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

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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 analyze 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 principle strains, tangential strains, equivalent strains, and the von-Mises equivalent stress from the contact surface to the depth of 0.05 mm to the bulk were obtained. The results of simulation can be used for prediction of steel behavior under different kinds of deformational processing.

Keywords High carbon steel · Contact surface · Nanostructuring · Deformation scheme · Simple shear · Torsion · Drawing

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 and 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 is 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 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 detail 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 the very complicated scheme. There is no consistent opinion about stress-strain state of the processed metal under torsion deformation. One of the points 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]. But it is mentioned by different researchers [18, 19] 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, and 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 and increase of temperature in the contact zone and as a result can cause damage and fracture of the workpiece [20–22]. 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 microstructure of pearlitic steel wire is presented in [9, 10].

2 Materials and methods

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

Simulation of high carbon steel behavior in contact zone between the workpiece and a tool in different methods was
carried out 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 all over the volume of the processed workpiece (Fig. 1).

Because the shape of a workpiece is different in methods under study, its dimensions were 3.0 mm in diameter or square cross section with edges 3.0×3.0 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. For simulation, properties of high carbon steel wire were specified in the form of stress-strain curve (Fig. 2) and corresponded to the standard ASTM A1007-15 [23].

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 because it corresponds to the drawing conditions with consistent lubricant. The Coulomb friction model was used for modeling interaction between contact surfaces of a workpiece and a tool. For all methods, the deformation rate was chosen 60 mm/s.

**Method based on simple shear in one deformation zone is as follows** Equal channel angular pressing (extrusion) (ECAP/ECAE) was chosen for the investigation as the method based on simple shear 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° (Fig. 3) [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].

**Method based on simple shear with torsion is as follows** This method includes operation of reduction treatment, combined with shear [24, 25]. 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. 4).

The specific aspect of this deformational processing is that additional shear deformation appears 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 is as follows** This method is known as twist extrusion (TE) [26, 27]. 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. 5) [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. 5). High hydrostatic pressure in the deformation zone is ensured by application of backpressure.

Continuous method of combined deformingal processing by drawing with torsion is as follows The laboratory setup was used for experimental part which makes it possible to combine drawing with torsion (Fig. 6).

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 [28, 29].

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 shear 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. 7. The results show that strain 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 von-Mises equivalent stress are uniform all over the cross section of the billet (Fig. 8). It will not cause any cracks or damage in 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 shear with torsion This method is characterized by combination of deformation by drawing with torsion. As it was mentioned before, the construction of the setup makes it possible to achieve the scheme of simple shear (see Fig. 4). As it is seen from Fig. 9, 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 von-Mises equivalent stress is presented in Fig. 10. Due to the eccentricity of the tool and rotation of a die (see Fig. 4), values of the von-Mises equivalent stress 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
method 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. 11). 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 (Fig 12). It can lead to cracks formation on the surface of the billet.

**Continuous method of combined deformational processing by drawing with torsion** Distribution of deformation in the workpiece from high carbon steel for the method of deformational nanostructuring based on drawing with torsion is presented in Fig. 13.

Complicated scheme of deformations appears 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 testifies the high intensity of such kind of deformational nanostructuring. From the obtained values of the von-Mises equivalent stress (see Fig. 14), 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.

**Comparison of the effectiveness of different methods of deformational processing** It is the well known fact that stress-strain state of the material on the contact surface between a workpiece and a tool has the significant role in properties formation. The formation of so-called white layer on the contact area is studied in different methods of metal processing and machining [30–32]. It was shown in [33–35]...
Fig. 8. Values of the von-Mises equivalent stress on the contact surface of the workpiece with the die for the method of deformational nanostructuring based on the scheme of simple shear: a scheme of simulation; b the entrance to the deformation zone; c the exit of the deformation zone.

Fig. 9. Distribution of deformation in the workpiece from high carbon steel for the scheme of simple shear with torsion: a principle strain, b tangential strain, c equivalent strain, d von-Mises equivalent stress.
Fig. 10. Values of the von-Mises equivalent stress on the contact surface of the workpiece with the tool for the method of deformational nanostructuring based on the scheme of simple shear with torsion: a scheme of simulation; b the entrance to the deformation zone; c the exit of the deformation zone

Fig. 11. Distribution of deformation in the workpiece from high carbon steel for the scheme of simple shear in two deformation zones with torsion: a principle strain, b tangential strain, c equivalent strain, d von-Mises equivalent stress
that finite element analysis is applicable to study the white layer formation with high accuracy. But numerical validation of the experimental data is the rather difficult task because many factors should be taken into consideration in creating the theoretical model. Several approaches to theoretical description of white layer formation are presented in [36, 37]. It is proved that the strain rate intensity factor is the coefficient of the leading singular term in a series expansion of the quadratic invariant of the strain rate tensor in the vicinity of maximum friction surfaces. According to this approach, the constitutive equations should involve the strain rate intensity factor rather than the quadratic invariant of the strain rate tensor. The latter is usually involved in traditional constitutive equations used for the modeling of metal forming processes.

The effectiveness of different methods of deformational processing can also be estimated using the index of stress state as an indicator which characterizes metal stress state in the deformation zone [38]

$$k = \frac{\sigma}{T},$$

where $\sigma = 1/3(\sigma_1 + \sigma_2 + \sigma_3)$ is the mean stress (hydrostatic stress) and $T = \frac{1}{\sqrt{6}} \sqrt{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2}$ is the level of tangential stresses.

The index of stress state $k$ characterizes the ratio of mean level of normal and tangential stresses: when $k > 0$, tensile stresses predominate, and when $k < 0$, compression

![Fig. 12. Values of the von-Mises equivalent stress on the contact surface of the workpiece with the tool for the method of deformational nanostructuring based on the scheme of simple shear in two deformation zones with torsion: a scheme of simulation; b the entrance to the deformation zone; c the exit of the deformation zone](image)
stresses predominate. The stress state is considered to be tough at positive $k$ values and tough to high extent with higher $k$ levels. And vice versa stress state is considered to be soft at negative $k$ levels and much softer with higher absolute value of negative $k$.

For quantitative evaluation of stress state uniformity during processing, the complex $\omega$ was used [39].

$$
\omega = \frac{|\bar{k}|}{\sqrt{\frac{1}{n} \sum (k_i - \bar{k})^2}},
$$

(2)

where $\bar{k}$ and $k_i$ are the index of stress state values in the middle of the wire cross section and in the workpiece current point, respectively; $n$ is the number of measurement points according to the results of simulation in the software complex Deform-3D.

The higher the complex $\omega$ value, the more uniform is the metal stress state. And this complex can be calculated both for the whole chosen cross section and each line of points, in other words, for surface/center or input/output cross section of the processed metal. Using the complex $\omega$ makes it possible to take into consideration the variation of the workpiece dimensions during any kind of processing under constant conditions as well as the change of processing parameters at given dimensions of the workpiece. Hence, depending on the aim of the study, this approach can be used to solve both direct and inverse problems. Solution of the direct problem consists in estimation of stress-strain state of the processed material during any kind of processing when dimensions of the workpiece change and the technological modes of the process are preset, for example, in method based on simple shear with torsion and in continuous method of combined deformational processing by drawing with torsion. When the inverse problem is solved, it is necessary to determine the values of the stresses and strains in the workpiece when its dimensions do not change but processing parameters can be different, for example, in ECAP or TE.

On the next stage of the theoretical investigation, the comparison of values of the hydrostatic stress was performed (Fig. 15). Simulation was performed for the beginning of methods under study. Values of mean normal stress are presented for the layers of the processed metal with 0.0025 mm and 0.05 mm from the surface of the workpiece.

The obtained results show that during ECAP, tensile stresses are predominant. It means that processing during this method may lead to crack formation on the surface of the workpiece. That is why this method in most cases is used for processing of ductile metals and alloys [12]. Twisting causes the
appearance of shear stresses underlie yield and plastic slip. This is proved by results of simulation of that methods where torsion deformation is used (see Fig. 15b, c, d). Existence of hydrostatic stress in the thin layer of the processed workpiece surface area means that the scheme of such deformation is preferable for processing of materials with different level of ductility.

4 Conclusions

Simulation of different methods of deformational nanostructuring showed the 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 is not very high. It allows to process high carbon steel saving its ductile properties.

5. For quantitative evaluation of stress state uniformity during processing, the complex $\omega$ is proposed. The calculation is based on the values of index $k$ which characterizes the ratio of mean level of normal and tangential stresses. The application of this complex makes it possible to estimate the uniformity of stress-strain state of the material under different kind of deformational processing.

6. The comparison of values of the hydrostatic stress of different methods of deformational processing was performed. The obtained results showed the difference of hydrostatic stresses on the surface of the processed workpiece during method based on simple shear (equal channel angular pressing), 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. These data can be used for prediction of crack formation on the contact surface between the workpiece and a tool.

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

**Declartions**

**Ethics approval** We further confirm that any aspect of the work covered in this manuscript that has involved either experimental animals or human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

**Consent to participate** We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

**Consent for publication** We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing, we confirm that we have followed the regulations of our institutions concerning intellectual property.

**Conflict of interest** The authors declare no competing interests.

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