Development of copper wire deformation technology

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Abstract: *The paper studies the evolution of microstructure and mechanical properties of copper wire during a new combined deformation process. The essence of the technological process is deformation of wire in a rotating equal-channel step matrix and subsequent drawing. The matrix rotates around the wire axis and thereby creates stress due to equal-channel angular drawing and twisting in the matrix. The deformed copper wire was investigated by transmission electron microscopy and EBSD analysis, as well as tensile tests and microhardness determination. The deformation resulted in an ultrafine-grained gradient microstructure having a high component of high-angle grain boundaries. The tensile strength of the deformed copper wire compared to the undeformed one increases more than twice from 302 to 635 MPa, and the yield strength increases from 196 to 306 MPa, an increase of 56%. The use of such hardened copper wire in construction will reduce the weight of the structure by reducing the diameter.*
KEYWORDS: *WIRE, DRAWING, TWISTING, COPPER, TECHNOLOGY.*

1. Introduction

One of the most promising methods for increasing the strength and plastic properties of metals is the formation of ultradisperse structures in materials using deformation methods. However, despite numerous developments, modern methods have a number of significant limitations in terms of continuity and productivity of process flows [7-8]. One of the most effective methods for obtaining an ultrafine-grained structure is the methods of severe plastic deformation (SPD) [9-10].

Equal channel angular pressing (ECAP), which is probably the most widely used severe plastic deformation technology, is considered as a promising method to achieve the desired high degrees of deformation [11-13]. Recently, based on this method, a large number of its modifications have appeared [14-16], some of which make it possible to obtain high-quality products [16-18].

However, despite numerous developments, the problem of creating a new deformation scheme that is as close as possible to industrial conditions and is of scientific and practical interest from the point of view of mass production remains unresolved. One of such schemes may be a new continuous scheme of equal-channel angular pressing and drawing (ECAP-drawing) [19-21]. Its key feature is that, unlike other combined methods, there is no rolling stage. Continuity of deformation is ensured by the drawing process, which occurs immediately after the ECAP process. Due to this unique deformation pattern, a fairly high level of tensile stress develops in the cross section of the workpiece, and incorrect selection of technological parameters will lead to breakage of deformed wire.

However, despite the listed advantages, ECAP drawing has a disadvantage associated with the manufacturability of the process. To achieve a high level of detailing, several deformation cycles are required. In practice, this means either sequential replacement of the ECA-matrix and drawing tool after each pass (for a single-pass drawing mill), or the creation of a sufficiently long production line (for a multi-pass drawing mill). Therefore, further relevant direction for the combined ECAP-drawing process development is the creation of an additional level of deformation, which will reduce the required number of deformation cycles. In this case, it is necessary to take into account the fact that due to this additional deformation, the cross-section of the wire should not change much, since if the cross-section is reduced, the effect of any existing stage of combined process may decrease, and if it is increased, the deformation process may be impossible. All these parameters correspond to the torsion operation, which, when developing SPD processes, is represented as a classical high-pressure torsion process [4,29,37].

The key difference between the developed technology studied in this work and the ECAP-drawing technology is that in an equal-channel stepped matrix, due to rotation around the axis of the workpiece, it is twisted, which makes it possible to achieve an additional level of deformation in the entire section. When the wire enters the die, its cross-section is calibrated in the die channel. An equal-channel stepped matrix, which stands before drawing, ensures the implementation of transverse and longitudinal shear deformations, which eliminates the main disadvantage of drawing process - low ductility.

In this regard, the use of an improved deformation method that combines torsion, simple shear and classical drawing process makes it possible to realize a higher level of metal processing and expand the boundaries of traditional structural materials use.

2. Material and research methodology

To implement the combined technology during the process of copper wire deformation, an industrial drum drawing machine V-1/550M was used. The deformation was carried out at room temperature using the Bc route (the rotation of wire after each deformation cycle was carried out at 90°). The number of passes is 3. The 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.

The technology of twisting process in an equal-channel stepped matrix followed by drawing does not differ significantly from classical drawing (Fig.1). At the first stage, the 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 the wire is fixed in the drawing drum pliers.

Figure. 1 *Scheme of wire straining new process: 1 - wire, 2 - drawing block, 3 - bed, 4 - drive gear, 5 - intermediate gear, 6 - bandage, 7 - equal-channel stepped die, 8 - die stand, 9 - die hole*

Next, two equal-channel segments are installed around the wire step matrix and are inserted into the bandage according to 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 equal channel stepped matrix is set in motion.

The preparation of samples for metallographic analysis was carried out using a Struers electrolytic sample preparation unit. All samples were examined in the middle plane of the sample to avoid the influence of peripheral regions. The effectiveness of hardening after deformation was assessed by measuring Vickers microhardness at a random load of 0,5H.

3. Experimental results

Metallographic analysis of deformed copper wire was carried out using an optical microscope to observe structure refinement general appearance. A cross-sectional optical microscope examination shows a gradient structure (Fig. 2). The surface layer is refined to 500 nm to a depth of ≈ 1 mm. Further, the grain size increases towards the central part of the wire and amounts to 4 μm. The longitudinal structure is elongated and parallel to the drawing direction in the surface layer and is more uniform in grain towards the center.

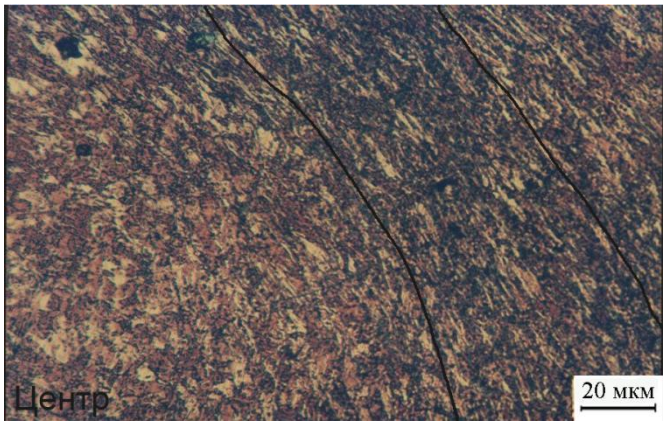

Fig. 2 *Microstructure of copper wire after 3 cycles of deformation*

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

After the metallographic analysis, a microhardness study was carried out. The initial microhardness after annealing was 77 HV. After 3 deformation passes, the hardness increased almost 3 times. Thus, the average value of microhardness in the surface layers was 216 MPa, in the middle layers - 174 MPa, and in the center of the wire 155 MPa. This scatter in microhardness can be explained by the formation of a gradient structure and strengthening of grain boundaries due to an increase in the dislocation density.

Considering resulting gradient structure, it was decided to study the change in microhardness along the wire cross section after each pass. In order to construct a microhardness profile, measurements were carried out through each millimeter of the sample cross-section 3 times at each point of the graph. The results for each point were averaged. The graph is shown in Fig. 3. As can be seen from the graph, due to the presence of a gradient structure across the cross section of the rod, a smooth drop in the level of microhardness towards the center of the wire is observed.

5. Conclusion

The work examines copper wire deformed using a new technology, the distinctive feature of which is the combination of a shear pattern and tension pattern in one deformation zone. The alignment was made possible by simultaneous deformation of the 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 central part of the wire and amounts to 4 μm. Analysis of tensile diagrams showed that the tensile strength of deformed copper wire, compared to undeformed copper wire, more than doubles from 302 to 635 MPa, and the yield strength increases from 196 to 406 MPa. Also, after 3 passes of deformation, the hardness increased almost 3 times. Thus, average value of microhardness in the surface layers was 216 MPa, in the middle layers - 174 MPa, and in the center of the wire 155 MPa. This scatter in microhardness can be explained by the formation of a gradient structure and strengthening of grain boundaries due to an increase in dislocation density. Such high microhardness values of the surface layer help to increase the wear resistance of the wire, and the soft center increases its plastic properties.

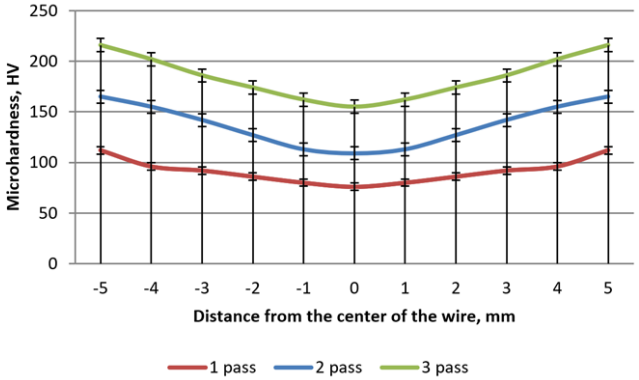

Fig. 3 *Microhardness of copper wire in cross section*

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