Materials Physics and Mechanics 43 (2020) 44-49 Received: November 28, 2019

ANALYSIS OF THE DEGREE ISOTROPIC DEFORMATION, STRENGTH AND STRUCTURE STEEL SAMPLES AFTER SEVERE DEFORMATION BY SHIFTING

A.P. Zhilyaev[1,2*], A.G. Raab[1,3], I.S. Kodirov[3], G.I. Raab[1,3]

[1]Magnitogorsk State Technical University. G.I. Nosova, Magnitogorsk, Russia

[2]Institute of Metal Superplasticity Problems of the Russian Academy of Sciences, Ufa, Russia

[3]Research Institute of Advanced Materials Physics at USATU, Ufa, Russia

*e-mail: alex.zhilyaev@hotmail.com

Abstract. The article presents the results of computer simulation and physical research of severe deformation by free torsion of long-length specimens with a round cross-section of steel 10 at a temperature of 600°C. Based on virtual approaches in the Deform 3D software package, the deformed state of the samples, including the distribution of accumulated strain in the bulk workpiece, was investigated. A physical experiment was carried out, the structure and microhardness in the longitudinal section of the samples were studied. The principles of the mutual influence of the degree of anisotropy of the deformed state on the formation of the structure and mechanical properties are established. The anisotropic (gradient) nature of the formation of the structure and mechanical properties in bulk samples using the free torsion method and the accumulation of super high, up to e~6, large shear strains in the pre-crystallization temperature range of plastic processing is established.

Keywords: a degree of isotropy (gradient), structure and mechanical properties, free torsion, severe plastic deformation, computer simulation

1. Introduction

The residual change in the structural state and properties resulting from plastic deformation and the subsequent differences in these properties in different directions in the volume of the metal are usually called deformation (secondary) anisotropy [1,2]. The degree of isotropy of the deformed and structural states, as well as the mechanical properties of metals, is a consequence of specially created or technologically dependent orientation of crystals formed as a result of plastic deformation in metalworking processes. Anisotropy, as a rule, is initially absent in metal polycrystals after high-temperature annealing i.e., specially created homogeneous structural state or vice versa, anisotropy is specially formed by methods of directed crystallization. It is obvious that the anisotropy of structural and mechanical properties, their accounting and targeted use, starting from the design stage, helps to increase the reliability, durability of machine parts, and structural elements, as well as the effective use of constructional materials.

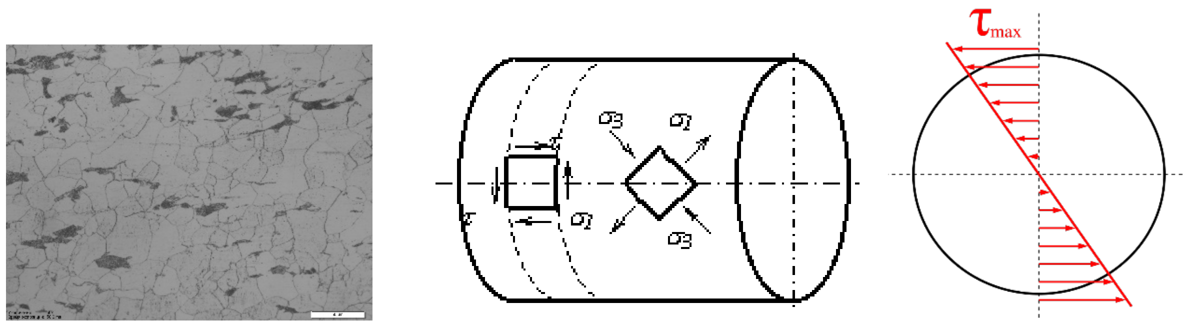
In a number of SPD methods [3-11], for example, such as equal channel angular pressing (ECAP), deformation by a simple shear of a fairly high uniformity is used, but a simple shear is not a monotonic deformation and, as a result, leads to the formation of an anisotropic state, in particular, mechanical properties [12-14]. As a rule, SPD leads to a significant (1.5-3 times) increase in strength characteristics of deformed materials, however,

http://dx.doi.org/10.18720/MPM.4312020_5

the ductility of the material also decreases noticeably, which limits the area of their structural application. Recently, as an alternative to bulk UFG materials, consideration has been given to obtaining bimodal and gradient structural states that provide a combination of high strength and ductility in bulk materials [15,16]. For example, in axisymmetric semi-finished products or products, it is possible to create a different-grain state with larger grains in the central zones and ultrafine grains in the surface regions. Such anisotropic/gradient states provide high wear resistance of the surface layers and enhanced fatigue performance properties, for example, shafts and other rod-like products. In this regard, the technique is investigated in the work, which provides the possibility of the accumulation of gradient shear strains under conditions of free torsion of a cylindrical workpiece [17]. The aim of the work was to study the parameters of the anisotropic deformed state using virtual and experimental research methods and to reveal the patterns of their influence on the formation of the structure and properties of samples of steel 10 under severe torsional deformation and a temperature close to the recrystallization temperature.

2. Materials and methods

As a material for research, we used rods 10 mm in diameter from low-carbon steel 10 with a chemical composition: C 0.12 – Si 0.26 – Mn 0.42 (wt.%) And an average grain size of 15 μm (Fig. 1a). The rods had a tensile strength ~ 460 MPa, a yield strength ~ 350 MPa, and an elongation to failure ~ 25%.



a) b) c)

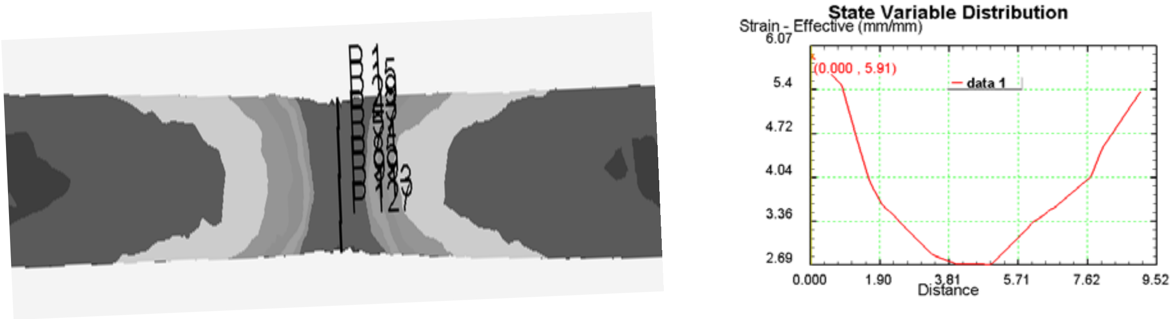
Fig. 1. a – the microstructure of steel 10 in the initial state (light microscopy, x500), b – the stress state on the surface of a round rod during torsion, c – the distribution of shear stresses in the cross-section of a round rod during torsion

The study of the deformed state of the free torsion process was carried out by computer simulation using the software product DEFORM-3D. The specified boundary conditions: the number of mesh elements of the workpiece grid – 70,000; the rotation speed of the movable die – 12.5 rpm; workpiece diameter – 10 mm, length – 250 mm, temperature – 600°C. Rheological behavior was taken from the database of the software product for steel AISI1010, a direct analog of steel 10.

A physical experiment was carried out by fixing both ends of a sample heated to 600°C in a movable and fixed lathe chuck and subsequent rotation of the spindle at a speed of 12.5 rpm. The deformation temperature was chosen slightly lower than the recrystallization temperature threshold of steel 10. At the time of the destruction of the workpiece, the number of revolutions was recorded. Vickers hardness (HV) was measured using a Micromet-5101 micro-indentation tester with a load of 100 g for 15 s. The number of measurements for each sample was at least 15. Quantitative and qualitative analysis of the structure of the studied material was carried out on a metallographic light microscope. The average grain/subgrain value was determined according to GOST 5639-82.

3. Results of experiments and their discussion

Computer simulation of free torsion. According to the results of computer simulation in the DEFORM 3D software product of the free torsion scheme of a cylindrical sample, a picture and a graph of the distribution of strain intensity in the transverse direction of the average longitudinal section of the localized deformation zone are presented.



a) **b)**

Fig. 2. The picture of the deformed state (a) and the graph of the distribution of accumulated strain in the cross-section of the localized deformation zone (b) for free torsion of a steel 10 sample

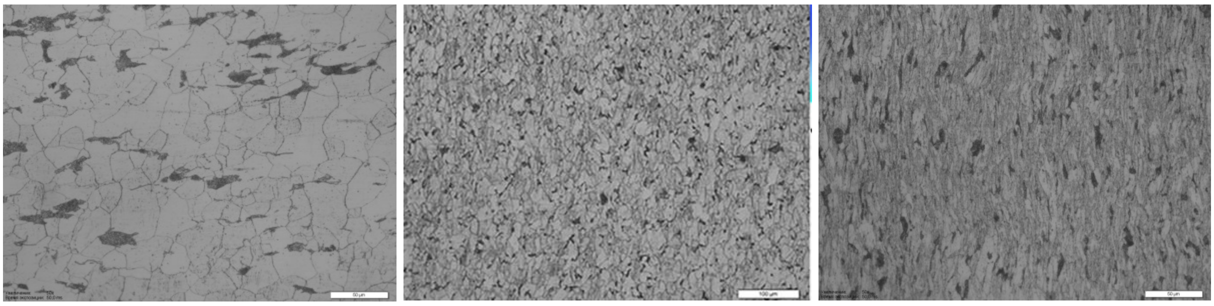
The analysis of the obtained picture and the distribution graph of the accumulated strain shows that strain, during torsion, is localized and the region has anisotropy of the strain distribution in both longitudinal and transverse directions. The maximum value of the accumulated strain e = 5.91 (Fig. 2) is observed in the surface layers of the workpiece, and the minimum e = 2.69 in the central layers on the longitudinal axis of rotation (symmetry). The anisotropic distribution of strain in the axial direction is associated with the phenomenon of localization of deformation and in the transverse direction with the nature of the free torsion scheme (see Fig. 1c), in which, theoretically, the shear stresses on the central axis of symmetry are zero. However, a fairly high level of strain is observed in the central region, which is apparently related to the effects of the internal interaction of the plastic layers of the deformation zone.

Experimental investigation of the free torsion method. Experimental studies have shown that the destruction of the workpiece under free torsion and the initial temperature of the workpiece 600°C occurs after 27 revolutions. Moreover, the deformation zone at the initial stage covers the entire volume of the sample, then becomes unstable and migrates along the longitudinal axis, and is finally localized in its central part. This effect is apparently associated with increased underlining of the sample from the dies during deformation.

Fig. 3. Sample of steel 10 after free torsion until a fracture

As a result of experimental work, prototypes were obtained after free torsion and fracture (Fig. 3).

Microstructure investigation. The study of the structural states of the localized zone of the deformation zone is presented in Fig. 4.



a b c

Fig. 4. a – the structure of the initial state, b – the structure of the central region of the localized deformation zone, c – the structure of the peripheral region of the localized deformation zone. Light microscopy

The study of the structural state of the localized deformation zone under free torsion revealed a number of its features. So in the peripheral region, a mechanical texture is formed with elongated grains directed at an angle of 90 degrees to the generatrix of the surface. In this case, the coefficient of grain elongation is up to 3, with grain sizes in the transverse direction 1-3 μm. A more equiaxed structure with a grain size of 3-7 μm is formed in the central region. It should be noted that in the localized deformation zone structural defects in the form of pores are not observed. Structural studies indicate dimensional anisotropy of the grain structure in the deformation zone, and a structure with larger grains are formed in the central region of the workpiece, and smaller in the peripheral region. This is consistent with the generally accepted position on the relation between the value of accumulated strain and the intensity of refinement of the structure. The formed structure in the deformation zone has a pronounced gradient type.

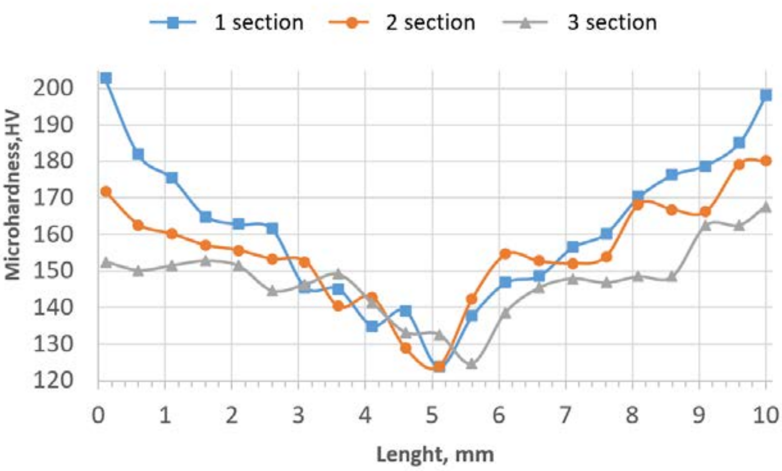


Fig. 5. The change of microhardness in the transverse direction of the longitudinal section of the deformed rod, where, 1 is the region of the deformation zone, 2 – 50 mm from the deformation zone, 100 mm from the deformation zone

Mechanical properties investigation. HV microhardness was measured to study the mechanical properties of samples after free torsion. Measurements were made according to the diameter of the cross-section of the rods in the deformation zone and two regions of the deformable rod located at a distance of 50 and 100 mm from the center. The microhardness measurements HV in the transverse directions of the longitudinal sections of the deformed sample are shown in Fig. 5. Based on the results of microhardness measurements, it can be concluded that anisotropy (gradient) of mechanical properties is formed in the transverse direction of the deformation zone. In the deformation zone, an almost double difference in microhardness is observed between the central and peripheral regions. Moreover, lower hardening corresponds to lower values of accumulated deformation, which is consistent with generally accepted patterns during cold deformation.

4. Conclusions

Using the free torsion method, samples of steel 10 at a temperature of 600°C were obtained, under conditions of limitation of localization of deformation. Using computer simulation and physical research, the parameters of the deformed state, structure, and properties for these conditions are studied. The anisotropy of the deformed state, the anisotropy of the structure and mechanical properties, in particular, microhardness, and their relationship in numerical terms are established.

Structural studies indicate dimensional anisotropy of the grain structure in the deformation zone, and the structure with larger grains is formed in the central region of the center and smaller in the peripheral region, which indicates its pronounced gradient type.

The obtained principles are reflecting the relationship between the deformed and structural states, as well as microhardness, and they are consistent with generally accepted ideas about the relationship of these parameters during plastic deformation in the precrystallization temperature range.

Acknowledgements. *The study was financially supported by the Ministry of Science and Higher Education of the Russian Federation within the framework of the implementation of the Resolution of the Government of the Russian Federation of April 9, 2010 No. 220 (Contract No. 075-15-2019-869 from May 12, 2019).*

References

[1] Ashkinazi EK. *Anisotropy of engineering materials.* Leningrad: Engineering; 1969. (In Russian)

[2] Miklyaev PG, Fridman YB. *Anisotropy of the mechanical properties of metals.* Moscow: Metallurgy; 1986. (In Russian)

[3] Segal VM, Reznikov VI, Kopylov VI, Pavlik DA, Malyshev VF. *Processes of plastic structure formation.* Minsk: Science and Technology; 1994. (In Russian)

[4] Valiev RZ, Zhilyaev AP, Langdon TG. *Bulk nanostructured materials: fundamental principles and applications*. St. Petersburg: Eco-Vector; 2017. (In Russian)

[5] Zhilyaev AP, Langdon TG. Using high-pressure torsion for metal processing: Fundamentals and applications. *Prog. Mater. Sci*. 2008;53(6): 893-979.

[6] Rudskoy AI. *Nanotechnology in Metallurgy.* St. Petersburg: Nauka; 2007. (In Russian)

[7] Rudskoy AI, Kodzhaspirov GE. *Technological fundamentals of obtaining ultrafine-grained metals*. St. Petersburg: Publishing House of the Polytechnic University; 2011. (In Russian)

[8] Utyashev FZ, Raab GI. *Deformation methods for producing and processing ultrafine-grained and nanostructured materials.* Ufa: Gilem; 2013. (In Russian)

[9] Dobatkin SV, Sauvage X. Bulk Nanostructured Multiphase Ferrous and Nonferrous Alloys. In: Zehetbauer MJ, Zhu YT. (eds.) *Bulk Nanostructured Materials.* Weinheim: WILEY-VCH; 2009. p.571-603.

[10] Glezer AM, Levashov EA, Koroleva MJ. *Structural nanomaterials (study guide)*. Moscow: MISiS; 2011. (In Russian)

[11] Kodzhaspirov GE, Rudskoy AI, Rybin VV. *Physical foundations and resource-saving technologies for manufacturing products by plastic deformation*. St. Petersburg: Nauka; 2007. (In Russian)
[12] Raab GI, Raab AG, Shibakov VG. Analysis of shear deformation scheme efficiency in plastic structure formation processes. *Metalurgija.* 2015;54(2): 423-425.
[13] Raab GI, Kulyasov GV, Valiev RZ. Investigation of the mechanical properties of bulk ultrafine-grained titanium billets obtained by equal-channel angular pressing. *Proceedings of the RAS. Metals.* 2004;2: 36-39. (In Russian)
[14] Zherebtsov S, Kudryavtsev E, Salishchev G. Mechanisms of microstructure refinement in titanium during “abc”deformation at 400°C. *Mater. Sci. Forum.* 2011;667-669: 439-444.
[15] Wang Y, Chen M, Zhou F, Ma E. Three strategies to achieve uniform tensile deformation in a nanostructured metal. *Acta Materialia.* 2004;52(6): 1699-1709.
[16] Malygin GA. Strength and ductility of bimodal grain metal nanoparticles. *Solid State Physics.* 2008;50(6): 990-996.
[17] Raab AG, Raab GI, Semenov VI, Aleshin GN, Podrezov UN, Danilenko NI. Effect of drawing and free torsion patterns on strain heterogeneity and structural changes in low-carbon steel blanks, forging and stamping. *Processing of materials by pressure.* 2013;12: 14-20. (In Russian)