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Research Article

Influence of Ultrafine Structure on the Properties of the Steel Strip, Rolled on the Longitudinal Wedge Mill

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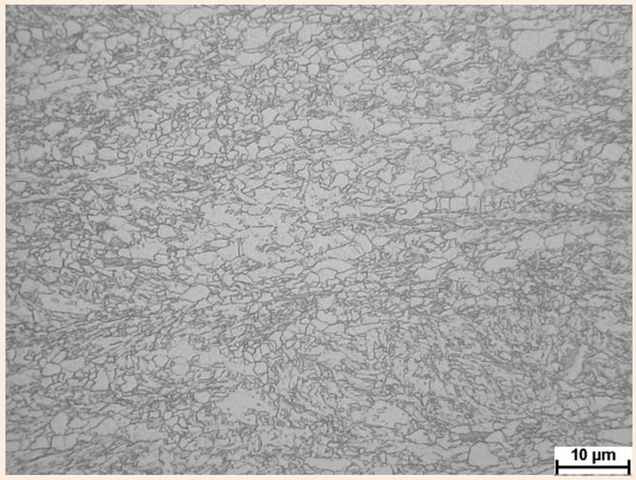
Abstract
In the paper the influence of ultrafine structure on the properties of steel strips was investigated, obtained during the process of deformation nanostructuring. Slabs with ultrafine structure were obtained during hot-rolled process of steel St3Gsp (C – 0.14...0.2; Mn – 0.8...1.1; Si – 0.15...0.3; P – up to 0.04; S - up to 0.05; Ni – up to 0.3; Cr - 0.3; N – up to 0.008; Cu – up to 0.3; As – up to 0.08) in the working rolls with wavelike working surface and in five stands mill of new construction. The paper found that to obtain good mechanical properties and the structure of the bands, made from steel St3Gsp, the temperature of the end of the rolling process should be 850 - 860 °C, whereas the temperature of the cooling of hot-rolled strips on collecting roller table should be 610 - 650 °C. The cooling mode is monotonic on the air, in water and on the air.

Keywords: metal rolling, a rolling mill, a steel slab, structure, strain-stress state (SSS)



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Introduction

Monotonic deformation of the workpiece, in other words a permanent increase in length during pressing, rolling and drawing, and decrease of cross-section or height during forging process, leads to the fact that for the large deformations its size in some directions is extremely small. This dramatically reduces the area of the subsequent use of such workpieces. That is why the development of deformation methods allowing to process workpieces of large cross-sections without significant change of their original shapes and sizes should be recognized as an area of intense research around the world.

Currently to produce materials with ultrafine-grain structure (UFG) without significant change of their sizes the methods of severe plastic deformation (SPD) are used. These methods are primarily implement a shift with a total power of 2 - 3 [1-5]: torsion under high quasi-hydrostatic pressure, equal channel angular pressing, multiple isothermal forging and radial-shear rolling, etc. Aforementioned researches and other studies of last decade [6-9] have shown, that the materials inherent high physical and mechanical properties, if they produced by the SPD nanostructure methods. The metals and alloys with submicron- and nanocrystalline structure exhibit unusually high and useful strength and ductility.

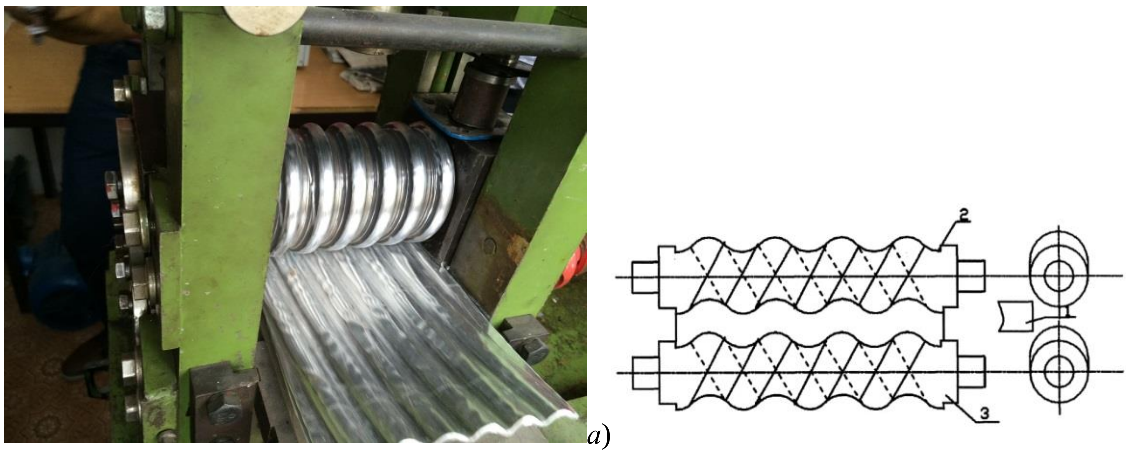
Thus, it can be concluded, that the SPD methods are modern economically feasible methods to produce metallic materials with complex of high mechanical properties. Implementation of these prospects have the immediate value for the development of new technologies to produce steel and alloys made products with the complex of high mechanical properties.

In the known works [1-9], the interest to produce nanomaterials is associated with the possibility to get workpieces and products with the breakthrough technologic and performance characteristic [9]. However, the theoretical bases of the steel nanostructure processes are still under the generalization of the experimental data [9]. As for now, there is no strict methodology of changing associated with the metal forming [9]. Therefore, the fundamental task of materials science and theory of plasticity is to create scientific bases of evolution of the structure and properties of ultrafine-grained steels and alloys in deformation processes.

The aim is to study the properties of ultrafine-grained structural steels obtained during the deformation nanostructuring.

Equipment, materials and experimental procedure

Rolling of the foil is well-known and widely used SPD method. However, there is a little use of the foil, because of the small cross-section of it. Therefore, the spiral work surface of the rolls was designed (**Figure 1**) in order to produce semi-finished products with UFG structure [10]. These rolls perform SPD without any significant change of the forms and size of the semi-products. In addition, five-stands rolling mill [11] was designed to roll the strips of the semi-products with UFG structure (**Figure 2**).



a) *b*)

a – mill; *b* – rolling scheme

Figure 1 Rolling mill with two spiral rolls: *1* – workpiece; *2* – upper roll; *3* – lower roll

A continuous rolling mill comprises working stands, AC motor, a clutch, idle rollers, driven rolls, a stand housing, bedplate. The stands have the driving mechanism from the AC motor. Further, the stands contain working and backup rolls with the constant diameter, but in tandem stand the diameter of the working rolls decreases, but the diameter of the backup rolls increases in the direction of rolling. Hereafter the rotation of the rollers is produced via an individual nipple, a regulator, a pinion stand and spindles. The diameters of working and backup rolls are given by formula:

$$D_{i+1} = \frac{h_i \cdot D_i \cdot n_i}{h_{i+1} \cdot n_{i+1}} \frac{(1+s_i)}{1+s_{i+1}} \quad D_{j-1} = \frac{h_j \cdot D_j \cdot n_j}{h_{j-1} \cdot n_{j-1}} \frac{(1+s_j)}{(1+s_{j-1})} \quad (i = 1, 2, \ldots, N;\ j = N, \ldots 2, 1) \qquad (1)$$

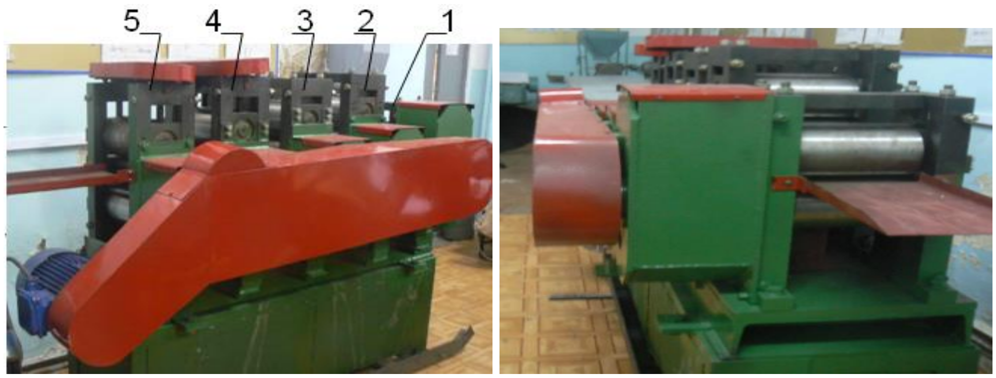
where h_i, h_j – thickness of a rollable strip in stand i or j;
n_i and n_j – rate of rotation of rolls in stand i or j;
N – ordinal number of the stand;
s_i and s_j – forward slip on the output from the rolls in stand i or j;
D_i and D_j – diameters of working rolls i and back up rolls j in the previous stand.

In the proposed mill the horizontal axes of upper and lower rolls of the first three stands are without any screw down gear, and they are shifted from the rolling axe in vertical direction by

$$\Delta x_i = 0{,}25 \cdot k_n \cdot D_{pi} \cdot \alpha_i^2, \qquad (2)$$

where D_{pi} – the diameter of a new working rolls of *i*-stand;
k_n – regrind coefficient;
α_i - a tolerable angle of bite for rolls of *i*- stand.

It should be noted, that the given distance between the working rolls increases by the value of forward slip from one stand to another.



1, 2, 3 – four rolls stands without screw down mechanism; *4, 5* – four rolls stands with screw down mechanism

Figure 2 Five-stand longitudinal-wedge mill

A workpiece material was steel St3Gsp. The workpieces with the dimensions of 6 × 150 × 200 *mm* were heated up to 1180 ^oC for 3 hours. Rolling was performed up to 5 *mm* of thickness on the mill with spiral rolls in three passes. Then the transitory workpiece was heated up to 1100 ^0C, and rolling was undergoing till the thickness of 1.5 *mm* on the five-stand longitudinal wedge mill.

Rolling in the rolls with spiral work surface was performed by the following procedure. The workpiece were introduced between up and lower rolls, and then it was deformed by the throats and dumps with the drift equal to $\varepsilon = \Delta h_B / H_o$ and $\varepsilon = 2\Delta h_B / H_o$ (Δh_B - height of throat and dump; H_o – height of the blank before rolling).

Drafting schedules were varied during rolling in five stand mill, also air cooling time and forced water cooling time were varied (**Table 1**). To simulate cooling of the strips in the coils, rolled strips were cooled in the furnace, which was heated up to 500 ^oC.

The temperature of the strips was measured after heating, also during rolling process and cooling. It was measured by the single channel instrument Testo 925 (Testo AG, Germany) by the use of fast and reliable thermocouples (thermocouple probe Type *K* (NiCr-Ni). The temperature range is varied from 50 to +1100 ^0C. Errors are -40... + 900 ^0C - ± (0.5 ^0C + 0.3% from the measured value), -50…-40, +900...+1100^0C - ± (0.7 ^0C + 0.5% from the measured value). Resolution is 0.1 ^oC (-50 to +199.9 ^0C), 1 ^0C (in the rest range of measurement).

To calculate a stress-strain state (SSS) a specialized standard software MSC.SuperForge was used. A three-dimensional geometric model of the workpiece was set in the CAD Inventor program and imported to the CAE MSC.SuperForge software. At making a final model of a starting workpiece there was used a three-dimensional element CTETRA (quadrangular tetrahedron), which is used for the 3D modeling.

The large laboratory mill was used to calculate SSS and the technical characteristic of the working stands of the proposed mill. The instruments assume to be absolutely stiff and imply only thermal conductivity and heat transfer properties, another words specific conductivity, specific heat transfer and density was taking into account, whereas mechanical properties are not regarded. The instrument material was ShH15 was chosen from the database. The software default the density and thermal properties for this material.

Table 1 Plan of experiment

Variants	One pass in the stand, %					Air cooling time	Water cooling time	Air cooling time
	№ 1	№ 2	№ 3	№ 4	№ 5			
1	20	20	20	15	10	6	0	0
2	20	20	20	15	10	5	1	0
3	20	20	20	15	10	4	1	1
4	20	20	20	15	10	3	2	1
5	20	20	20	15	10	2	3	1
6	20	20	20	15	10	1	3	2
7	20	20	20	15	10	0	5	1
8	20	20	20	15	10	0	4	2
9	20	20	20	15	10	0	3	3
10	20	20	20	15	10	0	2	4
11	20	20	20	15	10	0	1	5

Interface between a fixed roll and deformable material of the slab was simulated by means of contact conditions between the surface of the rolls and surface of the rolled sheet. During modeling the contact conditions of the rolls and deformable material were changing. This enabled to simulate a slip between the roll and the material of rolled workpiece. The interface or contact between the roll and sheet of steel was simulated by Coulomb friction. The coefficient of friction was assumed as 0.3.

During rolling the temperature condition consists of heat exchange between roll, sheet and environment, also it consists of heat emitted from metal deformation. The rolling process was performed at room temperature, therefore starting temperature of the roll was equal to 20 ^{0}C.

A metallographic analysis was carried out by optical microscope «Axiovert - 200 MAT». Images were processed by VideoTesT "Metal 1.0". In the experiments the energy disperse spectrometer JNCAENERGY (England) was used, which was mounted on the electron probe microanalyzer JEOL (Dzheol). The accelerating voltage was 25 *kV*, the magnification range of JEOL instrument starts from 40 up to 40000 times.

Operating principal is based on that the microanalyzer emitted a high energy (25 *keV*), narrow (1 *mm*) beam of electrons, directed on the sample, where it runs up in raster, and scans the sample, at this secondary electrons are registered, which is emitted by the sample. The resulting picture is very similar to the optical photo, but due to the fact that the electron beam is very thin (≈ 1-2 *μm*) depth of focus are significantly higher than those of optical images, and used magnification significantly higher, respectively, it is possible to distinguish the smallest constituents of the sample.

A quantitative analysis of the defect substructure parameters was performed by standard methods [12]. Slides for metallographic examination were prepared traditionally on grinding and polishing wheels. To etch the samples a concentrated solution of nitric acid in ethanol was used.

Mechanical properties of the rolled St3Gsp steel slabs were tested on automated plant MV-01m; allowing to carry out mechanical tests on the made microslides and promptly assess the strength and ductility properties without preparation of tensile samples [13].

The experimental work was performed as follows. Measuring head was reinstated in a lower position. The microslice was set on the lift table and by rotating the lift table the microslice was camped till the contact of the ball and the microslice. The load indicator was set to zero. Then the software of reading and result recording of reference index «*P* - *t*» and *«σ - δ»* was launched, by using IBM PC keyboard and «ISPYTANDAT» directory.

Results and Discussion

Results of the study of the temperature distribution after the rolling in each stand of the five-stand mill presented in the **Table 2**. The Table shows that the strip temperature falls when moving from one stand to the other; the lowest temperature is 855 °C at the end of the rolling.

Table 2 Experienced rolling temperature conditions

Preheating temperature	Slab temperature after rolling in stand No. (^{0}C)					Slab temperature after cooling
	1	2	3	4	5	
1100 ±7.3	1063 ±6.2	1019 ±6.1	972±6.2	937±4.9	867±6.81	813±5.81
1100 ±2.8	1069 ±4.8	1026±5.3	983±5.4	942±5.7	873±4.62	779±4.32
1100±6.3	1072±4.6	1018±4.2	994±6.1	941±4.3	857±5.62	742±3.97
1100±6.8	1065±5.6	1024±6.7	976±3.2	933±6.5	871±3.18	728±4.62
1100±4.7	1067±4.4	1012±4.6	963±4.6	937±4.2	854±6.23	656±3.61
1100±6.1	1064±3.2	1023±5.1	973±5.8	928±7.8	871±3.58	668±3.78
1100±5.2	1069±6.8	1018±6.2	974±6.2	935±8.2	839±5.36	521±5.52
1100±6.8	1073±5.7	1013±5.5	981±7.1	947±5.3	854±6.13	547±3.28
1100±4.2	1048±8.9	1022±4.6	979±6.3	932±4.3	873±5.82	658±3.36
1100±5.7	1075±5.7	1018±3.9	983±3.5	931±6.3	856±3.87	697±7.23
1100±4.9	1073±8.4	1021±6.3	968±4.2	934±3.7	858±7.12	713±5.36

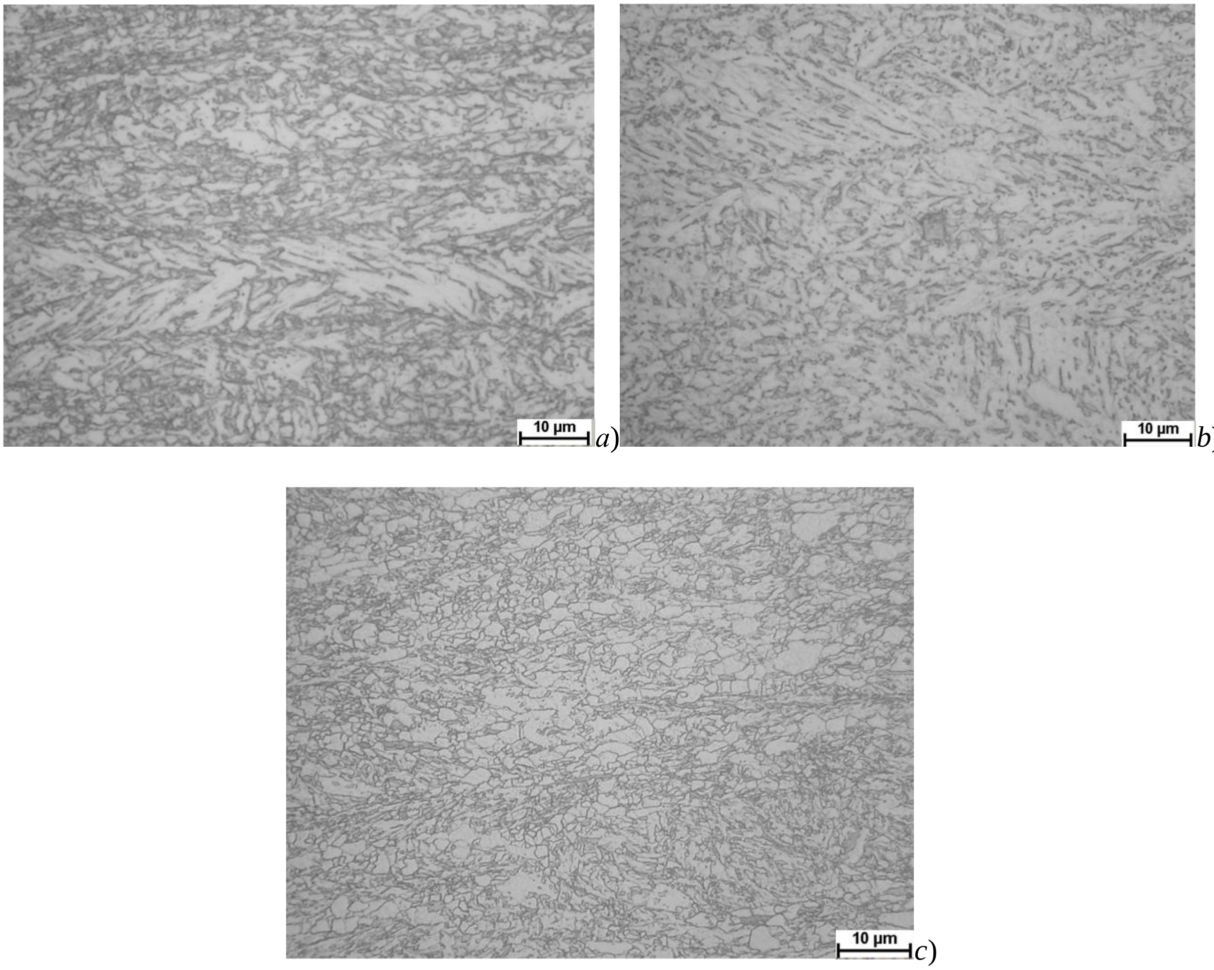
Based on the numerical modeling results, it was established:

- rolling in the proposed instrument allows to deform the thin workpiece without changing its sizes by the repeated bending. The instrument has equal sizes of throats and bumps of the work surface of the roll, and also the throats and bumps of the upper roll, which are located opposite to the throats and bumps of the bottom roll respectively with the draft;
- repeated bending can increase the degree of shear deformation. All these allow to reach the effective structure refinement, another words to improve the quality of sheets produced;
- the use of thin workpiece and alternating strain by bending of thin slab leads to the productivity gain and to the decrease labor hours of produced sheets, at this energy-power characteristics of the process decreases;
- during the rolling in spiral rolls a tangential and axial stress in a tensile area have a positive sign, whereas a compression zone has a negative sign. At this radial stresses on the strip surface are equal to zero, but along the thickness of the workpiece have negative value;
- during rolling in spiral rolls disalignment occurs, which arise during rolling of throats and bumps along the width of the strip, that creates additional macro share along the cross-section of the workpiece and also enables the increase of the deformation intensity;
- in case of rolling in rolls with spiral work surface the increment of deformation intensity is twice higher than during rolling in cylindrical rolls (at conventional rolling the average value of deformation intensity along the strip section equals to 1.1 ... 1.2; at rolling in spiral rolls the average value of strain intensity equals to 2.2 ... 2.6);
- the increase of strain intensity will lead to the formation of equiaxed uniform of ultrafine structure along the cross-section of the strip;
- at rolling in stands of linear-wedge mill the intensity of strain and stress along the cross-section of the strip is evenly distributed.

Study of the workpiece on the optical microscope after hot rolling in spiral rolls and heating at 1100 °C shows that the metal grains of a slab gradually acquire a spherical shape (**Figure 3, *a*, *b*, *c***). Deformation and heating of the steel results in the formation of a homogeneous recrystallized microstructure with grain size 1.3 – 4.6 μm (Figure 3, *c*). Based on the data of optic electron microscope the average size of slabs reduces up to 220-240 *nm*.

The study of St3Gsp steel samples, rolled on the five-stand mill and cooled according to different modes (Table 1), showed that

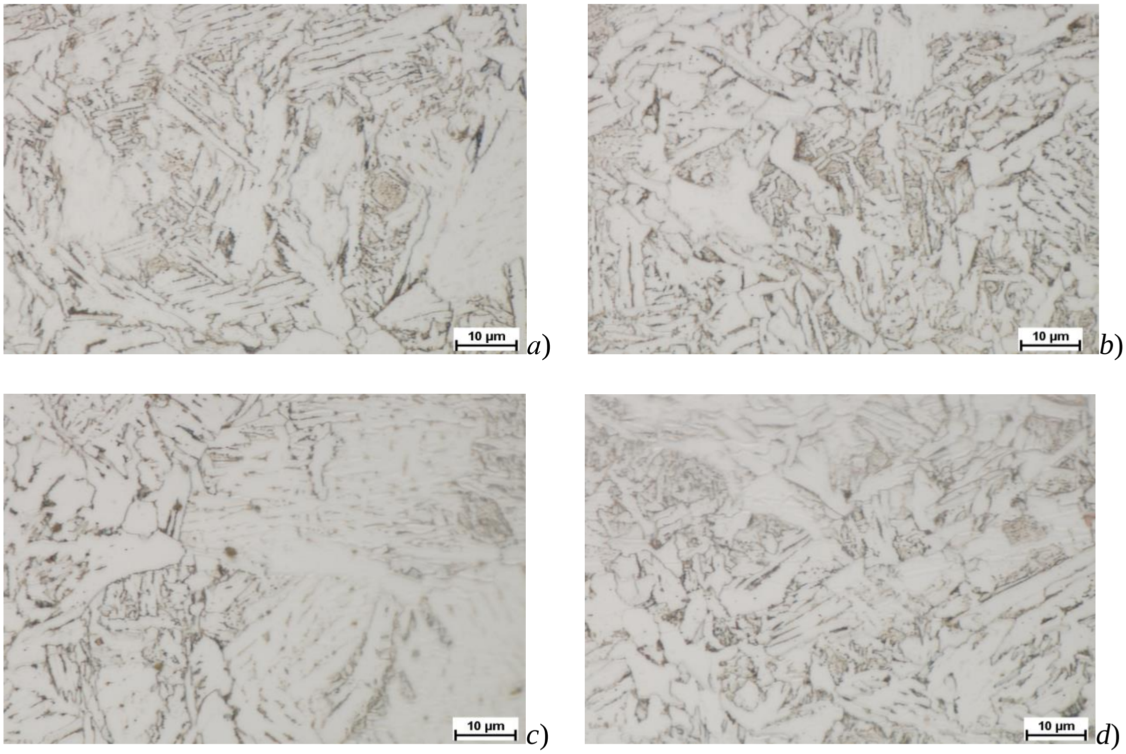
- strips rolled according to mode 1 have a structure of fine ferrite and granular pearlite. Small ferrite size is 22 – 36 *µm*. A granular pearlite size is 26- 41 *µm*. Free cementite size is 4 – 5 points (**Figure 4, *a***);



a – after the first pass; *b* – after the second pass; c – after the third pass

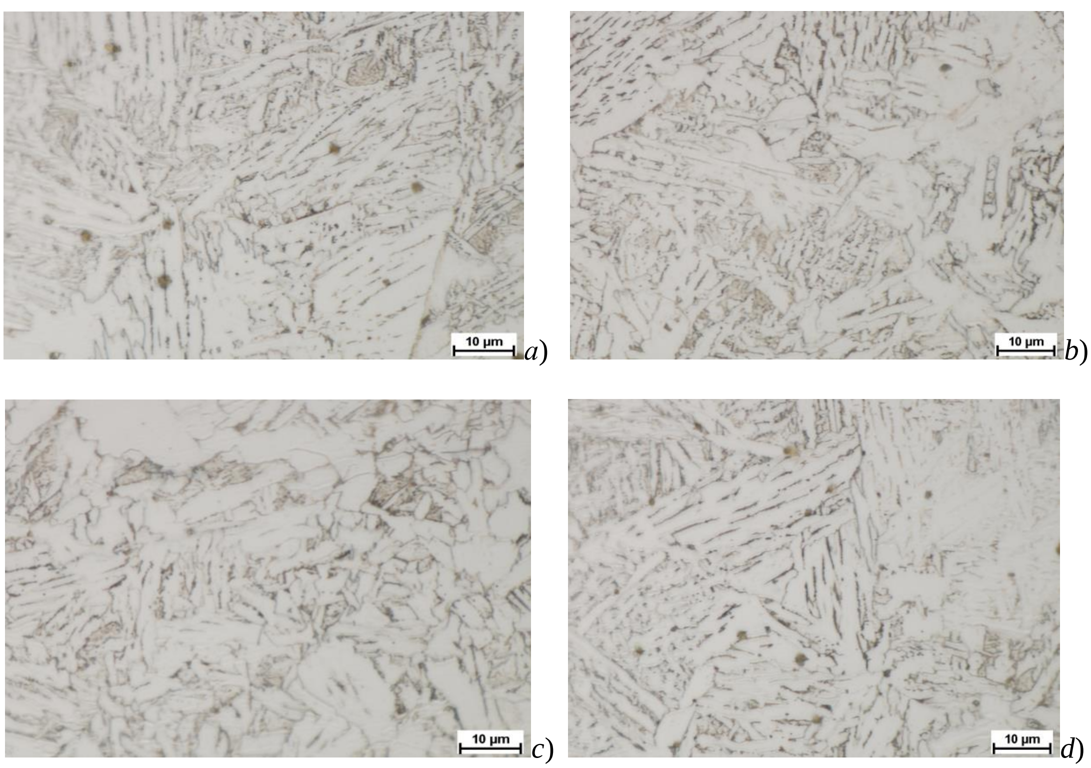
Figure 3 Microstructure of the steel St3Gsp after hot rolling in the rolls with spiral work surface and heating up to 1100 ^{o}C temperature

- rolling and cooling of slabs by mode 2 lead to the formation of granular pearlite structure with the sizes 24 – 33 *µm* and of fine ferrite structure with the sizes 17 – 29 *µm*, and also excess cementite structure with the points 1 – 3 (**Figure 4, *b***);
- the metal structure of slabs deformed and cooled by 3^{d} and 4th modes has a lamellar pearlite structure. The interlamellar distance is n = 0.11 - 0.16 *µm*. The size of a colony is 18 – 28 *µm*. The metal structure comprises small ferrite and excess cementite. Small ferrite size is 17 - 29 *µm*, excess cementite is 1 – 3 points (**Figure 4, *d***);
- the uniform, fine-grained structure along the width of the workpiece can be produce by using modes 5 and 6 (**Figure 5, *a, b***). Research shows, that strips rolled by the modes 5 and 6 have ferrite + pearlite with the grain size equal to 15 – 21 *µm*. Strip temperature reduction till 650 – 670 ^{o}C at the accelerated cooling of the strip in the temperature range of intensive cementite allocation, that promotes the formation of very fine cementite precipitates (points 1 - 2);
- after rolling and cooling by modes 7 and 8 binate crystal grains form along the cross-section of the strip, hereby pearlite with the particles of carbide phase allocated (**Figure 5, *c, d***). Grain size is 14 - 32 *µm*. Size of precipitated cementite equals to 1 – 3 points;



a – variant 1; *b* – variant 2; *c* – variant 3; *d* – variant 4

Figure 4 St3Gsp steel microstructure after hot rolling in five-stand mill



a – mode 5; *b* – mode 6; *c* – mode 7; *d* – mode 8

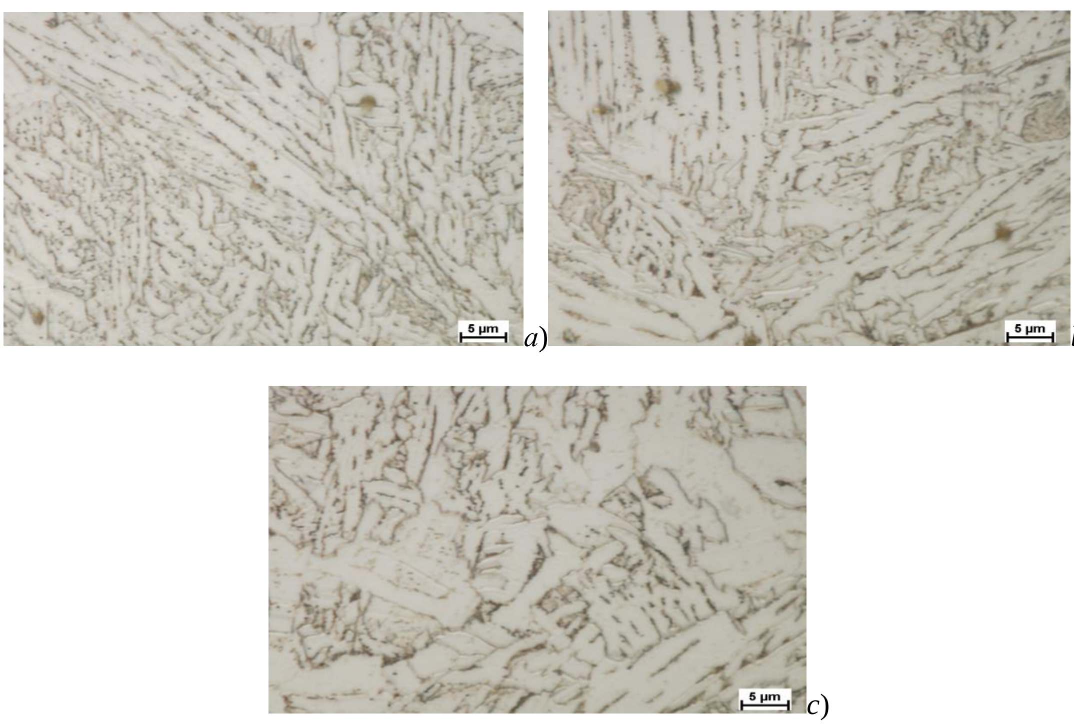
Figure 5 St3Gsp steel microstructure after the hot rolling on the five-stand mill

- the analisys of the rolled strips according to the modes 9-10 showed that a short-term cooling on the air and in the water leads to the formation of the lamellar perlite with the interlamellar distance equals to 0.15 - 0.17 μm, and with colony sizes equals to 23 – 42 μm (**Figure 6, *a, b***). At the finishing temperature of accelerated cooling being 600 – 670 °C relatively large precipitation of cementite (1 – 3 points) forms along the boundaries of ferrite grains. The size of ferrite grains is 22 – 42 μm along the thickness of the strip.
- time reduction of water cooling (mode 11) leads to the formation of perlite grains with the sizes of 12-20 μm (**Figure 6, *c***). Besides the size of cementite grains (4 – 5 points) increases and ferrite grains form with irregular shape and poorly defined boundaries, and also it has different sizes (12 – 16 μm).

Fine grained structure formation in the metal and large cementite precipitation during rolling and cooling according to modes 1 – 4 and 9 – 11 is a result of inheritance of a fine-grained structure. The formation of such structures is also associated with the creation of conditions for full primary recrystallization in the deformed austenite matrix of the metal at high temperature rolling, as well as for the slow - fast - short-term water cooling of hot rolled steel strips. It is known that smaller is the initial austenite grain of metal, smaller is the inherited ferrite+pearlite structure.

There is a binate structure during rolling and cooling according to modes 7 and 8, which is associated with the rapid and prolonged water cooling of hot rolled strips.

The formation of a relatively fine-grained structure of the metal during rolling and cooling of the slabs under modes 5 and 6 is connected with the inheritance of fine-grained structure, a primary recrystallization in the austenitic matrix of the metal during rolling in a five stand mill and with the inheritance by metals of fine grained ferrite + perlite structure at the rational mode of cooling.



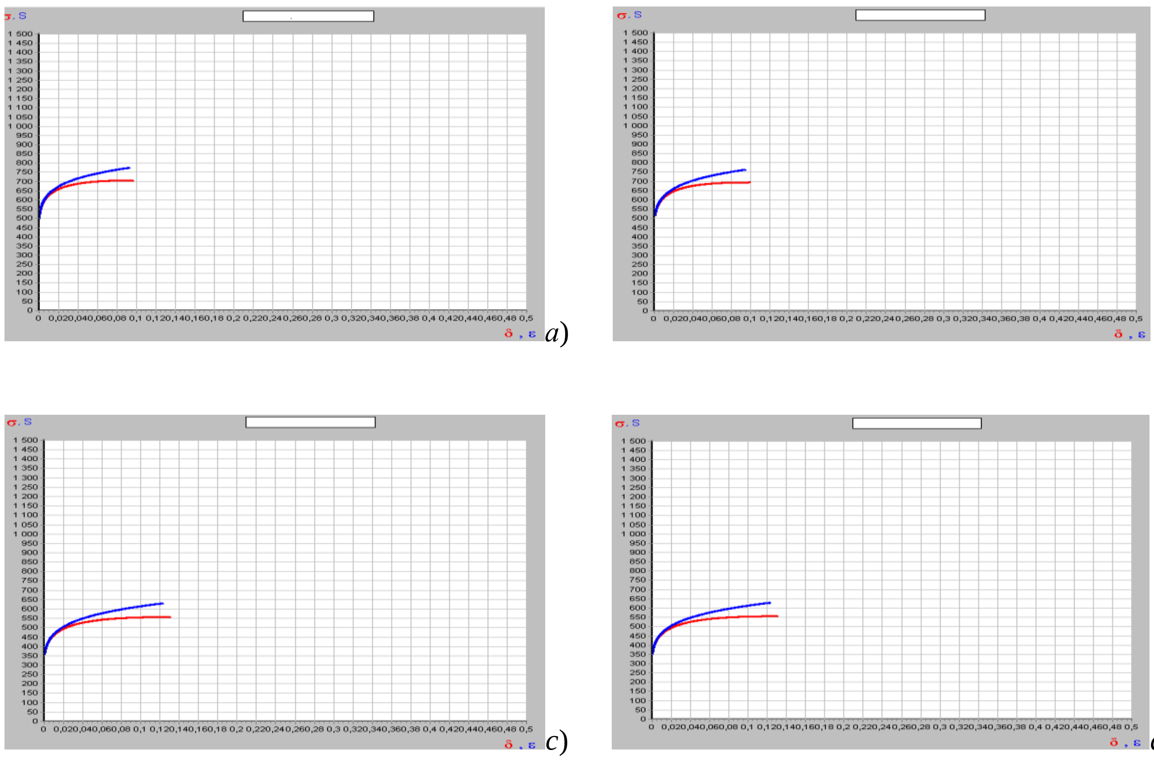
a – mode 9; *b* – mode 10; *c* – mode 11

Figure 6 St3Gsp steel microstructure after the rolling in the five-stand mill

According to the results of the mechanical properties study, it was established that:

- after the rolling and slow cooling (modes 1 and 2) the surface of a slab has the elevated values of yield limit, tensile strength and hardness (HB = 211.6 – 223.2; HRC = 18.3 – 21.4; HV = 208.3 – 212.1; HRV = 89.2 – 91.3; σ_B = 621.5 – 662.3 MPa; $\sigma_{0.2}$ = 431.5 – 458.3 MPa; δ_p = 0.1413 – 0.1328) (**Figure 7 *a, b***);

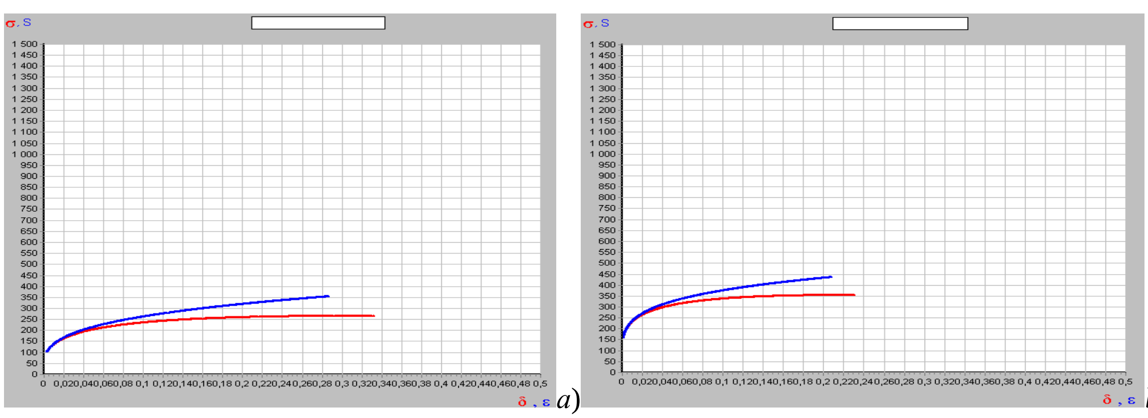
- usage of a short-term water cooling of slabs after rolling (modes 3, 4, 9, 10 and 11) allows to get mechanical properties without widmanstatten signs on the surface of slabs (**Figure 7 *c, d*** and **Figure 9 *a, b, c***).
- these surfaces have a relatively high value of yield strength, tensile strength and hardness (HB = 161.3 – 174.6; HRC = 14.1 – 17.3; HV = 161.1 – 173.2; HRV = 74.5 – 78.2; σ_B = 523.7 -593.8 MPa; $\sigma_{0.2}$ = 336.8 – 393.4 MPa; δ_p = 0.1413 - 0.1328);
- the slabs cooled by modes 5 and 6 have the following rational value of mechanical properties (HB = 82.3 – 112.2; HRC = 7.2 – 9.3; HV = 77.3 – 102.3; HRV = 45.6 – 54.2; $\sigma_{0.2}$ = 131.5 – 189.2 MPa; σ_B = 273.3 – 363.7 MPa; δ_p = 0.2421 – 0.3516) (**Figure 8 *a, b***).
- after the rolling and cooling by modes 7 and 8, there were produced mechanical properties with the following Widmanstaet signs on the surface of the slabs (HB = 468.3 – 487.3; HRC = 51.2 – 56.4; HV = 479.3 – 513.2; HRV = 156.7 – 169.3; $\sigma_{0.2}$ = 1213.3 – 1373.3 MPa; σ_B = 1426.3 – 1537.2 MPa; δ_p = 0.0412 - 0.0453).



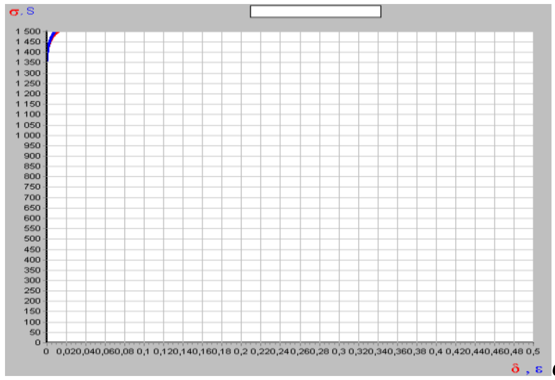
a) *b*) *c*) *d*)

- *a* – mode 1; *b* – mode 2; *c* – mode 3; *d* – mode 4

Figure 7 Mechanical properties of the sheets surface made from steel St3Gsp after the hot rolling in the five-stand mill



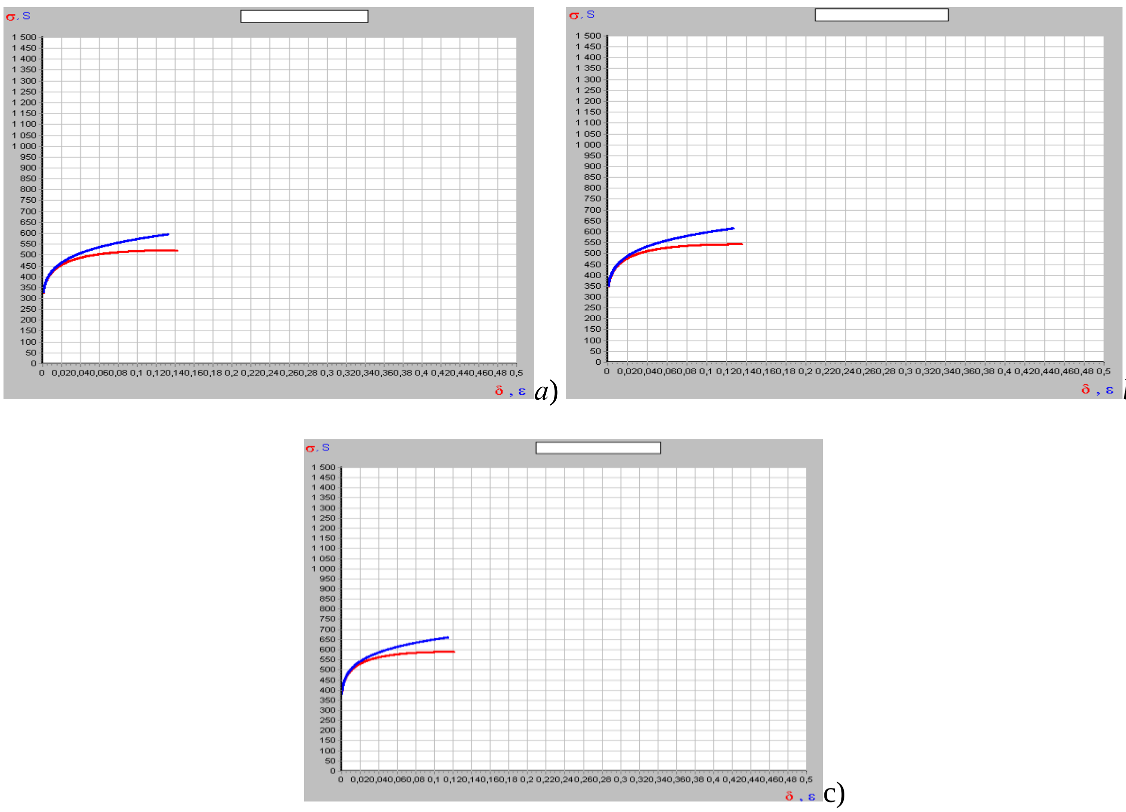
a) *b*)



c)

a – mode 5; *b* – mode 6; *c* – mode 8

Figure 8 Mechanical properties of the sheets surface made from steel St3Gsp after the hot rolling in the five-stand mill



a – mode 9; *b* – вариант 10; *c* – mode 11

Figure 9 Mechanical properties of the sheets surface made from steel St3Gsp after the hot rolling in the five-stand mill

Conclusions

1. To obtain the required structure and mechanical properties of the metal made from steel St3Gsp it is required to run rolling of the strips with the temperature equals to 850 – 870 °C at the end of the rolling and with the cooling temperature equals to 650 – 670 °C of hot rolled strips on the runoff table according to a monotonous mode of cooling on the air, in the water and on the air;
2. The binate crystallites forms in the microstructure of the hot rolled strips when the finishing temperature reaches 840 – 850 °C and the cooling temperature at the runoff table reaches 520 – 550 °C. Meanwhile a structure with Widmanstaet signs forms on the surface of slabs;
3. Processing under modes 1 - 4 and 9 – 11 resulted in obtaining fine grained structure in 1.5 *mm* thick slabs and the formation of relatively large cementite along the thickness of a strip.

4. The hot-rolling of ultrafine-grained alloys in newly designed five-stand mill allows to keep fine-grained microstructure of the steel;
5. Hot rolling in the rolls with spiral work surfaces and heating up to 1100°C enables to produce a recrystallized UFG structure in thin sheet slabs made of St3Gsp steel.

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