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Characteristics of Rolling In the Helical Rolls and Its Influence on the Formation Processes of Nanostructured State in the Metallic Materials

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Abstract

This article presents the results of studies of the effect of number of passes on the parameters of St3sp steel microstructure while rolling strips in the helical rolls. A comparative analysis of the grain size structures after rolling the strips in the helical rolls with various passes at the deformation temperature of 1100 ^{o}C is given in this article. The results of studies of the evolution of microstructure of workpieces at various stages of their production in the helical rolls have shown the possibility of obtaining strips with ultrafine structure using the intensive plastic deformation. It is shown that the parameters of the evolution of the defect structure in the individual crystallites depend on the micro and macro stress. The formula which allows us to determine the intensity of the shear stress at the octahedral crystal lattice site under the certain values of the intensity of the shear stress by the deformation is withdrawn. It is proved that the refinement of the structure while rolling in helical rolls occurs not only during the inclusion of additional slip systems, but also positive conditions can occur in the stress state conditions of the rolling in these rolls which unlocks the dislocation and increases their mobility. It is established that the accumulation of energy in the ensemble of defects and its reset by adjusting the ensemble of defects in the state with increased regularity occurs as a result of the energy accumulation of external forces and motion activation of defects of crystalline structure. The relaxation processes are activated while redesigning the ensemble of defects and the reinforcing processes occur in the metal structure.

Keywords: *St3sp, rolling, helical rolls, severe plastic deformation, submicrocrystalline state, grain size*.

Introduction

Nowadays, contemporary materials science is directed to solve the problem of obtaining ultrafine-grained materials with large-angle grain boundaries by using the methods of severe plastic deformation (SPD) [1-13]. The SPD methods are very diverse and can be based on the application of various schemes of deformation, high pressure, temperature and other factors.

It should be noted that the SPD methods refer to the heteronymic bulk deformation scheme (torsional stretch, equal channel angular pressing, screw pressing, comprehensive forging, shear rolling, drawing with torsion, etc.) [14-17]. A change of the stress state of the circuit occurs while using these methods, which owns a positive affect on the structure formation process and allows us to obtain more dispersed and homogeneous structure.

It is known [2-13] that the bulk nanostructured materials with a grain size of 0.1 - 0.2 microns and specific substructure, consisting of the lattice and grain boundary dislocations and disclinations can be obtained by the methods of SPD. This structure is characterized by large elastic distortions of the crystal lattice. It is believed that such fine-grained structure should provide a high level of both plastic and strength properties due to the special strained high angle grains, which allows us to realize a grain boundary sliding.

It is well known [18] that sliding of edge and screw dislocations and twinning is possible in any crystal only in the cases along certain crystallographic planes defined by the geometry of the structure, and in some areas, lying in these planes. Despite the fact that there are few amounts of the same type of sliding systems (or twinning), only one system acts predominantly at each moment of deformation, but different slip systems may operate at different stages of deformation.

The authors of the paper [18] believe that in the beginning, the deformation occurs by the system which is more positively oriented to the direction of maximum stress. The plastic shift usually starts on the slip system, which operates the largest shear stress, and self-slip occurs at the critical value of Schmid voltage.

In paper [18] it is noted that the regulation of the ratio of edge and screw dislocations allows us to create optimal combination of dislocation components in that way that at first deformation will be provided by edge dislocations with low Peierls barrier, and further development of plastic deformation will be provided by screw dislocations. It creates prerequisites for using the opportunities of thermal-deforming processing by varying not only the density and feature of dislocation distributions, but also by varying the type of dislocation components that take part in preferential deformation.

On the basis of the materials presented in this work [1], it should be noted that the use of deformation schemes with the shift can provide plastic deformation during the initial moment of processing by the movement of the edge dislocations, and its further development can take place by the motion of screw dislocations.

According to the opinion of authors of works [1,18], the type of stressed state and the ratio of stress components in the deformation behavior have a significant impact in the field of material deformation, as well as its ultimate structure and properties. A change in the properties in the right direction can be achieved by changing the stress-strain state (SSS) and the deformation conditions, also varying the degree of deformation and the temperature. Therefore, the questions related to the study of the impact on the structure and mechanical properties of materials' SSS in the deformation zone, the methods and the amounts of deformation, forms of the provisional and final heat treatment, alloy hardening mechanism and others continues to remain as important issues.

There are some different evidences about the impact of the normal stresses on the mobility of screw dislocations [1]. For example, one of them is that the large normal stresses on slip plane greatly increase the yield stress and decrease the mobility of screw dislocations. Large compressive stresses contribute to the creation of the dislocation structure with a predominance of the helical orientation. During the action of the large normal compressive stress on the slip plane occurs a reduction of mobility of screw dislocations. However, significant shear stresses should have a positive effect on the mobility of screw dislocations component, since it would allow split dislocations to change the slip plane easier (in terms of energy), and if more positive, it would be blocked according to the point of view of Schmid law.

In this work [1], it is emphasized that during conducting the analysis of the stress state of the body, it is extremely important to consider the shear stress required to create the residual shear of solid state particles, since the effect of the relative shift on the flow process is often superior to the influence of other factors, such as the normal stress, anisotropy, and others.

Nowadays, a considerable amount of factual material is accumulated and fundamental theoretical investigations of the basic laws which determine the formation of the microstructure and its evolution during plastic deformation in metallic materials with a body-centered (BCC) and face-centered crystal (FCC) lattice is carried out [19-25]. However, the publications indirectly confirm the impact of SSS on the formation of structures.

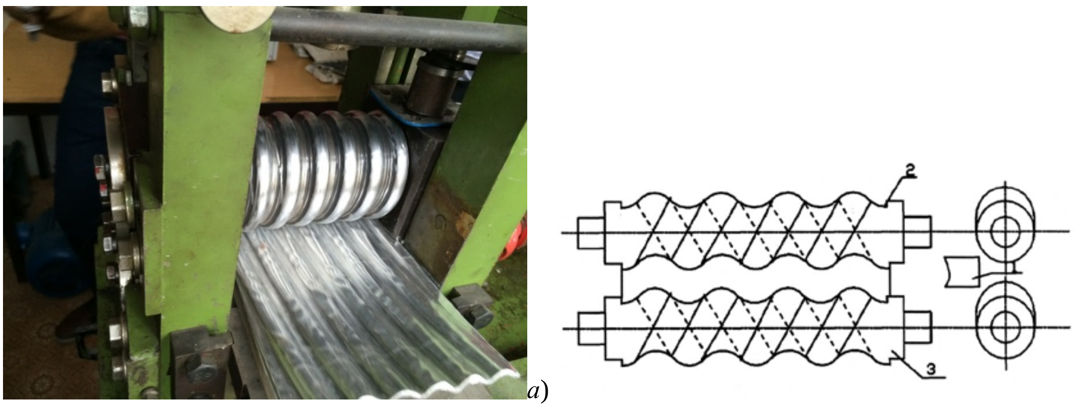
It should be noted that the theoretical studies about the impact of SSS in the slip plane on the intragranular and intergranular flow of the metal has not been carried out till today. Therefore, the study about the impact of SSS in the slip plane on the formation of structures in metals and alloys remains to be an important issue. Because of this, currently the scientific study about the peculiarities of structure formation and mechanical properties of SPD and the impact of SSS appearing in the slip planes on the laws of structure formation and properties remains to be an important scientific problem.

The aim of the paper is to study the impact of SSS in the slip plane on the structure formation while rolling strips in the helical rolls.

Equipment, materials and the methods of experiment

Among the known methods of SPD, rolling foil is widely used in practice. However, because of the small cross-section of the foil, it has a little use for subsequent forming operations. Therefore we have developed a tool with rolls with helical working surfaces (Figure 1) to produce semi-finished products with UFG structure [26], implementing the SPD without significant changes from their original shape and size.

The tool for hot rolling of steel and alloy comprises upper and lower rolls with helical work surfaces. Thus oppositely disposed projections and cavities of the upper and lower rolls are formed by spiral lines.



a) *b*)

a – the mill; *b* – the rolling scheme

Fig. 1 The rolling mill DUO with the helical rolls: *1* – workpiece; *2* – the upper roll; *3* – the lower roll

Rolling the workpiece in these rolls is performed as follows. The workpiece is fed into the nip between the rolls and during the first pass it is rolled with the compression unit $\varepsilon = \Delta h_B / H_o$, and during the subsequent passes it is rolled with a compression unit $\varepsilon = 2\Delta h_B / H_o$ (where Δh_B is the height of the protrusion or depression depth of undulating working surface; H_o is a workpiece height before rolling). This rolling ensures efficient refinement of the structure along the entire cross section of the workpiece by alternating bending deformation in longitudinal and cross sections of the workpiece.

Thus there is an offset of formations in the rolling projections and depressions across the width of the rolled strip, which creates additional macro shift along the cross section of the workpiece. Creating macro shift grinding leads to an effective structure of metals and alloys and also creates good conditions for obtaining a roll with a high quality.

The St3sp steel was selected as the workpiece material. The workpieces with the size of 6×150×400 *mm* were heated at the temperature of 1100 °C for 2 hours and they were rolled on the mill with helical rolls. Rolling on the mill with helical rolls was carried out until it reached the thickness of 5.4 *mm* with three aisles. Then, heating of intermediate workpieces was performed twice until the temperature reached 1100 °C and the hot rolling in the helical rolls with two and three passes till the thickness of 5.0 and 4.4 *mm* was performed after each heating respectively.

Metallographic analysis was performed by using energy disperse spectrometer JNCAENERGY (England), mounted on electron probe microprobe JEOL (Jeol) at an accelerating voltage of 25 *kV*. The range of increase of this instrument JEOL ranges from 40 to 40,000 times. The principle of the microprobe: high-energy (25 *keV*) narrow (1 *mm*) beam of electrons is directed onto the sample, where it is set in the screen (frame) by scanning the sample with the recorded secondary electrons emitted by the sample.

The obtained picture is very similar to the optical photo, but due to the fact that the electron beam is very thin (≈ 1-2 microns) , the depth of focus is much higher than that of optical photo and used increase is much higher; respectively, it is possible to distinguish the smaller structural components of the sample. Structural studies of the deformed samples were also performed by the transmission electron microscopy of thin foils on the electron microscope JEM-2100CX while the accelerating voltage of 200 *kV*.

For preparing the samples for the studies on the electron microscopy, the standard techniques of electrolytic necking of flat samples and the method of electropolishing and inkjet, using an electrolyte composition like 10% of perchloric acid and 90 % of glacial acetic acid was used. Before the jet polishing, the samples were mechanically ground to a thickness of 0.2 *mm*, then the disks with a diameter of 3 mm were cut from them, they were polished by the electrochemical method in order to remove defective layers and only then the jet polishing was provided until the formation of the hole.

Quantitative analysis of the parameters of the defect substructure was carried out by standard methods [11]. Microsections for metallographic study were prepared according to traditional methods in the grinding and polishing circles. The concentrated nitric acid solution in ethanol was used for etching samples. Grain size (D_3, microns) was determined by secants (by measuring ~ 300 grains) on the assumption that the grains are spherical, and the average value was based on the chord (X) by the formula: $D_3 = 4/\pi \cdot X_{average}$.

The SSS in the slip plane of steel St3sp was studied in the paper. It is known [18] that the steel St3sp in the austenitic region has FCC lattice, thus the plastic deformation takes place mainly under the influence of shear stress on the tightly packed octahedral planes {111}. These planes are equally inclined to the coordinate axes.

The infinitesimal IARF tetrahedron was identified in order to determine the SSS on the octahedral plane crystal lattice, so that its three faces would be parallel, and the fourth would be inclined to the coordinate planes (Figure 2). The position of the fourth of the inclined face is defined by the direction of cosines of the $\vec{n}$ normal of the sloping site with respect to the unit vectors of the coordinate axes $\vec{e}_x$, $\vec{e}_y$, $\vec{e}_z$: $n_x=\cos(\vec{n},\vec{e}_x)=\cos\alpha_x$; $n_y=\cos(\vec{n},\vec{e}_y)=\cos\alpha_y$; $n_z=\cos(\vec{n},\vec{e}_z)=\cos\alpha_z$.

If the area of the inclined face is ΔF, then the area of the remaining faces will be as following: $\Delta F_x = \Delta F \times n_x$; $\Delta F_y = \Delta F \times n_y$; $\Delta F_z = \Delta F \times n_z$.

To the sloping face acts full tension $\vec{p}_n$ and its three components, which are: $\vec{p}_n = \{\vec{p}_x, \vec{p}_y, \vec{p}_z\}$.

From there

$$\Delta Fx = \Delta F \times nx;\ \Delta Fy = \Delta F \times ny;\ \Delta Fz = \Delta F \times nz. \tag{1}$$

$$p_n = \sqrt{p_x^2 + p_y^2 + p_z^2}\,. \tag{2}$$

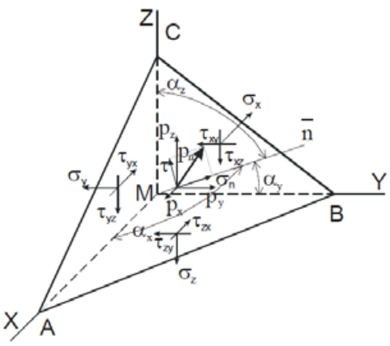


Fig. 2 The state of stress of the crystal lattice

When it is accepted that the voltage in the coordinate areas x, y, z are known, then the sum of the force projections in the direction of the coordinate axes must be zero in order to provide a tetrahedron balance: $\sum X = 0$; $\sum Y = 0$; $\sum Z = 0$.

Let consider the first equation:

$$-\sigma x \Delta F_x - \tau_{yx}\Delta F_y - \tau_{zx}\Delta F_z - p_x \Delta F = 0. \qquad (3)$$

After substituting into the equation (3) the expressions for ΔF_x, ΔF_y, ΔF_z and the reduction of ΔF, we get:

$$p_x = \sigma_x n_x + \tau_{yx} n_y + \tau_{zx} n_z. \qquad (4)$$

In a similar way it can be got the other two equations of equilibrium

$$p_y = \tau_{xy} n_x + \sigma_y n_y + \tau_{zy} n_z; \qquad (5)$$

$$p_z = \tau_{xz} n_x + \tau_{yz} n_y + \sigma_z n_z. \qquad (6)$$

In the shorthand, the system of equations (4), (5) and (6) takes the following form: $p_i = \sigma_{ji} n_i$, i,j=x, y, z .

According to the obtained expressions (4), (5) and (6), if the nine components of the stress state in three mutually perpendicular planes of the coordinate lattice are known, then it is possible to determine the total stress on any area, passing through the considered coordinate lattice. Thus, the state of stress in the crystal lattice is completely determined by nine components of stress in three mutually perpendicular areas, passing through this point.

The normal stress in the inclined plane is defined as the sum of the projections of the component $\{p_x, p_y, p_z\}$ on the normal to the area $\vec{n}$ $\sigma_n = p_x n_x + p_y n_y + p_z n_z = p_i n_i = \sigma_{ji} n_j n_i$.

Tangent voltage is determined by the following formula $\tau = \sqrt{p_n^2 + \sigma_n^2}$.

The following equation can be applied for the octahedral sites of the crystal lattice: $n_1^2 + n_2^2 + n_3^2 = 1$.

From there $n_i = \dfrac{1}{\sqrt{3}}$.

The values of normal and shear stresses on packed octahedral area can be determined by substituting the value of the direction of cosines in the expression of the normal and shear stresses in the inclined plane in the principal axes of the coordinates.

The normal stress on the octahedral plane is equal to the average main stress: $\Sigma_{oct} = \sigma_{average}$.

The shear stress on the octahedral crystal lattice plane can be determined by the following formula:

$$\tau^2 = p_n^2 + \sigma_n^2 = \sigma_1^2 n_1^2 + \sigma_2^2 n_2^2 + \sigma_3^2 n_3^2 - \left(\sigma_1 n_1^2 + \sigma_2 n_2^2 + \sigma_3 n_3^2\right)^2;$$

$$\tau^2 = \frac{1}{3}\sigma_1^2 + \frac{1}{3}\sigma_2^2 + \frac{1}{3}\sigma_3^2 - \left(\frac{1}{3}\sigma_1 + \frac{1}{3}\sigma_2 + \frac{1}{3}\sigma_3\right)^2 =$$

$$= \frac{1}{9}\left(2\sigma_1^2 + 2\sigma_2^2 + 2\sigma_3^2 - 2\sigma_1\sigma_2 + 2\sigma_2\sigma_2 + 2\sigma_3\sigma_1\right) =$$

$$= \frac{1}{9}\left[\left(\sigma_1^2 - 2\sigma_1\sigma_2 + \sigma_2^2\right) + \left(\sigma_2^2 - 2\sigma_2\sigma_3 + \sigma_3^2\right) + \left(\sigma_3^2 - 2\sigma_1\sigma_3 + \sigma_1^2\right)\right] =$$

$$= \frac{1}{9}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]$$

From there

$$\tau = \pm\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} = \pm\sqrt{\frac{2}{3}\left|I_2(D_\sigma)\right|}.$$

$$I_2(D_\sigma) = -\frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]$$

It is known [27] that the shear stress intensity is determined by the next expression:

$$T = \frac{1}{\sqrt{6}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} = \sqrt{\left|I_2(D_\sigma)\right|}.$$

Then the shear stress on the octahedral crystal lattice plane equals to the following:

$$\tau = \pm\sqrt{\frac{2}{3}}T. \qquad (7)$$

From the materials of the paper [18], it is shown that plexus dipoles and forest dislocations occur during deformation, which results the formation of an irregular network of dislocations as the strain increases. The dislocation density reaches 10^{10} sm^{-2}. The dependence of the stress flow on the dislocation density according to the Taylor theory expressed by the next formula [18]:

$$\tau_т = Gb\sqrt{\rho}/2\pi K, \qquad (8)$$

where G is the shear modulus; b is the Burgers vector; K is the hardening coefficient; ρ is a density of dislocations lying in the slip plane.

It should be noted that occurring shear stress must exceed the flow stress during the plastic deformation of metals with FCC lattice on the octahedral plane, which is determined by the following formula (8).

A specialized standard program MSC.SuperForge was used in order to calculate the SSS. A three-dimensional geometric model of the workpiece and tools has been constructed in the CAD program and imported into Inventor CAE program MSC.SuperForge.

The workpiece with the size of 6×150×400 mm from the steel St3sp was used in order to investigate the rolling process in rolls with the helical work surfaces. The rolling process was simulated in three-dimensional environment with a partition of the workpiece on 4-node elements (CTETRA). The rheological properties of steel St3sp at the temperature 1100 °C were set from the database of «MSC.SuperForge» software system. In this case, the material of the workpiece was taken as an isotropic elastic-plastic with a non-linear hardening (BISO). The friction coefficient was adopted as 0.3 on the surface of the tool with the workpiece. Tools were regarded as absolutely rigid bodies.

The program «MSC.SuperForge» was activated. The followings were calculated by the step method: move of U, the components of the strain tensor ε, strain rate tensor components ξ, stress tensor components σ, the intensity of the deformation Γ, shear stress intensity T_i, the temperature distribution over the volume of the workpiece.

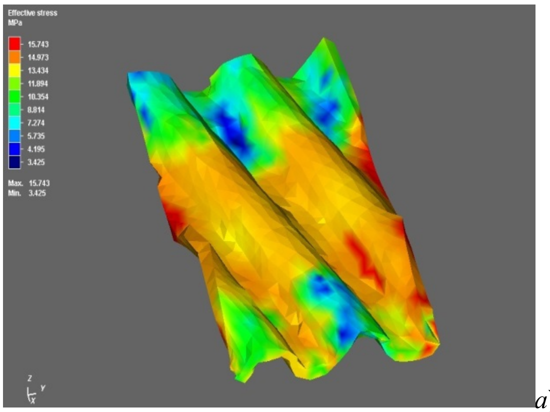
Results and discussion

The process of deformation in the spiral rolls can be divided into two stages. In the first stage, the ledge of the upper roll bends the strip toward the cavity of the lower roll. In the second stage, the macro shear deformation occurs under the sloping surfaces of the projections or depressions of the rolls.

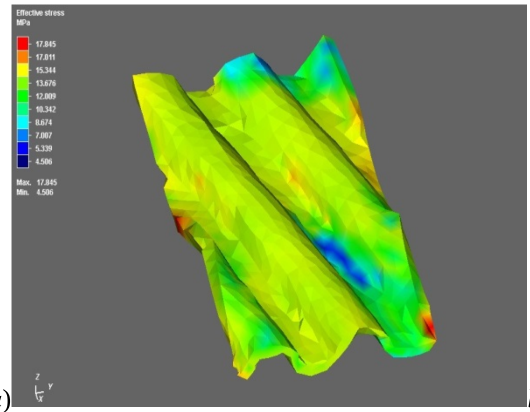
Figures 3, 4 show the picture of the distribution of intensity shear stress and strain intensity in the workpiece during rolling in a spiral rolls.

On the basis of numerical simulation results, it is revealed that:

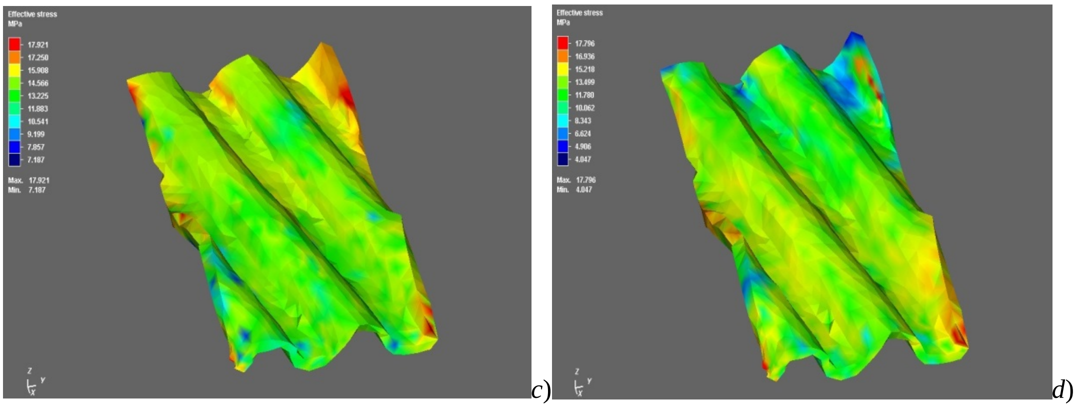
- in the initial moment of rolling, the intensity of shear stress and deformation is localized in the contact zones of the workpiece with the working surfaces of the rolls of the projections;
- an increase in the unit of compression leads to a shift in focus intensity of shear stress and strain on the contact areas to the strip zones which are located under the slanted working surface of protrusions and recesses of the rolls (Figures 3, 4);
- during the rolling process of screw rolls, the contact areas of the tool with the strip was cooled, and the temperature rises in the localization zones of deformation;
- in the second and third, etc. transitions of the rolling in screw rolls, the intensity of shear stress and deformation was located under the sloping portions of the protrusions and depressions of the rolls.
- the developed method of strip rolling in the helical rollers provide intensive alternating deformation of the strip under the slanted working surfaces of the projections and recesses of the rolls with a slight compression. The probable maximum shift is realized on the ratio of the projection т to the width of the cavity п which is equal to 0.8 ... 0.9.



a)



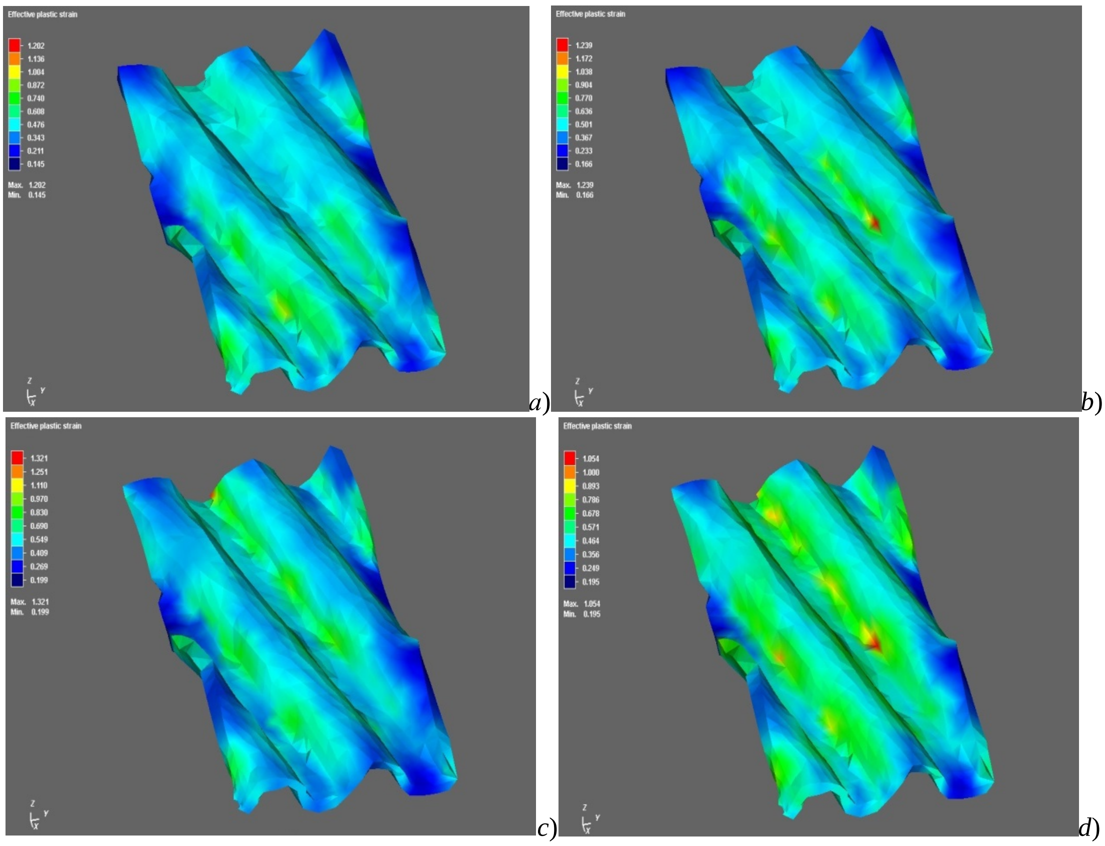
b)



a – the first pass; *b* – the second pass; *c* – the third pass; *d* – the fourth pass
Fig. 3 The picture of stress intensity distribution in the workpiece during rolling in a screw rolls

It should be noted that at the initial moment of rolling in the spiral rolls, the intensity of helical tangential stresses concentrate on areas of contact of strips with the projections of the rolls, which could lead to the intrusion of protrusions of the tool to the body of the workpiece, without bending strip. The spiral rolls should be manufactured with a ratio of curvature radius of the protrusion of the roll to its length 0.15 ... 0.2, depending on the geometrical dimensions of the roll in order to eliminate the intrusion of projections into the body of the workpiece. Then the prints from the roll projections will be eliminated in the subsequent stages of rolling.

Thus, the macro shifting deformations are localized in the contact zones of the workpiece while rolling in the left-handed lower and right-handed upper rolls with oppositely situated projections and depressions. In subsequent stages, the focus of deformation localization is transferred to the workpiece portions which are located under the inclined portions of the projections and depressions of the rolls. Such concentration of macro shear deformation over the section of the workpiece promotes obtaining the strip with a fine-grained structure through the rational selection of rolling deformation modes.

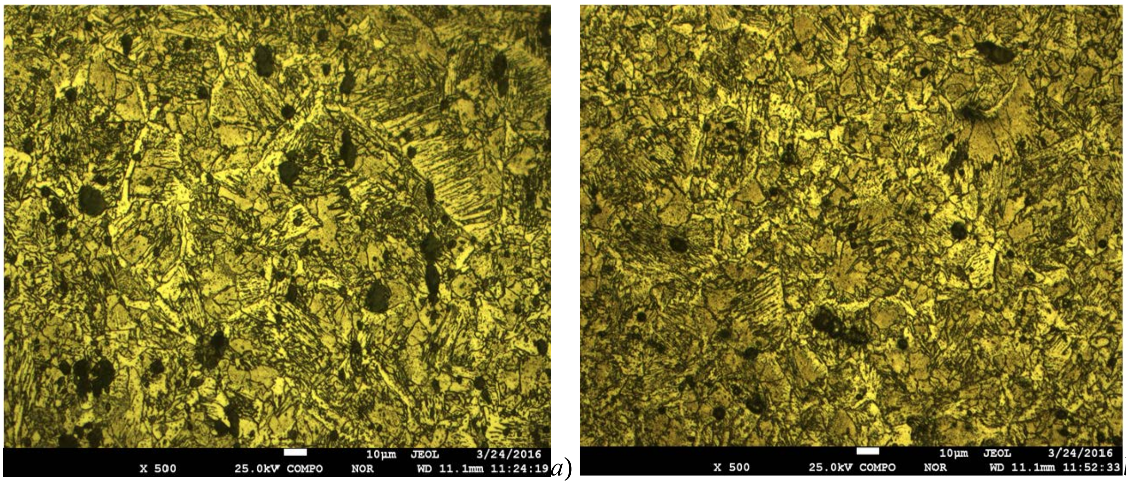


a – the first pass; *b* – the second pass; *c* – the third pass; *d* – the fourth pass
Fig. 4 The picture of deformation intensity distribution in the workpiece during the rolling in the screw rolls

In the initial state, the workpiece made of the St3sp steel owned inhomogeneous microstructure that consisted of large unrecrystallized grains with an average size of ~ 287 μm in the longitudinal and ~ 267 μm in the transverse directions and spaced along their boundaries of small grains with the size ~ 32-35 μm.

The study of the structural state of the steel St3sp after rolling in the helical rolls with the intensity shear stress on the octahedral plane ranging from from 1.96 *MPa* to 3.248 *MPa* (first pass) shows that the micro striped structural state is formed in the cross section perpendicular to the rolling plane (Figure 5, *a*, *b*). At the same time, the density of intragranular dislocations is increased, the shear strips with the width up to 4 – 6 μm are formed. The deformation in the form of shear strips occurs mainly in the large grains.

The most probable widths of micro strips with large angle boundaries after rolling with one pass accept the range of 3 to 7 μm from the maximum (very rarely observed) values of this magnitude ~ 9 μm (Figure 5, *a*, *b*). The width of micro strips with low-angle boundaries can vary from 2 μm to 4 μm at the most probable value of about 2 μm.



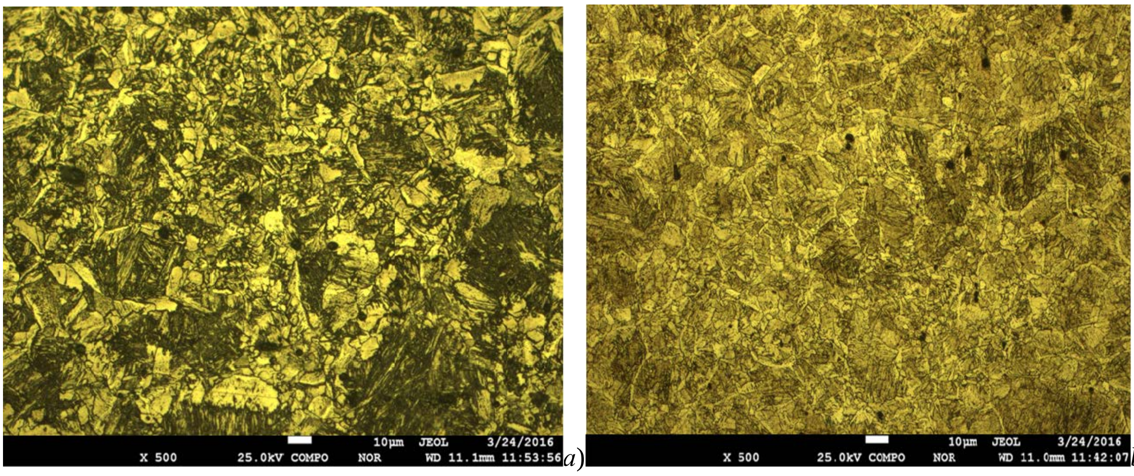
a) *b*)

a – a longitudinal section; *b* – a cross-section

Fig. 5 The microstructure of the steel St3sp after rolling in helical rolls, the first pass

Further rolling of the workpiece in the helical rolls by 2 (Figure 6, *a*, *b*) and 3 passes (Figure 7, *a*, *b*), with the increase of the intensity of the shear stress on the octahedral plane, results in the reduction of the width of micro strips, and also thinner shear strips are formed on the borders of the initial relatively broad micro strips. The range of the shear stress intensity comprised from 2.167 *MPa* to 3.376 *MPa* by 2 passes of rolling, and from 2.658 *MPa* to 3.465 *MPa* by 3 passes of rolling, respectively.

After rolling by 3 passes, brightly noticed striped structure with the distance between boundaries not exceeding 0.4 – 1.6 μm with the most probable values of 0.6 – 2 μm is formed in the cross section of the strip (Figures 6, *a*, *b*, and 7, *a*, *b*).

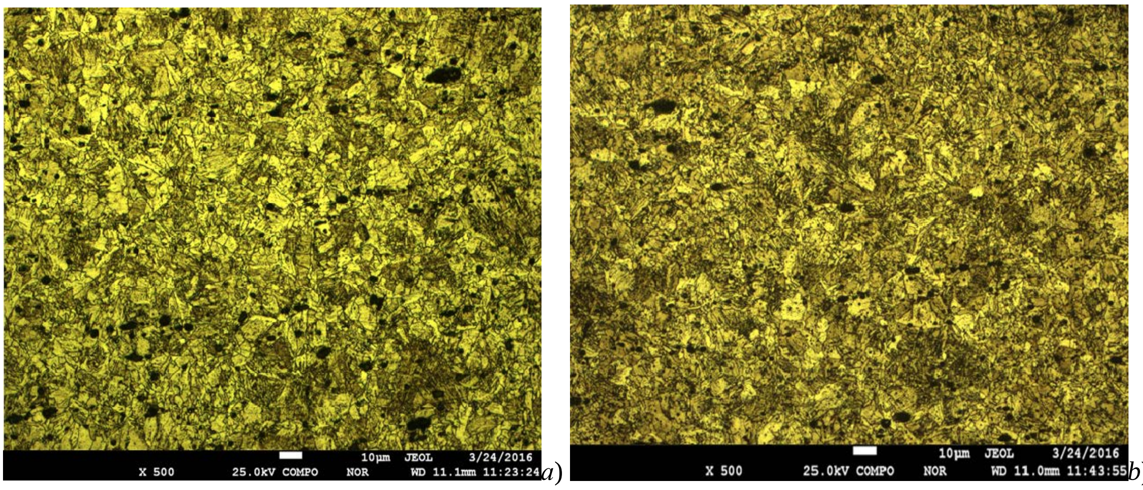


a) *b*)

a – a longitudinal section; *b* – a cross-section

Fig. 6 The microstructure of the steel St3sp after rolling in the helical rolls, the second pass

The heating of deformed workpieces by 3 passes until the temperature reached 1100 °C and rolling in the helical rolls with the intensity of the shear stress on the octahedral plane ranging from 2.107 *MPa* to 3.453 *MPa* (the fourth pass) led to the further refinement and development of grain-subgrain structure in the steel St3sp. The size of the individual grains reaches 8 – 14 μm (Figure 8, *a*, *b*).

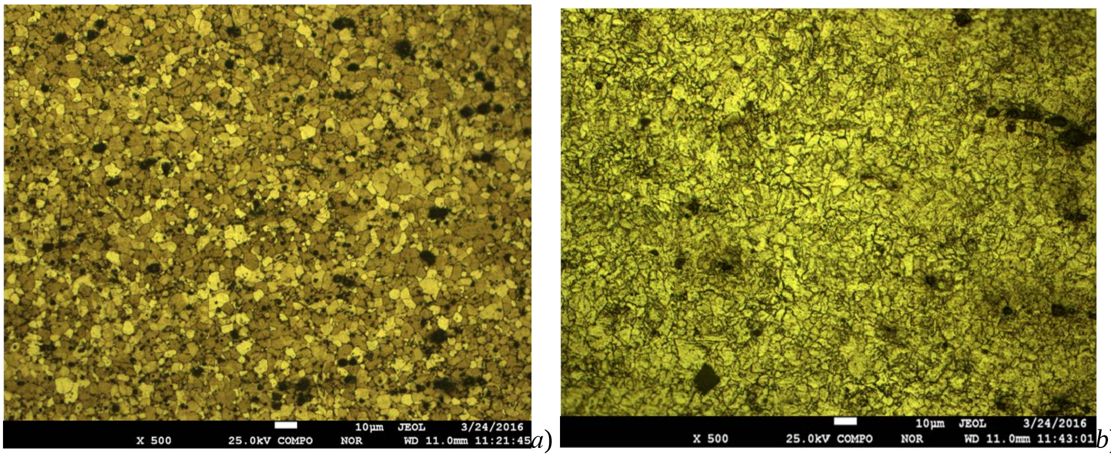


a) *b*)

a – a longitudinal section; *b* – a cross-section

Fig. 7 The microstructure of the steel St3sp after rolling in the helical rolls, the third passage

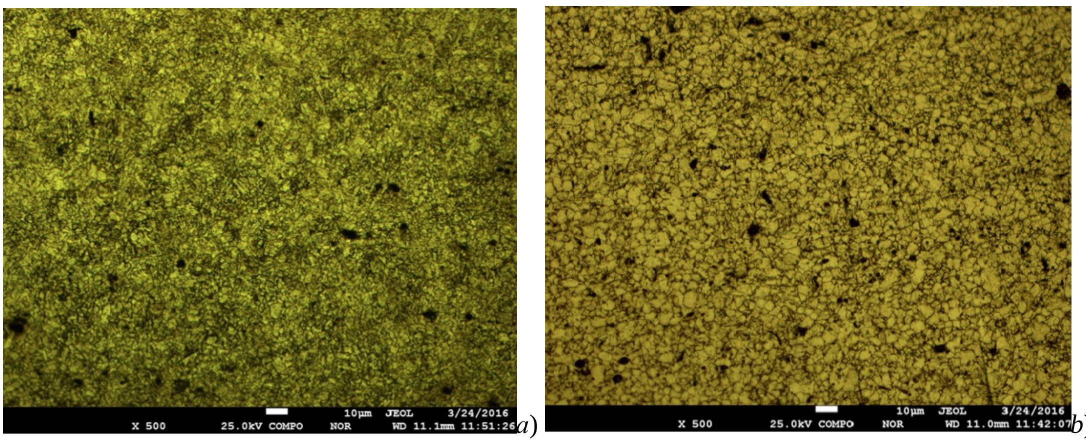
Rolling at the temperature of 1100 °C in the helical rolls with the intensity of the shear stress on the octahedral plane ranging from 2.678 *MPa* to 3.561 *MPa* has led to the formation of homogeneous and equiaxial structure on the longitudinal and cross sections of the workpiece (Figure 9, *a*, *b*). At the same time, it is clear that there is a further grinding of grain-subgrain structure. As a result of providing softening processes, the recrystallization structure throughout the volume of rolling strips with an average grain size of about 2 – 5 μm is formed in the metal of the workpiece. The large angle boundaries are formed in the border areas of the grains. The dislocation density is very high and it was not possible to calculate its value according to the structure of the image.



a) *b*)

a - a longitudinal section; *b* - a cross-section

Fig. 8 The microstructure of steel St3sp after rolling in the helical rolls, the fourth passage



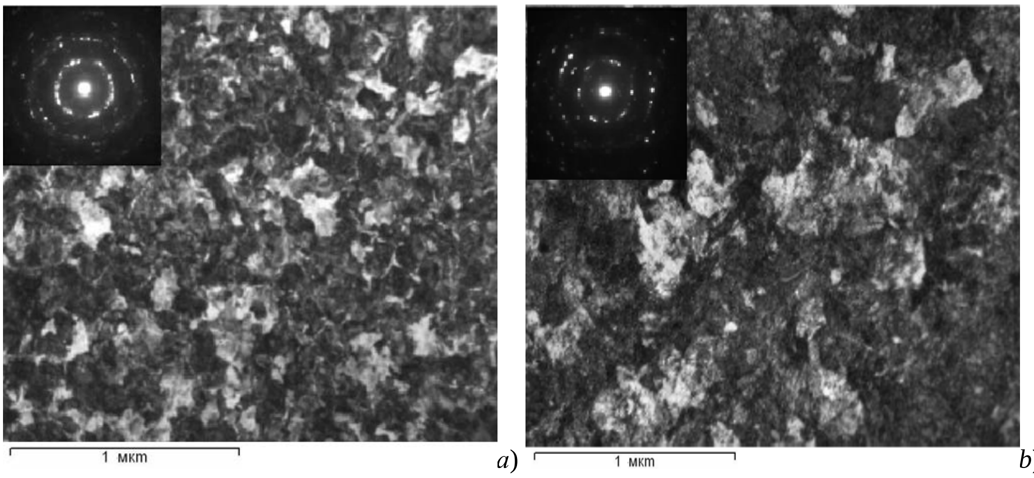
a) *b*)

a - a longitudinal section; *b* - a cross-section

Fig. 9 The microstructure of steel St3sp after rolling in the helical rolls, the fifth passage

The heating process and subsequent rolling of the workpieces deformed in the helical rolls by 5 passes, with the intensity of the shear stress on the octahedral plane ranging from 2.793 *MPa* to 3.842 *MPa* leads to the formation of structures with ultrafine size. The structure in the range of ultrafine size and which equals from 950 to 970 *nm* is formed as a result of the passage of the primary recrystallization throughout the volume of rolled strips (Figure 10, *a*, *b*).

The obtained ultrafine structure is characterized by the grain size uniformity throughout the volume of the material. A large number of clear reflexes along the rings of electron diffraction suggest that the majority of grains in the structure own to high angle boundaries.



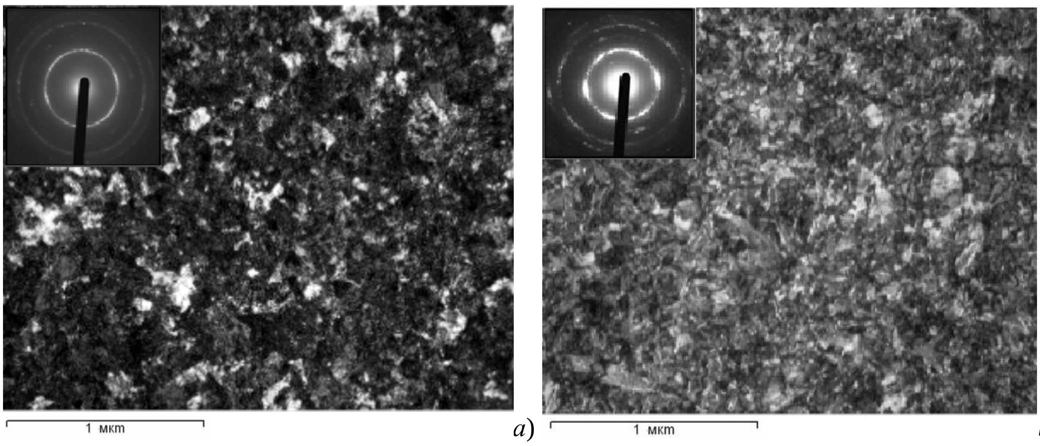
a) *b*)

a - a longitudinal section; *b* - a cross-section

Fig. 10 The microstructure of the steel St3sp after rolling in the helical rolls, the sixth passage

Heating process at 1100 °C and rolling in the helical rolls, the workpiece deformed with six passages in these rollers with the intensity of the shear stress on the octahedral plane ranging from 2.975 *MPa* to 4.023 *MPa* allows to form the uniform and equiaxed structure in the longitudinal and cross-sections of the workpiece (Figure 11, a, b). At the same time, it is clear that there is a further refinement of grain-subgrain structure.

The grains own to an equiaxial and ultrafine structures with an average size of about 620 – 640 *nm* in the transverse and longitudinal sections of the workpiece. The diffraction picture is characteristic for the UFG-structure state with predominantly high angle boundaries. The dislocation density is very high and it was not possible to calculate its value by to the image of the structure.



a) *b*)

a - a longitudinal section; *b* - a cross section;

Fig. 11 The microstructure of the steel St3sp after rolling in the helical rolls, the seventh passage

In order to investigate the effect of rolling on the formation of microstructures of the steel St3sp, the rolled strips in the helical rolls by 7 passes were further rolled at the same rolls at the temperature of 1100 °C (Figure 12). It is evident that rolling at the temperature of 1100 ^{o}C with the intensity shear stress on the octahedral plane ranging from 3.374 *MPa* to 4.318 *MPa* significantly affects the steel microstructure. The microstructure of the steel St3sp, rolled by 8 passes in the helical rolls is characterized by the presence of ultrafine structure (Figure 12, *a*, *b*). The average size of subgrains is 330 – 360 *nm*.

After rolling in the helical rolls, the structure becomes substantially nonequilibrium, boundaries of the structure elements become blurred, and significant azimuthal blur reflections occur on the electron diffractions. All of these indicate a high level of internal stress in the grains. The electron diffraction patterns for the given structures have quasi

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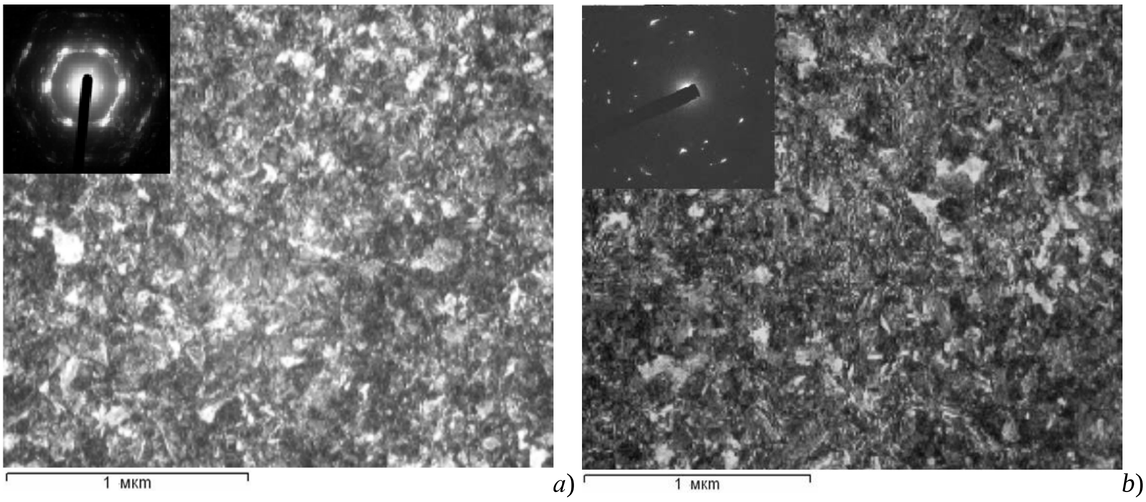
ring characteristics (Figure 12, *a*, *b*, *inset*). The separate reflexes are distinctive on rings; their distribution on the ring indicates the presence of high angle misorientation between the fragments.

According to the received information, in the first pass, the main part of the plastic deformation is carried out by the formation of micro strips. During the earlier passages, formed microstrips do not participate actively in the plastic deformation in the subsequent passes. Only the state of the crystal is changed which is mounted inside of it. It is cleared of dislocations; the thickness of microstrips is decreased and the disorientation is increased.

Such microstrips during the continuing plastic deformation of the sample are rotated as a whole, and they are arranged parallel to the direction of the metal flow. At the same time, they combine bundles, bags or meso-strips which are spread along the direction of the metal flow over long distances. One meso-strip is separated from the other by the areas of approximately equiaxed cellular structure. Then the new formations occur in the form of powerful shearbands. While rolling in the helical rolls, these microstrips are regarded as nuclei of the recrystallization. Thus, the formed fine recrystallized grains, while rolling, are immediately involved in the process of fragmentation and as a result refinement of the structure occurs.



a - a longitudinal section; *b* - a cross-section

Fig. 12 The microstructure of the steel St3sp after rolling in the helical rolls, the eighth passage

It should be noted that a number of types of dislocation structures develops sequentially during rolling the steel St3sp in the helical rolls, and the transition from one type to another type of structure is clearly correlated with the stage of plastic deformation. The uniform distribution of dislocations is observed at the initial stage. By the end of this stage, the dislocation structure becomes inhomogeneous - the coil structure is formed. The end of this stage is characterized by the formation of a coiled structure along the all volume of the material.

The beginning of the second stage is connected with the closure of dislocation tangles and the formation of a cellular structure. By the end of the second-stage, the cell structure covers the entire volume of the sample. The onset of the third stage is correlated with the formation of disoriented structure. Its fraction increases with the number of passes, while the volume of the cellular structure decreases. Development of the fourth stage is associated with the flow of processes of fragmentation and primary recrystallization structure in the entire volume of material.

It can be assumed that with the increasing degree of deformation in the subsequent rolling passes in the helical rolls, the refinement of the structure is provided not only by twinning but also by the formation of the cellular substructures as a result of development of the dislocation slip processes. At the high degrees of accumulated deformation, the boundaries of the twins and subgrains are transformed into large-angles.

The frequency or phasing of the occurring changes for the selected volume should be emphasized, while the dynamic equilibrium is stored overall for the system in the rolling process in the helical rolls. It means that fragmented and recrystallized grains are formed in the steel during each moment of rolling process of steel in the helical rolls.

Subsequently, the common thing for the steels St3sp during rolling in the helical rolls is the formation of a mixed type structure with the combination area of fragmented and recrystallized structure. Consequently, the basic mechanisms of deformation will be different for these areas. For the recrystallized grains – it is a mass transfer and diffusion intragranular gliding. At the same time, grain boundary sliding will be important for the areas of the fragmented grains.

It is known [28] that the presence of large-angular boundaries shows the implementation of dislocation-disclination mechanism of reorientation of the crystal lattice, which is developed in two stages: the formation of the substructure with non-zero components of the tensor density of disclinations; its collective relaxation in the discrete boundaries of disorientation. This mechanism is one of the most universal mechanisms of fragmentation of the crystal, including the formation of submicron and nanocrystalline structural conditions in a wide range of metals and alloys.

It should be noted that the action of the alternating mechanisms of the deformation provides the fragmentation and reorientation of the crystal lattice while rolling in the helical rolls. The large-anglular boundaries with the high density are formed in the cross direction of the workpiece.

Thus, the evolution of the structure of the steel St3sp during the rolling process in the helical rolls is in the following order:

- the formation of the deformation substructure (dislocation and twin) with a strips with the width of 0.6 – 2 μm;
- the formation of transverse boundaries within the strips, increasing of the internal stress and distortion of the initial crystal lattice and fragmentation of grains;
- the development of softening processes as a primary recrystallization with the formation of ultrafine structure with the size of 330 – 360 *nm*.

Conclusions

1. The results of the study of the microstructure evolution of the long workpieces at various stages of their production in the helical rolls have shown the possibility of obtaining strips with the ultrafine structure by using the intensive plastic deformation.
2. It was found that the parameters of the evolution of the defect structure in the individual crystallites depend on the micro and macro stress state.
3. The formula is given which allows us to determine the intensity of the shear stress on the octahedral area of the crystal lattice during the certain values of the intensity of the shear stress along the deformation zone;
4. It is shown that the deformation pattern by type of simple shift is realized during rolling in the helical rolls, which is characterized by the constant change of the angle between the direction of action of maximum shear stress and the direction of the greatest extension and the vertical axis of the workpiece .
5. It has been determined that while rolling in the helical rolls, the influence of the stress state on the formation of structures during the deformation is manifested through different activations of slip systems. The macroscopic plastic deformation is the result of summation of multiple shear acts arising under the influence of dislocation slip, activated at the given stress state.
6. It is predicted that the dissipation of the deformation energy during rolling in the helical rolls is on the way of generation, redistribution, accumulation and annihilation of defects of the crystalline structure of the material.
7. It is proved that the refinement of the structure while rolling in the helical rolls occurs not only by the inclusion of additional slip systems, but also positive conditions for unlocking the dislocation and increasing their mobility are created during the conditions of the stress state of the rolling in these rolls.
8. It is established that the periodic accumulation of energy in the ensemble of defects and its reset by restructuring the ensemble of defects in the state with the increased regularity occurs as a result of the accumulation of the energy of external forces and motion activation of crystalline structure defects. Therefore, the activation of the relaxation processes is possible from the energy point of view, i.e. softening processes in the process of the deformation and inter-deformation pauses.

REFERENCES

[1]. Pashinskaya E.G. Physical and mechanical basics of the structure refinement with the combination of plastic deformation. Donetsk: Edition "Weber", 2009. 352 p.

[2]. Stolyarov V.V., Valiev R.Z. Obtaining metastable ultrafine alloys by an equal channel angular pressing. Metals. 2004. No. 2. pp. 5-11.

[3]. Markushev M.V., Murashkin M.Yu. Mechanical properties of submicrocrystalline aluminum alloys after severe plastic deformation by an angular pressing. Physics of Metals and Metallography. 2000. T. 90, No. 5. pp. 92-101.

[4]. A.V. Yelantsev, A.A. Popov, S.L. Demakov, E.V. Elantseva. The study of the structure and properties of aluminum materials subjected to severe plastic deformation. Physics of Metals and Metallography. 2004. T. 97. No. 1. pp. 64-70.

[5]. Yunusova N.F. Islamgaliev R.K., Valiev R.Z. High-speed superplasticity in the aluminum alloys 1420 and 1421, subjected to an equal channel angular pressing. Metals. 2004. No. 2. pp. 21-27

[6]. Valiev R.Z., Islamgaliev R.K., Alexandrov I.V. Bulk nanostructured materials from severe plastic deformation. Progr. Mater.Sci. 2000. Vol. 45. p. 103-189.

[7]. Langdon T., Furukawa M., Nemoto M., Horita Z. Using an egual-channel angular pressing for refining the grain size. JOM. 2000. Vol. 52. No. 4. pp. 30-33.

[8]. S.A. Firstov, Yu.N. Podrezov, V.I. Kopylov, N.I. Danilenko. The structural sensitivity of the mechanical properties of an Armco iron subjected to an equal channel angular pressing. Metals. 2004. No. 1. pp. 96-102.

[9]. Raab G.I., Valiev R.Z. Obtaining the nanostructure in titanium by the method of an equal channel angular pressing. Metallurgy and heat treatment of metals. 2000. No. 9. pp. 27-32.

[10]. Valiev R.Z. Approach to nanostructured solids through the studies of submicron drained polycrystals. Nanostructured Materials. 1995. Vol. 6. pp. 73-82.

[11]. A.N. Tyumentsev, Yu.P. Pinzhin, A.D. Korotaev, et. al. Electron microscopic studies of grain boundaries in the ultrafine nickel produced by severe plastic deformation. Physics of Metals and Metallography. 1998. T. 86, No. 6. pp. 110-120.

[12]. A.V. Byakova, V.F. Gorban, V.N. Castles, Yu.N. Podrezov, S.A. Firstov. Surface nanostructure of titanium for improving the efficiency of diffusion welding. Metal Physics and the latest technology. 2006. T. 28, No. 2. pp. 173-181.

[13]. Mulyukov R.R., Starostenkov M.D. Structure and physical properties of submicrocrystalline metals prepared by severe plastic deformation. Acta Metallurgica Sinica (English Letters). 2000. Vol. 13. No. 1. pp. 301-309.

[14]. Tutyshkin N.D. Axisymmetric compression of thin layer of plastic material. Research on Plasticity and Metal Forming. Tula: Tula Polytechnic Institute, 1984. pp. 80-85.

[15]. Nichols F.A. Plastic Instabilities and Uniaxial Tensile Ductilities. Overview. ActaMetal. 1980. Vol. 28. pp. 663-673.

[16]. O.M. Smirnov, A.N. Ershov, V.A. Kropotov, et. al. Influence of the combined load on the parameters of punching of flat disks in a state of superplasticity. Forging and stamping production. 1997. No. 1. pp. 79-81.

[17]. O.M. Smirnov, A.N. Ershov, S.E. Chumachenko, V.A. Kropotov. Analysis of the stress-strain state of the workpiece in the axisymmetric punching process upset with the torsion. Forging and stamping production. 1998. No. 6. pp. 9-12.

[18]. P.I. Poluhin, S.S. Gorelik, V.K. Vorontsov. Physical fundamentals of plastic deformation. Textbook for high schools. M.: Metallurgy, 1982. 584 p.

[19]. M.I. Mazurskii, F.W. Enikeev, R.A. Vasin, et.al. Influence of the high-temperature load on the characteristics of dislocation slip and structural rearrangements in the titanium alloy BT22 at small strains. Physics of Metals and Metallography, 1999. T. 88, No. 5. pp. 90-94.

[20]. V.K. Berdin, M.V. Karavayeva, S.K. Nureyev. Influence of the hot deformation under one- and two-component loading on the evolution of the lamellar microstructure and deformation behavior of titanium alloy BT9. Metals, 2002. No. 5. pp. 60-66.

[21]. C.R. Park, Y.W. Chang, C.G. Park. Microscopic Mechanism of Slip Transfer during the Plastic Deformation. Journal of the Korean Institute of Metals and Materials, 1994. Vol. 32. pp. 1315-1320.

[22]. O.I. Bylja, R.A. Vasin, A.G. Ermachenko. The influence of simple and complex loading on strycture changes in two-phase titanium alloy. Scriptamaterialia. 1997. Vol. 36, No. 8. pp. 949-954

[23]. I.A. Vakulenko, V.G. Razdobrev. Structural changes during the bending- stretching deformation of cold-rolled carbon steel. Metals. 2004. No. 3. pp. 86-90.

[24]. I.L. Yakovleva, L.E. Kharkina, Yu.V. Khlebnikova. Structure and properties of eutectoid steel У8 after the high temperature deformation. The results of metallographic examination and mechanical tests. Physics of Metals and Metallography. 2004. T. 98, No. 4. pp. 66-74 .

[25]. K.A. Padmanabhan, J. Schlipf. Model for grain boundary sliding and its relevance to optimal structural superplasticity. P. 1. Theory. Mat. Sci. and Technol. 1996. Vol. 12, No. 5. pp. 391-399.

[26]. S.A. Mahsekov, B.N. Absadykov, L.A. Kurmangalieva, et.al. The instrument for the hot rolling of metals and alloys. Patent of RK №16804 Publ. 16.01.2006, Bull. No.1,2.

[27]. V.L. Kolmogorov. Mechanics of metal forming. M.: Metallurgy, 1986 - 688 p.

[28]. A.N. Tyumentsev, I.A. Ditenberg. Structural state with a high curvature crystal lattice in submicrocrystalline and nanocrystalline metallic materials. Proceedings of the universities. Physics 2011, No. 9. pp. 26 - 36.