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Evolution of Copper Microstructure Subjected to Combined Twisting and Drawing Technology

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This work studies evolution of copper microstructure during a combined deformation process. The essence of this process is in deformation of copper wire in a rotating equal-channel stepped matrix with subsequent drawing. Deformed wire is examined using transmission electron microscopy and EBSD analysis. After three cycles of deformation, an ultrafine-grained gradient microstructure with a high component of high-angle grain boundaries is obtained.

Key words: copper, wire, twisting, drawing, microstructure.

У роботі досліджено еволюцію мікроструктури міді в процесі нового суміщеного процесу деформування. Суть цього процесу полягає в деформуванні мідного дроту в обертовій рівноканальній ступінчастій матриці, що обертається, і подальшому волочінні. Дослідження деформованого дроту проводилося за допомогою просвітної електронної мікроскопії й аналізи EBSD. Після трьох циклів деформування одержано ультрадрібнозернисту ґрадієнтну мікроструктуру, що має високу складову висококутових меж зерен.

Ключові слова: мідь, дріт, скручування, волочіння, мікроструктура.

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1. INTRODUCTION

In the production of current conductors and thermal engineering, cop-

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per is used as a material with high electrical and thermal conductivity. Abroad, interest in problems of physical and mechanical properties of functional conductor materials forming has recently increased due to the need to stabilize properties of current conductors and increase their reliability, including in heavily loaded cable systems, windings of motors and generators, and low-current computer networks. Also, in recent years, technologies for the production of copper products, its grades, and research methods have been continuously improved. As a result, it turned out that old approaches for explaining phenomena that arise in production conditions ceased to fulfil their role.

As a result of large deformations, grain structure of the metal reached the level of nanosizes, and the workpieces themselves turned out to be highly textured, both due to a very high level of deformation and due to the absence of intermediate annealing, latter being dictated by the energy and resource saving. The structure and texture formation processes under large accumulated deformations are of particular interest. Therefore, in the last two decades, much attention has been paid by researchers to the production of ultrafine-grained (UFG) structures in metals and alloys by methods of intense (large) plastic deformation (SPD), due to the possibility of a sharp increase in their strength by up to 2–5 times [1–7]. At the moment, technologies that most effectively refine the structure include methods that, during multicycle processing, implement a simple shear scheme. However, despite the large number of methods developed and research conducted, all methods of severe plastic deformation developed to date have many different shortcomings, the most important of which is the limitation of workpiece in size [8–10]. Therefore, development of new processes for producing high-strength materials with improved strength properties is a relevant and important issue for the development of production. In this regard, the use of an improved drawing method, combining torsion methods that implement a simple shear scheme and classical process of drawing through a die, makes it possible to expand boundaries of traditional structural materials use.

The process developed in this work is based on the method of drawing in a rotating die; this technology is aimed at the reducing of drawing force at the contact between the tool and workpiece and allows obtaining a gradient structure. Following this technique, scientists [11] developed a shear drawing method, which consists of drawing of original workpiece through an asymmetrical conical channel formed by two dies with simultaneous rotation of one of the dies [11]. An important difference between our method and the method described in [11] and other known methods of intensive drawing is that the workpiece is twisted in an equal-channel stepped matrix due to its rotation around the axis of workpiece, which makes it possible to achieve twisting throughout the entire volume of the workpiece with subsequent calibration cross section due to the passage of die channel. Drawing after severe plastic deformation in a rotating equal-channel stepped matrix was chosen because of the simplicity of the process and high tensile stresses arising directly in the deformation zone, which ensures the straightness of wire during processing. An equal-channel stepped matrix, which stands before drawing die, ensures the implementation of transverse and longitudinal shear deformations, this will eliminate the most important drawback of the drawing process, namely, low plasticity.

In this regard, the purpose of this work is to study the processes of structure formation in copper subjected to deformation using the combined technology of twisting in an equal-channel stepped matrix and drawing.

2. EXPERIMENTAL

Physical laboratory experiments were carried out in order to study the effectiveness of developed technology. The model material was wire made of commercially pure copper grade M1 (99.9 Cu) with a diameter of 6.5 mm.

The essence of technological process is the deformation of wire in a rotating equal-channel stepped matrix and subsequent drawing. The matrix rotates around the wire axis and thereby creates tension due to equal channel angular drawing and twisting in the matrix. Rotation of matrix is carried out in a specially designed mechanism, which is installed in the equipment line of drawing mill in a block with technological lubrication, which allows the supply of lubricant to the matrix and the die in the drawing block (Fig. 1). The lubricant consists of soap shavings and serves to reduce the forces that arise when pulling the rods through the working grooves of the die.

Special design of rotation module is a series of alternating gears installed in a vertical plane, connected by two frames. Rotating die design consists of two separate segments, which allows sharpened wire to be threaded first into the drawing die and the front end of the wire to be secured in the drawing drum jaws, then, laid the wire between the segments of equal-channel stepped matrix. Two matrix channels (input and output) are located parallel to each other, with the central channel at an angle of 145° to the input and output channels. The inlet and outlet channels are conical in shape to facilitate wire removal and lubricant injection into the die. The bandage of rotating installation has the same geometry, which makes it possible to bring two segments together without additional fasteners. The matrix is installed in the bandage using wedging type. Rotation of matrix is carried out by transmitting torque from the drive gear through the intermediate gear to the matrix band, in which it is installed.

Technology of twisting process in an equal-channel stepped matrix

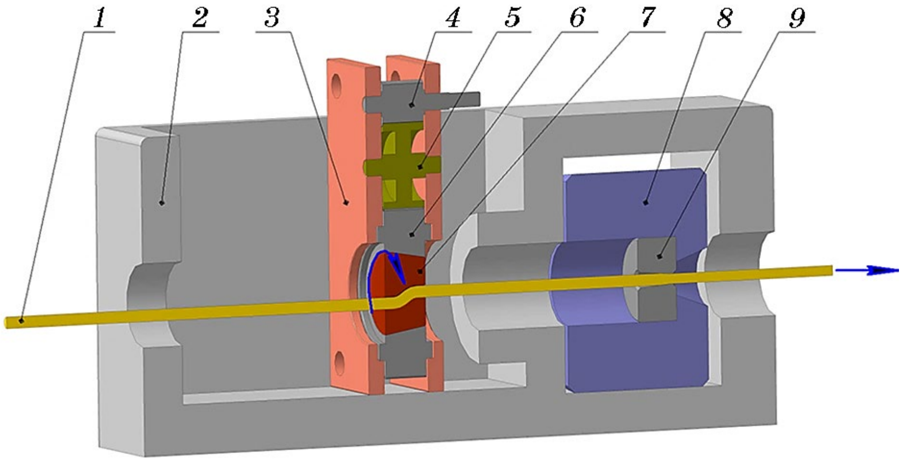


Fig. 1. Scheme of wire deformation combined process: wire (*1*), drawing block (*2*), bed (*3*), drive gear (*4*), intermediate gear (*5*), bandage (*6*), equal-channel stepped die (*7*), die stand (*8*), die hole (*9*).

followed by drawing does not differ significantly from classical drawing. At the first stage, wire is sharpened on a sharpening machine to the required diameter. Next, the wire is passed through a chamber with lubricant in which the rotation mechanism is installed. The wire passes through the hole in the die bandage and then through the hole in the die. The front end of wire is fixed in the drawing drum pliers. Next, two segments of an equal-channel stepped matrix are installed around the wire and inserted into the bandage using the wedge principle. At this stage, all preparatory operations are completed.

After which the mill is started up, reaching the planned drawing speed, and in parallel the mechanism that rotates the equal-channel stepped matrix is set in motion.

An important condition for the occurrence of this process is the coordination of drawing speeds in the die and in the equal-channel stepped matrix with the rotation speed. The forces created in the workpiece being processed should not exceed material tensile strength.

To implement the combined technology when deforming copper wire, an industrial drum drawing machine B-1/550M was used. Deformation was carried out at room temperature using the *Bc* route (the rotation of the wire after each deformation cycle was carried out at 90°) [12, 13]. The number of passes is 3. Reduction in wire diameter after each deformation cycle is 0.5 mm. So, after 3 passes of deformation, we obtained a wire with a diameter of 5.0 mm.

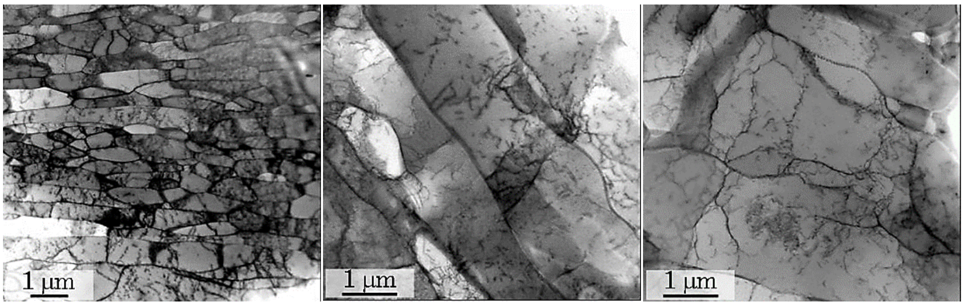
Metallographic analysis was carried out using a JEM2100 transmission electron microscope. Foil was made from planes perpendicular and parallel to the drawing direction.

Diffraction techniques for measuring crystal orientation in localized areas, such as EBSD, now play an important role in characterizing small-scale microstructural features. EBSD analysis was carried out on a Philips XL-30 REM instrument with a field cathode. To distinguish between low-angle grain boundaries and high-angle grain boundaries, statistical analysis was performed using a critical misorientation angle of 15°.

3. RESULTS AND DISCUSSION

Metallographic analysis of deformed copper wire was first carried out using an optical microscope to observe general appearance of structure refinement. Cross-sectional optical microscope examination shows a gradient structure. Surface layer is refined to 500 nm to a depth of ≅ 1 mm. Further, grain size increases towards the central part of the wire and amounts to 4 µm.

Figure 2 shows TEM photographs of microstructure. The first image was obtained at a distance of ≅ 0.2 mm from the surface of wire (surface layer) (Fig. 2, *a*). As can be seen, grain boundaries are fibrous and curved, which is usually characteristic of a large number of defects; average grain size is 500 nm. Following TEM image was obtained at a distance of ≅ 2 mm from the wire surface (middle layer) (Fig. 2, *b*). Bimodal structure, which consists of small grains with high-angle boundaries and large grains with a developed substructure, was formed. Average grain size is 2 µm. A fine structure is formed inside the grains in the form of clusters of dislocations and cells. And the last image was obtained from the central part of wire (Fig. 2, *c*). The structure presented a cellular dislocation structure of deformation origin with an average grain size of 4 µm. Observed as large grains with a small number of subboundaries, as well as grains containing large



a *b* *c*

Fig. 2. Microstructure of a deformed copper wire in a cross-section: surface layer (*a*); middle layer (*b*); the central part (*c*).

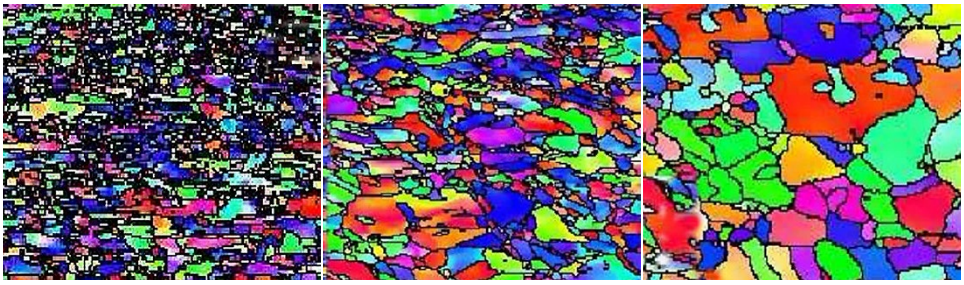

a *b* *c*

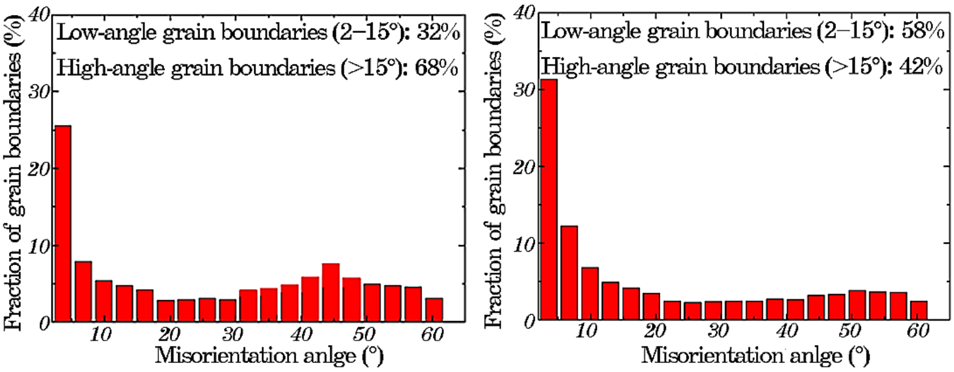
Fig. 3. Orientation maps of copper wire microstructure in cross-section: surface layer (*a*); middle layer (*b*); the central part (*c*).

number of subboundaries.

EBSD analysis was performed for quantitative analyse of high-angle and twin boundaries at different depths presence (Fig. 3). As a result of EBSD analysis, it was found that almost all grains are involved in twinning process; such active twinning leads to increasing of high-angle boundaries. Formation of new high-angle boundaries leads to a decrease in average grain size. As described in [14, 15], the voltage required for twin nucleation increases with decreasing grain size faster than the voltage required to activate slip. This can explain the fact that the largest number of twins occurs in the middle layer of wire.

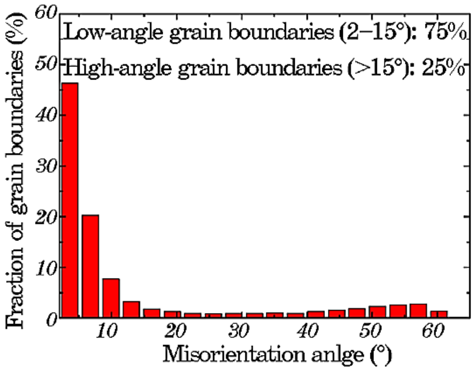
The proportion of high-angle boundaries in the surface layer of deformed wire is 68%, in the middle layer—≅ 42%, and in the centre—≅ 25% (Fig. 4).

The formation of a gradient microstructure after deformation by a combined technology in a rotating equal-channel stepped matrix and



a *b*

Fig. 4. Histograms of misorientation angles in copper: surface layer (*a*); middle layer (*b*); the central part (*c*).



c

Continuation of Fig. 4.

subsequent drawing is associated with the existing deformation mechanism. Due to the combination of two deformation processes, large grains are constantly refined on the surface with increasing deformation. Moreover, during drawing, formation of new boundaries does not occur; all fragmentation of the structure occurs in an equal-channel stepped matrix during shear deformations due to mechanical twinning. Therefore, the main formation of structure is realized during shear deformation in the matrix, which is inherited during drawing.

4. CONCLUSION

The work examines copper wire deformed using a new technology, distinctive feature of which is the combination of a shear pattern and a tension pattern in one deformation zone. The alignment was made possible by simultaneous deformation of wire in a rotating equal-channel stepped matrix and drawing. As a result of deformation, copper wire with a gradient structure was obtained. The surface layer is refined to 500 nm to a depth of ≅ 1 mm. Further, the grain size increases towards the central part of wire and amounts to 4 µm. The proportion of high-angle boundaries in the surface layer of deformed wire is 68%, in the middle layer—≅ 42%, and in the centre—≅ 25%.

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