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IDENTIFICATION OF REGULARITIES OF CHANGES IN ENERGY-POWER PARAMETERS DEPENDING ON THE DESIGN OF THE ROLLER NODE OF A NEW RADIAL-SHEAR MILL BY COMPUTER SIMULATION

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This paper proposes a radial-shear mill (RSM) of a new design, which allows by rolling or rolling and pressing operations obtaining high-quality rods and wires. In addition, it proposes the method of computer calculation of the energy-power parameters of bar extrusion at the RSM of the new design. Mathematical dependences and calculation algorithm were described, which allow calculating energy-power parameters of the combined bar manufacturing process at a given level of technological parameters. Based on the results of analytical studies and computer modeling, the energy-power parameters were defined and analyzed, in addition, the laws of their changes were determined. It is shown that, regardless of the alloy grade or type, when rolling billets on a new RSM with smooth rolls, the strain force is larger in magnitude compared to rolling in helical rolls. It was found that, in comparison with rolling of bars in smooth and helical rolls, their processing by a combined rolling-pressing process leads to an increase in the deformation force of alloys M1 and D16 by 1.1–1.15 and 1.15–1.3 times, respectively. It is shown that during the deformation of the rods on the new RSM, by controlling the paths of the metal flow in the deformation zone, intensive grinding of the metal structure can be achieved. It was found that when pressing the bars on the new RSM, the temperature of the workpiece increases up to 420 °C, which leads to a sharp decrease in the force required for deformation. The nature of the temperature distribution of the pressed metal in the deformation zone was determined. The adequacy of the models was proved by comparing calculated values of the power parameters of extrusion, obtained by engineering technique and numerical simulation

Keywords: electric motor power, smooth roll, rolling force, rolling moment, radial shear mill, bar, power parameters, helical roll

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1. Introduction

Currently, a wide range of products is made of non-ferrous metals [1, 2]. Among these products, aluminum and copper profiles, bars and wires with increased strength are of considerable interest. As the volume of production of the above products increases, the scope of their application increases significantly. Aluminum and copper profiles, rods and wires are used in large quantities in capital and residential construction, in car building and shipbuilding, in the construction of cottages and for interior and exterior decoration of industrial interiors, etc.

The modern development of rolling technology of mini-production is characterized by resource- and energy-saving technology and the desire to use all metal waste from the metallurgical and engineering industries [1, 2]. In mini-industries, combined technologies are used, where, through the use of several metallurgical redistributions and operations, metal products are produced. At the same time, mini-production equipment operates on the organizational principles of a single unit for the production of a given product. It should be noted that the optimization of the operational properties of products made of non-ferrous metals is impossible without improving the equipment and creating its new types. Therefore, the development of the design of new mills is an urgent task.

2. Literature review and problem statement

Literature review shows that the most effective method of producing profiles of various geometrical sizes is pressing [1]. However, pressing does not allow continuous deformation of metals and alloys. In addition, a major drawback of pressing is the occurrence of large contact friction on the container wall during deformation. Contact friction creates intense heating of the press products during their extrusion. All this creates obvious limitations on the permissible temperature-and-speed pressing regimes, reduces processing productivity and leads to the use of additional complex cooling systems. In addition, due to an increase in the coefficient of friction, the press balance and pressing force of the profiles increase. An increase in processing forces reduces the resistance and rigidity of the matrix, punch and container. Based on the aforementioned, the cost of press equipment is increasing.

It is known [1, 2] that continuous pressing methods like Conform, Extrolling and Linex are used in industry to increase the economic and technological efficiency of the production of wire rods from non-ferrous metals. These are promising methods of metal forming, which eliminate the disadvantages of traditional pressing methods. It should be noted that the Linex continuous pressing method did not find application in industry.

When using the above methods of continuous pressing, such as Conform, Extrolling and Linex, the heated billet is deformed with a special tool [1, 2]. In case of using the Conform method, a special tool consists of the impeller moving in the form of an annular groove, a fixed shoe with a stop and a matrix mounted in the shoe stop. When using the Extrolling method, the working tool consists of two rolls of the same diameter. These rolls form an open gauge of circular cross-section, at the exit of which a matrix is mounted with the necessary gauge hole.

Processing materials of the above methods leads to the following advantages [2]:

– pressing blanks with the active action of friction forces, which leads to a reduction in energy costs in the press shop;

– release of good-quality press products;

– due to the reduction of the technological cycle, pressing reduces the cost of production.

However, a number of significant disadvantages do not allow applying the above methods of continuous pressing under industrial conditions.

The main disadvantage of the Conform method is the appearance of reactive forces of contact friction of the workpiece on a stationary tool [2]. The specified disadvantage leads to an increase in power parameters of the pressing process. It should be noted that friction on the shoe leads to a decrease in tool wear resistance and an increase in the uneven distribution of stress and deformation during pressing. It is known that uneven distribution of deformation leads to heterogeneity of the properties of the press products, which is unacceptable for products from metals and alloys.

It should be noted that the Extrolling method is not widely used in production [3]. The reason for this is an unstable process and not creating enough pressure to extrude metal through the matrix. Most researchers believe that the reason for this is the use of a round open gauge and location of the matrix on the common vertical axis of the rolls.

Despite the noted shortcomings, the above methods of continuous pressing are currently being actively improved by leading experts of various countries [4].

The combined continuous method of rolling-pressing (CRP) and the method of combined continuous casting and rolling-pressing (CC&RP) was developed in [3]. When using these methods, a workpiece of the appropriate size was rolled in a closed box caliber formed by rolls with a protrusion and an annular groove, then pressed into a matrix installed at the outlet of the box caliber. The matrix is located at some distance from the axis of the rolls.

When applying the methods of CRP and CC&RP, active forces are created by the interaction of the rolls with the deformable workpiece. These forces make it possible to uniformly deform the metal of the workpiece and reduce the rolling-pressing force, which is necessary for extruding the bar. Note that in the rolling-pressing process, these methods additionally cause alternating deformations. The occurrence of alternating deformation is associated with the deformation of the workpiece metal, first by vertical compression, and then by horizontal elongation as it moves along the deformation zone. In this case, the workpiece metal is deformed by the opposite horizontal compression in front of the matrix mirror. Such alternating deformation increases the quality of the manufactured products.

The results obtained in [3] showed that using CRP and CC&RP methods, it is possible to obtain bars with a given high productivity with specified mechanical properties, structure and geometric dimensions. The application of these methods also allows reducing by 1.5–2 times the total cost of manufacturing bar products. This decrease is primarily associated with a decrease in capital and labor costs, as well as a decrease in the energy intensity of the process. Thus, the use of the method of combined casting and rolling-pressing makes it possible to obtain a good economic effect.

However, the application of the above rolling-pressing methods does not make it possible to obtain an ultrafine-grained (UFG) structure in metal. The reason is the quasimonotonic nature of the deformation. All this does not provide the manufacture of rods with high physical and mechanical properties [5].

The quality of the manufactured bars is determined not only by the production technology, but by the property of the initial continuously cast billet (ICCB). Research conducted by scientists in many countries shows that the processes occurring in the mold have a significant influence on the formation of the cast structure of the ICCB [6–9]. Moreover, the development of physical and chemical heterogeneity is significantly affected by the distribution of temperatures in the melt, by the intensity and direction of heat removal, and by the development of diffusion redistribution of impurities, etc.

The optimization of the supply of the melt to the crystallizers is determined by the following factors: the intensity of the melt flows; the depth of penetration of the jets of the supplied melt into the liquid well; uniformity and direction of circulation flows, etc.

Controlling the flows of the melt entering the crystallizer is associated with considerable difficulties and requires the use of a number of measures, some of which are currently used in practice: electromagnetic braking and mixing; vibration coolers of special designs; glasses with various configurations of inlet and outlet openings, etc.

Currently, methods of intensive plastic deformation (IPD) for grinding the ICCB structure are widely developed and widely used [10–14]. These methods are explored for the manufacture of products with a submicro- and nanocrystalline structure. To obtain such a structure, the workpiece is treated with nonmonotonic deformation. Note that metals and alloys with UFG structure have comparatively very high and useful physical and mechanical properties. In IPD methods, a tool deforms a metal with active and variable strain rates in magnitude and direction. This leads to a change in the sign of deformation and the drawing directions of the material. The metal flow under these conditions acquires a rotational («vortex») character. However, in industrial conditions, it is almost impossible to produce rods and pipes using this method.

Over the past two decades, in the industrial production of hot-rolled bars of metals and alloys, radially shear rolling (RSR), which deforms the workpiece under IPD conditions, has been widely used [15–17]. RSR is a good way to obtain the UFG structure in long bars [17, 18]. This type of rolling is one of the effective processing methods that ensure uniform deformation. According to many researchers, IPD is the most efficient processing method, which allows producing high-quality products at a low cost. Spiral macrostructure is formed during processing by the method of IPD. The formation of such a macrostructure is associated with the force and kinematic conditions of the application of the load on the workpiece. The movement of metal layers along a helical line with different pitch and elevation angle makes it possible to finely grind the structure.

It should be noted that SPD is of great importance in the production of bars from titanium and aluminum alloys. This is due to a number of advantages of this rolling over other processes of metal forming. At the same time, the relative complexity of studied parameters of the CPD process and strong dependence of product quality on deformation modes require further development of the scientific base. An essential criterion for the quality of a metal is the correspondence of its structure to specified characteristics, for example, uniformity over the cross-section. Energy efficiency and resource saving are also of great importance in production.

Thus, the analysis of scientific and technical literature leads to the following conclusions:

– for the production of non-ferrous metal bars, the most promising is the application of combined processing methods that syndicate separate types of pressure processing in one line;

– using the known combined methods of pressing it is impossible to obtain a press product with UFG or nanocrystalline structure, providing high physical and mechanical properties of the rods;

– RSP does not provide for the manufacture of bars of non-ferrous metals with exact geometric dimensions, while using this method it is impossible, in a continuous way, to obtain press products without press residues.

In the present work, a radial-shear mill (RSM) of a new design is proposed (Fig. 1, *a*) [19]. This mill produces bars of small diameters from metals or alloys with a UFG structure by the combination of hot screw rolling and pressing. The RSM for pressing rods and wires contains the main drive, a working stand, a roll unit (Fig. 1, *b*) and a press matrix (Fig. 1, *c*). The three-roll working stand of RSM consists of a bed, in the bores of which the nodes of the work rolls are mounted after 120°. Work rolls are mounted on cushions. Torque to the rolls is transmitted via spindles from individual electric motors. The stands of the new mill are designed with the possibility of arranging rolls with different angles to the rolling axis and a tangential displacement of 18 mm relative to it. The rolls of this mill have wavy-cone-shaped areas of capture and compression and a calibrating section (Fig. 1, *b*). Note that the protrusions and depressions of the wavy-conical sections are made along a helical line. In this case, geometric dimensions of the protrusions and depressions gradually decrease in the rolling direction. It should be noted that the matrix of this mill has working sections in the form of sequentially arranged, cross-sections of gradually narrowing truncated cones and a calibrating section. Truncated cones have non-parallel bases and crosswise positioning large or small generatrixes.

Pressing rods and wires of steel and alloys on the RSM is as follows. The heated billet is fed into the gap between the helical rolls and deformed by the protrusions and depressions of the wavy-conical section and calibrating section of the rolls. The rolls, rotating with rotational movement, rotationally and translationally move the metal of the workpiece and squeeze it through the hole of the matrix. In the matrix of this mill, the workpiece is also deformed rotationally and progressively. In the calibrating part, the workpiece takes the form of a bar or wire of the required size.

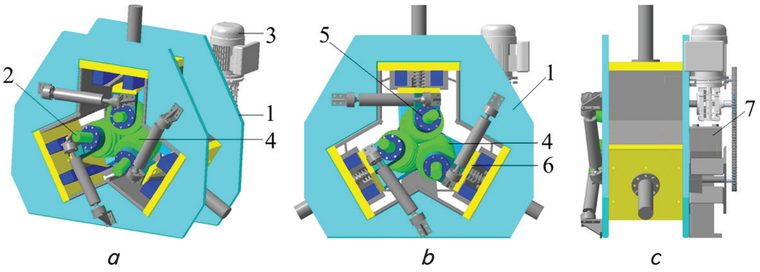


Fig. 1. Combined radial-shear mill of a new design:
a — radial-shear mill, *b* — front view: 1 — mill body; 2 — roll neck; 3 — electric motor; 4 — rolls; 5 — cushions; 6 — wedge; 7 — matrix; *c* — side view

It should be noted that when designing a new design of RSM for continuous pressing of non-ferrous metal rods, the main problem is to determine the force parameters that occur during rolling in screw rolls to create the pressure necessary for extruding the metal through a matrix.

3. The aim and objectives of the study

The aim of this work is to identify the influence of the main factors of the processes of rolling and rolling-and-pressing the bars on the RSM of a new design on the structural and power parameters of the deformation zone. To achieve this aim, the following objectives are accomplished:

– to calculate the power parameters of bar rolling in smooth and helical rolls, as well as rolling and pressing on the RSM of a new design;

– based on the numerical calculations to select the electric motor power sufficient for rolling or rolling and pressing a certain type of bar;

– to determine the stress-strain state (SSS) of the workpiece depending on the technological parameters of rolling or rolling and pressing;

– based on the numerical calculations to determine their influence on the pattern of formation of non-ferrous metal structures.

4. Materials and methodology for determining the SSS and power parameters of bar pressing on RSM of a new design

MSC.SuperForge was used for simulation of rolling in smooth and helical rolls, as well as the combined process of rolling and pressing of rods on RSM with helical rolls and a matrix [20, 21]. For this, a three-dimensional geometric model of the workpiece, rolls and matrix was built in the Inventor CAD software (Fig. 2) and imported into the CAE software MSC.SuperForge. To create a finite element model of the workpiece, rolls and matrix, a three-dimensional volumetric element CTETRA (four-node tetrahedron) was used, as well as to model three-dimensional bodies. The calculation time was 30–40 minutes on a PentiumDuo computer with a clock frequency of 3.4 GHz and 2 GB of RAM.

In CAE software of MSC.SuperForge, the workpiece model was divided into a finite element mesh consisting of 68,000 elements. During the modeling process, due to the elongation of the workpiece, the number of elements gradually increased to 76,000 elements.

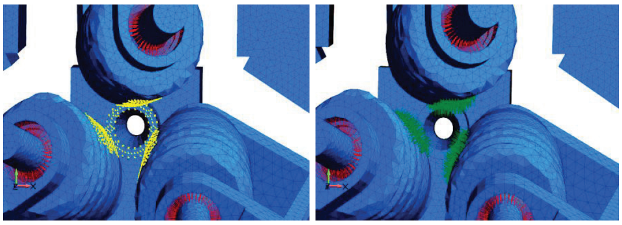

a *b*

Fig. 2. Solid-state model of the rolls with helical surfaces and matrixes: *a* — application of torque to the working rolls; *b* — application of force to the working rolls

A round billet of copper alloy M1 and aluminum D16 with a size of ∅40×150 mm was used to study the rolling process of the rods in smooth and helical rolls, as well as the combined process of rolling and pressing in a continuous RSM. An analogue of these alloys is Cu-ETP and ENAW-2024 alloys, respectively. According to the material library of MSC.SuperForge software, these alloys are applicable for modeling cold and hot deformation processes at appropriate temperatures. Rolling or rolling and pressing was performed at room temperature on RSM to a diameter of 9 mm. To simulate the plasticity of the workpiece material, the Johnson-Cook elastoplastic model was chosen. Rheological properties were set from the database of the MSC.SuperForge software.

Technical characteristics of the proposed RSM were used to calculate the SSS and rolling efforts. In MSC.SuperForge, the instruments are absolutely rigid and provide only the properties of thermal conductivity and heat transfer, i. e. thermal conductivity, specific heat and density are taken into account, and mechanical properties are ignored. From the material database, tool material 9X1 steel was assigned. Since there is no 9X1 steel in the MSC.SuperForge database, the software used the rheological properties of the closest foreign analogue – German steel DIN-102Cr6. The program assigned density and thermal properties to this material by default. Since the rolling process takes place at room temperature, the initial temperature of the rolls was taken to be 20 °C.Interaction between the hard rolls, matrix and deformable material of the workpiece was modelled using contact surfaces that describe contact conditions between the surfaces of the rolls, matrix and surface of the rolled bar. To describe the friction forces arising between the rolls and workpiece, the Amonton – Coulomb law was used, the coefficient was 0.3.

In the MSC.SuperForge software SSS, the contact pressure, contact area, rolling force and temperature distribution over the volume of the pressed billet are step-by-step calculated. In this case, for clarity, the calculation results were divided into four stages (in terms of the percentage) in regard to the total deformation time, in other words, the following intervals were selected: the first stage is 25 percent of the total time, the second stage 50 %, the third stage 75 % and the fourth stage is 100 %.

It should be noted that geometric characteristics of the deformation zone, having the form of a truncated cone. Kinematic and boundary conditions, as well as the defining relations of the deformable body, are adjusted at each step of the associated boundary value problem in MSC. SuperForge software. At the same time, MSC.SuperForge software provides calculation results in the form of distribution fields of the corresponding parameters over the volume of the deformed body or in the form of numerical values of the studied parameters in the nodes of the deformed mesh.

The force *F* acting on the roll is calculated by the equation [22]:

$$F=q\cdot A, \tag{1}$$

where q – contact pressure; A – contact surface area.

In MSC.SuperForge software, the digitized three-dimensional model can be used to calculate highly accurately the contact surface area in the deformation zone. In the work, the contact surface area was calculated by dividing the rolling force by the contact pressure.

The discount relatively small moment caused by the horizontal force is not considered, the torque that must be applied to each work roll for rolling or rolling and pressing on the RSM was calculated by the formula [22, 23]:

$$\tau=F\cdot r, \tag{2}$$

where r – arm of force.

It should be noted that the position vector of application of force was found by the following equation [22, 23]:

$$r=\frac{D+d}{2}\frac{b_m}{d}, \tag{3}$$

where d – the average diameter of the workpiece in the deformation zone: $d=(d_0+d_1)/2$ (d_0, d_1 – the diameter of the original billet and the diameter of the resulting billet, respectively); b_m – the width of the deformation zone, determined by the equation: $b=F/l$ (l – length of the deformation zone).

The length of the deformation zone was determined by the formula [22]:

$$l=\sqrt{D\cdot(\Delta h/2)}, \tag{4}$$

where D – average roll diameter in the deformation zone: $D=(D_0+D_1)/2$ (D_0, D_1 – the diameter of the roll in the entrance of the deformation zone and the diameter of the roll at the exit of the deformation zone, respectively); Δh – calculated value determined according to the equation: $\Delta h=h\cdot\varepsilon$ (h – height of the contact surface in the deformation zone: $h=A_0/d_0$, A_0 – cross-sectional area of the original billet, ε – average compression: $\varepsilon=1-1/\lambda$, λ – average hood, $\lambda=A_0/A_2$, A_2 – cross-sectional area of the resulting billet).

The power of rolling bars in smooth and helical rolls, as well as their processing by the combined rolling-pressing process (without taking into account friction in the roll necks) was calculated by the equation [23–25]:

$$P_n=\tau\frac{\pi\cdot n}{30}.$$

The motor torque τ_{dr} of the designed mill was calculated by the formula [26, 27]:

$$\tau_{dr} = \frac{Q}{i \cdot \eta}, \tag{5}$$

where i – gear ratio from engine to mill roll; $\eta = 0.9 \div 0.94$ – engine efficiency.

The static moment consists of the rolling moment M_r, friction f and idling M_i.

A moment, applied from the spindle site (from the electric motor), was equal to 0.7 M_r. The moment of friction is 0.05÷0.15, and idling 0.02÷0.045 of the nominal engine torque.

The maximum torque during rolling should not exceed the kM_n value. The nominal moment M_n is the main passport characteristic of the engine and is always known. The motor overload factor k is recorded in the engine passport and, depending on the execution of the shut-off system, varies within $k = 2.25 \div 2.75$ (when the maximum speed of rotation of the armature of the engines is reached, this value may decrease to 1.8÷1.9).

To ensure reliable operation of the engine without overheating, the root-mean-square (equivalent) moment $M_{r.m.s}$ brought to the motor shaft should not exceed M_n of the engine [22–27]:

$$M_e = M_{r.m.s} = \sqrt{\frac{\sum_{i=1}^{n} M_i^2 \tau_i}{\sum_{i=1}^{n} \tau_i}} \le M_n, \tag{6}$$

where M_i – moments of rolling and idling; τ_i – rolling, idle and cycle time.

The power of the electric motor required for the drive of the RSM rolls was calculated by the formula [22, 26]:

$$P_{dr} = 1.4\, M_e \cdot \omega_{dr},$$

where 1.4 – safety factor; $\omega_{dr} = (P_{dr} \cdot \pi)/30$ – engine speed, rad/s; $P_{dr} = \omega_{r.truck} \cdot u$ – angular speed of the engine, rpm; $\omega_{r.truck}$ – frequency of the roll rotation, rpm; u – the gearbox gear ratio is taken equal to 3.13.

The initial data for calculating the power of the electric motor were: static rolling moment reduced to the engine shaft, rolling time in the mill, cycle time, idle and friction torque. In this case, the statistical moment was varied in the range from 5 to 40 kN·m.

5. Discussion of computer modeling results

5. 1. Calculation of the force parameters of rolling bars in smooth and helical rolls, as well as their rolling-pressing on RSM of a new design

Fig. 3–8 show the contact pressure distribution, deformation force and the temperature profile in the workpiece during the rolling of the rods in the smooth and helical rolls and rolling-and-pressing them on the RSM. The workpiece temperature was 20 °C.

Based on the obtained results of numerical modeling it was found that:

– at the initial moment of rolling or pressing and rolling, the contact pressure localizes on the zones of gripping of the workpiece with the working surfaces of the rolls;

– an increase of the drawing down, in other words, time of deformation, leads to an increase of the contact area, contact pressure (Fig. 3) and deformation force (Fig. 4, 5) over the entire deformation zone;

– regardless of the alloy grade, when pressing billets on RSM with smooth rolls, the contact pressure (Fig. 3, *a*, *b*) and deformation force (Fig. 4) are greater in magnitude than when pressing billets on RSM with helical rolls;

– with an increase of the drawing-dawn during the rolling and pressing process, the contact pressure (Fig. 3, *c*) on the matrix increases, which is characteristic of the extrusion process, at the same time the contact pressure on the rolls also increases. All these are associated with an increase in back pressure in the deformation zone because of the action of the extrusion force;

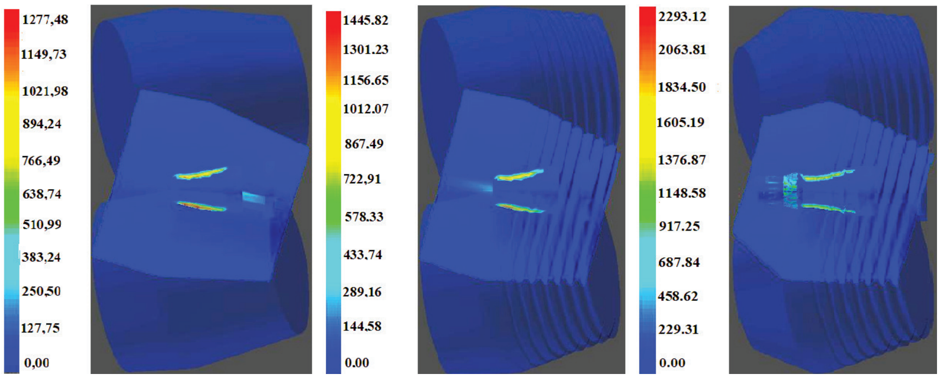
– when rolling and pressing of the rods on RSM, the magnitude of the contact pressure (Fig. 3, *c*), force and moment of the deformation (Fig. 6) on the rolls (P_r and M_r) is greater than the contact pressure, force and the moment of the deformation on the matrix (P_m and M_m);

– rolling in the smooth and helical rolls, as well as rolling and pressing on the RSM leads to an intensive increase of the temperature in sections of the bars, located in the zones of metal contact with the roll and matrix, i.e. with an increase of the drawing-dawn, a gradual increase of the temperature till the temperature of hot deformation on the surface of the workpiece occurs (Fig. 7);

– when rolling and pressing on the RSM of a new design, the processing forces and moments raise with an increase of the drawing-dawn (Fig. 6, 8);

– calculated by engineering methodology and computer modeling forces and the moment of rolling and pressing showed a sufficiently high convergence of the calculus (Fig. 8);

– the results of calculating the power of the electric motor showed a linear dependence of this value on the equivalent torque. Using these calculations, electric motors with a power of 15 kW were selected for the projected mill (Fig. 9).



a *b* *c*

Fig. 3. Contact pressure (MPa) distribution over the workpiece during rolling the rods of copper alloy M1 on RSM with: *a* — smooth, *b* — helical rolls and *c* — rolling and pressing it in the helical rolls and matrix

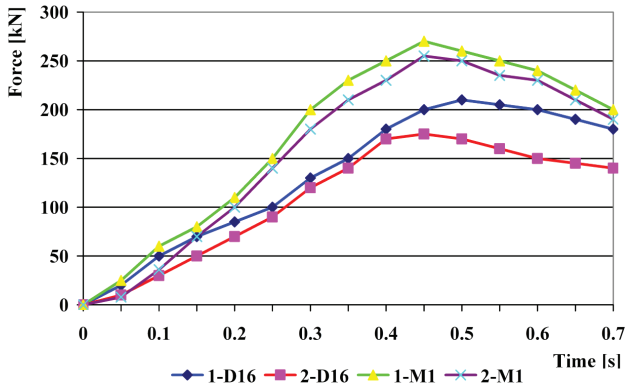


Fig. 4. Picture of changes in deformation forces when rolling rods of aluminum alloy D16 and copper alloy M1 on RSM with smooth and helical rolls: 1-D16 – smooth rolls; 2-D16 – helical rolls; 1-M1 – smooth rolls; 2-M2 – helical rolls

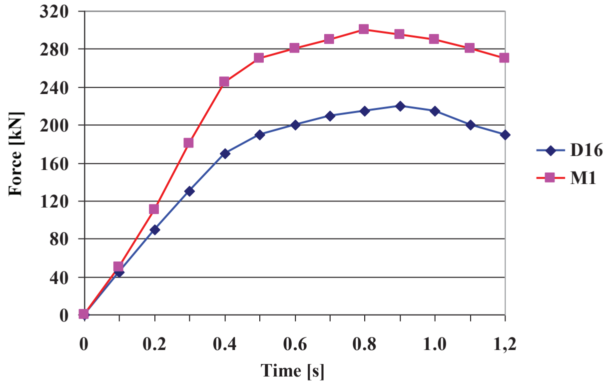


Fig. 5. Picture of changes in deformation forces when rolling and pressing rods of aluminum alloy D16 and copper alloy M1 on RSM with helical rolls and a matrix

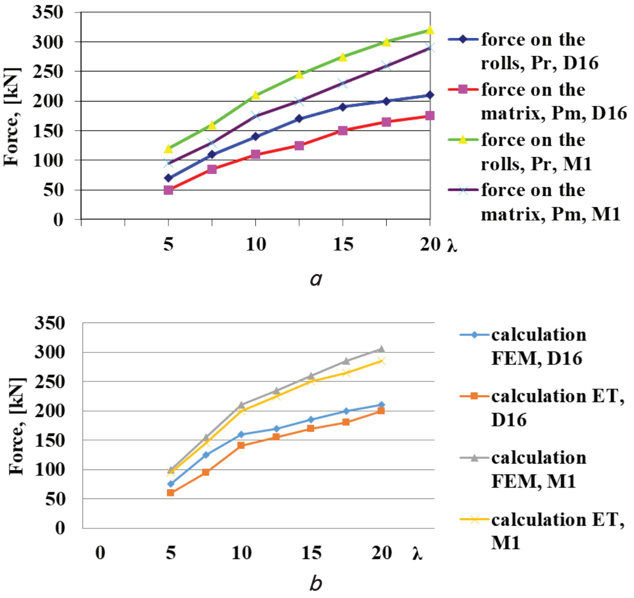


Fig. 6. Dependence of the: *a* – force P_r and P_m; *b* – moment M_r and M_m on the rolls and the matrix from the drawing-dawn λ during rolling-pressing of aluminum (D16) and copper (M1) alloy rods on RSM at room temperature

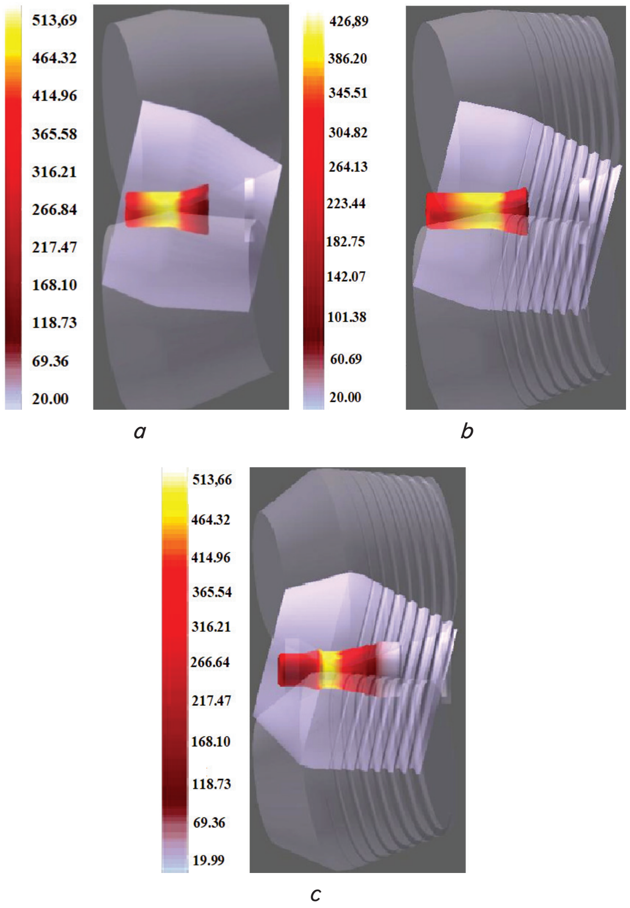


Fig. 7. Picture of the temperature (°C) distribution over the workpiece when rolling rods of copper alloy M1 on the RSM with: *a* – smooth rolls; *b* – helical rolls; *c* – rolling and pressing with helical rolls and matrix

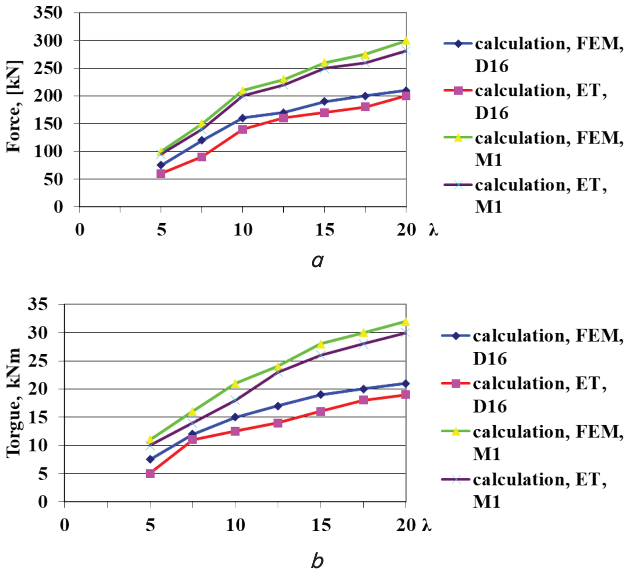


Fig. 8. Dependence of force and moment of rolling and pressing, calculated by the finite element method (FEM) and engineering technique (ET), on the drawing-down λ when processing aluminum alloy D16 and copper alloy M1 on RSM: *a* – force and *b* – moment

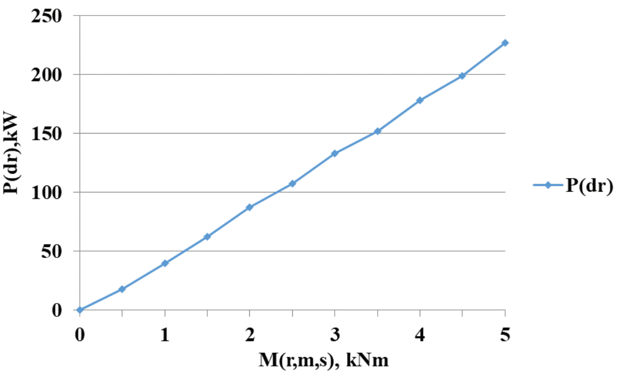


Fig. 9. Dependence of motor power on the equivalent torque

5. 2. Calculation of SSS when rolling rods in smooth and helical rolls, as well as their rolling-pressing on RSM of a new design

Based on the obtained results of the computer modeling of rolling and rolling-pressing of the billets from aluminum D16 and copper M1 alloys on RSM, it was found that:

– when rolling in smooth and helical rolls, the stress intensities *T*, deformation Λ and strain rates *H* acquire the greatest value in the surface zones of the workpiece, while in the central zone they have the lowest value;

– during rolling-pressing, *T*, Λ and *H* also acquire the greatest importance in the surface zones of the billet, while in the central zones they have a moderate value. At the same time, during the pressing of the workpiece in the matrix, these indicators are aligned over the entire section of the manufactured products;

– when rolling blanks in smooth and helical rolls, as well as rolling-pressing, the wrought metal flows along a helical path at different speeds of the outer and inner layers, which leads to the occurrence of macro-shear deformations in the surface zones of the blank;

– during rolling billets in helical rolls and rolling-pressing, due to the flow of metal at different speeds in the protrusions and valleys of the rolls, severe macro-shear deformations occur in the surface zones and adjacent zones of the billet;

– during rolling-pressing, the occurrence of severe macro-shear deformations leads to a significant increase in the surface zones of the workpiece (more than 15), while this value is leveled out when the metal passes through the matrix;

– when rolling billets in smooth and helical rolls, significant vibrations occur in comparison with rolling-pressing of billets on RSM;

– an increase in the elongation ratio, feed and roll angles leads to an even greater increase in H and in the surface area of the workpiece.

5. 3. Discussion of the results of the study

One of the main factors influencing the energy-power parameters of the rolling and combined process of rolling and pressing is a drawing-down during the deformation. Therefore, the authors calculated the forces and the moment of the combined rolling-pressing at the RSM of a new design with various drawing-downs.

Analysis of the calculated data showed that with an increase in drawing, the magnitude of the forces increases in the smooth and helical rolls during rolling-pressing, which is characteristic of the pressing process. The increase of forces on the rolls is associated with an increase in the pressure of the backwater in the deformation zone due to the action of the pressing force. It is found that the magnitude of the forces, arising on the rolls, is always large, compared with the forces arising in the matrices. In our opinion, the reason for this is the appearance of large prop forces in the deformation zone due to the action of the pressing force with large extractors.

It is found that during rolling-pressing on RSM, the contact pressure on the rolls is greater than the contact pressure on the matrix. The reason for this is the smaller contact surface of the workpiece with the rolls than the contact surface of the workpiece with the matrix, and an increase in the back pressure in the deformation zone from the action of extrusion forces.

Based on the results obtained, it can be noted that when rolling in smooth and helical rolls, due to the occurrence of vibration, a sufficiently good condition is not created for stable process control. This does not allow manufacturing rods from non-ferrous metals with precise geometric dimensions.

The results obtained prove that the use of a combined rolling-pressing process in helical rolls and a matrix allows for the stable pressing of the rods. This creates sufficient force and pressure to push the metal through the die. All this makes it possible to produce rods of non-ferrous metals with precise geometric dimensions in a continuous way, without press residues.

An analysis of the power parameters of rolling-pressing in helical rolls and a matrix proves that deformation by this process does not cause large contact frictions on the surface of the rolls and matrix. This is due to the deformation of the metal by torsion. Contact friction does not create intense heating of the bars during their hot extrusion. All this will not create an obvious limitation on the permissible temperature and speed modes of pressing and will not reduce the processing productivity, as well as will not lead to the use of additional complex cooling systems.

Comparison of the energy power parameters obtained by the engineering method (due to the large volume of the method is not given) and computer modeling show a sufficiently high convergence of the calculated values, the regularities are used, which are in vain to the practical data. Deviation of computer simulation data from the analytical calculation data was within 15 % for the force and moment of pressing. Consequently, the proposed method of force and moment distribution of pressing on the RSM can be recommended for practical use in technological and design calculations.

On the basis of the conducted research, it was found that during rolling and pressing in the RSM, compressive stresses appear in the deformation zone, while the metal flows along programmable paths. All this leads to the development of the severe shear components of the strain tensor in the deformation zone, i.e. conditions are created for the development of volumetric macroshift, thereby conditions for a good study of the metal structure. Such conditions of deformation are favorable for defect-free deformation for any deformable material, including non-ferrous metals and alloys.

It should be noted that the development of severe shear deformations and their concentration on the surface volume of the workpiece are accompanied by controlled heating of the metal. The temperature effect of heating is up to 100...420 °C, which makes it possible to reduce the heating temperature before pressing, to optimize the temperature range of deformation.

Increasing the temperature of the workpiece at room temperature deformation on the new mill of RSR leads to a sharp decrease in the effort required for deformation. Such an increase in the temperature is associated with the development of macro-shear deformation and their localization in the surface zone of the workpiece. The pattern of the connection of the workpiece deformation effort with the direction of the deformation displacements is that the plastic deformation of the surface zone of the workpiece in the screw direction drastically reduces the component of the force required for the occurrence and development of deformations in the axial direction.

In this regard, RSM is recommended for hot processing of non-ferrous metals. With a low value of resistance to deformation, such an increase in temperature is not expected.

Thus, when pressing the billet in the proposed RSM, the metal is formed under conditions of alternating radial deformation. In this case, the workpiece is twisted around its axis, which leads to the movement of each metal particle in the deformation zone along a helical (helicoidal) trajectory. Such a turbulent movement of the metal leads to an intensive study of the structure and mixing of non-metallic inclusions in the peripheral and central zone. All this led to higher quality.

It should be noted that the use of the proposed rolling-pressing method makes it possible to obtain an ultrafine-grained (UFG) structure in the metal. All this ensures the production of rods with high physical and mechanical properties.

The main disadvantage of the proposed rolling-pressing method is the impossibility of producing profiles of different shapes and geometries. The strong dependence of the shape and geometrical dimensions of the profiles on the calibers of the matrix requires further development of the scientific base for rolling-pressing of billets on RSM of a new design.

6. Conclusions

1. The methodology for calculating the energy-power parameters of bar pressing on the RSM of a new design was improved and calculation proved that with the combined pressing of the bars, the magnitude of the force and the moment of deformation increases both on the rolls up to 320 kN and on the matrix up to 32 kN·m.
2. The calculation selected three electric motors with a capacity of 15 kW for pressing bars of non-ferrous metals with a diameter of up to 9 mm.
3. The stress-strain state of the workpiece is determined depending on the technological parameters of pressing on a new design RSM and it is shown that when pressing in the deformation zone, compressive stresses arise in magnitude.
4. It is shown that during the deformation of the bars on the new RSM, due to the appearance of deformation intensities of more than 15 in the deformation zone of the cross-section of the workpiece, an ultrafine-grained structure with a size of 1–10 μm is formed.

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