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# THE STUDY OF THE QUALITY OF HOT THIN BEAMS OBTAINED BY ROLLING ON A LONGITUDINAL WEDGE MILL

**Abstract.** The article presents an analysis of the influence of temperature-deformation processing regimes on the microstructure of 08kp steel during rolling on a longitudinal-wedge mill (LWM) using the physical modeling on the plastometer STD 812; it also considers kinetics of growth and decay of austenite, as well as the conditions for the formation of a fine-grained structure. The quantitative data was obtained by the finite element method and the «MSC.SuperForge» software and the main regularities of the distribution of the stress-strain state as well as the temperature during rolling the blanks on LWM was established. The rational technology of rolling thin strips of steel 08kp has been developed and tested under laboratory conditions. Particular attention is paid to the analysis of the influence of the rolling and cooling regimes on the formation of a fine-grained structure in steel 08kp. It is established that rolling thin bands of steel 08kp on LWM leads to an increase in strength and plastic properties of sheet metal.

**Key words:** strip rolling, low-carbon steel 08kp, austenite, ferrite, perlite, microstructure, cold-hardening, experiment, hardening, softening, recrystallization.

**Introduction.** Starting from the end of the twentieth century and still now, a sheet metal with a thickness of less than 2 mm made of low-carbon steel is considered to be the most important structural material in the automotive industry and other leading branches of engineering [1, 2]. In recent years, the demand for hot-rolled thin-sheet steel has been increased and, thus, an increase in the volume of production of steel plate with a thickness of less than 2 mm has occurred. Production of hot-rolled extra-thin sheet products is planned to be carried out at the level of requirements for the quality of cold-rolled sheet. Even a partial use of hot-rolled sheet products by the consumer instead of cold-rolled sheets of the same thickness gives a significant economic effect due to its lower costs for additional redistribution (cold rolling, annealing, etc.).

Thus, the tendency of producing thin hot-rolled stripes, a part of which is independent commodity products and a part of which is used to replace cold-rolled metal, has become a reality and it still continues to grow in the world practice [2]. More than 30% of strips with a thickness of 1.0-2.5 mm and higher is contained in a typical assortment of cold-rolled structural steel. At the same time, the proportion of strips with a thickness of 1.0-3.0 mm is about 60% in the range of broadband hot rolling mills. As a prerequisite for this trend, we can note an increase in the efficiency of orders and decrease in production costs [2-5].

According to the authors of papers [2, 6], the most perspective area is using the thin hot-rolled strips to replace cold-rolled sheet products of general purpose. The analysis of the order book of metallurgical combines of the CIS countries showed that about 15-20% are cold rolled strips with the thickness of 1.0-3.0 mm, supplied in accordance with GOST 16523 with the quality of the surface finish of groups 2 and 3.

At the same time, the share of stripes of 1.5-1.8 mm thickness makes up about 30-35% of this amount (or about 6-7% of the annual production volume of the shop), and bands of 2.0-3.0 mm thickness is about 45-50% (about 8-9% of annual production). Up to 75-80% of the metal in the assortment group under consideration is supplied with the properties of the exhaust category *G* and about 14-16% with properties of the extractor category *N*.

The production of thin hot rolled products is a complex process, characterized by a large number of technological factors [7]. The mechanical properties of hot-rolled thin strips are affected by the chemical composition and structure of the metal, the formation of which is determined by the temperature-deformation modes of rolling, and the regularities of this influence have a complex character.

It should be noted that the current trend in the market of sheet steels is the expansion of the nomenclature within strengthening the quality requirements, including structure and mechanical properties [8]. The structure of hot-rolled sheets is uneven in thickness, which is primarily due to the unevenness of the deformation and the temperature gradient. Therefore, an important step is the selection of rational temperature-deformation modes of rolling.

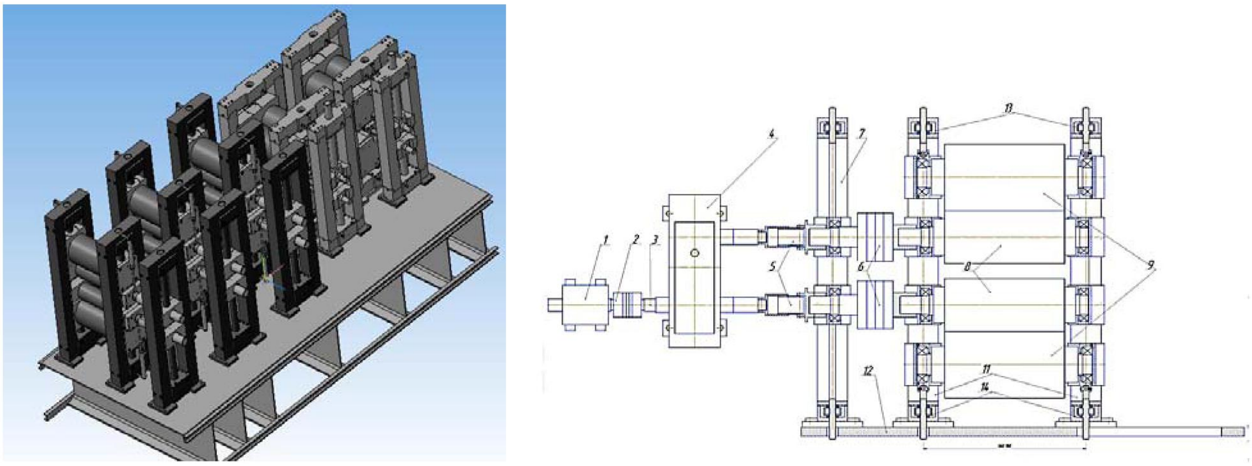
A significant drawback of rolling extremely thin strips on continuous wide-band mills is the impossibility of meeting the optimal temperature conditions for ending the hot rolling (compression in the critical temperature range $Ar_3$-$Ar_1$ leads to the formation of an uneven grain structure that does not meet the requirements of GOST 16523) [9]. Large grain and a variety of granularity of the structure can lead to uneven deformation of the metal during stretching and cause the formation of breaks. A uniform structure is also necessary for hot-rolled strips, which can be a cost-effective sub-roll for cold rolling mills. A mixed structure with coarse grains of ferrite in the surface layers of the strip, which is unevenly deformed in cold rolling mills with a reduction ratio of 70-80%, can cause transverse cracks along the lateral edges of the strip [9]. Cold rolling does not eliminate the coarse graininess obtained during hot rolling; in non-uniform grains in a hot-rolled strip similar grains are formed in cold rolled sheets. A roll with a structure consisting of uneven or small grains is poorly deformed and the strip breaks occur [9].

It is outlined in the paper [9] that the surface heterogeneity can be associated with a different chemical composition along the section of the strip, and ferrite rolling at a temperature below the Ar1 point in the region of the single-phase ferritic structure of the metal will provide a uniform structure for the extra-thin bands. However, data on the effect of ferrite rolling on the microstructure and the mechanical properties of low-carbon steels are not enough, there is no complete idea of its effect on the quality of the metal, so it is relevant to study the features of the formation of microstructure and the mechanical properties of extremely thin low-carbon steel at low rolling-end temperatures.

It should be noted that it is possible to meet all requirements to the structure and properties of sheet steel produced in the hot rolling mill by organizing the control and controlling the formation of the structure and properties of steel in the mill's processing line [8]. Responding promptly to market demands, while significantly reducing the time and costs for the development of new types of metal products, will allow an automated design of technological modes of production of rolled products. As the first step in this direction, there should be mathematical modeling of the structure formation during rolling in different mills.

The aim of these studies is to study the distribution of accumulated deformation on the formation of the structure and properties of a metal of low-carbon steel 08kp during the rolling of thin strips on a longitudinal-wedge mill.

**Materials and experimental procedure.** A multifunctional longitudinal-wedge mill (LWM) of a new design (figure 1) is proposed for the rolling of sheets of steels and alloys [10]. This mill contains electric motors, reducers, gear stands, universal spindles, couplings, stands with working and supporting rolls. At the same time, in the first three stands there are two supporting rolls, and in the last two stands there are four supporting rolls. Rotation of working rolls in the decreasing rolling direction is carried out through bearing stands by five motor-reducers with an angular velocity $\omega = \upsilon \cdot R$ (where $\upsilon$ is the rolling speed in each mill stand, R is the radius of work rolls in each mill stand). In this case, the distances between the stands are increased by the amount of advance, and the adjustment of the distance between working rolls is made by single screw press mechanisms located at the top and bottom of the mill stand and bearing stands [19].



a b

Figure 1 – Multifunctional longitudinal-wedge mill (*a*) and the structure of its working stands (*b*):
1 - motor-reducer; 2 - coupling; 3 - shaft; 4 - pinion cage; 5 and 6 - spindles; 7 - bearing cage;
8 - working rolls ($D_{P1}$ = 180 mm, $D_{P2}$=150 mm, $D_{P3}$ = 125 mm, $D_{P4}$ = 106 mm, $D_{P5}$ = 94 mm);
9 - supporting rolls ($D_{OP}$ = 220 mm); 11 - stand; 12 - base plate; 13 and 14 - pressure mechanisms

It should be noted that working rolls in each stand have a constant diameter, and in successive cages the diameter of these rolls decreases in the rolling direction. A thin strip is cut at the output.

The effect of heating and rolling on LWM and on cooling by water on the structure and properties of rolled sheets of steel 08kp having the following chemical composition was studied in the paper, %: C – 0.08; Mn – 0.45; Si – 0.17; P – 0.035; S – 0.04; Cr – 0.11; Ni – 0.25; Cu – 0.25).

The initial grain size of the austenite after heating in the furnace was 100 μm [11]. The time of interidentification pauses by law is the constancy of seconds in the rolling of thin strips in the LWM. The resistance of low-alloy deformation is described by the equation [12]:

$$\sigma_s = 1530\,u^{0,1019}\,\varepsilon^{0,1344}\exp(-0,00253\,T), \tag{1}$$

The grain size of the austenite $d_\gamma$ of low-alloy steel, depending on the initial grain sizes $d_o$, the holding time $t$, the temperature $T$ and the universal gas constant $R$, were determined by the formula [13]:

$$d_\gamma = \left[d_0^3 + 5{,}47\cdot 10^{20}\cdot t\cdot \exp\left(-\frac{460000}{RT}\right)\right]^{\frac{1}{3}}. \tag{2}$$

The passage of metadynamic or static recrystallization is characteristic for hot rolling [11]. One of the methods for modeling recrystallization is the expression «Johnson-Mehl-Avrami-Kolmogorov» (JMAK). For the static recrystallization of low-alloy steel, the recrystallized volume can be determined by the formula [14]:

$$X_{srex} = 1 - \exp\left[-0{,}693\left(\frac{t}{t_{0,5}}\right)^{0,5}\right] \tag{3}$$

Time required for 50% of static recrystallization of low-alloy steel is the following [14]:

$$t_{0,5} = 4{,}92\cdot 10^{-17}\, d_\gamma\, \varepsilon_{инт}^{\;-2}\,\dot{\varepsilon}^{-0,33}\exp\left(-\frac{88000}{RT}\right). \tag{4}$$

After static recrystallization of low-alloyed steel, the austenite grain size can be determined by the formula [14]:

$$d_{рек} = 12000 \cdot d_{\gamma}^{0,33} \cdot \varepsilon_{инт}{}^{-0,79} \exp\left(-\frac{88000}{RT}\right). \qquad (5)$$

where $\varepsilon_{int}$ is the strain intensity.

Analysis of the above formulas shows that it is necessary to determine the stress-strain state (SSS) under various rolling regimes in order to predict the structure formation in the hot rolling of strips on a longitudinal-wedge mill.

A specialized standard software «MSC.SuperForge» [15, 16] was used for the calculation of SSS for the rolling of blanks on multifunctional LWM. A 3-dimensional (3D) geometric model of a rolled sheet and a deformable tool was built in the CAD program of Inventor, and imported into the CAE program «MSC.SuperForge». A 3D element CTETRA (four-node tetrahedron) which is commonly used for modeling 3D bodies was used while creating the finite element model of the initial workpiece and the tool [19].

It should be noted that the technical characteristics of the working stands of the proposed mill were used to calculate SSS. In «MSC.SuperForge», tools are taken absolutely rigid and they provide only the properties of thermal conductivity and heat transfer while the mechanical properties are ignored. From the materials database, the material of the ShKh15 tool was assigned. For this material, the density and thermal properties are assigned by the program by default.

A workpiece with the measurements 5×20×50 mm was used in the LWM for investigating the rolling process. The rheological properties of steel 08kp at a temperature of 900 °C were set from the database of the software complex «MSC.SuperForge». In this case, the workpiece material was taken by isotropic elastoplastic with nonlinear hardening.

The interaction between the rigid rolls and the deformable workpiece material is simulated by means of contact surfaces that describe the contact conditions between the rolling surfaces and the surface of the rolled sheet. During the simulation, the contact conditions are constantly updated, reflecting the rotation of the rolls and deformation of the material, which makes it possible to model the sliding between the roll and the material of the workpiece which is being machined. The contact between the roll and the sheet is modeled by the Coulomb friction, the coefficient of friction was adopted as 0.3 [17].

The temperature regime during rolling consists of the exchange of heat between the rolls, the sheet and the surrounding medium, and also from the thermal effect due to deformation of the metal. The rolling process takes place at room temperature, so the initial temperature of the rolls is assumed to be 20 °C.

The program «MSC.SuperForge» was launched. The stepwise method was used to calculate the components of strain tensors, deformation rates and stresses, intensity of stresses and deformations, as well as temperature distribution over the volume of the workpiece.

The samples with the measurements Ø10.0×15.0 mm were tested by compression on an STD 812 plastometer (figure 2) [18] in order to determine the effect of the deformation degree and the subsequent water cooling on the 08kp steel structure.

Figure 2 – Thorn Plastometer STD 812

This plate allows to test the samples at temperatures up to 1500 °C with a heating and cooling rate of up to 100 K/sec, at deformation rates of up to 50 $s^{-1}$ for torsion, stretching and compression, deformation rates and up to 0.7 at compression, up to 0.4 at tension and up to 10.8 at torsion. During the test, continuous or fractional compression/stretching or torsion with a given degree and strain rate at each pass is realized.

The tests were carried out in a vacuum with a constant rate and strain temperature. Cylindrical samples were used to carry out the experiments, and a K (NiCr-Ni) thermocouple was used to measure and control the temperature changes. The type of K thermocouple was welded to the side surface of the samples. The samples in an induction heater were heated to 800, 900 and 1000 °C at a constant rate of 5° C/s, kept at this temperature for 10 s and deformed by cyclic compression at the rolling speeds of the longitudinal-wedge mill (table 1). When drawing up the experiment plan, the time of the interdisciplinary pause was determined on the basis of the law by the constancy of seconds in rolling during a five-kilometer longitudinal-wedge mill. In the intervals of cyclic deformation, after switching off the electric drive of the installation, the sample remained clamped and the active loading was followed by the relaxation stage. After the test, the samples were removed from the container and, in accordance with the experimental design, the samples were cooled in air and water within a natural environment of room temperature.

Table 1 – Physical simulation experiment plan

| № var. | $\varepsilon_1$, % | $t_1$, c | $\varepsilon_2$, % | $t_2$, c | $\varepsilon_3$, % | $t_3$, c | $\varepsilon_4$, % | $t_4$, c | $\varepsilon_5$, % | $\tau_{\text{в}}$, c | $\tau_{\text{в.о}}$,c |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Testing temperature – 800 $^0$C | | | | | | | | | | | |
| 1 | 20 | 4 | 20 | 3,3 | 20 | 2,4 | 15 | 1,6 | 10 | 2 | 10 |
| 2 | 20 | 4 | 20 | 3,3 | 20 | 2,4 | 15 | 1,6 | 10 | 8 | 4 |
| 3 | 20 | 4 | 20 | 3,3 | 20 | 2,4 | 11 | 1,6 | 10 | 6 | 6 |
| Testing temperature – 900 $^0$C | | | | | | | | | | | |
| 4 | 20 | 4 | 20 | 3,3 | 20 | 2,4 | 15 | 1,6 | 10 | 2 | 10 |
| 5 | 20 | 4 | 20 | 3,3 | 20 | 2,4 | 15 | 1,6 | 10 | 8 | 4 |
| 6 | 20 | 4 | 20 | 3,3 | 20 | 2,4 | 15 | 1,6 | 10 | 6 | 6 |
| Testing temperature – 1000 $^0$C | | | | | | | | | | | |
| 7 | 20 | 4 | 20 | 3,3 | 20 | 2,4 | 15 | 1,6 | 10 | 2 | 10 |
| 8 | 20 | 4 | 20 | 3,3 | 20 | 2,4 | 15 | 1,6 | 10 | 8 | 4 |
| 9 | 20 | 4 | 20 | 3,3 | 20 | 2,4 | 15 | 1,6 | 10 | 6 | 6 |

Note: $\varepsilon_1$- single reduction in the first stand; $t_1$ - interidentification pause after the first stand; $\varepsilon_2$ - single reduction in the second stand; $t_2$ - an interdisciplinary pause after the second stand; $\varepsilon_3$ - single reduction in the third stand; $t_3$ - an interdisciplinary pause after the third stand; $\varepsilon_4$ - single reduction in the fourth stand; $t_4$ - an interdisciplinary pause after the fourth stand; $\varepsilon_5$ - single reduction in the fifth stand; $\tau_{\text{в}}$ - time cooling in air; $\tau_{c.w}$ - time cooling with water.

Plastometer STD 812 is a fully digital closed-loop thermomechanical test system. It is based on software based on an easy-to-use Windows OS and a block of powerful processors that provide an interface for the creation, execution and processing of physical modeling and thermomechanical testing programs.

The heart of the STD 812 plastometer is the digital control system of the third series. It sends signals for controlling the thermal and mechanical tests at the same time by means of digital closed-loop thermomechanical systems. In order to achieve maximum flexibility in testing materials, the system of the STD 812 plastometer can be fully operated in both stand-alone and manual modes, or in a combined way, if it is necessary.

The computer management system includes a desktop computer with Windows OS and a powerful industrial computer built into the management console. A desktop computer with Windows OS has a flexible multi-tasking Graphical Interface of the industry standard for the development of programs for modeling and analysis of data.

The grids used for metallographic analysis were prepared according to the traditional method on grinding and polishing circles. A solution of nitric acid in ethyl alcohol was used with the purpose of etching samples.

The metallographic analysis was performed using a universal NEOPHOT 32 (KarlZeiss, Jena) universal microscope (Germany). The Neophot 32 microscope is designed for metallographic microscopy and photography. Observation can be made by the method of light and dark field, in polarized light, with a change in the magnification magnitudes. Magnification of the microscope, unit: from 10 to 2000. The microscope is equipped with a digital mirror camera Olimpus by the output of the image and by saving the images to the computer.

**Results and discussion.** The rolling process in the proposed mill can be divided conditionally into four stages. Therefore, the data for the four stages were taken as a percentage of the total deformation time in order to illustrate the results of the calculation, i.e. the following intervals were selected: the first stage 20, the second stage 40, the third stage 60 and the fourth stage 80 percent of the total deformation time.

The distribution of the intensity of deformations and stresses, as well as the temperature during the rolling of strips on the LWM is illustrated in the figure 3.

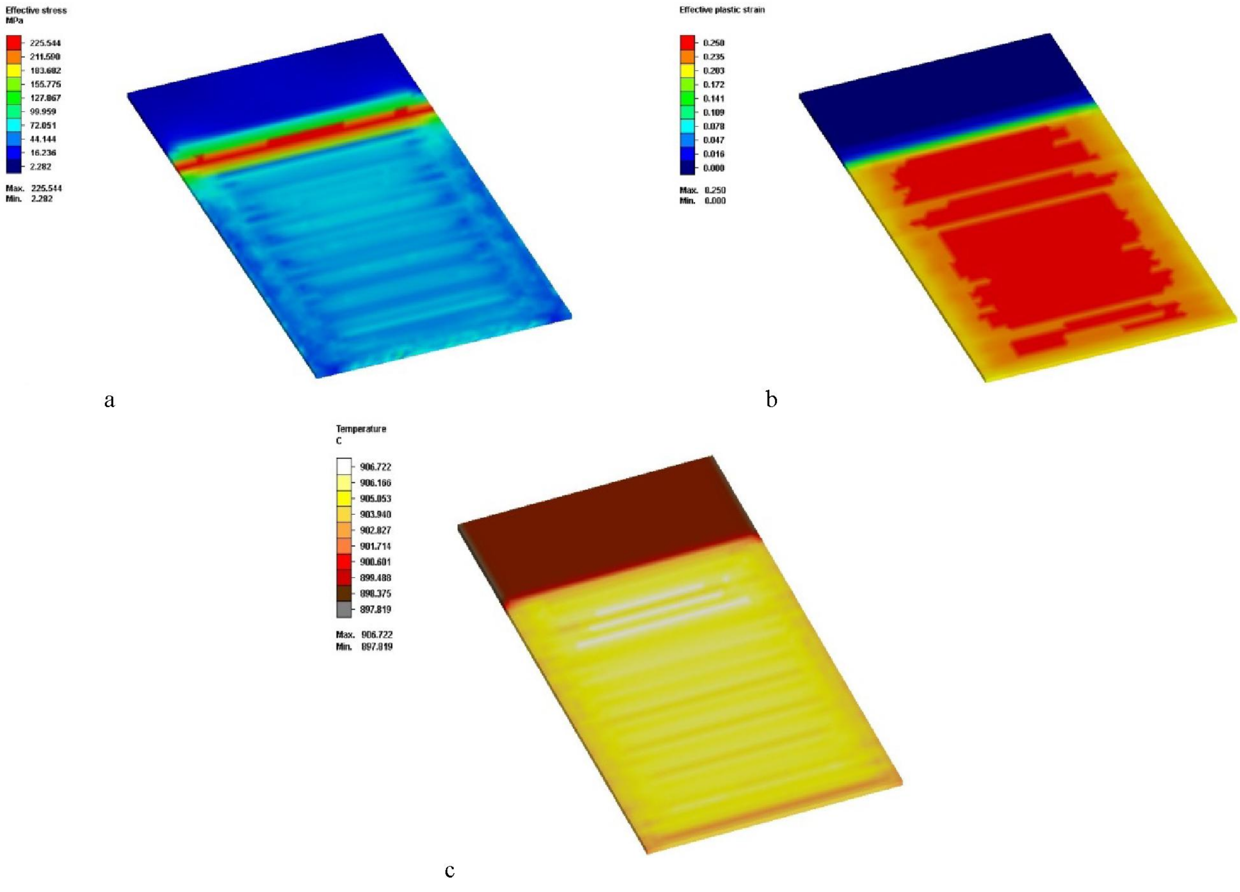



Figure 3 – The pattern of intensity distribution of stresses (*a*), deformations (*b*) and temperature field (*c*) in the workpiece during rolling on the last stand of LWM (rolling temperature is 900 °C)

Calculation and analysis of SSS shows that:

1. The intensity of deformation and stress are localized in the zones of metal capture by rolls while rolling in the first stand of the LWM;

2. The values of the intensity of strain and stress increase in the center and along the edges of the deformed workpiece with an increasing compression;

3. Continuous rolling of the billet on the subsequent LWM stands allows to gradually transfer the areas of concentrated deformation from the center to the middle part of the strip, and then into the contact zone of the rolls with the rolled billet;

5. Gradual transfer of sites with localization of deformation from the center to the surface conducts to a more even distribution of the accumulated deformation;

6. The most uniform distribution of the accumulated deformation along the height and length of the rolled strip was obtained by rolling with a single reduction in the first stand 20%, in the second stand 20%, in the third stand 20%, in the fourth stand 15%; in the fifth stand 10%;

7. The temperature in the hot metal-roll contact zones decreases during the rolling process in the first stand;

8. The sections of the metal with high temperature move together with the deformation center while rolling in the second, third, fourth and fifth stands;

9. During the rolling on the LWM, the sections of the bands located in the contact zone of the metal with the roll are cooled intensively, while outside the zone of the deformation zone and the metal regions located in the deformation zone are heated intensively.

The change in the fraction of recrystallized grains in the metal structure of the bands along the LWM stands is demonstrated in figure 4. It can be seen from the figure that after-rolls in the first stand of LWM, the fraction of recrystallized grains along the cross section of the strip is 0.112 ... 0.418.

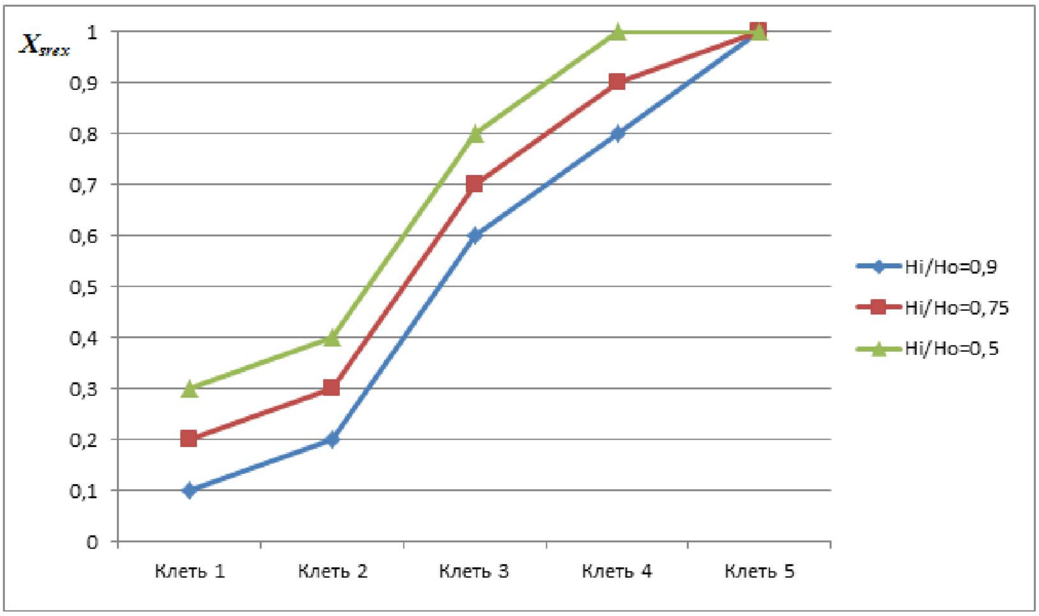



Figure 4 – The graph of the change in the volume fraction of the recrystallized structure during the rolling of hot-rolled strips on the LWM (where $H_i$ is the distance to the studied point along the height of the rolled strip, and $H_0$ is the height of the strip)

It should be noted that after rolling on the medium stands of LWM, the proportion of recrystallized grains along the section of the billet is 0.615 ... 0.811. At the same time, recrystallization almost completely passes through the central zones of the workpiece because of the large value of the degree of shear deformation and the moderate strain rate. However, due to the appearance of friction and, as a result, the appearance of zones of hindered deformation in the surface zones of the strip does not completely recrystallize the grains. In addition, recrystallization also does not completely pass through the zones located between the surface and central zones of the bands.

The structure is completely transformed from coarse-grained to fine-grained (recrystallized) during the rolling process on the last stands of LWM, because of the smallness of the zones of hindered deformation and the obtaining of these zones of sufficient degree of shear deformation.

Thus, during the rolling process of 08kp steel according to the proposed technological process, recrystallization takes place practically in the entire volume of the strips because of the accumulation of the degree of shear deformation and the measured strain rate along the workpiece cross-section, which increases its mechanical properties. In addition, a high degree of deformation reduces the anisotropy of the properties of the rolled strips.

The change in the average size of the recrystallized grains on five stands of LWM is shown on figure 5. The largest reduction in the size of the crystallized grains occurs during rolling on average (up to 22.253 ... 42.927 µm) and the penultimate stand (up to 18.264 ... 23.921 µm). After rolling on the last LWM stand, a fine-grained, homogeneous structure with an average recrystallized grain size of 8.27 ... 11.693 µm is formed.

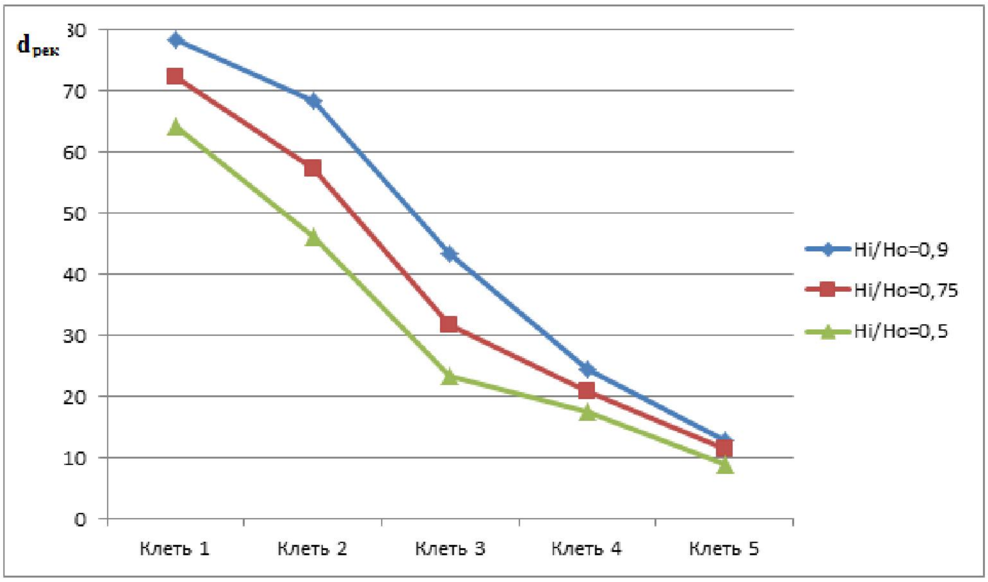



Figure 5 – The graph of the change in the average size of the recrystallized grain during rolling hot-rolled strips on the LWM

Thus, from the above data it can be seen that after rolling on LWM, a fine-grained and homogeneous microstructure is obtained which contributes to an increase in ductility, toughness and strength.

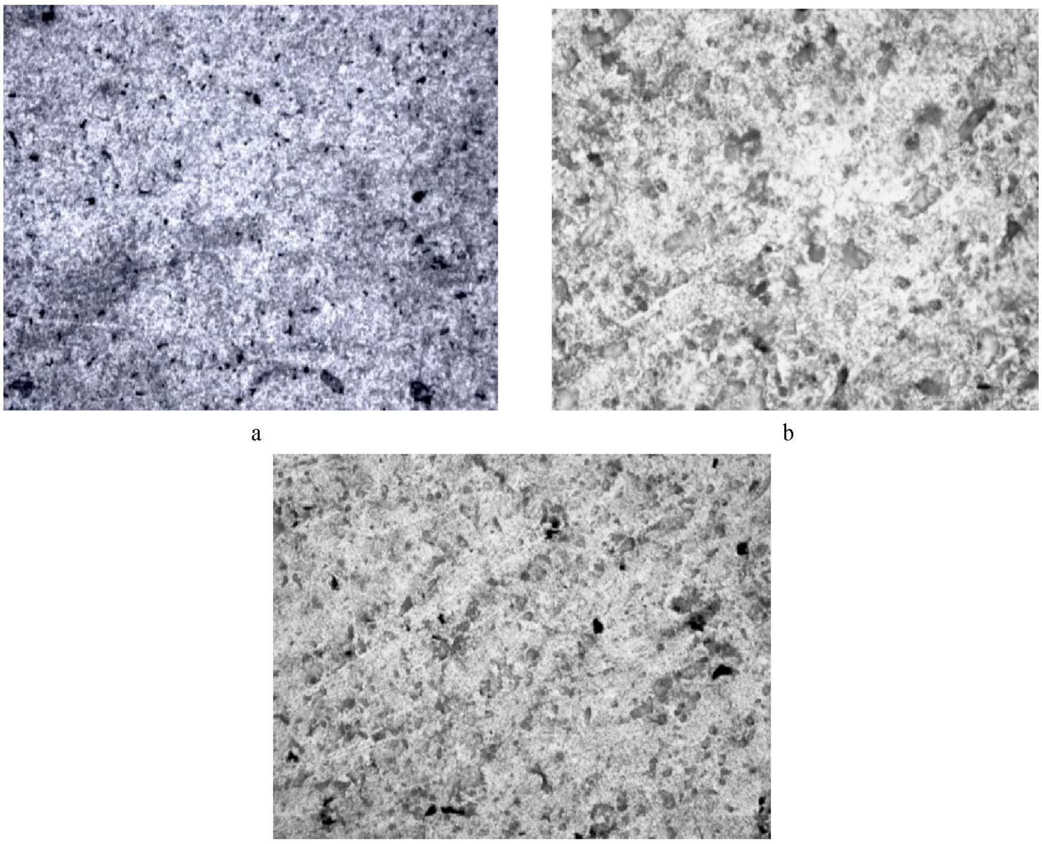
Table 2 shows the results of a temperature study, and figures 6-8 show the results of a microstructure study of samples from 08kp steel treated with rational deformation modes for rolling thin strips on a multifunctional LWM.

Table 2 – Temperature conditions of physical modeling

| # var | The temperature of the sample after rolling in the stand №. ($^0$C) | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| 1 | 800 | 796 | 791 | 787 | 781 |
| 2 | 800 | 794 | 791 | 787 | 783 |
| 3 | 800 | 793 | 788 | 781 | 778 |
| 4 | 900 | 898 | 893 | 886 | 879 |
| 5 | 900 | 895 | 891 | 887 | 873 |
| 6 | 900 | 892 | 891 | 889 | 883 |
| 7 | 1000 | 993 | 988 | 981 | 978 |
| 8 | 1000 | 995 | 991 | 986 | 977 |
| 9 | 1000 | 996 | 992 | 987 | 979 |

The study of the structure of the original sample from 08kp steel showed that they have a relatively coarse-grained and unevenly distributed structure with a grain size of 141 microns.

The quantitative analysis of the microstructures of the samples tested in versions 1, 2 and 3 at a temperature of 800 °C showed that the samples throughout the entire section have a relatively coarse-grained structure (figure 6). Deformation by rational rolling regime and rapid cooling in air and slow cooling in water leads to the formation of coarse-lamellar perlite with an interplastic distance n = 0.64-0.83 µm and colony sizes of 41-67 µm, with a banded ferrite with a measurement of 59-101 µm. Relatively small cementite is formed (point 1-2) (figure 6, *a*) at the temperatures of the end of slow cooling in water along the boundaries of grains of ferrite.



a b

c

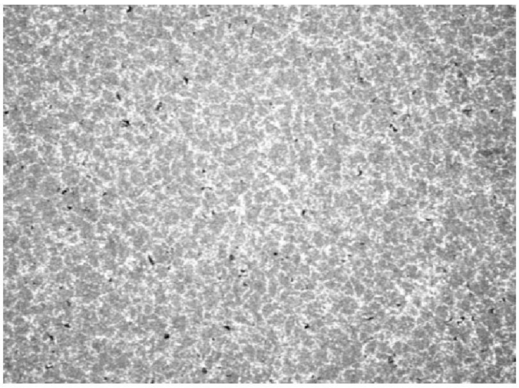
Figure 6 – Microstructure of steel 08, planted at a temperature of 800 °C in accordance with option 1 (*a*), 2 (*b*) and 3 (*c*)

Analyzing the structure of samples of 08kp steel, precipitated by rational rolling regimes on the LWM and cooled by variants 2 and 3, one can come to the following conclusion. Reducing the temperature of the samples to 770-780 °C and providing slow cooling in air and rapid cooling in water lead to the formation of a plate perlite with an interlaminate distance n = 0.48-0.62 μm and approximately the same colony sizes of 48-73 μm. In this case, the cementite size increases (point 2 - 3) and ferrite is formed with a relatively elongated shape and large dimensions (83 - 124 μm) (figure 6, *b*, *c*).

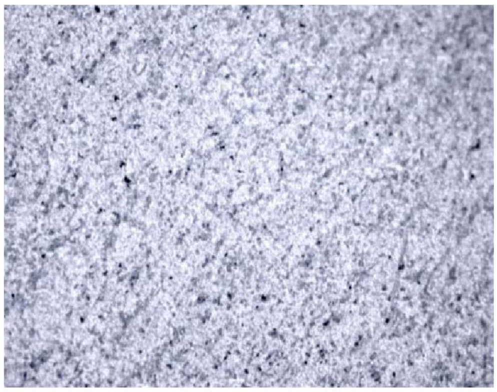
During the precipitation of steel slump 08kp, the formation of a coarse-grained structure is connected to the deformation of the samples in the two-phase region (temperature 780-800 °C) of austenite and ferrite ($Ar_1$-$Ar_2$). In addition, the treatment of the above temperature-deformation modes leads to the appearance of a gradient of hardening of austenite and ferrite grains throughout the entire volume of the strip. In turn, the gradient of cold work leads to the formation of a coarse-grained structure. Under the conditions of such cold work, the passage of static recrystallization during cooling according to variants 1-3 leads to an increased growth of some grains along the cross section of the sample.

According to the microstructure of 08kp steel, obtained by deformation by rational rolling regimes on the LWM and cooling according to the variant 4, it can be seen that the structure consists of small equiaxed grains (figure 7, *a*). This structure has a thin-sheeted perlite with interplastic distance n = 0.22-0.32 μm and colony dimensions of 24-32 μm. During this deformation, ferrite with dimensions of 21-35 μm and excess cementite of 1 - 2 points are formed. In addition, there are relatively long grains in the structure. These grains are divided into subgrains which indicate the passage of dynamic and static recrystallization during processing by rational deformation regimes and interidentification pauses. It should be noted that the proportion of long grains is much less than equiaxed.

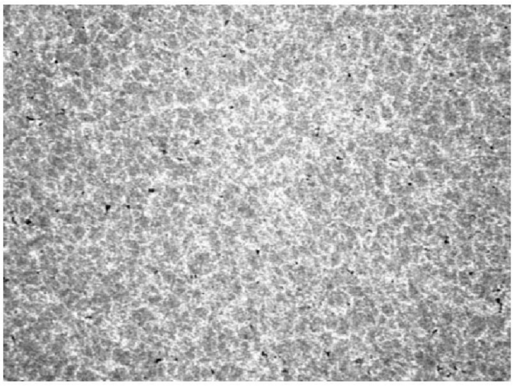
Samples precipitated at 900 °C in rational rolling regimes and cooled in versions 5 and 6 also have a fine ferrite structure with dimensions of 25-37 μm, a thin-plate perlite consisting of alternating plates of ferrite and cementite, with an average interplastic distance n = 0.28 - 0.33 μm (figure 7, *b*, *c*). The size of the colonies of thin-plate perlite reaches 24-36 μm, while the dimensions of excess cementite correspond to 2 to 4 points.



a



b



c

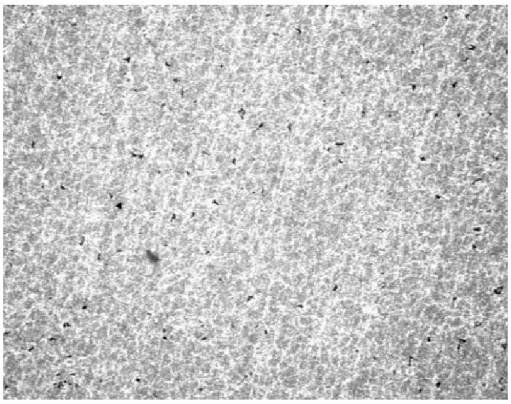
Figure 7 – Microstructure of steel 08kp planted at a temperature of 800 °C according to the variants 4 (*a*), 5 (*b*) and 6 (*c*)

Based on the study of the microstructure of 08kp steel precipitated at a temperature of 1000 °C on rational rolling regimes on the LWM, it is concluded that a uniform fine-grained structure with the thickness of the samples can be obtained by deforming and cooling by the variant 7 (figure 7, *a*). It follows from the analyzed structures that the samples deformed and cooled according to the variant 7 have a ferrite + perlite structure with a grain size of 34-46 μm. Accelerated cooling of the sample in the temperature range of intensive isolation of cementite contributes to the formation of very small precipitates of cementite (points 1-2) (figure 8, *a*).

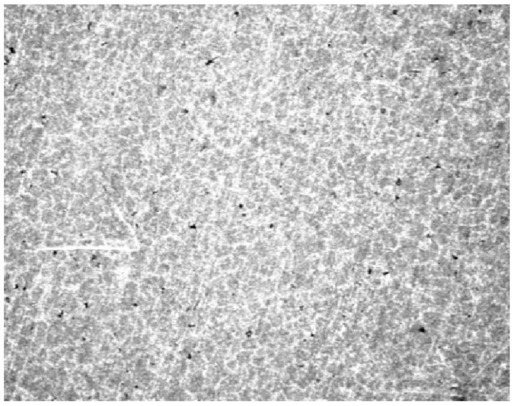
The dimensions of the grains of rolling on the LWM cooled by options 8 and 9 at a temperature of 1000 °C has increased according to rational rolling regimes (figure 8, *b*, *c*) in comparison with the dimensions of the grains deformed at a temperature of 900 °C and cooled according to variants 5 and 6. Analysis of the obtained data showed that the coarsening of the grain sizes of the supercooling in variants 8 and 9 is related to the passage of complete primary recrystallization in the austenite matrix, and also to the increase in the dimensions of the austenite grains at a relatively high temperature. Deformation according to rational rolling regimes on LWM and cooling according to variants 8 and 9 lead to the formation of a medium-grained structure of ferrite + perlite with a grain size of 43 - 57 μm along the cross section. A study of the structure made it possible to establish that spheroidization of perlite, ferrite, and excess cementite is observed after cooling. In this case, the size of the isolated cementite is 2-3 points (figure 8, *b*, *c*).

We believe that the formation of a relatively coarse-grained structure during precipitation based on rational rolling regimes on the LWM and cooling according to the variants 7, 8 and 9 is related to the passage of primary recrystallization in the deformed austenite matrix at a precipitation temperature much higher than the phase transformation temperature, and also by increasing the austenite grain size at high temperature. It is known that the larger the size of the original austenite grain, the larger the inherited ferrite + perlite structure.

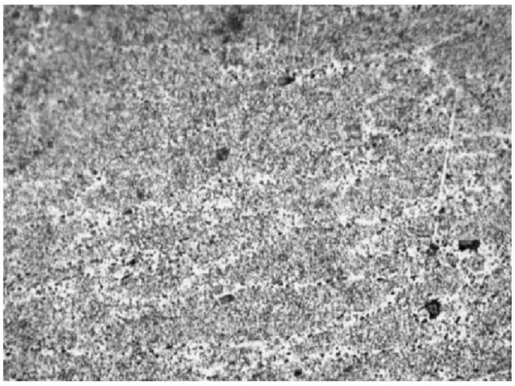
Using the above results, we developed a rational technology for the production of fine bands with a fine-grained structure on the LWM. This technology was tested in the laboratory.



a



b

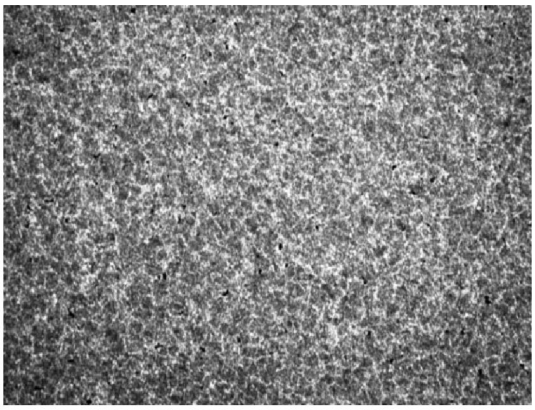


c

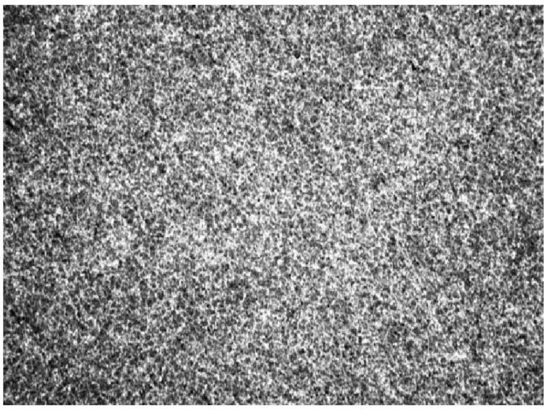
Figure 8 – Microstructure of steel 08kp precipitated at a temperature of 1000 °C according to variants 7 (*a*), 8 (*b*) and 9 (*c*)

While testing the technology, the initial billet of 08kp steel of 8 mm thickness was heated to a temperature of 900 °C, held for 30 minutes and rolled on LWM to a thickness of 1.5 mm. Rolling of the strip on the LWM was carried out with a single reduction in the first stand by 20%, in the second stand by 20%, in the third stand by 20%, in the fourth stand by 15%; in the fifth stand by 10%. The rolled first strip was cooled in air and water, respectively, 2 and 10 seconds, and the second strip was respectively cooled for 8 and 4 seconds.

A study of the structural state of 08kp steel after rolling on the LWM showed the followings (figures 9 and 10):

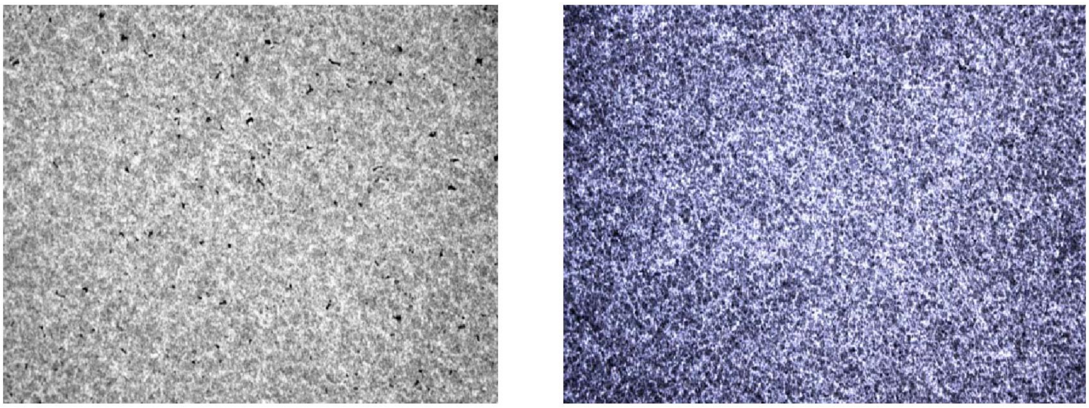


*a*



*b*

Figure 9 – Microstructure of 08kp steel rolled on LWM at a temperature of 900 °C
for a rational mode of deformation and cooling in air and water, respectively for 2 and 10 seconds:
*a* – in the longitudinal section; *b* – in the cross section



*a* *b*

Figure 10 – Microstructure of steel 08 kp rolled on LWM at a temperature of 900 °C for a rational mode of deformation and cooling in air and water, respectively for 8 and 4 seconds: *a* – in the longitudinal section; *b* – in the cross section

- while rolling and cooling in air and water respectively for 2 and 10 seconds, cross sections, perpendicular and parallel to the rolling plane, a ferrite + perlite structure with a size range from 12 to 18 μm is formed;

- rolling and cooling in air and water, respectively for 2 and 10 seconds leads to the formation of a plate-like perlite structure with an interlaminate distance n = 0.18-0.24 μm and a colony size of 18-22 μm. The structure consists of excess cementite 2-3 points;

- during rolling, cooling in air and water, respectively for 8 and 4 seconds according to the height and width, ferrite grain bands own spherical shapes with the dimensions of 21-24 m;

- deformation on LWM and cooling in air and water, respectively for 2 and 10 seconds leads to the formation of a structure of lamellar perlite with an interlaminate distance n = 0.23-0.31 μm and colony sizes of 25-29 μm. However, the value of cementitious precipitates corresponds to scores of 2-3, which is irrational.

A higher strength and yield strength, relative elongation and narrowing values are observed in the 08pc steel sample rolled on LWM, compared to the traditionally produced sheets.

**Conclusion.**

1. It is established that during rolling on the LWM occurs a gradual redistribution of the strain intensity from the center to the middle part of the strip, and then to the contact zone of the rolls with the rolled workpiece;

2. Gradual transfer of the intensity of deformation from the center to the surface leads to a more even distribution of the accumulated deformation;

3. A uniform distribution of the intensity of strain and stress along the height and length of the rolled strip, as well as a uniform fine-grained structure can be obtained by rolling the LWM with a single reduction in the first, second, third stands by 20%, and in the fourth and fifth stands, respectively by 15% and 10 %;

4. It has been established that dynamic and static recrystallization occurs in the temperature range of 800÷1000 °C and deformation rates of 1.5÷5 m/s in the structure of 08kp steel, depending on the temperature-deformation modes of treatment;

5. It has been proved by physical modeling that in order to ensure a fine-grained structure in 08kp steel, it is necessary to perform rolling of strips on LWM with a rolling temperature of 900 °C and a cooling temperature of hot-rolled strips in a discharge roller conveyor in monotonic regime in air, water and air cooling;

6. It has been established that large grains of irregularly stretched shapes of different sizes occur during the high-temperature austenitic or austenitic-ferrite rolling in the microstructure of hot-deformed thin bands.

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## БОЙЛЫҚ-СЫНАЛЫ ОРНАҚТА ЫСТЫҚТАЙ ЖАЙМАЛАНЫП АЛЫНҒАН ЖҰҚА ЖОЛАҚТЫҢ САПАСЫН ЗЕРТТЕУ

**Аннотация.** Мақалада STD 812 пластометрінде физикалық модельдеуді қолданып, бойлық-сыналы орнақта (БСО) жолақты жаймалаған кезде 08кп болатының микроқұрылымына өңдеудің температура-деформациялық режімінің әсері талданғанған, аустениттің өсу және ыдырау кинетикасы қарастырылған, ұсақтүйіршікті құрылымның қалыптасуының жағдайы айтылған. Жұмыста БСО дайындаманы жаймалағанда, оның металында пайда болатын кернеулі-деформациялы күй зерттелген. Шеттік элемент әдісін және

MSC.SuperForge бағдарламасын қолданып, БСО жаймалауды компьютермен моделдеудеп кернеулі-деформацияны күй мен температураның таралуының негізігі заңдылықтары анықталған. 08кп болатын жаймалаудың ұтымды технологиясы жасалап, зертханалық жағдайда тексерілген. БСО орнақта жаймалаудың және салқындату режімдері, 08кп болатынан жасалған дайындама құрылымына қаншалықты әсер ететіндігіне жұмыста ерекше көңіл бөлініп, талдаунған. 08кп болатынан жасалған жолақты БСО орнақта жаймалаған кезде, қаңылтыр металының беріктік пен илемділік қасиетері жоғарлайтындығы жұмыста анықталған.

**Түйін сөздер:** жолақты жаймалау, төменгі көміртекті 08кп болаты,аустенит, феррит, перлит, микроқұрылым, қақталу, тәжірибе, беріктену, беріксіздену, рекристаллизация.

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## ИССЛЕДОВАНИЕ КАЧЕСТВА ГОРЯЧЕКАТАНЫХ ТОНКИХ ПОЛОС ПОЛУЧЕННЫХ ПРОКАТКОЙ В ПРОДОЛЬНО-КЛИНОВОМ СТАНЕ

**Аннотация.** В статье путем использования физического моделирования на пластометре STD 812 выполнен анализ влияния температурно-деформационных режимов обработки на микроструктуру стали 08кп при прокатке на продольно-клиновом стане (ПКС), рассмотрена кинетика роста и распада аустенита, отмечены условия образования мелкозернистой структуры. Методом конечных элементов и программой «MSC.SuperForge» получены количественные данные и установлены основные закономерности распределения напряженно-деформированного состояния, температуры при прокатке заготовок в ПКС. Разработана и в лабораторных условиях опробовано рациональная технология прокатки тонких полос из стали 08кп. Особое внимание уделено анализу влияния режимов прокатки на ПКС и охлаждения на формирование мелкозернистой структуры в стали 08кп. Установлено, что прокатка в ПКС тонких полос из стали 08кп приводит к увеличению прочностных и пластических свойств металла листового проката.

**Ключевые слова:** прокатка полос, низкоуглеродистая сталь 08кп, аустенит, феррит, перлит, микроструктура, наклеп, эксперимент, упрочнение, разупрочнение, рекристаллизация.

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