A. VOLOKITIN, I. VOLOKITINA, E. PANIN, A. NAIZABEKOV, S. AKSENOV, D. KUIS

ISSN 0543-5846
METABK 61(1) 237-240 (2022)
UDC / UDK 669.15.24.26:620.175.001.4:539.374:620.18 =111

FINITE ELEMENT METHOD (FEM) SIMULATION OF PROCESSING OF AISI-316 AUSTENITIC STAINLESS STEEL BY HIGH-PRESSURE TORSION (HPT) PROCESS AT THE CRYOGENIC COOLING

Received – Primljeno: 2021-05-25
Accepted – Prihvaćeno: 2021-08-10
Preliminary Note – Prethodno priopćenje

In this work the high-pressure torsion process of AISI-316 stainless steel in cryogenic conditions is studied by means of finite element simulation. The stress and strain distributions are analyzed and compared with the ones obtained for ambient temperature. It is shown that the cooling to cryogenic temperature do not affect the equivalent strain distribution significantly. At the same time, the stress values are significantly different - with cryogenic cooling, the level of compressive stresses increases by about 20 %. The simulation of microstructure evolution in Deform-3D program showed that the use of cryogenic cooling makes it possible to further grind the original structure.

Keywords: stainless steel, severe plastic deformation, high-pressure torsion, stress-strain state, microstructure

INTRODUCTION

High-pressure torsion (HPT) is the severe plastic deformation method producing ultrafine-grained and nanostructured samples [1-3]. Initial specimens in the form of disks are deformed by torsion under conditions of high hydrostatic pressure of 1 to 10 GPa.

Plastic deformation by torsion of the sample is carried out due to the rotation of one of the strikers. The amount of accumulated plastic strain is controlled by the rotation angle of the movable anvil.

The geometric shape of the sample is such that the bulk of the material is deformed under quasi-hydrostatic compression. As a result, the deformable sample does not damage, despite the intensive plastic deformation [4]. Similar method is applicable for processing of ring samples according to the scheme proposed by S. Erbel [5].

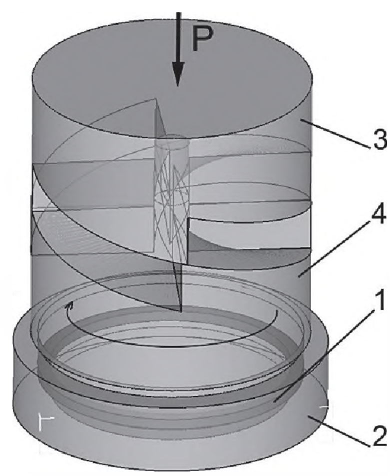
Recently, the HPT process of stainless steel in the die of the new design at ambient temperature was investigated [6].

The main feature of new design of that stamp was a double helix system at two deforming tools. It was found that initial structure of 12 μm can be grinded up to 0.8 μm after several passes. It is known that deformation at cryogenic conditions allows to more intense grinding of grains [7-8]. The aim of this work is the simulation of processing of AISI-316 austenitic stainless steel by high-pressure torsion (HPT) process at the cryogenic cooling.

FEM SIMULATION

The simulation was performed using commercial FE-code Deform. The mechanical properties of the material deformed at cryogenic conditions were determined according to the data available in [9]. The developed material database of the AISI-316 steel at cryogenic conditions is available via DOI: 10.17632/6m5r-6f2z5g.1. This database was selected for simulation of the material properties. The 3D model of stamp utilized for HPT process is presented in Figure 1. This model was designed in the framework of previous study [6].

The initial workpiece had an annular shape with a diameter of 76 mm, width of 3,5 mm and thickness of 3 mm. The deformation was carried out at temperature of -196 °C. The non-isothermal type of calculation was set. The vertical velocity of the punch was 1,5 mm/sec. The rotational movement of deforming element is provided by spiral contact with punch inner surface. Detailed information about kinematic features of the model is described in [6]. The implementation of shear deformation



1 – workpiece, 2 – lower stamp,
3 – punch, 4 - deforming element

Figure 1 Model of stamp

E. Panin (e-mail: cooper802@mail.ru), Karaganda Industrial University, Temirtau, Kazakhstan; A. Volokitin, I. Volokitina, A. Naizabekov, Rudny Industrial Institute, Rudny, Kazakhstan; S. Aksenov, National Research University Higher School of Economics, Moscow, Russia; D. Kuis, Belarusian State Technological University, Minsk, Belarus

in this process needs high adhesion of the workpiece to the tool. Therefore, at the contact of the workpiece with the lower stamp and the deforming element, the value of friction coefficient was set to 0,45. The absolute tetrahedral mesh was built on the workpiece. The minimal element size was set to 0,3 mm, the maximal element size was set to 0,6 mm, remeshing options were set as default.

RESULTS AND DISCUSSION

Figures 2(a,c) present the distributions of the equivalent strain within the half of the vertical cross-section of the specimen after four passes. The histograms of the equivalent strain area distribution are presented in Figures 2(b,d).

The comparative analysis of two models was revealed that the strain distribution in both cases does not change significantly. The area of the region [0 ÷ 0,75] was increased from 7 % to 23 %. The reason of this effect is lower level of material plasticity due to cryogenic conditions. The largest part of the cross-section is occupied by the zone in which the level of strain is in the range of 1,3 – 1,4. The largest strains are distributed on the inner face of the ring - from 5,8 – 5,9 in the center to 4,6 - 4,7 at the edges.

To study the stress state, the parameter "Average hydrostatic pressure" was considered which is called in Deform program as "Stress-Mean", because it allows to estimate the magnitude of the stresses taking into account the sign, i.e., to estimate the magnitude of the tensile and compressive stresses. The value of this parameter is determined by the formula:

$$\sigma_{AV} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}, \qquad (1)$$

where σ_1, σ_2, σ_3 - are the main stresses.

Figures 3 and 4 show the distribution of average hydrostatic pressure in the cross-section at two temperatures.

As it can be seen, deformation at cryogenic conditions creates larger compressive stresses. At 20 °C the

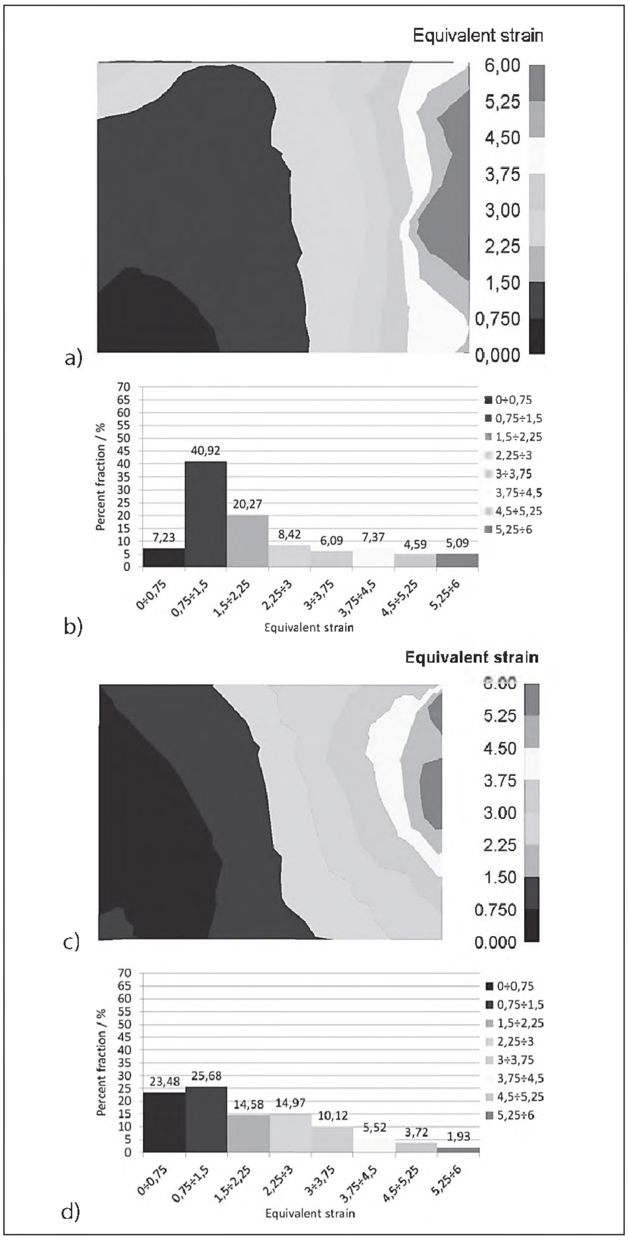


Figure 2 Distribution of the equivalent strain in the cross-section after the 4th pass: a, b - at 20 °C; c, d - at -196 °C

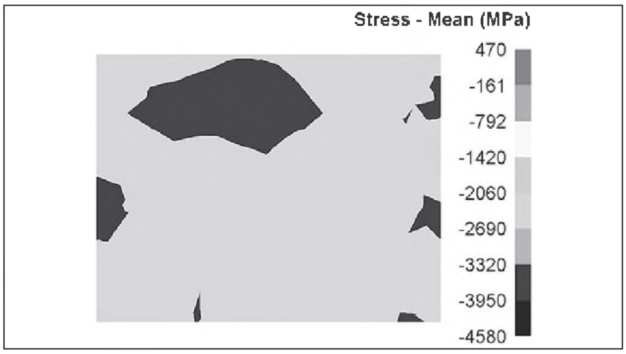


Figure 3 Average hydrostatic pressure in the cross-section at the 4th pass at 20 °C

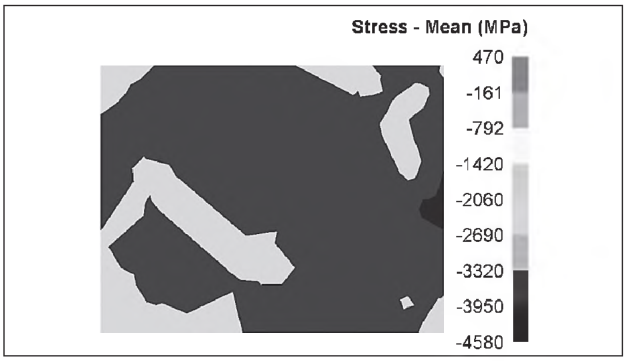


Figure 4 Average hydrostatic pressure in the cross-section at the 4th pass at -196 °C

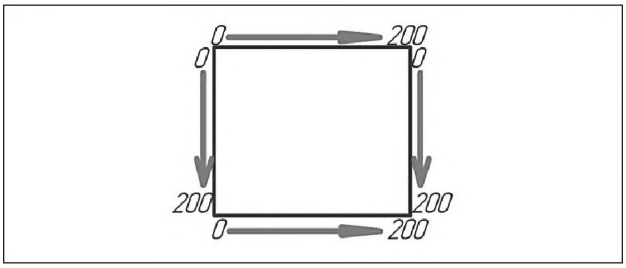


Figure 5 Scheme of calculation direction of Lode-Nadai coefficient at faces of cross-section

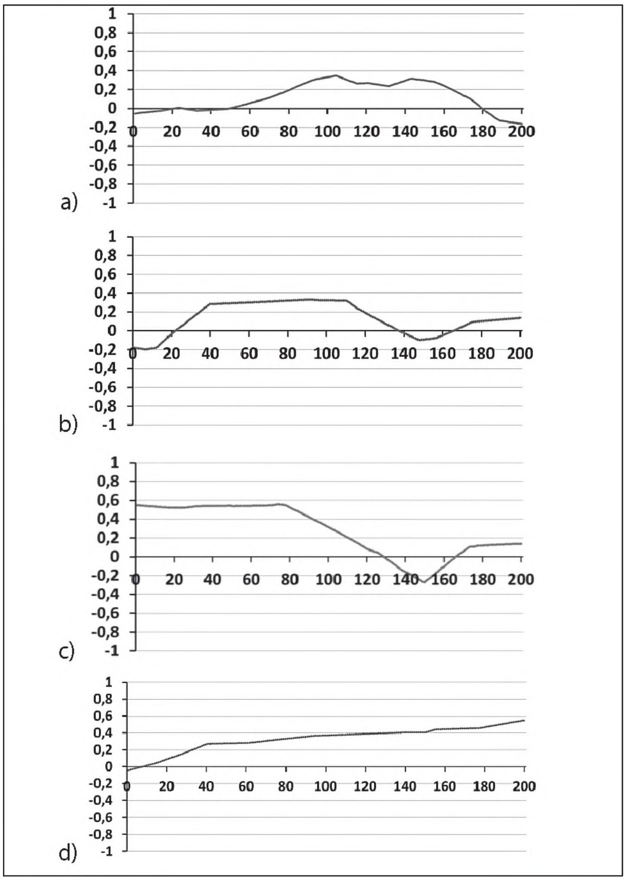


Figure 6 Lode-Nadai coefficient: a – upper face; b - right face; c - lower face; d - left face

average stress value is -3 200 MPa. With decreasing of temperature to -196 °C, the absolute compressive stress is increased. The mean value of average hydrostatic pressure at this temperature reaches -3 850 MPa. For a more detailed analysis it was decided to use a complex indicator of the stress-strain state - Lode-Nadai coefficient [10]. This characteristic allows one to determine which type of deformation is realized at the particular point - stretching, compression or shear. Lode-Nadai coefficient is calculated by the formula:

$$\mu = 2 \cdot \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} - 1, \qquad (2)$$

The value of the coefficient varies from -1 to 1. Value from 0 to 1 corresponds to compression; value from 0 to -1 corresponds to stretching; value of the coefficient tending to 0 corresponds to shear.

To calculate this coefficient, 200 control points were created on each face (Figure 5), in each of which the values of the main stresses were recorded. The results of the calculation of the Lode-Nadai coefficient on each face of the workpiece section are shown in Figure 6.

The lower left corner is essentially a "dead zone", where the torsion effect is absent; the upper right corner experiences torsion from the two faces of the tool. Moreover, due to the pinching in the area of the joint of the faces and the influence of the torque in this angle, a shear region with a small fraction of tension is created, where the value of the Lode-Nadai coefficient is -0,15÷-0,2. In the opposite lower - left corner, the value of the Lode-Nadai coefficient is 0,55, which indicates the presence of a purely compressive zone.

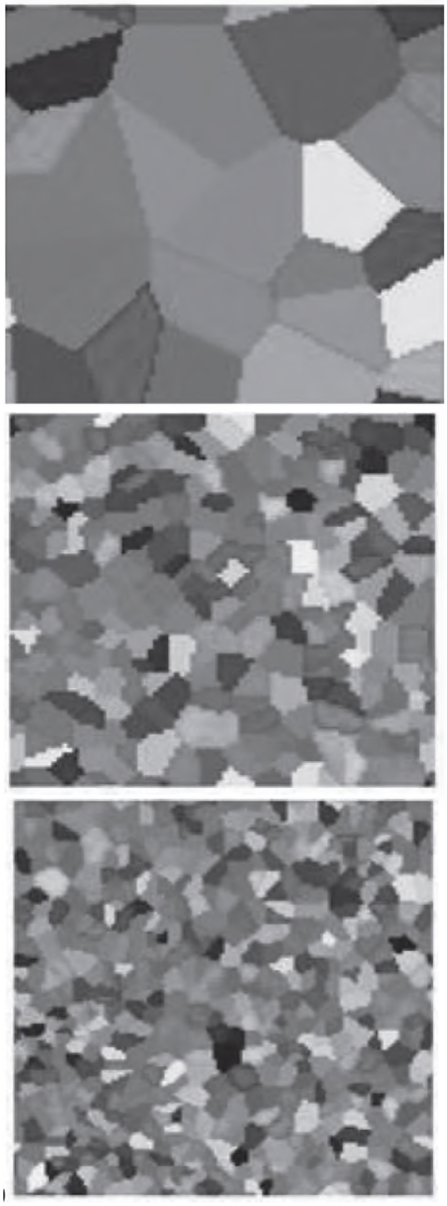


Figure 7 Microstructure evolution: a – initial structure; b - at 20 °C; c - at -196 °C

At the opposite corners (upper left and lower right), similar deformation patterns are formed. In the upper - left corner, the value of the Lode-Nadai coefficient is -0,05, which indicates a shift pattern. In the lower right corner, the value of the Lode-Nadai coefficient is 0,15, which indicates a shift pattern with a small fraction of compression.

Simulation of the microstructure evolution was conducted using Cellular Automata method. As this simulation is performed after the main calculation, it was decided to investigate the microstructure evolution in the most processed area. Using this method, it can be predicted not only the size, but also the shape of the grains. Detailed description of this simulation method is described in [6].

Simulation of microstructure evolution (Figure 7) of initial structure of 12 µm showed that after 4 passes at 20 °C it can be grinded up to 0.8 µm and up to 0.6 µm after 4 passes at -196 °C.

CONCLUSIONS

The study of the high-pressure torsion process of AISI-316 stainless steel in the die of the new design using cryogenic cooling, as well as a comparative analysis with deformation at ambient temperature, showed that the strain distributions in both cases are do not change significantly. At the same time, the stress vales are significantly different - with cryogenic cooling, the level of compressive stresses increases by about 20%. The simulation of microstructure evolution in Deform-3D program showed that the use of cryogenic cooling makes it possible to further grind the original structure.

Acknowledgments

This research was funded by the Science Committee of the Ministry of education and science of the Republic of Kazakhstan (Grant № AP08856353).

REFERENCES

[1] F. Z. Utyashev, G. I. Raab, Deformation methods for obtaining and processing ultrafine-grained and nanostructured materials, Ufa, Gilem, 2013, 214-222.

[2] A. P. Zhilyaev, T. G. Langdon, Using high-pressure torsion for metal processing: Fundamentals and applications, Progress in Materials Science 53 (2008), 893-979.

[3] C. Xu, Z. Horita, T. G. Langdon, The evolution of homogeneity in processing by high-pressure torsion, Acta Materialia 55 (2007), 203-212.

[4] O. L. Khasanov, E. S. Dvilis, Z. G. Bikbaeva Methods of compaction and consolidation of nanostructured materials and products, Tomsk: Tomsk Polytechnic University Publishing House, 2008, 82-85.

[5] S. Erbel, Mechanical properties and structure of extremely strain-hardened copper, Metals Technology 6 (1979), 482-486.

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

[7] K. Edalati, J. M. Cubero-Sesin, A. Alhamidi, I. F. Mohamed, Z. Horita, Influence of severe plastic deformation at cryogenic temperature on grain refinement and softening of pure metals: Investigation using high-pressure torsion, Materials Science and Engineering A-Structural Materials Properties Microstructure and Processing 613 (2014), 103-110.

[8] G. H. Zahid, Y. Huang, P. B. Prangnell, Microstructure and texture evolution during annealing a cryogenic-SPD processed Al-alloy with a nanoscale lamellar HAGB grain structure, Acta Materialia 57 (2009), 3509-3521.

[9] R. Bidulský, J. Bidulská, F.S. Gobber, T. Kvačkaj, P. Petroušek, M. Actis-Grande, K-P. Weiss, D. Manfredi, Case Study of the Tensile Fracture Investigation of Additive Manufactured Austenitic Stainless Steels Treated at Cryogenic Conditions, Materials 13 (2020), 3328.

[10] V. M. Segal, V. I. Reznikov, V. I. Kopylov, D. A. Pavlik, V. F. Malyshev, Processes of plastic structure formation of metals. Minsk, Nauka i tekhnika, 1994, 118-123.

Note: Translated by D. Rahimbekova, Temirtau, Kazakhstan