PROBLEMS OF ULTRAFINE GRAINED STRUCTURES IN SOME ALUMINUM ALLOY WORKPIECES AND THEIR SOLUTIONS BY SEVERE PLASTIC DEFORMATION METHODS

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Numerous studies have found that one of the most progressive areas of improving the quality of sheet metal is to obtain a more fine-grained structure. The aim of the research is to design the rational technology of rolling strips from aluminium alloys with ultra-fine grained structure by uniform distribution of stress-strain state and refinement of the microstructure of the metal. The quantitative data has been obtained and the basic stress-strain state, as well as temperature distribution patterns was established by the MSC.SuperForge program during modelling rolling in the helical rolls and longitudinal wedge mill with different numbers of passages and the single reduction. It is proved that rolling in the helical rolls with oppositely located projections and depressions leads to the localization of SSS in the contact zones of the work piece at the beginning of the rolling, and then in the zones under the inclined portions of the projections and depressions of the rolls. It is established that deforming in the stands of the LWM allows gradually to transform accent of the SSS from the surface zones to the central layers of the work piece, and after that uniformly deform the strips along the length of it. The rational technology of aluminium alloys rolling was developed and tested in the laboratory. The special attention is paid to analysis of the influence of the rolling conditions in the helical rolls and LWM on the formation of the microstructure of aluminium alloy. Research results of the microstructure evolution of long length work pieces at the different stages of their production show the possibility to manufacture the strips with UFG structure by using helical rolls and LWM.

Keywords: aluminium alloys, rolling, helical rolls, longitudinal wedge mill, stress-strain state, numerical simulation, single reduction

1. Introduction

Severe plastic deformation (SPD) is one of the methods of producing compact nanomaterial and submicrocrystalline materials [1-19]. The method is based on the formation of highly fragmented and disoriented structures with the signs of recrystallized amorphous state. The different methods are used to achieve

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a large deformation of the material [1-9]: torsion under a quasi-hydrostatic pressure, an equal channel angular pressing, a rolling, a comprehensive forging, etc. The essence of these methods is based on the multiple SPD of the shift of the processed materials, thus the value of a true logarithmic degree of deformation is equal to 4-7. As a result, bulk samples with a virtually non-porous structure could be obtain along with the decrease of the grains in the average size.
Particularly perspective is considered the implementation of SPD for the workpieces of light and corrosion-resistant structural alloys on the basis of aluminium and titanium, conventionally used in the medicine, aerospace and shipbuilding industries.

Equal channel angular pressing (ECAP) remains to be the most popular method of SPD of processing the metal bars, as it allows to preserve the essential dimensions of the workpiece during the formation of nanostructures [9,12,13,16,17]. According to [14,15] SCRI CM "Prometei" has been produced the ultrafine-grained (UFG) structure in the deformed high strength welded aluminium alloys 1561 and 1575 (Al-Mg and Al-MgSc system) by the ECAP. The designed mode provides producing the semi-finished products with higher levels of strength and ductility. It was established that the rapid increase in the tensile strength and yield strength is achieved by the first ECAP passage. However, the emerged cellular structure owns imperfect low-angle boundaries. Therefore, the multiple repeatedly reprocessing was produced for the formation of UFG structure with more stable large angular boundaries. With the purpose to reduce the manufacturing content of the process the experimental-industrial assimilation of the ECAP rods (∅ 85 mm) of an aluminium alloy 1561 after 3 intersecting channels (instead of the traditional 2) was carried out in the SCRI CM "Prometei" together with the JSC “VILS”. So, the comparison of the 2 methods showed that ECAP in the three-channel matrix allows obtaining higher values of the strength in the 1561 alloy compare with the compression in the two-channel matrix with the same number of passages.

Furthermore, the studies [14,15] show the stability of an alloy structure, which occur after heating of the work pieces above 200 °C. When the heating temperature is increased till 400 °C, the rate of the decline in the mechanical properties slows down. The increase in the duration of heating at the selected temperature range does not affect the properties of the samples. Thus, ECAP allows forming the UFG structure, which provides a high level of strength and ductility.

The work [18] describes deformation methods for obtaining the nanostructured alloys with effect of the shape memory (ESM) on the basis of nickel titanium (nanonitinol), in particular by using high-pressure torsion. Application of this method demonstrates a record value of the maximum strength (till 2700 MPa), the yield stress (2000 MPa), reactive stress at ESM (1300-1500

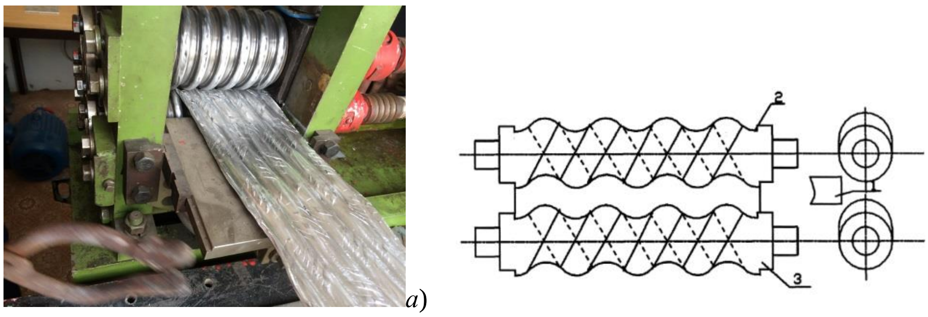
MPa) at 15-20% ductility, and high thermal stability structures and properties. For the first time the 3D nanostructured alloys with ESM was obtained.

It should be noted that with the help of the above described methods of SPD, it becomes difficult to produce the sheet material with an ultrafine or nano-grain structure. The sheet material with an UFG structure can be obtained by different technological and constructive ways: application of the workpieces and rolls with a wavy or corrugated surface, asymmetric rolling, uneven cooling of the peal through its thickness and width, and the application of the crossed rolls, as well as rolls with a protrusion on the surface, etc. [19]. The authors of the work [19] note that in all above described cases, the intensive macroshift is achieved as a result of local deformation effects on the rolled metal.

The work [20] reviewed a method of multiple sequential alternating bending of the steel strip after hot rolling (the method of deformation accumulation through bending). The application of alternating bending in comparison with the ordinary rolling allows rolling the sheet workpiece without changing its thickness, as well as deforming the workpiece by the cyclic bending for indefinite times. As a result, hot-rolled strips with the UFG structure and the size of ferrite grain of 1 micron or less have been obtained. Thus, many new designs of the rolls are proposed to improve the quality of the sheet products. However, many rolls could not be applied widely in the production because of the complexity of their manufacture, or difficulty of installing them on the rolling mills. The purpose of the work is developing the rational technology of aluminium alloys rolling by calculating the stress-strain state (SSS) of the deformation during rolling the sheet metal and its uniform distribution throughout the volume of billet.

2. Materials and methods of the experiment

A tool with the helical rolls has been designed to produce the workpieces with UFG structure (Fig. 1) [21]. This tool implements the SPD without significant changes in the shape and the size of the original billet. A continuous LWM has also been designed [22] for rolling strips from the billets with UFG structure (Fig. 2). The tool provides hot rolling of alloys, and it consists of the upper and lower rolls with the helical working surfaces. Thus, oppositely located projections and depressions of the upper and lower rolls are performed according to the left-hand side and wright-hand side spiral lines, respectively. The rolling of the workpiece in the helical tool is provided by the following way. The workpiece is put into the nip between the rolls, then it is rolled with the single reduction $\varepsilon = \Delta h_B / H_o$ at the first pass, and with the single reduction equal to $\varepsilon = 2\Delta h_B / H_o$ in the subsequent passes (where Δh_B is the height of the projection or the depth of the depression of the helical working surface; H_o is the height of the workpiece before rolling). Such rolling ensures efficient refinement of the microstructure along the entire cross section of the workpiece by alternating bending deformation in longitudinal and cross sections of the workpiece. Thus, the offset generated during rolling projections and depressions across the width of the rolled strips is formed, which creates additional macro shift at the cross section of the workpiece. Creating the macroshift leads to an effective refinement of the microstructure of the alloy, in another words, it creates conditions for obtaining the high-quality alloy.



a) *b*)

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

Fig. 2. Five stand longitudinal-wedge mill: *1,2, 3* – the four-high stands without the pressure device; *4, 5* – four-high stands with the pressure device

The continuous LWM contains the work stands, motor, coupling, bearing non-powered rolls, working driven rolls, base frame and base plate. The drives of the stands have the actuators of AC motor. The rotation of the rolls is carried out through individual clutch, gear cage and spindle. Thus, the diameter of the working rolls decreases in the sequentially located stands, and the diameter of the supporting rolls increases through the direction of rolling.

A specialized standard program MSC.Super Forge was used to calculate the SSS [23]. A three-dimensional (3D) geometric model of the rolls and workpiece were constructed in the CAD program Inventor and imported into CAE program MSC.Super Forge. 3D volume element CTETRA (four-noded tetrahedron) was used to simulate 3D bodies and was implemented while creating a finite element model of the workpiece and rolls. The calculating time of the process was 30-40 minutes on the computer Pentium Duo with a clock frequency of 3.4 GHz and 2 GB RAM.

Rectangular cross-sectional samples with the dimensions of 6 × 100 × 200 *mm* were used for calculating. The material of the stretching workpiece $AlCu_4Mg$, also known as ENAW-2024, with a deformation temperature range of 20 - 450 °C was designated from a database of materials. The elastoplastic model of Johnson-Cook was chosen for simulating the plasticity of the workpiece material. The tools were accepted as absolutely rigid in MSC.SuperForge and only the thermal conductivity and heat transfer properties such as thermal conductivity, specific heat capacity and density were taken into account, and the mechanical properties were ignored. The tool steel was selected as the material for the rolls by default, besides the density and thermal properties were also assigned by default. The process of rolling took place at room temperature, therefore the initial temperature of the rolls was accepted as 20 °C. The contact between the roll and the workpiece was modelled by Coulomb friction, and the friction coefficient was adopted as 0.3. The rolling process was carried out according to the following regime: heating until the temperature reaches 320 °C, rolling by 4 passes in the helical rolls to 5.9 *mm* thickness, cooling and rolling at the room temperature on the LWM to a thickness of 1.5 *mm*.

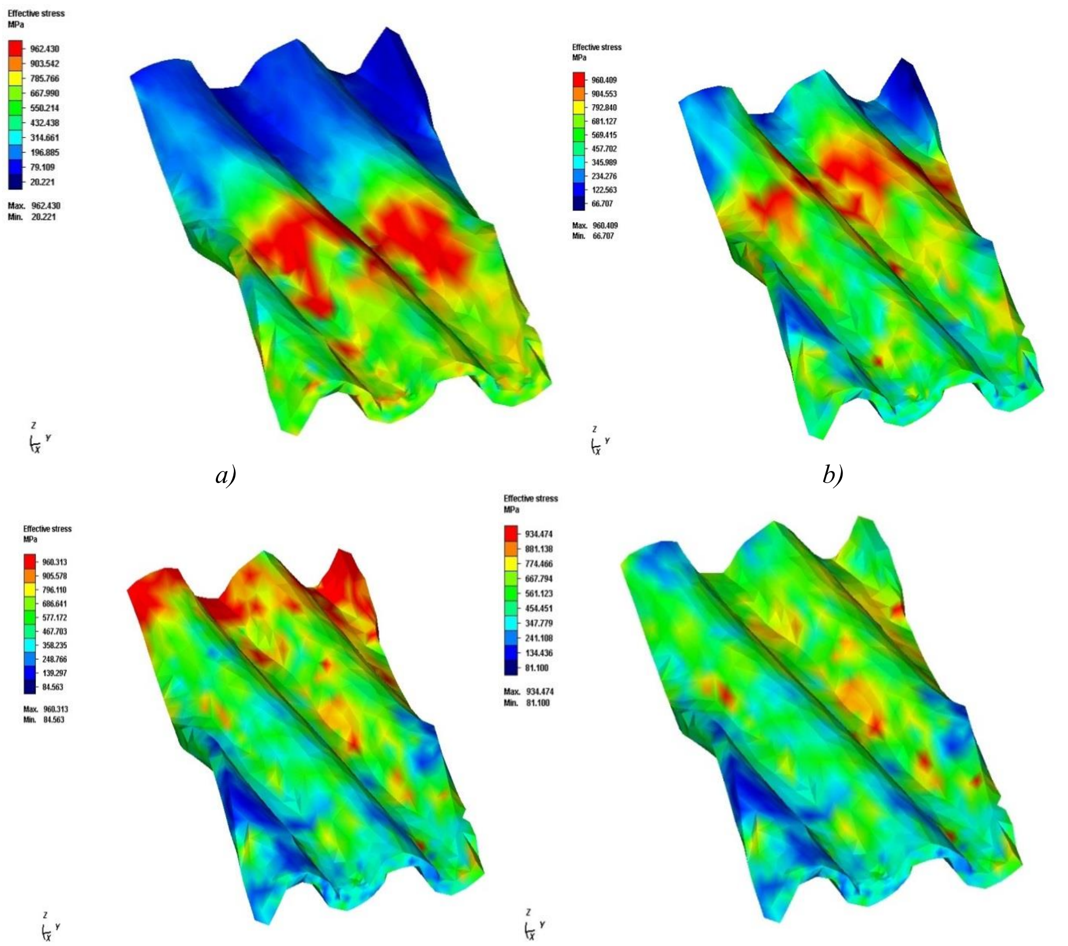
The components of the strain tensor ε, the components of the strain rate tensor ξ, the components of the stress tensor σ, the intensity of deformation, the stress intensity, the temperature distribution over the volume of the workpiece were calculated by the step method. In this case, the data for four stages in the percentage value of full-time deformation was taken for the clarity of displaying the calculation results, so the following intervals were chosen for achieving this objective: the first stage 25%, the second stage 50%, the third stage 75% and the fourth stage 100% of the full deformation time. The rolling of the aluminum strips was then conducted in the laboratory. The metallographic analysis was performed using an energy dispersive spectrometer JNCAENERGY (England), mounted on the electron probe microanalyzer JEOL (Dzheol) at an accelerating voltage of 25 *kV*. The range of increase of the JEOL instrument ranges from 40 to 40,000 times.

The quantitative analysis of the mechanical properties and the parameters of the defect substructure were carried out by the standard methods [16]. The microsections for metallographic study were prepared according to traditional methods on the grinding and polishing circles. The concentrated nitric acid solution in ethanol was used for etching the samples. Grain size (D_g, microns) was determined by the secant method (by measuring ~ 300 grains) on the assumption that the grains have the spherical form, based on the value of an average chord (X) by the formula: $D_g = 4/\pi \cdot X_{\text{average}}$. The samples were subjected to the heat treatment (HT), consisting of a hardening and subsequent aging before testing their tensile. The heating temperature for quenching was 450 °C, keeping time at this temperature was 2 hours, and then they were cooled in oil. Aging was performed at 120 °C during 5 hours.

3. Results and discussion

Conditionally, the process of deformation in the helical rolls can be divided into two stages. In the first stage, the projection of the upper roll bends the strip towards the depression of the lower roll. In the second stage, the macro shift deformation occurs under the inclined surfaces of the projections or depressions of the rolls. Figs. 3 - 5 illustrate the intensity pattern of the stress and strain distribution, as well as the distribution of the temperature field in the workpiece during rolling process in the helical rolls by 4 passages. The temperature of heating of the workpiece was 320 °C. On the basis of the numerical simulation results, it is established that:

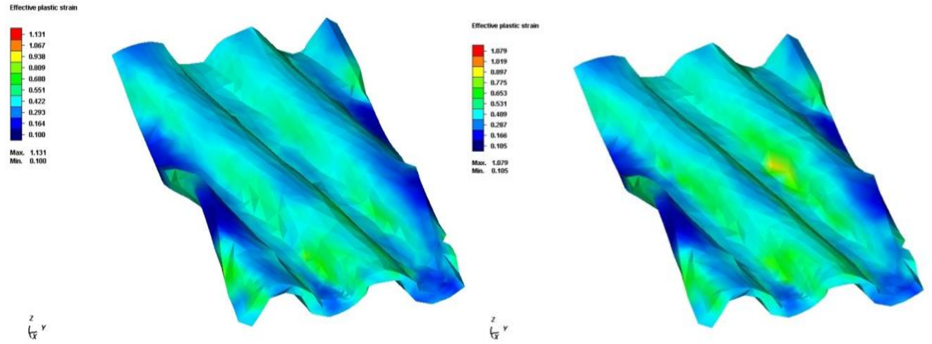
- at the initial stages of rolling, the stress and strain intensity are localized in the contact areas of the workpiece with the working surfaces of the projections of the rolls;
- an increase of the single reduction leads to a shift of stress and deformation intensity from the contact areas towards the zones of strip which are located under the slanted working surface of protrusions and depressions of the rolls (Figs. 3, 4);
- in the process of rolling in the helical rolls, the contact zones of the tool with the strip are cooled down, while the temperature rises in the zones of bending deformations action (Figure 5);
- the magnitude of the intensity of stress and strain increases under the inclined portions of the projections and depressions of the rolls in the second, third and fourth passes of the rolling in the helical rolls;
- the developed method of strip rolling in the helical rolls provides the intensive alternating deformation of the strips compare with the little change of the cross-section of the rolled strip. The maximum shift is implemented with respect to the widths of the projection and depression which is equal to 0.8 ... 0.9.



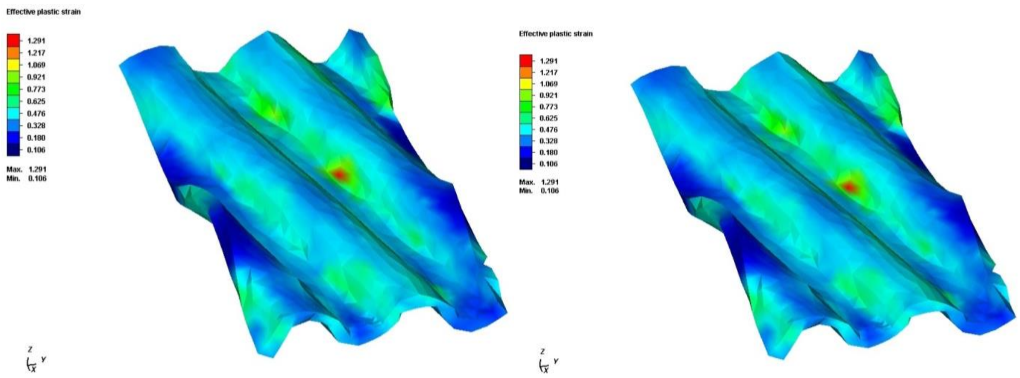
a) *b)*

c) *d)*

Fig. 3. Stress intensity distribution pattern in the workpiece during the rolling process in the helical rolls (rolling temperature is 320 °C): *a* – the first pass; *b* – the second pass; *c* – the third pass; *d* – the fourth pass



a) *b)*



c) *d)*

Fig. 4. Deformation intensity distribution pattern in the workpiece during the rolling process in the helical rolls (rolling temperature is 320 °C): *a* – the first pass; *b* – the second pass; *c* – the third pass; *d* – the fourth pass

Figs. 6 – 8 present a picture of the intensity distribution of strain and stress, as well as the temperature field during rolling strips on the LWM. The temperature of heating the workpiece is 20 °C.

The calculation and analysis of SSS demonstrates:

1) During rolling in the first stand of the LWM, the intensities of stresses and strains are localized in the areas of capturing the metal by the rolls;

2) With an increase of the compression, the intensity values of the stress and deformation are increased in the centre and at the edges of the deformable workpiece;

3) A deformation in the subsequent stands of LWM allows to gradually transit the areas of concentrated deformation intensity from the surface zone to the central layers of the workpiece, and then evenly deform the strips along the entire length of it (Figs. 6, 7);

4) An uniform distribution of the stress and deformation intensity along the stands of the mill leads to the more uniform distribution of the shift deformation intensity (accumulated strain) along the deformation zone;

5) The most uniform distribution of the accumulated strain along the height and length of the rolling strips obtained by rolling with a single reduction as follows: 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%;

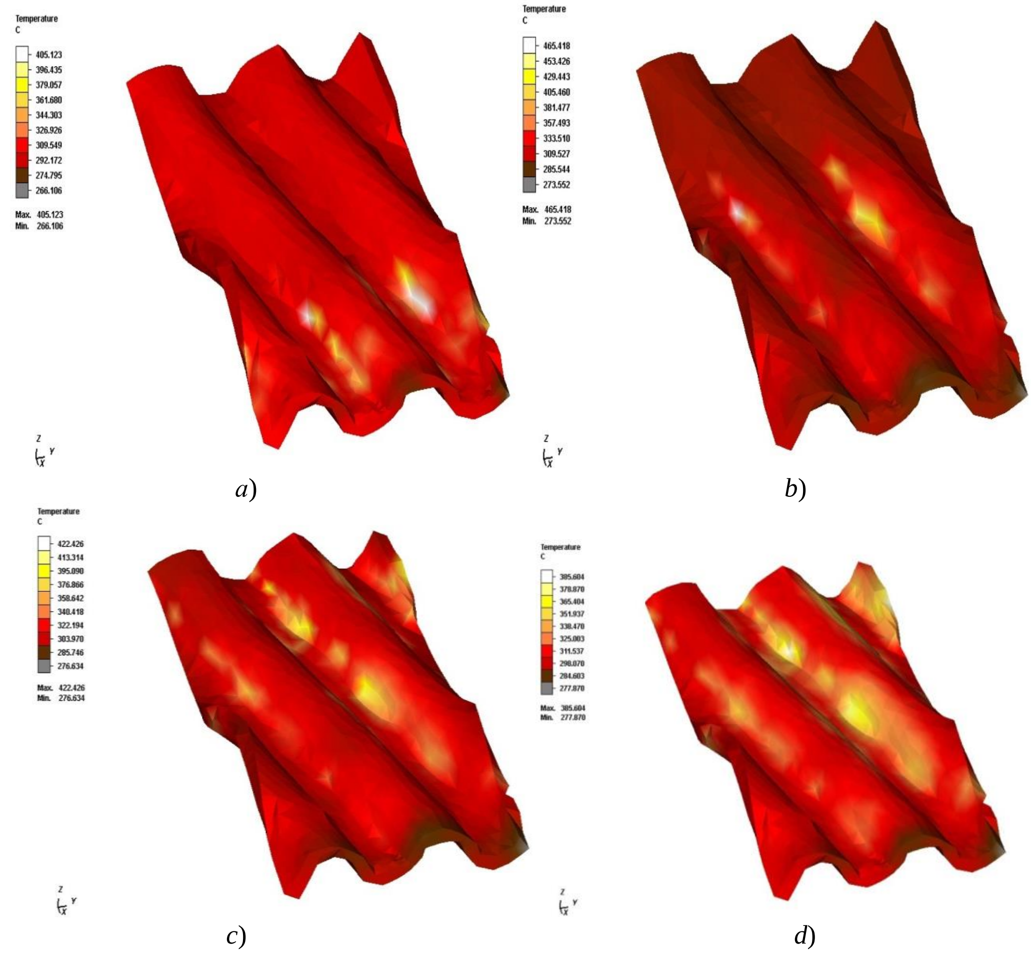


Fig. 5. The picture of the temperature field distribution in the workpiece during rolling in the helical rolls
(rolling temperature is 320 °C): *a* – the first pass; *b* – the second pass; *c* – the third pass; *d* – the fourth pass

6) Rolling on the LWM leads to an intensive cooling of the sections of the strips which are located in the contact zone of the metal with the roll (Fig. 8).

7) During rolling process in the stands of the LWM, the temperature increases in the zones of deformation localization;

8) During rolling in the stands of LWM, some areas of metal with relatively high temperature are moved together with the deformation zones (Fig. 8).

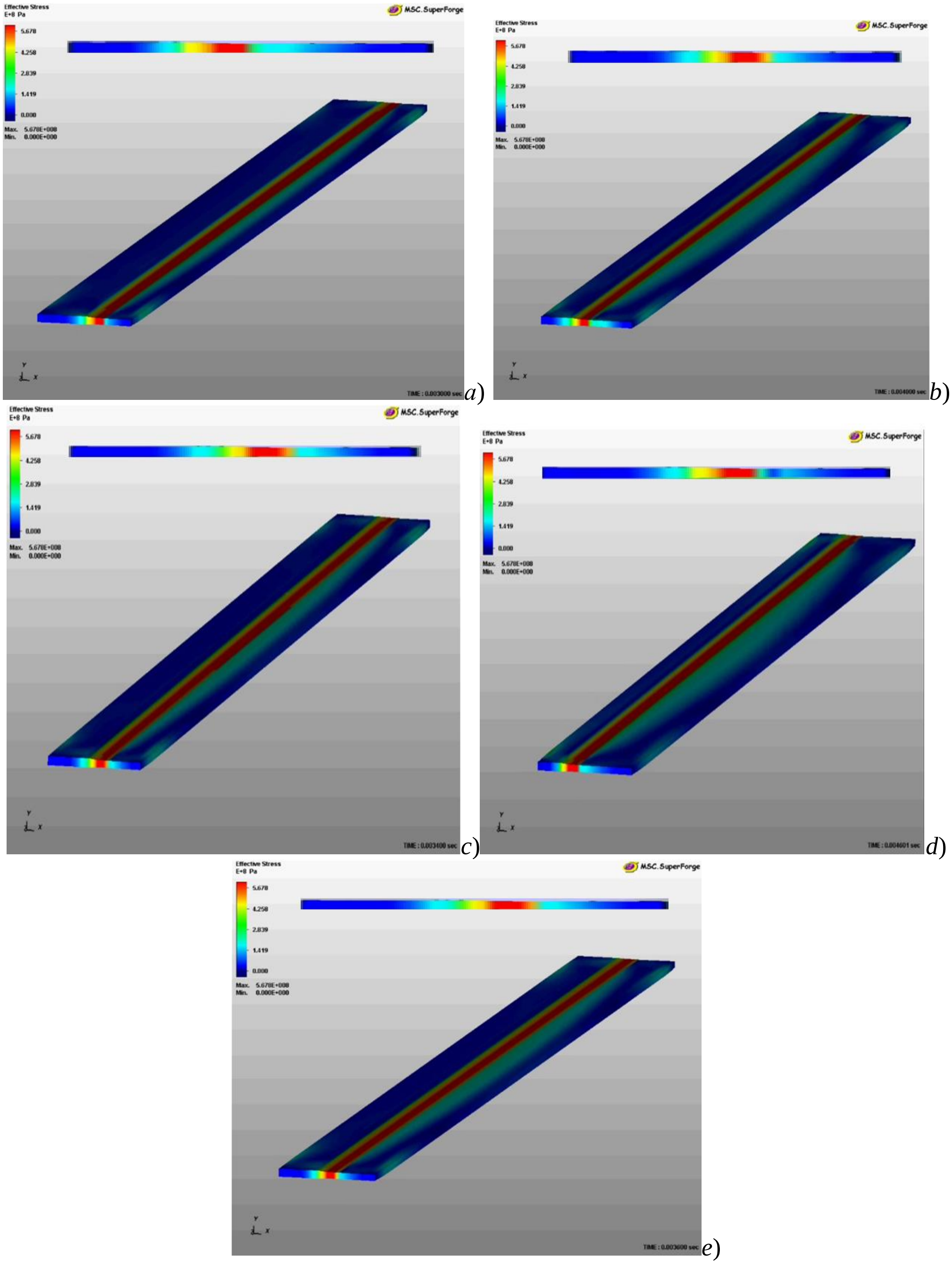


Fig. 6. The stress intensity distribution pattern in the workpiece during rolling on the LWM (the rolling temperature is 20 °C): *a* – the first stand; *b* – the second stand; *c* – the third stand; *d* – the fourth stand;
e – the fifth stand

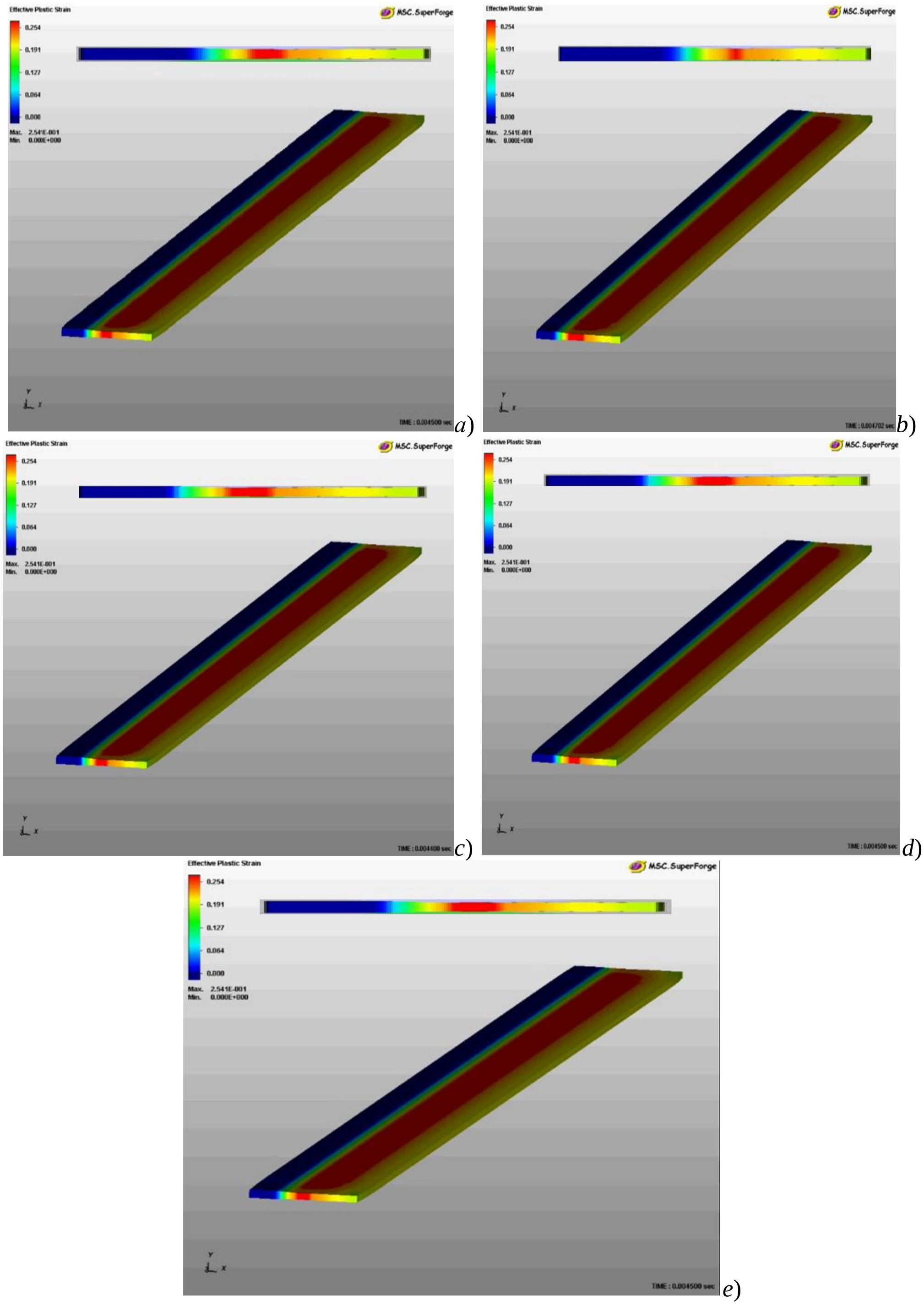
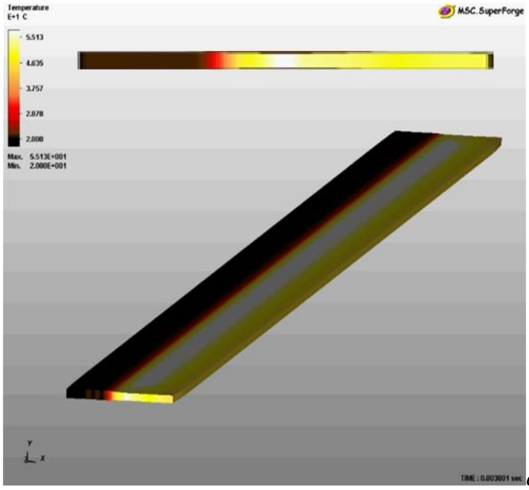
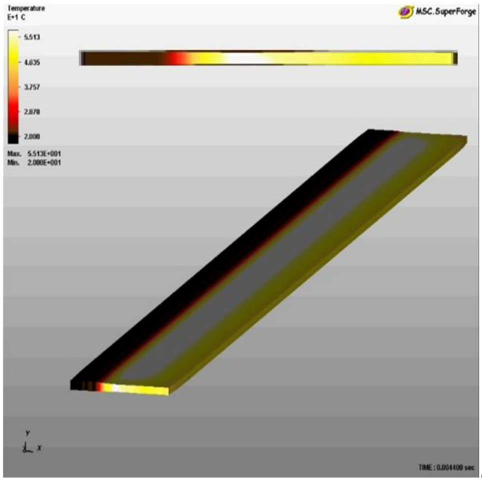


Fig. 7. The deformation intensity distribution pattern in the workpiece during rolling on the LWM (the rolling temperature is 20 °C): *a* – the first stand; *b* – the second stand; *c* – the third stand; *d* – the fourth stand; *e* – the fifth stand

Using the obtained results of the SSS distribution along the cross section of the workpiece during rolling in the helical rolls and LWM, a technology of manufacturing strips with an UFG structure was implemented. This technology has been tested in the laboratory conditions.



a)



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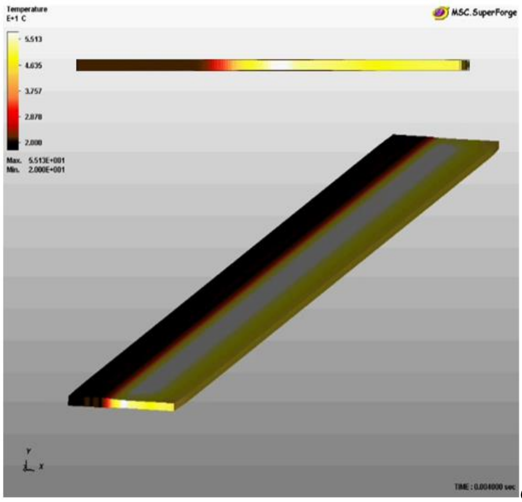

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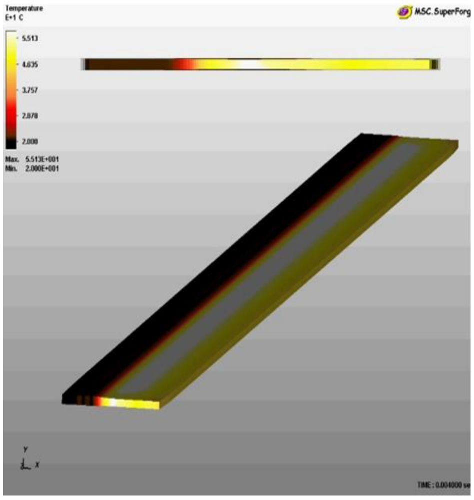

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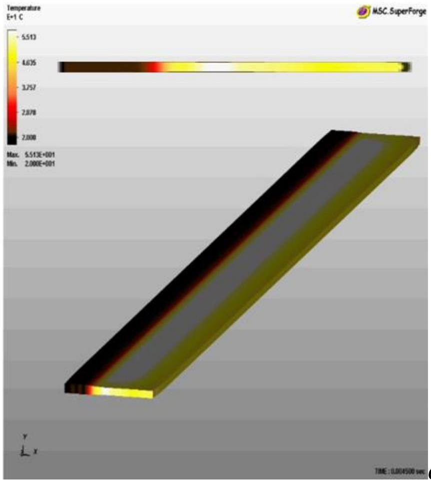


e)

Fig. 8. The temperature field distribution pattern in the workpiece during rolling on the LWM (the rolling temperature is 320 °C): *a* – the first stand; *b* – the second stand; *c* – the third stand; *d* – the fourth stand;
e – the fifth stand

While testing the technology, the initial workpiece from ENAW-2024 aluminium alloy and with 6 mm thickness was heated until the temperature reached 320 °C, then it was kept for 30 minutes and rolled by 4 passages in the helical rolls to 5.9 mm thickness. Further, the obtained workpiece was heated until the temperature reached 320 °C and rolled by 4 passages in the helical rolls to 5.7 mm thickness. After rolling in the helical rolls, the workpiece was cooled down till the room temperature and deformed on the LWM at the room temperature until the thickness of 1.5 mm.

The study of the microstructure has showed that the workpiece of ENAW-2024 alloy has a heterogeneous microstructure at the initial state, which consisted of large unrecrystallized grains having an average size of about 302 μm in the longitudinal direction and ~ 318 μm in the transverse direction. In addition, there are small grains with the size of ~ 45-53 μm located along its boundaries.

The study of the structural condition of ENAW-2024 aluminium alloy after rolling in the helical rolls by 4 passages shows that:

- the micro stripped structural condition is formed in the cross section perpendicular to the rolling plane;
- the density of intragranular dislocations is increased;
- the shear bands with the width of 16 - 18 μm are formed;
- the deformation in the form of shear bands takes place mainly within the large grains;
- the most possible values of the widths of microbands with large angle boundaries after rolling by 4 passages are in the range of 12 - 16 μm; the maximum value (very rarely observed) of this quantity is ~ 19 μm.

- the width of microbands with low-angle boundaries can vary from 2 – 6 μm, at the most possible value of about 4 μm.

Further heating to a temperature of 320 °C and deforming the workpieces in the helical rolls by 4 passages led to:

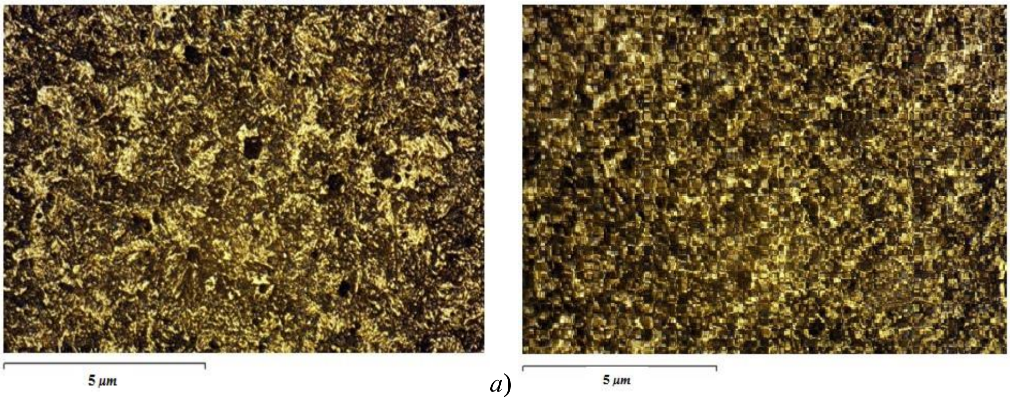
- the formation of the homogeneous and equiaxial structure on the longitudinal and cross sections of the workpiece;
- there is a further refiniment of grain-subgrain microstructure;
- the polygonized or recrystallization structure throughout the volume of rolled strips with an average grain size of about 12 – 18 μm is formed, as a result of the carriage of softening processes in the metal blank;
- the large angle boundaries are formed in the border areas of the grains.

The dislocation density is very high and as a result it was not possible to calculate its value by the structure of the image.

It can be assumed that with an increasing level of deformation on the subsequent passes of the rolling process in the helical rolls, the structure refinement occurs not only by twinning, but also by the formation of porous substructures as a result of the development of slip dislocations processes. At high degrees of accumulated deformation, the boundaries of the initial twins and subgrains are transformed into large angles.

It is known [25] that the presence of large-angular boundaries shows the implementation of dislocation-disclination mechanism of reorientation of the crystal lattice, which is developed in two stages: the formation of a substructure with non-zero components of the tensor density of disclinations; its collective relaxation in the discrete boundaries of disorientation. This mechanism is one of the most universal mechanisms of fragmentation of the crystal, including the formation of submicron and nanocrystalline structural conditions in a wide range of metals and alloys. Thus, the action of the alternating mechanisms of deformation provides the fragmentation and reorientation of the crystal lattice while rolling in the helical rolls. At the same time, the large angular boundaries are formed in the transverse direction of the workpiece with a high density.

The deformed strips were further rolled on the LWM at a room temperature with the purpose of investigating the effect of rolling on the LWM on the formation of the microstructure of ENAW-2024 aluminum alloy (Fig. 9). It is evident that the rolling at a room temperature greatly affects the alloy microstructure. The microstructure of ENAW-2024 aluminium alloy, after rolling in the helical rolls by 4 passages and on the LWM, is characterized by the presence of subgrains formed inside the former deformation bands (Fig. 9, *a*). The average size of the subgrains is 820 – 930 nm.



a) b)

Fig. 9. The microstructure of ENAW-2024 aluminium alloy after rolling in the helical rolls and LWM: *a* –after four passes; *b* – after eight passes

Rolling in the helical rolls by 8 passes and on the LWM at a room temperature leads to the formation of structures with an UFG size. As a result of conducting the softening processes along the volume of rolled strips, the structure in a range of an ultrafine size is formed and equals to 430 – 520 nm (Fig. 9, *b*). The obtained UFG structure is characterized by the uniformity of the grain size throughout the volume of the material. The images of the microstructure after rolling on the LWM present a clear picture of the grain boundaries. The view of the microstructure indicated the formation of grains with predominantly large angle boundaries. Thus, the evolution of the structure of ENAW-2024 aluminium alloy during rolling in the helical rolls and LWM in the following order:

- formation of the deformation substructure (dislocation and twin) with a strips of about 16 - 18 μm in a width;
- formation of the cross boundaries inside the strips, increase of the internal stresses and distortions of the original crystal lattice;
- development of the softening processes such as polygonization and primary recrystallization with the formation of ultrafine grain structure with the size of 430 - 520 nm.

The results of evaluation of strength and ductility parameters of the ENAW-2024 alloy after rolling in the helical rolls and LWM are shown in Table 1. It should be noted that the strength properties of the UFG material influences not only the average grain size, but, mostly, its nature, size and distribution of its dispersed particles. Additionally, conducted energy dispersive spectrum mapping (energy dispersive X-ray microanalysis, mapping the surface of the elemental composition) of the surface showed that the plate S-phase (Al_2CuMg) is extracted in the ENAW-2024 alloy at the grain boundaries. This process reduces the effects of aging. These particles grow as the development of the aging process, and reinforcement T-phase ($Al_{12}Mn_2Cu$), whose coherent particles are distributed uniformly in the body of grains, dissolves, which leads to a drop-in strength. High strength is achieved if the T-phase with coherent boundaries is released homogeneously throughout the volume of the grain.

Table 1

The mechanical properties of ENAW-2024 alloy (at room temperature) after rolling in the helical rolls and on the LWM

The state of the alloy ENAW-2024	$\sigma_{0,2}$, MPa	$\sigma_в$, MPa	δ, %
along the direction of rolling			
Rolling in the helical rolls 4 passes + LWM+ heat treatment	286	438	9,8
Rolling in the helical rolls 8 passes + LWM+ heat treatment	304	488	10,6
transversely to the direction of rolling			
Rolling in the helical rolls 4 passes + LWM+ heat treatment	289	441	9,8
Rolling in the helical rolls 8 passes + LWM+ heat treatment	310	497	10,4

The alloy deformed by 4 passages in the helical rolls demonstrates lower levels of strength and ductility than after rolling by 8 passages in the helical rolls. This is due to the fact that the structure of the alloy after deforming by 4 passes in the helical rolls consists of larger grains and contains stitch accumulation of S-phase, angled at 45 ° to the stretching axis, i.e. they coincide with the direction of action of maximum shear stresses. Lowering the strength characteristics of the alloy after rolling in the helical rolls by 4 passages are also connected with an increase of S-phase fraction in the volume. It is shown that ENAW-2024 alloy demonstrates the highest mechanical properties after rolling by 8 passages in the helical rolls and on the LWM. Apparently, it is connected to the optimum combination of structural strengthening, associated with the size of grains and dispersive hardening, mainly connected with the coherent particles of the T-phase in the body of grains.

4. Conclusions

First of all, rolling in the lower left-handed and upper right-handed rolls with the oppositely located projections and recesses leads to the localization of the deformation intensity in the contact zones of the work piece at the initial stage of rolling, and in the subsequent stages – in the zones below the inclined portions of the projections and depressions of the rolls. Further, rolling in the stands of the LWM allows to gradually move the zones of SSS concentration from the surface zones to the central layers of the work piece, and then uniformly deform the strip along the its length.

Moreover, the results of the microstructure evolution of the long work pieces at various stages of their production have shown the possibility of obtaining strips with an UFG structure by using the helical rolls and LWM. In addition, it has been established that the rolling in the helical rolls plays the main role in the technological scheme of processing, whose action results in an intensive refinement of the metal microstructure. Finally, it is shown that the sheet material of ENAW-2024 aluminium alloy ensures a uniform formation of UFG structures with an average size of 430 – 520 nm, which can lead to the increase in the strength properties of the alloy and preserves good ductility.

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