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EFFECT OF HIGH-PRESSURE TORSION ON MICROSTRUCTURE CHANGES IN MICROALLOYED STEEL

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The most common method of manufacturing parts is metal pressure treatment, as a result of which the entire reserve of strength and ductility of the material is not exhausted. Therefore, the issues of the influence of plastic deformation on the cyclic durability and endurance limits of steel rings are relevant. In this article experimental studies of the effect of high pressure torsion in a die of new design on the evolution of the microstructure and the change of mechanical properties have been carried out. As a result, the fundamental possibility and efficiency of using the proposed method for the formation of ultrafine grained structure and increasing the strength properties of steel rings has been proved. Strain was carried out at ambient temperature in six passes. The strain resulted in an ultrafine-grained structure with an average grain size of 0.5 μm and a great number of large-angle boundaries. The strength properties of microalloyed steel increased almost threefold compared to the initial state, the microhardness also increased threefold, i.e. increased from 760 MPa in the initial state to 1935 MPa after strain. The greatest increase in strength properties occurred in the first 3 cycles of strain.

Keywords: severe plastic deformation, microstructure, high pressure torsion, steel, mechanical properties

Introduction

The desire for the highest possible efficiency in the production and use of components is reflected in the growing development of complex production processes and specialized materials. For the development of production processes, this means a tendency to reduce the number of different production steps while using materials as efficiently as possible. In terms of material performance, against a background of increasingly important, lightweight construction, high strength with good ductility is of great importance [1,2]. Most manufacturing processes for processing metallic materials cause local or global changes in material properties. These production properties, in turn, can be used purposefully to increase component performance or decrease material usage in reverse order. Thus, by adapting the manufacturing process to purposefully tune certain local material properties, synergistic effects can be used to improve overall component production efficiency.

The dynamic development of various industries, including aviation and mechanical engineering, as well as the ever-increasing requirements for structural materials contribute to the improvement of research on improving their mechanical properties. One of the ways to improve mechanical properties is to refine the material structure.

Ultrafine grained and nanocrystalline materials have been the subject of extensive research for a long time, since their mechanical properties allow us to expect great potential as structural materials [3-7]. To expand the possibilities of using ultrafine-grained materials as structural and functional materials, to make products with unique mechanical and physical properties, it is necessary to develop a method that would allow obtaining semi-finished products with improved characteristics. These include large cross-section, uniform grain size equiaxed ultrafine grained structure in any cross-section, high proportion of large-angle grain boundaries, and without sharp texture and areas with crystallo-graphically close grain orientation. The new method should take into account the factory realities, i.e. it should be easily adaptable to the existing press equipment equipped with simple and inexpensive technological tooling, and have market potential, which implies minimization of the introduced strain energy per unit mass of the ultrafine-grained product.

Such a method, apparently, should be sought among cyclic methods of deformation processing of metals and alloys, which include comprehensive isothermal forging, equal channel angular pressing (ECAP), helical extrusion and others that allow during the deformation processing to preserve or restore the original three-dimensional shape of the blank, regardless of the degree of deformation [8-15].

One such method is high-pressure torsion (HPT). In the process, shear strains are introduced into flat disc specimens by torsion under high hydrostatic pressure stresses. During the process, the sample is placed between two dies and twisted by the rotation of one die or the opposite rotation of both dies [16]. Grain size grinding in the HPT process is generally slightly more efficient than in the ECAP process, so a finer grain structure and higher mechanical properties can be obtained through this method [17,18]. However, although extensive research has been carried out in this area, the behavior and fundamental principles are not yet fully understood because, for example, such materials have extraordinary strength. The ductility, though, is too low, and also discs treated in this way have anisotropic properties between the center and the edges. As a result of the analysis of scientific and patent literature, the high-pressure torsion technology was selected as the most optimal processing technology for ring workpieces. However, this technology is most often applied to disk-shaped workpieces. So the next stage of research is to develop a special design of the die allowing to implement this process of severe plastic deformation, as well as to assess the possibility of stable flow of the process.

As is known, during high-pressure torsion, the movement of the straining tool consists of two types: translational and rotational. Presses are ideally suited as a working mechanism to implement this method, allowing for high hydrostatic pressure during compression. However, the main difficulty is the need to perform the torsion operation along the axis of the workpiece. This requires a certain torque to be transmitted to the straining tool, which is often not possible due to the design features of most presses. So the only possible option in this case is to ensure the torsion of the straining tool at a constant rectilinear motion of the press punch. The solution to this technical problem can only be realized in practice with a compound straining tool that includes both displacement and rotation units.

On the basis of modeling in the software package Deform given in papers [20-22] drawings of design have been developed. The design consists of several parts: the upper striker which is driven by the progressive motion of the press; the lower striker which is driven by the progressive motion of the upper striker and the die. There are 4 periodic spiral shaped notches on the bottom edge of the upper striker. A cylindrical hole is provided in the center of the upper striker for the rod of the straining element and to ensure alignment of both strikers. The lower striker has several steps. This design solution is necessary because in this case we are talking about straining a circular workpiece and not a disk workpiece (Fig. 1).

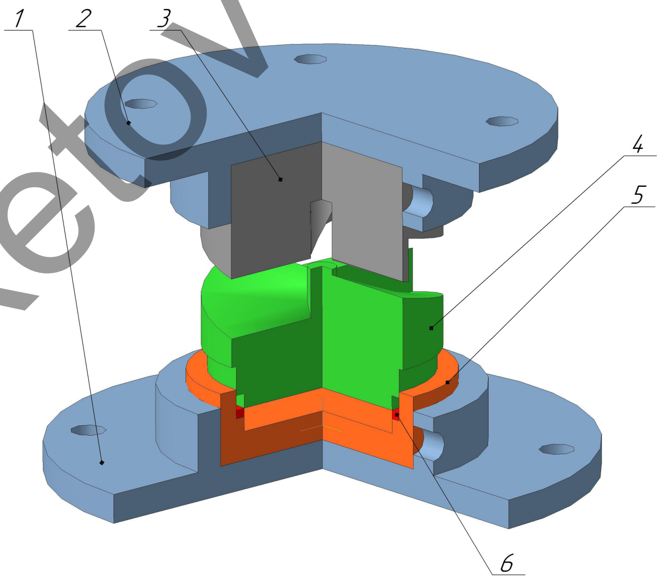


Fig.1. General view of the complete construction: 1 - bottom carrier, 2 - top carrier, 3 - upper striker, 4 - lower striker, 5 - matrix, 6 - piston ring.

The purpose of this work is to study the effect of high-pressure torsion in dies of new design on the structure and properties of 06MBF steel.

1. Materials and Methods

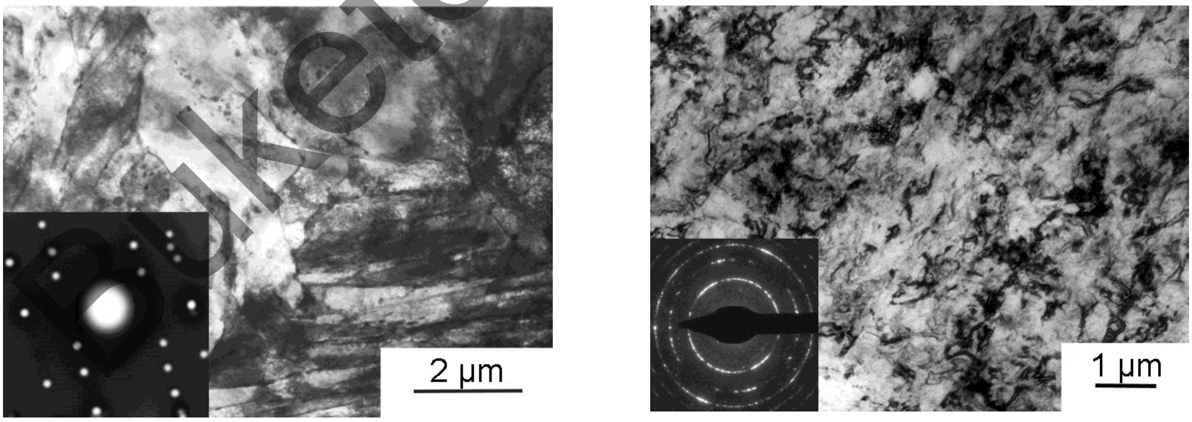
The initial workpiece had a ring shape with a diameter of 76 mm, a width of 3.5 mm, and a thickness of 3 mm. Steel 06MBF (Fe-0,1Mo-0,1V-0,06Nb-0,09C, wt.%) in the initial ferrite state was chosen as an object of the study. Initial workpieces of 06MBF steel were quenched at 910°C (15 min.), followed by high tempering at 660°C (30 min.). Assembly of the structure and the experiment itself was carried out in the laboratory on a single-column hot-stamping crank press model PB 6330-02, the force of which is 1000 kN. The strain was carried out at room temperature. Number of strain cycles is 6. To verify the ability to maintain the microstructure and mechanical properties during heating, the specimens were subjected to heating after strain. For this purpose, the samples after the HPT were cut into thin plates 10 mm thick and exposed to 450 - 600°C for 15 min with cooling in water. The fine structure was studied on a JEM 2100 transmission electron microscope. Thin foil for microstructure study was prepared by thinning with electrolitic polishing in an electrolyte of 400 ml H_3PO_4 and 60 g CrO_3 at room temperature and 20V, the current density was $2.5 A/cm^2$.

Mechanical tests for uniaxial tension were performed at ambient temperature on Instron 5882 machine with a strain rate of 1.0 mm/min. The tensile specimen were prepared according with method described in [23]. The strain of the sample was measured by an Instron strain gauge. According to the results of tests, the strength and ductility characteristics were determined: yield strength, tensile strength, and elongation.

Micromechanical properties were monitored during all periods of the study by measuring the microhardness. To measure the microhardness, an imprint was made on the sample surface under static load in accordance with GOST 9450-76. The indenter was a diamond tip in the form of a square pyramid with a square base. The load was 1 N. The root mean square error of the micro-hardness determination on many prints is an indication of the accuracy of the instrument. The error in the mechanical tests did not exceed 3%.

2. Results and discussion

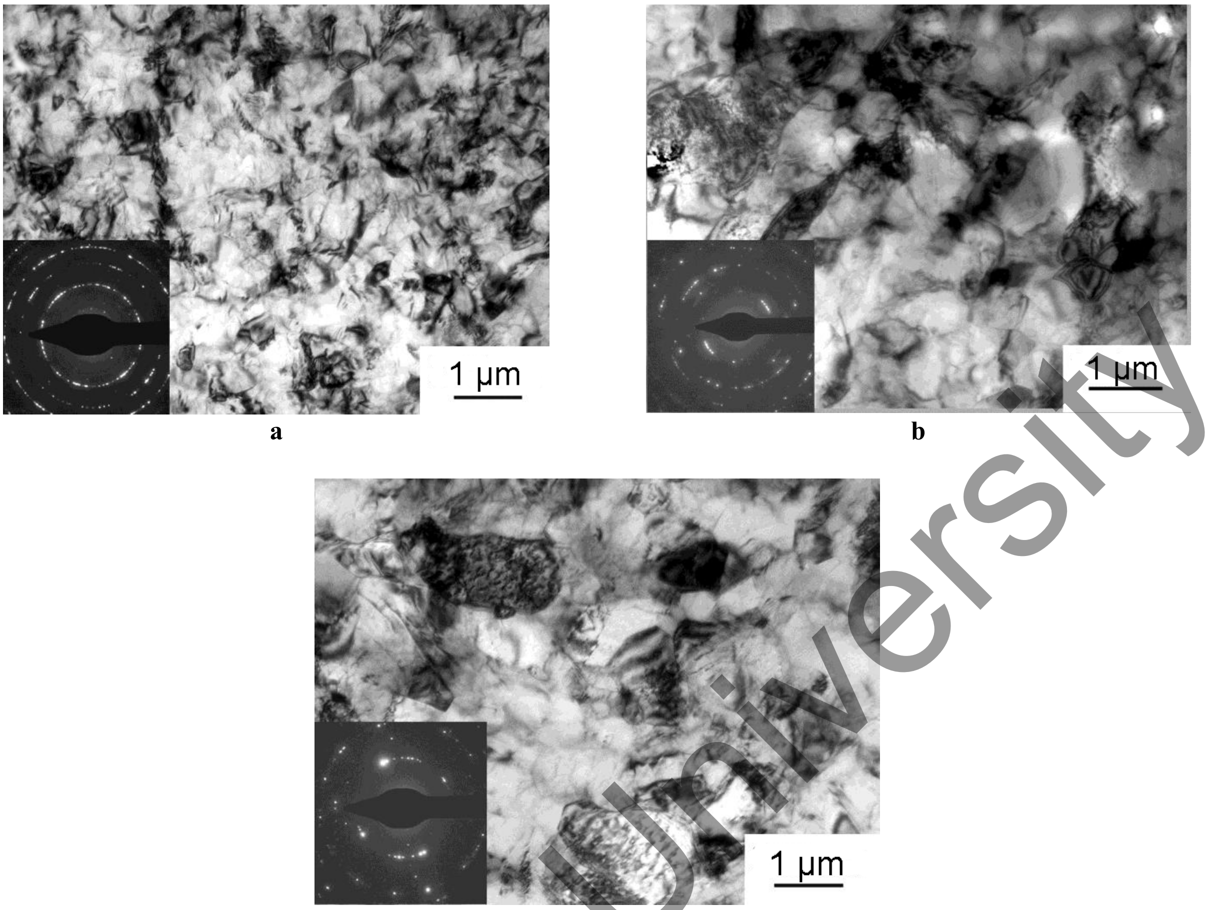
In the initial state, the structure of unstrained samples consists of ferrite grains, which inherited the morphology of batch martensite, after quenching, with a grain size of 18 μm (Fig. 2a). High-pressure torsion straining resulted in intensive dispersion of the structural components down to 0.5 μm (Fig. 2b). The grain boundaries are blurred. The electronograms shown in Figure 2 are a system of reflexes with azimuthal blurs and broadened X-ray lines. This indicates a high level of internal stresses in the grains. On the electronogram after strain by the HPT method, the lines have a circular character with clearly distinguishable individual reflexes evenly distributed throughout the ring (Fig. 2b). This indicates the presence of high-angle misorientations between the structural elements from which the electronogram was obtained.



a b

Fig.2. Microstructure of 06MBF steel: a) – initial state; b) – after 6 cycles of deformation.

Figure 3a shows that heating the samples to 450°C does not lead to a significant increase in grain; the structure retains the ultrafine grain structure with an average grain size of 0.6 μm. The electronogram still has a circular character. Increasing the temperature to 500°C leads to a return process, the grain size increases to 1 μm (Fig. 3b). Grain boundaries become equilibrium, dislocation density decreases. Heating to 550°C leads to the beginning of recrystallization processes. This can be seen in the nascent grains, the average grain size is about 2 μm.



a

b

c

Fig.3. Microstructure of 06MBF steel after heating: a) – 450ºC; b) – 500ºC; c) – 550ºC.

Tensile tests showed that the resulting ultrafine-grained structure has improved strength properties. The results in the initial state are: yield strength is 263 MPa and tensile strength is 465 MPa, and relative elongation is 32%. The formation of ultrafine grained structure after 6 cycles of strain by the HPT method leads to an increase in the ultimate strength up to 1315 MPa compared to the initial state. The yield strength increases to 1064 MPa. The value of ductility decreases sharply compared to the initial state up to 14%.

The microhardness results correlate with the mechanical tensile test data and indicate that the HPT in the new die allows for a fairly uniform hardness across the entire cross-section of the ring. After 6 cycles of strain by the HPT method, the microhardness increases almost threefold from 760 MPa to 1935 MPa as compared to the initial state. In this case, the main increase in hardness falls on the first 3 passes - 65%.

Conclusion

The study confirmed the pattern of strain-hardening of microalloyed steel rings with an increase in the number of strain cycles. Significant changes in microstructure initiated by high-pressure torsion in a new kind of die allowed to achieve the following most important results:

1. The electron microscopic analysis showed that the strain by torsion under high pressure leads to intensive dispersion of structural components from 18 to 0.5 μm. And the obtained ultrafine grain structure is preserved when heated up to 450°C.
2. The tensile tests showed that the obtained ultrafine-grained structure has increased strength properties. The results of microhardness determination correlate with the data of mechanical tensile tests and testify to the fact that the HPT in the new die allows to obtain a sufficiently homogeneous hardness over the entire cross section of the ring.

REFERENCES

1 Surzhikov A.P., Lysenko E.N., Malyshev A.V., Petrova A., Ghyngazov S.A., Aimukhanov A.K. Phase transformations in ferrites during radiation-thermal sintering. *Eurasian phys. tech. j,* 2020, Vol.17, No.1, pp. 144-153. doi:10.31489/2020No1/26-34

2 Alizadeh M., Samiei M. Fabrication of nanostructured Al/Cu/Mn metallic multilayer composites by accumulative roll bonding process and investigation of their mechanical properties. *Materials & Design,* 2014, Vol. 56, pp. 680–684. http://dx.doi.org/10.1016/j.matdes.2013.11.067

3 Valiev R.Z., Estrin Y., Horita Z., et al. Producing bulk ultrafine-grained materials by severe plastic deformation: ten years later. *JOM*. 2016, Vol. 68, pp.1216-1226. doi:10.1007/s11837-006-0213-7

4 Kasenov B.K., Kasenova Sh.B., Sagintaeva Zh.I., et al. Synthesis and X-ray investigation of novel nanostructured copper-zinc manganites of lanthanum and alkali metals. *Eurasian phys. tech. j.*, 2021, Vol. 18, No. 1, pp. 29-33. doi: 10.31489/2021No1/29-33

5 Lezhnev S., Panin E., Volokitina I. Research of combined process rolling-pressing influence on the microstructure and mechanical properties of aluminium. *Advanced Materials Research*, 2013, Vol.814, pp. 68-75. doi:10.4028/www.scientific.net/AMR.814.68

6 Furukawa M., HoritaZ., Langdon T.G. Application of equal-channel angular pressing to aluminum and copper single crystals. *Materials Science Forum,* 2007, Vols. 539-543, pp. 2853-2858. doi::10.4028/www.scientific.net/MSF.539-543.2853

7 Polyakov A.V., Semenova I.P., Raab G.I. Peculiarities of ultrafine-grained structure formation in Ti Grade-4 using ECAP-Conform. *Advanced Materials Science,* 2012, Vol.31, pp. 78-84.

8 Lezhnev S.N., Naizabekov A.B., Panin E., Volokitina I.E. Influence of combined process "rolling-pressing" on microstructure and mechanical properties of copper. *Procedia Engineering,* 2014, Vol.81, pp. 1499 – 1505. doi: 10.1016/j.proeng.2014.10.180

9 Naseri R., et al. An experimental investigation of casing effect on mechanical properties of billet in ECAP process. *International Journal of Advanced Manufacturing Technology,* 2017, Vol. 90, pp. 3203–3216. doi:10.1007/s00170-016-9658-1

10 Murashkin M.Yu., et al. Enhanced mechanical properties and electrical conductivity in ultrafine-grained Al alloy processed via ECAP-PC. *J. Mater. Sci.* 2013, Vol. 48, pp. 4501-4509. DOI:10.1007/s10853-013-7279-8

11 Xu C., Horita Z., Langdon T.G. The evolution of homogeneity in processing by high-pressure torsion. Acta Materialia, 2007, Vol.55, pp. 203-212. doi: 10.1016/j.actamat.2006.07.029

12 Raab G., Valiev R., Lowe T., Zhu Y. Continuous processing of ultrafine grained A1 by ECAP-Conform. *Mater. Sci. and Eng.,* 2004, Vol. 382, pp. 30–34. doi:10.1016/j.msea.2004.04.021

13 Dao M., Lu L., Asaro R., Hosson J., Ma E. Toward a quantitative understanding of mechanical behavior of nanocrystalline metals. *Acta Materialia*, 2007, Vol. 55, pp. 4041-4065. doi:10.1016/J.ACTAMAT.2007.01.038

14 Lezhnev S., Volokitina I., Koinov T. Research of influence equal channel angular pressing on the microstructure of copper. *Journal of Chemical Technology and Metallurgy,* 2014, Vol. 49, pp. 621-630.

15 Chukin M.V., Polyakova M.A., Emaleeva D.G., Gulin A.E. Creating UltrafineGrain Structure in High Strength Bimetallic Steel–Copper Products. *Steel in Translation*, 2014, Vol. 44, No. 4, pp. 320–323.

16 Zhilyaev A., Langdon T. Using high-pressure torsion for metal processing: Fundamentals and applications. *Progress in Materials Science*, 2008, Vol. 53, pp. 893-979. doi:10.1016/J.PMATSCI.2008.03.002

17 Kawasaki M., Ahn B., Lee H.J., et al. Using high-pressure torsion to process an aluminum–magnesium nanocomposite through diffusion bonding. *J. Mater. Res*., 2015, Vol. 31, pp. 88-99. doi:10.1557/jmr.2015.257

18 Volokitina I.E., Volokitin A.V., Panin E.A., Latypova M.A., Kassymov S.S. Microstructure evolution of steel-aluminum wire during deformation by "equal-channel angular press-ing-drawing" method. *Eurasian phys. tech. j.,* 2022, Vol.19, No.1, pp. 73-77. doi:10.31489/2022No1/73-77

19 Choi I., Schwaiger R., Kurmanaeva L., Kraft O. On the effect of Ag content on the deformation behavior of ultrafine-grained Pd-Ag alloys. *Scripta Materialia*, 2009, Vol.61, pp.64-67. doi:10.1016/j.scriptamat.2009.03.007

20 Horita Z., Fujinami T., Langdon T. The potential for scaling ECAP: Effect of sample size on grain refinement and mechanical properties. *Materials Science and Engineering A*., 2001, Vol. 318(1-2), pp. 34-41. doi:10.1016/S0921-5093(01)01339-9

21 Volokitin A., Volokitina I., Panin E., Naizabekov A., Lezhnev S. Strain state and microstructure evolution of AISI-316 austenitic stainless steel during high-pressure torsion (HPT) process in the new stamp design. *Metalurgija,* 2021, Vol. 60(3-4), pp. 325-328.

22 Volokitin A., Naizabekov A., Volokitina I., Lezhnev S., Panin E. Thermomechanical treatment of steel using severe plastic deformation and cryogenic cooling. *Mater. Letters,* 2021, 304, 130598. doi:10.1016/j.matlet.2021.130598

23 Erbel S. Mechanical properties and structure of extremely strain-hardened copper. *Metals Technology,* 1979, Vol.6, pp. 482-486.

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