Hindawi
Modelling and Simulation in Engineering
Volume 2019, Article ID 8563830, 10 pages
https://doi.org/10.1155/2019/8563830

Research Article

Development and FEM Modeling of a New Severe Plastic Deformation Process according to the Reverse Shear Scheme

Alexander F. Tarasov, Alexander V. Altukhov, Eduard P. Gribkov, and Aleksandr R. Abdulov

Computer and Information Technology Department, Donbass State Engineering Academy, Akademichna 72, Kramatorsk 84313, Donetsk Region, Ukraine

Correspondence should be addressed to Alexander V. Altukhov; astratsl@gmail.com

Received 27 May 2019; Revised 29 August 2019; Accepted 7 September 2019; Published 16 October 2019

Academic Editor: Aiguo Song

Industrial commercial use of SPD processes is in some cases hindered by the complexity of equipment and high loads on the tool associated with high hydrostatics upon implementation of existing deformation processes. New and modified SPD schemes are offered relatively often, so the methods for their creation, modeling, and ways of improvement are of particular interest. Therefore, the article provides a classification of SPD schemes, which are divided into several groups depending on the nature of the material flow in the deformation zone. The second attribute of the fission process is the volume of the metal, contemporaneously located in the plastic deformation zone. An analysis of the influence of SPD schemes on the features of formation of a plastic deformation zone allows us to identify promising ways to modify them. A new SPD process is proposed, called as the "Reverse Shear" (RS), in which the workpiece is deformed under conditions of flat deformed state, uniform in each cross section along the entire length of the workpiece. The RS process allows us to change the paths of deformation to redistribute strain within the workpiece volume due to different positioning of a workpiece in a die. To justify the proposed deformation scheme, the SPD processes are divided into groups and an analysis of the deformation schemes' features, which are analogs of RS, is performed. Simulation of the considered SPD processes was performed using FEM, implemented in specialized QForm CAE-system. A study of the influence of a tool with inclined surfaces on formation of a deformation zone in a workpiece during RS and analogues has been carried out. The degree of deformation nonuniformity in a cross section for the considered deformation schemes has been determined, and the possibilities of the proposed process are shown in comparison with analogues. The advantage of the RS scheme is the absence of unformed edges of the workpiece, which reduces material consumption, increasing the accumulated degree of deformation by one operation and reducing the tooling complexity to obtain workpieces with a desired structure. It also provides an opportunity to deform workpieces by various routes (RS-60 and RS-180) and to more specifically develop or select SPD schemes based on modeling. Changing the aspect ratio of the workpiece cross section also allows us to manage the change in its stress-strain state during deformation. Comparisons with the experiment carried out for three operations of deformation of a Cu-ETP copper sample by the RS-60 route show that the simulation results correspond to the real process.

1. Introduction

Existing processes of severe plastic deformation (SPD) are based on the creation of essential gradient of material plastic deformation, which is carried out according to the scheme of simple shear [1, 2]. Researches show that such a deformation scheme is necessary to obtain ultrafine-grained (UFG) materials, the grain boundaries of which are highly (more than 15 degrees) misoriented [3, 4]. In this case, the degree of accumulated plastic strain should exceed 2 [5]. Classification of different types of SPD processes was performed in a number of papers. The basic types of processes have been identified in accordance with different ways of creating simple shear scheme [1, 2].

This group of processes is actively developing; deformation schemes are modified for more efficient creation of the UFG structure in the bulk material. Development of the process takes place within the scope of basic deformation modification schemes in order to increase the degree of grain boundary misorientation, to ensure uniform properties

throughout the volume of workpieces, to increase the degree of applicability of metal, etc. [6]. However, despite obtaining improved mechanical properties of workpieces, introduction of the SPD technologies into production processes is hampered by technological disadvantages of the existing workpiece deformation schemes [7]. Providing the industrial applicability is an important aim, and it requires substantial modification of basic SPD processes to improve their manufacturability [8]. A positive example is the Conform process and the corresponding equipment that implements the scheme of continuous ECAE process. The Conform process is implemented with the rotational movement of the tool, and it is used to deform lengthy workpieces, being actively used in industry [9].

Deformation conditions of the workpieces in the SPD processes determine the stress-strain state (SSS) of material during processing, as well as the microstructure and mechanical characteristics of the obtained materials [5]. The sequence of the operations of forming the workpieces forms the route of deformation [10].

The use of various deformation routes is related to the fact that, at each stage of the SPD process, there is a task of intensifying the shear strain and subsequent leveling of the accumulated strain throughout the volume of the workpiece.

At each shaping stage, the elements of the workpiece volume are in different conditions of deformation and dead zones may also appear. The location of the dead zones is determined by the type of process [3, 4]. For example, in the ECAE process, the deformation zone moves along the workpiece when it passes through a die with angular channel. In this case, dead zones are formed at the edges of the workpiece [11–21]. Similar deformation conditions are realized during Twist Extrusion (TE) [5].

A scheme for deforming workpieces with variable cross-sectional shape of the workpiece from a rectangle to a parallelogram and vice versa has also been developed (Simple Shear Extrusion (SSE)) [22]. This process implements a simple shear deformation scheme during extrusion of a workpiece through a matrix with variable shape of the working channel. To increase the uniformity of the properties distribution over sections of the workpiece, it is rotated around the longitudinal axis before each stage of deformation (ECAE, SSE) [23] or matrices are used with rotation to different directions upon TE [24].

If during the SPD process the entire volume of the workpiece is deformed simultaneously (MAF, CCDF), the dead zones are formed in the corners created by the tool or in the area adjacent to the free surface. During deformation, these parts of the workpiece move without significant deformations [8]. Therefore, in order to align the properties throughout the workpiece volume, deformation are carried out in several directions (ECAE, TE) or the shape of the workpiece is changed [5]. Simultaneously, with the elimination of dead zones of the workpiece, the overall degree of plastic strain of the material is increased. For example, a square or a rectangular cross section of the workpiece is transformed into a round one during the process of deformation; after that the original shape of the workpiece is restored, thus providing cyclicality of the process [7].

Improvement of deformation schemes is carried out on the basis of an experiment or by simulation of SPD processes using numerical methods and CAE systems [4]. Modification of schemes and boundary conditions for simulation of the SPD processes leads to the change of plastic deformation area, affects the strain hardening area and, accordingly, provides final distribution of mechanical characteristics throughout the volume of workpiece [25].

New and modified SPD schemes are offered relatively often; therefore, methods of their creation, directions, and ways of improvement are of particular interest. Analysis of influence of the SPD schemes on the features of formation of plastic deformation zone makes it possible to determine promising ways for their modification. Ultimately, on the basis of modeling, it is possible to develop or select SPD processes more purposefully. Thus, for purposeful development of new deformation schemes, it is required to study the possibilities of controlling the flow of metal in the deformation zone.

2. Simulation Results of Reverse Shear Technology

To highlight general laws of material behavior in the basic SPD processes, we classify them according to a number of features characterizing the deformation schemes applied. A common feature of all SPD processes is deformation under plane strain conditions, which provides a simple shear scheme in the volume of workpieces [2].

Considering the basic SPD processes from the point of view of system approach, it can be noted that they are divided into several groups according to the nature of the material flow in the deformation zone (see Figure 1). The first group assumes the presence of axial symmetry of the material flow during deformation. Such processes include HPT, TE, CEC, and SSE [5, 22]. For this group of processes, the distance from its axis of symmetry is important for the deformation of the workpiece.

The second group includes processes without axial symmetry of the deformation zone: ECAE, CCDF, and MAF [4, 5, 13, 26–28]. The combined use of two or more different SPD processes allows us to achieve leveling of deformation throughout the cross section of the workpiece; for example, one can sequentially deform the central part and the peripheral zones of the cross section of the workpiece [29].

In the processes of the third group, the deformation zone is divided into parts between separate workpieces (ARB process), which are deformed jointly, or parts of one workpiece (RCS process) [29].

The second attribute of the division process is the volume of the metal, which is simultaneously located in the zone of plastic deformation. In a number of processes (ECAE, TE, CEC, and SSE), the workpiece is sequentially moved through the zone of plastic deformation. In this case, the deformation zone has the form of a narrow area in which shear deformations are localized. The rectangle selected in the body of the original workpiece takes the form of a parallelogram after deformation. A common disadvantage of the schemes with sequential movement of the workpieces through the zone of plastic deformation is the presence of marginal zones in which

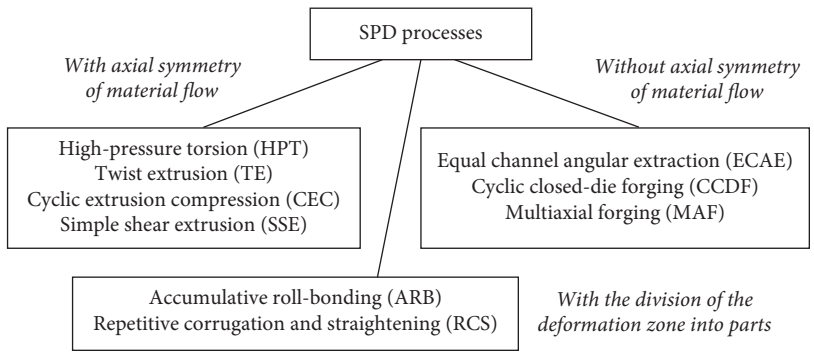

Figure 1: Division of SPD processes into groups.

the metal is not deformed with the required degree of deformation. The modification of the punch shape in the ECAE [19] scheme allows us to reduce the volume of unformed end zones of the workpiece and reduce uneven distribution of accumulated strain over the volume of the workpiece.

It should be noted that the use of TE, SSE, and other processes with axial symmetry requires creation of a backpressure force at the workpiece exit from the matrix [5, 29]. The backpressure force is necessary to eliminate the longitudinal component of the flow of the workpiece material, which appears when the shape changes or the channel of the matrix (TE) is rotated. In this case, more complicated die tooling and synchronization of the work of the working press cylinders are required.

In other processes (HPT, CCDF, and MAF) in conditions of plane strain state, the entire volume of the workpiece is deformed simultaneously. In this case, it is difficult to control the process of metal flow, since its character practically depends only on the aspect ratio of the cross section of the workpiece as well as on friction on the surface of its contact with the tool. The deformation zone in these processes is significantly larger and can cover the entire volume of the workpiece at some stages of deformation. Therein, the boundaries of the deformation region are formed by the tool and parts of the workpiece, between which a shear occurs. For example, when implementing the MAF scheme, only one side of the workpiece is free in the direction of material flow [4]. Thus, the shape and location of dead zones depend on the type of process that determines the location and shape of the plastic deformation zone (CCDF (on the axis of the workpiece) and MAF (in the corners along the diagonal of the workpiece)).

Let us consider in more detail the RCS process, which is implemented under conditions of a relatively low hydrostatic pressure in the deformation zone. The RCS process is proposed by Huang et al. [30].

During the first operation, the workpiece is deformed by a pair of punches with protrusions. Workpiece transverse deformation is limited because of friction between the workpiece and the protrusions of the punches, which creates simple shear scheme of deformation. The protrusions on the punches produce division of the workpiece into parts and the deformation of each one with displacement in opposite directions. It creates several foci of deformation along the length of the workpiece (highlighted in Figure 2).

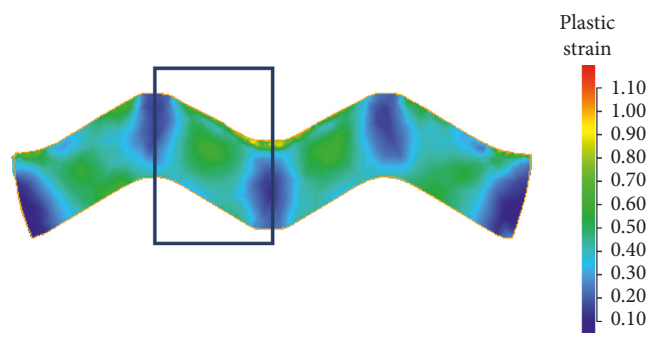

Figure 2: The repetitive corrugation and straightening (RCS) deformation process scheme [30].

During the second operation, deformation is performed by flat punches. Thus, the original shape of the workpiece is restored and the deformation process becomes a cyclical one. Deformation of the workpieces by punches with protrusions and by flat ones recurs several times with an offset along the length of the workpiece. This ensures uniform deformation of the entire volume of the workpiece and elimination of dead zones opposite the protrusions of the punches.

The deformation schemes, which are similar in nature to the RCS, are proposed in [4, 8]. In particular, the authors Babaei et al. [31] proposed a scheme for deforming workpieces by repetitive forging (RF), in which deformation is performed by two types of punches in a rectangular matrix (see Figure 3). The workpiece element for RF is highlighted by the rectangular frame in Figure 2.

The RF process can be represented as an analogue of RCS, in which a rectangular workpiece element between the protrusions of the die is highlighted and the boundary conditions on the lateral surfaces of this element are changed. The offset of the side faces of the workpiece is limited by the tool [31]. At the first stage, punches with the angle of 45° change the cross section of the workpiece in the form of a square and it takes the form of a parallelogram. In the second stage, the deformation is performed by flat punches and returns the shape of the workpiece cross section to the original form. The cycle of the two deformation operations is repeated several times to obtain the UFG structure in the workpiece. The advantage of the scheme is

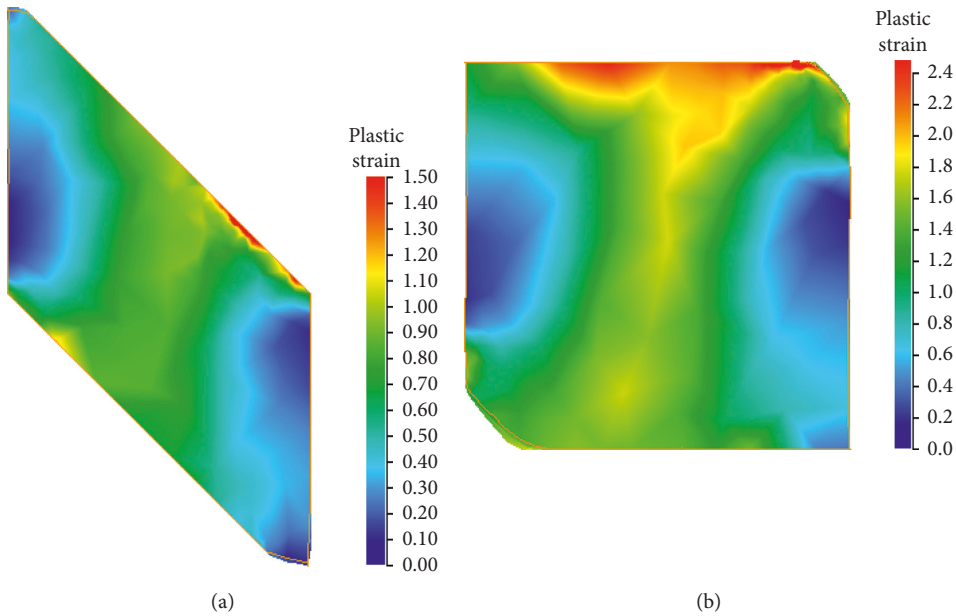

Figure 3: Diagram of the deformation of the workpiece cross section in the process of repetitive forging (RF) [31]: (a) after the first operation; (b) after the second operation.

the ability to process sufficiently long workpieces. In addition, each cross section of the workpiece is in uniform SSS.

The results of the FEM calculations (see Figure 3) for a workpiece of copper Cu-ETP at a temperature of 20°C, with dimensions of $20 \times 20 \times 40$ mm, show that in the process of deformation along the longitudinal axis of the workpiece, an accumulated plastic strain localization zone is formed. Rotation of the workpiece by 90 degrees does not eliminate the uneven distribution of accumulated strain over the cross section of the workpiece with an increase in the number of operations.

A similar solution with change in the geometry of the punch, workpiece, and the processing routes was proposed by the authors in [32, 33] (see Figure 4). The proposed processing route RS-180 can also be viewed as an RCS scheme, in which the part of the workpiece between the two offset protrusions of the upper and lower punches is highlighted (see Figure 3). But this scheme allows you to change the position of the workpiece between the stages of deformation (routes RS-180 and RS-60) to obtain a more uniform distribution of properties in the volume of the workpieces.

In contrast to the RF scheme, the vertical faces of the punches move with the workpiece and create active friction forces on the side surfaces of the workpiece. The advantage of this processing route is the exclusion of burrs in the corners of the punches, more opportunities for changing the processing routes in the process of the workpieces deformation. The possibility of changing the deformation routes and the cross-sectional shapes of the workpieces is shown in Figure 4. For processing, any form of the initial section of the workpiece can be applied, which fits the matrix. By stopping the deformation in an intermediate position, the shape of the final section of the workpiece can be changed.

Because of the geometry of the punches, the proposed process allows us to change the position of the workpiece contact surfaces at each operation and thus reduce the localization in the plastic deformation zone. Localization of deformation occurs in the center of the workpiece cross section. The closed corners of the punches allow us to change the cross-sectional shape of the workpiece from the parallelogram directly onto the parallelogram with the change of sharp corners on blunt, and vice versa. Possible options for rotation of the workpiece are between the stages of deformation at 180° and/or approximately 60° (see Figure 5). These change the strain-stress state of the workpiece material. Changing the aspect ratio of the workpiece cross section also allows us to manage the change in its SSS during deformation. With respect to the parties less than one, the RS-60 route can significantly reduce initial contact of the workpiece surfaces and the tool in the 2nd and further operations, which reduces the localization of deformation in cross section.

Let us consider the change in the SSS in the cross section of a workpiece during reverse shear process. In the initial position (see Figure 5(a)), the workpiece is located between two punches in the die and is in contact with its sidewalls. In the process of deformation by the upper punch, the deformation zone is formed along the diagonal of the cross section between obtuse angles of the punches. Upon further movement of the punch (Figure 5(b)), the contact surface with inclined faces of the punch increases. In this case, an increase and rotation of the center of intense plastic deformation relative to the center of the workpiece in the direction of the sharp corners of the die occur (see Figure 5(c)). The workpiece areas adjacent to the sides of the punches are deformed significantly less.

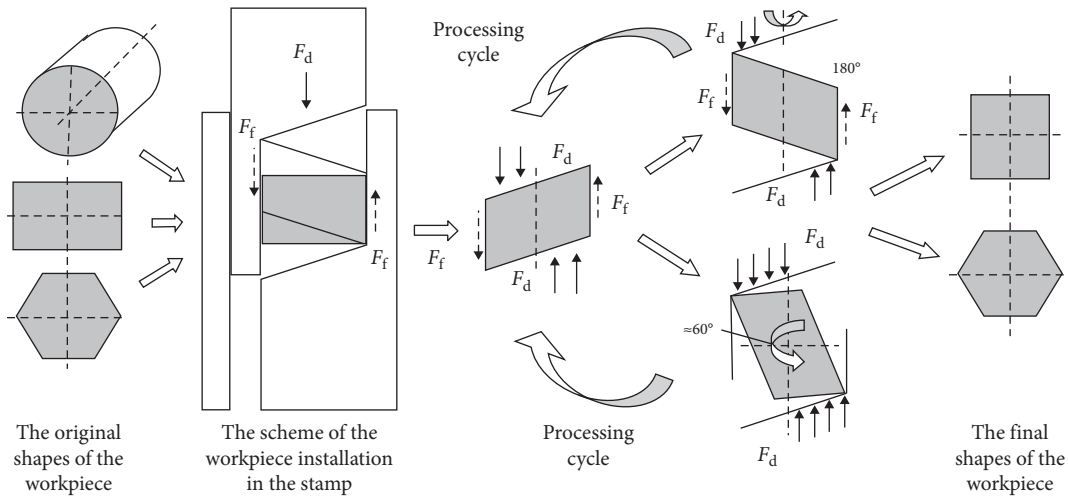

Figure 4: Various processing routes (RS-180 and RS-60) for the reverse shear scheme (RS) [32].

The final shapes of the workpiece at each stage, except for the last one, are shown in Figure 5(c). For all subsequent operations, the initial position of the workpiece is shown in Figure 5(d). The character of strain distribution over the section of the workpiece at each stage of RS-60 route changes insignificantly (see Figures 5(c)–5(e)). At the same time, the values of deformation grow at each transition of deformation, as can be seen from the change in the scales of accumulated deformations.

After extracting out of the die, the workpiece is rotated in space around the longitudinal axis and reinstalled in the die (see Figure 5(d)). The nature of changes in the zone of plastic deformation in each operation is similar. There is an increase in the accumulated degree of deformation in the cross section of the workpiece. The size of areas with reduced deformation decreases at each stage of deformation. At the last stage, the punch stops at an intermediate position (see Figure 5(f)). In this case, a cross section of workpiece is formed in the form of a hexagon or a rectangle, depending on the aspect ratio of the original workpiece.

One of the most important indicators of technological capabilities of SPD processes is the uniform distribution of accumulated strain within the cross section and length of the workpiece. This parameter affects the amount of waste after processing. To estimate the distribution of the accumulated strain within the cross section of the workpiece, we use the coefficient of nonuniformity of deformations (1) [25].

Application of this factor allows us to compare accumulated average values of the degree of deformation in the cross section of workpieces for various deforming processes.

Evaluation of the strain distribution within the cross section of the workpiece is performed as follows:

$$K_e = \frac{1}{2}\left(\left|\frac{e_{\max} - \langle e_i \rangle}{e_{\max}}\right| + \left|\frac{e_{\max} - \langle e_i \rangle}{e_i}\right|\right), \quad (1)$$

$$\langle e_i \rangle = \frac{e_{i1}S_1 + e_{i2}S_2 + e_{i3}S_3}{S_1 + S_2 + S_3}, \quad (2)$$

where $e_{\max}$ is the maximum value of the deformation within the cross section of the workpiece; $<e_i>$ is the average value of the strain within the cross section of the workpiece; e_{i1}, e_{i2}, and e_{i3} are the average values of deformation for the three zones of the workpiece, with minimum value, average value, and maximum; S_1, S_2, and S_3 are areas of each of the three deformation zones, respectively, mm^2.

The calculations were carried out for all the considered processes under the same conditions of deformation: temperature −20°C, coefficient of friction between the tool and the workpiece −0.3 according to Levanov [34], the material of the workpiece is commercially pure copper Cu-ETP. Indicators of the deformed state of the workpieces in the considered processes SPD are given in Table 1. In particular, the FEM calculations of the RS-60 process showed that the average values of the degree of deformation are 0.9 in the second and subsequent operations for workpieces with dimensions 20 × 18 × 80 mm and at the angle of the deforming surface of the punches −30° (see Figure 5). Thus, the scheme proposed by the authors leads to intensification of shear deformations and to the increase in accumulated degree of deformation at each deformation operation.

As a result of the conducted studies of the considered SPD processes, it can be noted that nonuniformity of deformations after the first deformation stage does not differ much as a whole, with a minimum nonuniformity of 0.65 for the RS process and a maximum of 0.72 for the RCS process. For the RCS process, the nonuniformity of deformations is adversely affected by the end zones and the kink areas of the workpiece, in which the material remains weakly deformed, which leads to an increase in the nonuniformity of deformations.

Evaluation of the degree of deformation for each process should be carried out with an indication of the features of the technological parameters of each scheme. So, for RCS and RF processes, the return to the original shape of the workpiece occurs in two operations: (1) from a square (rectangular) section shape into a parallelogram; (2) from a parallelogram to a square (rectangular). Consequently, the

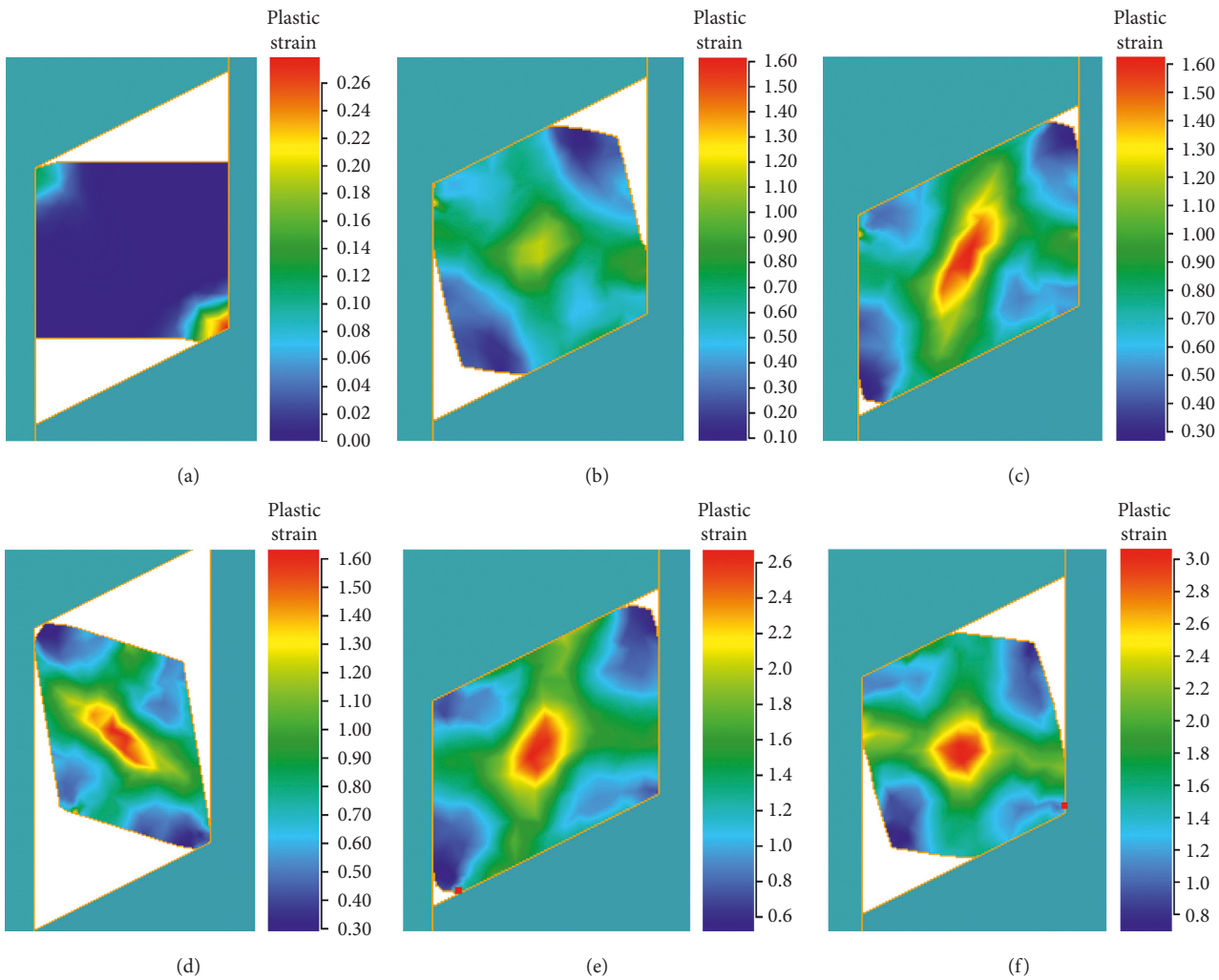

Figure 5: Distribution accumulated plastic strain values for the deformation operations using the RS-60 deformation route: 4 operations, material used is Cu-ETP copper, and friction 0.5 according to Levanov [34]. Workpiece dimensions: width 20 mm, height 18 mm, and length 80 mm. (a) Original position of the workpiece in the die. (b) Intermediate position of the workpiece at the 2nd stage of deformation. (c) Position of the workpiece at the end of the 2nd stage of deformation. (d) Original position of the workpiece at the 3rd stage of deformation. (e) Position of the workpiece at the end of the 3rd stage of deformation. (f) Final position of the workpiece at the 4th stage of deformation.

accumulated strain should be compared after two deformation operations. For the RS process, in which the transformation from square to parallelogram occurs in the first deformation operation, and in the subsequent operations from the parallelogram to the parallelogram with the opposite angle of inclination, the degree of deformation in the first operation is two times less than the degree of deformation of each subsequent operation. And, thus, it is difficult to correctly estimate the degree of accumulated strain for the processes under consideration in a single deformation operation. It is more correct to compare the obtained results after 4-5 operations of deformation.

3. Experimental Research

To check the adequacy of the simulation results, commercially pure copper Cu-ETP workpieces were deformed with initial dimensions of $20 \times 14 \times 40\ \text{mm}^3$, which was divided into two parts, each 20 mm long. A dividing grid with a mesh size of 2×2 mm was deposited on the inner end surface of one part of the workpiece. The workpiece was preliminarily annealed at the temperature of 500°C for 2 hours. After that, at a room temperature of 20°C, deformation was performed according to the process diagram, a reverse shear for 3 times. The angle of inclination of the deforming punches' surfaces was 30°. The workpieces were deformed on a 500 kN press (Figure 6(a)). Graphite-based lubricant was applied to the contact surfaces of the punches. The deformation force was 375 kN for the first operation and 420–430 kN for subsequent operations.

Assessment of the accumulated strain was carried out using dividing grids according to the method of Renne [35].

The change in the dividing grid, the shape of the selected layers, and cells in the horizontal 1, 2, and 3 directions and

Table 1: The values of the workpieces' deformed state parameters in the process of SPD.

Process type/angle of deformation surfaces	Average values of the degree of accumulated strain (e_i)	Coefficient of nonuniformity of deformation (K_e)
RCS/30°	0.45	0.72
RF/45°	0.7	0.68
RS/30°	0.45 (for the first operation) 0.9 (for the following operations)	0.65

vertical 4 and 5 directions show the position of characteristic zones of strain distribution in the cross section of the workpiece. The most significant metal displacements are observed in the central zone of the cross section of the workpiece (see Figure 6(b)). The center of the greatest deformations is elongated along the largest diagonal of the workpiece. Figure 6 also highlights the areas in which the results of the deformation simulation are of the smallest value. The position of the tool relative to the workpiece 7 is also shown. As a whole, the images of the dividing grid show that the character of the distribution of deformations in the cross section of the workpiece corresponds to the results of modeling by the finite element method.

The initial position of the workpiece in the die before performing the second deformation operation is shown in Figure 6(c), and in the intermediate position—in Figure 6(d). The change in the position and shape of the selected cells shows that the metal flows intensively along the inclined surface of the punch (cells 3 and 4) and is inhibited on the lateral surface of the tool (cells 1 and 2). With further movement of the tool, cell 2 will significantly change its shape and cell 1 will remain in the stagnant zone near the sidewall of the tool.

For quantitative comparison of the results of numerical modeling with the experiment, the graphs of distribution of accumulated strains in the cross section of the workpiece for the selected points are shown (Figure 7). Comparison of data for three operations of the RS-60 route confirms adequacy of the simulation. In particular, the zones along vertical sides of the punches are deformed less than in the center due to the influence of friction forces. Discrepancies between the results of experimental and theoretical studies of accumulated deformation amounted to an average of 17%.

4. Discussion of the Results

Analysis and systematization of the schemes of known SPD processes allow us to purposefully select, modify, or develop new schemes for deforming workpieces to obtain the UFG structure. In particular, analysis and identification of the considered SPD processes' features show that in a number of deformation schemes, the center of plastic deformation does not cover the entire volume of the workpiece, but successively moves from end to end along the length of the workpiece (ECAE, TE, and CEC). These deformation schemes do not allow high-quality deformation of the end sections of workpieces, which reduces the volume of a part of the workpiece with the UFG structure.

On the basis of the performed analysis, a new method of SPD of workpieces was proposed according to the reverse shear scheme, in which all cross sections of the workpieces are in the same SSS [32]. The proposed solution differs in that during deformation process active friction forces are created on vertical faces of the workpiece due to the change in the tool design. At the same time, the RS scheme allows changing cross-sectional angles of the workpiece from sharp to blunt and vice versa in one turn of deformation. This increases the accumulated degree of deformation in a single operation and reduces the complexity of obtaining workpieces with the desired structure. To do this, the workpiece after extraction from the die is rotated in space using one of the routes (by 180° [32] or approximately by 60° [33]). In particular, rotation of the workpiece by 60° allows changing the boundary conditions on the lateral surfaces of the workpiece, and this way reduces the size of dead zones. This increases uniformity of distribution of accumulated deformation over the cross-section of the workpiece.

The presence of two deformation routes RS-180 and RS-60 allows us to select the route more effectively to set the required distribution of deformations over the cross-section of the workpiece. The advantage of the scheme is the absence of unformed edges of the workpiece, which reduces material consumption. However, it should be noted that these schemes do not completely eliminate unevenness of deformation over the cross section of the workpiece. To solve this problem, it is necessary to select deformation routes that include several types of SPD processes of various types. In particular, the RS process is effectively combined with twist extrusion [25]. This is due to the fact that the distribution of deformations over the cross section in these processes is of the opposite nature. During twist extrusion—the peripheral regions, and during RS—the center of the cross section of the workpiece is more intensively deformed.

To assess the adequacy of the mathematical model, the experimental studies of the reverse shear for copper workpieces of rectangular section were performed. The accumulated deformation, which was estimated using the method of dividing grids, was used as a criterion of adequacy. It was confirmed that maximum deformations during reverse shear occur in the central part of the billet section. In this case, the zone of greatest strains is elongated along the largest diagonal of the section. The obtained experimental images of the dividing grid correspond to the results of modeling by the finite element method. Errors in determining the accumulated deformations did not exceed 17%, which indicates adequacy of the theoretical model.

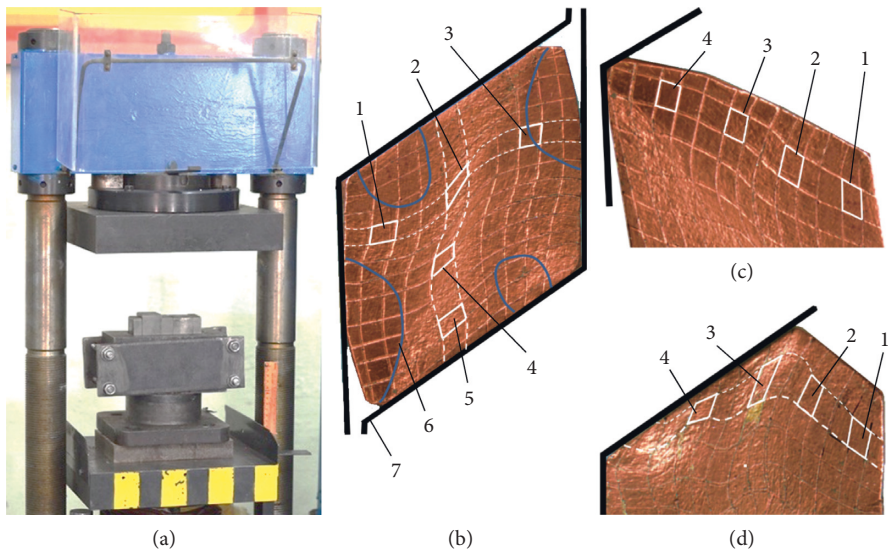

Figure 6: The results of experimental study of deformation of workpieces according to the RS-60 route. (a) Press and die for deforming of workpieces. (b) Position of the workpiece at the end of the 1st stage of deformation. (c) Initial position of the workpiece in the die. (d) Intermediate position of the workpiece at the 2nd stage of deformation.

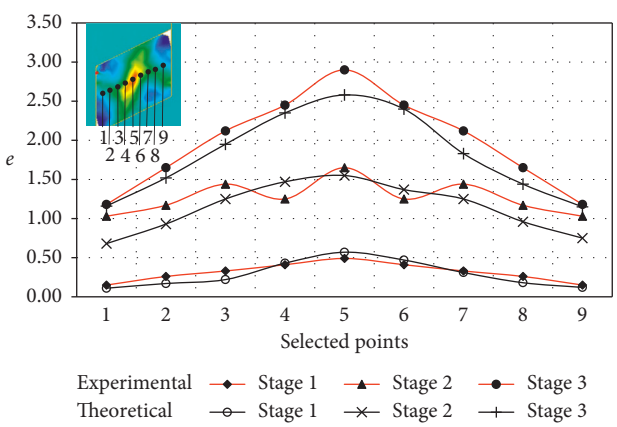

Figure 7: Distribution of accumulated strain for theoretical and experimental data for 3 operations of deformation at the RS-60 route.

5. Conclusion

The QForm [36] package can be successfully implemented to simulate multistage SPD processes and analyze the distribution of strains over the volume of the workpiece.

Modification of existing SPD schemes is carried out in the direction of minimizing of the number of operations and reducing the nonuniformity of deformation throughout the volume of the workpiece due to the use of various deformation routes.

In the development of classifications of SPD schemes, the study of the features of the center of plastic deformation in various deformation processes allows us to substantiate the choice or to suggest a modification of the schemes of intensive plastic deformation processes including combined machining processes.

The proposed reverse shear scheme can be considered as an analogue of the RCS or RF process, obtained by changing the shape of the tool, the workpiece, and the deformation routes. The use of the proposed form of punches leads to intensification of workpiece deformation. At the same time, the side surfaces of punches are actively involved in the deformation process and create active friction forces on the lateral faces of the workpiece.

This process allows us to increase the degree of change of the original cross-sectional shape of the workpiece at successive stages of deformation. The section of the workpiece in the form of a parallelogram also takes this form in a single technological operation. In this case, the original sharp corners become obtuse and vice versa without intermediate recovery of the shape in the form of a rectangle.

Analysis of distribution of strain across the section of the workpiece in various processes also allows us to create deformation routes including various plastic deformation schemes and thus improves the quality of the products obtained (RS and TE). Considering that the strain distribution over the section of the workpiece is uneven and decreases to the periphery together with this process, it is efficient to use the method of TE, in which the maximum accumulated deformation is on the periphery of the cross section of the workpiece. Applying successively these two methods as part of a combined treatment process, it is possible to ensure the alignment of properties in the volume of the workpiece while maintaining the flat scheme of the deformed state and the UFG structure.

Applying the reverse shear SPD method with a change in the deformation route (turns to 180° and 60°) allows us to control the distribution of accumulated deformation over the section of the workpiece. If it is necessary to obtain improved properties of the workpiece in the center, it is best to use the RS method along the RS-180 route in which deformations are more localized in the center of the workpiece. Otherwise, it is better to use RS-60.

A comparison with the experiment was carried out for three operations of a Cu-ETP copper workpiece deformation along the RS-60 route and showed that the simulation results correspond to the real process.

Data Availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflicts of Interest

The authors declare that there are no conflicts of interests regarding the publication of this paper.

Authors' Contributions

All authors participated in the design of this work and performed equally. All authors read and approved the final manuscript.

Acknowledgments

This study was performed by using FEM, implemented in QForm, a specialized commercial CAE-system. We thank QFX Simulations Ltd for providing the software.

References

[1] V. M. Segal, "Severe plastic deformation: simple shear versus pure shear," *Materials Science and Engineering: A*, vol. 338, no. 1-2, pp. 331–344, 2002.

[2] V. M. Segal, "Metal processing by severe plastic deformation," *Russian Metallurgy (Metally)*, vol. 2006, no. 5, pp. 474–483, 2006.

[3] G. Faraji, H. S. Kim, and H. T. Kashi, *Severe Plastic Deformation: Methods, Processing and Properties*, Elsevier, Amsterdam, Netherlands, 2018.

[4] A. Azushima, R. Kopp, A. Korhonen et al., "Severe plastic deformation (SPD) processes for metals," *CIRP Annals*, vol. 57, no. 2, pp. 716–735, 2008.

[5] Y. Beygelzimer, R. Kulagin, Y. Estrin, L. S. Toth, H. S. Kim, and M. I. Latypov, "Twist extrusion as a potent tool for obtaining advanced engineering materials: a review," *Advanced Engineering Materials*, vol. 19, no. 8, 24 pages, 2017.

[6] I. Sabirov, N. A. Enikeev, M. Y. Murashkin, and R. Z. Valiev, *Bulk Nanostructured Materials with Multifunctional Properties*, Vol. 118, Springer International Publishing, Berlin, Germany, 2015.

[7] A. Rosochowski, "Processing metals by severe plastic deformation," *Solid State Phenomena*, vol. 101-102, pp. 13–22, 2005.

[8] V. M. Segal, V. I. Reznikov, V. I. Kopylov et al., "The processes of plastic structure formation of metals," *Minsk: Science and Technology*, p. 232, 1994 in Russian.

[9] P. Minakowski, "Fluid model of crystal plasticity: numerical simulations of 2-turn equal channel angular extrusion," *Technische Mechanik*, vol. 34, no. 3-4, pp. 213–221, 2014.

[10] P. Ponce-Peña, E. López-Chipres, E. García-Sánchez, M. A. Escobedo-Bretado, B. X. Ochoa-Salazar, and M. A. González-Lozano, "Optimized design of an ECAP die using the finite element method for obtaining nanostructured materials," *Advances in Materials Science and Engineering*, vol. 2015, Article ID 702548, 8 pages, 2015.

[11] L.-Q. Zhang, X.-L. Ma, G.-W. Ge, Y.-M. Hou, J.-Z. Zheng, and J.-P. Lin, "Equal channel angular extrusion simulation of high-Nb containing β-γ TiAl alloys," *Advances in Materials Science and Engineering*, vol. 2015, Article ID 285170, 7 pages, 2015.

[12] Y. Estrin, H.-E. Kim, R. Lapovok, H. P. Ng, and J.-H. Jo, "Mechanical strength and biocompatibility of ultrafine-grained commercial purity titanium," *BioMed Research International*, vol. 2013, Article ID 914764, 6 pages, 2013.

[13] R. Z. Valiev, Y. Estrin, Z. Horita, T. G. Langdon, M. J. Zehetbauer, and Y. T. Zhu, "Fundamentals of superior properties in bulk NanoSPD materials," *Materials Research Letters*, vol. 4, no. 1, pp. 1–21, 2016.

[14] V. A. Beloshenko, A. V. Voznyak, Y. V. Voznyak, L. A. Novokshonova, V. G. Grinyov, and V. G. Krasheninnikov, "Processing of polypropylene-organic montmorillonite nanocomposite by equal channel multiangular extrusion," *International Journal of Polymer Science*, vol. 2016, Article ID 8564245, 8 pages, 2016.

[15] J. Lin, W. Ren, Q. Wang, L. Ma, and Y. Chen, "Influence of grain size and texture on the yield strength of Mg alloys processed by severe plastic deformation," *Advances in Materials Science and Engineering*, vol. 2014, Article ID 356572, 9 pages, 2014.

[16] S. Farè, N. Lecis, and M. Vedani, "Aging behaviour of Al-Mg-Si alloys subjected to severe plastic deformation by ECAP and cold asymmetric rolling," *Journal of Metallurgy*, vol. 2011, Article ID 959643, 8 pages, 2011.

[17] M. Matvija, F. Martin, O. Milkovič, M. Vojtko, R. Kočiško, and M. Glogovský, "Microstructure changes and improvement in the mechanical properties of as-cast AlSi7MgCu0.5 alloy induced by the heat treatment and ECAP technique at room temperature," *Advances in Materials Science and Engineering*, vol. 2018, Article ID 5697986, 11 pages, 2018.

[18] A. T. Abbas, M. A. Taha, A. E. Ragab, E. A. El-Danaf, and M. I. A. El Aal, "Effect of equal channel angular pressing on the surface roughness of solid state recycled aluminum alloy 6061 chips," *Advances in Materials Science and Engineering*, vol. 2017, Article ID 5131403, 11 pages, 2017.

[19] O. Nejadseyfi, A. Shokuhfar, A. Azimi, and M. Shamsborhan, "Improving homogeneity of ultrafine-grained/nanostructured materials produced by ECAP using a bevel-edge punch," *Journal of Materials Science*, vol. 50, no. 3, pp. 1513–1522, 2015.

[20] O. Nejadseyfi, A. Shokuhfar, and S. Sadeghi, "Feasibility of attaining uniform grain structure and enhanced ductility in aluminum alloy by employing a beveled punch in equal-channel angular pressing," *Materials Science and Engineering: A*, vol. 651, pp. 461–466, 2016.

[21] I. P. Renne, E. A. Ivanova, E. A. Boyko, and Y. M. Filigarov, "Non-uniformity of deformation at a flat plastic flow. Part 1. Stationary plane flow," *Tula: Publishing House of the Tula Polytechnic Institute*, vol. 159, 1971.

[22] N. Pardis and R. Ebrahimi, "Deformation behavior in simple shear extrusion (SSE) as a new severe plastic deformation technique," *Materials Science and Engineering: A*, vol. 527, no. 1-2, pp. 355–360, 2009.

[23] E. Bagherpour, F. Qods, R. Ebrahimi, and H. Miyamoto, "Microstructure and texture inhomogeneity after large non-monotonic simple shear strains: achievements of tensile properties," *Metals*, vol. 8, no. 8, p. 17, 2018.

[24] Y. E. Beygelzimer, O. V. Prokof'eva, and V. N. Varyukhin, "Structural changes in metals subjected to direct or twist

extrusion: mathematical simulation," *Russian Metallurgy (Metally)*, vol. 2006, no. 1, pp. 25–32, 2006.

[25] O. F. Tarasov, Y. Yu. Beygelsimer, and O. V. Altukhov, "Method for combined multiple severe plastic deformation of a blank with a change of direction of deformation," Donbas State Machine-Building Academy, Kramatorsk, Ukraine, Ukraine Patent UA102213, 2015, http://base.uipv.org/searchINV/search.php?action=viewdetails&IdClaim=217077&chapter=biblio.

[26] W. Guo, Q. Wang, B. Ye, and H. Zhou, "Enhanced microstructure homogeneity and mechanical properties of AZ31-Si composite by cyclic closed-die forging," *Journal of Alloys and Compounds*, vol. 552, pp. 409–417, 2013.

[27] G.-Z. Zhao, L. Yang, X.-X. Duan et al., "Microstructure evolution and mechanical properties of AZ80 alloy reheated from as-cast and deformed states," *Transactions of Nonferrous Metals Society of China*, vol. 22, pp. s450–s456, 2012.

[28] A. K. Parimi, P. S. Robi, and S. K. Dwivedy, "Severe plastic deformation of copper and Al-Cu alloy using multiple channel-die compression," *Materials & Design*, vol. 32, no. 4, pp. 1948–1956, 2011.

[29] R. Ebrahimi, A. Rezvani, and E. Bagherpour, "Circular simple shear extrusion as an alternative for simple shear extrusion technique for producing bulk nanostructured materials," *Procedia Manufacturing*, vol. 15, pp. 1502–1508, 2018.

[30] J. Y. Huang, Y. T. Zhu, H. Jiang, and T. C. Lowe, "Microstructures and dislocation configurations in nanostructured Cu processed by repetitive corrugation and straightening," *Acta Materialia*, vol. 49, no. 9, pp. 1497–1505, 2001.

[31] A. Babaei, G. Faraji, M. M. Mashhadi, and M. Hamdi, "Repetitive forging (RF) using inclined punches as a new bulk severe plastic deformation method," *Materials Science and Engineering: A*, vol. 558, pp. 150–157, 2012.

[32] O. F. Tarasov and O. V. Altukhov, "Method of multiple severe plastic deformation of workpiece with change of direction of deformation," Donbas State Machine-Building Academy, Kramatorsk, Ukraine, Ukraine Patent UA76206, 2012, http://base.uipv.org/searchINV/search.php?action=viewdetails&IdClaim=181538.

[33] O. F. Tarasov, O. V. Altukhov, and O. F. Tarasov, "Method of repeated reversing intensive plastic deformation of blank," Ukraine Patent UA88811, 2014, in Ukrainian, http://base.uipv.org/searchINV/search.php?action=viewdetails&IdClaim=198814.

[34] A. N. Levanov, "Improvement of metal forming processes by means of useful effects of plastic friction," *Journal of Materials Processing Technology*, vol. 72, no. 2, pp. 314–316, 1997.

[35] I. P. Renne, "Experimental methods for the study of plastic form changes in the process of metal forming using a dividing grid," *Tula: TPI*, vol. 146, 1970 in Russian.

[36] N. Biba, A. Alimov, A. Shitikov, and S. Stebunov, "The implementation of microstructural and heat treatment models to development of forming technology of critical aluminum-alloy parts," *AIP Conference Proceedings*, vol. 1960, no. 1, Article ID 040004, 2018.