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Structure and properties of the contact wire obtained by ECAP with forming

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Abstract

This paper presents the results of the development of a promising method for manufacturing contact wires for high-speed railways. The developed method is based on the principles of severe plastic deformation and the combination of metal-forming processes. The solution obtained is a combination of equal-channel angular pressing with the forming of a shaped contact wire with a cross-sectional area of 120 mm^2 in one tooling. A feature of the work is that with the help of a comprehensive study by the methods of finite element computer modeling and a physical experiment, not only the stress-strain state of the deformation zone was investigated but also an analysis was made of the effect of deformation heating, which plays an important role when working with dispersion-hardened alloys, such as Cu-0.65Cr. It was established that the temperature in the equal-channel angular pressing zone reached 490°C to 505°C, and during shaping, it rose to 510°C to 530°C. In the course of a physical experiment, a laboratory sample of a contact wire with a tensile strength of 410 ± 8 MPa and an electrical conductivity of 35 ± 2% IACS was obtained. Post-deformation aging led to an increase in tensile strength up to 540 ± 20 MPa and restoration of electrical conductivity up to 76 ± 2% IACS. Due to the formation of a stripe structure of a grain-subgrain type with recrystallized grains along the boundaries, the plasticity of the contact wire sample reached 20%.

1. Introduction

At present, for the manufacture of contact wires, commercially pure copper and strain-hardened low-alloy copper alloys are used. With the development of high-speed rail transport, the technical requirements for contact wires have increased significantly. If one considers loads on traditional railway lines at low speeds (up to 160 km·h^{-1}), then, according to [1,2], the tension force of a wire with a cross-sectional area of 100 mm^2 is about 10 kN, which corresponds to a voltage of 100 MPa. For a wire made of commercially pure copper, the ultimate tensile strength is 350 MPa to 370 MPa, which corresponds to a safety factor of about 3.5. To ensure the normal operation of the contact network (including stable current collection) at a train speed of about 300 km·h^{-1}, it is necessary to increase the tension force to values of the order of 30 kN for an area of 150 mm^2 and up to 20 kN for an area of 110 mm^2 [2,3]. In addition to high tensile forces, the contact wire experiences cyclic thermal loads due to friction and current flow. The wire temperature can reach 160°C to 180°C. Such temperature values are close to the values of the temperature at the beginning of recrystallization of commercially pure copper (for brand M1 $T_{recryst.}$ ~180°C).

Thus, for high-speed rail transport, there is a need to use a new generation of contact wires, which must meet a set of requirements for physical, mechanical, and operational characteristics. In accordance with the new requirements, the tensile strength of the wire must be more than 500 MPa while maintaining the electrical conductivity at the level of 75% to 85% IACS [4].

One of the solutions to the problem outlined above is low-alloy heat-strengthened bronzes. Since the manufacturing process of contact wires is based on metal forming technologies, in the production of wires from such materials, special attention must be paid to deformation heating, which affects the formation of the structure and properties of the finished wire. One of the modern approaches in the processing of metals by pressure is the use of methods based on the principles of severe plastic deformation, which make it possible, due to the active refinement of the structure and the deformation stimulation of phase transformations, to significantly increase the complex of mechanical and physical properties in low-alloy heat-strengthened bronzes [5-7]. These methods include, for example, equal-channel angular pressing according to the Conform scheme (ECAP-Conform). The creation of such processes presents certain difficulties and requires a thorough analysis of the technological features of the methods used.

This work is aimed at studying deformation heating, as well as the features of structure formation and phase transformations in the process of manufacturing a laboratory sample of a contact wire, using the ECAP method with forming with post-deformation aging.

2. Experimental

A dispersion-hardened Cu-0.65% Cr alloy with high electrical conductivity was chosen as the research material. The initial state was obtained by holding at a temperature of 1050°C for 1 h, followed by quenching in water to form a supersaturated chromium solid solution in a copper matrix. In the initial state of the sample, a coarse-grained structure was observed with an average grain size of 180 ± 5 μm. Tensile strength was 230 ± 20 MPa, microhardness was 760 ± 40 MPa. The electrical conductivity was 30 ± 2% IACS.

To study the distribution of thermal fields in the process of deformation, the authors used mathematical modeling by the finite element method in the Deform 3D environment. Within the framework of this simulation, the following boundary conditions were determined: hardening curves for the material of the original workpiece (Cu-0.65% Cr) were set according to preliminary rheological studies on the Gleeble 3500 complex. The simulation was performed taking into account the increase in metal temperature from the thermal effect of plastic deformation (deformation warm-up). The heat exchange coefficient of the tool with the workpiece was taken equal to 11 $N\cdot s^{-1}\cdot mm^{-1}\cdot °C$ (11,000 $W\cdot(m^{-2} \times °C)$). The thermal conductivity coefficient – 391 $W\cdot(m \times K)^{-1}$, heat capacity – 7 $J\cdot(g\times°C)^{-1}$, radiation 0.3, Poisson's ratio 0.33, Young's modulus 1.15×10^5 MPa.

The deformation was carried out by the ECAP method with wire forming on the RKUP-20 installation. Processing was carried out for 1 cycle of deformation. The diameter of the original workpiece was 20 mm, length 100 mm. The temperature of the matrix was 450 ± 10°C, and the initial temperature of the sample was 450 ± 10°C [8]. The strain rate was 5 $mm\cdot s^{-1}$.

The structure of the obtained samples was analyzed using scanning and transmission electron microscopy (TEM Jeol JEM-2100, Tescan MIRA 3 LMH with EBSD attachment).

The microhardness of the samples was measured using a Duramin-2 microhardness tester. Mechanical tensile tests were carried out according to GOST 1497-84 using an Instron 5982 tensile testing machine. The sample was at least 3 samples for each state under study. Studies of electrical conductivity were determined according to GOST 7229-76 using a VE-27NC eddy current meter, with the values converted to the IACS standard (International Annealed Copper Standard).

3. Results and discussion

Deformation heating can play an important role in the formation of the structure and properties in precipitation-hardened alloys. Upon heating, the process of decomposition of a supersaturated solid solution is activated, which is aimed at additional hardening by dispersed particles [6,8-10]. However, in the process of deformation processing, it is not always possible to control the temperature conditions directly in the deformation zone. It should be noted that for carefully studied and stably flowing, and in some cases monotonous, traditional processes, such as rolling and drawing, a fairly accurate experimental and analytical determination of temperature conditions is possible. In such processes, heating and further temperature distribution in the billet are quite stable and predictable. However, in the case of nonmonotonic, high-intensity deformation processes, which are also characterized by a complex tooling configuration, the determination, and control of temperature fields in the deformation zone becomes a non-trivial task. These processes also include the ECAP method studied in the present, combined with the forming of the contact wire profile. To solve this problem, an integrated approach was used, including finite element computer modeling and a physical experiment with thermometering using a thermal imager.

Figure 1(a) shows the result of computer simulation in the form of temperature distribution fields in the longitudinal section of the billet during ECAP with wire forming. Analysis of the data obtained shows that the temperature in the ECAP zone reaches 490°C to 505°C, the temperature during the forming of the wire is distributed fairly evenly and ranges from 510°C to 530°C. The maximum heating is achieved in the zone of pressing (forming) of the wire and reaches 530°C. At this level of heating in the Cu-0.65Cr alloy during deformation, the aging process actively develops, which affects the nature of the formation of the dislocation structure in the material and the physical and mechanical properties. Temperature measurement during a physical experiment using a thermal imager (Testo 872) (Figure 1(b)) showed that, under the condition of preheating the sample to 450°C, the maximum recorded outlet temperature was 460°C, which generally correlates with the value of computer simulation – 490°C.

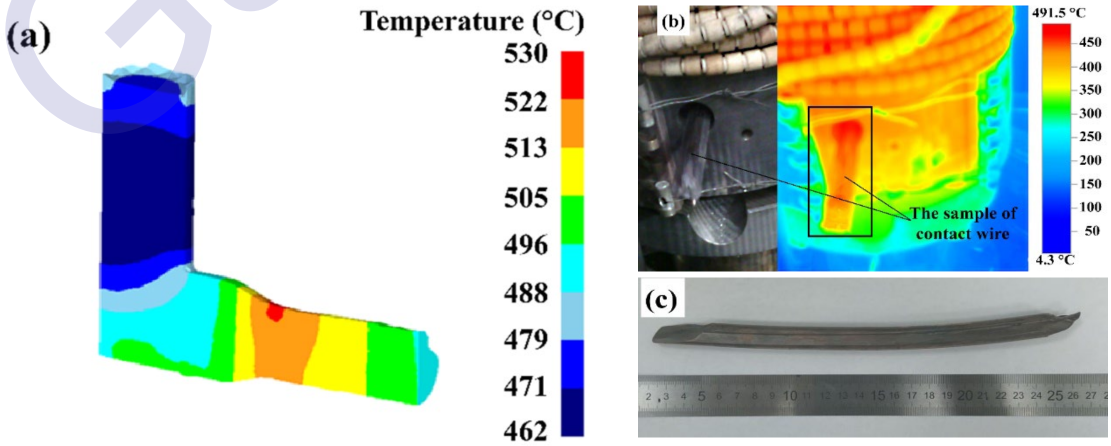

Figure 1. (a) Temperature distribution fields during the 1st ECAP cycle with forming, (b) image of the tooling and temperature fields of the sample (TESTO 872), and (c) the sample of a contact wire obtained by the ECAP method with forming.

In the course of a physical experiment using the ECAP method combined with forming, a laboratory sample of a shaped contact wire with a cross-sectional area of 120 mm^2 was obtained (Figure 1(c)). To achieve an increased set of properties, the resulting sample was subjected to post-deformation aging at 450°C for 1 h.

Structural studies were carried out at different structural levels. At the mesolevel (SEM), an accumulation of recrystallized grains between the bands was observed. In the EBSD pattern, small recrystallized grains ~2 μm to 3 μm in size were observed within the band boundaries (Figure 2). This type of dynamic recrystallization directed along the boundaries of the bands is continuous [11-13]. Recrystallized grains indicate local heating in the boundary regions. A developed subgrain structure is observed in the body of the bands.

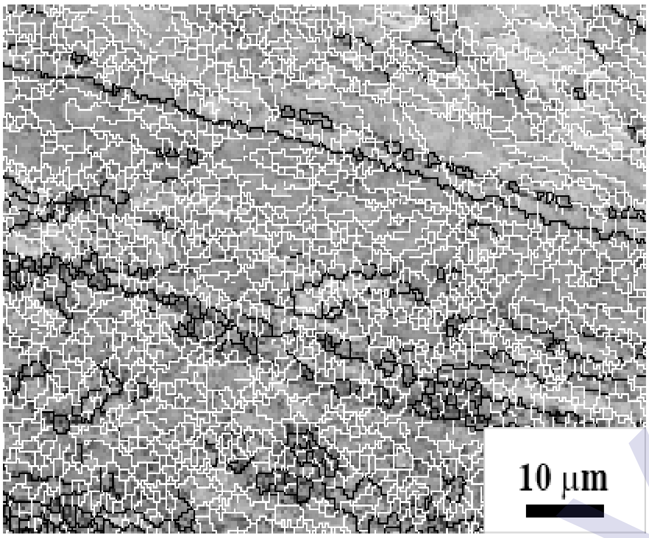

Figure 2. Structure of Cu-0.65Cr alloy: map of low-angle (white lines) and high-angle (black lines) boundaries.

Microstructure studies (TEM) indicate a significant refinement and the formation of a stripe-type structure with an average transverse fragment size of 410 ± 8 nm (Figure 3(a)). Dispersed particles fixed on dislocations were observed in the body of the fragments. The average particle size was ~20 nm [17]. The tensile strength to destruction was 470 ± 20 MPa, and the electrical conductivity was 35 ± 2%.

Post-deformation aging at 450 ± 10°C for 1 h led to the formation of thinner fragment boundaries, while their average transverse size did not change to 400 ± 18 nm (Figure 3(b)). In the body and along the boundaries of the fragments, finely dispersed particles of the second phases with an average size of ~25 nm were also observed.

The tests of the mechanical properties show that 1 cycle of deformation treatment according to the proposed scheme made it possible to increase the strength characteristics by 2 times, so the tensile strength to destruction was 470 ± 20 MPa. The electrical conductivity remained practically unchanged and amounted to 35 ± 2% IACS (Table 1).

The tests of the mechanical properties show that 1 cycle of deformation treatment according to the proposed scheme made it possible to increase tensile fracture strength characteristics by a factor of 2. Electrical conductivity after aging was restored to a value of 76 ± 2% IACS, and the tensile fracture strength due to dispersion hardening reached the value of 540 ± 15 MPa. One should note rather high values of relative elongation in tension, which after aging reached a value of 20%. This may be due to the high temperature of deformation and the presence of recrystallized grains within the boundaries of the bands.

Improving the modern production of contact wires for high-speed railway networks is an urgent task, the solution of which will allow reducing travel time, increasing the volume of freight and passenger traffic, and reducing the cost of repair and maintenance of railway networks.

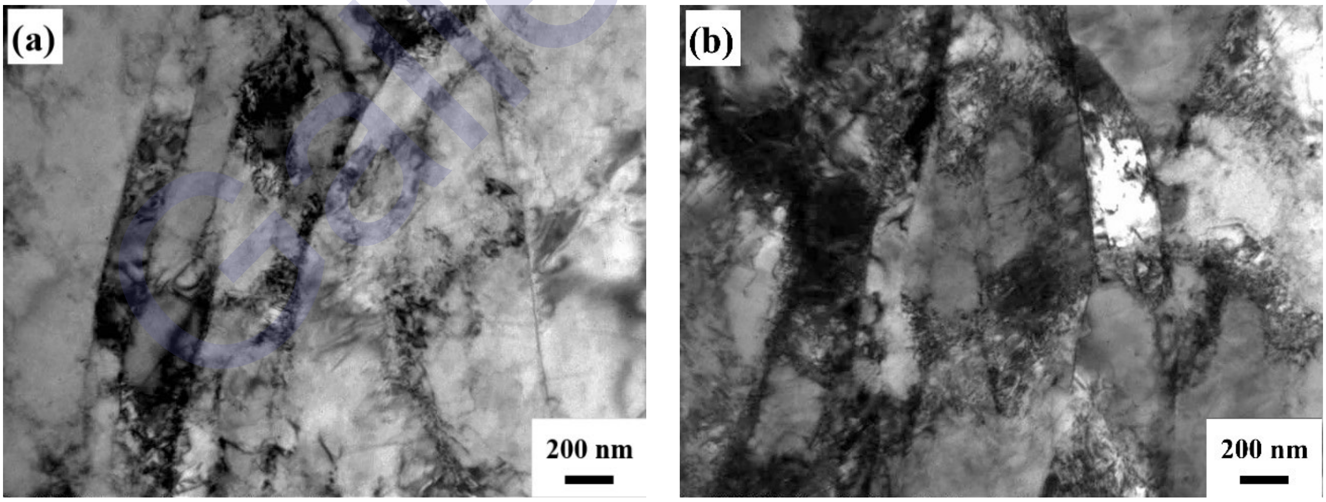

Figure 3. Microstructure imaging (TEM) (a) after ECAP, and (b) after ECAP with forming and aging.

Table 1. Physical and mechanical properties after ECAP with forming and aging.

State	UTS (Mpa)	YTS (Mpa)	HV (Mpa)	Elongation (%)	Electroconductivity (% IACS)
ECAP with forming	470 ± 20	400 ± 10	1120 ± 50	16 ± 2	35 ± 2
ECAP with forming and aging	540 ± 20	475 ± 10	1450 ± 50	20 ± 2	76 ± 2

Table 2. Properties of alloys of the Cu-Cr and Cu-Cr-Zr systems after ECAP.

Work	Regime	UTS (MPa)	Elongation (%)	Electroconductivity (% IACS)
Present work	ECAP-forming 1 pass	540 ± 20	20 ± 2	76 ± 2
[22]	ECAP 8 passes + aging	580	≈6	81
[23]	ECAP 8 passes + aging	618		35
[24]	ECAP 8 passes	550	9.3	≈68

Analysis of data from the world practice of copper contact wire production shows that their production is based on the use of technologies based on continuous casting-rolling mills and subsequent drawing [15-21]. It should be noted that the leading manufacturers in this field prefer to use low-alloyed heat-strengthened alloys as the main material of the contact wire, for example, alloys of the Cu-Cr, Cu-Cr-Zr systems.

Copper alloys of the Cu-Cr, Cu-Cr-Zr systems, in particular, combine high strength and heat resistance, together with high electrical conductivity. Traditional methods of processing them (for the production of contact wires) include hot deformation processing by rolling, which is carried out at temperatures close to the melting point, which leads to the recrystallization of the crushed structure. Thus, one of the main tasks is to transfer the temperature regime of deformation processing below the recrystallization temperature region.

The studies carried out in the framework of this work show that the use of a scheme with a combination of ECAP with a forming operation makes it possible to obtain a finished contact wire in one operation of deformation processing. The use of such a technological solution provides a reduction in the number of operations and inter-operational costs and also reduces the required production space compared to the traditional processing scheme. At the same time, the temperature of the product at the exit from the tooling, first, does not reach the recrystallization temperature, and, second, corresponds to the aging temperature, which favorably affects the properties of the finished product.

The comparative Table 2 shows that the strength of this alloy, as a rule, reaches the level of 500 MPa to 600 MPa after several cycles of deformation processing and post-deformation aging, while ductility can significantly decrease. In this paper, a more technologically advanced method is considered, which makes it possible to achieve a rational set of functional properties in a smaller number of processing cycles.

4. Conclusions

1. It was established that for 1 cycle of ECAP combined with forming and post-deformation aging, it was possible to obtain a contact wire with a strength of 540 ± 20 MPa, a relative elongation of 20%, and an electrical conductivity of 76% IACS.

2. In the course of computer simulation, it was found that the maximum heating occurred in the zone of wire forming and the heating value of the workpiece reached 510°C to 530°C.

3. Using the ECAP method with forming followed by aging, an experimental sample of a contact wire with a cross-section of 120 mm^2 was obtained. As a result of deformation processing, a grain-subgrain structure of a stripe type was formed with an average transverse size of fragments of 400 ± 18 nm with an ensemble of fine particles of the second phases with a size of ~25 nm.

4. Despite the high heating temperature, the time for deformation treatment was not sufficient for the aging process to take place completely (electrical conductivity increased from 30% to 35% IACS). Deformation by ECAP with forming at a billet and matrix temperature of 450°C was accompanied by continuous recrystallization, during which new recrystallized grains ~2 μm to 3 μm in size were formed along the band boundaries.

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