 72-75% IACS;
- ultimate tensile strength: 550-560 MPa;
- ductility 16-20%;
- number of twists: 6;
- number of bends: 4.

In comparison with the conventional processing (quenching – drawing $\epsilon=70\%$ – aging) providing an ultimate tensile strength of 520 MPa, a ductility of 5%, an electrical conductivity of 72-75% IACS, we have attained a higher set of properties in contact wire [11].

**Conclusions**

- Using mathematical modeling, we have investigated the stress-strain state, thermal fields and processing parameters for the processes of radial swaging and ECAP-Conform with the extrusion of shaped sections of contact wire.

- It has been established that the intensity of strain in the process of radial forging after the second unit is distributed rather uniformly and reaches 3.5. After ECAP-C, the accumulated strain reaches $\epsilon=6-7$, while in the central region of the wire's cross section slightly smaller values of $\epsilon=5-6$ prevail.

- It has been shown that in the process of ECAP-Conform deformational heating to 550 °C occurs in the peripheral region of the zone of shape-forming of the wire sections. It has been found that at all of the three stages of plastic processing, compressive stresses prevail (a «mild» deformation procedure), which has a beneficial effect on the quality of a produced item.

- As a result of physical modeling, we have produced samples of contact wire for HSR with a new set of physico-mechanical and performance properties, having an electrical conductivity of 72-75%, an ultimate tensile strength of 550-560 MPa, a ductility of 16-20%. For the bronze of the investigated chemical composition, this is a new enhanced set of physico-mechanical properties.

- As a result of plastic processing via the proposed procedure, there forms a homogeneous banded structure with particle precipitation predominantly at boundaries, with the size of fragments inside the bands equal to 300-500 nm.
Acknowledgements

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

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 pp 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 pp 28-32 (in Russian)
[4] 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)
[5] Utyashev F Z 2008 Modern methods of severe plastic deformation (Ufa: USATU) p 313 (in Russian)
[6] 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)
[7] Dedyulina O K and Salishchev G A 2013 Formation of ultrafine-grained structure in medium-carbon steel 40Cr-Mn-Ni-Mo by rotary forging and its influence on mechanical properties Fundamental research 1 pp 701-706 (in Russian)
[8] Tyurin V A 1990 Forging on radial swaging machines (Moscow: Mechanical engineering) p 256 (in Russian)
[9] Asfandiyarov R, Raab G and Aksenov D 2018 Analysis of the stress-strained state of billets processed by rotary forging with special shape of the tool Solid State Phenomena, Accepted for publication
[10] Sosenushkin E N 2013 Technologies of constructional nanomaterials from the position of synergetic approach News of National Technical University “Kharkov polytechnical institute” 42 pp 156-166 (in Russian)
[11] Osintsev O and Fedorov V 2004 Copper and copper alloys. Domestic and foreign brands (Moscow: Mechanical engineering) p 336 (in Russian)