Review of scientific-applied research and industrial application of radial shear rolling technology

S. P. Galkin, *Dr. Eng., Prof., Dept. of Metal Forming* [1, 3], *e-mail: glk-omd@yandex.ru;*
T. Yu. Kin, *Leading Engineer, Postgraduate Student* [1], *Dept. of Metal Forming, e-mail: tatianakin@mail.ru;*
Yu. V. Gamin, *Cand. Eng., Associate Prof., Dept. of Metal Forming* [1, 3], *e-mail: y.gamin@mail.ru;*
A. S. Aleshchenko, *Cand. Eng., Associate Prof., Head of Dept. of Metal Forming* [1, 3], *e-mail: judger85@mail.ru;*
B. V. Karpov, *Head of Research and Development Center "OMD"* [2], *e-mail: karpov.bv@misis.ru*

[1] *National University of Science and Technology «MISIS» (Moscow, Russia)*
[2] *Research and Development Center "OMD" (Moscow, Russia)*
[3] *JSC "Istok ML" (Moscow, Russia)*

Radial-shear rolling technology (RSR) is a modern, effective technique for obtaining structured semi-finished and final bar products from various metals and alloys, including hard-to-deform ones. Due to design features (feed angle 18–20 °, rolling angle 0–12 °, taper angle of roll 10 ± 2,5 °) implemented in the RSR equipment (mini-mills) and unique trajectory-deformation conditions, the possibility of obtaining ultrafine-grained functional-gradient structure is realized. At the same time, mini-mills are characterized by compactness and versatility of working tools, which allows to reduce labor costs and follow the concept of lean production. This article reviews the industrial application of technology and equipment of RSR and scientific and applied research in this direction by various scientific groups, outlines the elements of theory, as well as the main stages of development and implementation. The reviewed publications indicate the demand for and prospects of application of RSR technology for obtaining products with a unique combination of properties.

Key words: radial-shear rolling, trajectory, deformation coefficients, deformation scheme, steel billet, gradient structure, rolling mini-mill, roll adjustment, recycling, deformation of continuously cast billets.
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1. Introduction

In modern classification of metal forming processes, the radial-shear rolling (RSR) is defined as a particular case of screw rolling of solid workpieces in the range of large feed angles (18 ° or more) using three-roll mill with special calibration of rolls.

The development of RSR process as a new method of metal forming started with comprehensive studies on increasing the productivity of screw piercing mills carried out at MISIS (1970-ies) under the supervision of P. I. Polukhin and I. N. Potapov. It was found that increase in the feed angle not only increased axial speed and productivity of piercing, but also qualitatively changed the conditions of metal deformation. At small feed angles traditional for piercing (up to 12–15 °), the axial zone of the workpiece is subject to the formation of a cavity, which is known as the Mannesmann effect. In the range of large feed angles (up to 18–24 °), the opposite effect is observed. The metal is intensively compacted over the entire cross-section, and the internal fracture is excluded, even with reduction of more than 25 %.

Depending on the geometry of deformation zone and elongation ratio (diameter reduction) per pass, two main variants of the RSR are distinguished (**Fig. 1**).

Variant "a": rolling in one pass with high elongation ratios (4–6 or more) in rolls which have the reduction section with an inclination angle of the roll generatrix to the rolling axis of 12–50 ° (inventor's certificate of the USSR, No. 1055551, application 09.05.1977).

Variant "b": multi-pass rolling with limited elongation ratios per pass (no more than 3–4) in rolls which have the reduction section with an inclination angle of the roll generatrix to the rolling axis of 6–12 ° (inventor's certificate of the USSR, No. 786120, application 04.07.1979).

The main function of variant "a" is a deformation of continuously cast billets to intensive compact and process the metal structure over the entire cross-section. The RSR stand of this variant was supposed to be used as a reduction stand as part of section rolling mills and pipe rolling plant. A planetary screw rolling mill with a similar purpose, but with a different operating principle, was developed abroad [1]. The variant "b" is a universal method, which is designed to rolling many deformable materials, including those with low-ductility and difficult-to-form. It is used in reverse rolling and rolling by mini-mills.

Both variants of the RSR were developed and comprehensively tested on a specially designed (together with EZTM JSC) full-size three-roll mill "MISiS-100T" with the possibility to rotate the rolls at a feed angle of 10–24° [2]. According to variant "a", experimental batches of round bars with a diameter of 55–60 mm from continuously cast carbon and stainless steel billets with a diameter of 120–125 mm were rolled in one pass. Pre-deformed workpieces with a diameter of 105–120 mm from high-speed steels R6M5, R18, tool

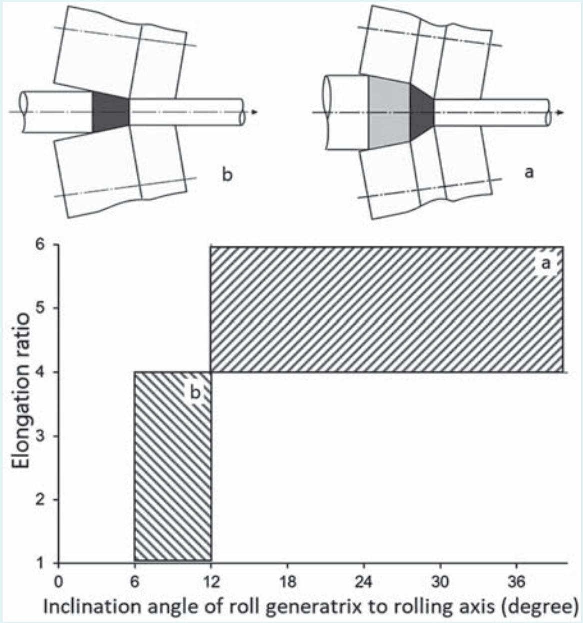


Fig. 1. Two main variants of RSR depending on geometry of deformation zone and elongation ratio per pass

steel Kh12, heat-resistant nickel-based alloys KhN77TYuR, KhN56VMTYu, KhN51VMTYuKFR, etc. were rolled to obtain a bar with a diameter of 55 mm according to variant “b”.

The results of experimental studies of the RSR process using “MISiS-100T” mill have domestic and world priority. Based on them, for the first time in the world, a method and mill for reverse multi-pass screw rolling was created and tested.

Due to high level of industrial readiness of studies, technology of radial-shear rolling and reversing RSR mills of an original design for producing rods and workpieces with a diameter of 50 to 300 mm were quickly developed together with EZTM JSC and specialists from industrial companies. For the first time in the world, unique complexes were developed and successfully moved to operations as follows [2]:

– bar and wire rolling mill 350/250 with reduction stand of RSR, allowing the rolling of workpieces from alloy steels and alloys of more than one thousand grades, including those with low-ductility and difficult-to-form (1984, “Electrostal” Metallurgical Plant JSC);

– two-stand mill “RSR-130” with the first reversing stand for the production of critical-use rolled products from more than 35 grades of titanium alloys (1989, VSMPO-AVISMA);

– reversing mill “RSR-500” for production rolled product from zirconium alloys from ingot with diameter of up to 450 mm (1987, SC “Chepetsky Mechanical Plant”).

Based on many years of research and industrial production, MISIS has been actively developed the concept of mini-mills of radial-shear (helical) rolling of a new generation to produce structured rods of small sections from almost any deformable metals and alloys since the 1990-ies. RSR mini-mills are a technological complex with structurally preset parameters of rolling for production of rods with a unique structure and a high level of properties. These mills are distinguished by their compactness, versatility of the working tool, simplicity, and financial accessibility.

The latest has become a factor in the widespread use of RSR in scientific research. Over the past 10 years, more than 7 scientific and educational Russian and foreign organizations have equipped their laboratories with RSR mini-mills designed by MISIS. The number of publications on the topic of the structure refinement of metals and alloys in long length products using radial-shear rolling has increased sharply. Almost all currently known results of RSR using as a means of obtaining an ultrafine-grained, functionally gradient structure of metals in long length products were made possible by mini-mills.

It is interesting to note that in many publications the achieved results were related to screw rolling in general, and not to the particular case of RSR. This is not quite correct. In real practice, a positive effect is possible and practically proven only for a narrow region of the factor space of screw rolling, namely in the following ranges: feed angles 18–20 °; rolling angles 0–12 °; taper angles of caliber 10 ± 2.5 °. These optimal parameters are integrated into the design of MISIS mini-mills. With other settings, the result can change significantly and lead to the opposite effect, for example, to destruction of the metal during rolling.

The method of radial-shear rolling and new generation of mini-mills have become widespread in the research and production fields. More than 40 complexes with RSR mini-mills are successfully operating at enterprises in the Russian Federation, Kazakhstan, Belarus, Germany, Korea and other countries, since they have proven to be very effective for solving various problems of metal forming.

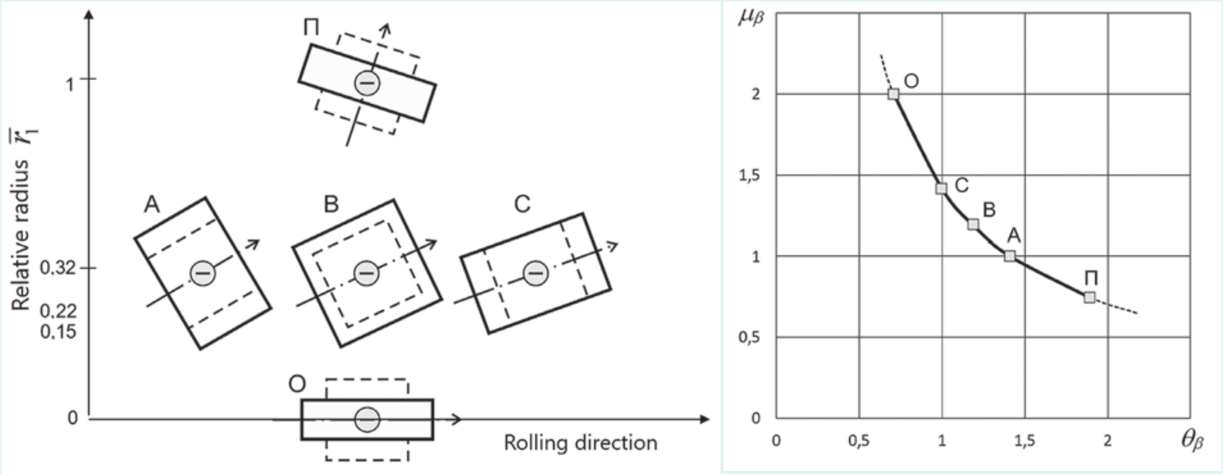
2. Elements of theory and design of RSR mini-mills

It is well known that processes of screw rolling are among the most difficult for theoretical description and experimental study. This is primarily due to the helical nature of the metal flow in the deformation zone. Based on condition of constant volume, the analytical description of process features taking into account developed rotational-shear strain is shown in study [3]. In particularly, it was demonstrated, that for arbitrary trajectory the angle of inclination increased during rolling as its radius decreased in such a way that at each moment of time the condition is met (accurate to torsional deformation) as follows:

$$tg\beta^* \cdot \rho^{*3} = const\,, \qquad (1)$$

where β^* and ρ^* are current values of angle of inclination of trajectory and its radius, respectively.

A theoretical assessment revealed a unique feature of the RSR process, which consists in the possibility of simultaneous implementation of various linear deformation schemes for different layers of the workpiece. Using the example of rolling with a feed angle $\beta = 20°$ and an elongation ratio of 2, the strain state of various layers of rolled workpiece is presented in **Fig. 2** and **Table 1**.



a *b*

Fig. 2. Graphic representation of the strain state of various layers of rolled products (*a*) and layer-by-layer changes in the linear deformation pattern (*b*) during RSR [3]

Table 1. **Strain state of various layers of rolled workpiece during RSR [3]**

Layers and dots	Relative radius	Trajectory coefficients			Analogous of process
		μ_β	θ_β	λ_β	
Surface layers (П)	1	0.75	1.89	0.71	There is no analogue in stationary processes
A	0.32	1.00	1.41	0.71	Rolling a narrow strip (flattened strip) with a large spread without elongation
B	0.22	1.19	1.19	0.71	Rolling strip of medium width with equal longitudinal and transverse strain
C	0.15	1.41	1.00	0.71	Rolling a wide sheet without spread
Central layers (O)	0	2.00	0.71	0.71	Pressing, drawing round profile

The deformation scheme implemented in the surface layers of the workpiece between the surface and point A in Fig. 2, *b* is a unique feature of the RSR and described as deformation with compression of the trajectory elements in the movement direction and stretching across the trajectories.

Parameters μ_β, θ_β, λ_β are trajectory coefficients of strain: elongation ratio, normal strain, and radial strain, respectively. These parameters determine the local shape change of small trajectory-oriented elements in three mutually perpendicular directions, respectively, along the trajectory, across the trajectory, and along the radius of the workpiece.

In a case of an initial workpiece with radius r_0 is rolled into a rod with radius r_1, then the strain coefficients for a small material element moving along an arbitrary helical trajectory of relative radius (with a radius equal to $\overline{r}_1$ from the rolled workpiece radius r_1) are:

$$\mu_\beta = T_\beta \cdot \left(\frac{r_0}{r_1}\right)^2 \ (2), \quad \theta_\beta = \frac{1}{T_\beta}\left(\frac{r_1}{r_0}\right) \ (3), \quad \lambda_\beta = \left(\frac{r_1}{r_0}\right) \ (4),$$

where

$$T_\beta = \sqrt{\frac{tg^2\beta_1 + \overline{r}_1^{\,2}}{tg^2\beta_1 + \overline{r}_1^{\,2}\left(\frac{r_0}{r_1}\right)^6}} \qquad (5)$$

is a correction coefficient for helicoidal movement with trajectory inclination angle on the surface of rolled workpiece β_1.

Rotation angle $\Delta\beta$ of velocity vector in deformation zone can be used as a characteristic of rotational strain. It is calculated as the difference between the angles of inclination of the helical trajectory of the element after exit from the rolls and before entering them according (6):

$$\Delta\beta = arctg\frac{tg\beta_1 \cdot \overline{r}_1\left[\left(\frac{r_0}{r_1}\right)^3 - 1\right]}{tg^2\beta_1 + \overline{r}_1^{\,2} \cdot \left[\left(\frac{r_0}{r_1}\right)^3 - 1\right]} \qquad (6).$$

Rotation angle of the velocity vector $\Delta\beta$ reaches significant values and is sharply unevenly distributed over the radius of the rolled product (**Fig. 3**). In the near-central thin layers at $\overline{r}_1 = 0.05$–0.20, a sharp maximum is observed with adjacent zones of a steep gradient. As the feed angle decreases, the nonuniformity increases and the maximum zone becomes sharper. In some cases, usually during deformation of cast metal with weakened intergranular bonds, this circumstance can contribute to a decrease in the deformability of workpieces and the formation of characteristic discontinuities.

Under the described conditions, a naturally compositional, functionally gradient structure of the metal is formed.

Roll units of RSR mills are the most geometrically complex type of rolling tool. In analytical analysis and design

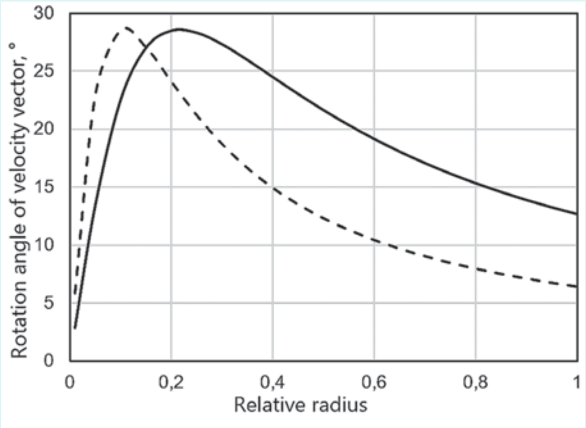


Fig. 3. Change in rotation angle of velocity vector along relative radius of rolled product at feed angle of 20 ° (solid line) and 10 ° (dashed line)

calculations, the virtual pitch point technique was found to be very effective [4, 5]. The basis of the technique is invariant geometric relationships obtained because of the synthesis of well-known approaches by Yu. M. Mironov and P. K. Teterin.

The authors of studies [4, 5] used the concept of virtual feed angle β and rolling angle δ, the numerical values of which vary along the rolling axis l and the roll axis L (Fig. 4, *a*). In particular, in an arbitrary section located at a distance l from the geometric pitch point, the value of the virtual feed angle β is found from the equality:

$$ctg^2\beta = ctg^2\gamma + \left(\frac{l}{E}\right)^2 \qquad (7)$$

or from invariant:

$$P \cdot tg\beta = E \cdot tg\gamma = const\ , \qquad (8)$$

where γ and E are the crossing angle of the roll and rolling axes and the shortest distance between them, respectively; P is a distance between the rolling and the roll axes in the section under consideration.

The developed technique is applicable for comparative analysis of the geometry of mini-mills of radial-shear (helical) rolling of various types and new designs of mini-mills according to the principle “from the deformation zone” to the selection of rational elements and units of the rolling mill and their spatial relationship [6].

Within the framework of the approach, finite analytical dependencies describing the relationship between the geometric parameters of the location of the rolls and the deformable workpiece were obtained, it is very convenient for parametric design in CAD systems. In paper [7], a parametric model was calculated and constructed, which makes it possible to automatically rebuild the deformation zone for new initial parameters and quickly determine the overall dimensions and spatial position of the rolls and the deformation zone of the mini-mill (**Fig. 4**).

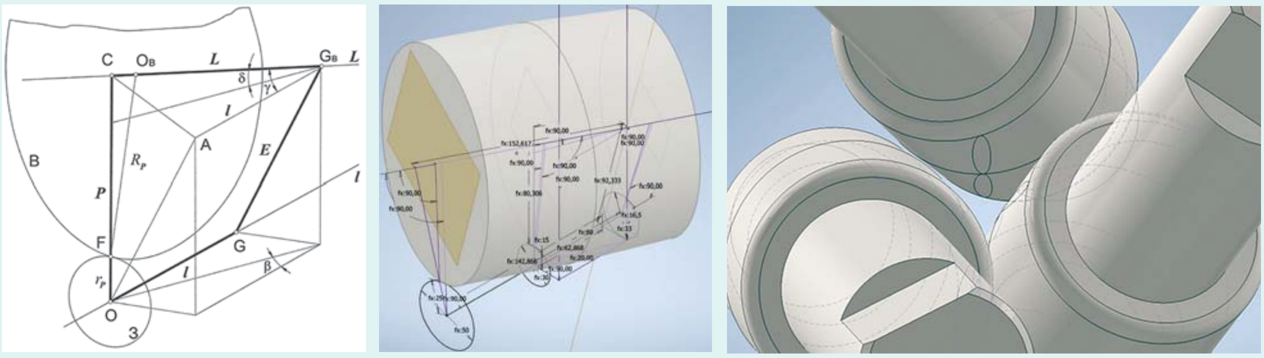
Using the theory and principles outlined above and modern finite element systems, studies of the design parameters of operating screw rolling stands were carried out [8], and many original designs of screw rolling stands were developed and patented [9].

3. Scientific-applied research of RSR technology

At MISIS, theoretical and applied research of RSR technology started in the second half of the 1970-ies and continues to this day. During this period, the RSR process was used for various groups of ferrous and non-ferrous metals, low-density alloys, powder materials, special steels, and other materials. Below is an overview of the main research directions of RSR process for each group of materials and potential use of finite element method (FEM) for process simulation.

3.1. Simulation of RSR process: features and possibilities

The RSR process is characterized by a complex change in temperature-speed and deformation parameters in the deformation zone. In most cases, the analysis of these parameters is impossible in a real process. Due to this, in recent years, RSR has been actively studied using modern software packages for simulation based on FEM (QFORM, DEFORM, etc.). It makes possible to predict process parameters and



(*a*) (*b*) (*c*)

Fig. 4. Stages of creating adaptive model for designing a deformation zone profile: calculation scheme (*a*); work roll profile (*b*); three-dimensional assembly of deformation zone (*c*) [7]

properties of the finished product, identify the causes of possible defect formation, and therefore, select the most suitable deformation modes for real processes.

Through the example of studying aluminum alloys, an analysis of the influence of deformation modes on the process conditions of the RSR of commercial pure aluminum (AA1050) was carried out. It was shown that based on the FEM simulation, it was possible to select deformation modes to obtain the required properties [10].

The numerical simulation of RSR process of aluminum alloy 5754 at temperatures of 300 and 350 °C and rotary velocities of 50 and 100 rpm was performed in study [11]. According to results, the analysis of strain-stress state, influence of temperature and rotary velocity of rolls on temperature distribution, strain, and strain rate was carried out. The study was aimed at developing optimal deformation modes for hard-to-deform aluminum alloys of the 5XXX series.

Using QFORM program, the process features of the RSR of the Al–Mg–Sc alloy while varying the elongation ratio (from 1.2 to 2.4) and rotation velocity (from 15 to 120 rpm) were analyzed in the study [12]. It was shown that the temperature field in the deformation zone was determined by significant differences in the geometry of metal flow trajectories in the surface layers and the axial zone. Based on the analysis of the flow trajectories of deformed metal in the deformation zone, the features of the RSR process and their influence on the forming parameters were identified and described (**Fig. 5**). The presence of an external cyclic zone of metal trajectory movement determines the alternating nature of strain development and formation of an external finely dispersed structural layer.

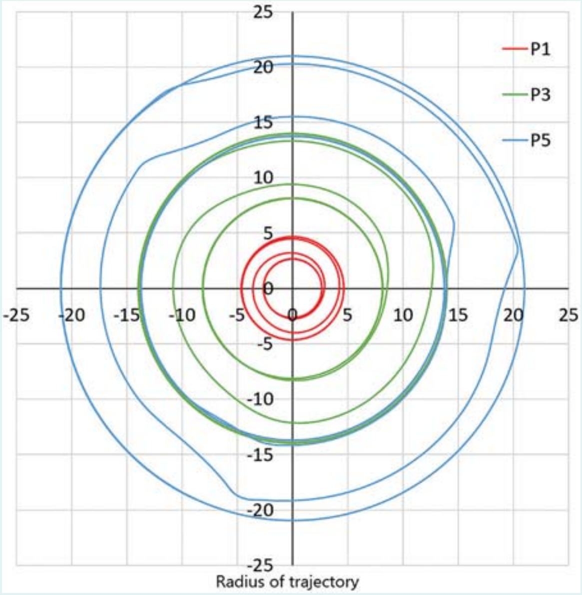


Fig. 5. Projection of point trajectories: P5 (surface), P3 (mid-radius), and P1 (axial zone) on the cross-section of workpiece at $\mu = 2.4$ [12]

Numerous studied show the potential of using computer simulation for theoretical studies of the RSR process. Attempts are being made to simulate the probability of occurrence of ring fracture of the metal in the deformation zone, which, in turn, is one of the criteria that determines the rational technological parameters of the RSR [13].

3.2. Research in field of metal forming using RSR

3.2.1. Titanium alloys

Improving the mechanical and performance properties of titanium alloys, widely used in various industries, through new technological processes is a promising direction of modern research.

The increase in the mechanical properties of workpieces for medical use from commercial purity titanium alloy (VT1) with RSR technology is considered in study [14]. The initial workpiece with a diameter of 30 mm was rolled to finished rod with a diameter of 15 mm using SVP-8 mill at temperature of 500 °C with subsequent water cooling. It was shown that the rod had a gradient structure with an ultrafine-grained equiaxed region on the surface and elongated grains in the central zone. The formation of this type of structure led to increase in strength properties by 1.5 times, with a slight decrease in ductility.

According to results of study [15], a technological process for producing rods from titanium alloy VT22 with an ultra-fine-grained structure using RSR in combination with subsequent heat treatment (aging) was developed. The initial workpiece with a diameter of 40 mm was deformed to the rod with a diameter of 22 mm using mini-mill “14–40” with total elongation equal to 3.3. The microstructural analysis revealed that RSR resulted in a significant refinement of the grain structure, with an average grain size of approximately 0.4 μm. In addition, subsequent aging at 450 °C for 5 hours ensured an increase in the strength properties of the VT22 alloy by more than 20 % compared to the initial state.

The influence of thermomechanical treatment (RSR in the temperature range 850–750 °C followed by aging at 500 °C) on the mechanical properties and creep of the VT22 alloy is considered in study [16]. The authors found that the yield strength of the alloy increased by 30–40 % during tensile tests in the temperature range of 20–500 °C while maintaining acceptable ductility (4–12 %) in comparison with the initial state due to the used processing scheme. Moreover, under creep conditions at 473 ºC, an increase in creep resistance was observed in the stress range two times lower than the yield strength.

In subsequent work [17], the analysis of the influence of cyclic load on the resistance to fatigue fracture of the VT22 alloy with an ultrafine-grained structure obtained through the RSR process was carried out. The behavior of the alloy under low- and high-frequency loading in the region of stresses below the yield strength was studied at the mesoscale level. It was revealed that, in comparison with high-frequency loading in the region of ultra-high-cycle fatigue, the durability of the material at low loading frequency in comparable ranges of applied stress levels of 950–600 MPa was three orders of magnitude lower. The dislocation structure created during RSR with subsequent heat treatment (aging) had less resistance to the accumulation of dislocations at the stage of crack initiation under low-frequency loading than under high-frequency loading. However, in comparison with traditional production technologies, the VT22 alloy obtained through the RSR process had higher durability characteristics.

The influence of thermomechanical treatment using RSR on the structural-phase state and mechanical properties of the VT35 pseudo β-alloy was studied in the paper [18]. The RSR was carried out using mini-mill "14–40" at a temperature of 850 °C in 5 passes to a final diameter of 16 mm. This treatment led to refinement of the grain structure of the alloy. In addition, it was found that the resulting structure was stable up to a temperature of 750 °C. During subsequent annealing in the temperature range of 420–500 °C for 5 hours, the thin-acicular α-phase was precipitated, which made it possible to significantly increase the tensile strength (from 860 to 1200 MPa) while maintaining acceptable ductility (~7 %).

To increase the efficiency of titanium production, the studies on the production of hot-deformed titanium rods of small diameters were carried out. The possibility of obtaining a two-phase titanium alloy VT-8 with a controlled structure and mechanical properties from small-diameter ingots (up to 200 mm) only using the RSR method without intermediate treatment was demonstrated in the study [19]. It was shown the influence of rolling routes and thermal deformation conditions on the structure and mechanical properties of the alloy; the obtained characteristics corresponded to the requirements of current regulatory documentation.

The results of experimental testing of the technological capabilities of RSR mini-mills for production of titanium rods with a diameter of 10–40 mm from initial workpieces produced by SC "Chepetsky Mechanical Plant" were presented in the study [20]. Forged rods with a diameter of 60 mm from alloys 3M, PT-3V, and VT3-1 were used as initial workpieces. The experimentally tested technological scheme and RSR mini-mills can be used to create a high-technology rolling system with a flexible production program. The options of design arrangement of mini-mill stands and a rational technological scheme for their operation were proposed.

3.2.2. Aluminum alloys

The demand for aluminum alloys has increased significantly in recent years due to the development of aerospace, chemical and other industries. At the same time, most semi-finished products from aluminum alloys are manufactured using pressing processes [21], which are associated with high production costs. Below is a series of works devoted to the study of deformation processing of industrial and new aluminum alloys using RSR.

The features of the deformation behavior of alloys 1050A (AD0) and 2017A (D1) were considered in studies [22, 23]. Based on the results of plastometric tests, the computer simulation of the RSR process was performed and the features of the strain state and distribution of temperatures and stresses were determined. Using the data obtained, a deformation scheme was selected and experimental rolling of workpieces with a diameter of 25 mm to a final diameter of 20 mm was carried out in one pass using the RSR mini-mill "14–40" at a feed angle of 18 ^{0}. According to the results, the rolled workpieces had no surface defects and deviations in straightness and diameter. In addition, it was established that deformation heating was associated with the magnitude of deformation, and as a result, can be used when selection the initial heating temperature of workpieces.

A qualitative improvement of the properties of aluminum alloys and development of processing technologies remain an urgent research task. Hence, the study of the influence of RSR on the evolution of the microstructure and mechanical properties of the aluminum alloy AMg6 was carried out in the paper [24]. It was shown that with a deformation degree up to e ~ 2.4, a significant decrease in grain size occurred from 200 to 5 µm, while a homogeneous structure was formed. This, in turn, led to an increase in strength ($\sigma_в$, $\sigma_{0,2}$ increased to 370 and 200 MPa, respectively) without loss of ductility. Rolling was carried out using RSR mini-mill "14–40".

To improve the quality of semi-finished products from aluminum alloy D16T (Al–4.4·Cu–1.6·Mg) due to obtaining a fine-grained structure, deformation modes during RSR were determined [25]. The rolling was carried out using the RSR mini-mill "10–30" according to a stage scheme in the temperature range of 380–180 °C with a decrease in the temperature in the pass by 50 °C to a final diameter of 13 mm. Deformation at temperatures above 380 °C led to workpiece destruction due to grain growth and a decrease in the ductility of the alloy. It was established that the selected technological mode resulted in uniform structure refinement, reducing the average grain size in the longitudinal section from 10 to 5 µm. Additionally, the average size of subgrains in the surface layers and central part was reduced to 0.9 µm.

The pilot industrial testing of the technology for producing rods from a continuously cast billet of aluminum alloy D16 (T) (A2024) using RSR mills was carried out [26]. Tensile tests on mechanical properties revealed that the best performance was found in samples with a diameter of up to 35 mm, i.e. with a total elongation ratio $\mu_\Sigma > 4.2$. The plastic properties of experimental rods exceeded the GOST 21488-97 requirements by 2.1–2.5 times over the entire studied range of elongation ratios, starting from 2.07. In this case, there was an increase in elongation by 5.7–6.8 times compared to the initial cast state (**Fig. 6**).

The formation of microstructure and mechanical properties of A2024 alloy (D16) obtained by multipass RSR was studied in works [27, 28]. The analysis of the size and distribution of phase particles showed that rolling at lower temperatures made it possible to increase mechanical strength due to more intensive grinding of the undissolved Fe-containing phase. The gradual decrease in the rolling temperature in each pass allowed to achieve high strength values ($\sigma_B = 430$ MPa and $\sigma_{0.2} = 255$ MPa) while maintaining a plasticity level of ~15 %, comparable to some methods of severe plastic deformation (SPD).

Series of studies on the effect of RSR on the microstructure and mechanical properties of the new high-strength aluminum alloy of Al–Zn–Mg–Fe–Ni [29–31], alloy A7075 (V95) [32], and alloy of Al–Mg–Sc system (01570) system were carried out [33]. Due to various deformation modes, rods with a gradient structure over the cross-section were

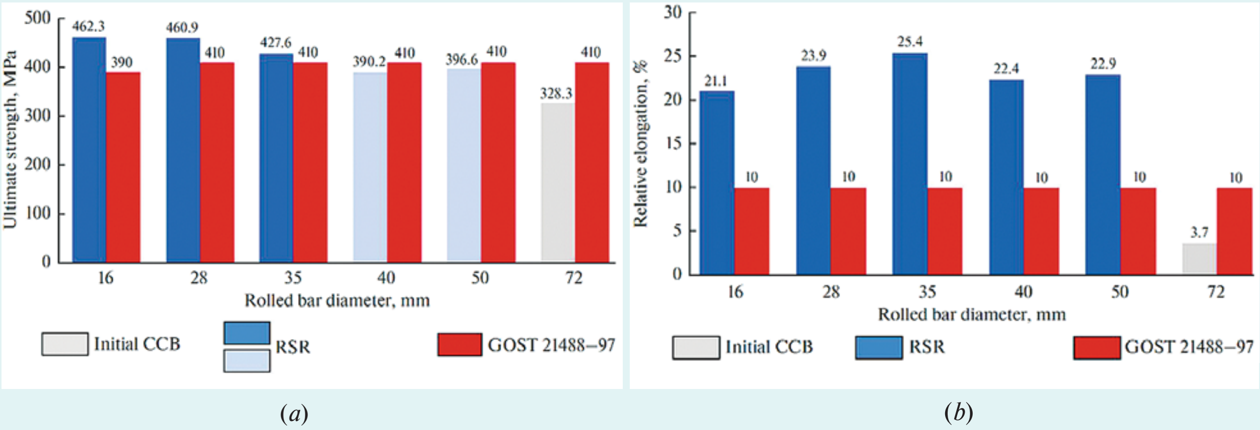


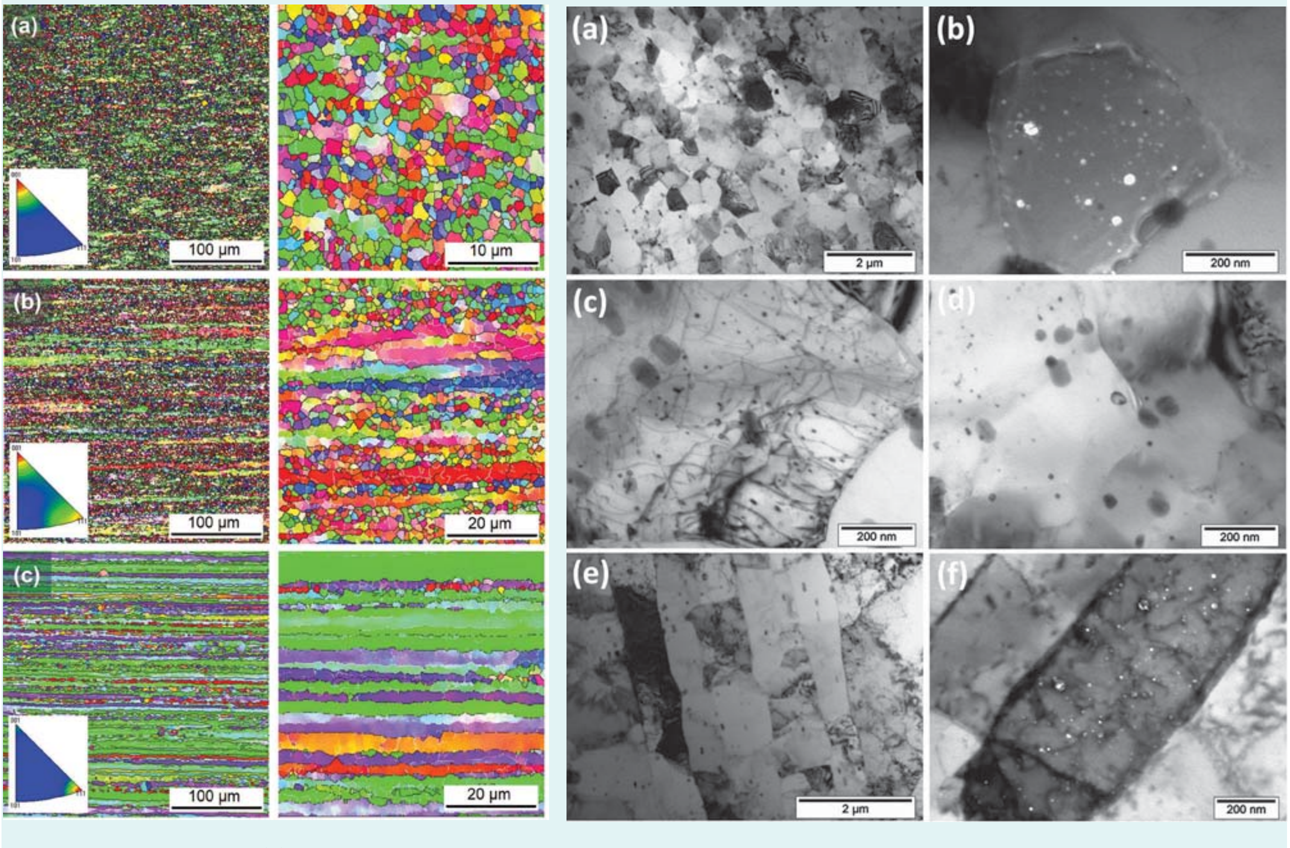
Fig. 6. Ultimate strength (*a*) and elongation (*b*) of A2024 alloy in rods with various diameters [26]

obtained. The surface layers had a fine, predominantly recrystallized grain structure, and the central zone retained predominantly deformed fibrous grains (**Fig. 7, *a***). The uniform distribution of inclusions of intermetallic phases and their relatively compact morphology were also observed.

Transmission electron microscopy (TEM) analysis showed that the alloy 01570 had a deep hierarchical structure, characterized by the presence of submicron-sized particles and nanoparticles of the $Al_3(Zr,Sc)$ phase with a size of 10–20 nm (**Fig. 7, *b***). The obtained mechanical properties (**Fig. 8**) exceeded in strength almost all deformation methods considered for this alloy, including cold rolling, and equal channel angular pressing (ECAP) methods. In this case, elongation was higher than at longitudinal rolling, but inferior to methods of SPD.

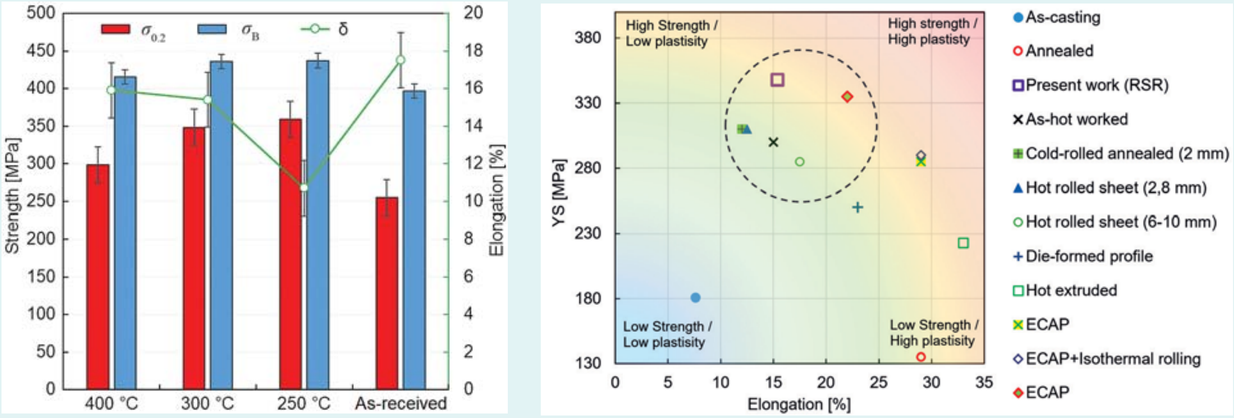
3.2.3. Zirconium alloys

Obtaining an ultrafine-grained structure (UFG) in zirconium alloys used in nuclear energy is considered in the literature as one of the ways to improve the level of their properties. However, existing industrial methods do not allow to achieve the required effect.



(*a*) (*b*)

Fig. 7. Microstructure of rod with a diameter of 10 mm from Al–Mg–Sc alloy after RSR: (*a*) EBSD, (*b*) TEM [33]



(*a*) (*b*)

Fig. 8. Mechanical properties of rods from Al–Mg–Sc alloy obtained by RSR method (*a*); Comparison of mechanical properties of Al–Mg–Sc alloy processed by different deformation methods (*b*) [33]

To evaluate the applicability of RSR for structure refinement of a zirconium alloy to a level increasing radiation resistance, the workpiece of the alloy of Zr-1% Nb system was deformed to a final diameter of 20 mm in 8 passes using RSR mini-mill [34]. Based on results of plastometric tests and computer simulation of the RSR process, the selection of deformation modes was made. The results obtained showed that RSR was an effective method of plastic deformation for obtaining a UFG structure in a zirconium alloy with a reduction per pass up to 15 %. The RSR process was also used for obtaining UFG structure in alloy of Zr-2,5% Nb system (E125) in the study [35]. The initial rod with a diameter of 37 mm was rolled to a final diameter of 20 mm in 7 passes. According to results, during the RSR process, a gradient structure with an equiaxial UFG zone in the peripheral regions (0.7–0.8 μm) and an oriented rolled texture with individual large grains (1.0–1.5 μm) in the axial zone was formed. The authors of the study noted that the resulting UFG structure with predominantly high-angle boundaries and large crystallographic misorientation of grains can improve the performance properties of the alloy.

The influence of accumulated strain on the formation of structure and properties of zirconium alloy grade E110 is considered in paper [36]. To implement the process, sequential rolling of the workpiece was carried out using two RSR mini-mills "14–40" and "10–30" along the route 37→20 mm in 8 passes and 20→13 mm in 2 passes, respectively. The microstructural analysis of the final rod showed that with an increase in the deformation in the peripheral zones, there was no additional refinement of grains reached sizes of 300–600 nm. At the same time, processing of the central zone with an oriented rolled structure into a more equiaxed one occurred, which led to a decrease in the severity of the gradient.

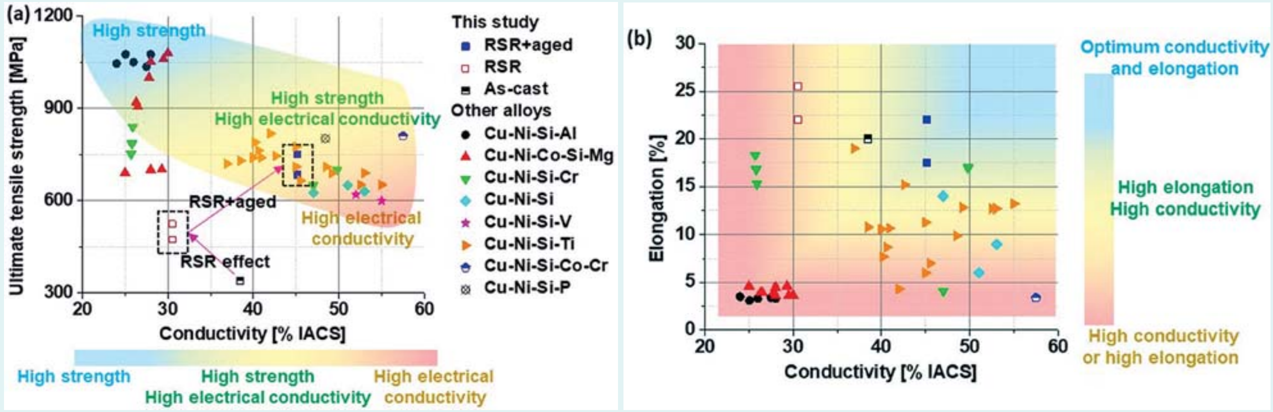
3.2.4. Magnesium alloys

The study on increasing the mechanical properties of pure magnesium using RSR is presented in the paper [37]. It was shown that the deformation in 6 passes with a gradual decrease in temperature in the pass led to a significant refinement of the structure (grain size ~5 μm) and an increase in strength properties (σ_B =191 MPa, $\sigma_{0,2}$ = 116 MPa) while maintaining plasticity at the level δ = 13 %. With a subsequent increase in the number of passes (up to 11), the tendency towards greater grain refinement (up to ~1 μm) and an increase in strength characteristics remained, but further embrittlement of the material occurred.

The comparative analysis of the texture contribution to the level of mechanical properties of the MA2-1hp magnesium alloy after RSR and ECAP was presented in the study [38]. As noted in the study, both methods make it possible to form a fine-grained structure in the alloy with an average grain size of 2–7 μm. However, the texture formed after RSR, in addition to grain refinement, allows to increase the yield strength and ultimate tensile strength to 200 and 324 MPa, respectively, at a sufficiently high elongation equal to 15 %. Also, the features of grain refinement mechanisms, texture, and mechanical properties of magnesium alloy after RSR were analyzed in the study [39].

3.2.5. Copper alloys

The RSR process efficiency as a new industrial alternative to the production of semi-finished products in the form of rods with a diameter of 10–55 mm from electrical copper alloy of the Cu–Ni–Cr–Si system is shown in the study [40]. The RSR process combined with subsequent thermal treatment (aging) resulted in the formation of a gradient microstructure with an excellent combination of strength, ductility, and electrical conductivity (**Fig. 9**). It was demonstrated that dislocations made the primary contribution to strength after RSR, with the second most significant contribution was associated with a reduction in grain size. After aging, the strength was mainly contributed by precipitates and dislocation components both on the surface and in the center of the rod. The alloy was strengthened by 50 % with elongation within the range of 17–22 % after RSR and heat treatment and had an electrical conductivity of 45.17 % IACS compared to 30.52 % IACS for the material after RSR. Thus, the RSR process in combination with appropriate heat treatment (aging) makes it possible to obtain a structurally inhomogeneous copper alloy, which stands out among various copper alloys in its



(*a*) (*b*)

Fig. 9. Comparison of properties of Cu–Ni–Cr–Si alloy with various copper alloys: ultimate tensile strength and conductivity (*a*), elongation depending on electrical conductivity (*b*) [40]

combination of strength, electrical conductivity, and ductility (Fig. 9).

The study of RSR modes on the microstructure and microhardness of rods from copper grade M1 in the deformation temperature range of 20–400 ºC was carried out in work [41]. The results revealed that in the resulting rods, areas with different microstructures were formed in the cross-section, which also affected the microhardness values.

3.2.6. Co–Cr–Mo alloys

For the first time in world practice, the MISIS research group has been carried out studies on producing semi-finished products in the form of long rods from a medical alloy of the Co–Cr–Mo system using the RSR method. These alloys have a high resistance to deformation [42] and are subjected to polymorphic transformation γ (FCC) → ε (HCP) in the temperature range of ~960–1000 °C [43, 44], which causes limitations and difficulties in deformation process. At the moment, preliminary experimental rolling has been carried out. It was shown the fundamental possibility and potential of implementing the RSR technology for the Co–28Cr–6Mo alloy [45, 46]. Rods with a diameter of 29 and 18 mm with a total elongation ratio of 3.86 and 10.03 were obtained, respectively. The microstructure of the rods after deformation was quite uniform with the average grain size equal to 10–20 μm. It was also found that inclusions of the intermetallic σ-phase led to the formation of defects in the alloy due to its brittleness (non-deformability). Further research will be aimed to selection of optimal modes of deformation and heat treatment to obtain the best combination of mechanical properties and the most preferred processing modes.

3.3. Research in the field of combined processes

The use of RSR technology for producing long, small-diameter rods with high performance properties for medical applications, including bone implants, has become an important research topic in recent years. The combined high-temperature thermomechanical processing based on the RSR and rotary forging (RF) can be one of the development trends. To predict the strain distribution over the product section, the simulation of combined RSR and RF processes was carried out using FEM method in software package QFORM in the study [47]. For the shape memory alloy of Ti–Zr–Nb system, it was experimentally confirmed that when combining two methods, the advantages of each were used, namely a high level of plastic deformation and productivity of RSR and obtaining smooth surface and homogeneous microstructure of the workpiece after RF. A similar approach makes the combined deformation method industrially promising for producing long rods.

The combination of various metal forming methods (RSR, ECAP and RF) under conditions of technological cycle of “Matek-SMA Ltd.” and the experimental production of the Baikov Institute of Metallurgy and Materials Science to improve the mechanical and functional properties of the rods and wire was considered in the study [48]. Based on data obtained, prospects for the development of existing deformation methods were shown, in particular, through the design and manufacture of new unique equipment.

4. Industrial application of RSR technology

4.1. RSR technology for preliminary deformation of steel continuously cast billets before piercing

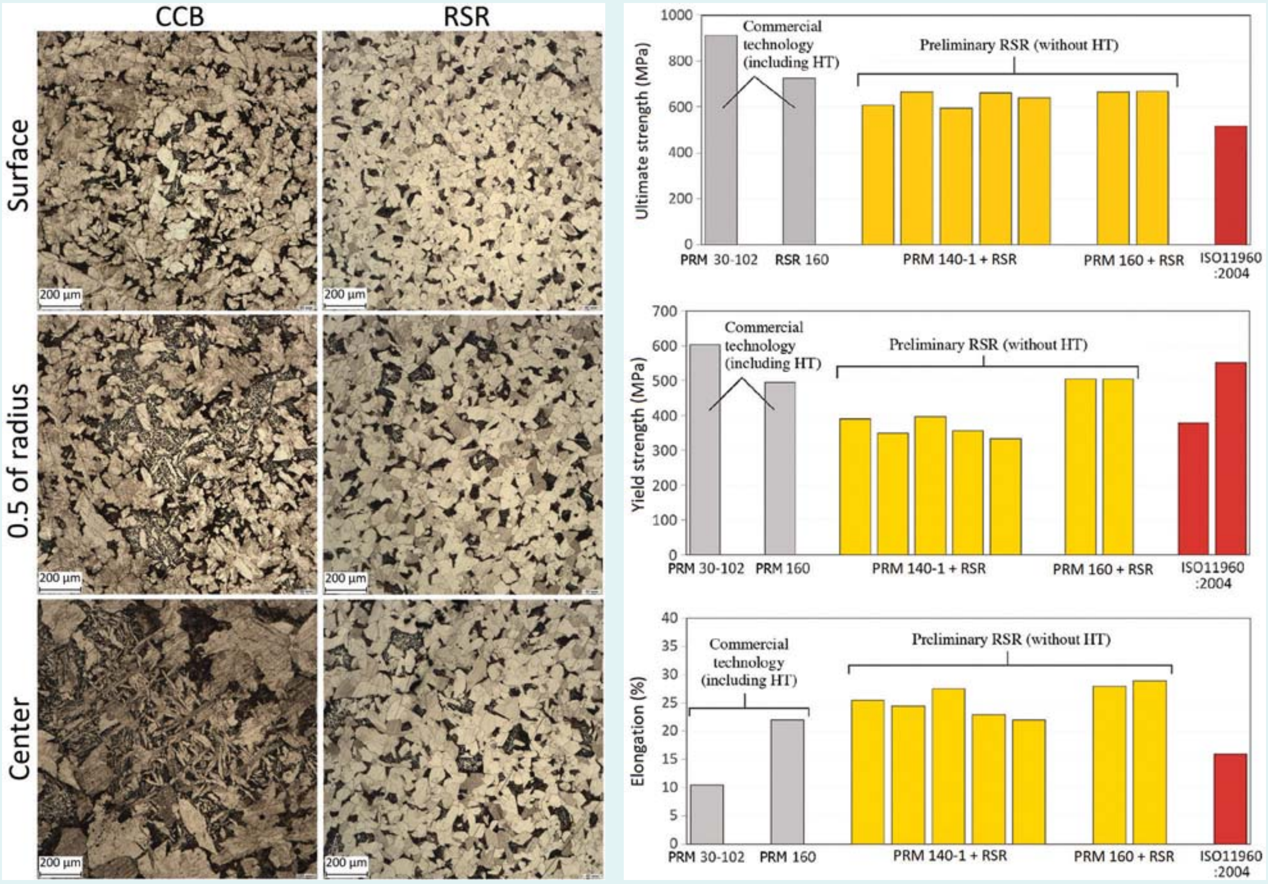
Among the promising technological schemes to produce seamless pipes from continuously cast billets (CCB) is a scheme that includes preliminary deformation of the billet in a radial-shear rolling mill before piercing [49, 50]. The complex of research, development, design, and engineering works to create a technology and radial-shear rolling stand of a special design for preliminary deformation of continuously cast billets at feed angles of 18 ° under the conditions of the operating pipe rolling mill PRM-160 unit was carried out by NUST “MISIS” together with Pervouralsk New Pipe Plant JSC (PNPP JSC). At the first stage [51], the influence of preliminary radial-shear rolling of CCB with diameters of 150–156 mm from steels 12Kh1MF, 18KhMFB and 18Kh3MFB on the structure and properties of seamless pipes was studied. The rolling was carried out using MISIS 100T mill at feed angles equal to 21 °. It was shown that RSR made it possible to intensively refine the structure of continuously cast billets and to ensure the processing of the cast structure by 70–90 % at elongation ratios of 2.0–2.2 (**Fig. 10, *a***). Pipes produced at PRM-160 PNPP from such billets fully complied with the requirements of ISO 11960:2004 for strength group J55 ($\sigma_\text{в}$>517 MPa; $\sigma_{0.2}$>379 MPa; δ>16 %). At the same time, the level of plastic properties of the experimental pipes (in terms of elongation δ_5, %) was 1.6–1.8 times higher than the requirements of the standard. To achieve a comparable level of properties using the current technology, additional heat treatment of the pipes was necessary (**Fig. 10, *b***).

For the full implementation of the RSR technology in the conditions of operating PRM-160 unit, a three-roll stand of special design was manufactured and supplied [52].

The stand equipment was fully compatible with the group drive of the PRM-160 in terms of spatial geometry, cardan transmission strength and engine power. The stand was installed as replacement equipment on the base of an existing stand of a three-roll rolling mill. The spatial arrangement of the roll group was optimized for the conditions of rolling bars of various diameters with minimal reconfigurations of the input and output sides. Work rolls with a diameter of 290 mm had a universal calibration, which ensured the rolling of CCB with a diameter of 156 mm to a pipe workpiece of any diameter in the range of 90–150 mm, and a CCB with a diameter of 220 mm to a pipe workpiece with a diameter of 170–210 mm from carbon and alloy steels such as 12Kh1MF, 15Kh5M, 08Kh18N10T, etc. The maximum permissible elongation ratio per pass was 3.0–3.3 at a feed angle of 18 °. The torque on one roll does not exceed 40 kN·m, and the engine power did not exceed 1500 kW.

It was practically confirmed that the use of RSR stand with roll feed angles of 18 ° provided a wide range of workpieces for piercing from CCB of one or two diameters 156 and 220 mm. It also increased the technological plasticity of metal during piercing, reduced the development of initial surface defects, and weakened the influence of (negative) structural features of continuously cast metal on the quality of the final product.

The effect of using preliminary deformation of CCB in screw rolling mills was also presented in studies [53, 54]. The authors proposed a technology to produce high-strength pumping and compression pipes, as well as pipes in cold-resistant and corrosion-resistant versions using the operation of preliminary deformation of the CCB in a three-roll screw rolling mill before piercing in the PRM-80 line of Sinarsky Pipe Plant JSC. The present technology is shown in terms of ensuring a high level of mechanical properties and obtaining a fine-grained structure.



(*a*) (*b*)

Fig. 10. Microstructure of steel 12Kh1MF before deformation (left column) and after RSR (right column) (*a*) and comparative mechanical properties of pipes (*b*) [51]

4.2. RSR technology for deformation of heat-resistant alloys

To increase the efficiency of production of bars with small diameters from heat-resistant alloys, the RSR of a small-diameter ingot (60 mm) from the heat-resistant alloy KhN73MBTYu in semi-industrial production conditions was studied in the work [55]. It was shown that the structure, mechanical properties, and long-term heat resistance of the resulting rods with a diameter of 20–25 mm met the requirements for long products according to TU 14-1-1973–77. Tested technological solutions had a high degree of readiness for industrial implementation in the conditions of mini- and micro-metallurgical plants.

4.3. RSR technology for recycling of long products

The use of RSR method for low-cost recycling technologies of long metal products that have expired their service life to obtain new products is a promising direction for the development of this method. The development of a resource-saving technology to produce rolled product from used train axles using the RSR 90–220 mini-mill is one example of such an application of RSR. According to results, the new technology was successfully tested on real axles taken out of service [56]. The technological scheme for producing round long products from used train axles consists of the following operations: (**Fig. 11**).

OJSC “Ochersky Machine-Building Plant” put into a service a modular section with an innovative technology for repair recycling of used pump rods based on the RSR mini-mill “14–40”. In this case, RSR ensures an extension of the life cycle of used pump rods due to the plastic processing of rods of a larger diameter to a smaller diameter. As a result, the surface of the product is renewed, microdefects are eliminated, and the properties of the metal are restored [57]. Repaired pump rods are provided with the same warranty as new ones. Pump rods are made from structural alloy grades 15N3MA, 40G2, 40KhGM, 15Kh2GMF, 20KhGNMFA, 20N2M, 35KhN2M and other rolled products, which are in demand in various industries. It increases the relevance of low-cost recycling.

In addition, works are being carried out on the use of RSR technology and mills for recycling scrap rods and some metal products from ferrous and non-ferrous metals to obtain a finished product in a marketable form. A new technology for recycling scrap ferrous metal rods (reinforcement) was realized using RSR mills to obtain a commercial product in the form of rods with an ultra-fine-grained gradient structure [58].

5. Conclusion

An overview of the main stages of development and implementation of the radial-shear rolling method, the current level of research and development in the direction of RSR, as well as the potential application of technology and equipment indicate the great potential of the method laid down by the developers in the first stages of research. Due to this, urgency of the studies has been maintained for decades and

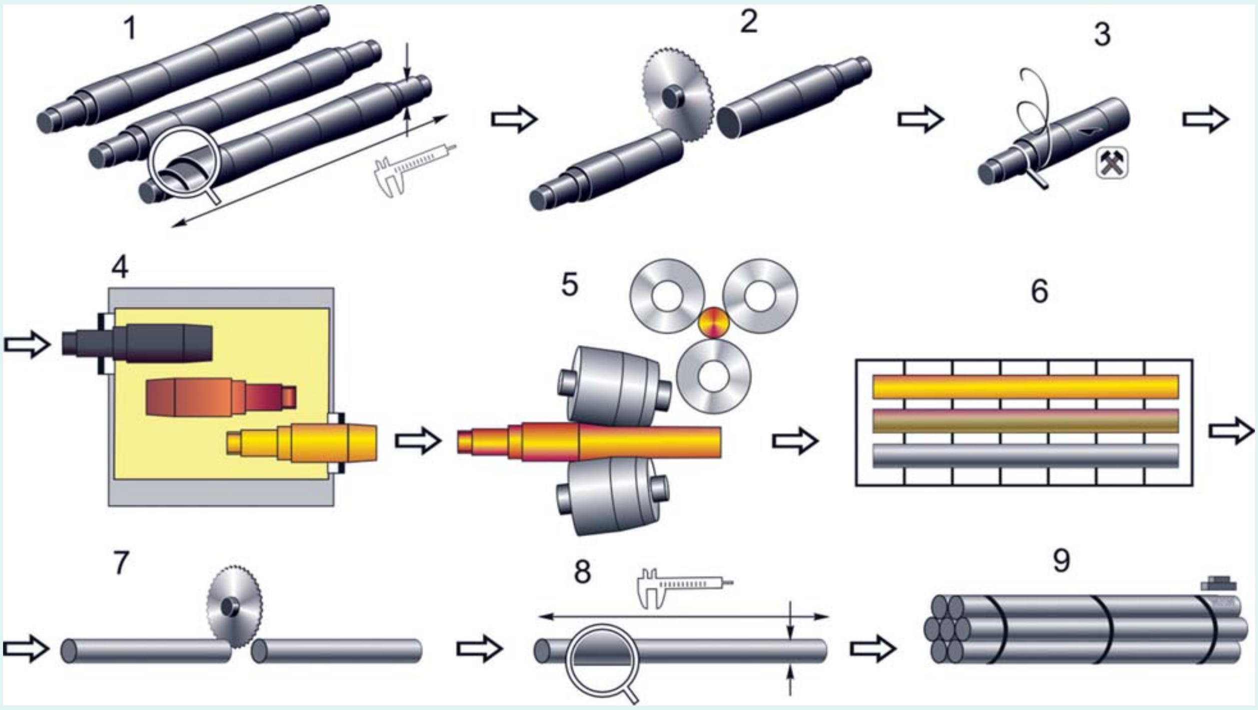


Fig. 11. Technological scheme for producing round bars from used train axles [56]. ***1*** **– inspection and sorting of axles;** ***2*** **– cutting the axle into 2-4 initial workpieces;** ***3*** **– chamfering in areas of difference in diameters, surface repair (if necessary);** ***4*** **– heating of the initial workpieces;** ***5*** **– RSR; 6 – cooling of the resulting rolled product in the refrigerator;** ***7*** **– cutting into measured lengths and removing back-end defects;** ***8*** **– control inspection, control of geometric dimensions;** ***9*** **– marking, packaging**

promising research directions have been formed both in the field of application of RSR technology for new materials and in the development of new technical solutions for equipment.

The RSR method opens new opportunities for the development of high-technology processes and obtaining products from various steels and other metals and alloys with a unique set of properties. Numerous works presented in the scientific literature and briefly summarized in this review indicate the demand for RSR as an effective method for producing structured metals and alloys in long lengths. This method allows to study materials that were previously classified as difficult to deform or non-deformable. In addition, the implementation of RSR technology and equipment leads to a significant reduction in labor costs and production waste, which is fully consistent with modern principles of lean production.

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