Development of severe plastic deformation methods for the production of contact wires from a Cu-Zr alloy for high-speed railways

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Abstract. Zirconium is, like chromium, one of the most promising alloying elements. Microalloying with these elements enables increasing significantly not only the mechanical characteristics of copper alloys by cold deformation methods, while preserving a high electrical conductivity, but also imparting hot-strength properties. At room temperature, zirconium bronze is slightly inferior to chromium bronze in terms of strength characteristics, but it has a higher electrical conductivity and ductility. This set of properties determines the operational efficiency of wires. Another important parameter is the wear resistance of wires. Taking into account the operational restrictions related to wear, amounting to 20% of the wire’s cross-sectional area, wires can be strengthened not across the whole section, but with a gradient, i.e. with a stronger surface layer and a weaker core. This will enable providing an enhanced wear resistance and strength of a wire and further increasing its ductility and bending fatigue limit.

One of the methods to produce such properties is the method of rotary active alternating bending, which enables, in the conditions of multi-cycle processing, accumulating a high level of strain predominantly in the surface layers of wires. In this work, we present the study of this method with respect to the formation of a gradient-type structure in the samples of a Cu-Zr alloy, with the use of computer and full-scale modeling.

1. Introduction

Requirements to the properties of modern products and structural materials become higher and more specific. First of all, it refers to the responsible metal products operating under extreme conditions in aerospace, chemical, medical and other industries. In recent years, to increase the strength characteristics by the formation of ultrafine grained (UFG) and nanostructured structures, methods of severe plastic deformation (SPD) have found a wide application. Materials obtained by such processing, for example nanostructured aluminium and copper, can become harder than high-strength steels, but they have a very low ductility and become brittle.

One of the ways to improve the mechanical characteristics of products while maintaining their operational properties is to obtain metallic materials with a gradient structure. It was revealed that the gradient structure of a material, in which the grain size belongs to the nanoscale on a surface and to a coarse-grained scale in the center of a billet, is promising for the improvement of the physical and mechanical characteristics and operational properties of metals and alloys.

The presence of a gradient of the strain and structure can be of interest for controlling the local properties of materials, i.e. for obtaining surface areas with a noticeable increase of the strength properties, in long-length metallic semi-products. The combination of more durable surface layers...
with a plastic core in resulting materials can improve their wear, bending, fatigue and crack resistances [6,7].

The aim of the present work is to study the new method of rotational active alternating bending with the possibility of forming a gradient structure in the process of non-monotonic (alternating) plastic deformation. With this aim, the deformed state of billets obtained by rotational active alternating bending using computer simulation was investigated [8].

2. Material and experimental procedure

For the study we selected the Cu-Zr alloy having a standard chemical composition (table 1). Before the full scale modeling of deformation treatment of the alloy under study, computer simulation of rotational active alternating bending was made for an analysis of the investigated method (figure 1a). A simplified scheme, which includes one bend with the subsequent turning of the workpiece to 180° relative to its longitudinal axis, was used.

**Table 1.** Chemical composition and deformation treatment temperature of the investigated alloy

| Alloy   | The content of alloying elements, wt.% | Deformation treatment temperature, °C |
|---------|---------------------------------------|--------------------------------------|
| Cu - Zr | Cu: 99.82, Zr: 0.18                  | 20                                   |

![Figure 1](image)

**Figure 1.** Scheme of rotational active alternating bending for deformation processing of long-length billets of various metals and alloys(a): 1 – housing, 2 – rollers, 3 – billet

3. Computer simulation of rotational active alternating bending

Computer simulation of the process of rotational active alternating bending of Cu-Zr alloy rods was made using rheological properties, which were included in the software. The application package DEFORM3D was used to implement the numerical simulation. In order to conduct modeling in the application package DEFORM3D, three-dimensional models were created in the software product Kompas-3D. The model of a 10x10 mm square rod with a length of 300 mm was used as the billet.

The following conditions were accepted for simulation:
1. The billet material in the initial state is isotropic and has no initial stresses.
2. The temperature is fixed at 20°C.
3. The tool is an absolutely rigid body.
4. In order to simulate the whole process of the passing of a workpiece through the rollers and obtain stable results of simulations, the number of simulation steps was taken equal to 150.
5. The number of finite elements is equal to 70000.
6. The friction coefficient between the tool and the billet is equal to 0.12.
7. The pull speed is assumed to be 60 m/min.
8. The rotation of rollers is free and occurs due only to the contact friction.

4. Results of simulation and analysis

Figure 2 shows the strain intensity after one and two operations of rotational active alternating bending. Analyzing the first picture, it should be noted that the deformation intensively increases already at the first stage of bending, and not only peripheral, but also central areas of the workpiece are processed. The graph of the distribution of strain intensity over the cross section of the sample has a hyperbolic shape. Moreover, in the region, where compressive stresses prevail (contact with the roller), the strain reaches approximately 1.4, and in the opposite region where tensile stresses occur, it amounts about 1.0, so the average value over cross section is equal to 0.4. After second bending with the change of deformation direction by 180°, the strain value reaches 1.95 in the compression zone and 1.76 in the opposite region, where tensile stresses occur, with an average value of about 1.0.

![Figure 2. Strain intensity distribution in longitudinal section after the deformation: a – first bend, b – second bend](image)

Such an intensive deformation of the billet during processing by the method of rotational active alternating bending is associated with the arrangement of the rollers, their geometrical parameters and the conditions of their rotation about the axis of pulling. Thus, the mathematical model shows that by one cycle of processing by the method of rotational active alternating bending, the accumulation of a large strain intensity is possible in the conditions of high processing speeds of long-length products.

5. Conclusions

According to the results of experiments it was determined that the use of the method of rotational active alternating bending leads to a significant increase in the level of accumulated strain in the surface areas of the billet. So after one processing cycle the level of strain in the cross section of the billet changes is between $e = 0.4$ and $e = 1.4$ and after two cycles with a rotation of the billet to 180° before the second bend it changes in the interval from $e = 1.0$ to $e = 1.9$. This distribution indicates the gradient distribution of strain in the cross section of the billet with its maximum values in the peripheral regions of the deformed long-length square billets.

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