DEFORMATION OF COPPER BY HIGH-PRESSURE TORSION

Irina Volokitina[1], Andrey Volokitin[2], Dmitry Kuis[3]

[1] Rudny Industrial Institute, 50 let Oktyabrya str. 38, Rudny 111500, Kazakhstan
E-mail: irinka.vav@mail.ru
[2] Karaganda State Industrial University, Republic Ave. 30, Temirtau, 101400, Kazakhstan
[3] Belarusian State Technological University, 13a Sverdlova str., Minsk, 220006, Belarus

Received 08 February 2020
Accepted 15 April 2020

ABSTRACT

Findings of a study are presented below regarding the formation of ultrafine-grained structure in M1 grade copper under severe plastic deformation (SPD) by high pressure torsion at room temperature. The process was modeled in the Deform 3D package in order to verify the implementation of high-pressure torsion method (HPT) in new matrix. It allowed identifying "weak points" of the process, evaluating stress-strain state of the workpiece at each cycle step, strain intensity obtained in one full cycle of this method, and also required strain force. A laboratory experiment showed that after 8 cycles of deformation, an almost uniform structure with a subgrain size of ~ 0.3 μm forms in the copper. Tensile strength increased from 105 MPa to 380 MPa, elongation decreased from 28 % to 13%.

Keywords: microstructure, matrix, stress-strain state, mechanical properties, copper.

INTRODUCTION

To implement the plans facing the economy of the Republic of Kazakhstan, it is necessary to provide main industries with high-quality metal products with unique physical, mechanical and other operational properties. Often the solution to these problems is associated with high energy costs. In the conditions of lean use of energy and raw materials, the problem of energy and resource-saving methods for getting materials with properties is of great practical importance. These should combine both high strength and ductility, while using relatively simple and inexpensive devices that allow spending minimum possible amount of time to process products.

Traditional processes of plastic deformation, such as rolling, drawing, pressing, forging, etc., do not provide an effective solution to the problems of structure formation. When these methods are implemented, the plasticity resource is largely depleted directly in the process of deformation. As a result, processed materials have insufficient plasticity, and effects of deformation are only partially realized. The possibility of achieving a high strain rate in such processes is linked with multiple decrease of cross dimensions of processed products, consequently leading to significant processing pressures and the difficulty to get high properties in large sections.

Methods of severe plastic deformation, in contrast to traditional methods of metal forming aimed primarily at shaping, are used to significantly change the structure, phase composition, physical and mechanical properties [1 - 5]. As a result of SPD the length of grain and subgrain boundaries significantly increase in metal materials, and the static and dynamic dilatation of atoms in crystal lattice noticeably changes. Through this process, the strength characteristics of metals are getting increased by many times while maintaining sufficiently high plastic properties [6 - 9]. The most studied of all SPD methods is the high pressure torsion method. This method was developed by P.U. Bridgman (Nobel Prize in Physics in 1946) in the 1950s and further developed in the works of L.F. Vereshchagin, N.S. Yenikolopyan, V.E. Panin and other scientists from Russia, USA, Austria, Japan and China. One of drawbacks of HPT is the limiting grain refining, especially in pure metals, in the range of 300 nm - 500 nm [10 - 11].

The aim of this work is to study the changes in the microstructure and mechanical properties of M1 grade copper in heat-treated state during deformation by HPT in a new design matrix.

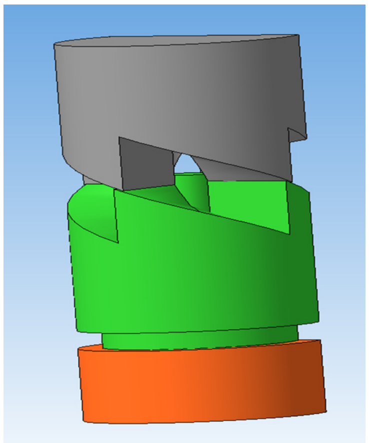

Fig. 1. High pressure torsion matrix model: a - distribution of logarithmic strain intensity ε_{int} over the workpiece cross section; b - distribution of equivalent stresses σ_{eq} over the workpiece cross section; c - distribution of medium stress σ_{med} over the workpiece cross section.

EXPERIMENTAL

A matrix of special design was developed in order to implement the process of high-pressure torsion on the existing equipment of department laboratory. This allows realizing high-pressure torsion process due to the rectilinear motion of striker relative to the body (Fig. 1).

The rectilinear motion of the upper striker, with upper part of the matrix fixed to it, transmits torque to it due to contact friction forces directed at inclined angle to counterpart of the matrix. As a result, the rectilinear motion turns into torsion motion.

The matrix consists of three parts. The lower part is a fixed matrix, into which a sample is placed in the form of a disk with a diameter of 30 mm and thickness of 5 mm. There is a rotating part of matrix having a lower flat surface in contact with the workpiece. And the upper surface, which is a spiral shape, consisting of four segments. The upper part of matrix is fixed in the upper striker, also having a spiral shape, consisting of four segments.

At the initial moment segments are disconnected, then upper and lower parts of the matrix come closer together. The central part of matrix is torqued due to segments of the matrix located at acute angle and spiral shape, and the pressure on the sample is directly happened.

To verify the implementation of method, the above-mentioned process was modeled in Deform 3D package. It allowed identifying "weak points" of the process, evaluating stress-strain state of the workpiece at each cycle step, strain intensity obtained in one full cycle of this method, and also required strain force. All these factors are necessary to assess the implementation of method, as well as design of technological equipment, selection of power equipment for the experiment, on the basis of which we can guide the degree of change in the structure of workpiece material.

The temperature of workpiece, as well as the temperature of matrix, was chosen equal to 20°C, in order to obtain optimal values of strain-stress state parameters and deformation forces.

A laboratory experiment was conducted on existing hydraulic press PB 6330-02 model after modeling and determining the geometric and technological parameters of the deformation.

The samples were torsion under high pressure (P = 6 GPa) at a temperature of 20°C, the number of cycles is n = 8. The thickness of samples for deformation was 5 ± 0.15 mm and was chosen on the basis of sufficient comprehensive hydrostatic compression during deformation by HPT method.

Preparation of samples for metallographic analysis was carried out on the electrolytic sample preparation unit Struers.

All samples were examined in the middle plane of the sample to avoid the influence of peripheral areas. The obtained samples were considered in two sections: transverse and longitudinal. The structure and phase composition of the alloy were analyzed by optical and transmission electron microscopy. Qualitative and quantitative analyses of the microstructure of the groundmass and primary phases was carried out using an optical microscope LEICA, equipped with an attachment for determining the microhardness of individual phases, as well as software for determining the grain score and the number of phases on mechanically polished and etched by Keller's reagent thin sections.

A fine structure was examined on a transmission electron microscope (TEM) JEM2100 in the magnification range from 1000 to 50000 times. The objects for TEM were prepared by polishing with a Tenupol-3 device at a temperature of -28°C and a voltage of 20V in a 20 % solution of nitric acid in methyl alcohol. The surface of the samples for recording was prepared by means of jet polishing on a Tenupol-3 device.

To assess the mechanical characteristics of the alloy after HPT, the torsion-tearing machine MI40KU was used. Standard samples of a cylindrical shape (diameter of the working part 3 mm, length - 15 mm) were tested in accordance with state standard GOST 1497-84. To carry out a tensile test from workpieces on a lathe, a sample was prepared for stretching of the III-d type. Stretching speed of samples is 0.5 mm min^{-1}, which corresponds to a strain rate of 0.56×10^{-3} s^{-1}.

The microhardness was determined on an AntonPaar hardness tester in accordance with state standard GOST 9450-76 by the method of indenting a diamond pyramid with an angle between opposite faces of 136° with a load of 1N and a loading time of 2 s. To calculate the microhardness value, an average value of 5 measurements was used in each considered area.

RESULTS AND DISCUSSION

Stress-strain state (SSS) during deformation was analyzed according to distribution results:

- logarithmic strain intensity (strain effective) – ε_{int};
- equivalent stress (stress effective) – σ_{eq};
- hydrostatic pressure or medium stress (stress mean) – σ_{med}.

Logarithmic strain intensity (strain effective)

The results of SSS distribution during deformation by torsion method under high pressure are presented in Fig. 2. As a result of modeling, the logarithmic strain intensities are determined by Mises criterion ε_{int}. Based on the data obtained, it was found that in the process of deformation the highest logarithmic strain is observed along outlines of workpiece as there is an influence of external friction. Analyzing SSS of sections of obtained samples, it was found that the distribution of deformation over the entire volume of deformable workpiece is very uniform. Moreover, the degree of deformation of inner layers practically does not differ from the degree of deformation of surface layers - this can be gone by the uniform coloring of inner and outer layers in the cut section (Fig. 2(a)).

Equivalent stress (stress effective)

The stress state of workpiece at the time of deformation is the most important characteristic in order to get high-quality metal. The results of distribution of equivalent stresses σ_{eq} during HPT are presented in Fig. 2(b). Environmental stress and required values in central layers of workpiece are up to 450 MPa and up to 630 MPa in outer layers.

Hydrostatic pressure or medium stress (stress mean) – σ_{med}

An important factor that significantly affects the efficiency of structure formation, especially for low-plastic and hard-to-deform materials, such as titanium, is the value of hydrostatic pressure. The application of hydrostatic pressure provides a high uniformity of distribution of stresses, strains and structural state, contributes to the creation of favorable conditions of contact friction, preservation of plasticity resource.

The quality of metal, for example, the best processing of the cast structure and welding of internal defects, is positively affected by the presence of compressive stresses inside deformable body arising during pressing. These stresses can be characterized by the distribution of medium stress σ_{med} over the workpiece section, (see

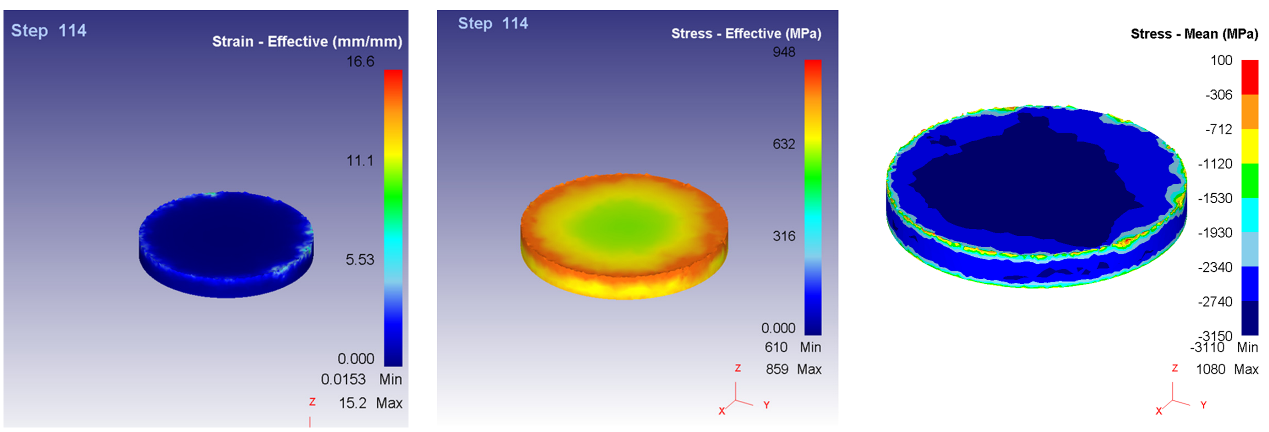

Fig. 2. Distribution of SSS during deformation by HPT method: a - after 3 cycles of deformation; b - after 6 cycles of deformation; c - after 8 cycles of deformation.

Fig. 2(c)). The more the absolute value of medium compression pressure (negative hydrostatic pressure) is, the higher is the ductility of metal; and the less the tensile stresses play in principal stress scheme, the greater the ability to plastic deformation shown by the metal. High hydrostatic pressure significantly increases the deformability of materials. It is also known that high hydrostatic pressure activates dislocation slip, suppresses return processes, leads to fragmentation of the structure at lower than usual degrees of deformation.

The nature of distribution σ_{med} shows that in the deformation zone, except for small zones, compressive stresses prevail. The maximum principal stresses of the workpiece are not more than 1080 MPa, the distribution of maximum principal stresses are concentrated mainly on the periphery of workpiece.

After analysis using the “Damage” tool, it was revealed that there is no danger of destruction of the workpiece, even after ten cycles of deformation.

Photographs shown in Fig. 3 were obtained as a result of metallographic analysis of the microstructure, after the laboratory experiment.

The first three deformation cycles revealed a strong heterogeneity of the microstructure. In the cross section perpendicular to the anvil plane there are regions with cellular dislocation structure (Fig. 3(a), which are interspersed by fragmentation strips spreading almost parallel to the anvil plane and, accordingly, perpendicular to the torsion axis.

Strips density increases significantly after 6 cycles of deformation, as the strip moves from central to peripheral part of the sample.

8 cycles of deformation lead to the fact that almost entire volume of metal is represented by an anisotropic ultrafine-grained structure, regardless of differences in degrees of deformation of central and peripheral parts of the sample. Boundaries of subgrains are characterized by strongly distorted shape, which indicates their nonequilibrium state. At the same time, there are individual grains with almost straight boundaries of disorientation. The largest submicrocrystalline grains, as a rule, are divided into equiaxial subgrains with sizes of tenths of a micron. A high anisotropy of misorientations of discrete and continuous type is found in copper. This is a consequence of a high anisotropy of displacement and rotation fields during torsional deformation under pressure in a new matrix.

As it is known, the grain size is an extremely important characteristic of metals and alloys, which determines the level of structurally sensitive mechanical properties. Therefore, in addition to studying structural changes during deformation, we studied mechanical properties of workpieces after each type of tensile deformation at room temperature.

Deformation by HPT method led to a significant increase in the strength characteristics of copper and a strong decrease in ductility values: tensile strength increased from 105 MPa to 380 MPa, elongation decreased from 28 % to 13 %. The increase in strength is linked with an increase in the density of dislocations and small-angle boundaries in the structure. It is also the reason for decrease in ductility, as there is a number of short- and long-range energy barriers hindered the dislocation movement in the polycrystal, which confirms earlier metallographic studies. Such changes in mechanical properties are linked with formation of capable token-passing dislocations from one grain to another grain with a high-angle boundary in the structure. These grains were formed by globularization of lamellar component during continuous and intermittent dynamic recrystallization happened while deformation process.

It should be added that “typical tensile curves of M1 grade copper after torsion under high pressure compared with tensile curves of heat-treated samples are charac-

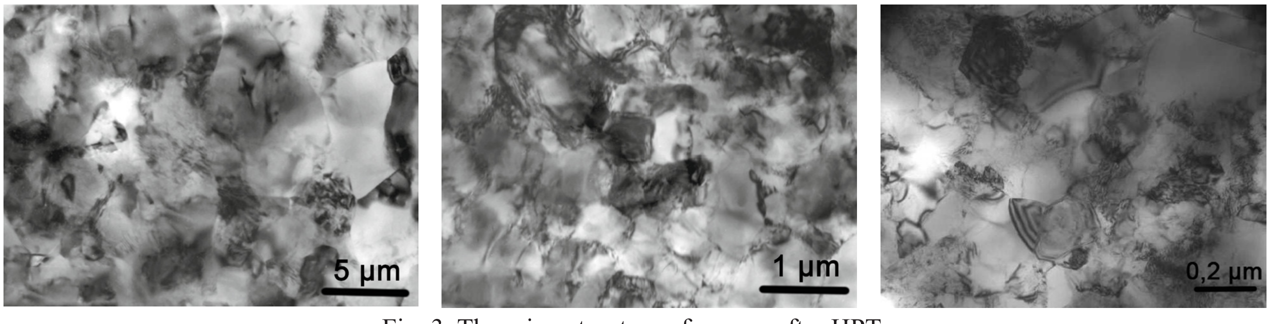

Fig. 3. The microstructure of copper after HPT.

terized by a small uniform plastic deformation and a significant increase in the length of concentrated plastic deformation until destruction point. This mechanical behavior is typical for metal materials treated by SPD.

CONCLUSIONS

The matrix of special design was developed in order to implement the process of high-pressure torsion on the existing equipment in the laboratory of Pressure metal treatment department. This matrix allows the high-pressure torsion process to be realized due to the rectilinear movement of the striker relative to the body. The modeling was carried out in the DEFORM software package in order to assess the possibility of deformation of titanium alloy in the matrix of a new design and in order to assess the influence of stress-strain state on the structure processing. The possibility to provide shear strain in processed metal is shown based on SSS analysis. As a result of shear strain we have got ultrafine-grained structure.

The microstructure after 8 passes is strongly crushed and consists mainly of deformation fragments and subgrains. When analyzing the structure, a large number of individual grains were found. They have the shape of almost regular polygons with a low dislocation density, which indicates their origin through dynamic recrystallization.

The deformation by HPT method led to significant increase in strength characteristics of the alloy and strong decrease in ductility values: tensile strength increased from 105 MPa to 380 MPa, ductility decreased from 28 % to 13 %.

REFERENCES

1. R.Z. Valiev, T.G. Langdon, Principles of equal-channel angular pressing as a processing tool for grain refinement, Prog. Mater. Sci., 51, 2006, 881-981.
2. G. Kurapov, E. Orlova, I. Volokitina, A. Turdaliev, Plasticity as a physical-chemical process of deformation of crystalline solids, Journal of Chemical Technology and Metallurgy, 51, 2016, 451-457.
3. G.I. Raab, E.I. Fakhretdinova, R.Z. Valiev, L.P. Trifonenkov, V.F. Frolov, Computer Study of the Effect of Tooling Geometry on Deformation Parameters in the Plastic Shaping of Aluminum Wire Rod by Multi-ECAP-Conform, Metallurgist, 59, 11-12, 2016, 1007-1014.
4. G.I. Raab, A.G. Raab, R.N. Asfandiyarov, E.I. Fakhretdinova, Combined and consecutive SPD processing techniques, Machines. Technologies. Materials. Proceedings, Volume III «MATERIALS», 2017, 187-188.
5. I. Volokitina, A. Nayzabekov, S. Lezhnev, D. Kuis, M. Knapinski, ECAP processed silumin AK9 modified by ligature Al alloy: Microstructure and mechanical properties, Journal of Chemical Technology and Metallurgy, 54, 2, 2019, 397-405.
6. Y.G. Jin, I.H. Son, S.H. Kang, Y.T. Im, Three-Dimensional Finite Element Analysis of Multi-Pass Equal-Channel Angular Extrusion of Aluminum AA1050 with Split Dies, Materials Science and Engineering, 503, 2009, 152.
7. P. Frint, M.F.-X. Wagner, S. Weber et al., An experimental study on optimum lubrication for large-scale severe plastic deformation of aluminum-based alloys, Journal of Materials Processing Technology, 2017. 239, 2017, 222-229.
8. M.V. Chukin, N.V. Kopceva, J.J. Efimova, O.A. Nikitenko, M.A. Polyakova, Criterion estimation of severe plastic deformation efficiency from the position of their influence on the carbon steel structures evolution, CIS Iron and Steel Review, 2010, 28-31.
9. G.G. Kurapov, E.P. Orlova, I.E. Volokitina, A. Turdaliev, Plasticity as a physical-chemical process of deformation of crystalline solids, Journal of Chemical Technology and Metallurgy, 51, 2016, 451-457.
10. D.K. Orlova, T.I. Chashchukhina, L.M. Voronova, M.V. Degtyarev, Effect of temperature–strainrate conditions of deformation on structure formation in commercially pure copper deformed in Bridgman anvils, Phys. Met. Metallogr., 116, 2015, 951-958.
11. E.N. Popova, V.V. Popov, E.P. Romanov, V.P. Pilyugin, Effect of the degree of deformation on the structure and thermal stability of nanocrystalline niobium produced by high-pressure torsion, Phys. Met. Metallogr., 103, 2007, 407-413.