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ГЕОЛОГИЯ ЖӘНЕ ТЕХНИКАЛЫҚ ҒЫЛЫМДАР СЕРИЯСЫ

♦

СЕРИЯ ГЕОЛОГИИ И ТЕХНИЧЕСКИХ НАУК

♦

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INFLUENCE OF TECHNOLOGICAL PARAMETERS OF ROLLING IN SCREW-SHAPED ROLLS AND LONGITUDINAL WEDGE MILL ON FORMATION OF NANO-STRUCTURE IN THIN SHEETS FROM ALUMINUM AD31ALLOY

Abstract. New technology for the production of sheet metal with a nanostructure is presented in the article. Screw-shaped roll was used to develop severe plastic deformation and therefore to obtain nanostructure. The stress-strain state (SSS) of the workpiece during rolling in screw-rolled rolls and longitudinal-wedge mill (LWM) was investigated. Finite element method and the MSC.SuperForge software were exploited to obtain quantitative data and establishthe main distribution regularities of SSS and temperature during modelling of rolling process in the screw-shaped roll and LWM with different number of passes and single reduction. A rational technology of rolling of aluminum AD31 alloy has been developed andtested under the laboratory conditions. Analysis of the influence of the rolling modes in screw-shaped rolls and LWM on the formation of nanostructures in an aluminum AD31 alloy was in particular interest.

Keywords: aluminum alloys, nanostructure, rolling, stress-strain state, numerical simulation, intensity of stresses and deformations, single reduction.

Introduction. The progress in the development of aviation, machinery construction and other industries is largely ensured by the development of new materials and the technology of manufacturing various products made from them, including rolled sheet products [1]. Nowadays rate of specific weight of aircraft equipment is achieved due to use of aluminum and titanium alloys of high strength, low density and high corrosion resistance.

It should be noted that one of the main factors influencing into the level and anisotropy of the properties of sheet material from aluminum alloys, obtained by the existing technology, is the nonuniformity of deformation in different parts of the workpiece [2]. Therefore, to create scientifically grounded modes of deformation of aluminum alloys, it is necessary to develop new methods or tools to reduce the nonuniformitydistribution of deformation.

To obtain high-quality strips with a nanostructure, without significant changes in their dimensions, severe plastic deformation methods (SPD) can be used, such as: torsion under high quasi-hydrostatic pressure, equal-channel angular pressing, overall isothermal forging and radial shear rolling, etc. [3-9]. SPD methods are mainly realizedby macro-sheardeformations, with a total degree of more than 2-3. Macro-shear deformations cause changes in the structure of the metal due to transgrained sliding, which does not depend on the crystalline orientation of the grains. The result of these changes is an increase of the level and uniformity of metal mechanical properties, as well as a decrease of their anisotropy.

In the above given works and other researches of the last decade [10-13], it has been shown that nanostructured by SPD method materials have very high physical and mechanical properties. In this case, metals and alloys with submicro- and nanocrystalline structure exhibit unusually high and useful strengths and plasticity.

Intensive macro-shears in the process of sheet rolling can be provided by different technological and constructive methods [14]: the use of workpieces and rolls with a wavy or corrugated surface, asymmetric rolling, uneven cooling of rolling in its thickness and width, by using of crossed rolls, and the rolls with a ledge on surface, etc. The authors of work [14] note that in all these cases, intensive macro shears are achieved as a result of local deformation effects on the rolling metal.

The Japanese company "JFE Steel" offered a method of multiple consecutive alternating bending of the steel strip after hot rolling [15]. It can be seen from the materials of the work that, in contrast to usual rolling, the use of alternating bending makes it possible to roll a sheet workpiece without changing its thickness. Therefore, this method allows deforming the sheet workpiece by cyclic bending unlimited number of times. This makes it possible to obtain hot-rolled strips with an ultrafine-grained structure. According to the authors of work [15], this method of rolling can be used in industry to raise the quality of rolled metal.

Thus, in order to increase the quality of sheet roll products, many new constructions of rolls and tool shapes have been offered. However, many rolls and tools have not found wide application in production due to the following reasons: the complexity of their manufacture; the difficulty of installing them on rolling mills, etc.

The purpose of the work is to calculate the stress-strain state (SSS) of deformation during rolling of sheet metal and its uniform distribution over the volume of the workpiece, as well as development of a rational technology for rolling of aluminum AD31 alloy.

Materials and the method of experiment. To obtain workpieces with a nanostructure, an instrument with screw-shaped rolls and a continuous five-cage longitudinal-wedge mill (LWM) for strip rolling were developed [16, 17].

Instrument for metals rolling contains upper and lower rolls with screw-shaped working surfaces. At the same time, oppositely placed projections and hollows of the upper and lower roll are made along the left and right screw-shaped lines, accordingly.

Continuous LWM for rolling sheets made of steels and alloys contains electric motors, reduction gears, pinion stands, universal spindles, couplings, stands with working and supporting rolls (figure 1). At the same time, in the first three stands there are two, and in the last two stands, four support rolls. Rotation of working rolls decreasing in the rolling direction is carried out through bearing stands by five motor-reducers with an angular velocity $\omega = \upsilon \cdot R$ (where υ is the rolling speed in each mill stand, R is the radius of working rolls in each mill stand). Herewith, the distance between the stands is increased on the rate of outrunning, and the adjustment of the distance between working rolls is made by single wormscrewdown mechanisms located at the top and bottom of the mill stands and bearing stands.

It should be noted that the working rolls in each stand have a constant diameter, and in consecutively placed stands the diameter of rolls decreases in the direction of the rolling. At the output, a thin strip is cut or winded into rolls.

For the development of the technological process allowing uniformly distribute the cumulative deformation, another word to obtain high-quality strips of aluminum AD31alloy, and also to determine the optimum single squeezing value, the SSS of the workpiece was investigated during rolling in screw-shaped rolls and LWM.

MSC.SuperForge was used to calculate the SSS of the strip. The three-dimensional geometric model of the workpiece and rolls was built in the CAD Inventor program and imported into the CAE program MSC.SuperForge.Three-dimensional (3D) element CTETRA (a four-nodal tetrahedron) was used to create the finite-element model of the workpiece and rolls. The calculation time of the process was 30-40 minutes on a computer with a clock frequency of 3.4 GHz and 2 GB RAM.

Rectangularsamples with dimension of 6×100×200 mm were used for the calculation. From the materials database AD31 alloy with a deformationtemperature range of 20-450 °C was assigned. Johnson-Cook's elastic plastic model was chosen to model plasticity of the workpiece material. In MSC. Super Forge for modelinginstruments are taken absolutely rigid and only properties of heat conductivity and heat transfer are taken into account, whereas mechanical properties are ignored. As the material of the rolls, on default, tool steel is selected, density and thermal properties of which are also assigned on default.The rolling process takes place at a room temperature, so the initial temperature of the rolls is assumed equal to 20 °C. The contact between the roll and the workpiece is modeled by the Coulomb friction, the friction coefficient was 0.3.

The rolling was carried out according to the following mode: heating up to a temperature of 380 °C, rolling by four passes in screw-shaped rolls to a thickness of 5.9 mm and rolling at a temperature of 100 °C on a LWMup to a thickness of 1.5 mm.

MSC.SuperForge software has been launching. By stepwise method thedeformation and stress tensor components and the temperature distribution along the volume of workpiece were calculated. At the same time, the calculation results are shown by dividing the total deformation time to the four stages (in percent). The following intervals were selected: the first stage 25, the second stage 50, the third stage 75 and the fourth stage 100 percent from the total deformation time.

In the laboratory conditions a strip rolling was made from aluminum AD31alloy in screw-shaped rolls and LWM. The chemical composition of this alloy is shown in table 1.

Table1 – Chemical composition of aluminum AD31alloy

The content of alloying elements, mass. %					
Mg	Si	Cu	Mn	Cr	Fe
0.45 – 0.50	0.41 – 0.48	0.001 – 0.015	0.001 – 0.01	0.001 – 0.003	0.18 – 0.21

Aluminum AD31alloy was tested after treatment in screw-shaped rolls and LWM. Mechanical tests of experimental materials included: static tensile tests to determine the standard characteristics of material, such as $\sigma_в$, $\sigma_т$ ($\sigma_{0.2}$), δ, impact viscosity, hardness.

Before the mechanical test, the samples were heat treated, consisting of tempering and subsequent senescence. The heating temperature for tempering was 450 ^oC, extracting at this temperature was 2 hours, cooling was in oil. Senescence was carried out at a temperature 120 °C during 5 hours.

The metallographic analysis was carried out by using an energy-dispersive spectrometer JNCA ENERGY (England) mounted on a JEOL electron-probe microanalyzer at an accelerating voltage 25 kV. The range of the JEOL device increases from 40 to 40,000 times. Structural features of the deformed samples were also researched with the help of transmission electron microscope (TEM) JEM-2100CX at accelerating voltages 200 kV.

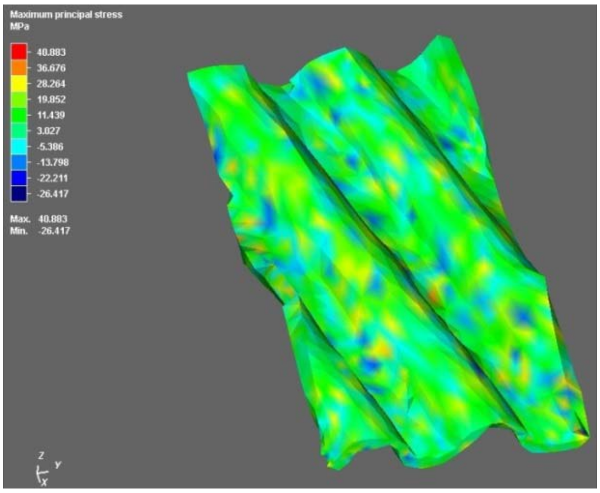
A quantitative analysis of the mechanical properties and parameters of the defective substructure was carried out by standard methods [18]. The thin sections for metallographic analysis were prepared according to the traditional method of grinding and polishing circles. For etching the samples, a concentrated solution of nitric acid in ethyl alcohol was used. The grain size (D3, micron) was determined by the secant method (according to measuring ~ 300 grains) under the assumption that the grains have a spherical form, based upon the average chord value (X) according to formula: $D_g = 4/\pi \cdot X_{med}$.

Results and discussion. The process of deformation in screw-shaped rolls can be divided into two stages. In the first stage, the projection of the upper roll bends the strip towards the hollow of the lower roll. In the second stage, due to the development of torsional stress a macroshift deformation occurs under the inclined surfaces of the projection or hollows of the rolls.

On figures 1 and 2 the distribution picture of the main stresses is shown, as well as the intensity of stresses and deformations and the temperature field in the workpiece when rolling in screw-shaped rolls by the four passes. The temperature of the workpiece heating is 380 °C.

Based on the numerical modelling results, it is established that:

- capture of workpiece by screw-shaped rolls leads to the appearance in the deformation zone minimalby value stretching σ_{11} and σ_{22}, also squeezing σ_{33} stresses;
- further rolling in the screw-shaped rolls leads to the appearance of normal stresses in the deformation zone σ_{11}, σ_{33} and σ_{22}, changing in range: σ_{11} - from 22.211 to 28.264 MPa (Figure 1, *a*); σ_{33} - from – 30.569 to 21.018 MPa (Figure 1, *b*); σ_{22} - from – 30.243 to 12.726 MPa (figure 1, *c*);
- at the initial rolling moment stresses and deformations intensity are localized in the zones where the workpiece and working surfaces of the rolls projections are contacted;
- an increase in a single reductionleads to a shift of stress and deformation intensity accent from the contact zones to the zones where the strips located under the inclined working surfaces of the rolls projections and hollows (Figure 2, *a, b*);



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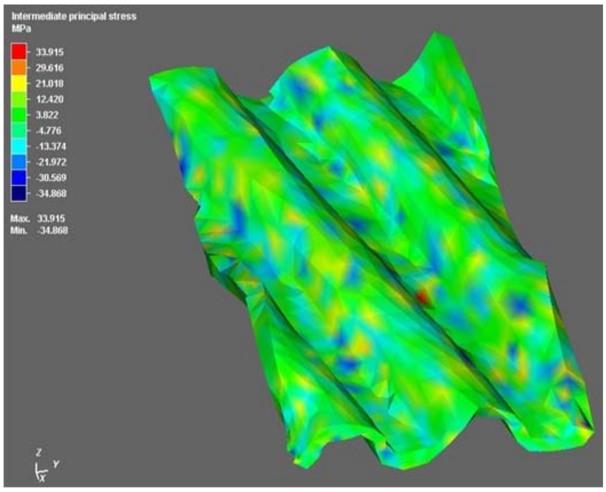

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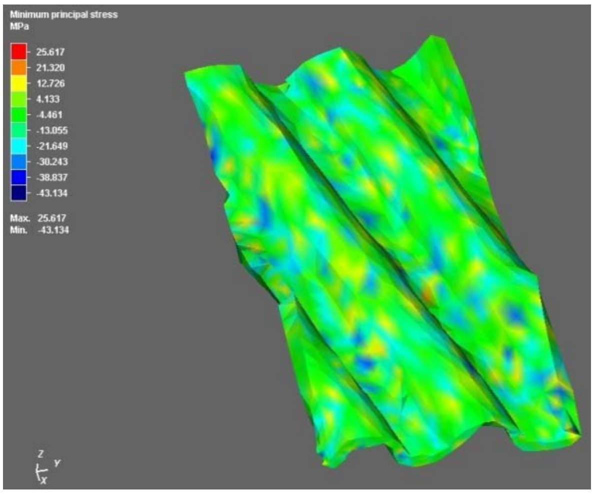


c)

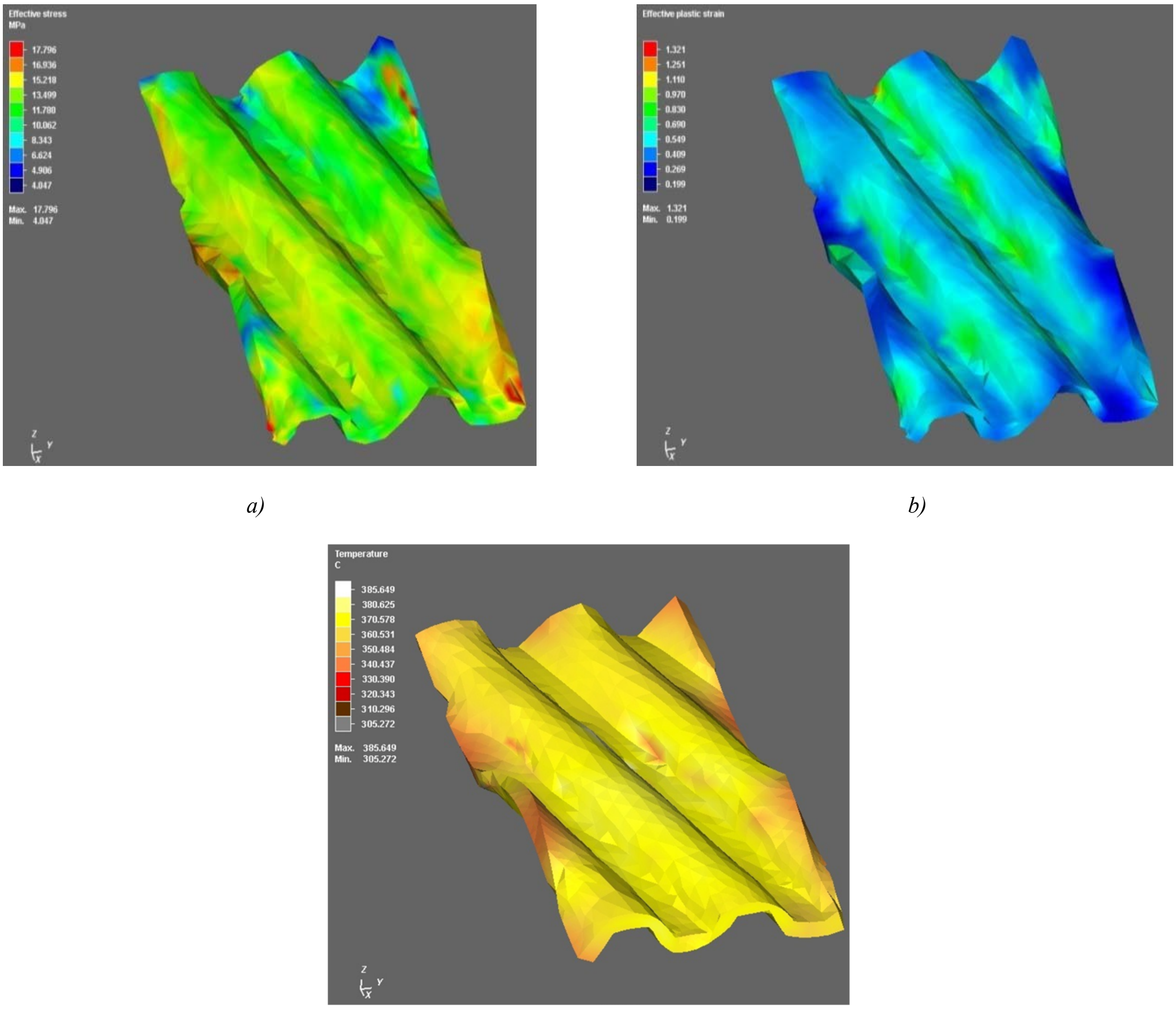
Figure 1 – Picture of the main stresses distribution in workpiece when rolling in screw-shaped rollers (temperature of rolling is 380 °C): *a* – stressσ_{11}; *b* – stressσ_{22}; *c* – stressσ_{33}

- duringrolling in screw-shaped rolls, the contact zone of the tool and the strip is cooled (figure 2, *c*), while in the areas of bending deformations action the temperature slightly rises;
- in the second, third and fourth passes of rolling in screw-shaped rolls, the values of stresses and deformations intensity increase under inclined sections of projections and hollows of the rolls;
- the developed method of strip rolling in screw-shaped rolls, provides intensive alternating-sign strip deformation at a slight squeezing;
- the maximum possible shift is realized with a ratio of the width of projection to the width of hollow equal to 0.8–0.9.

On figures 3 and 4 pictures of deformation and stress intensity, also the temperature pattern at strip rolling in LWMarepresented. Workpiece heating temperature is 100 °C.

Calculation and analysis of SSS of the workpiece shows, that:

- during the capture of the workpiece by the first, second, third, fourth and fifth stand of LWMsmall tensile σ_{11}, squeezing σ_{33} and σ_{22} stresses are generated in the deformation zone;
- further rolling of the workpiece in LWM leads to the appearance of normal stresses σ_{11}, σ_{33} and σ_{22} in the deformation zone, changing in the range: σ_{11} - from -27.008 to 131.287 MPa (Figure 3, *a*); σ_{33} - from– 22.852 up to 103.211 MPa (Figure 3, *b*); σ_{22} - from – 50.958 to – 233.033 MPa (Figure 3, *c*);



a) *b)*

c)

Figure 2 – Picture of stress *(a)*, deformation (b) andthe temperature (*c*) intensity distribution in workpiece at rolling in screw-shaped rolls (rolling temperature 380 °C)

- during the rolling in the first stand of LWM, the intensities of stresses and deformations are localized in the zones of metal capture by rolls;

- with increasing of the intensity values of stresses and deformations squeezing, increase in the center and along the edges of the deformed workpiece;

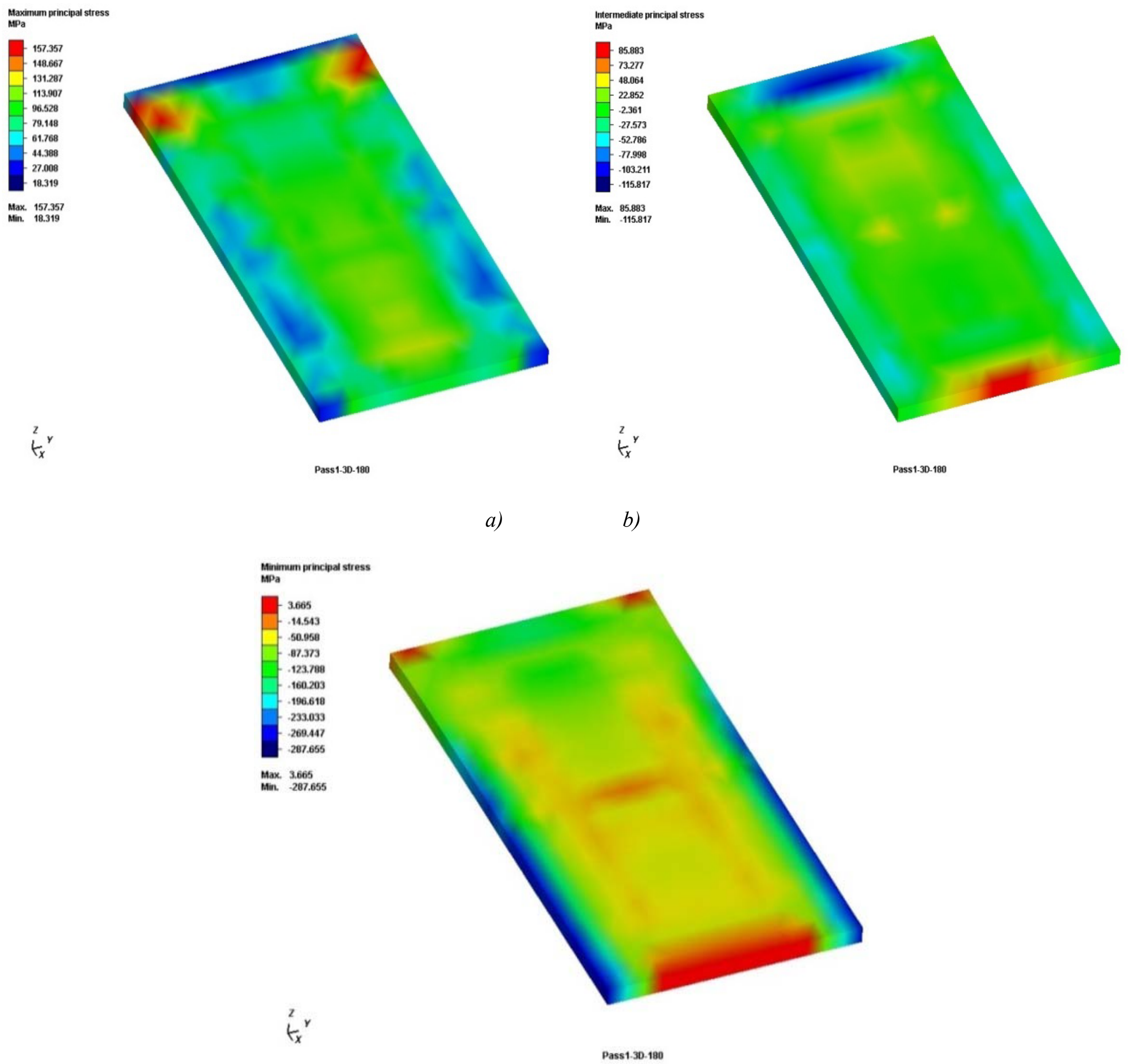
- continuous rolling of the workpiece in subsequent LWM stands allows gradually to move the areas of concentrated deformation from the center into the contact zone of the rolls and the rolled workpiece (Figure 4, *a, b*);

- gradual transfer of areas with localization of deformation from the center to the surface leads to a more even distribution of the accumulated deformation;

- the most even distribution of the total intensity of stresses and deformations along the height and length of the rolled strip was obtained during rolling with a single squeezing in the first stand, 20%, in the second stand 18%, in the third stand 13%, in the fourth stand 15%; in the fifth stand 12%;

- rolling in LWM leads to intensive cooling of the strips sections located in the contact zone of the metal with the roller (figure 4, *c*);

- during the rolling in the second, third, fourth and fifth stands, the sections of the metal with low temperature move together with the deformation zone (figure 4, *c*).



a) *b)*

c)

Figure 3 – Picture of main stresses distribution along the workpieces during rolling in LWM (rolling temperature is 100 °C):
a – stressσ_{11}; *b* – stressσ_{22}; *c* – stressσ_{33}

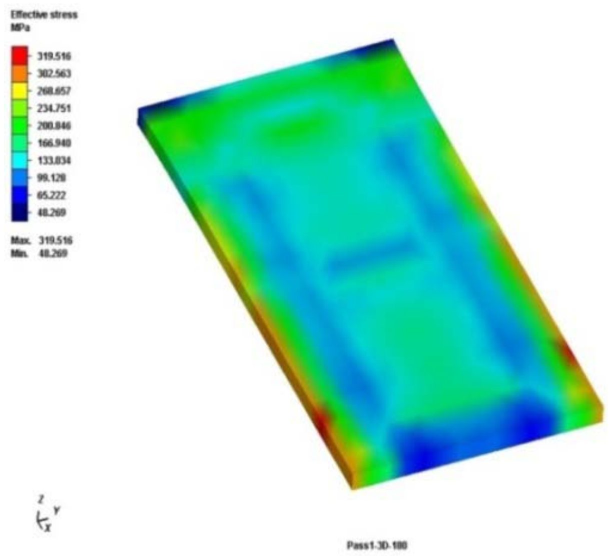
It should be noted that under all conditions of rolling in screw-shaped rolls and LWM, most of the plastic zone is under a comprehensive uneven squeezing and under some conditions on a small part of the strips located under the inclined working surfaces of the projections and hollows of the screw-shaped rolls, and also small tensile stresses appear at the edges of the strips, rolled in LWM;

At the work [19] of above given method a graphic of the limiting plasticitywas constructed and a calculation of efficiency of plasticity resource (EPR) was made.

The graphic of the limiting plasticity changing (figure 5) shows that the area of maximum plasticity for the aluminum AD31alloy lies in the temperature range of 300–400 °C.

At temperatures 100 and 200 °C, the aluminum AD31alloy has a high speed hardening and a relatively low level of ultimate plasticity (figure 5). Consequently, this alloy has a reduced technological deformability.

At temperatures above 300 °C, the increase of $\bar{\varepsilon}$ significantly reduces the strain hardening, which leads to a substantial increase of the aluminum AD31alloy plasticity. The value of $\Lambda_p(\varepsilon)$changes at a rate



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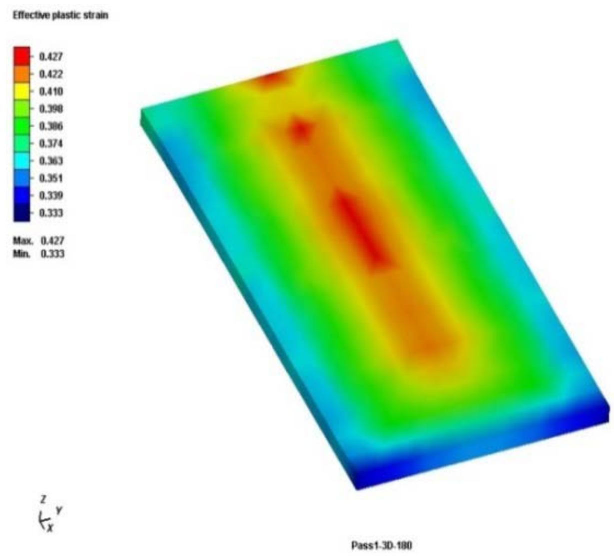

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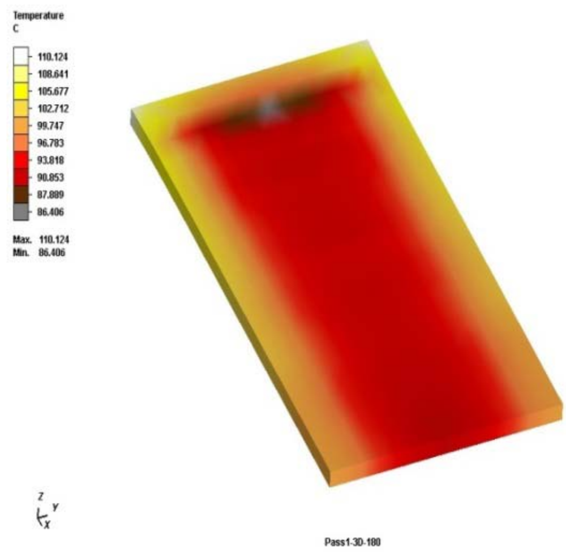


c)

Figure 4 – Picture of intensity distribution of stresses*(a*), deformation (*b*) and the temperature (*c*) in workpieces at rollingin LWM (rolling temperature is 100 ^oC)

0.25–2.5 at temperatures up to 300 °C, then in the range from 300 to 400 ^oC this index reaches values from 1.25 to 9.1 (figure 5). Consequently, the temperature range from 300 to 400 ^oC is the best for plastic deformation of alloy, since at these temperatures the processes of dynamic polygonization and recrystallization are undergoing,which stabilizes the structural state of the alloy.

In general, the aluminum AD31alloy is characterized by a sufficiently high level of ultimate plasticity and has a wide range of satisfactory deformability. The value of ultimate plasticity increases with the increasingtrial temperatureat the examined deformation speeds. In this case, the value of Λ_p is higher for a lower speed of deformation, when the processes of dynamic weakeningmanage to passfully.

It should be noted that when rolling of screw-shaped rolls and LWM stripes of aluminum AD31alloy, the degree of use of the plasticity resource does not exceed one, which shows that there is no disturbance of the continuity of workpiece material in the applied metal processingby pressure (figure 6).

Using received results according to distribution of SSSalong the cross section of the workpiece during rolling in screw-shaped rolls and on LWM, a technology for manufacturing strips with a nano-structure was developed. This technology was tested under the laboratory conditions.

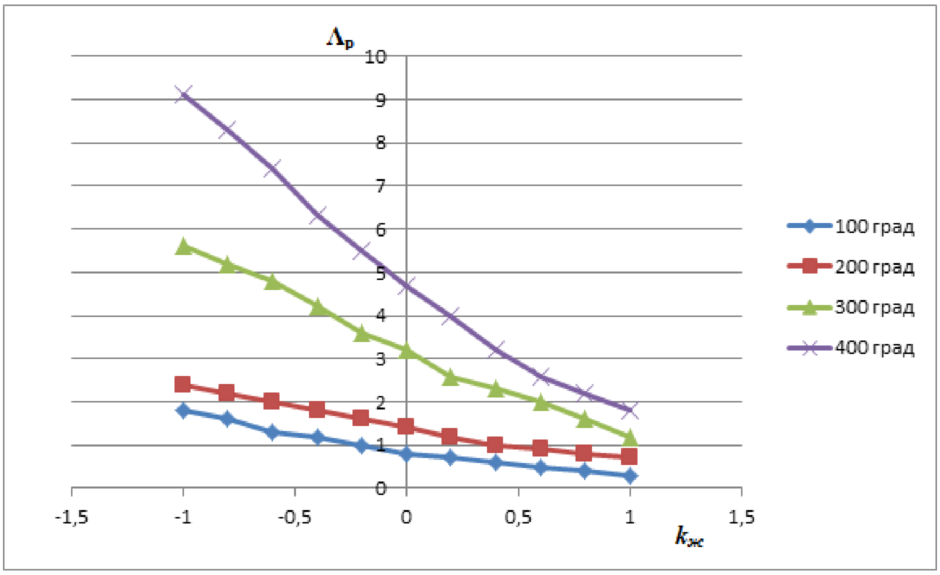


Figure 5 – Curves of limiting plasticity of aluminum AD31 alloy

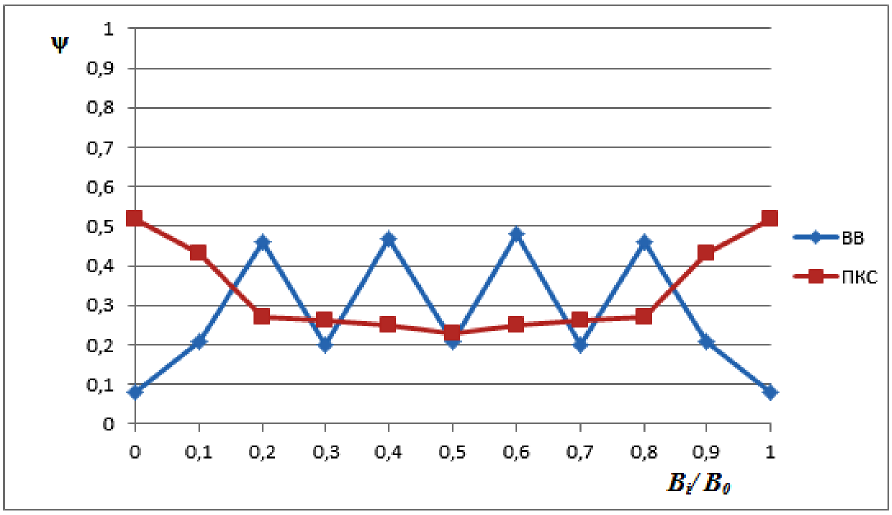


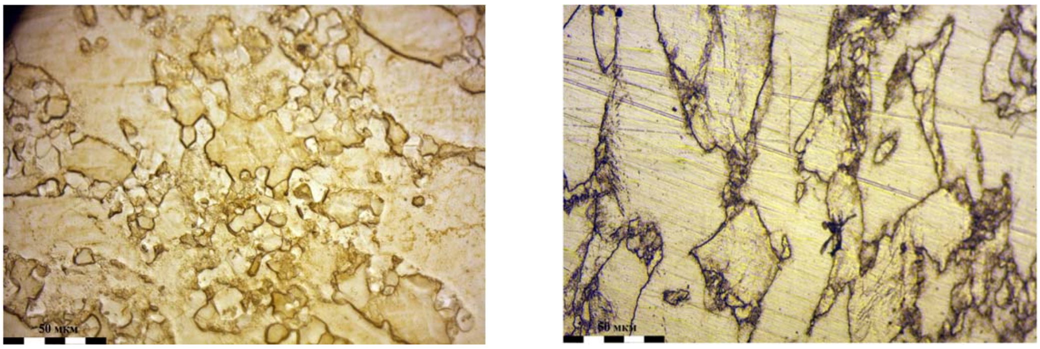
Figure 6 – Distributionof EPR on the surfaces of workpieces at stripes rolling inscrew-shaped roll sand LWM (B_i – distance till investigating point along the strip width; B_0 –width of deformation zone)

Rolling of strips on the mill with screw-shaped rolls and LWM was carried out according to the following modes:

- heating of the workpiece with thickness of 8 mm up to a temperature 380 °C, aging for 2 hours, rolling with two passes in screw-shaped rolls a thickness of 7.8 mm, heating at a temperature 380 °C, aging for 30 minutes, rolling with two passes in screw-shaped rolls up to a thickness of 7.6 mm, cooling and heating at a temperature of 100 °C, aging for 30 minutes, rolling on a five-stand LWM to a thickness of 1.5 mm;
- heating the workpiece with thickness of 8 mm up to a temperature 380 °C, aging for 2 hours, rolling with four passes in screw-shaped rolls up to a thickness of 7.8 mm, heating at a temperature 380 °C, aging for 30 minutes, rolling with four passes in screw-shaped rolls up to a thickness of 7.6 mm, cooling and heating at a temperature of 100 ° C, aging for 30 minutes, rolling on a five-stand LWM to a thickness of 1.5 mm;
- heating the workpiece with thickness of 8 mm up to a temperature 380 °C, aging for 2 hours, rolling with four passes in screw-shaped rolls up to a thickness of 7.8 mm, heating at a temperature 380 °C, aging for 30 minutes, rolling with four passes in screw-shaped rolls to a thickness of 7.6 mm, cooling and

heating at a temperature of 380 ° C, aging for 30 minutes, rolling with four passes in screw-shaped rolls up to a thickness of 7.4 mm, cooling and heating at a temperature of 100 ° C, aging for 30 minutes, rolling on a five-stand LWM to a thickness of 1.5 mm;

In the initial state workpiece made of AD31 alloy had non-uniform microstructure, which consisted of large non-recrystallized grains with a moderate size of ~ 87 micron in longitudinal and ~ 98 micron in cross directions and located along their boundaries of small grains with size ~ 14-18 micron (figure 7).

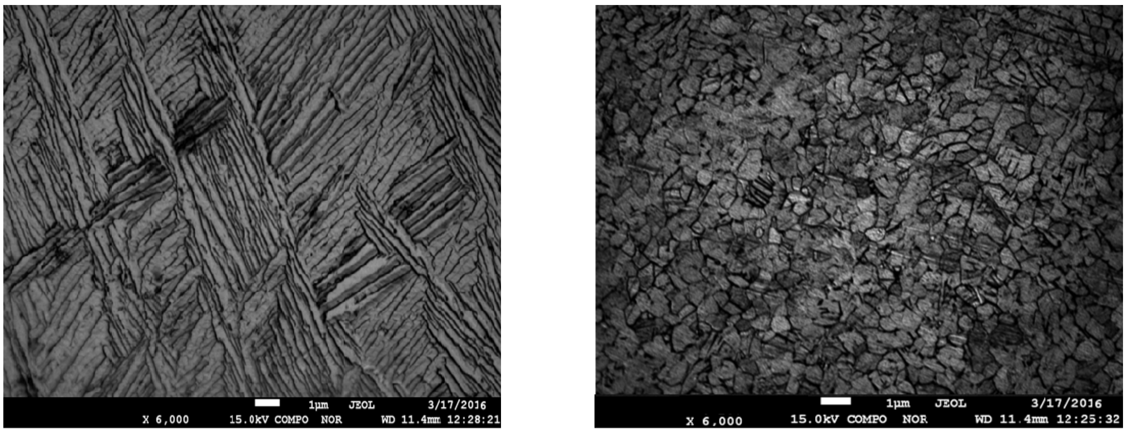


a) *b*)

Figure 7 – Microstructure of aluminumAD31 alloy in an initial state: *a* – longitudinalsection; *b* – cross section

Investigationof the microstructure showed that rolling in screw-shapedrolls at a temperature of 380 °C with four passes leads to a strong grain fragmentation into the thin strip shearswith width of about 645 – 850 nm. Inside the strips, cross boundaries are formed and multiple micro-twinning develops, as a result of which the structure is strongly crushed.

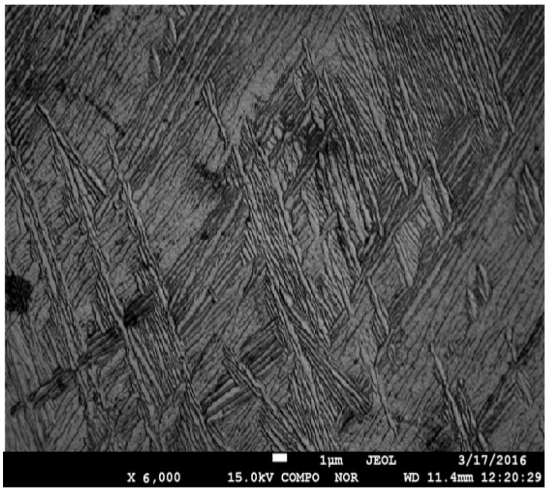
In the process of investigation, it was found that after four passes an anisotropic submicrocrystalline state forms in the testing alloy- the grain sizes in different directions are 3-4 times different: 5820-6260 nm in the plane of the parallels (figure 8, *a*) and 940÷1050 nm in the plane perpendicular to the rolling directions (figure 8, *b*). In our opinion, this is a consequencetypical for deformation by bendingand rotations under the pressure of high anisotropydisplacementfield and turnings.



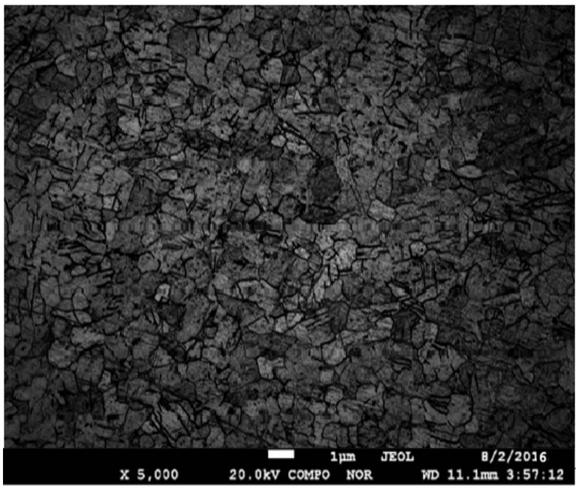
a) *b*)

Figure 8 – Microstructure of aluminumAD31 alloy after rolling with four passes in screw-shaped rolls:
a – longitudinal section; *b* – cross-section

Rolling of the workpiece at temperature of 100 °C on LWM, that was previously deformed in screw-shaped rolls with four passes, leads to the formation of a fibrous structure with an ultrafine-grained size. As a result, stretching the grains in the rolling direction along the entire volume of rolled strip forms a fibrous structure in the range of ultra-fine grain size and it equals to ~ 3800-4900 nm in the longitudinal direction of rolling (figure 9, *a*); ~ 830-950 nm in the cross direction of rolling (figure 9, *b*). Received ultrafine-grained structure is characterized by uniform grain size overall the volume of material.



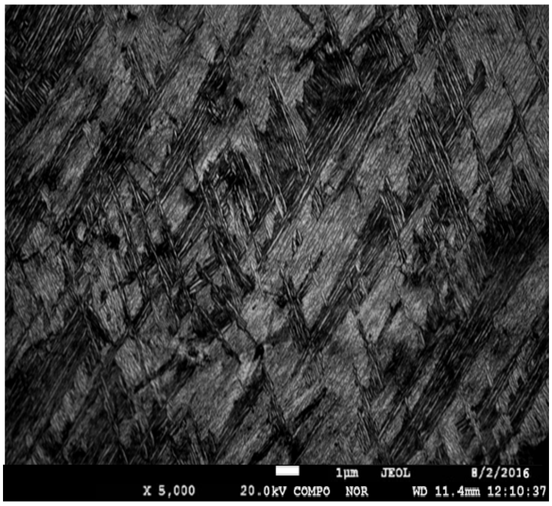
a)



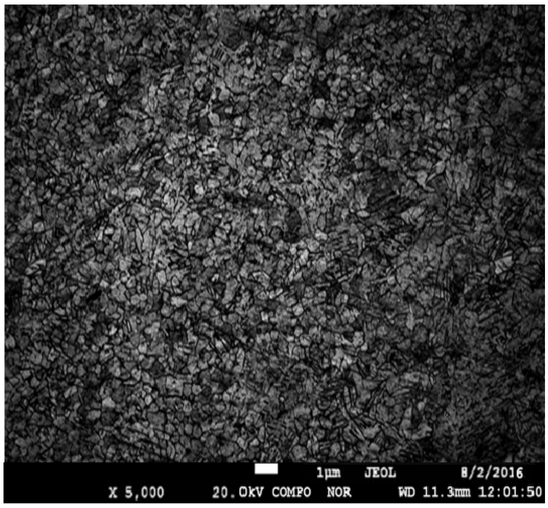
b)

Figure 9 – Microstructure of aluminumAD31 alloy after rolling with four passes in screw-shaped rolls and on LWM:
a – longitudinal section; *b* – cross-section

A different picture is observed in the AD31 alloy when rolling in screw-shaped rolls with eight passes. It was found that rolling by eight passes at a temperature 380 °C leads to the division of the strip structure into deformation, intermediate and microstrips consisting of subgrains separated by small and large-angle boundaries. Consequently, as the number of passes increases, the microstrips are grinded into parts due to the formation of shear strips, an increase in the share of the large-angle boundaries is observed, and a mixed structure is formed. In this case, deformation of workpieces at a temperature of 380 °C in screw-shaped rolls with eight passes leads to the formation of a uniform and equiaxedstructure in the longitudinal and cross sections of the workpiece (figure 10). It is seen from this microstructure that further grinding of grain-subgrain structure takes place. In the longitudinal section, the grain workpieces of substructure are definitely stretched along the direction of bending (figure 10,*a*), while in the cross section they have an equiaxed shape with an average size of about 680-740 nm (figure 10, *b*). The density of dislocations is very high and it was not possible to calculate itsvolume from the images of the structure.



a)



b)

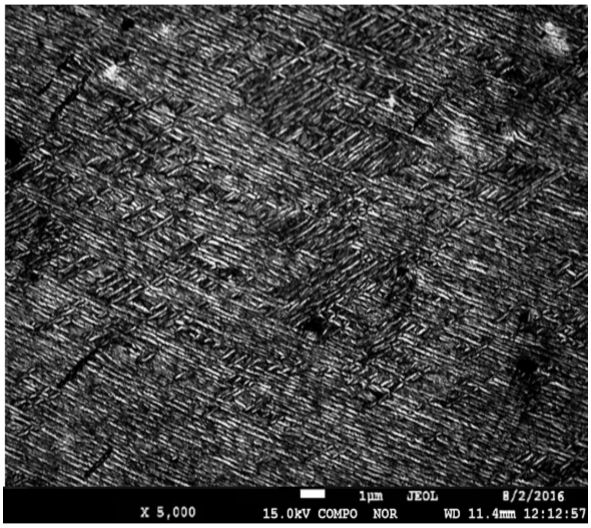
Figure 10 – Microstructure of aluminumAD31alloy after rolling by eight passes in screw-shaped rolls:
a – longitudinal section; *b* – cross-section

Thus, at rolling with eight passes the further evolution of the structure takes place, namely, the quantity of lattice and grain-boundary dislocations decreases, and clear contours of extinction appear at grain boundaries, i.e. all the signs of dynamic return and dynamic recrystallization through a continuous mechanism appear. As a result of these processes, a UFG structure forms in material,which consist of crystallites, with size of 680-740 nm.

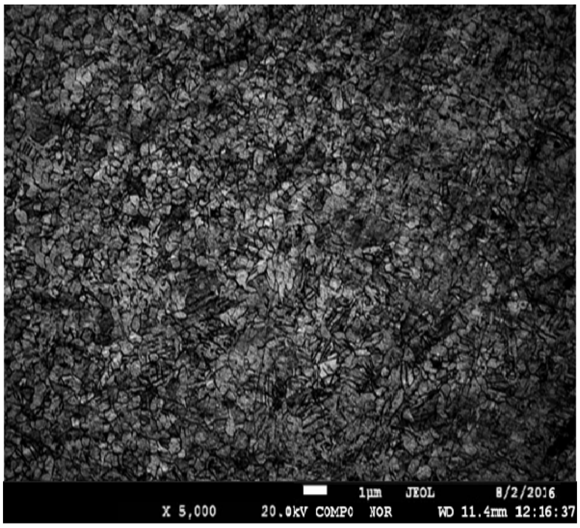
Consequently, the relaxation of elastic energy during rolling in screw-shaped rolls with eight passes in AD31 alloy is carried out by two mechanisms: the first is fragmentation and the second is dynamic recrystallization.

It should be noted that with the increase of the number of rolling passesin screw-shaped rolls, the grinding of the structure passes not only by twinning, but also by the formation of cellular substructures as a result of the development of slidingdislocation processes. At large degrees of accumulated deformation, the boundaries of the former twins and subgrains are transformed into large-angle ones.

Rolling of the obtained strips on the LWM at a temperature 100 ^{o}C leads to formation of an ultrafine-grained structure with an average size from 950 to 1120 nm in the longitudinal section (figure 11, *a*) and from 550 to 680 nm of the cross-section of the workpiece (figure 11, *b*). Obtained UFG structure is characterized by uniform grain size throughout the entire volume of the rolled strip. On the images of microstructure after the rolling on LWM, a clear image of the grain boundaries was observed, which indicates the formation of grains with predominantly large-angle boundaries.



a)



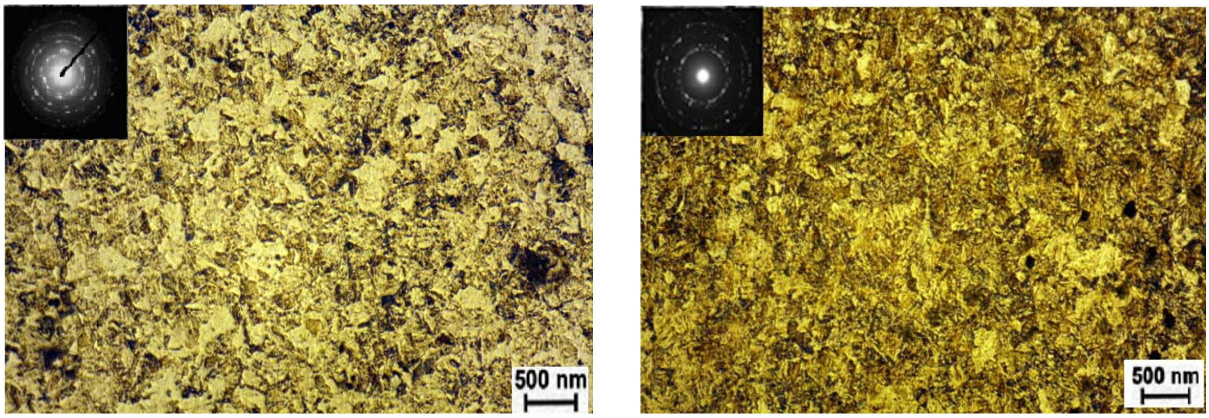
b)

Figure 11 – Microstructure of aluminumAD31 alloy after rolling with eight passes in screw-shaped rolls and on LWM: *a* – longitudinal section; *b* – cross-section

After rolling by twelve passes in screw-shaped rolls in an aluminum AD31alloy, non-uniform grain-subgrain structure is formed. Grains and subgrains have a non-equiaxed shape and stretched along the direction of bending and rotation. The average size of the grain-subgrain elements structure in cross and longitudinal sections of workpiece is (125±40) nm (figure 12, *a*).The diffraction image shows that the nanocrystalline structure contains predominantly high-angle grain boundaries with a non-equilibrium structure leading to increase of grain boundaries energy.

Microstructural non-uniformity in the volume of workpieces is significantly reduced in the subsequent plastic deformation by rolling in LWM. Rolling with a total squeezing up to 90% leads to the formation of a microstructure with an average characteristic size of almost equiaxed elements = 95±20 nm, which corresponds to the nanostructured state (figure 12, *b*).

Naturally, the rolling on LWM at a temperature 100 °C provides additional deformational hardening. Annealing for 1 hour at 200 °C practically does not change the nature of the microstructure, and the nanostructural state of the aluminum AD31alloy is preserved, only insignificantly increases an average grain-subgrain structure, reaching 125±30 nm (figure 13). Increasing of temperature up to 300 °C at the



a)   *b*)

Figure 12 – Microstructure of aluminumAD31alloy after rolling with twelve passes in screw-shaped rolls and on LWM:
a – after rolling inscrew-shaped rolls; *b* – after rolling in screw-shaped rolls and on LWM

same duration initiates the process of recrystallization. The growth of an average grain-subgrain structure becomes more noticeable and composes 145±10 nm. The value of subgrain size after annealing at 400 °C, compose 180±45 nm. After annealing at 450 °C, the grain size increased to 262±48 nm, and after annealing at 500 °C the structure of the aluminum AD31alloy became fine-crystalline with an average grain size 5.3±0.3 micron.

Mechanical properties of the flat samples from AD31alloy were determined at room temperature on Instron 5882 installation at the rate of deformation 10^{-3} s^{-1}. It is established that the properties of the AD31alloy, subject to rolling in screw-shaped rolls and on LWM, are significantly higher than the initial values. In particular, the temporary resistance to break of $\sigma_B$increases to20%, and the plasticityfor one and a half time higher than the corresponding parameter of the initial samples (table 2). Such combination of sufficient strength (σ_B = 255 MPa) and good plasticity (δ = 14%) opens wide possibilities to use this material in practice.

It is known [20] that an increase of aluminum AD31alloy strength is achieved when the Mg_2Si particles have a size of not more than 0.25 micron. An analysis of the obtained data showed that when rolling in screw-shaped rolls and LWM, particles of Mg_2Si with size ~ 40±50 nm are formin the structure of aluminumstrips.

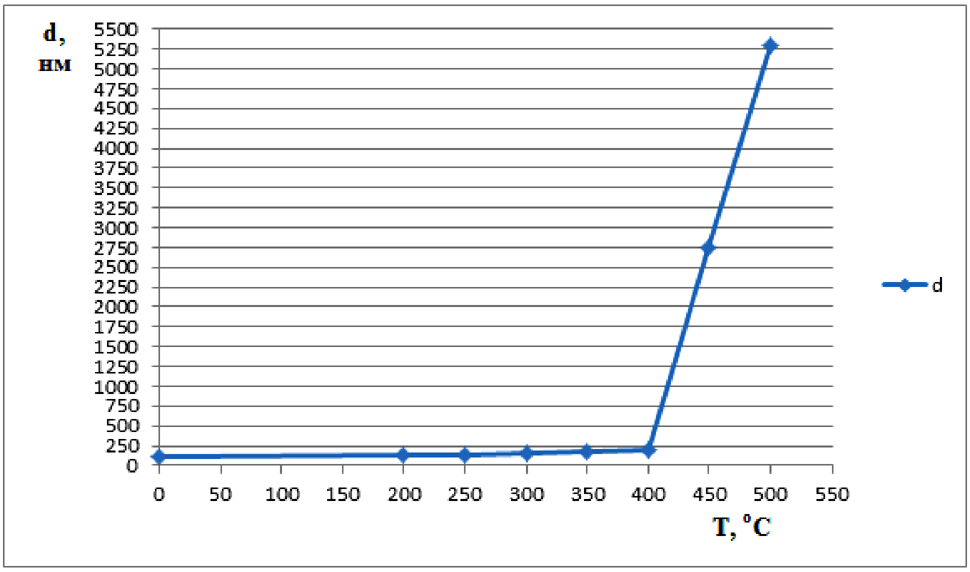


Figure 13 – Influence of annealing temperature (*T*, °C)
on the grain-subgrain structure of strips (*d*, nm) rolled inscrew-shaped rolls and on LWM

Thus, after rolling in screw-shaped rolls with twelve passages and LWM in an aluminum alloy AD31, relatively uniform, equilibrium nanostructure with an average typical size of grain-subgrain structure less than 100 nm was formed. This structure provides a high statistic strength (σ_t - 275 MPa, σ_B - up to 295 MPa) and a good plasticityof aluminumstrips from the AD31alloy under uniaxial tension.

Table 2 – Mechanical properties of AD31 alloy at room temperature

Processing	σ_B, MPa	$\sigma_{0.2}$, MPa	δ_p, %	δ, %
Rolling by four passes inscrew-shaped roll sat 380°C and rolling on LWMat 100 °C	285 ±4	265 ±7	5.5 ±0.2	22.5 ±0.4
Rolling by eight passes in screw-shaped rolls at 380°C and rolling on LWM at 100 °C	292 ±2	270±5	6.2 ±0.6	23.0 ±0.6
Rolling by twelve passes in screw-shaped rolls at 380°C and rolling on LWM at 100 °C	295 ±2	275 ±2	7.2 ±0.7	24.7 ±0.6
Original sample	236 ±3	199 ±1	3.5 ±0.1	17.0 ±0.2

Conclusion:

1. An uneven equiaxed nanograin with weak signs of deformation texture is formed during hot (rolling in screw-shaped rolls) and cold rolling (rolling on LWM) of the sheets from the aluminum AD31alloy during annealing in the temperature range 300-400 °C, depending on the composition accordingto primary recrystallization mechanism;
2. UFG recrystallized structure by the mechanism of primary recrystallization is obtained in hot (screw-shaped rolls) and cold rolling (LWM) sheets from aluminum AD31alloy when heating up to a temperature of 500 °C, aging is 2 hours in oil and age-hardening at temperature 120 °Cduring 5 hours;
3. The rolling in the lower left-screw and upper right-screw rolls with opposite projections and hollows leads to localization of deformation intensity in the initial stage of rolling in the contact zones of workpiece, and in subsequent stages - in the zones under the inclined sections of the rollsprojections and hollows;
4. Concentration of deformation intensity in the contact zones and under the inclined sections of the rolls projections and hollows assists by means of selection of rational deformation modes of rolling to obtain strips with a nanosized structure;
5. It is shown that after rolling in screw-shaped rolls by twelve passes and on LWM ofaluminum AD31alloy, a relatively uniform, equilibrium nanostructure with an average grain-subgrain structure less than 100 nm can be formed. This structure provides high static strength and good plasticity of aluminum strips at uniaxial tension.

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АД31 АЛЮМИНИЙ ҚОРЫТПАСЫНАН ЖАСАЛҒАН ЖҰҚА ҚАҢЫЛТЫРЛАРДА НАНОҚҰРЫЛЫМНЫҢ ҚАЛЫПТАСУЫНА БҰРАНДАЛЫ ПІШІНБІЛІК ПЕН БОЙЛЫҚ-СЫНАЛЫ ОРНАҚТА ИЛЕМДЕУДІҢ ТЕХНОЛОГИЯЛЫҚ ПАРАМЕТРІНІҢ ӘСЕРІ

Аннотация. Осы мақалада наноқұрылымы бар құңылтырлы илемді жасаудың жаңа технологиясы ұсынылғын. Бұрандалы пішінбілік дамытатын қарқынды пластикалық деформацияны қолдану жолымен айтылған наноқұрылым қаңылтырлы материалда алынған. Айтылған жұмыста дайындаманы бұрандалы пішінбілік пен бойлық-сыналы орнақта илемдеген кезде, ода пайда болатын кернеулі-деформациялы күй зерттелген. Шеткі элемент әдісімен және MSC.SuperForge бағдарламасымен бұрандалы пішінбілік пен бойлық-сыналы орнақта илемдеуді модельдеп, кернеулі-деформациялы күй мен температураның таралуының негізгі заңдылықтары анықталған және сандық мәліметтері табылған. Илемдеуді модельдеген кезде әртүрлі өтім саны және дара жаншулар қолданылған. АД31 алюминий қорытпасын жаймалаудың ұтымды технологиясы жасалып, зерханалық жағдайла сыннан өткізілген. АД31 алюминий қорытпасын бұрандалы пішінбілік пен бойлық-сыналы орнақта илемдеген кезде, осы қорытпада наноқұрылымды қалыптастыратын илемдеу режімін талдауға ерекше көңіл бөлінген.

Түйін сөздер: алюминий қорытпасы, наноқұрылым, илемдеу, кернеулі-деформациялы күй, сандық модельдеу, кернеу мен деформация қарқындылығы, дара жаншу.

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ВЛИЯНИЕ ТЕХНОЛОГИЧЕСКИХ ПАРАМЕТРОВ ПРОКАТКИ В ВИНТООБРАЗНЫХ ВАЛКАХ И ПРОДОЛЬНО-КЛИНОВОМ СТАНЕ НА ФОРМИРОВАНИЕ НАНОСТРУКТУР В ТОНКИХ ЛИСТАХ ИЗ АЛЮМИНИЕВОГО СПЛАВА АД31

Аннотация. В настоящей статье представлена новая технология получения листового проката с наноструктурой. Наноструктура получена путем применения интенсивной пластической деформации, развиваемой винтообразным валком. В работе исследовано напряженно-деформированное состояние (НДС) заготовки при прокатке в винтообразных валках и продольно-клиновом стане (ПКС). Методом конечных элементов и с помощью программы MSC.SuperForge получены количественные данные и установлены основные закономерности распределения НДС, температуры при моделировании прокатки в винтообразных валках и ПКС, с различным количеством проходов и единичного обжатия. Разработана и в лабораторных условиях апробирована рациональная технология прокатки алюминиевого сплава АД31. Особое внимание уделено анализу влияния режимов прокатки в винтообразных валках и ПКС на формирование наноструктур в алюминиевом сплаве АД31.

Ключевые слова: алюминиевые сплавы, наноструктура, прокатка, напряженно-деформированное состояние, численное моделирование, интенсивность напряжений и деформаций, единичное обжатие.

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