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DEVELOPMENT OF NEW MILL DESIGN AND OUTGOING ROLLER TABLE FOR HOT ROLLING OF THIN STRIPS

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ABSTRACT

This article presents a new multi-functional mill of a new design. The main technical characteristics of the mill is its ability to reduce the diameter of the working rolls in the direction of rolling and to provide the rotation of working rolls through the bearing stand with the five gear motors of 15 kW. Technical characteristics of projected multi-functional mill allow producing the hot-rolled and cold-rolled thin strips of steel and alloys, copper strips of thickness of less than 1 mm, titanium and aluminum sheets of thickness of 2-0.5 mm, and silver strips of thickness of less than 2 mm; it also provides rolling from the precious metals, etc. The stress-strain state of heavily loaded components of the proposed mill is calculated by using APMW in Machine (HASP) software. It is proved that the magnitude of elastic deformation and displacement of the mill rolls is small while rolling in the new mill. It is also proved by the conducted research that sufficiently high rigidity of rolls of the mill stands and the equivalent stresses arising in the rolls do not exceed the maximum allowed value of the ultimate strength for the material.

The patterns of the change in the microstructure of the steel A1 during the physical simulation of rolling and cooling on new longitudinal wedge mill and outgoing roller table have been investigated in this article with the use of modern high-precision equipment Gleeble 3500. The conditions of the steel A1 during a multi-stage compression at different temperatures and strain rates have been described from the single position. The analysis of influence of the temperature modes of cooling on the microstructure of the steel A1 during the transportation at new outgoing table has been conducted. The kinetics of growth and decomposition of austenite has been considered, and the conditions of ultrafine-grained structure formation have been marked.

Key words: Mill design, Roller table, Hot rolling, Thin strips.

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INTRODUCTION

Improving the efficiency of mechanical engineering development is an important issue of national economies of CIS countries. The quality of the sheet-rolled metal products, as it is known, depends on many aspects[1]. The characteristics of technological units also influence on it significantly. Making the radical improvements in the quality requires large capital investments. At the same time, the quality is one of the component of competitiveness, and such result can be achieved by radical modernization of existing technological equipment. Trends of improving the equipment units of the continuous rolling are determined by the desire to increase the efficiency of the process and effectiveness of use of equipment, to expand the range of products, which are potentially suitable for the processing on particular equipment.

The range of mills of hot rolling has undergone significant changes in the last decades: minimal thickness of the hot-rolled steel strips has been decreased from 1.8-2.0 mm to 0.8-1.2 mm[2]. The strips of such thickness were previously produced only on the cold rolling mills. However, there is a number of mechanical engineering enterprises and construction industries which prefer to employ cheaper hot rolled strips, in case if their mechanical characteristics and surface quality meet the demanded requirements.

The main directions of improving the production of thin hot-rolled sheet are the followings[2,3]: equipping the workshops with a new high-performance equipment; improving the quality of surface of the strips, and increasing the preciseness of their size; improving the mechanical properties of the material of sheet; increasing the productivity of mills and equipment; increasing an usable output, decreasing the production costs.

It is known[2] that the basic technological scheme of industrial production of hot-rolled sheets is the process of individual coils rolling related to the thin tapes and strips on continuous or reversing mills with their following cutting by the length and width at different equipment of longitudinal and transverse cutting. In this case, the thin sheets of steel and alloys mainly are rolled on the wide-strip mills of sheet rolling. The construction of such mills leads to high production areas, specific capital and operating costs, increasing consumption of metal, energy, fuel and lowering productivity.

It should be noted that a complex energy-intensive technology is used in many countries in order to produce the thin sheets of steel. This technology consists of the followings: relatively thick slab casting – hot rolling – forced cooling at outgoing roller table – descaling – cold rolling – levelling – finishing[2,3]. Each stage of technological process of thin sheets rolling is carried out in a separate workshop of the metallurgical enterprise.

Therefore, in many countries scientists believe that the creation of casting-rolling units (CRU) is one of the most important and promising areas of manufacturing the thin sheets of steel and alloys. The CRU include the machines of continuous casting of thin slabs and the units for rolling these slabs[4,5]. A simple and compact technology, a specialized range of products targeted at specific consumer, regional raw materials in the form of the scrap metal, new technologies and equipment, low specific investment and short construction cycle, as well as a high labor productivity converted CRU into one of the most dynamic and effective directions in the metallurgy.

It was possible to connect two stages of the manufacturing process of thin strips in the combined CRU. All of the mentioned above allowed obtaining such economic benefits as[4]: reducing the time of the metal pass in the production cycle; reducing the capital investment; reducing an energy consumption, increasing a capital turnover and reducing the storage costs; ensuring an economical production of small batches; improving the quality of the hot strips.

Analysis of the data given in the work[6] showed that the hot-rolling mills of an imported manufacture are produced by the specific designs. Therefore, the spare parts and accessories are purchased from the same manufacturer at a relatively high price because of the great difficulty or impossibility of their production by the third-party companies.

The easiest way to improve the quality of the rolled metal is to reduce the diameter of the work rolls, which leads to a decrease in rolling force and a favorable effect on the final product[1]. However, often, it is impossible or limited to reduce the diameters of the working rolls because of the structural features of the frame of the rolling mill; it is also related to the fact that while reducing the diameter of the roll, the deflection roller increases and the roller assembly strength decreases. At the small diameters of the working rolls the deflection of roll can be achieved by using the back-up rolls of a large diameter. However, the drive is organized by backup rolls considering the fact that reducing the size of the work rolls to the values that do not allow to use them as a drive.

It should be noted that one of the disadvantages of existing mills with the drives through supporting rolls is an absence of the backwater work and backup rolls along the rolling axis. This leads to the bending of the rolls in a horizontal plane. Such bending negatively affects the quality of the finished product[6]. Another disadvantage of these mills is the presence of buoyancy from the transmitted moment on the working and supporting rollers. It should be noted that there is a circumferential force along the rolling line in such mills. All this may lead to a reduced quality of the hot-rolled strips. It is known[1] that the transmission of torque by friction between the rolls results in the loss of a maximum torque.

Currently, there are several ways of improving the mechanical and operating properties. These ways include an alloying, a heat treatment, a controlled rolling and an accelerated cooling[7]. The most promising direction of the development of the production technology of high plastic steels is a controlled rolling with the subsequent accelerated controlled cooling (ACC). A cooling is carried out from the rolling heat by exhausting the heat by the cooling environment (water) supplied to the hot surface of roll. In this case, the method and the feed rate of water on the metal significantly affect the final properties of the finished steel. In order to produce the competitive products, the most modern sheet mills (SM) are equipped with the installations of a controlled cooling, which are located in the mill line of the rolling stand[8].

It should be noted that the most significant development of the ACC system is seen in Japan[7,9]. The Japanese company of the steel production NKK Corporation has developed and put into the operation system OLAC (on-line Accelerated Cooling) for the production of the shipbuilding rents. In the further future, the majority of mills of Japan, the USA and Europe were equipped with the similar units, which in turn influenced the invention of various new systems and designs. The most common systems can be highlighted at the moment[7,9]:

- ADCO (Adjust cooling) – controlled cooling system;
- ACP (Accelerated cooling process) – a process of accelerated cooling;
- CWC (Curtain water cooling) – a cooling water curtain;
- DAC (Dynamic accelerated cooling) – dynamic accelerated cooling;
- ICS (Intense cooling system) – a system of intensive accelerated cooling;
- OLAC (On-line accelerated cooling) – an accelerated cooling in the mill stream (further development of the system - Super OLAC);
- KLC (Kobe steel’s accelerated cooling) – controlled rolling and accelerated cooling of Kobe Steel;
- MACS (Multipurpose accelerated cooling system) – a system of universal accelerated cooling;
- MACOS (Mannesmann accelerated cooling system) – accelerated cooling system of Mannesmann;
- HDTLFS (High density tube laminar flow cooling) – laminar cooling jets;
- WPC (Water pillow cooling) – cooling by the water pad.

Each of these introduced systems has a unique set of design and complexes of the technological characteristics such as a method of supplying water to the surface, operating pressure and water flow rate, the geometrical dimensions of the cooling zone, the distance from the cage, the presence of an equipment for screening the strip edges, etc.[7] The choice of this or that system of ACC, first of all must be done according to the sort of the produced product and also the required indicators of the operational and mechanical properties. It is also possible to combine multiple systems in a single line mill to increase production efficiency.

In the case of conducting the analysis of ways of producing strips and sheets of hot rolling, it can be concluded that the sheet rolling workshops commonly use the methods of the controlled cooling of hot rolled steel strip moving, which are based on the water supply nozzle to the upper and lower surfaces of the strip[10]. It should be noted that the area of the nozzle of the torch, which is fed through the refrigerant (water) to the surface of the ingot, substantially depends on the pressure or flow of refrigerant. A steam pillow is formed between the cooler and the surface of the strip, while applying the cooler to the hot-rolled strip, which prevents the heat removal from the hot metal and reduces the intensity and uniformity of cooling. This is the cause of instability in the mechanical properties of finished steel strips due to the low controllability of the process of heat removal from the cooling object. In addition, the use of a conventional nozzle cooling leads to a significant contamination of coolant (water) and working area by the steam, dust and scale, resulting in non-stationary operating characteristics of the controlled object and control automation equipment. In this case, there can be several hundred nozzles in the nozzle cooling system, some of which periodically goes down. Consequently, the nozzle cooling system itself becomes the main reason of disruptions of metal cooling uniformity.

These noted shortcomings of the nozzle cooling of the metal does not allow providing a high quality of the rolling, which is needed for the use of the hot-rolled products, for instance, it is not suitable for the production of thin strips made of a carbon steel.

Thus, the growing competition in the steel market is forcing manufacturers to improve the quality and consumer properties of their products, as well as avoiding the strong increase in the prices of their products. Improved quality and consumer properties of the product can be achieved by improving the production equipment and the development of new technologies[2,5]. Development of the accelerated controlled cooling systems is a promising trend in improving the technical and economic indicators of the sheet mills. Nowadays, the main problems of ACC systems are the followings[7]:

- Providing the cooling uniformity over the sheet thickness by selecting an optimum relationship between the volume and velocity of water flow from the top and bottom of the sheet;

- Providing opportunities of a differentiated cooling of the different parts of the sheet (the head and the end portions, edges) by using the screens, nozzles and collectors with an individually controlled volume and the water feed rate;
- Extending the sort of producing product by increasing the range of cooling rates;
- Increasing the temperature control accuracy during cooling through the use of advanced automated systems;
- Reducing the energy and material cost of equipment for cutting the cost of production;
- Providing flatness of the strips during an intensive cooling;
- Developing a fundamentally new design of outgoing roller table which provides the decrease in the wear rollers of it.

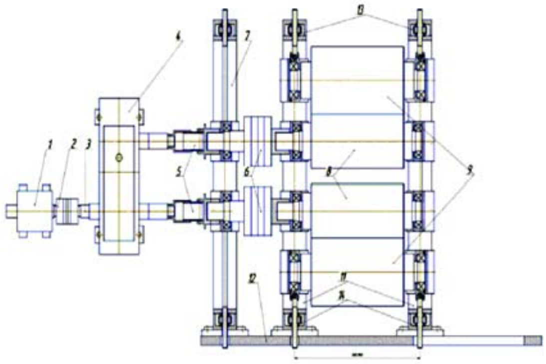
An analysis of numerous literatures[11] suggests that the existing approaches in improving the work of the mill and outgoing roller table do not allow a sharp increase in their work efficiency. In our point of view, the improvements in the quality of hot-rolled strips can only be achieved by using the mill and roller table of a fundamentally new design.

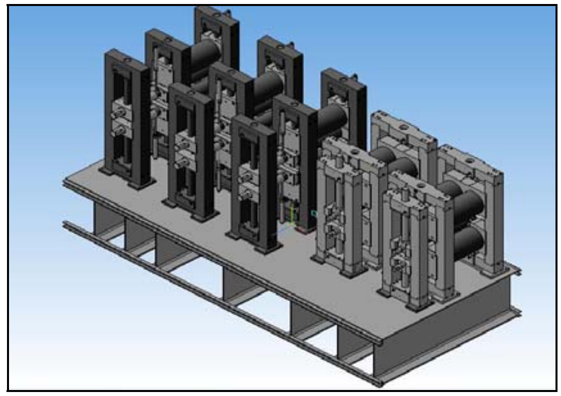
It should be noted that the diverter roller of the outgoing roller table, being one of the mass elements, is subjected to the intensive wear and frequent breakage that results in significant failures of the roller conveyor[11]. About 280-330 rollers are broken down every year; only because of the barrel wear of the collecting roller of the outgoing roller table NSHPS-1700 "ArcelorMittal Temirtau" JSC, which includes 80% of an annual consumption of rollers.

The aim of the work is to provide calculation and construction of the new multi-functional mill design and outgoing roller table for the rolling of thin sheets of high quality and to study the influence of austenitizing mode, hot deformation and subsequent cooling at the new mill and outgoing roller table on the structure and properties of sheets made of a carbon steel.

Equipment and methods of study

A multi-functional longitudinal wedge mill (LWM) of a new design for the hot rolling of thin strips made of steel and alloys has been proposed, with the purpose of avoiding the above mentioned problems and obtaining the high-quality sheets, as well as reducing the energy power parameters (Fig. 1)[12].





1 – Gear motor; 2 – Coupling; 3 – Shaft; 4 – Gear stand; 5 and 6 – The spindles; 7 – Bearing cage; 8 – The work rolls; 9 (The first three stands) and 10 (The last two stands are not shown) – the supporting rolls; 11 – Bed; 12 – Supporting plates; 13 and 14 – The pressing mechanisms

Fig. 1: Multi-functional longitudinal wedge mill for rolling strips

Multifunctional LWM for rolling the sheets of steel and alloy contains the motors, gearboxes, gear cages, universal spindles, couplings, and cages with working and supporting rolls (Fig. 1). In this case, there are two supporting rollers installed in the first three stands and the four support rolls installed in the last two stands. The rotation of the decreasing work rolls in the rolling direction is realized through the bearing cage of five gear motors with an angular velocity of $\omega = \upsilon \cdot R$ (where υ is the rolling speed in each mill stand; R is the radius of the work rolls in each mill stand). In this case, the distance between the stands are increased by the amount of timing, but distance adjustment between the work rolls is produced by the uniform worm push mechanisms, located above and below the trails mill and bearing cages.

The rolling of strips made of steel and alloys on the multifunction LWM is realized as in the following way. A winded or continuously light-gage poured slab (the thickness of the thin slab should correspond to the maximum angle of capture for the rolls installed in the first stand) enters into the decoilers or the inlet section of rolling. Beginning of the thin slabs is supplied into the rolling of the first stand of the proposed mill through pulling and straightening rollers, the welding machine, the loop strip with the drive bogies, the tension rollers, as well as through the device of the thickness measurement. During rolling the thin strips through the successive rolling mill in the direction in which the distance between the working rolls from one stand to the other lead to an increased value in the cage, there is a reduction to reach the required height and thickness of the strip.

It should be noted that the work rolls in each stand have a constant diameter, and the diameter of rolls is reduced in the rolling direction in the sequentially arranged stands. A cutting of thin strips or coiling the thin strip into its rolls happens at the exit.

Producing the diameter of the working rolls decreasing in the rolling direction allows reducing the pressure of metal significantly on the rolls in stands located at the end of the rolling mill and the mill to increase the rigidity of the mill. Reducing the force acting on the rollers, as well as increasing the rigidity of the mill stands on the one hand allows reducing the size of the stands and power of the drive, and to increase the accuracy of the rolled strip on the other hand.

Increasing the distance between the work rolls from one stand to the other stand by an amount in the given stand leads to decrease of an interstand tension to a predetermined value. This is achieved through strict implementation of constant-second volumes while rolling in different stands. Reducing an interstand tension to a predetermined value allows avoiding the tearing strips during the rolling process on the one hand, and reducing energy and power parameters of the rolling on the other hand.

Implementation of the rotation of rolls from five gear motors of AC through five gear stands allows rolling the strips made of steels and alloys at the minimum value of industrial noise.

Implementation of the rotation of the rolls of the work stands through five bearing cages allows positioning the spindles horizontally, which allows transferring the torque moments to the work rolls of the mill stands without the vibration load. All this contributes to obtaining the strips with precise geometric dimensions.

Production of the first three mill stands with two supporting rolls and the last two mill stands with four supporting rolls ensures a minimal elastic deformation of the work rolls of the last mill stands and thus allows obtaining the strips with a minimum gage.

Regulating the distance between the rolls of pinch uniform worm mechanisms arranged above and below the frame of the mill and bearing stands, allows rolling the sheets strictly symmetrically with respect to the rolling axis. This allows obtaining the strips without breaking and bending with a minimum different thickness.

The calculations of strength and rigidity were provided for checking the accuracy of the project calculation of the size of the work and backup rolls in each of five stands.

The strength and stiffness of work (work roll diameter: D_{P1} = 180 mm; D_{P2} = 150 mm; D_{P3} = 125 mm; D_{P4} = 100 mm; D_{P5} = 75 mm) and supporting (the diameter of all supporting rolls – D_{SUP}= 220 mm) rolls of the multi-functional mill was investigated in hot (1100°C) rolling of strips made of the A1 steel with the size of 0.7 × 300 mm. The steel 60XSMF was used as a roll material. The tackle with the thickness of h_0 = 3.5 mm was used as the material of the original workpiece. It should be noted that the A1 steel has the following chemical composition%: C – 0.15; Mn – 0.95; Si – 0.29; P – 0.011; S – 0.012; V – 0.11; Ti – 0.012; Cu – 0.20; As – 0.020). In the CIS countries, St3Gsp steel is used as the analogue of the experimental steel A1 (C – 0.14...0.2; Mn – 0.8...1.1; Si – 0.15...0.3; P – to 0.04; S – 0.05; Ni – to 0.3; Cr – to 0.3; N – to 0.008; Cu – to 0.3; As – to 0.08)

The following input data (written according to the correspondence) was for the hot rolling of the strip in the first, second, third, fourth and fifth mill stand: the height of the strip after rolling – h_1 = 2.576 mm; h_2 = 1.708 mm; h_3 = 1.148 mm; h_4 = 0.84 mm; h_5 = 0.7 mm; absolute reduction – Δh_1 = 0.924; Δh_2 = 0.868; Δh_3 = 0.56; Δh_4 = 0.308; Δh_5 = 0.24; single compression – ε_1 = 26.4%; ε_2 = 33.7%; ε_3 = 32.8%; ε_4 = 26.8%; ε_5 = 16.7%; strip – $\upsilon_1 = h_5 \cdot \upsilon_5 / h_1$ = 0.7 × 2.085/2.576 = 0.5 m/s; υ_2 = 0.68 m/s; υ_3 = 1.03 m/s; υ_4 = 1.526 m/s; υ_5 = 2.085 m/s;

Using a known technique[1], it could be determined the energy-power parameters of rolling strips on the multifunctional LWM.

It was also defined the distribution of forces between the working and supporting rolls according to the formula set forth in the work[13], at the same time taking into consideration that the minimum diameter of the rollers after rounding is as follows:

$$P_P = P \frac{1}{1+\left(\dfrac{D_{SUP}}{D_P}\right)^4}, \; kN$$

$$P_{\text{sup}} = P - P_P, \; kN,$$

where *P* is the maximum rolling force, *kN*.

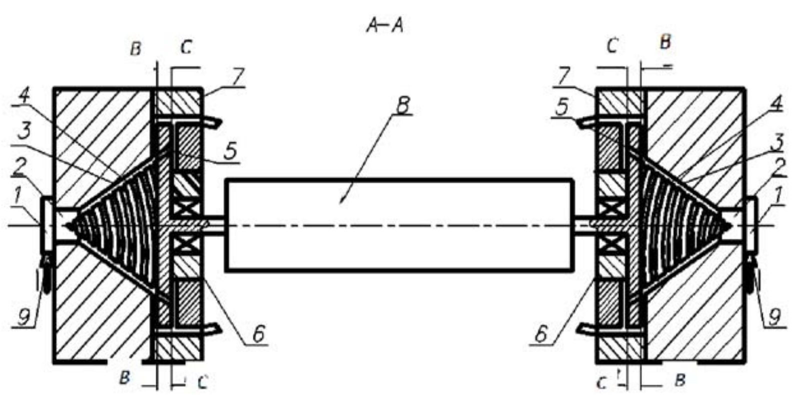
The procedure of calculating the rolling force and torque, as well as the indicators of elastic deformation of the roller was realized by implementing the APMW in Machine (HASP) system. APMW in Machine (HASP) computer modeling system allows exploring the kinematics, dynamics of mechanisms with an ability to calculate the force and moment of rolling, as well as the indicators of an elastic deformation of the rolling unit as separate stands, and the mill as a whole.

The procedure of calculating the roll for the strength is as follows: a model of the roller was created in APMW in Machine program, then the support was demanded and the load was given, which acts on the roller. The applied load was determined from the above calculations. After that, the parameters of the roll material were set and the calculation was performed.

While providing calculations by APMW in Machine program, the following data were used:

- The first stand: P_{work} = 16.6486 kN; P_{SUP} = 37.115 kN; M_{tor} = 0.42 kN·m; T = 1.098 kN (difference in front and back tensions applied to the two working rolls); q = 371.4 N/mm (pressure on the rollers);
- The second stand: P_{work} = 8.14 kN; P_{sup} = 37.66 kN; M_{tor} = 0.3 kN·m; T = 0.611 kN; q = 376.6 N/mm;
- The third stand: P_{work} = 2.8738 kN; P_{sup} = 35.926 kN; M_{tor} = 0.182 kN·m; T = 0.39 kN; q = 359.2 N/mm.
- The fourth stand: P_{work} = 2.2476 kN; P_{sup} = 28.6548 kN; M_{tor} = 0.152 kN·m; T = 0.38 kN; q = 305.4 N/mm;
- The fifth stand: P_{work} = 1.7848 kN; P_{sup} = 17.294 kN; M_{tor} = 0.106 kN·m; T = 0.246 kN; q = 273.8 N/mm.

The paper proposes a new design of the outgoing roller table with a hollow roller (Fig. 2)[14].



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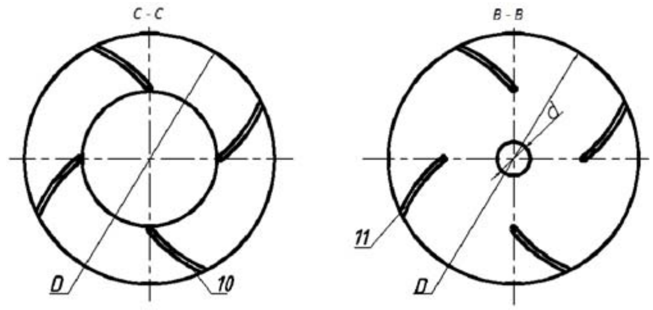


1 – Swirler; 2 – Vortex tube; 3 –Diffuser; 4 – Turbine; 5 – Reduction; 6 – Bearing support; 7 – Cooling nozzle; 8 – Hollow rollers; 9 – Injector

Fig. 2: Hollow roller with an individual drive

Transportation and cooling of the hot-rolled strips is performed by the following ways:

Water is supplied from the pump unit into the roller (Fig. 2) under a high pressure, which passes through the injector 9, accelerated and supplied to the swirler 1, where it acquires a swirling motion and enters into the vortex tube 2 through the cylindrical spiral. Swirling water flow, entering the narrowing gap between the walls of the vortex tube 2 and conical turbine 4, is accelerated and enters into the spiral groove of the turbine 4. A flow is further swirled here, and passing through a diffuser 3, it accelerates a turbine 4. By passing through the helical grooves of the conical part of the turbine 4, the water under a high pressure enters into the peripheral portion of the turbine and enters into the helical groove 10, or passing through the opening 5, it arrives in the spiral groove 11. All this can further accelerate the turbine 4. The water flowing out of the nozzle 7 under a pressure at an angle of 40-45°, cools the hot-rolled strip with its jet sprays.

The use of water under high pressure, injectors, swirlers, vortex tubes, diffusers, turbines with the helical grooves on the surface of holes creates forces and torques on the rolls surface in order to provide a rotational movement of the rollers, and thereby it can transport the hot sheets without using the individual motor drives. The direction of the cooling nozzles at an angle of 40-45° to the cooled hot rolled strip allows cooling the strip uniformly and the direction of the cooling nozzles at an angle of less than 40° or more than 45° does not allow cooling the strips uniformly across an entire section.

New outlet roller table allows producing the cooling of the hot metal without using a special apparatus, which is used for the required cooling. All this reduces the material and energy costs spent for transporting and cooling the strips.

The samples with the size of Ø 10.0 × 15.0 mm were tested by the compressions on the testing complex Gleeble-3800 in order to determine the level of an influence of the deformation and subsequent water cooling on the structure of A1 steel. The main characteristics of the Gleeble are presented on the sites www.gleeble.com and http://tmslab.spbstu.ru.

The plastic deformation of samples made of A1 steel was performed on the module of “tension-compression”. Heating of the samples was carried out with a speed of 100°C/*s* to 1100°C and held at these temperatures during 1 hr. Further, each heated sample was cooled to a temperature of 800, 900 and 1000°C, deformed by the cyclic compression at the speeds of rolling on the LWM (Table 1). In the distances of the cyclic deformation, after the shutting down the electric installation, the sample remained jammed by the strikers and active loading was changed by the relaxation stage. Subsequently the samples were cooled by air, water and by the natural way to the room temperature.

Table 1: Plan of the physical modeling experiment

No.	ε_1, %	t_1, s	ε_2, %	t_2, s	ε_3, %	t_3, s	ε_4, %	t_4, s	ε_5, %	τ_a, s	τ_w, s
Testing temperature – 800^{0}C											
1	25	4	20	3	17	2,4	15	1,8	12	2	9
2	25	4	20	3	17	2,4	15	1,8	12	5	6
3	25	4	20	3	17	2,4	15	1,8	12	8	3
Testing temperature – 900^{0}C											
4	25	4	20	3	17	2,4	15	1,8	12	2	9
5	25	4	20	3	17	2,4	15	1,8	12	5	6
6	25	4	20	3	17	2,4	15	1,8	12	8	3
Testing temperature – 1000^{0}C											
7	25	4	20	3	17	2,4	15	1,8	12	2	9
8	25	4	20	3	17	2,4	15	1,8	12	5	6
9	25	4	20	3	17	2,4	15	1,8	12	8	3

Note: ε_1 - Single reduction in the first stand; t_1 - Interdeformation pause after the first stand;
ε_2 - Single compression in the second stand; t_2 - Interdeformation pause after the second stand;
ε_3 - Single compression in the third stand; t_3 - Interdeformation pause after the third stand;
ε_4 - Single reduction in the fourth stand; t_4 - Interdeformation pause after the fourth stand;
ε_5 - Single reduction in the fifth stand; τ_a - Time of air cooling; τ_w - Time of water cooling.

Microsections for the metallographic study were prepared according to the traditional methods in the grinding and polishing circles. A solution of a nitric acid in ethanol was used for etching the samples.

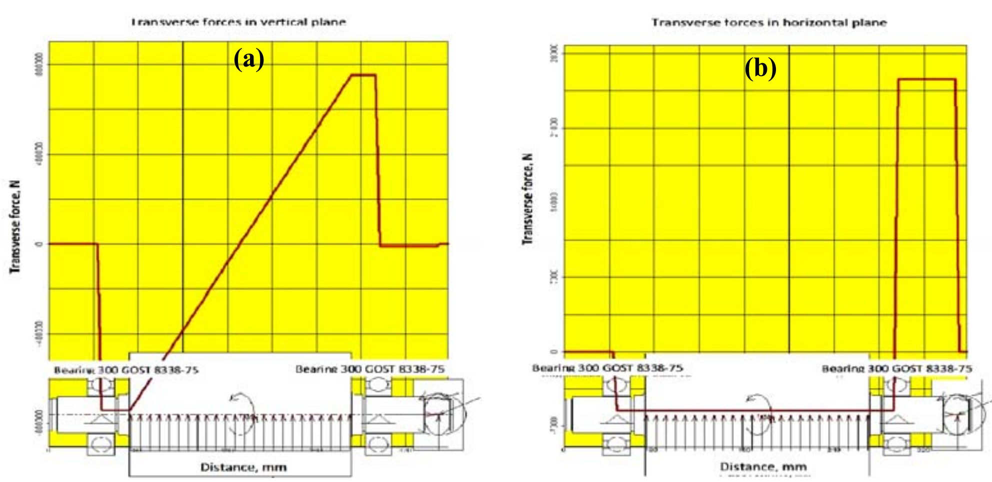
Metallographic analysis was conducted using the universal microscope NEOPHOT 32 (KarlZeiss, Jena) (Germany). The microscope Neophot 32 is intended for the metallographic microscopy and creating photographs. Monitoring can be done by light and dark field methods, in the polarized light, with the change of increasing multiplicity. Magnification of the microscope from 10 to 2000. The microscope is equipped with a digital camera Olimpus with an output of the resulting image and saving the images to computer.

RESULTS AND DISCUSSION

Figs. 3-7 present the results of the calculation of force, rolling torque of strips of A1 steel with the size of 0.7 × 300 mm, equivalent stress, as well as the indicators of the elastic deformation of the roller assembly of the last stand of the new mill.

Based on the results obtained by computer simulation it is revealed that:

- In all stands the largest maximum transverse forces arise in the horizontal plane of drive neck of the roll (Fig. 3), and the axial forces also arise in the roll neck on the side of drive stands. In this case, the highest vertical forces arise in cross section of the roll neck;



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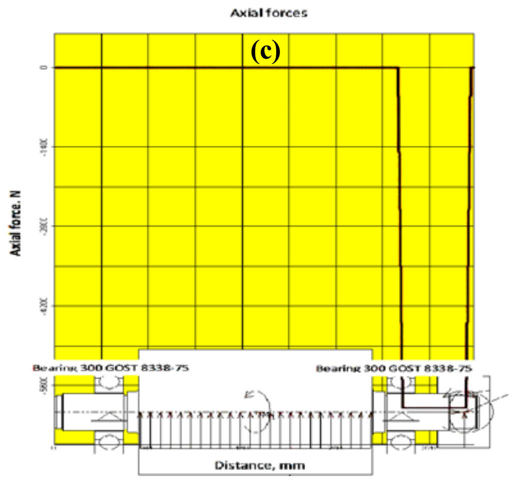
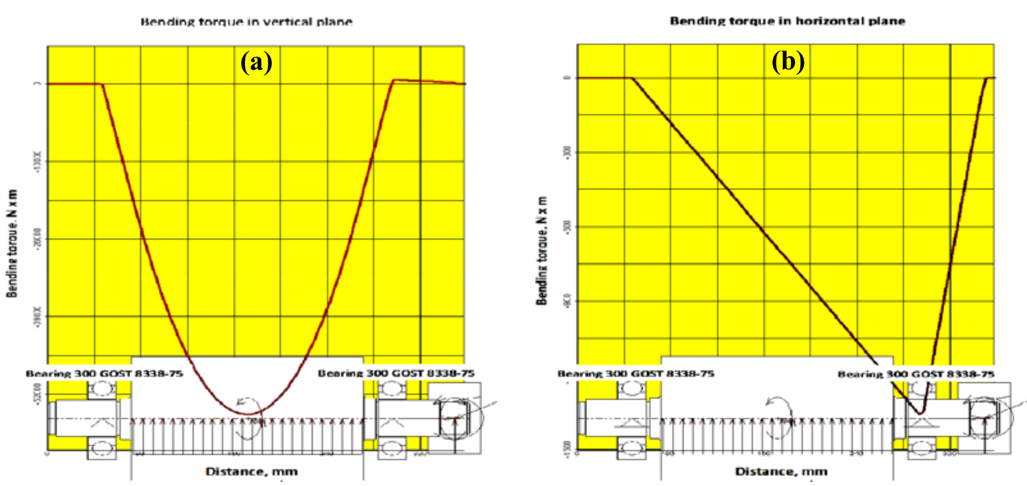


***c*)**

a - Transverse forces in vertical plane; b - Transverse forces in horizontal plane;
c - Axial forces

Fig. 3: The distribution of rolling forces in the last stand of the longitudinal wedge mill

- In five-stand mill the largest bending moments in the vertical plane occur in the middle of the roll body, and the bending torques in the horizontal plane focus on the drive neck of the roll. In this case, the torque, which is the largest in magnitude, equally distributes from the center to the roll neck on the side of drive stands (Fig. 4). It should be noted that the bending torque changes slightly during the transition from one stand to another;



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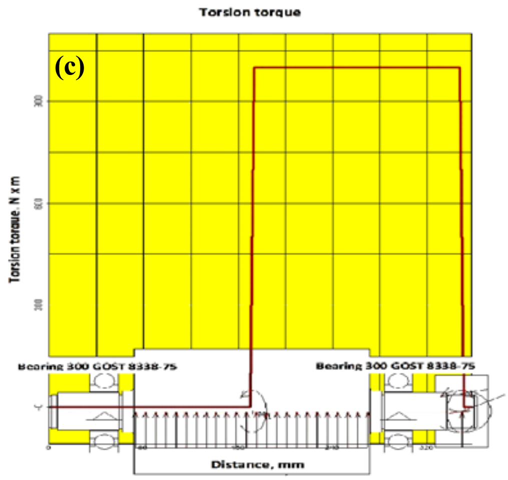
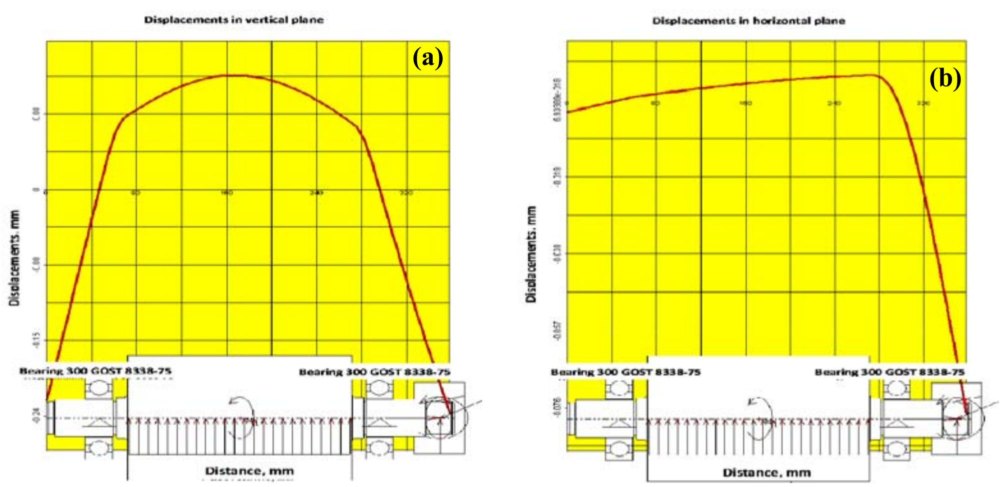


a - Bending torque in vertical plane; b - Bending torque in horizontal plane; c – Torsion torque

Fig. 4: The distribution of bending torque and torsion of rolling in the last stand of longitudinal wedge mill

- In all stands, the maximum amount of displacement in the vertical plane concentrates on the roll necks and in the middle of the roll bodies, and the displacement in horizontal plane and axial displacement are localized on drive neck of the roll (Fig. 5). It should be noted that the displacement value is increased from the stand to stand insignificantly; this indicates about a sufficient rigidity of the system;



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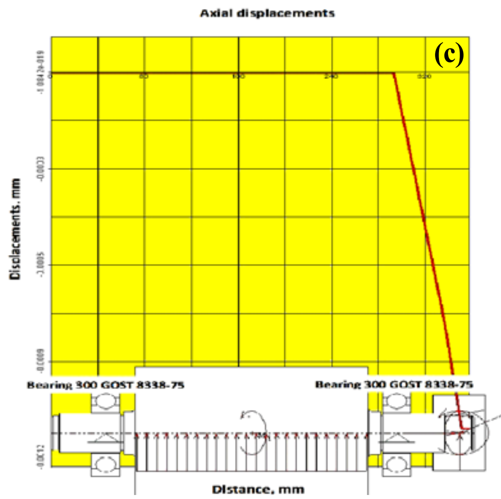
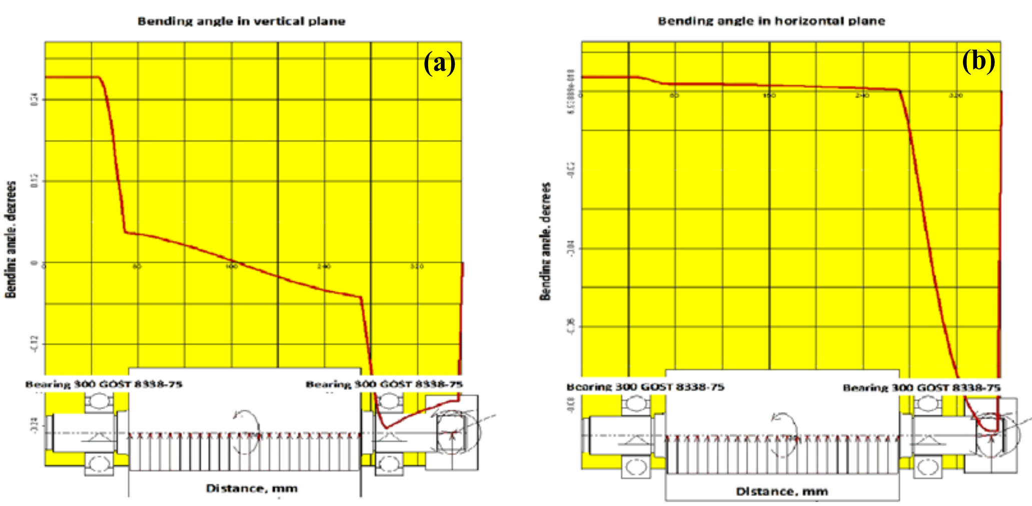


a - Displacement in vertical plane; b - Displacement in horizontal plane;
c - Axial displacement

Fig. 5: The distribution of the displacement in the last stand of longitudinal wedge mill

In the multi-functional mill, the largest bending angle in vertical plane are localized in the roll neck. In this case the bending angle in the horizontal plane and the angle of torsion focus on the drive neck of the roll (Fig. 6). It should be noted that the bending angle is increased insignificantly during the transition from one stand to another, which indicates about a sufficient rigidity of the system;



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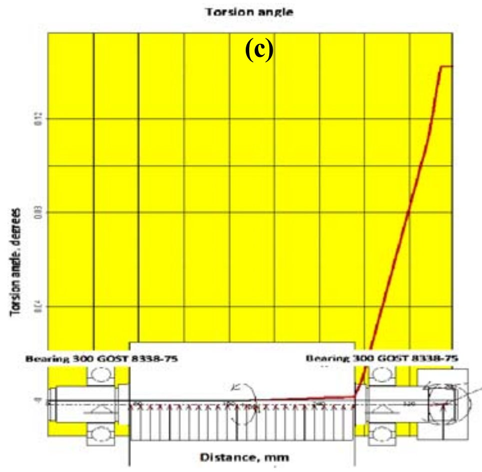
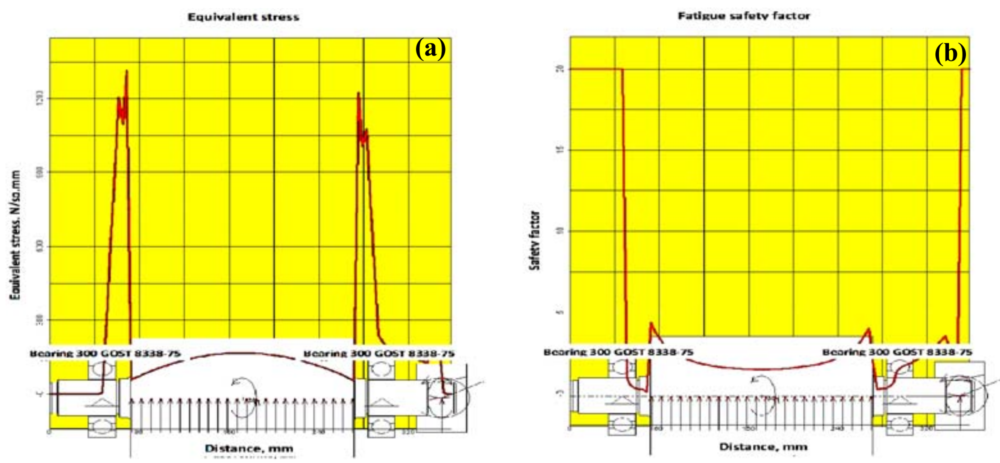


a - Bending angle in vertical plane; b - Bending angle in horizontal plane;
c - Torsion angle

Fig. 6: The distribution of bending and torsion angles in the last stand of longitudinal wedge mill

- During the rolling in the rolls of the proposed mill, the maximum values of equivalent stresses encountered in the mill do not exceed the maximum acceptable value of the strength limit of the selected material of rollers (60 HSMF steel). So the equivalent stresses in roller bodies of the last stand of the mill is equal to 150 MPa, and for the roll neck, it equals to 1300 MPa (Fig. 7, *a*). The obtained maximum value of equivalent stress 1300 MPa does not exceed the maximum acceptable value of the strength tensile of 60 HSMF steel (1470 MPa). It should be noted that the value of equivalent stresses is reduced insignificantly during the transition from one stand to another. This is related to the fact that the size of a supporting rollers in the stands remains unchanged, and the rolling forces are decreased during the transition from one stand to another;
- Distribution of fatigue safety factor for designing the rolls of mill stand satisfies the fatigue strength as a whole. Thus, the fatigue safety factor in roll body of last stand of the mill is equal to 2.3. Such value of the strength factor satisfies the fatigue strength while taking the safety factor of fatigue strength as 1.5 (Fig. 7, b).

Thus, it is defined in the work that the magnitude of elastic deformation of elements of the rolls is low, which indicates a sufficiently high rigidity of the roll assembly of stands of the new mill. This guarantees obtaining a transverse polythickness and flatness in the rolled strips within the required tolerances. It is proved that the equivalent stresses, occurred in the stand rolls of the multi-functional longitudinal wedge mill, do not exceed the maximum acceptable value of the tensile strength of the selected material of the rolls, and the safety factor satisfies the fatigue strength.



a - Equivalent stress; b - Fatigue safety factor

Fig. 7: The distribution of equivalent stress and fatigue safety factor in the last stand of longitudinal wedge mill

Figs. 8-10 present the microstructure of samples of A1 steel obtained during the temperature-deformational modes of the rolling of thin sheets on the multifunction longitudinal wedge mill.

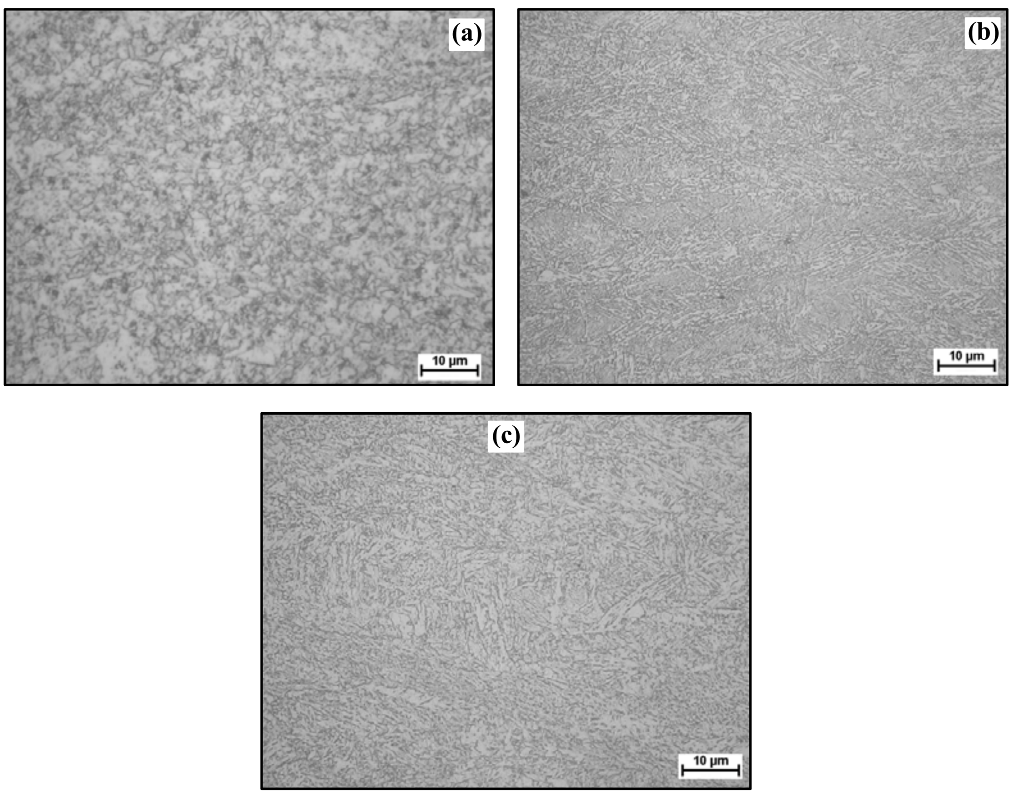
The study of the initial structure of A1 steel showed that there are relatively large grains with average size of 213 microns in the structure of the sample. The grains are equally distributed, and they are elongated along the axis of symmetry of the sample.

Studies of the sample structure, treated according to the above mentioned modes indicated that the most homogeneous and fine-grain structure of pearlite is formed at 900°C of precipitation, during the mode of deformation and cooling by the variant 4 (deformation ends at a single-phase area) (Fig. 8, *a*). The formation of homogeneous and fine pearlite grains is related to the deformation of steel in a single-phase austenite area and with the decrease in the sample temperature to 600-650°C during early mode of the strip cooling. Such mode of deformation and cooling promotes intensive separation of cementite.

Analysis of A1 steel microstructure deformed at the temperature of 900°C led to the conclusion that the samples rolled and cooled by the variant 4 have the structure of ferrite + perlite with the size of ferrite of 12-18 microns. Rapid cooling of the sample in a temperature range of intensive selection of the cementite promotes the formation of very fine precipitates of cementite (1-2 points) (Figs. 8, *a*).

Deformation at 900°C and cooling the samples according to variants 5 and 6, lead to the formation of pearlite lamellar structure with interlamellar distance n = 0.22-0.33 microns and with the size of the colony 14-16 microns. The structure consists of the average ferrite, with the size of 21-33 microns, and the excess cementite 2-3 points (Figs. 8, *b*, *c*).

Formation of such a relatively medium-grained structure during the sediment and cooling the samples according to variants 5 and 6 can be explained by the passage of the primary recrystallization in the austenite matrix and by the inheritance of the medium-grained structure of ferrite + perlite metal during slow cooling. However, the amount of the cementite precipitates corresponds to 2-3 points, which can be considered as irrational.

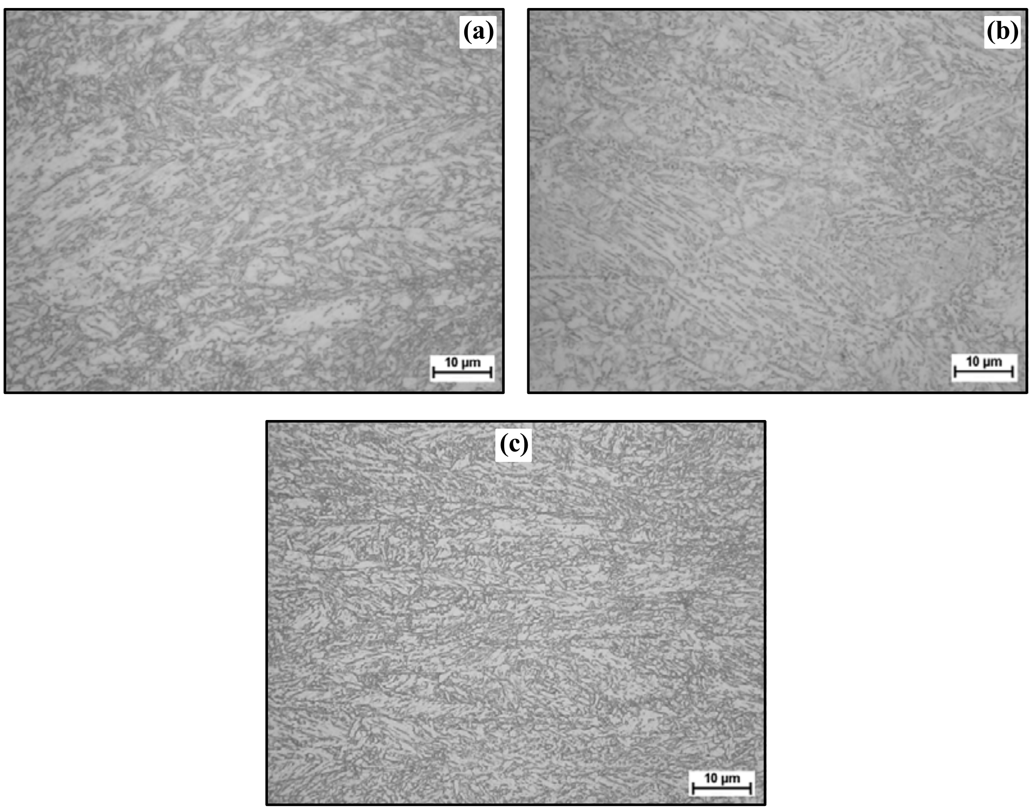


***a* – Variant 4; *b* – Variant 5; *c* – Variant 6**

Fig. 8: The microstructure of A1 steel upset at the temperature of 900°C

The increase of the sediment temperature up to 1000°C results in an overall enlargement of the grain (Fig. 9). Thus, samples, which are upset and cooled according to the variants 7-9, have a structure with a large ferrite size of 31-38 microns, thick-lamellar pearlite, composed of alternating plates of ferrite and cementite with an average interlamellar distance n = 0.33-0.48 microns. The size of the colonies of roughly lamellar pearlite is 24-31 microns, while the size of the excess cementite is equal to the 3-4 points.

The formation of such large-grain structure during the sediment and cooling according to the variants 7-9 can be explained by the creation of conditions for the passage of a complete primary recrystallization of the deformed austenite matrix at a high temperature sludge and increase in the size of austenite grains at a high temperature. It is known that the larger the size of the original austenite grain, the larger the inherited structure of ferrite + perlite.

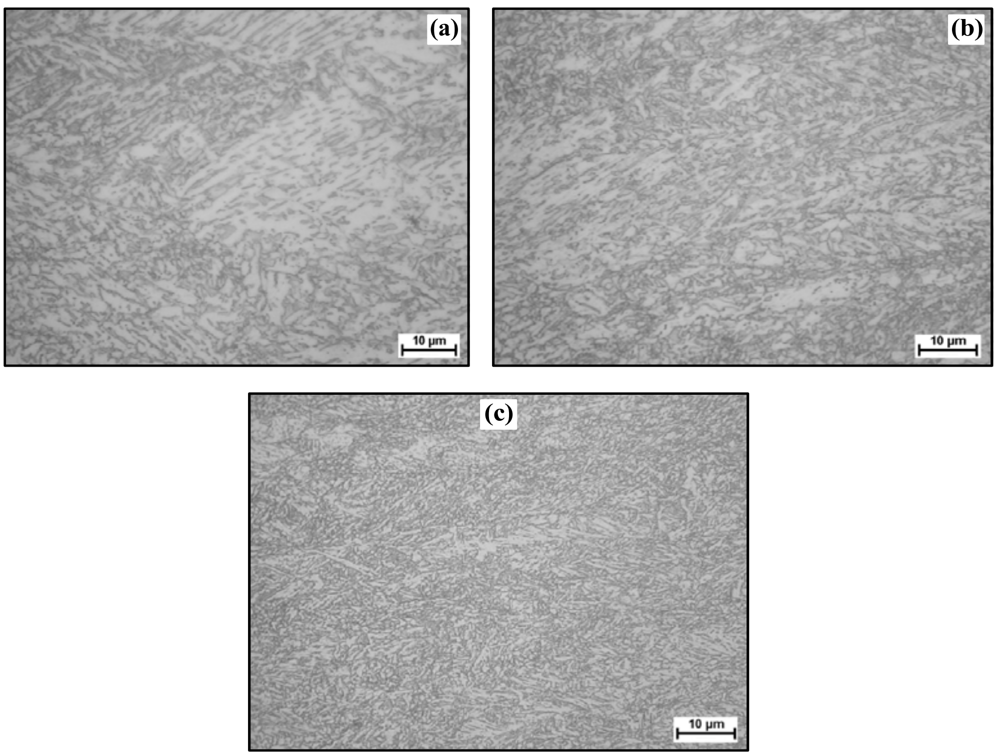


a – Variant 7; *b* – Variant 8; *c* – Variant 9

Fig. 9: The microstructure of A1 steel at 1000°C

The sizes of grains deformed according to variants 2 and 3 at temperature of 800°C, have increased (Fig. 10) in comparison with the grain size deformed at 900°C. Mostly, it is connected with the fact that the decrease in the sediment temperature at the last stage of fractional deformation temperature up to 800°C, and subsequent slow cooling by water leads to formation of coarse-lamellar pearlite with a interlaminar distance of n = 0.52-0.68 microns and the size of the colony of 37-47 microns, as well as the size of streaky ferrite 27-34 microns and excess cementite with 2-3 points (Figs. 10, *b*, *c*).

There have been significant changes in the microstructure of the samples (Fig. 10, *a*) deformed at temperature of 800°C and cooled by the variant 1 (Table 1). Hence the sediment according to the variant 1 and subsequent rapid cooling by water leads to the formation of a lamellar sorbite with interlamellar distance with n = 0.16-0.28 microns and with different sizes of colony of 21-43 microns. Furthermore, the size of cementite is decreased (1-2 points) and irregularly shaped ferrite is formed with poorly defined boundaries, as well as with different sizes (27-35 microns).



a – Variant 1; *b* – Variant 2; *c* – Variant 3

Fig. 10: The microstructure of A1 steel upset at 800°C

The presence of such different grain structure during sediment and cooling by the variants 1-3 can be explained by a gradient of hardening of austenitic and ferritic grains throughout the transverse section of the strip at the lower temperature of deformation. During slow cooling the recrystallization in the conditions of such gradation causes enlarged growth of grain across the sample.

Thus, the analysis of microstructure of A1 steel can lead to the conclusion that the homogeneous fine-grain structure of samples according to their thickness can be obtained while deforming and cooling by water according to variant 4 (Fig. 8, *a*).

It is established by the results of the studies of structure that internal structure of A1 steel is formed by the same patterns during the latest modes of cooling.

CONCLUSION

(i) New design of outgoing roller table and multi-functional LWM has been proposed, which provides the reduction of energy-power parameters of rolling and improves the quality of thin strips. Semi-industrial mill a new design was constructed;

(ii) It has been established that the magnitude of elastic deformation of elements of the rolls is low, which indicates a sufficiently high rigidity of the roll stands of the new mill. This guarantees obtaining a transverse polythickness and flatness of rolled strips within the required tolerances.

(iii) It is proved that equivalent stresses of the roll stand of the multi-functional LWM do not exceed the maximum acceptable value of the tensile strength of the selected material rolls.

(iv) It has been determined that the rolling of strips should be produced at a temperature of 900°C of end-rolling, and the temperature of cooling 600-650°C in order to ensure the rational structure of strips made of A1 steel. In this case hot-rolled strips at outgoing roller table of new design should be cooled with water according to the earlier cooling mode.

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