

*The paper proposes a radial shear mill (RSM) of a new design, which allows manufacturing metal rods of small diameters or wires with a fine-grained structure. The paper presents the results of modeling the evolution of the structure during hot rolling-pressing of aluminum alloy 7075 on the RSM. Mathematical modeling of the technological process was carried out using the MSC.SuperForge, and the empirical Johnson-Mehl-Avrami-Kolmogorov equation was used to predict the passage of softening processes. Due to the absence of the coefficients of the Avrami equation, a series of experiments on physical modeling of the rolling-pressing technological process were conducted on an STD 812 torsion rheometer. The experiments were conducted at the temperature range of 250–450 °C and a strain rate of 1.0–20 s<sup>-1</sup>. By using physical modeling, it was proved that during processing on the RSM, it is necessary to develop a torsional deformation over the entire section of the workpiece, which leads to effective refinement of the structure. The derived formulas and simulation modeling of the obtained values of the stress-strain state (SSS) were used to simulate the technology of the combined process. Moreover, rational temperature-rate conditions were determined to deform the workpiece on the RSM. It was proved by mathematical modeling that shear deformations develop along the entire section of the workpiece during processing on the RSM, which leads to effective refinement of the structure and the formation of a fine-grained structure in the rods, i. e. products of the required quality are manufactured*

**Keywords:** aluminum alloy, mathematical modeling, Avrami equations, physical modeling, recrystallization, microstructure

# DEVELOPMENT OF TECHNOLOGIES FOR HOT PRESSING OF RODS MADE FROM 7075 ALUMINUM ALLOY ON A RADIAL-SHEAR MILL OF A NEW DESIGN – NUMERICAL MODELING

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## 1. Introduction

Today, the quality of any metal product, including rods and wires, is associated with the change in shape, determined by the change in the linear and angular components of the strain tensor [1, 2]. Structural changes in a material depend not only on the linear component of the deformation tensor, but also on the development of macroshear deformations. Macroshear deformations significantly refine the metal structure. For this reason, they must be taken into account when choosing the types of processing and developing technology.

According to [3], it can be seen that the drawing corresponds to triaxial opposite schemes of the stress-strain state (SSS). In this case, the workpiece metal is drawn along the drawing direction. The rotation of the principal axis of the strain tensor relative to this direction is small. All this allows drawing to be attributed to a quasi-monotonic process. During drawing, the subgrains are deformed in a plane flow, i. e. in the direction of drawing, the subgrains lengthen, and in the radial direction, their sizes decrease by almost five times at the true degree of deformation  $\leq 6$ . However, macro-shear deformations do not develop along the section of the workpiece. As a result, subgrains acquire an elongated shape,

which leads to an increase in the anisotropy of the properties of bar products and wire.

In this regard, the development of a technology for rolling rods on the RSM of a new design is an urgent task of rolling production, as the development of shear deformations along the entire section of the workpiece leads to effective refinement of the structure and the formation of a fine-grained structure in rods from 7075 aluminum alloys.

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## 2. Literature review and problem statement

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At present, the main method for the production of rods and wires is drawing in monolithic dies [1]. This method is well studied theoretically. Reliable equipment is used for its implementation. The undoubted advantages of drawing round wire in monolithic drags are the simple deformation scheme according to the “circle-circle” system and the design of the tool.

It is known [2] that drawing in roller die increases the uniformity of deformation over the section of the workpiece and thereby increases the plastic properties of the wire, especially if deformation is carried out according to the “circle-circle” system. However, the “circle – shaped section – circle” gauge systems, used in practice, significantly complicate the design and increase the number of roller dies.

In [4–6], various variants of equal channel angular broach (ECAProt) are proposed. These methods are carried out by repeatedly pulling the wire through a special tool having 2 channels intersecting at an angle. Continuous deformation is carried out by installing the required number of tools on the drawing mill. ECAP method ensures the non-monotonicity of the deformation process of the workpiece, while large accumulated degrees of shear deformation in the metal are achieved.

The authors of the works [7–9] have developed a method in which the workpiece is alternately deformed in intersecting channels. It should be noted that the dies have the form of disks of the same diameter with eccentrically located channels and the possibility of rotation. In addition, Continuous Shear Drawing (CSD), based on equal channel angular pressing principles, can be used to obtain a homogeneous microstructure with fine globular cementite.

In the papers [10–12], shear drawing technologies are presented. In these works, the research was carried out in a special device, where the drawing of rods and wires is carried out by macro shear. The dies of the device have a special geometrical shape, they rotate around the drawing axis. This method provides a high degree of shear deformation, which leads to the formation of a fine-grained structure and can be used on the existing drawing equipment. However, its implementation requires a tool with a rather complex geometry. This method is quite promising and it is at the stage of laboratory research.

Experimental studies of the kinematics of the radial-shear broach (RSB) were first carried out in [13]. In that paper, it is shown that, at all other things being equal, the drawing force on the RSB installation is approximately 30 % lower than when drawing through a monolithic die. A laboratory study carried out on a wire made of steel grade U12A showed that the use of RSB makes it possible to increase the depth of penetration of deformation along the cross-section of the wire, to increase the deformability of the wire and to reduce the cycle of the technological process of manufacturing the wire.

The prototype of RSB is RSR, which has become widespread for the production of round bars, wires, etc. [14, 15]. It should be noted that RSR mills are the main equipment for the production of the above products [16, 17]. The productivity of the units and the quality of the manufactured products depend on these mills. In the known RSR mills, bar billets are processed in the deformation zone formed by three work rolls deployed at the feed and rolling angles and located at 120° around the deformable billet. These mills are relatively complex rolling equipment. This is due to the fact that, due to the rotation of the rolls at the feed angle, the rotational motion of the rolls is transmitted to the workpiece as a rotational-translational motion through the deformation zone.

In the case of RSR, two mechanisms of metal flow are realized simultaneously: longitudinal and rotational metal flows, providing a “helical” metal flow, which leads to the formation of a “spiral” microstructure in the metal. In this case, the degree of shear deformation increases significantly.

Most of the above processes use mini-mills [18]. In mini-mills, unique technological processes are used, where products of solid section from alloys of more than 300 brands are obtained by radial-shear deformation (RSD). When rolling in mini-mills, macro-shear displacements of metal particles dominate in the deformation zone. These movements deeply work out the structure at all levels of the metal physical structure. The properties of the metal are practically reaching their potential limit. In particular, plastic characteristics and many service properties increase by 1.5...2.0 times, compared to traditional methods of pressure treatment.

In [19], it is noted that by monitoring and controlling the formation of structures and properties of rods in the technological line of known mills, it is possible to obtain high-quality products. However, in order to determine the optimal temperature-deformation intervals for processing in such lines, leading to the formation of a fine-grained structure, a complex of experimental and industrial research is required. It should be noted that such research takes a certain amount of time and material consumption. Therefore, for the development of technological processes that allow obtaining high-quality products, it is necessary to study various processing modes by physical and computer modeling of the process and find rational modes that allow the manufacture of products with a fine-grained structure and high mechanical properties. The use of such modeling methods can significantly minimize the resource and time costs of conducting a study. Consequently, physical and computer modeling makes it possible to determine the rational temperature-deformation modes of rolling and pressing in a resource-saving way.

In this work, a radial shear mill (RSM) of a new design is proposed [20]. In this mill, by combining hot screw rolling and pressing, metal rods of small diameters or wires with a fine-grained structure are obtained.

The RSM for pressing bars and wires contains a main drive, a working stand, a roll unit and a press die. The three-roll working stand RSM consists of a bed, in the bores of which the work roll assemblies are mounted at 120° intervals. The work rolls are mounted on chocks. The torque is transmitted to the rolls through the spindles from the electric motors. The rolls of this mill have wavy-cone-shaped gripping and reduction sections and a sizing section. Note that the projections and valleys of the wavy-cone-shaped sections are made along a helical line. In this case, the geometric dimensions of the protrusions and valleys gradually decrease in the rolling direction.

To study the evolution of the microstructure, the Johnson-Mehl-Avrami-Kolmogorov model of grain refinement of metals and alloys was used [21, 22]. In this model, to describe changes in the microstructure of metal during hot working by pressure, a number of dependencies are used that describe the change in microstructure during static, metadynamic and dynamic recrystallization, as well as an equation for describing grain growth without recrystallization. It should be noted that these dependencies are difficult to use to predict the structure of the 7075 aluminum alloy during hot deformation on the RSM. This is due to the absence of the coefficients of the equation for this alloy under the conditions of processing on the RSM of a new design.

### 3. The aim and objectives of the study

In connection with the above, the aim of the work was: to develop a rational technology for hot pressing of aluminum alloy rods on a radial shear mill of a new design by using physical and computer modeling.

To achieve the aim, the following objectives were defined:

- to determine the coefficients and by the obtained Avrami equation to predict the structure of the aluminum alloy 7075 during hot deformation on the RSM of a new design;
- to calculate the stress-strain state (SSS) of the workpiece when pressing the bars on the new RSM by using computer simulation;
- to determine the rational temperature-rate conditions for deformation of the workpiece on the RSM of a new design by using the obtained Avrami equation and the SSS of the workpiece;
- to prove that during processing on the RSM, the rotational and translational deformation of the workpiece ensures the development of shear deformations along the entire section of the workpiece, which leads to effective refinement of the structure and the formation of a fine-grained structure in rods made of 7075 aluminum alloys.

### 4. Materials and methods of the research

To determine the coefficients of the Johnson-Mehl-Avrami-Kolmogorov equation, a series of experiments were carried out on the STD 812 torsion plastometer.

To determine the aforementioned coefficients of the equation, a series of experiments were carried out on a torsional plastometer STD 812 [23]. This plastometer allows testing samples at temperatures up to 1,500 °C with heating and cooling rates up to 100 K/s, at deformation rates up to 50 s<sup>-1</sup> in torsion and up to 1.0 s<sup>-1</sup> in tension and compression. During testing, continuous or fractional torsion, compression, or tension is realized with a given degree and rate of deformation at each pass. The plastometer is equipped with a control unit and computer software that automatically generates curves of resistance of metals and alloys to deformation, while easily determining the initial, intermediate and final geometric parameters of the samples.

Heating is carried out in an electric furnace or inductor, the heating and testing environment is air, argon, vacuum (10<sup>-4</sup> MPa). The sample temperature before testing, during and after testing is set according to any real law, as a

function of time. The sample is hardened in water, including instant quenching.

Aluminum alloy 7075 was selected as the workpiece material (chemical composition: Zn – 5.7; Mg – 2.5; Cu – 1.5; Cr – 0.19; Fe – 0.18; Si – 0.05; Ti – 0.06; Al – the rest). For the manufacture of samples with a homogeneous and relatively coarse-grained structure, the original bar stock 10 mm in diameter was subjected to homogenization annealing at a temperature of 470 °C for 30 hours.

Cylindrical specimens with a diameter of  $D=8$  mm and a base length of  $L=20$  mm were prepared from the annealed rods. A type  $K$  thermocouple was used to measure and control temperature changes. A type  $K$  thermocouple was welded onto the lateral surface of the samples. The samples were tested in a vacuum at a constant strain rate. The samples were heated to temperatures of 250, 300, 350, 400, 450 °C at a rate of 5 °C/s, held at this temperature for 250 s, and tested by torsion at a strain rate of 1.0, 10 and 20 s<sup>-1</sup>. In this case, the testing of the samples was carried out with a true degree of deformation of 1.0 and more with a deformation interval of 0.1.

In the proposed mill, the production of rods is carried out sequentially by applying the operation of rolling and pressing. Therefore, some samples were tested in two stages of deformation with a total degree of deformation of 0.6, 0.7, 0.8, 0.9. The pause duration between test stages was varied from 1 to 5 s.

After deformation of the samples to a given degree of deformation, they were quenched to fix the resulting metal structure. It should be noted that some of the samples were deformed to a strain of 0.6, 0.7, 0.8, and 0.9 and slowly cooled in an oven. Slow cooling was necessary to study the effect of static recrystallization on the metal structure.

To assess the effect of torsion on the structure of alloy 7075, metallographic studies were carried out. Sections for metallographic research were prepared according to the traditional method of grinding and polishing wheels.

The metallographic analysis was performed using a NEOPHOT 32 universal microscope (Karl Zeiss, Jena) (Germany). The Neophot 32 microscope is designed for metallographic microscopy and photographing. Observation can be carried out by the method of bright and dark fields, in polarized light, with a change in the magnification ratio. Magnification of the microscope, factor: from 10 to 2,000. The microscope is equipped with a digital SLR camera Olympus (Germany) with the output of the obtained image and saving the images to the computer.

To quantify the relative softening ( $RS$ ), we calculated the dynamic softening of the 7075 aluminum alloy [24, 25]:

$$RS = \frac{\sigma_p - \sigma_{p+0.5}}{\sigma_p}, \quad (1)$$

where  $\sigma_p$  – the value of the peak of the strain, and  $\sigma_{p+0.25}$  – the value of the strain, obtained at the deformation of 0.25 out of the limits of the strain peak. Dynamic hardening occurs at  $RS < 0$ , and dynamic softening occurs at  $RS > 0$ .

The work determined the volume fraction of recrystallized grains, the average size of the ground grains, the value of critical deformation, as well as the time and degree of deformation at which 50 % of recrystallization occurs. Further, using these data, the coefficients of the Avrami equation were calculated. To determine the unknown parameters of the Avrami equation, the method of least squares was used.

After finding the coefficients of the equation, Avrami estimated the accuracy of their approximation by the coefficient of determination  $R^2$ .

The MSC.SuperForge software was used to calculate the force and stress-strain state of rolled and then pressed rods [26]. A three-dimensional geometric model of the workpiece, rolls and matrix was built in the CAD program Inventor and imported into the CAE program of MSC.SuperForge. When creating a finite element model of the workpiece, rolls and matrix, a three-dimensional volumetric element CTETRA (four-node tetrahedron) was used, which is used to model three-dimensional bodies.

To study the process of rolling and pressing in the RSM of a new design, a round billet of 7075 aluminum alloy with a size of 40×150 mm was used. The blanks were pressed at temperatures of 200, 300, and 400 °C up to Ø9 mm. The Johnson-Cook elastoplastic model was chosen to model the plasticity of the workpiece material. The rheological properties were set from the database of the MSC.SuperForge software. The contact between the tool and the rod was modeled by the Coulomb friction law, the friction coefficient was taken as 0.3.

The MSC.SuperForge was launched, and the contact pressure, contact area, stress-strain state and temperature distribution over the volume of the pressed workpiece were calculated by the stepwise method.

**5. Results of microstructures at various temperature-deformation modes of bar processing on the RSM**

**5.1. Calculation of coefficients of the Avrami equation for predicting the structure of 7075 aluminum alloy during hot deformation of workpieces on the RSM of a new design**

Deformation resistance curve ( $\sigma_s - \bar{\epsilon}$ , stress – current – true degree of deformation) of 7075 aluminum alloy obtained by testing specimens by torsion at temperatures of 250, 300, 350 °C shows that the stress flow at the beginning of the test of each specimen increases intensively and then slowly decreases. Deformation of specimens by torsion at temperatures of 400, 450 °C also leads to a rapid increase in the flow stress at the beginning of testing, but further testing leads to a sharp drop in flow stresses.

Investigation of the initial structure of aluminum alloy 7075 showed that the structure of the sample contains relatively large grains with an average size of ~142 μm. The grains are unevenly distributed.

Deformation of specimens by torsion at a deformation rate of 20 s<sup>-1</sup> at temperatures of 250 and 300 °C led to a slight decrease in grain size. The average grain size varied from 82 μm to 97 μm. The grain size decreased comparatively more when testing samples under the same temperature conditions, but with a strain rate of 1.0 and 10 s<sup>-1</sup>. In these cases, the average grain size varied in the range of 63–76 μm. At the same time, the grain size was especially intensively refined at the first stage of testing.

It should be noted that the testing of samples by torsion at a speed of 1.0 and 10 s<sup>-1</sup> and at temperatures of 350 and 400 °C led to a significant refinement of the grain sizes in comparison with the original grain size. Thus, the samples tested under these temperature-deformation and velocity conditions had a relatively fine-grained structure with an average grain size of 29 and 34 μm, respectively. A

comparatively coarser-grained structure was obtained in specimens tested under the same temperature conditions, but at deformation rates of 20 s<sup>-1</sup>. In this case, the average grain size was 47 μm. However, here the fragmentation of grains also occurred more intensively at the first stage of deformation.

Analysis of the microstructures of the samples deformed at a temperature of 450 °C with a deformation rate of 20 s<sup>-1</sup> showed that processing at a high temperature and deformation rate leads to a relatively fine-grained structure with an average grain size of 56 μm. It should be noted that the samples deformed at a strain rate of 1.0 and 10 s<sup>-1</sup> received a relatively large fragmentation of grains. Their grain sizes are 39 and 43 microns, respectively. In this case, as at other test temperatures, the greatest grain size reduction occurs at the first test stage.

Table 1 demonstrates a certain volume fraction of recrystallized grains in the microstructures of the samples. This table shows that with an increase in temperature and a decrease in the deformation rate, the volume fraction of recrystallized grains increases.

Table 1

Volume fraction of recrystallized grains

Deformation rate, s <sup>-1</sup>	Test temperature, °C				
	250	300	350	400	450
1	0.46	0.76	0.83	0.96	1.0
10	0.37	0.64	0.7	0.87	0.95
20	0.31	0.56	0.66	0.81	0.87

It should be noted that, using the above data and the method of least squares, the coefficients of the Johnson-Mehl-Avrami-Kolmogorov equation were determined (see below). At the same time, to determine the volume fraction of recrystallized grains, the following Avrami equations were used [31, 32]:

– dynamic recrystallization:

$$X_{DRX} = 1 - \exp \left[ -0.639 \left( \frac{\bar{\epsilon} - 0.9\epsilon_p}{\bar{\epsilon}_{0.5}} \right)^2 \right]; \tag{2}$$

– metadynamic recrystallization:

$$X_{MRX} = 1 - \exp \left[ -0.639 \left( \frac{t}{t_{0.5}} \right)^{0.782} \right]; \tag{3}$$

– static recrystallization:

$$X_{SRX} = 1 - \exp \left[ -0.639 \left( \frac{t}{t_{0.5}} \right)^2 \right]; \tag{4}$$

where  $\bar{\epsilon}_{0.5}$  – true degree of deformation at 50 % recrystallization;  $t_{0.5}$  – time during which 50 % of recrystallization occurs;  $\bar{\epsilon}$  – true degree of deformation;  $t$  – deformation temperature.

The magnitude of the critical deformation, as well as the time and degree of deformation at which 50 % of recrystallization occurs, were determined by the formula:

$$\varepsilon_p = 4.1449d_o^{0.31} \cdot \varepsilon^{0.06} \exp\left(13,180/RT\right), \quad (5)$$

$$t_{0.5} = 0.794d_o^{0.34} \cdot \varepsilon^{-1.63} \dot{\varepsilon}^{-0.1243} \exp\left(18,045/RT\right), \quad (6)$$

$$\varepsilon_{0.5} = 1.325 \times 10^{-5} d_o^{0.17} \cdot \varepsilon^{0.05} \exp\left(53,350/RT\right), \quad (7)$$

where  $R$  – universal gas constant;  $T$  – absolute temperature;  $d_o$  – initial average grain size.

The average grain size was determined by the following formula:

– average size of the dynamic recrystallized grains:

$$d_{DRX} = 76.962 \cdot d_o^{0.22} \cdot \varepsilon^{-0.61} \dot{\varepsilon}^{-0.0412} \exp(-1,902.72/RT), \quad (8)$$

– average size of the metadynamic recrystallized grains:

$$d_{MRX} = 23.34 \cdot d_o^{0.28} \cdot \varepsilon^{-0.39} \dot{\varepsilon}^{-0.0346} \exp(-1,902.72/RT), \quad (9)$$

– average size of the static recrystallized grains:

$$d_{SRX} = 31.08 \cdot d_o^{0.21} \cdot \varepsilon^{-0.39} \dot{\varepsilon}^{-0.0297} \exp(-1,902.72/RT). \quad (10)$$

The average grain size for the entire deformation process was calculated using the equation:

$$d_{avg} = X_{SRX}d_{SRX} + X_{MRX}d_{MRX} + X_{DRX}d_{DRX} + \left(1 - (X_{SRX} + X_{MRX} + X_{DRX})\right)d_o. \quad (11)$$

After finding the coefficients of the equations, the calculation of the volume fraction of recrystallized grains and the average size showed that the determination value  $R^2$  changes in the range 0.67–0.91.

## 5. 2. Calculation of the SSS of the billet when pressing on the new RSM using computer simulation

On the basis of the obtained results of numerical modeling, it was found that when processing a billet from an aluminum alloy 7075 on the new RSM:

– at the initial stage of deformation, the contact pressure is localized in the gripping zones of the workpiece with the working surfaces of the rolls, and then increases throughout the deformation zone;

– at the final stage of deformation, the contact pressure increases in the matrix, which is characteristic of the extrusion process, while the contact pressure on the rolls also increases (Fig. 1, *a*). All this is associated with an increase in the back-up pressure in the deformation zone from the action of the extrusion force;

– the contact pressure on the rolls is greater than the contact pressure on the die. The reason for this is an increase in the contact surface of the billet during rolling with three rolls and an increase in the back pressure in the deformation zone from the action of extrusion forces;

– the temperature of deformation in the zones of contact of the workpiece metal with the roll and the matrix increases intensively (Fig. 1, *b*), i. e. with an increase in drawing, a gradual increase in temperature occurs on the surface of the workpiece;

– small tensile principal stresses  $\sigma_1$  appear on the surface of the workpiece, while the outer layer of each element is subjected to compressive principal stresses  $\sigma_2$  and  $\sigma_3$ .

## 5. 3. Rational temperature and rate modes of deformation of the workpiece on the RSM of a new design

When rolling in helical rolls and pressing in a die installed on the RSM of a new design, the metal flows along a helical path with different speeds of the outer and inner layers. The movement of metal flows with different speeds, causes intense shear displacements in the volume of the workpiece, which leads to a significant increase in the intensity of stress and strain, as well as the rate of deformation (Fig. 1, *c–e*). It should be noted that with an increase in the elongation ratio, angles of feed and rolling, a gradual increase in the intensity of deformation and the rate of deformation over the section of the workpiece occurs.

The calculation of the volume fraction of recrystallized grains and the average grain size for the stages of deformation and for the entire period of pressing the bars on the new mill showed that:

– during rolling of the billet in helical rolls at temperatures of 200, 300 and 400 °C, the volume fraction of recrystallized grains in the central layers of the billet is less than in the surface zones of the billet;

– deformation in helical rolls at a temperature of 200, 300 and 400 °C leads to a volume fraction of recrystallized grains in the peripheral and adjacent to the periphery zones of the workpiece equal to 0.4, 0.7, 0.8, respectively. This means partial and complete passage of dynamic polygonization and recrystallization in the studied zones;

– rolling in helical rolls at temperatures of 200, 300 and 400 °C leads to obtaining the volume fraction of recrystallized grains equal to 0.1, 0.3, 0.4, respectively in the central regions of the workpiece;

– during pressing rods in a matrix at temperatures of 200, 300 and 400 °C, the volume fraction of recrystallized particles in the areas of contact with the matrix varies in the range of 0.4, 0.8, and 0.9, and in the central zones – 0.3, 0.6 and 0.7, respectively;

– after the end of pressing at temperatures of 300 and 400 °C, the volume fraction of recrystallized grains over the cross-section of the workpiece is leveled and reaches values equal to 0.9, 1.0, while pressing at a temperature of 200 °C leads to the formation of a different-grain structure (the volume fraction of recrystallized grains changes in the range of 0.3–0.5).

Evaluation of the microstructure of aluminum alloy 7075 showed that when rolling billets in helical rolls at temperatures of 200, 300, and 400 °C, the grain size in its peripheral part is 95, 42 and 31  $\mu\text{m}$ , and in the center is 112, 84 and 76  $\mu\text{m}$ , respectively. At the same time, further pressing of the billets in the matrix at temperatures of 200, 300 and 400 °C leads to the formation of grains with an average size of 84, 39 and 31  $\mu\text{m}$  in the peripheral region of the rod and 76, 32 and 27  $\mu\text{m}$  in the central zone of the rod, respectively. It should be noted that further passage of static recrystallization in the metal structure at temperatures of 300 and 400 °C leads to the formation of a homogeneous microstructure with a grain size of 27 and 21  $\mu\text{m}$ , respectively. However, pressing the billet on the RSM at a temperature of 200 °C leads to the formation of a structure of different grains with an average grain size of 63  $\mu\text{m}$ .

In the work, according to the developed rational technology, rods were manufactured using the new RSM. Rolling-pressing of the bars was carried out in the following modes: heating up to 300 °C (mode 1) and up to 400 °C (mode 2) and rolling the initial rod with a diameter of

40 mm on helical rolls to a diameter of 14 mm and further pressing of the transitional rod in the matrix to a diameter of 9 mm.

#### 5.4. Regularities of refinement of the structure of aluminum alloy 7075 during rolling-pressing on the RSM of a new design

In the work, according to the developed rational technology, rods were manufactured using the new RSM. The rolling-pressing of the bars was carried out in the following modes: heating to 300 °C (mode 1) and up to 400 °C (mode 2) and rolling the initial rod with a diameter of 40 mm on helical rolls to a diameter of 14 mm and further pressing the intermediate rod in the matrix to a diameter of 9 mm.

Based on the study of the microstructure of the 7075 aluminum alloy, it was found that the initial rods have relatively unevenly distributed large grains with an average size of ~147 μm.

The study of the structural states of the 7075 aluminum alloy rolled in helical rolls at a temperature of 300 °C showed that a microstrip structural state is formed over a section parallel to the rolling plane. In this case, thin shear bands are formed at the boundaries of the original grains. It should be noted that after such rolling, in the central zone of the longitudinal section of the bar, a pronounced strip structure is formed with the distance between the boundaries not exceeding 32–62 μm with the most probable values of 42–56 μm. The width of microbands with low-angle boundaries can vary from 10 μm to 16 μm, with the most probable value being about 14 μm. A relatively fine-grained structure with a grain size of 21–28 microns is formed in the surface zone of this rod.

Pressing in a matrix of the new RSM leads to the formation of a structure with a fine-grained size. As a result of the passage of softening processes throughout the volume of the pressed rods, a fine-grained structure with a size from 12 to 22 microns is formed. The resulting fine-grained structure is characterized by grain size uniformity throughout the material. A clear image of grain boundaries was observed in the images of the microstructure after rolling-pressing on the RSM. The type of microstructure indicated the formation of grains with predominantly high-angle boundaries.

A different picture is observed in billets rolled in helical rolls at a temperature of 400 °C. It was found that when rolling in helical rolls, the strip structure is divided into deformation, transit and microstrips, consisting of subgrains separated by high-angle and low-angle boundaries. In this case, shear bands with a width of up to 12–46 microns are formed throughout the section. Deformation in the form of shear bands occurs predominantly inside large grains. The most probable values of the width of microbands with high-angle boundaries are in the range from 26 to 46 μm, with the maximum value of this value being ~52 μm. The width of microbands with low-angle boundaries can vary from 12 μm to 18 μm, with the most probable value being about 16 μm.

It was found in this work that the final pressing of the blanks in the RSM matrix leads to the formation of a fine-grained structure with a grain size of 8–12 μm. Fragmentation of the structure to a fine-grained level occurs due to the subgrain structure breaking up and the transformation of low-angle boundaries separating the original subgrains into high-angle boundaries.

The formation of a fine-grained structure in the 7075 aluminum alloy was reflected in their properties.

It was found that in the 7075 alloy, the ultimate tensile strength increases by 30 %, and the yield strength increases by about 1.5 times compared to the initial state (Table 2).

Table 2

Mechanical properties of alloy 7075 (at room temperature) after rolling on a new RSS

Alloy condition 7075	$\sigma_{0.2}$ , MPa	$\sigma_b$ , MPa	$\delta$ , %
Initial state	398	541	7
Along the rolling direction			
Mode 1	492	682	10.0
Mode 2	496	691	11.8
Across the rolling direction			
Mode 1	491	679	11.2
Mode 2	521	688	10.8

## 6. Discussion of experimental results

It should be noted that regardless of the test temperature and deformation rate, the metal flow curves during the test acquire an approximately parabolic shape. This kind of curves allows assuming that at the initial stage of deformation, the metal of the sample is intensely hardened, and in the subsequent stages, it is actively or passively softened.

Based on the analysis of the deformation resistance diagrams, it was concluded that the application of torsional deformation to the sample at temperatures of 250, 300, 350 °C leads to the formation of sections with steady metal flows on the curves ( $\sigma_s = \sigma_{set}$ ). The presence of such areas indicates the passage of dynamic recovery and polygonization, provided that the increment in the flow stress from the true deformation is equal to zero ( $d\sigma_s / d\bar{\epsilon} = 0$ ) [27]. It is known that the passage of dynamic polygonization leads to the formation of a stable homogeneous, but coarser-grained structure with a high level of physical and mechanical properties in the metal. In this case, the constancy of the size of the subgrains will be ensured due to the passage of the metal structure through the repolygonization process.

Furthermore, the measured RS values (2.1 %, 2.8 % and 3.4 %) prove that at temperatures of 250, 300, 350 °C, dynamic recovery and polygonization take place in the metal structure. At the same time, the obtained stress – true deformation curves under all test conditions are single-peak. Therefore, during testing, softening processes such as dynamic recovery and polygonization are continuously undergoing in the structure of the studied metal [28, 29]. In addition, the RS values at the second stage of deformation are less than at the first.

In our opinion, the presence of a pronounced maximum on the  $\sigma_s - \bar{\epsilon}$  curves tested by torsion at temperatures of 400, 450 °C, and a rapid drop in the flow stress is a fairly reliable indicator of dynamic recrystallization processes in the metal [27]. This means that torsion testing at temperatures of 400, 450 °C with large values of the true degree of deformation leads to intensive dynamic recrystallization.

tallization. This is associated with a significant increase in the rate of diffusion processes at the temperature range of 400–450 °C. It should be noted that the obtained RS values (6.2 % and 7.4 %) also prove that the torsion of the samples at temperatures of 400 and 450 °C leads to dynamic recrystallization.

Consequently, the processes of dynamic softening prevail over the process of hot work-hardening when twisting samples in the temperature range of 250–450 °C. Therefore, the curves of the deformation resistance ( $\sigma_s - \bar{\epsilon}$ ) have a corresponding strain hardening coefficient (the stress increment from true strain is greater than zero ( $d\sigma_s / d\bar{\epsilon} \geq 0$ )) at the test temperature. With this type of deformation, the dislocation structure of the metal changes. The number of dislocations increases strongly with the growth of  $\bar{\epsilon}$ , which allows for further dynamic processes in the structure of 7075 aluminum alloy. This contributes to the formation of a fine-grained stable structure in the area of large deformations.

It should be noted that with an increase in the deformation temperature and a decrease in the deformation rate, the stress values decrease, in comparison with a low temperature and a high deformation rate, while the maximum of the deformation resistance curves ( $\sigma_s - \bar{\epsilon}$ ) more and more shifts to the region of lower deformation.

Thus, at the initial stage of torsion, strain hardening of the 7075 aluminum sample occurs with different intensities, the density of dislocations increases, their non-linear interweaving, and then a cellular structure of hot work hardening are formed. In this case, the critical dislocation density is reached, corresponding to the critical degree of deformation  $\epsilon_{cr}$ . The  $\epsilon_{cr}$  value is usually 0.8–0.9 of the  $\epsilon_x$  value. It should be noted that the  $\epsilon_x$  value characterizes the degree of deformation when a stage of stress increment from true strain greater than zero ( $d\sigma_s / d\bar{\epsilon} > 0$ ) passes into a stage of stress increment from true strain less than zero ( $d\sigma_s / d\bar{\epsilon} < 0$ ), i. e. when the softening processes are intensified and prevail over the strain hardening process. With an increase in the degree of deformation in the metal, the processes of dynamic softening are more and more pronounced, the process of dislocations creeping develops and the required number of point defects accumulates. Subgrains of various types are formed in the structure, and the hot work hardening structure is gradually replaced by a polygonized and recrystallized structure. The share of equiaxed subgrains and grains is more and more growing. Such subgrains and grains are formed by “crawling” of primary subgrains by the subboundaries of another system, and/or by improving the cellular structure of the metal, and also by the passage of primary recrystallization in the metal structure.

However, we have not found the data on deformation resistance and structural studies for 7075 aluminum alloy at temperatures of 250, 300, 350, 400, 450 °C and strain rates within 1.0, 10 and 20 s<sup>-1</sup>, that is, at temperature-deformation and rate modes of pressing on the new RSM. In [30], a partial study of the deformation resistance and structure of aluminum alloy 7075 was carried out. However, with these data it is difficult to determine the coefficients of the Avrami equation and to predict the structural change of this alloy during pressing rods on the RSM of a new design.

On the basis of the data obtained, it can be concluded that when rolling billets in helical rolls, dynamic recrystallization in the peripheral region of the billet is much

easier than in its central regions. We believe that the reason for the good passage of such a softening process is an increase in the magnitude of the strain intensity and strain rate, as well as the temperature in the peripheral zones of the rolled billets. At the same time, the value of these parameters is much higher than the critical degree of deformation.

Further pressing of the billet, pre-deformed in helical rolls, leads to a less intensive passage of metadynamic and dynamic recrystallization in the peripheral zones of the billet. The reason for such a relatively slow passage of recrystallization is an increase in the friction force in the contact zones of the metal of the workpiece and the tool.

Thus, during rolling of the billet in helical rolls, the average grain size in the central layers of the billet is bigger than in the surface zones of the billet. However, after pressing the workpiece through the die, the grain sizes along the cross-section of the bar are aligned.

It was found that during rolling-pressing on the RSM according to mode 1, due to the passage of high solid solution hardening of the initial Al matrix in the metal structure and the presence of dispersed hardening phases, fragmentation is the dominant mechanism of elastic energy relaxation with an increase in the degree of deformation, while the small mechanism is dynamic recrystallization.

In our opinion, when rolling in an RSR mill according to mode 2, a gradual evolution of the structure occurs, namely, the number of lattice and grain-boundary dislocations decreases, clear extinction contours appear at grain boundaries, i. e. all signs of dynamic recovery and dynamic recrystallization are manifested by a continuous mechanism. As a result of these processes, a fine-grained structure is formed in the material.

Thus, during rolling in mode 2, the relaxation of elastic energy in alloy 7075 is carried out by two mechanisms – low fragmentation and dominant dynamic recrystallization.

It should be noted that our research is limited to obtaining an improved Johnson-Mehl-Avrami-Kolmogorov equation for aluminum alloy 7075. These equations can only approximately predict the change in structure when extruding rods from other aluminum alloys on the new design RSM. Therefore, for manufacturing rods from other alloys on the new RSM, it is necessary to carry out research for other non-ferrous alloys. When carrying out such studies, difficulties may arise due to the need to carry out a large amount of experimental work on a plastometer.

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## 7. Conclusions

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1. The coefficients of the Avrami equation for aluminum alloy 7075 were determined by carrying out plastometric torsion tests of samples at temperatures of 250, 300, 350, 400, 450 °C with a strain rate of 1.0, 10 and 20 s<sup>-1</sup> and metallographic analysis of their structure.

2. The derived formulas and simulation modeling of the obtained values of the stress-strain state are used to simulate the technology of the combined process and to determine the rational temperature-rate conditions of deformation of the workpiece on the RSM. In the simulation, the technology of the combined process was used and rational temperature-deformation modes for processing the workpieces were

determined (heating the workpieces to temperatures of 300 and 400 °C and rolling-pressing of rods on the RSM from Ø40 mm to Ø9 mm).

3. The rational temperature-rate conditions of deformation of the workpiece on the new design of RSM are determined by using the obtained Avrami equation and the SSS of the workpiece.

4. It is shown that the rotational-translational deformation of the workpiece arising during processing on the RSM ensures the development of shear deformations along the entire section of the workpiece, which leads to effective re-

finement of the structure and the formation of a fine-grained structure in the rods of aluminum alloys 7075.

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