New Combined Technology of Deformation "Rolling-Equal Channel Angular Pressing", Allowing to Obtain Metals and Alloys with Sub-Ultra-fine-Grained Structure

Abdrakhman Naizabekov, Sergey Lezhnev, Evgeniy Panin and Irina Volokitina

Additional information is available at the end of the chapter

Abstract

In this chapter, results of theoretical and laboratory research of combined process "rolling-pressing" using equal-channel step matrix are described. In theoretical studies, the empirical dependences for determining forces of rolling, extrusion, and back pressure in the matrix have been obtained. A program was compiled for finding the optimal value of the angle of intersection of channels in the matrix. In the study of kinematic parameters of the process were obtained formulas for determining diameters of the rolls, the values of which would provide the best capture angle of the workpiece. During computer simulation, the parameters of stress-strain state, temperature distribution, and the influence of the tilting of the workpiece on the process parameters were studied. In the laboratory experiment, the effect of the new combined deformation process "rolling-pressing" on the evolution of microstructure of copper was studied.

Keywords: combined process, rolling-pressing, modeling, experiment, microstructure, copper

1. Introduction

The research and development studies aimed at obtaining high-strength metals and alloys are currently of great scientific and practical interest. Production of metals with unique properties may be possible by reduction of grain through the implementation of intensive plastic deformation in the whole bulk of the deformable workpiece.

A range of new processes of metal-forming designed to produce metal with sub-ultrafine-grained structure whose basic principle refers to the realization of a simple shear scheme in the process of deformation has been recently developed. The equal channel angular pressing of billets [1] in the matrices of various designs is one of these methods. It provides an intensive plastic deformation without significant change of the original cross-sectional dimensions of the workpiece. However, it has a significant drawback—the length of the original billet is limited by the space of the equipment used, i.e., by the working stroke of the press punch. Furthermore, this method of deformation does not provide a continuous pressing process. That is why this method of obtaining a sub-ultrafine-grained metal structure has not found an industrial implementation. It is still in an object of investigation using relatively small samples under laboratory conditions.

The aim of this work is to develop and investigate a new method of deformation, allowing production of long-length workpieces with sub-ultrafine-grained structure at low energy costs.

2. Theory, materials, and research methods

For this purpose, at "Metal forming" Department of Karaganda State Industrial University, the combined process "rolling-pressing" with the use of equal-channel step matrix, calibrated [2] and smooth [3] rolls (**Figure 1**), was developed, which in comparison with conventional compression in equal-channel step matrix partially removes limitations on the sizes of initial billets.

The essence of the proposed method of deformation is as follows. The workpiece which is preheated at the beginning of deformation is applied to forming roll and is fed to the rolling rolls through the contact friction forces capturing it in roll gap. At output, it is pushed through the channels of an equal-channel step matrix. The next billet is served at the time when the workpiece is fully released from the gap of the rolls. Passing through the rolls and once in the matrix, it pushes out of the matrix the billet previously deformed. The process of pressing in this case is implemented through the use of contact friction forces acting at the surface of contact between the metal and the rotating rolls. This process, as noted above, can be applied using smooth and calibrated rolls. The comparative analysis shows that the later use is the
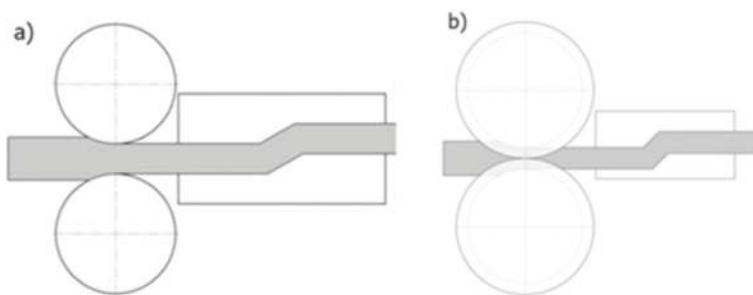

Figure 1. Scheme of combined process "rolling-pressing" with smooth rolls (a) and calibrated rolls (b).

most optimal solution, because it requires a smaller absolute compression of the billet during its rolling to push it through the channels of the matrix. Besides, the broadening of the workpiece in the rolls can be controlled, which in the case of using of smooth rolls should be calculated [4].

The feasibility of the "rolling-pressing" process requires that the projection on the X-axis of the sum of forces generated by the rolls in the deformation zone (marked as P_{ROLL}) is greater than the effort required to push the billet through the channels of the matrix (marked as P_{PRESS}), i.e.:

$$P_{\text{ROLL}} > P_{\text{PRESS}} \tag{1}$$

The projection on the X-axis of the sum of all forces acting at the deformation zone (**Figure 2**) is described by

$$P_{\text{ROLL}} = 2b_{\text{av}} \int_{\gamma_1}^{\alpha} \tau_{\text{av}} R \cos \theta d\theta - 2b_{\text{av}} \int_{0}^{\gamma} \tau_{\text{av}} R \cos \theta d\theta - 2b_{\text{av}} \int_{0}^{\alpha} p_{\text{av}} R \sin \theta d\theta \tag{2}$$

where b_1 and b_{av} are the width of the workpiece after deformation and average width; τ_{av} and p_{av} are the average tangential and normal stresses; R is the radius of the rolls; θ is the current angle; α is the angle of capture; γ and γ_1 are the angles characterizing the extent of zones of advance and lag, respectively.

Angles γ and γ_1 can be found using the methodology described in the work [5]. Integrate Eq. (2) assuming that $b_{\text{av}} = b_1$:

$$P_{\text{ROLL}} = 2b_1 R \tau_{\text{AV}} (\sin \alpha - \sin \gamma_1) - 2b_1 R \tau_{\text{AV}} (\sin \gamma - 0) - 2b_1 R p_{\text{AV}} (-\cos \alpha + 1) \tag{3}$$

Replacing in this equation $1 - \cos \alpha = \frac{\alpha^2}{2}$, $\sin \alpha = \alpha$, $\sin \gamma_1 = \gamma_1$, $\sin \gamma = \gamma$, and taking into account that $\tau_{\text{AV}} = p_{\text{AV}} \mu = \sigma_S \mu$, we get
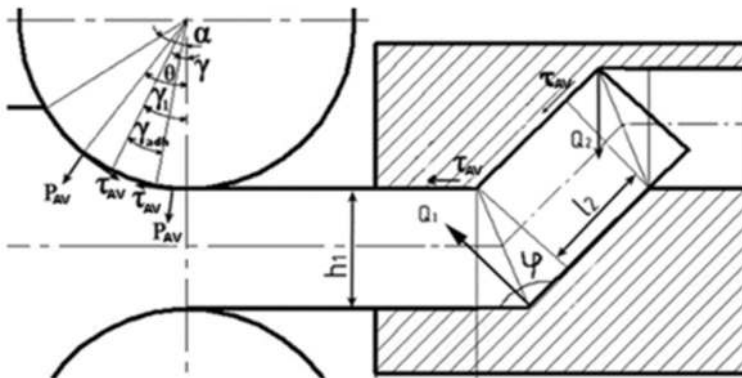

Figure 2. The scheme of forces during deformation.

$$P_{\text{ROLL}} = 2b_1 R\sigma_S \mu_1 (\alpha - \gamma_1) - 2b_1 R\sigma_S \mu_1 \gamma - 2b_1 R\sigma_S \frac{\alpha^2}{2} \tag{4}$$

where μ_1 is the coefficient of friction in the deformation zone during rolling. Finally, we obtain

$$P_{\text{ROLL}} = 2b_1 R\sigma_S \mu_1 \left(\alpha - \gamma_1 - \gamma - \frac{\alpha^2}{2\mu_1} \right) \tag{5}$$

When using grooved rolls, Eq. (5) takes the form:

$$P_{\text{ROLL\_CAL}} = 2R\sigma_S \mu_1 \left[b_1 \left(\alpha - \gamma_1 - \gamma - \frac{\alpha^2}{2\mu_1} \right) + h_{\text{av}} \alpha \right] \tag{6}$$

where h_{av} is the average height of workpiece in the deformation zone. In work [6], the formula for determining pressing forces in equal-channel angular matrix was obtained. Converting this formula taking into account the configuration of the channels of equal-channel step matrix, we obtain the formula for determining tonnage in this matrix:

$$P_{\text{PRESS}} = 2\sigma_S \mu_2 \left[(2l_1 + l_2)(b_1 + h_1) + 2h_1^2 tg\frac{\phi}{2} + \frac{tg\phi \cdot h_1}{\sqrt{3}\mu_2} \right] \tag{7}$$

In the study of back pressure from the matrix, the following dependencies were obtained:

$$Q_1 = \left(2b_1 R\sigma_S \mu_1 \left(\alpha - \gamma_1 - \gamma - \frac{\alpha^2}{2\mu_1} \right) - \sigma_S \mu_2 \left[\left(2l_1 + h_1 ctg\frac{\phi}{2} \right)(b_1 + h_1) \right] \right) / \sin \phi \tag{8}$$

$$Q_2 = Q_1 \cos(180 - \phi) - 2\sigma_S \mu_2 \sin\phi \left(l_2 + h_1 ctg\frac{\phi}{2} \right)(b_1 + h_1) \tag{9}$$

Dependencies (8) and (9) fair when using rolls with smooth barrel. When using grooved rolls, it must also take account of forces of friction in the deformation zone on the side contact metal with the rolls. Taking into account the assumptions that were adopted when defining the force of backpressure Q_1 at the first stage of deformation with smooth rolls, force of backpressure Q_{1C} for process with calibrated rolls is determined by the formula:

$$Q_{1C} = \left(2R\sigma_S \mu_1 \left[b_1 \left(\alpha - \gamma_1 - \gamma - \frac{\alpha^2}{2\mu_1} \right) + h_{\text{AV}} \alpha \right] - \sigma_S \mu_2 \left[\left(2l_1 + h_1 ctg\frac{\phi}{2} \right)(b_1 + h_1) \right] \right) / \sin \phi \tag{10}$$

When projecting forces are on the vertical axis, all forces in the deformation zone cancel out. Therefore, Eq. (9) for determining the force of backpressure Q_{2C} in the case of grooved rolls is not changed. For the normal course of the process must ensure:

$$\frac{P_{\text{PRESS}}}{h_1 b_1} < \sigma_S \tag{11}$$

Failure to comply with this condition, the metal in the area from the line connecting the centers of the rolls to equal-channel step matrix is repressed, increasing its transverse dimensions, thereby making the pressing process impossible.

One of the main factors influencing the pressing force is the angle of the junction of the channels of the matrix. To determine the optimal angle of junction of the channels of equal-channel step matrix, allowing the value of the compression force less than the force of rolling, a program in the Excel editor was compiled. This program allows us to determine the optimal angle of junction of graphically based plotting compression force depending on the angle of intersection of channels, and the rolling forces created by the rolls depending on the size of absolute compression. To comply with the condition (11), efforts were transferred to stresses:

$$\sigma_{ROLL} = \frac{P_{ROLL}}{h_1 b_1} \tag{12}$$

$$\sigma_{PRESS} = \frac{P_{PRESS}}{h_1 b_1} \tag{13}$$

where σ_{ROLL} is the stress in the cross section of the workpiece on the line connecting the centers of the rolls; σ_{PRESS} is the stress in the transverse section of the billet at the entrance to the matrix. As a result, graphs of σ_{ROLL}, σ_{PRESS}, and σ_S depending on the angle ϕ (**Figure 3**) were obtained.

Also, a study of kinematic parameters of this combined process was conducted. As noted above, a combined method of deformation of blanks "rolling-pressing" has advantages over previously known methods of pressing, but it has one drawback that it still does not ensure the
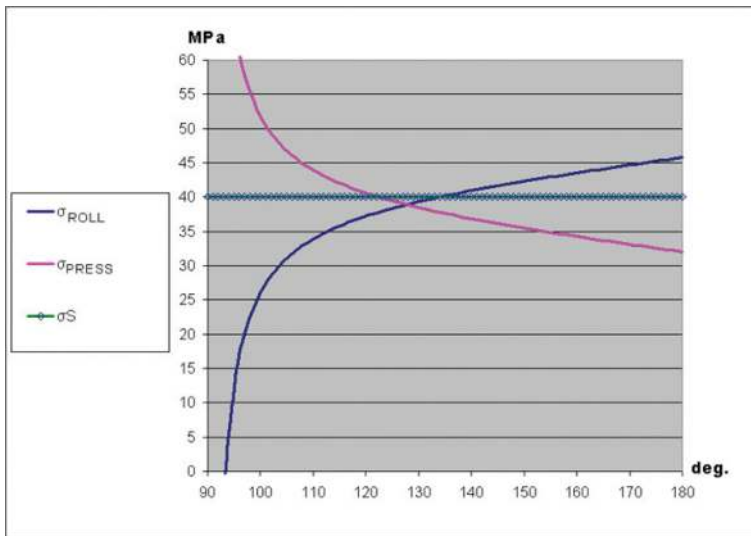

Figure 3. Graphs to determine the optimal angle of junction of the channels in the matrix.

continuity of the process, i.e., during deformation of a batch of blanks subsequent workpiece will push the previous. But after all deformation cycles, in the matrix will be the last not fully deformed workpiece. To remove this drawback, the scheme of combined process "rolling-pressing" with two pairs of rolls and equal-channel step matrix was proposed (**Figure 4**) [7, 8].

The essence of the proposed method of deformation is as follows. Preheated to a temperature of the beginning of the deformation the workpiece is fed to rolling rolls that captured it in roll gap by contact friction forces, and at the output from it, workpiece is pushed through the channels of equal-channel step matrix. After the workpiece exit from the channel matrix, it is captured by the second pair of rolls, which pull workpiece completely from the channels of the matrix. The advantage of this method is that during the implementation of this combined process, the proposed scheme ensures the continuity of the process and removes limitations on the sizes of initial billets.

After exiting from the matrix, the deformed billet will be redirected to the second pair of rolls that have to pull it out of the matrix; for capture of the workpiece by second pair of rolls, it needs to provide two conditions [9] as follows:

1.   Optimal capture angle;

2.   Optimal angular velocity of the rolls must be maintained so the workpiece that is in contact with the rolls is not jammed and slipped.

The final workpiece thickness (at the exit from the matrix) and roll diameters must be known to ensure an optimal capture. Determining the optimum speed of rotation of the rolls is a little complicated, since it is necessary to consider the influence of the matrix on the velocity of the workpiece. **Figure 5** shows the kinematic diagram of this method of deformation. Here, V_{01} is
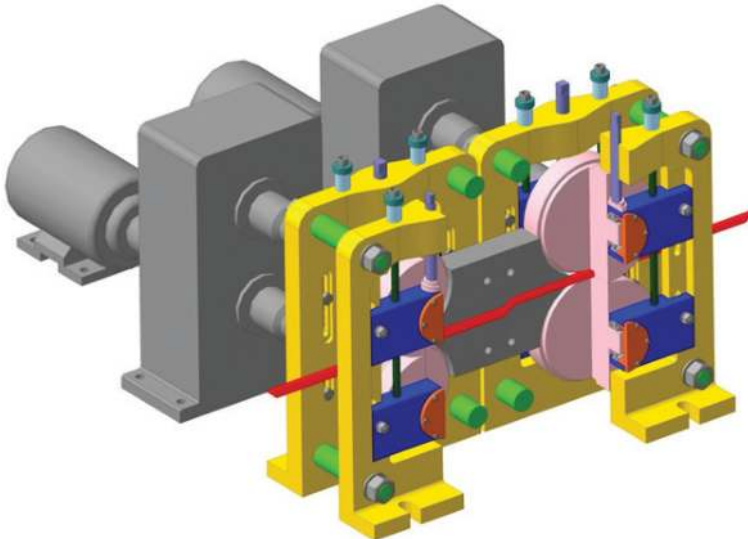

Figure 4. Combined process "rolling-pressing" with two pairs of rolls.
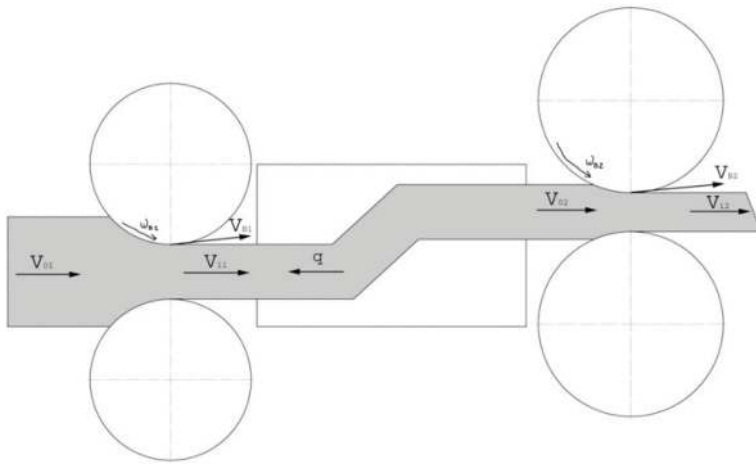
Figure 5. Kinematic diagram of the process "rolling-pressing" with two pairs of rolls.

the velocity of the metal at the entrance to the first pair of rolls; V_{11} is the velocity of the metal at the exit of the first pair of rolls; V_{02} is the velocity of the metal at the entrance of the second pair of rolls; V_{12} is the velocity of the metal at the exit of the second pair of rolls; V_{R1} is the rolling speed in the first pair of rolls; V_{R2} is the rolling speed in the second pair of rolls; ω_{R1} is the circumferential speed of the first pair of rolls; ω_{R2} is the circumferential speed of the second pair of rolls; q is the back pressure of matrix.

Equations were adopted on the following assumptions:

1.   an optimum angle of capture was adopted by 18°;

2.   as the whole construction is on one mill, we can take that both pairs of rolls are fed from the same electric motor. Therefore, the circumferential velocities of them are equal.

The result is the following formulas for finding the required diameter of the rolls:

$$D_2 = \frac{D_1(1 + S_1)}{\cos \alpha_2} \tag{14}$$

$$D_{2CAL} = \frac{R_{ROL\_1}(1 + S_{AV1})}{\cos \alpha_2} + h_1 \tag{15}$$

3. Computer simulation

The next stage of studying of this process was the simulation in program complex DEFORM. The purpose of this simulation was to investigate the stress-strain state of metal during the realization of combined process "rolling-pressing." Initially, the goal was to obtain a successful model in which the first pair of rolls has captured the workpiece, after which it crossed all channels of the matrix, at the output of which fell into the second pair of rolls which drew a blank from the matrix (**Figure 6**).

For investigation of the strain state, the study of parameter "strain effective" (**Figure 7**) was conducted, which includes the components of deformation in the following form:

$$\varepsilon_{EQ} = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2} \qquad (16)$$

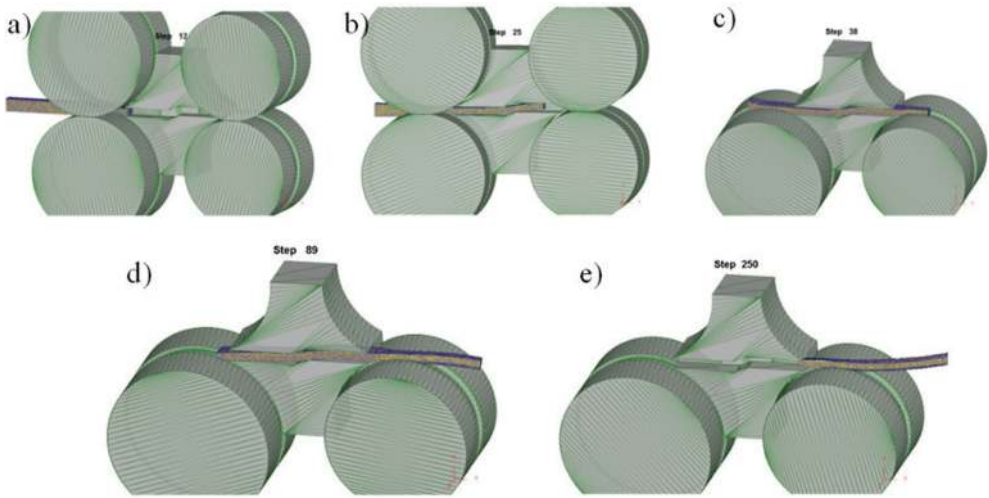where ε_1, ε_2, and ε_3 are main strains.

Figure 6. Stage of successful model with calibrated rolls: (a) the workpiece is in the 1st pair of rolls, (b) the workpiece is in the 1st pair of rolls and in the matrix, (c) the workpiece is in the both pairs of rolls and in the matrix, (d) the workpiece is in the matrix and in the 2nd pair of rolls, (e) the workpiece is in the 2nd pair of rolls.
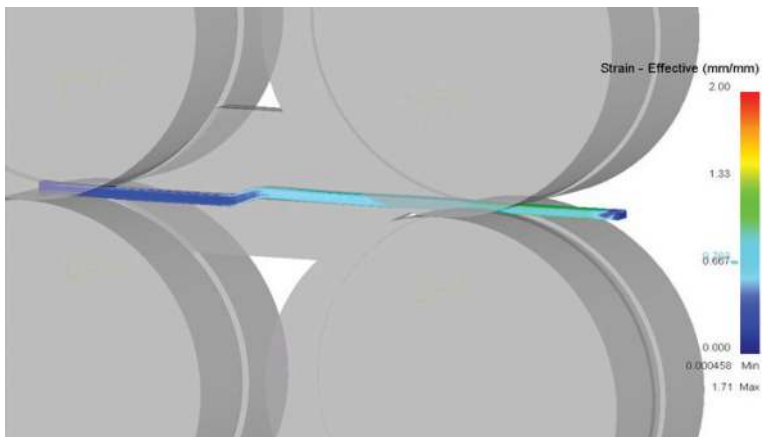

Figure 7. Strain state of the workpiece.

For investigation of the stress state, the study of parameter "stress effective" (**Figure 8**) was conducted, which is defined as follows:

$$\sigma_{EQ} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \tag{17}$$

where σ_1, σ_2, and σ_3 are main stresses.

For a detailed study of the stress and strain state, the modeling of process "rolling-pressing" was conducted by varying the main geometrical and technological factors that have a significant impact on the process. Analysis of the influence of various factors on the stress and strain state of this process showed that factors such as the angle of intersection of channels of the matrix, the coefficient of friction, temperature, and length of the channels of the matrix have a significant influence on the distribution of stresses and accumulated plastic deformation in the whole volume of the workpiece in the implementation of combined process.

The study of temperature conditions of this process (**Figure 9**) revealed that the temperature distribution over the cross section of the workpiece is uneven. A large temperature difference (up to 40°) can result in heterogeneity in physical properties. Therefore, to equalize the temperature difference in the cross section, it is recommended to carry out preheating of the matrix.
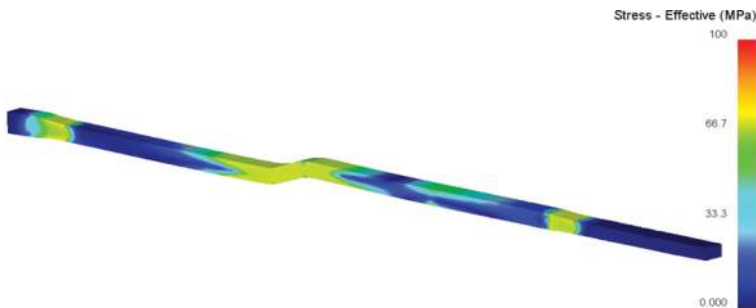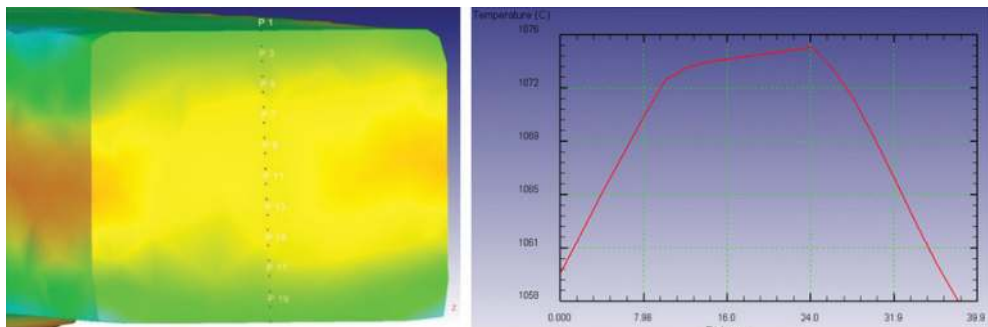

Figure 8. Stress state of the workpiece.

Figure 9. Study of temperature conditions.

In the study of the influence of the tilting of the workpiece (**Figure 10**) on the stress-strain state of the metal, it is established that the implementation of the tilting of the sample is not only has a positive effect on the distribution of accumulated plastic deformation and equivalent stresses in the workpiece, but also contributes to the restoration of the original shape of the cross section, which in some cases can play an important role.
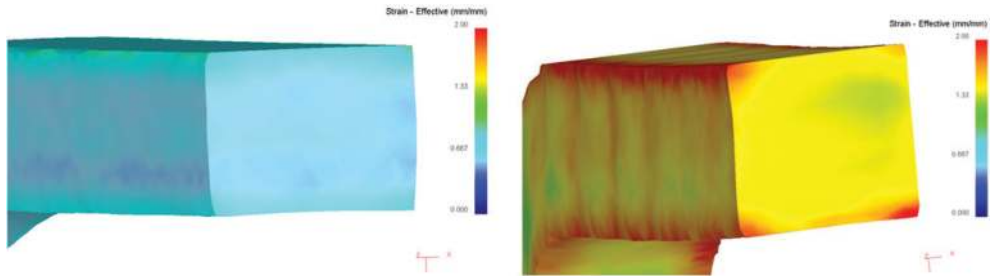

Figure 10. Impact of tilting on stress-strain state.

4. Laboratory experiments

After the simulation, laboratory experiments on the deformation of copper billets were carried by the combined process "rolling-pressing."" As material for the study, a copper alloy of M1 grade was taken. Before the "rolling-pressing" process, all samples were annealed, normalized, and tempered. Modes of heat treatment are given in **Table 1**. For the experiment, workpieces were made with dimensions $h \times b \times l = 16 \times 30 \times 200$ mm.

A laboratory experiment was conducted on designed stand for realization of the combined process "rolling-pressing" with the use of smooth rolls (**Figure 11**) based on rolling mill DUO-250. It was done in three passes.

At increasing temperatures, it is possible to start the process of grain growth during deformation. To exclude this growth, it is necessary to use the deformation temperature that is lower than the initial temperature of recrystallization [10]. Based on this fact, the experiment was conducted at ambient temperature.

With an increasing number of passes, the intensity of the dispersion of the structure increases, but it also increases the hardening of the material. As a result, the resource of plasticity is lost and further deformation and the use in industry of such a metal is impossible, since there is its destruction. For the reduction of the density of excess dislocations and increase of plasticity

Heat treatment mode	Temperature, °C	Time, min	Colling area
Annealing	600	16	Inside the oven
Normalizing	600	16	Air
Quenching	700	16	Water

Table 1. Heat treatment modes.

Figure 11. Experimental stand for realization of combined process "rolling-pressing."

resource, the metal should be heated at temperature that is lower than initial temperature of recrystallization. After determination of this temperature using equations [11], a laboratory experiment was performed. All billets after the "rolling-pressing" process were cut into pieces with a thickness of 5 mm and heated at temperatures of 100–270°C with duration of exposure 30 min and cooling in water.

The treated samples were studied in two sections: transverse and longitudinal, using optical and transmission electron microscopes (TEM). The resulting samples were also tested on a torsion-tensile machine to the test tension and compression. All the samples were studied in the mid-plane of the sample to avoid the influence of peripheral areas.

Preparation of thin sections for metallographic studies was carried out according to standard methods; for the study, an optical microscope Leica equipped with a set box was used for hardness testing. For the studies, at a transmission electron microscope JEOL JEM 2100, thin foils were prepared. For this purpose, from the sample using a precision cutting machine cutoff, the workpieces with a thickness of 250 μm that were subjected to fine grinding for removing the work-hardened layer. Then the samples were subjected to processing in the machine for electrolytic thinning Tenupol 5.

For determination the mechanical properties of copper after heat treatment and subsequent "rolling-pressing" process the torsion-testing machine MI40KU was used. For the testing, standard samples of cylindrical shape in quantities of 72 pieces were used, the diameter of the working part was 3 mm, working length was 15 mm, and tensile speed was 0.5 mm/min. This value corresponds to a strain rate equal to $0.56 \times 10^{-3}\,\mathrm{s}^{-1}$.

5. Results and discussion

5.1. Microstructure of copper before and after the "rolling-pressing" process

Figure 12 presents pictures of the microstructure of copper in the initial state and after preliminary heat treatments. In the structure of the deformed copper, twins are clearly shown (**Figure 12a**), after deformation and annealing grains of copper have more equiaxed grain form (**Figure 12b**).

To evaluate the effectiveness of the "rolling-pressing" process, it is necessary to compare the microstructure of copper samples before and after deformation. Photographs of the microstructure, obtained in the study of copper after the "rolling-pressing" process, are presented in **Figure 13**.

Microstructural studies of deformed copper billets by the combined process showed that before deformation copper has a coarse structure with twins. Grains have an average size equal to 100 μm (**Figure 13**). After the first pass, the structure is intensely reduced up to 40 μm compared with its initial state. In the transverse cross section, the structure is homogeneous and has equiaxed grains. However, in the longitudinal section, the structure has strokefest in
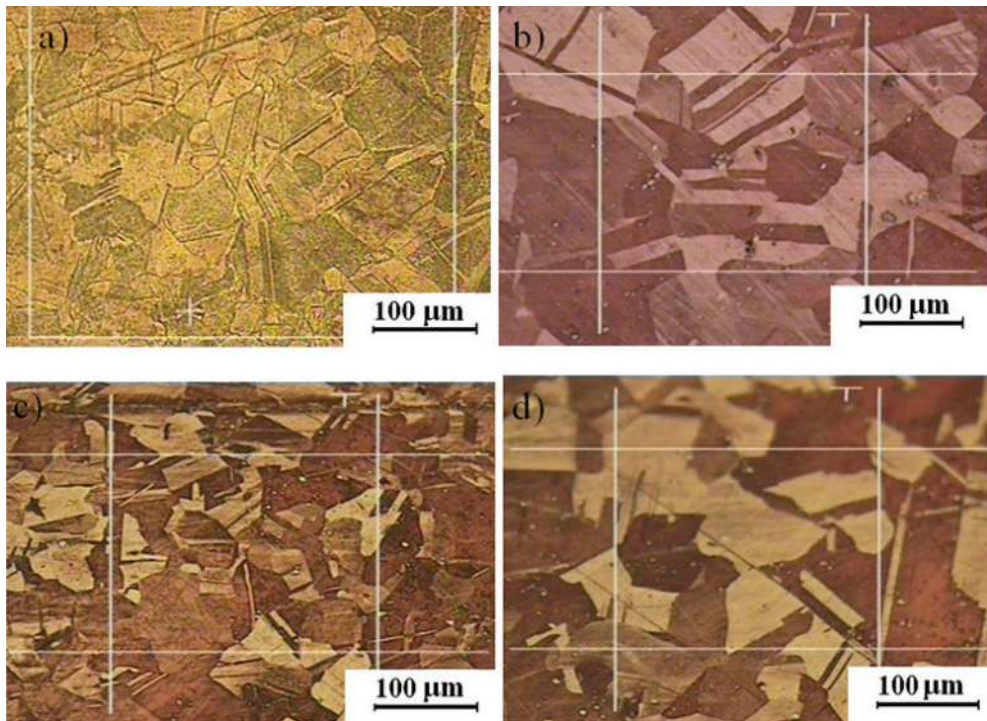

Figure 12. Optical photographs of the microstructure of the initial copper after pre-heat treatment: (a) initial microstructure, (b) annealing, (c) quenching, and (d) normalizing.

Figure 13. Optical photographs of the microstructure of the copper after three passes of "rolling-pressing" process: (a) initial microstructure, (b) annealing, (c) quenching, and (d) normalizing.

radial direction. Individual changes in the structure of copper after "rolling-pressing" were investigated using transmission electron microscopy (**Figure 14**).

During rolling after the first pass, there is a reduction in cross-border distances in both cross sections. Reducing of those distances is due to initial grains compression due to deformation. The creation of new borders occurs slowly, and all fragmentation occurs in the equal channel angular matrix. In accordance with the rule of Hall-Petch, the rolling in the first cycles leads to increasing the strength of parameters of copper by decreasing the interval between the boundaries in both cross sections.

Also, it was established that the second pass of combined process leads to the creation of the structure of mixed type: small recrystallized and deformed. Such structure is created due to the action of two processes: fragmentation in ECA-matrix and recrystallization during rolling. As the result, the copper with such structure has high ductility and strength. After the third pass, the copper structure shows a big part of large-angle boundaries.

TEM investigations have revealed that after two passes in the longitudinal direction elongated grains appear, which during next passes obtain more equiaxed grain form. Also there is an
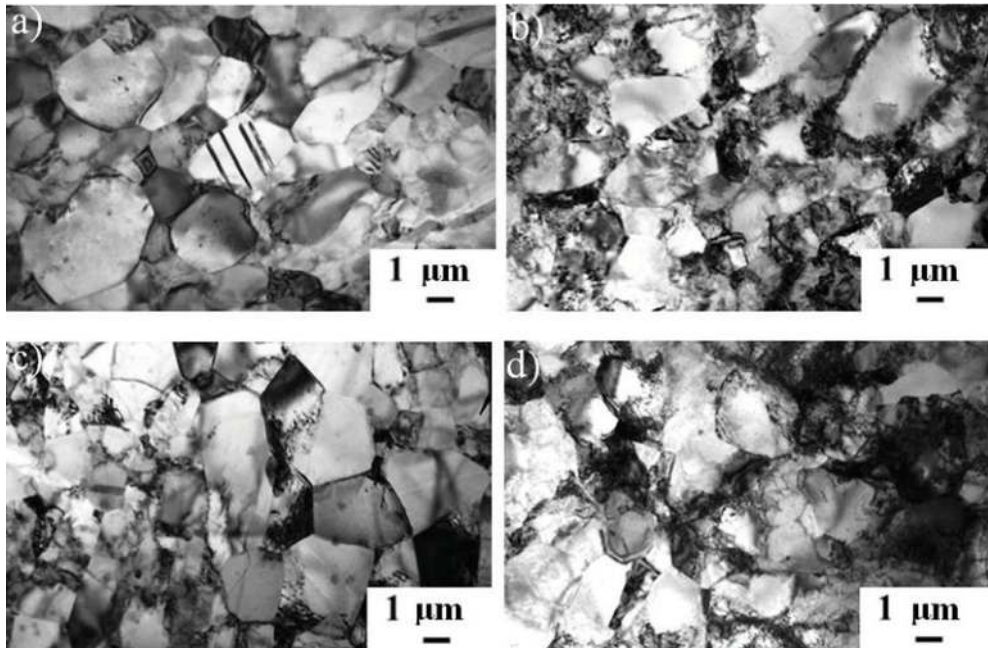
Figure 14. Microstructure of copper after three passes of the process "rolling-pressing" in equal-channel step matrix, obtained with a transmission electron microscope: (a) initial microstructure, (b) annealing, (c) quenching, and (d) normalizing.

increase in the part of borders with large angles. After three passes, copper forms the structure with an equiaxed form and an average size of grains equals to 3.5 μm.

Complex investigation of different preliminary heat treatments on copper billets deformed by the "rolling-pressing" process revealed that preliminary heat treatment almost has no effect on the size of grains of pure copper.

5.2. Mechanical properties of copper before and after the "rolling-pressing" process

The tests for determining microhardness by Vickers were performed using the optical microscope Leica equipped with a set box for hardness testing (**Figure 15**).

The results of microhardness and average grain diameter of copper after thermal pretreatment are presented in **Table 2**. In contrast to other alloys, copper has the highest hardness after slow cooling in air, and after rapid cooling in water hardness becomes the lowest. After the "rolling-pressing" process, measurement of microhardness by Vickers, tests for tension and compression was conducted.

The strength characteristics are represented by values of yield stress and tensile stress; plastic characteristics are represented by the values of relative contraction and elongation (**Table 3**).
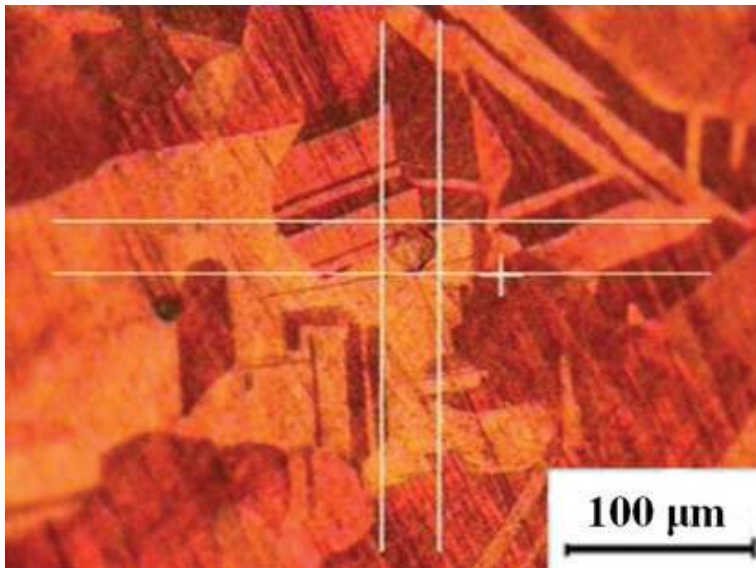
Figure 15. Determination of microhardness of copper.

Heat treatment process	Microhardness HV	Average grain diameter, μm
Initial microstructure	97.5	100
Annealing	104.6	125
Normalizing	109.5	105
Quenching	96.8	95

Table 2. Microhardness and average grain diameter of copper after preliminary heat treatment.

Heat treatment process	Microhardness HV	Yield stress, MPa	Tensile stress, MPa	ψ, %	δ, %
Initial microstructure	229.4	402	469	25.5	3.6
Annealing	215.7	360	374	36.3	8.0
Normalizing	236.8	402	502	22.2	5.7
Quenching	246.1	460	560	26.0	7.2

Table 3. Results of mechanical testing of copper after "rolling-pressing" process.

The most intensive hardening of copper occurs at relatively small degrees of deformation (two passes), then the process of hardening becomes slow, and during subsequent deformation, dynamic weakening occurs; as a result, the structure is less processed.

6. Conclusions

During the theoretical research of combined process "rolling-pressing" with equal-channel step matrix, the following results were obtained:

- Obtained empirical equations for determining the values of force of rolling, pressing, and back pressure from the matrix.

- Compiled a program for determining the optimal value of the angle of intersection of channels in the matrix, allowing you to quickly determine optimal conditions for the implementation of this combined process.

- Obtained formulas for determining diameters of the rolls, the values of which would provide the best capture angle of the workpiece.

- Studied, during computer simulation, parameters of the stress-strain state, temperature distribution, and the effect of the tilting of the workpiece on the process parameters. The results indicate the possibility of obtaining parts with sub-ultrafine-grained structure at realization of combined process "rolling-pressing."

After experiment for the study of influence of the "rolling-pressing" process on the microstructure of copper, the following results were established:

- After the first pass, the structure of copper is intensely reduced till about 40 μm.

- The creation of new borders occurs slowly; all fragmentation occurs in the ECA-matrix.

- After three passes in copper forms, the structure with an equiaxed form and average size of grains equal to 3.5 μm.

- A comprehensive study of the effect of different prethermal treatments on the structural changes in copper after the "rolling-pressing" process showed that preliminary heat treatment has little effect on the grain size of pure copper produced by severe plastic deformation.

At the same time, in almost identical grain size of the structure after the "rolling-pressing" process, the copper after quenching has greater values of the yield stress and tensile stress in comparison with copper obtained after other heat treatment processes.

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References

[1] Valiev RZ, Langdon TG. Principles of equal-channel angular pressing as a processing tool for grain refinement. Progress in Materials Science. 2006;**51**(7):881–981. DOI: 10.1016/j.pmatsci.2006.02.003

[2] Lezhnev SN, Naizabekov AB, Panin YA. Theoretical studies of the joint "extrusion-rolling" process aimed at making sub-ultra fine-grained structure metal. In: Tanger Ltd, editor. 20th Anniversary International Conference on Metallurgy and Materials; May 18-20. Brno, Czech Republic: Tanger Ltd; 2011. pp. 272–277

[3] Naizabekov A, Lezhnev S, Panin E, Koinov T. Theoretical grounds of the combined "rolling-equal-channel step pressing" process. Journal of Chemical Technology and Metallurgy. 2016;**51**(5):594–602.

[4] Naizabekov A, Lezhnev S, Panin E, Koinov T. Study of broadening in a combined process "rolling-pressing" using an equal-channel step die. Journal of Chemical Technology and Metallurgy. 2015;**50**(3):308–313.

[5] Fastykovsky AR, Peretyat'ko VN. Study of the effect of front back pressure on the length of the zones of sliding and sticking in the deformation zone during rolling. Izvestiya VUZ. Chernaya Metallurgiya. 2002;**2**:15–17.

[6] Naizabekov AB, Andreyashchenko VA. Determination of the effort during equal channel angular pressing. Technology of Production of Metals and Secondary Materials. 2006;**2**:120–124.

[7] Lezhnev S, Panin E. Investigation of the influence of geometric and technological factors on the stress-strain state of metal in the implementation of the combined rolling-pressing process. Advanced Materials Research. 2014;**936**:1918-1924. DOI: 10.4028/www.scientific.net/AMR.936.1918

[8] Naizabekov A, Lezhnev S, Panin E, Koinov T, Mazur I. Development and theoretical study of new scheme of realization of combined process "rolling-pressing" using equal channel step matrix. Journal of Chemical Technology and Metallurgy. 2017;**52**(2):186–192.

[9] Naizabekov AB, Lezhnev SN, Panin EA, Panin DA. Kinematics of the combined process "rolling-pressing" in equal channel step matrix. In: KSTU, editor. International Scientific-Practical Conference "Scientific-Technical Progress in Metallurgy"; October, 16-18. Temirtau, Kazakhstan: KSTU; 2007. pp. 238–242.

[10] Kopylov VI, Chuvildeev BN. The limit of grinding grains in equal-channel angular deformation. Metals. 2004;**1**:22–35.

[11] Lopatin YG. The evolution of the grain structure during deformation and annealing of microcrystalline materials obtained by equal channel angular pressing [thesis]. Moscow; 2010.