Comparative analysis of high carbon steel behavior on contact surface with a tool in different methods of deformational nanostructuring

Marina Polyakova
Nosov Magnitogorsk State Technical University
Aleksandr Gulin
Nosov Magnitogorsk State Technical University
Alexey Stolyarov
Magnitogorsk Hardware and Sizing Plant
Oksana Nikiforova (oksana-nikiphorova@yandex.ru)
Spbstu: Sankt-Peterburgskij Politehniceskij Universitet Petra Velikogo

Research Article

Keywords: high carbon steel, contact surface, nanostructuring, deformation scheme, simple share, torsion, drawing

Posted Date: March 19th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-247843/v1

Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on July 21st, 2021. See the published version at https://doi.org/10.1007/s00170-021-07618-x.

Abstract

Every method of deformational nanostructuring is characterized by typical scheme of the processing. One of the main aspects of such methods is the behavior of the processed metal on the contact surface with a tool. The aim of this study is to analyse the distribution of deformation from the contact surface of the workpiece to the bulk in different methods of deformational nanostructuring. High carbon steel was chosen for the analysis. Simulation was performed in ABAQUS software. Methods based on different kinds of deformation were chosen for the comparison: method based on simple shear in one deformation zone, method based on simple shear with torsion, method based on simple shear in two deformation zones with torsion, and continuous method of combined deformational processing by drawing with torsion. Data of the distribution of main strains, tangential strains, equivalent strains, and the Mizes stress from the contact surface to the depth of 0.05 mm to the bulk was obtained. The results of simulation can be used for prediction of steel behavior under different kinds of deformational processing.

1. Introduction

Manufacturing processes of metal ware production are based on different methods of deformational processing. It is evident that during such kind of processing metal microstructure changes causing the change of its mechanical properties. One of the important tasks of state-of the-art material science is to find effective ways to increase strength of metals. It is well known that in order to improve metals' strength it is necessary to choose the complex effect on microstructure combining methods of different physical nature: to use alloying elements, to apply any kind of thermal treatment or deformational processing.

When analyzing the existing approaches to increase of mechanical properties in metals [1] one can make the following conclusions. Firstly, at present time it is not enough to use any method which is based on the only one strengthening mechanism for steels. Secondly, choice of the grade of steel or alloying elements for it should be based on the prediction of the effects which can be probably occur on every stage of steel treatment. In order to implement different strengthening mechanisms during processing high carbon steel are preferable. Eutectoid steel in cooling has the only one critical point and at ambient temperature microstructure consists only from pearlite. It proves that properties of this steel will be uniform all over the whole volume of the processed workpiece. It makes it possible to deform this kind of steel with high values of deformation degree and to store the definite value of its ductility. Thirdly, the most effective way to increase strength properties in steel is to use the deformational processing. It leads to the decrease of grain size of the processed metals. In this case Hall-Petch equation makes it possible to predict the level of mechanical properties after deformational processing.

Existing methods of metal processing are based on different kinds of plastic deformation: tensile, compression, bending, and torsion. Every kind of plastic deformation causes peculiar changes in microstructure to its deformation scheme and stress-strain state in the processed metal.

Drawing is the main operation for wire production. At drawing the wire is processed by tensile and compression deformation which result in specific texture formation. In [2–5] the results of pearlitic steels microstructure evolution during drawing are presented. Influence of microstructure formation on mechanical properties of carbon steel wire with different carbon content was studied as well.

Bending as the kind of plastic deformation which is the basic one at wire descaling operation. During bending different parts of wire are deformed by tensile and compression deformation. Alternate bending is widely used in different technological processes both as auxiliary (coiling and recoiling) and separate (sheet forging, strengthening) operation. In contrast to traditional methods of metal processing in which total deformation is limited by dimensions of workpiece or the part the total deformation in bending actually in not limited at all. It increases the efficiency of the process. Peculiarities of wire bending are presented in [6, 7].

Twisting makes it possible to arrange several wires into one metal part – cable or rope. Torsion deformation is characterized by very complicated scheme. There is no consistent opinion about stress-strain state of the processed metal under torsion deformation. One of the point of view is based on the hypothesis that torsion deformation is maximum on the surface. Tangential stresses are considered to change in different ways from maximum values on the surface to the zero in the center of the processed workpiece [8]. Influence of torsion deformation on microstructure of pearlitic steel wire is presented in [9, 10].

It is the well known fact that methods of severe plastic deformation (SPD) allow to increase strength properties while ductility of metals does not decrease. At present time plenty of investigations are devoted to different aspects, both theoretical and experimental, of this kind of processing [11–17 and others]. But it is mentioned by different researchers [18, 19 and others] that at present time there are some difficulties in implementation of the existing SPD methods in the operating metal ware industrial technological manufacturing processes. It can be explained by their low processability, limits in workpiece dimensions, the necessity to design new equipment and tools. Traditional methods of improving mechanical properties of metals and alloys have already exhausted their technical and technological performance capabilities to a great extent. From this point of view, metal ware manufacturing technologies based on combination and integration of different operations in one continuous line, which result in refining the microstructure of processed metals and alloys are very promising.

One of the important aspects of any method of deformational processing is the contact interaction between the workpiece and a tool. Stress-strain state of the workpiece in the contact area with a tool depends on hard friction conditions, increase of temperature in the contact zone and as a result can cause damage and fracture of the workpiece [20–22 and others]. It can limit the possibility of implementation of SPD methods into industrial manufacturing technologies.

The aim of this study is to compare the level of deformation on the contact surface between a workpiece and a tool in different SPD processes in order to estimate their possibility to be applied at large scale production. For the comparison following methods based on different kinds of deformation were chosen: method based on simple shear in one deformation zone, method based on simple shear with torsion, method based on simple shear in two deformation zones with torsion, and continuous method of combined deformational processing by drawing with torsion.

2. Materials And Methods

High carbon steel was chosen for the analysis (Table 1).

Table 1
Chemical composition of high carbon steel grade 70 (wt. %)

Fe	C	Si	Mn	Ni	S	P	Cr	Cu
Balance	0,72 – 0,8	0,17 – 0,37	0,5 – 0,8	till 0.25	till 0.035	till 0.035	till 0.25	till 0.2

Simulation of high carbon steel behavior in contact zone between the workpiece and a tool in different methods was studied using ABAQUS software (licentiate Perm National Research Polytechnic University, Russian Federation). Finite element model of the contact area in different methods of deformational processing was established as the microvolume (cube with edges 0.3 mm) which was disposed on the workpiece surface. Dimensions of the mesh were equal to 0.03 mm. Workpiece was 3.0 mm in diameter or square cross section with edges 3.0x3.0 mm. The following boundary conditions were used for modeling. The workpiece from high carbon steel was considered to be the elasto-plastic body with density 7800 kg/m^3. Elastic modulus was equal to 212000 MPa, Poisson coefficient was equal to 0.28. Die was presented as the rigid body. Only the inner surface of the tool was modeled. Friction coefficient in all methods under study was chosen 0.06. For all methods the deformation rate was chosen 60 mm/s.

Method based on simple share in one deformation zone. Equal channel angular pressing (extrusion) (ECAP/ECAE) was chosen for the investigation as the method based on simple share in one deformation zone [11]. During ECAP a billet is multiple pressed through a special die in which the angle of intersection of two channels is usually 90^0 (Fig. 1) [12].

ECAP is considered to be one of the classical SPD methods. It is used to study the peculiarities of microstructure and properties formation for different metals and alloys [12, 15, 17, 18 and others].

Method based on simple share with torsion. This method includes operation of reduction treatment, combined with shear [23, 24]. Implementation of the method includes deformation of the metal according to the drawing scheme due to the applied attractive force through two consecutively located conical wire-drawing dies 1 and 2 with simultaneous rotation of one of the dies (2) (Fig. 2). semi-finished products by drawing with shift [23]

The specific aspect of this deformational processing is that additional shear deformation appear in the deformation zone due to both the eccentricity and applied transverse moment which cause the rotation of the second die.

Method based on simple shear in two deformation zones with torsion. This method is known as twist extrusion (TE) [25, 26]. TE is based on pressing out a prism specimen through a die with a profile consisting of two prismatic regions separated by a twist part (see Fig. 3) [26]. As the specimen is processed, it undergoes severe deformation while maintaining its original cross-section.

The mode of deformation in these zones is simple shear in the transversal layers, as in HPT. In terms of strain, at the first approximation, the billet during TE like passes through two “transparent” Bridgman anvils (see arrows in Fig. 3). High hydrostatic pressure in the deformation zone is ensured by application of backpressure.

Continuous method of combined deformational processing by drawing with torsion. The laboratory setup was used for experimental part which makes it possible to combine drawing with torsion (Fig. 4).in drawing with torsion of carbon steel wire.

Two consequently arranged along the longitudinal symmetrical axis dies (2, 4) are installed into the frame 1. The four-roll system 3 has the autonomous engine which makes it possible to apply torsion deformation to the moving wire 5 (moving direction is marked by an arrow). The novel step of this setup is to adjust these tools simultaneously on the moving wire. The research group received patents for invention from the Russian Federation patent office for the developed method and its setup [27, 28].

For the purpose of this investigation the simulation of drawing along the rout 3.0-2.86-2.75 mm together with rotating rate of the four-roll system at 200 RPM (revolutions per minute) as the most intensive kind of processing was performed.

3. Results And Discussion

Method based on simple share in one deformation zone. Distribution of deformation from the contact surface to the bulk of the processed workpiece for the method based on simple shear is presented in Fig. 5. The results show that strains distribution from the contact surface with the die to the bulk is rather uniform. Hence, this scheme of plastic deformation is contributory to the processed metal. Values of the Mizes stress are uniform all over the cross section of the billet (Fig. 6). It will be not cause any cracks or damage of the processed workpiece. From this point of view ECAP can be applied for several times to the same workpiece in order to get the uniform microstructure in the whole volume of the billet.

Method based on simple share with torsion. This method is characterized by combination of deformation by drawing with torsion. As it was mentioned before, the construction of setup makes it possible to achieve the scheme of simple share (see Fig. 2). As it is seen from Fig. 7, this scheme is characterized by high values of tangential strains. Values of equivalent strains change periodically. It may cause damage of the processed workpiece.

Distribution of the Mizes stresses is presented in Fig. 8. Due to the eccentricity of the tool and rotation of a die (see Fig. 2) values of the Mizes stresses start to increase in the entrance of the deformation zone. High values of this parameter can cause damage of the processed workpiece especially in its center. From this point of view this methods is recommended for processing metals with high ductility.

Method based on simple shear in two deformation zones with torsion. Results of simulation show that the workpiece undergoes intensive deformational processing (Fig. 9). Distribution of deformation is uniform from the surface to the bulk of the processed workpiece. But change of high values of the deformational parameters proves about the intensive interaction of the workpiece with the tool. It can lead to cracks formation on the surface of the billet.

Complicated scheme of deformations appear in the processed workpiece in drawing combined with torsion. Maximum values of deformation parameters are observed in 0.2 s after the beginning of the process. It testifyes the high intensity of such kind of deformational nanostructuring. From the obtained values of the Mizes stresses (see Fig. 12) it is evident that deformational processing by drawing with torsion does not lead to damage of the workpiece saving its' ductility. These results match well with known aspects that using torsion deformation during drawing, for example in roller dies, results in decrease of friction between a wire and a die. It simplifies intrusion of deformation in bulk of the processed workpiece.

4. Conclusions

Simulation of different methods of deformational nanostructuring showed following peculiarities of high carbon steel behavior on the contact surface between the processed workpiece and a tool:

1. Equal channel angular pressing is the method which is characterized by simple shear in one deformation zone. During this method the distribution of deformations from the surface area of the billet to the bulk is uniform. The level of deformations is not very high that is why the workpiece can be processed many times in ECAP.
2. High level of deformation is observed in method based on simple shear with torsion. It may cause damage of the processed workpiece. It is preferable to apply this method of deformational nanostructuring to ductile metals and alloys.
3. Twist extrusion is the method based on simple shear in two deformation zones with torsion. Rather complicated scheme of deformation makes it possible to get the uniform structure of the processed workpiece from the surface to its axis.
4. Level of deformations in continuous method of combined deformational processing by drawing with torsion in not very high. It allows to process high carbon steel saving its ductile properties.

The obtained analytical peculiarities can be used for theoretical prediction of high carbon steel under different kinds of deformational processing. The obtained data can be used as the basics to design new methods of deformational nanostructuring of steels.

Declarations

Funding

This research was carried out in the frame of the proposal 21-19-00763 to the Russian Science Foundation.

The research is partially funded by the Ministry of Science and Higher Education of the Russian Federation as part of World-class Research Center program: Advanced Digital Technologies (contract No. 075-15-2020-934 dated 17.11.2020).

Conflict of Interest

The authors declare no conflict of interest.

References

1. George E. Dieter. Adapted by David Bacon (1988). Mechanical metallurgy. SI Metric Ed. McGraw-Hill Book Company, London
2. Fang F, Hu X-j, Zhang B-m, Xie Z-h, Jiang J-q (2013) Deformation of dual-structure medium carbon steel in cold drawing. Mater Sci Eng A 583:78–83
3. Guo N, Luan B-F, Wang B-S, Liu Q (2011) Microstructure and texture evolution in fully pearlitic steel during wire drawing. Sci China Tech Sci 54:2368–2372
4. Pilarczyk JW (2011) Analysis of reasons for increase of tensile, yield strength and number of twists of wires drawn in pressure dies. Wire J Int 34(7):138–147
5. Huang H, Wang L, Li F (2011) Structure evolution in steel wires during drawing. Adv Mater Res 194–196:218–223
6. Oplatka G, Roth M, Vaclavic P (1986) Influence of a plastic bending deformation on the lifetime of wires and ropes. Proc. the 9th Congress on Material Testing. 44–48
7. Gillstrom P, Jarl M (2006) Mechanical descaling of wire rod using reverse bending and brushing. J Mater Proc Tech 172(3):332–340
8. Zilberg YuV, Kuznetsov DS, Mashura SV (2010) Effect of torsion on strength of low carbon steel wire. Steel 11:66–69. (in Russian)
9. Cordier-Robert C, Forfert B, Bolle B, Fundenberger J-J, Tidu A (2008) Influence of torsion deformation on microstructure of cold-drawn pearlitic steel wire. J Mater Sci 43:1241–1248
10. Guo N, Song B, Wang B-S, Liu Q (2015) Influence of torsion deformation on textures of cold drawing pearlitic steel wires. Acta Metall Sci 28(6):707–714
11. Segal V (2018) Review: Modes and Processes of Severe Plastic Deformation (SPD). Materials. doi:10.3390/ma11071175

12. Valiev RZ, Islamgaliev RK, Aleksandrov IV (2000) Bulk nanostructured materials from severe plastic deformation. Prog Mater Sci 45:103–189
13. Langdon TG (2013) Twenty-five years of ultrafine-grained materials: Delivering exceptional properties through grain refinement. Acta Mater 61:7035–7059
14. Zhilyaev AP, Langdon TG (2008) Using high-pressure torsion for metal processing: Fundamentals and applications. Prog Mater Sci 53:893–979
15. Umemoto M (2003) Nanocrystallization of steels by severe plastic deformation. Overview Mater Trans Special Issue on Nano-Hetero Structures in Advanced Metallic Materials 44(10):1900–1911
16. Figueiredo RB, Langdon TG (2009) Using severe plastic deformation for the processing of advanced engineering materials. Mater Trans Special Issue on New Functions Properties of Engineering Materials Created by Designing Processing 50(7):1613–1619
17. Azushima A, Kopp R, Korhonen A, Yang DY, Micari F, Lahoti GD, Groche P, Yanagimoto J, Tsujii N, Rosochowskij A, Yanagida A (2008) Severe plastic deformation (SPD) processes for metals. CIRP Annals - Manuf Tech 57:716–735. doi:10.1016/j.cirp.2008.09.005
18. Furukawa M, Horita Z, Nemoto M, Langdon TG (2001) Review: Processing of metals by equal-channel angular pressing. J Mater Sci 36:2835–2843
19. Zhu YT, Langdon TG (2004) Fundamentals of nanostructured materials by severe plastic deformation. JOM 56:58–63
20. Hosoda K, Asakawa M, Kajino S, Maeda Y (2008) Effect of die semi-angle and multi-pass drawing on additional shear strain layer. Wire J Int 11:68–73
21. Hwang SK, Back HM, Joo HS, Im Y-T (2015) Effect of processing routes in a multi-pass continuous hybrid process on mechanical properties, microstructure and texture evolutions of low-carbon steel wires. Met Mater Int 21(2):391–401
22. Stolyarov A, Polyakova M, Atangulova G, Alexandrov S (2020) Effect of die angle and frictional conditions on fine grain layer generation in multipass drawing of high carbon steel wire. Metals 10(11):1462. https://doi.org/10.3390/met10111462
23. Raab GI, Raab AG. Patent RU 2,347,633 (2009). Method for production of ultrafine-grained semi-finished products by drawing with shift
24. Chukin MV, Raab AG, Semenov VI, Aslanyan IR, Raab GI (2012) Application of the full factor experiment in the process of drawing with shear. Vestn Nosov Magnitogorsk State Tech Univ 4(40):33–37
25. Beygelzimer Y, Varyukhin V, Synkov S, Orlov D (2009) Useful properties of twist extrusion. Mater Sci Eng A 503:14–17
26. Varyukhin V, Beygelzimer Y, Kulagin R, Prokof’eva O, Reshetov A (2011) Twist extrusion: fundamentals and applications. Mater Sci Forum 667–669:31–37. doi:10.4028/www.scientific.net/MSF.667-669.31

27. Chukin MV, Polyakova MA, Golubchik EM, Rudakov VP, Noskov SE, Gulin AE, Patent RU 2,467,816 (2012). Method for obtaining ultra-fine grained semifinished material by drawing with torsion
28. Polyakova MA, Chukin MV, Golubchik EM, Gulin AE (2013) Patent RU 130:525. Setup for fabrication wire with ultra-fine grain structure

Figures

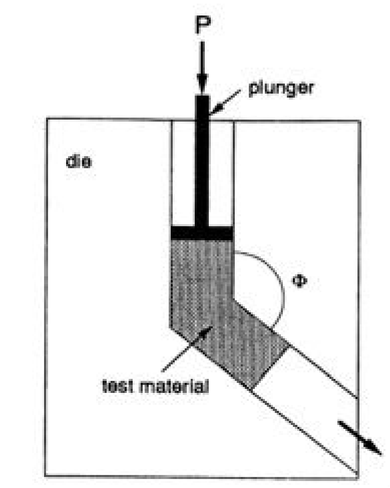

Figure 1

Principle scheme of equal channel angular pressing [12]

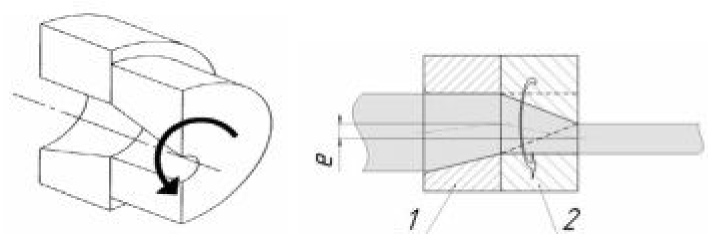

Figure 2

Principle scheme of method for production of ultrafine grained semi-finished products by drawing with shift [23]

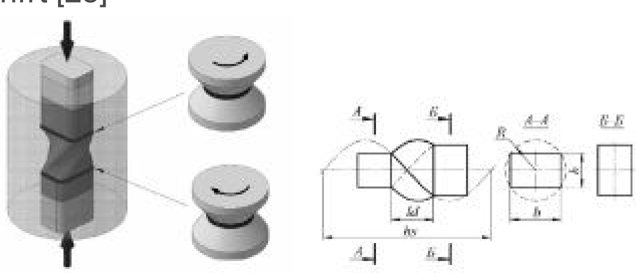

Figure 3

Twist extrusion scheme [26]

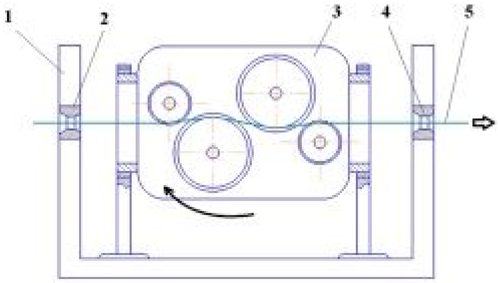

Figure 4

Principle scheme of the laboratory setup for combined deformational processing in drawing with torsion of carbon steel wire

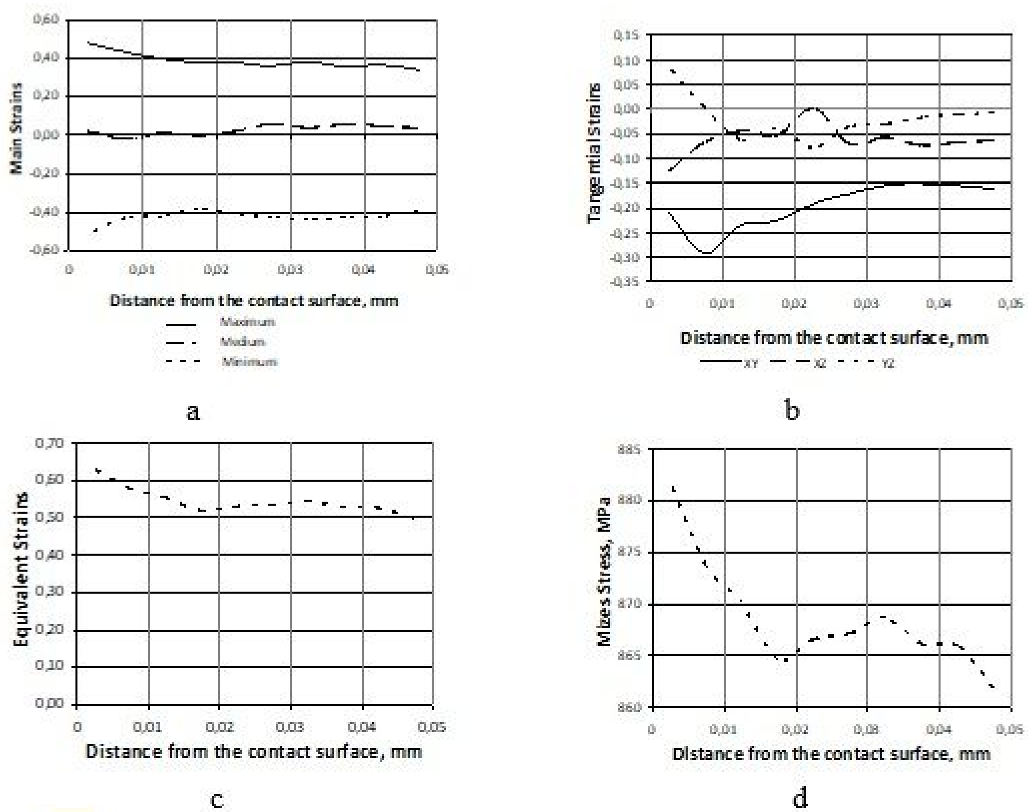

Figure 5

Distribution of deformation in the workpiece from high carbon steel for the scheme of simple share: a – main strains, b – tangential strains, c – equivalent strains, d – Mizes stress

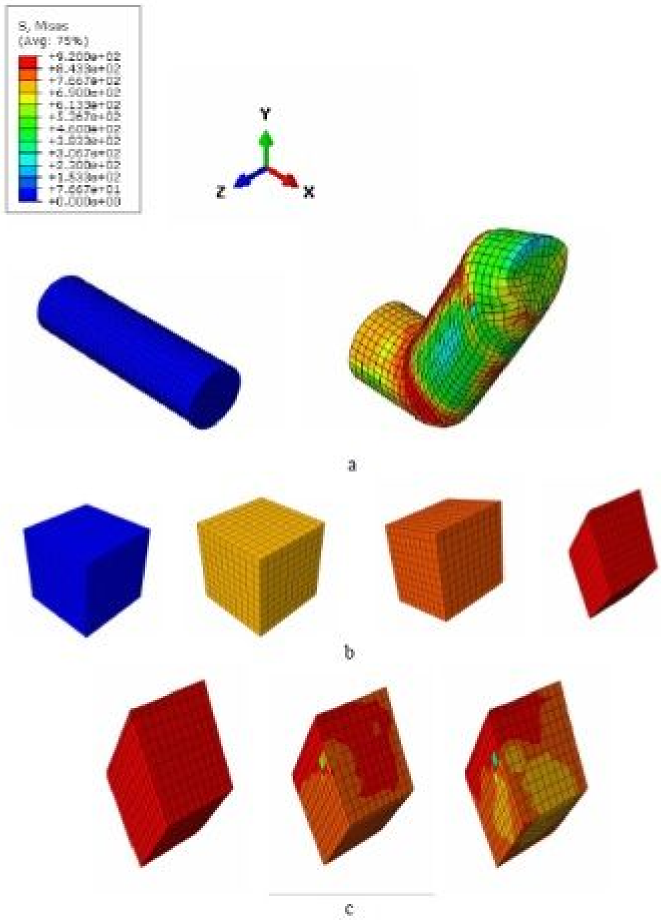

Figure 6

Values of the Mizes stress on the contact surface of the workpiece with the die for the method of deformational nanostructuring based on the scheme of simple share: a – scheme of simulation; b – the entrance to the deformation zone; c – the exit of the deformation zone

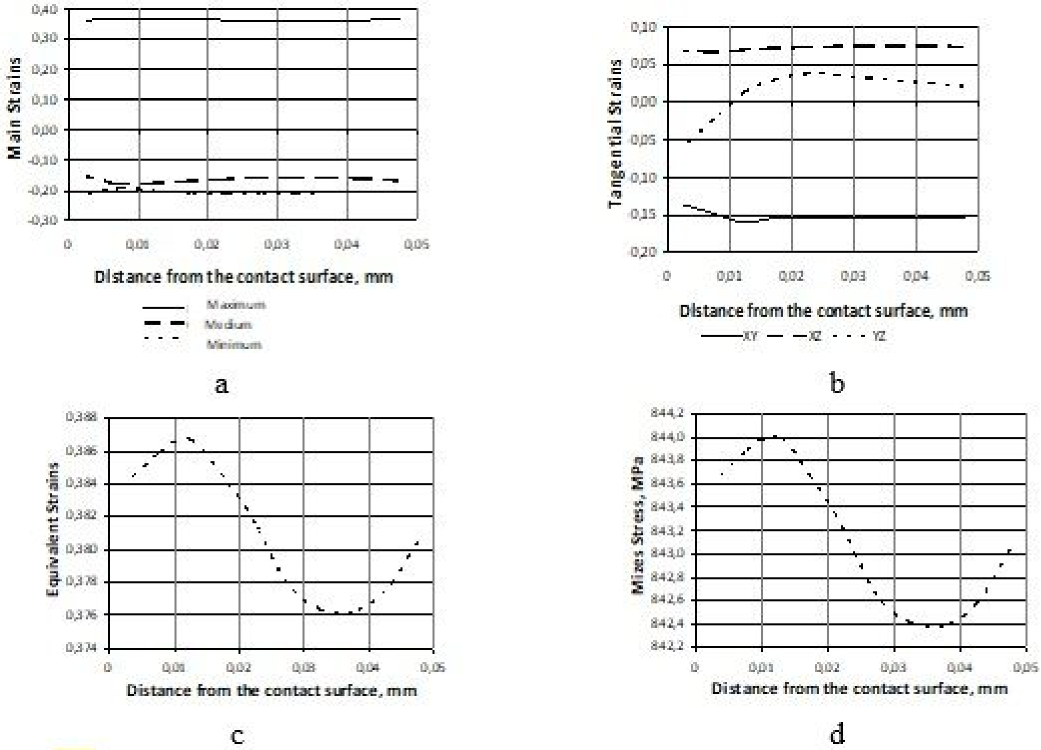

Figure 7

Distribution of deformation in the workpiece from high carbon steel for the scheme of simple share with torsion: a – main strains, b – tangential strains, c – equivalent strains, d – Mizes stress

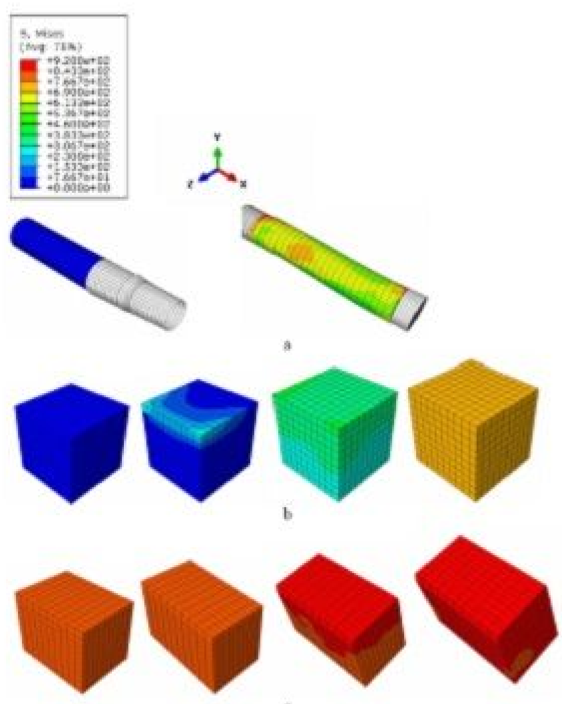

Figure 8

Values of the Mizes stress on the contact surface of the workpiece with the tool for the method of deformational nanostructuring based on the scheme of simple share with torsion: a – scheme of simulation; b – the entrance to the deformation zone; c – the exit of the deformation zone

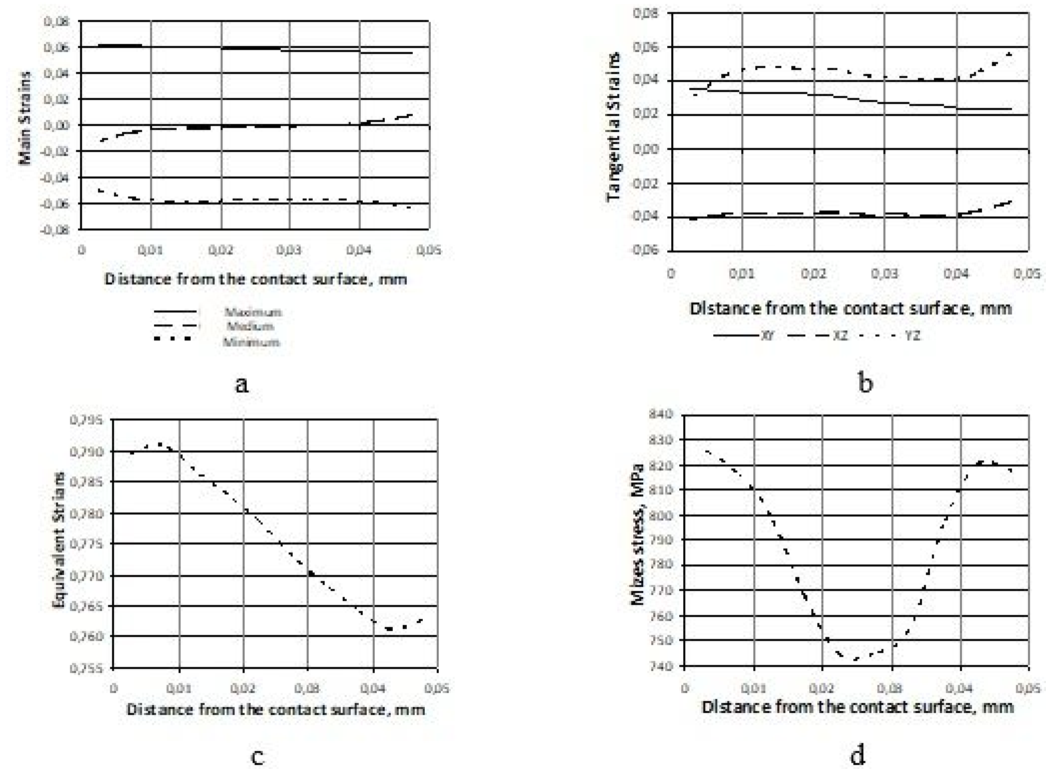

Figure 9

Distribution of deformation in the workpiece from high carbon steel for the scheme of simple share in two deformation zones with torsion: a – main strains, b – tangential strains, c – equivalent strains, d – Mizes stress

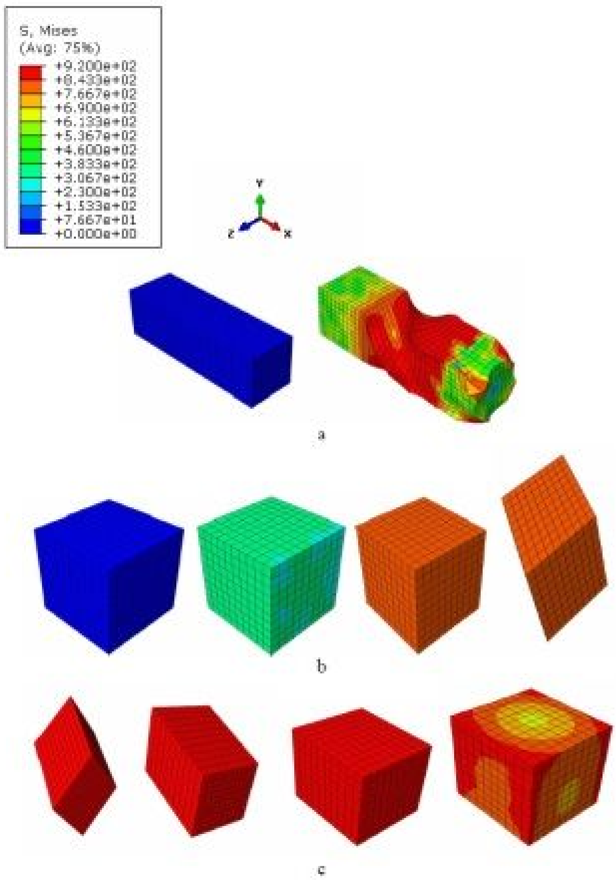

Figure 10

Values of the Mizes stress on the contact surface of the workpiece with the tool for the method of deformational nanostructuring based on the scheme of simple share in two deformation zones with torsion: a – scheme of simulation; b – the entrance to the deformation zone; c – the exit of the deformation zone

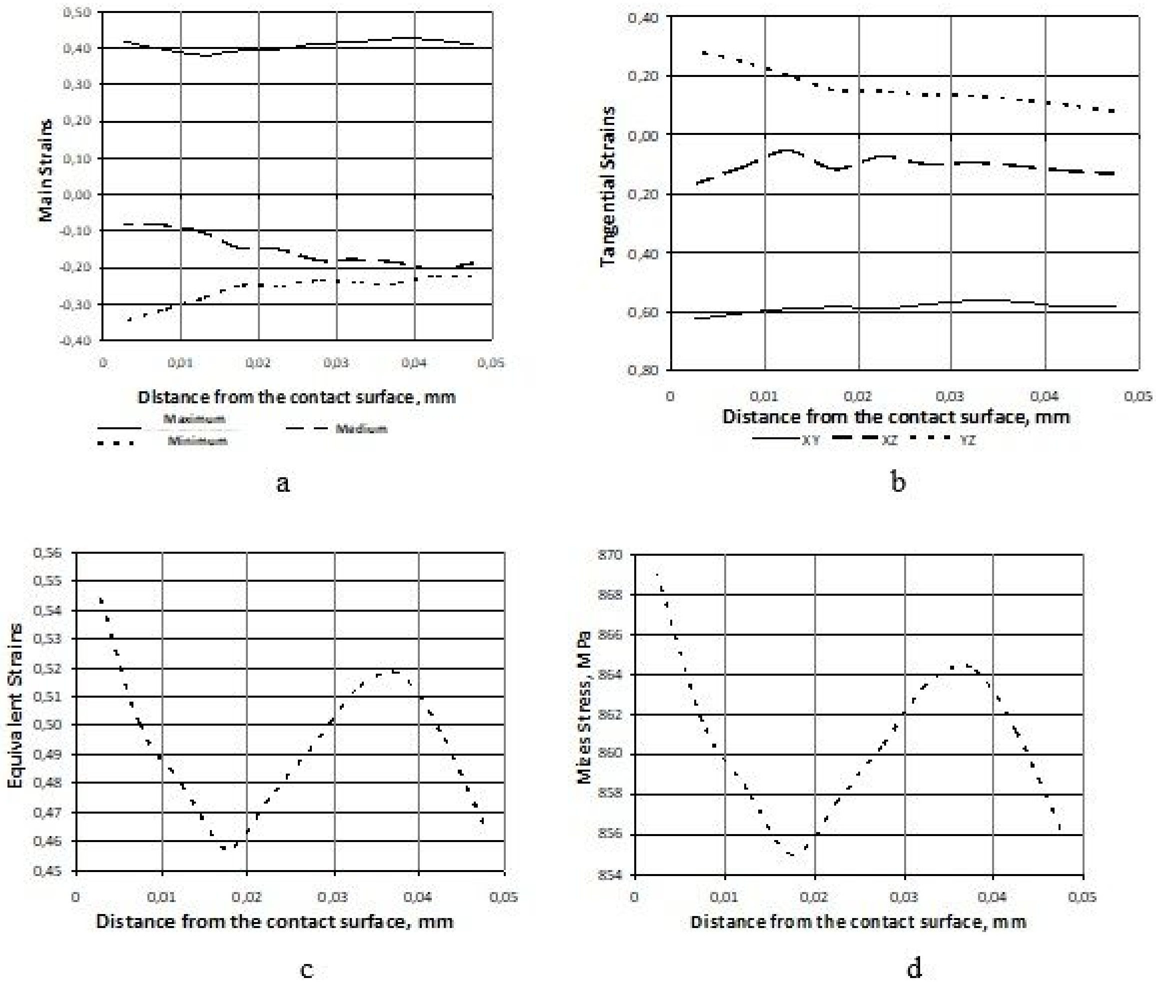

Figure 11

Distribution of deformation in the workpiece from high carbon steel for the method of deformational nanostructuring based on drawing with torsion: a – main strains, b – tangential strains, c – equivalent strains, d – Mizes stress

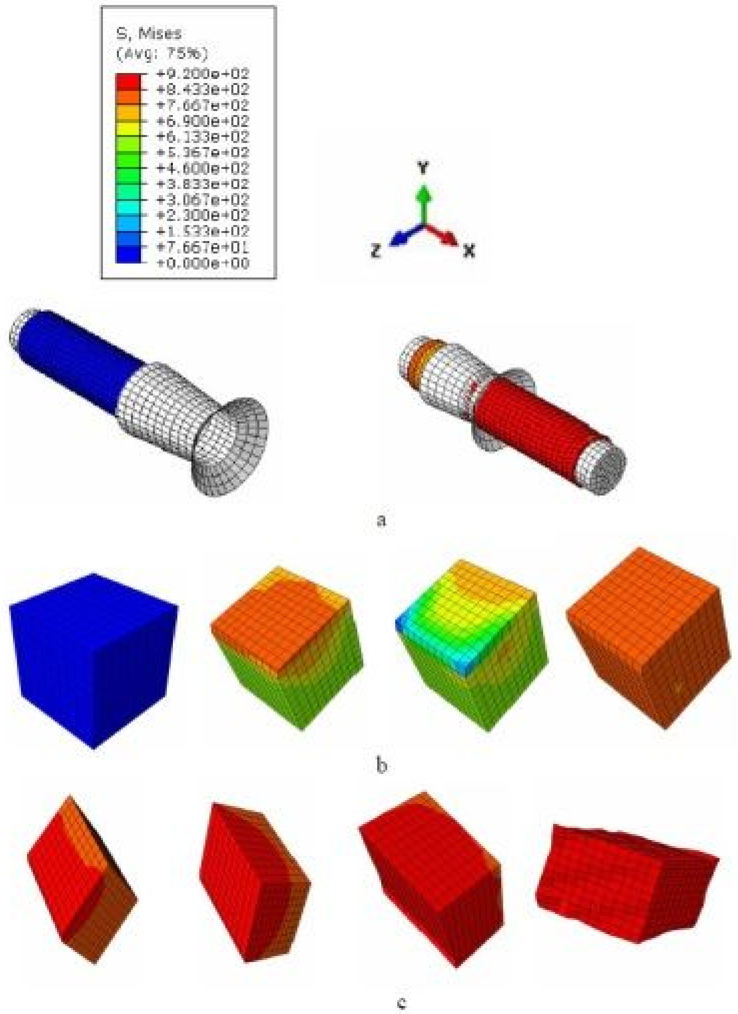

Figure 12

Values of the Mizes stress on the contact surface of the workpiece with the tool for the method of deformational nanostructuring based on drawing with torsion: a – scheme of simulation; b – the entrance to the deformation zone; c – the exit of the deformation zone