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Research Article

Development and Computer Simulation of the New Combined Process for Producing a Rebar Profile

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The study presents results of computer simulation by finite elements method of a new metal forming process combining the deformation of a billet with round cross-section on a radial-shear rolling mill and subsequent billet twisting in a forming die with a specific design. To analyze the efficiency of metal processing, the main parameters of the stress–strain state are considered: effective strain, effective stress, average hydrostatic pressure, and Lode–Nadai coefficient. The maximum value of effective strain up to 13.5 is achieved when a screw profile on the billet in the die is forming, which indicates an intensive refinement of the initial structure of the billet. During combined process, the nature of the deformation changes in the transverse direction from the axis of rotation to the surface. The central area of the billet is under the action of tensile stresses. In the peripheral part, compressive stresses grow. In the surface area, Lode–Nadai coefficient is 0.1 approximately, which indicates the high level of shear strain.

1. Introduction

Obtaining various ferrous and non-ferrous metals and alloys with ultrafine-grained (UFG) and nanocrystalline structures and, accordingly, a high level of mechanical and functional properties has been one of the main tasks of metal forming for more than a decade. One of the main ways to solve this problem is the use of various metal forming methods, which implement severe plastic deformation (SPD) during the deformation process [1–8], due to which a uniform and intensive refinement of the cast structure is carried out throughout the entire volume of the deformed billet. But, unfortunately, the use of most SPD methods in the real production of metal products is difficult for several reasons, including the fact that most of these methods do not allow processing long billets.

An alternative solution to the problem of using SPD during metal forming in industrial conditions is the development of combined metal forming methods with the implementation of SPD in the deformation process. Currently, several combined processes have already been developed [9–17], which allow processing long billets with enough degree of processing of the cast metal structure to obtain an UFG structure in it. At the same time, many of these combined deformation methods allow obtaining in the process of their implementation not only semi-finished products but also finished products. One of the latest developments in the process proposed in [18], which combines the reduction rolling of a rod of a round or square cross-section in a square caliber with twisting in a forming die (a twisting mechanism). This combined method makes it possible to obtain a rebar profile with a gradient UFG structure [19]. Despite the fairly simple design and effective processing of the initial billet (during one cycle of deformation, the deformation develops from 0.8 in the central layers of the billet to 1.4 in the surface layers), this method has a significant drawback associated with its manufacturability. When transferring production to a different size range, it is necessary not only to install a new die but also a new pair of rolls with the specified size gauge.

In order to improve the production process of a rebar profile, a new scheme for its formation (Figure 1) was proposed, which includes the deformation of a billet with round cross-section on a radial-shear rolling (RSR) mill and subsequent billet twisting in a forming die with a specific design (similar to the one presented in [18]). In this case, when the production changes to a new rebar profile size, there is only need to install a new die with the desired diameter, since the deformation of the billet with a different diameter on the RSR mill could be done by reducing or separating the rolls, which only changes the reduction value. In this case, a more intensive refinement of the metal structure will be carried out since it is known from works [20–22] that during RSR in the deformation zone, a stress state scheme close to all-around compression with large shear deformations is implemented, which is optimal for the formation of the UFG structure.

When developing any technological process, an important stage is its theoretical investigation, since the success of its implementation in real laboratory or production conditions will depend on it. At the same time, the most advanced method of theoretical investigation of the deformation process is its modeling by the finite element method (FEM). This approach gives the researcher answers to a number of questions: is this process possible in real conditions, will there be any defects on the workpiece, and will the equipment withstand the resulting loads during this process. In addition, an important factor is the ability to look "inside" the process, i.e., to evaluate all the process parameters at any point of the workpiece or tool at any stage, which is often impossible in real conditions.

The purpose of this study is to carry out a computer modeling of the proposed combined method for obtaining a rebar profile and its comprehensive study.

2. Materials and Methods

When creating a computer model of the new combined process, the parameters of the 10–30 RSR mill were used as the main equipment.

A rod with a diameter of 22 mm and a length of 120 mm was taken as the initial billet. The roll gap was set to produce a 19 mm diameter billet. When designing the die structure, it was decided to make it from two zones—a deforming screw and a smooth one, which serves as a stabilizer and gauge to the screw part (Figure 2). AISI 1015 steel was chosen as the material of the billet.

The following assumptions were made during the model creation in the DEFORM program:

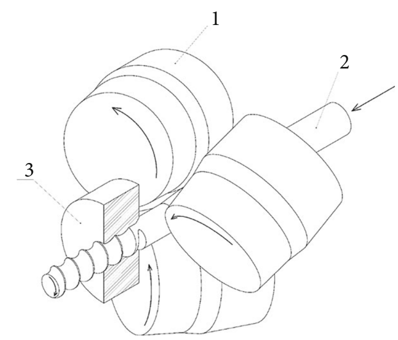


Figure 1: The combined process for producing the rebar profile:1—rolls, 2—billet, and 3—die.

(i) The material of the billet is isotropic, and there are no initial deformations, discontinuities, and inclusions;

(ii) The billet type—plastic and the tools type—rigid;

(iii) A mesh with 85,000 finite elements and an average element edge length of 1.3 mm is applied to the billet;

(iv) The billet material is AISI 1015 steel, and the hardening curve used in the calculation is shown in Figure 3;

(v) Initial heating temperature of the billet—1100°C;

(vi) The heat transfer coefficient between the billet and the tools was assumed to be equal to 5 kW/(m^2°C), as the recommended value by the DEFORM program for deforming processes. Heat transfer between the billet and the environment has been activated;

(vii) The rotation speed of the rolls was assumed to be equal to 100 rpm;

(viii) Friction coefficient on the rolls and on the die was set as 0.7 and 0.1 accordingly; and

(ix) 1000 calculation steps were set with a time increment of 0.01 seconds/step.

After the calculation, a model of a combined process was obtained, in which the billet at the first stage is rolled on an RSR mill, whereas a screw edge is formed on the surface of the billet at the exit from the deformation zone (Figure 4(a)). At the second stage, the billet enters the die and is subjected to twisting around its longitudinal axis at an angle corresponding to the configuration of the screw channel (Figure 4(b)).

At the same time, the screw channel of the die is sufficiently filled (Figure 5), which allows to obtain a predetermined rebar profile without the billet jamming or pressing it out at the entrance to the die.

When studying any metal forming process, one of the most important stages is the study of the stress–strain state. This makes it possible to evaluate the resulting values of strain and stresses, to identify the areas where their critical values occur, which, in turn, allows to analyze the durability of the tool and the probability of defects.

Given the fact that the developed deformation method has a fairly complex metal flow pattern, which changes as

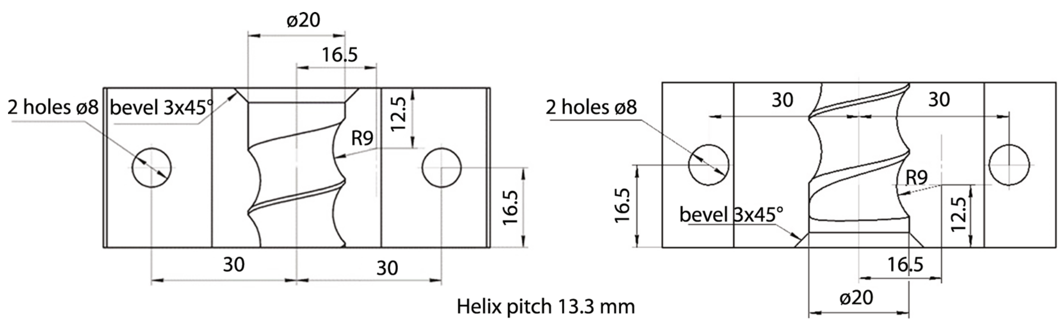


Figure 2: Die channel scheme.

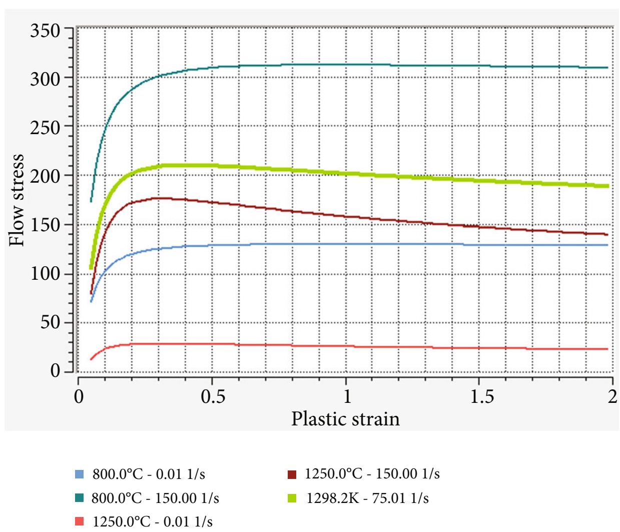


Figure 3: Hardening curve of AISI 1015 steel.

the billet moves along its longitudinal axis, it is most appropriate to consider the studied parameters in the longitudinal direction of the billet in two versions—on the surface and in the central part of the billet. This will allow not only to set the numerical values of stress–strain state parameters but also to estimate the resulting gradient distribution of accumulated factors (effective strain).

3. Results and Discussion

3.1. Strain Effective. To determine the strain values, it is necessary to find the values of the components of the corresponding tensor, which are very difficult to visualize for a three-dimensional metal flow. Therefore, usually, when considering stress–strain state parameters, a simple indicator of the strain intensity is used, or the so-called effective strain, which includes the strain components in the following form:

$$\varepsilon = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}, \quad (1)$$

where ε_1, ε_2, and ε_3 are the principal strains.

Studying the "effective strain" parameter showed that, at the stage of RSR, the accumulation of this parameter occurs mainly in the surface layers of the billet (Figure 6). After exiting the rolls on the billet surface, the strain values reach 6.75–8.5, gradually decreasing to 5 in the peripheral area.

When entering the screw channel of the die, the billet is subjected to severe deformation due to twisting. As a result, there is a significant increase in strain along the entire section of the billet. Thus, in the surface layers of the billet, which acquire a voluminous screw shape, the strain value reaches 11.0, gradually decreasing to 9.0 in the peripheral area. The central area at this stage of deformation is processed as intensively as possible—here, the strain value ranges from 8 to 9. Moreover, after passing the screw channel, a significant decrease in the spread of strain values can be noted.

3.2. Stress State. The Lode–Nadai coefficient was used to estimate the nature of the stress state [23]. This coefficient allows to evaluate the nature of the resulting deformation in the billet, i.e., to determine which type of deformation is realized at a particular point—stretching, compression, or shear.

The calculation of the Lode–Nadai coefficient is carried out according to the equation:

$$\mu = 2 \times \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} - 1, \quad (2)$$

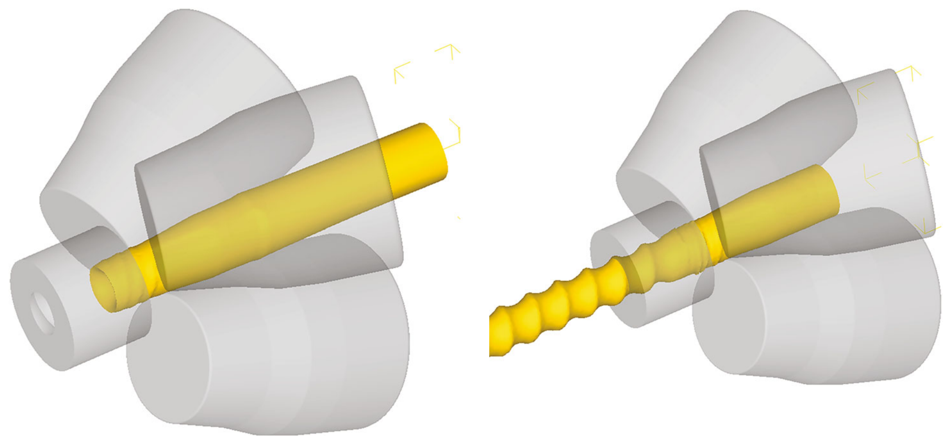
where σ_1, σ_2, and σ_3 are the principal stresses, MPa.

The coefficient value varies from −1 to 1. Value from 0 to 1 corresponds to compression; value from 0 to −1 corresponds to stretching; and a coefficient value that tends to 0 corresponds to a shear.

To calculate this coefficient along the initial length of the billet, 120 points were made in the central section with a distance of 1 mm. Studying longitudinal rolling showed that one measurement is enough to calculate this parameter [24]. However, in the case of the studied combined process, the billet, along with the translational one, also performs a rotational movement at each moment of time. Considering that the distribution of stress–strain state parameters considered above is heterogeneous, it was decided to calculate the Lode–Nadai coefficient in three longitudinal areas corresponding to the classification of Galkin [25]:

- the first measurement was made strictly along the longitudinal axis of rotation of the billet;

- the second measurement was made in the longitudinal direction with a shift of 5 mm from the axis of rotation, which corresponds to the peripheral area; and



(a) (b)

Figure 4: Deformation stages.

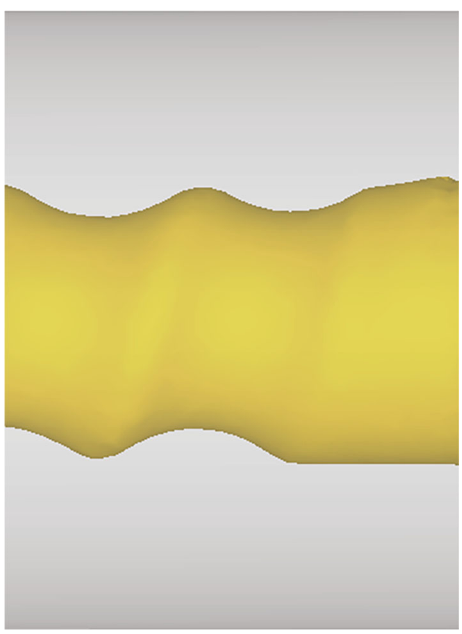


Figure 5: Screw channel filling.

- the third measurement was made in the longitudinal direction with a shift of 10 mm from the axis of rotation (at a distance of 1 mm from the surface), which corresponds to the surface area.

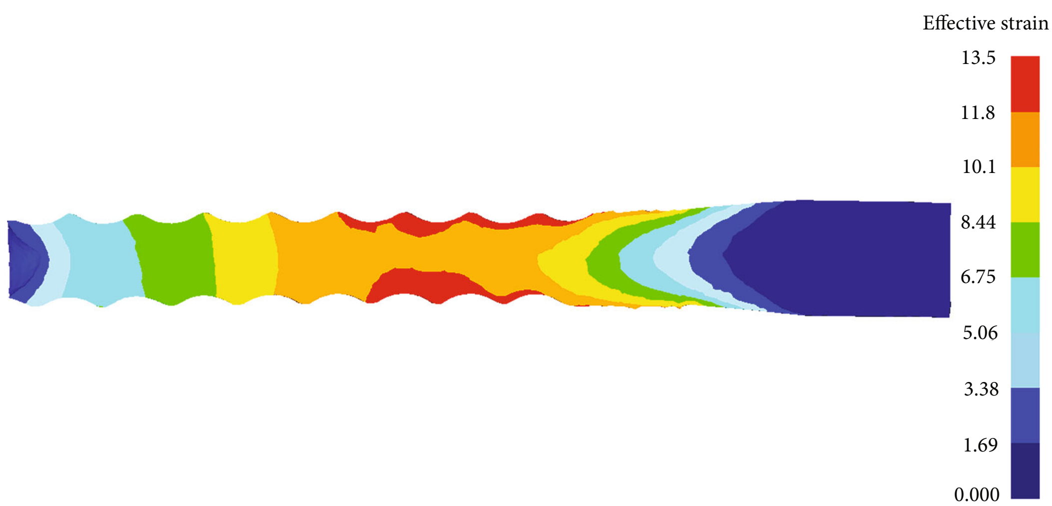
Figure 7 shows the patterns of changes in the metal flow trajectory in all three areas as it moves through the deformation zone in the rolls and the screw channel of the die. The flow trajectory in the central area (Figure 7(a)) does not change as it moves through the rolls and the matrix. In the peripheral area, after passing the deformation zone in the rolls, a counter-pressure zone is formed in the intermediate section between this deformation zone and the first screw channel in the die, which causes the billet to twist, as can be seen in Figure 7(b). As the metal moves along the screw channel, the twisting continues, and the level of metal flow along the height remains almost unchanged, which is reflected at the level of points at the end of the billet.

In the surface area (Figure 7(c)) occurs the most intense change in both the shape of the metal trajectory and its absolute speed, which is clearly visible by the change in the distance between neighboring points at the beginning and end of the deformation process. In the intermediate area between this deformation zone and the first screw channel in the die, there is an intensive twisting of the billet by 90°; after this portion of metal enters the screw channel, the twisting level increases from 90° to 270°. At the same time, in addition to compression in the cross-section, the billet is stretched in the longitudinal direction.

Since the deformation in the rolls and forming in the die at each moment of time is a strictly defined area of the billet, it is necessary to determine the approximate length of these zones. The contact area of the metal with the rolls is in the range of points No. 72–85 (Figure 8(a)). The forming area in the first screw channel of the die is in the range of points No. 102–109 (Figure 8(b)).

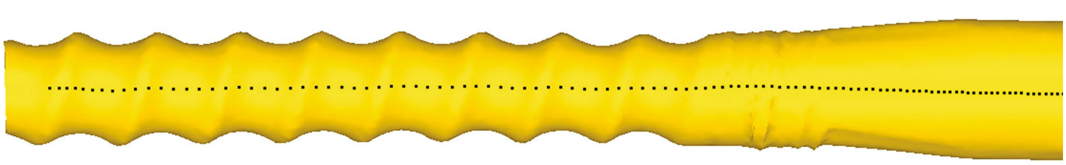
Figure 9 shows the results of calculating the Lode–Nadai coefficient for all three areas. Analyzing the rolling zone in the rolls showed that, in this section, the nature of the deformation changes in the transverse direction from the axis of rotation to the surface. The central area of the billet is under the action of tensile stresses ($\mu = -0.6$ to -0.7), which corresponds to the data of Galkin [25] on the nature of the metal flow during RSR. Moving away from the center, compressive stresses occur in the peripheral part ($\mu = 0.6 - 0.7$), which is a consequence of the pressure from the rolls in the deformation zone. The surface area is of the greatest interest since, in this area, the Lode–Nadai coefficient is 0.95–1.0 in longitudinal rolling, which, in fact, is only the effect of compressive stresses. However, in this case, the Lode–Nadai coefficient is approximately 0.1. This coefficient at a certain length (at several points in a row) indicates the presence of shear strain, which is also confirmed by Galkin [25] and the results obtained in the deformed state simulation, where it is seen

(a)

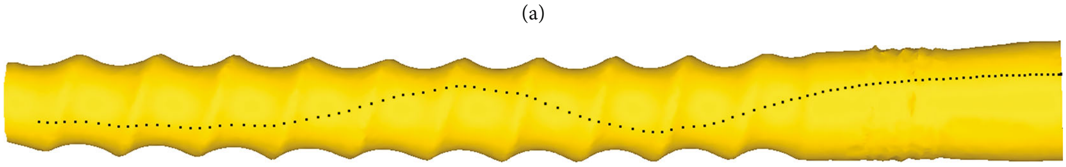


(b)

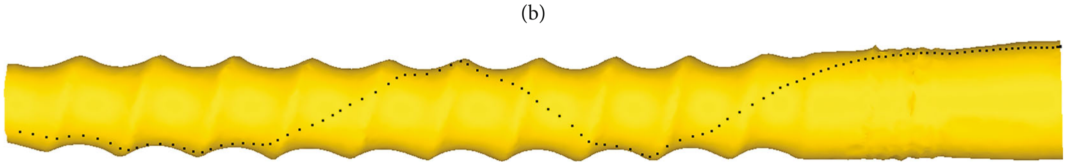
Figure 6: Distribution of effective strain on the surface (a) and in the center of the billet (b).



(a)



(b)



(c)

Figure 7: Metal flow paths in the (a) central, (b) peripheral, and (c) surface zones.

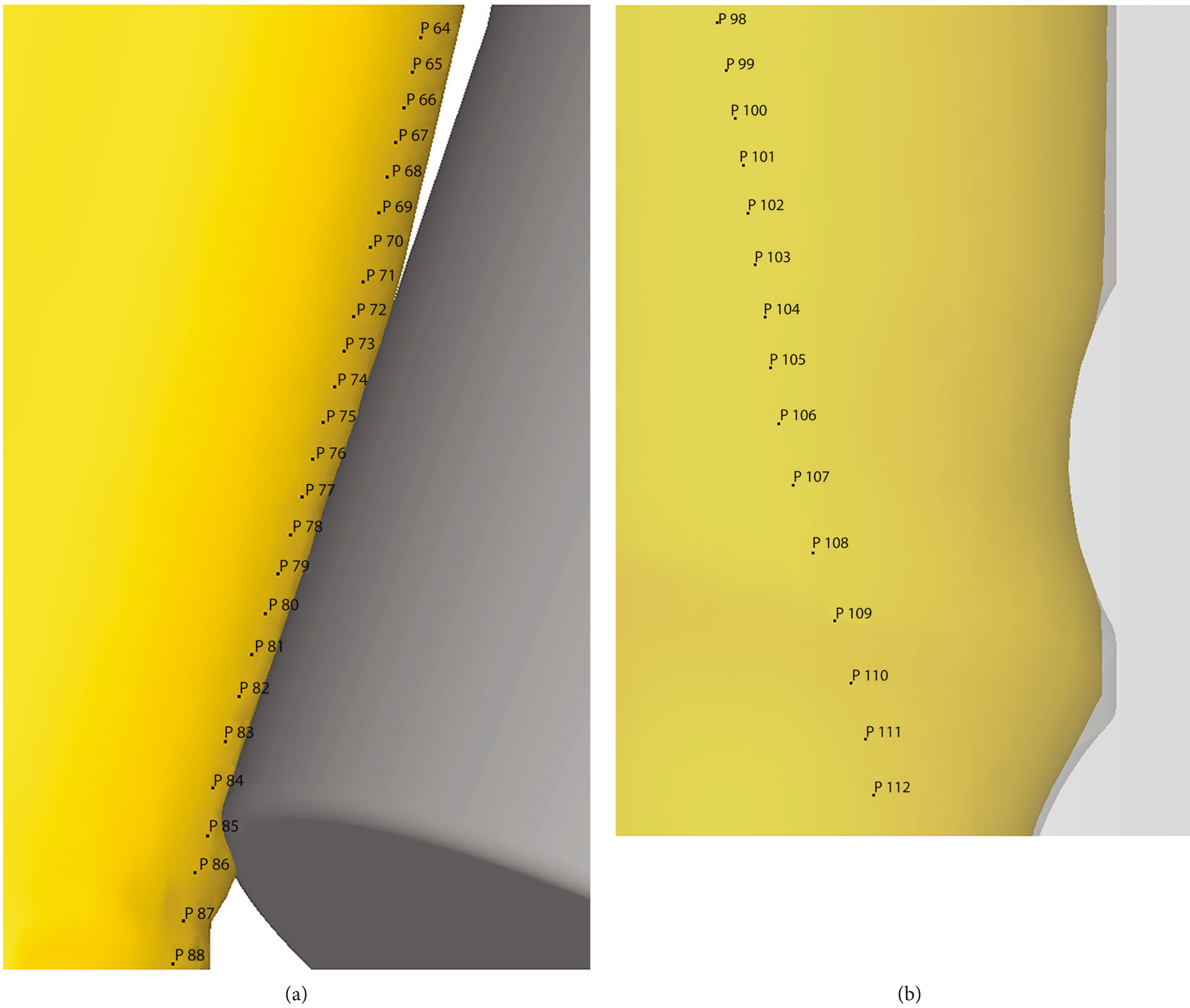


Figure 8: Length of (a) rolling and (b) forming zones.

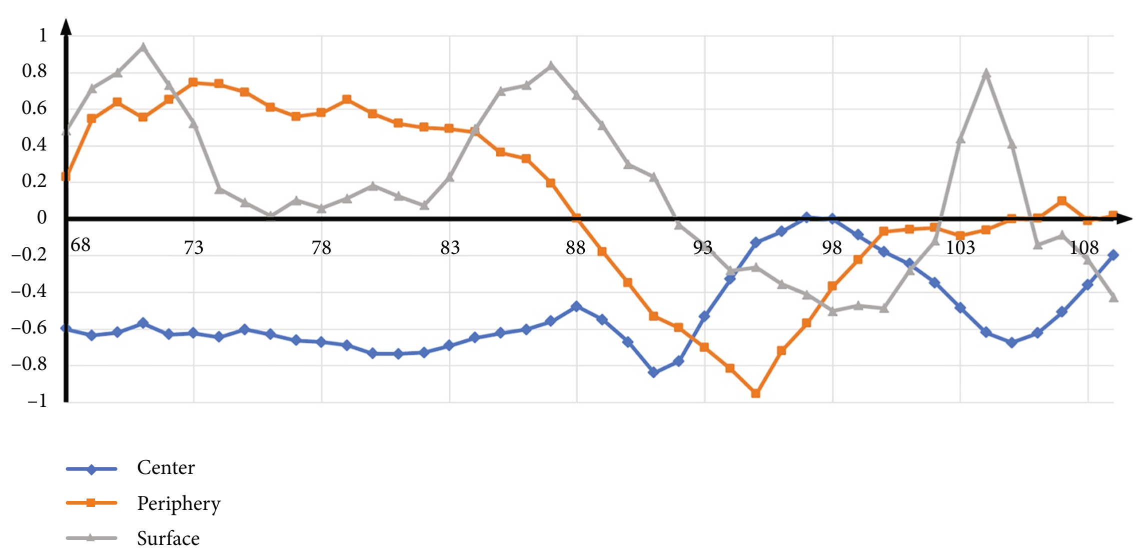


Figure 9: Lode–Nadai coefficient.

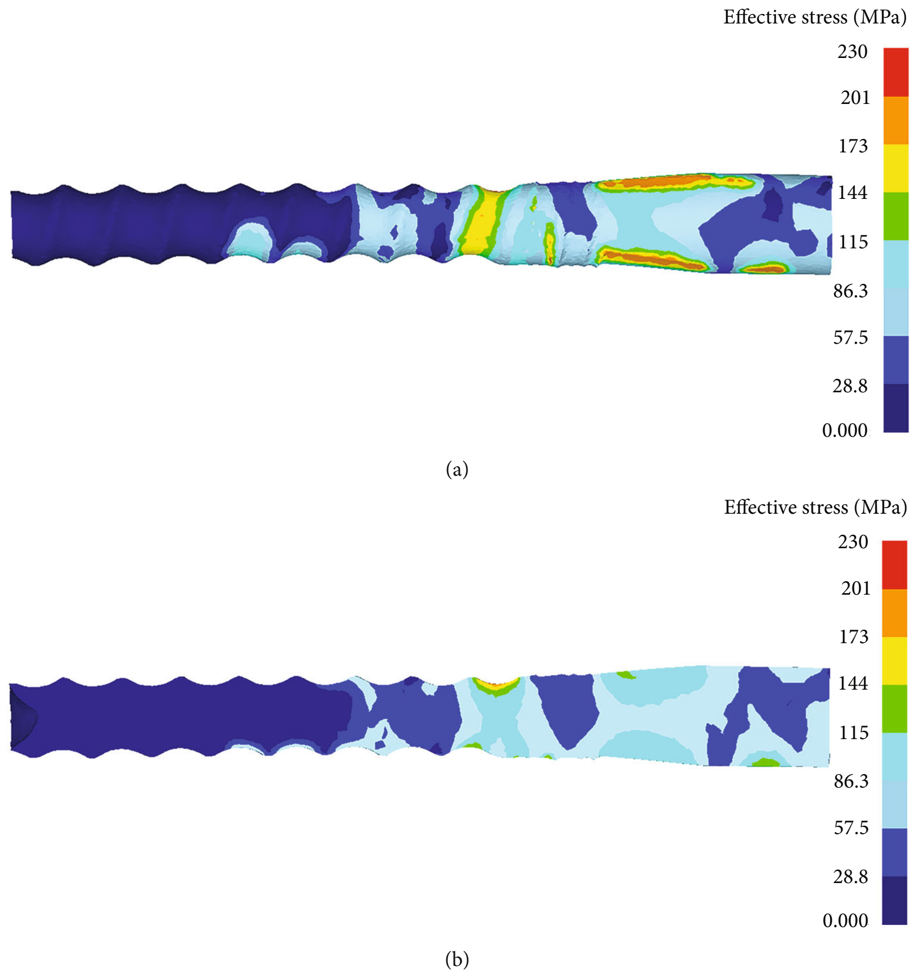


Figure 10: Distribution of effective stress on the (a) surface and in the (b) center of the billet.

that the greatest refinement of the metal is carried out in the surface layers.

When analyzing the forming zone, it was found that as the billet passes the screw channel section in the die, in all three areas, similar to as in RSR, deformations of different types are occurring. Moreover, the central and surface areas have approximately the same peak-like character of deformations, but different in sign. The peak's top corresponds to the moment of passing through the middle of the width of the screw channel. The central area is exposed to tensile stresses, at the entrance to the screw channel the Lode–Nadai coefficient is −0.2, in the center of the screw channel the Lode–Nadai coefficient reaches a maximum value of −0.67, and then gradually decreases again to −0.2.

In the peripheral area, due to the twisting process in the screw channel, shear deformations occurring along the entire length, which is reflected in the Lode–Nadai coefficient, the value of which is varied in the range of −0.05 to 0.1. The surface area, in addition to twisting, also receives some compression in height due to the introduction of a screw edge. As a result, the value of the Lode–Nadai coefficient in this area significantly changes its numerical value. At the entrance to the screw channel, the metal is subjected to pressure from the edge of the die, due to which compression occurs up to the middle of the channel width. This is reflected in the value of the coefficient, increasing up to 0.8. After overcoming a mid-channel section compressive deformation is terminated, as the contour of the billet conforms with the configuration of the channel. As a result, the coefficient value drops sharply to −0.1.

For further analysis of the stress state, the following parameters were considered: effective stress (or stress intensity) and average hydrostatic pressure (or mean stress). In RSR, the maximum values of the effective stress occur in the contact zones of the metal with the rolls, reaching a value of 200 MPa (Figure 10). In contact-free zones, the effective stress value ranges from 80 to 100 MPa. Entering the die, the maximum stress level develops only at the first turn, where the screw profile is formed. Here, the value of the effective stress is in the range of 140–150 MPa in the surface layers, and 90–100 MPa in the central area of the billet. In the subsequent turns, the stress value is relatively small (about 30 MPa), because in them the metal moves with the finished screw shape.

When considering the effective stress, it is necessary to understand that, being a subcortical expression, its value is always positive. To estimate the value of the stress, taking

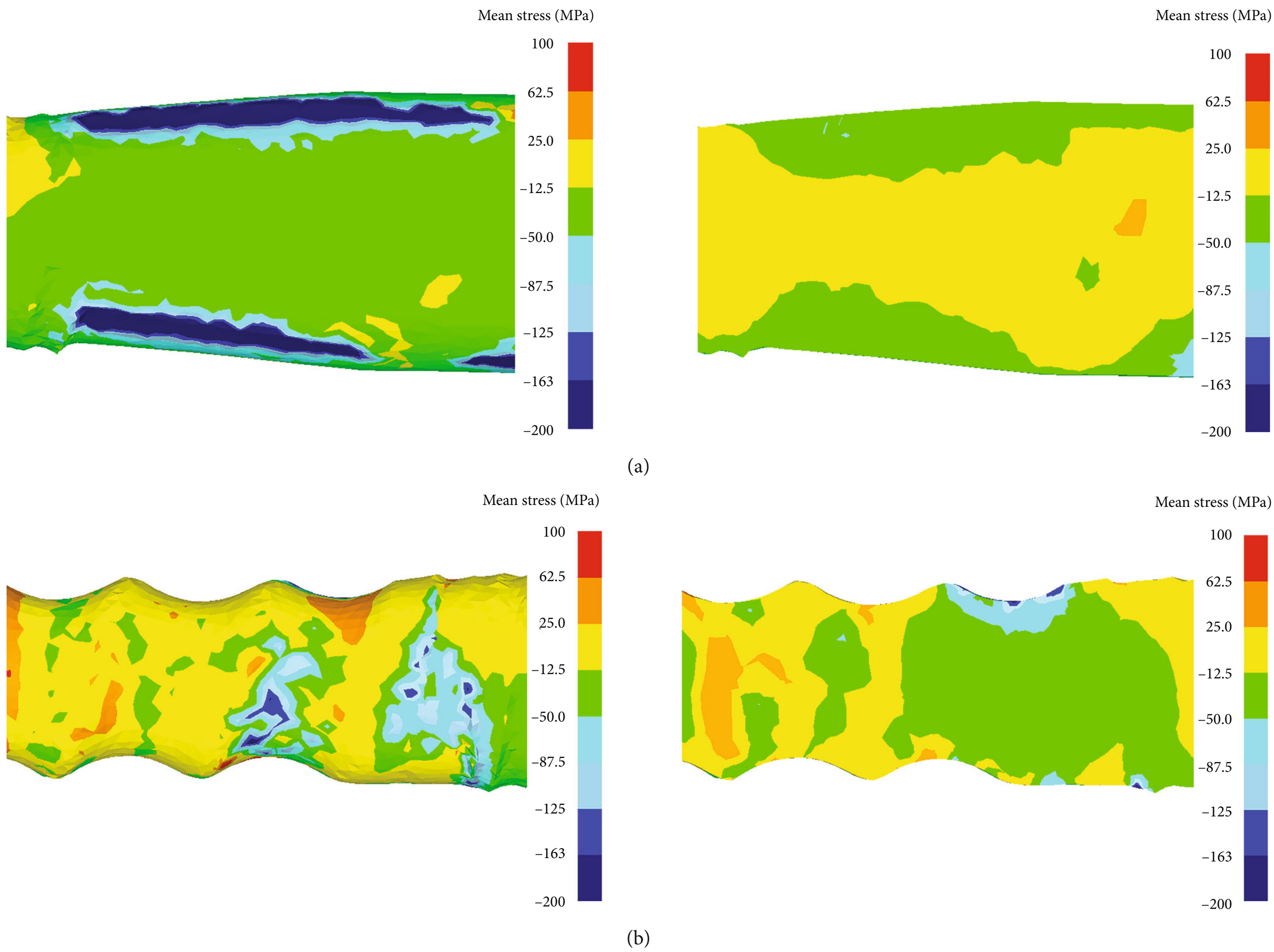


FIGURE 11: Mean stress at the surface and center of the workpiece during (a) RSR and (b) die forming.

into account the sign, it is advisable to consider the average flowing pressure or mean stress (Figure 11).

For the most effective evaluation of this parameter in DEFORM, it is recommended to set the scale range so that the zero mark approximately falls on any border of the color scale. This makes it easy to identify areas of tensile and compressive stress.

During RSR (Figure 11(a)), mainly compressive stresses develop in the contact areas of metal with the rolls, reaching a value of −200 MPa on the surface and decreasing to −12.5 closer to the central part of the billet. In contact-free areas, the value of this parameter reaches −50 MPa. During forming in the die (Figure 11(b)), compressive stresses with the value of about −80 MPa develop in the first turn in the surface layers, subjected to forming, and −60 to −40 MPa in the central part of the billet.

Since this combined process originates from conventional RSR, it would be appropriate to compare these deformation technologies. When analyzing the simulation results and experimental data of RSR [21, 26], it was revealed that this technology allows obtaining an UFG structure after 6–8 cycles. However, the maximum level of grain grinding is achieved only in the surface layers of the workpiece, whereas the grain size in cross-section has a high gradient distribution. With a combination of RSR and twisting, conditions for the formation of an UFG structure are created after one deformation cycle. At the same time, the level of metal processing along the cross-section has a significantly lower gradient level.

4. Further Development

The research carried out within the framework of the project AP14869135 “Development, research and production of hardened screw fittings with a gradient UFG structure by energy-efficient technology of metal forming” is aimed at solving the problems of improving the properties of various structural materials, significantly improving the quality of metal products obtained by metal forming, reducing energy and labor costs for its production, as well as to increase the manufacturability of previously known technologies for obtaining hardened screw fittings. As already noted above, in order to solve the problem of increasing manufacturability, a completely new energy-efficient technology for obtaining hardened screw fittings has been proposed, which combines RSR and twisting deformation in a die that ensures the formation of a screw profile of the reinforcement in a single process.

When implementing the proposed technology in practice, it will only be necessary to replace the die with the desired geometric dimensions. This is due to the fact that the deformation of workpieces of various diameters on a RSR mill is regulated by a simple reduction or dilution of the rolls. Among other things, the use of RSR instead of longitudinal rolling will provide a more intensive processing of the initial metal structure and ensure the formation of a gradient UFG structure, due to the fact that a stress state scheme close to comprehensive compression with large shear strain is implemented in the deformation zone during RSR. It is this deformation scheme that is optimal for the formation of an UFG structure in various materials with a minimum number of passes.

The results of studying the shape change and stress–strain state of the metal during the implementation of the investigated deformation scheme will later be used for the development, design, and creation of a combined stand for obtaining a hardened screw profile based on existing RSR mills. During the testing of the created combined stand, an experimental batch of screw fittings will be obtained and the dependences of changes in microstructure and mechanical properties on various process parameters will be determined.

The field of practical application of the results obtained during the implementation of the project is of high importance, since they will allow creating a new, scientifically based energy-efficient technology for obtaining finished metal products in the form of hardened screw fittings with a gradient UFG structure and an increased level of operational and mechanical properties. In addition, the result of the research will be new knowledge about the influence of the combined deformation scheme, combining RSR and the process of bar extrusion through a special die, providing additional twisting and the formation of the screw profile of the reinforcement, on the possibility of forming a gradient UFG structure in the metal. All this knowledge is of great interest for specialists in the fields of metal forming and materials science.

5. Conclusions

In this study, the FEM simulation results of a new deformation process combining RSR and twisting stages were presented. For twisting operation, a special die allowed to obtain a screw profile was constructed. Effective strain, Lode–Nadai coefficient, effective stress, and mean stress were selected as the stress–strain state parameters. All these parameters were considered on the surface and in axial section of billet at RSR and twisting stages. The maximum value of effective strain is achieved when a screw profile on the billet in the die is forming, which indicates an intensive refinement of the initial structure of the billet. In addition, due to compressive stresses in the die, the unevenness of the distribution of effective strain throughout the diameter of the billet in comparison with the area of RSR is reduced.

Data Availability

The DEFORM database used in this study is available from the corresponding author upon request.

Conflicts of Interest

The author(s) declare(s) that they have no conflicts of interest.

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