Evaluation of the effectiveness of the use of horizontal and vertical rolls in the "Rolling-pressing" process on the basis of the stress-strain state studying

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Abstract. In this work was performed a comparative analysis of the efficiency of horizontal and vertical rolls in the "rolling-pressing" process. The comparison was performed based on the study of stress-strain state of both variants with the aid of computer simulation in the program DEFORM-3D based on the finite element method. For analysis of the stress state was used the Lode-Nadai coefficient, allowing you to determine which type of deformation is realized at a specific point – tension, compression or shear. For analysis of the strain state was used equivalent strain, which allows to estimate the common level of accumulated strain. In the comparative analysis of parameters of SSS was revealed that the use of vertical rolls at the exit from the matrix during "rolling-pressing" process, allows you to achieve a more favorable distribution of deformation along the entire length of the deformable workpiece.

1 Introduction

In the current shortage of energy and raw materials there is very actual problem of energy-saving technologies, including the obtaining of materials with high strength and ductility.

This unique combination of properties is typical for subultra - and ultrafine-grained (SUFG and UFG) form of structural state of materials with a predominance of large-angular grain boundaries. The results of the application of sub-ultrafine-grained materials in the engineering and medical fields, show them a great future and the demand for products made of such materials.

However, demand growth is greatly restricted by the high cost of production of such materials due to high energy and labour intensity of their production. The most common and studied method of obtaining SUFG and UFG is equal channel angular pressing (ECAP) [1]. However, the disadvantage of this and many other known processes lies in their discrete nature, i.e. the impossibility of treating articles of relatively large length and the necessity of a large number of treatment cycles.

To solve the problem on introduction in manufacture of technology for sub-ultrafine-grained materials by severe plastic deformation (SPD), we developed a combined technology of deformation "rolling - equal channel angular pressing", allowing to obtain high quality bars with square or rectangular cross-section. In works [2-5] have presented a comprehensive studies of this process, that show advantages over the classic ECA-pressing. However, in several works [1, 6-7] it is known that to achieve grain size of the order of $10^{-7}$-$10^{-9}$ m necessary for the formation of sub-ultrafine-grained structure, is required to provide a deformable metal, the equivalent strain $\varepsilon > 3$. To achieve this level
of development is required a multi-cycle deformation. In particular, the implementation of ECA-
pressing need for at least 9 cycles [8], the implementation of combined process "rolling - equal
channel angular pressing" reduces desired number of cycles to 6-7 [4, 5], which is still high.
Therefore, further development of this combined process is the search of possible schemes of
implementation of the process, allowing to reduce the number of cycles of deformation required to
obtain sub-ultra-fine-grained structure.
One of the possible variants of this process is the use of universal stand instead of two horizontal
(figure 1). In this case, the workpiece when pushing in the matrix will be deformed for height and at
the exit from the matrix, once in the second rolls will be pulled out of the matrix, obtaining a
compression in width. In this case, the change of direction of deformation has a certain analogy with
the BC route [9], known from a number of works on ECA-pressing. It in multi-pass pressing the
direction of the workpiece deformation changes along the longitudinal axis at 90° to that in the
proposed scheme corresponds to rolling in the vertical rolls.

![Figure 1. Possible variants of rolls location in the combined process "rolling-equal channel angular
pressing".](image)

- a – with horizontal rolls at the exit of the matrix; b – with vertical rollers at the exit of the matrix.

2 Initial model
To confirm the hypothesis about the effectiveness of using vertical rolls instead of horizontal rolls was
performed a simulation of the combined process "rolling – equal channel angular pressing" in the
program DEFORM-3D. The dimensions of the original workpiece were 20x15x350 mm. Conditions
and assumptions in modelling:
- workpiece material in the initial state (before deformation) was isotropic and there was no initial
  stress and strain;
- workpiece was meshed from 180 000 finite elements with an average edge length of an element
  was equal to 0.5 mm;
- initial temperature of the billet was assumed to 1150 °C, also was attended deformation heating
  and heat transfer between the workpiece, tool and environment;
- tool was made absolutely rigid; the tool geometry (3D model) was created using the program
  KOMPAS 3D V15 and saved with the extension STL;
- model of the billet material was assumed to elastic-plastic;
– material adopted in the simulation is AISI 1015 steel corresponding to steel 15, the hardening curves were taken from the DEFORM library;
– coefficients of friction between the tool and the workpiece were selected based on recommendations from [2] equal to 0.5 at the contact of the workpiece with the rolls, and 0.1 on the contact of the workpiece with the matrix;
– roll rotation speed was equal to 60 rpm.

After the calculation of both models, in the workpiece were established 70 points along the longitudinal axis in increments of 5 mm, which was carried out measurements of the parameters of the stress-strain state (SSS) (figure 2). For the analysis, we selected stage of the process, when the workpiece is simultaneously rolled at both pairs of rolls.

![Diagram](image)

**Figure 2.** The location of the points to analyze the SSS parameters.

Conventionally the workpiece can be divided into the following areas:
1) area of rolling in the first pair of rolls (points 1÷12);
2) distance between rolling areas in the 1st pair of rolls and junction of channels in the matrix (points 13÷31);
3) area of junction of the channels in the matrix (points 32÷41);
4) distance between area of junction of channels in the matrix and area of rolling in the 2nd pair of rolls (points 42÷60);
5) area of rolling in the second pair of rolls (points 61÷70).

Since the studied models differ only in the location in space of the second pair of rolls, it is logical to assume that the values of the parameters will have differences only in the last area, in the rest areas they are identical.

### 3 Stress state
For analysis of the stress state, it was decided to use the coefficient of Lode-Nadai [10]. This coefficient allows to assess the nature of deformation occurring in the workpiece, i.e., to determine which type of deformation is realized at a specific point – tension, compression or shear.
Calculation of Lode-Nadai coefficient is calculated by the formula:

\[
\mu = 2 \cdot \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} - 1,
\]

where \(\sigma_1, \sigma_2, \sigma_3\) – main stresses, MPa.

The value of the coefficient varies from -1 to 1. A value from 0 to 1 corresponds to compression; from 0 to -1 corresponds to the tension; the value of the coefficient tends to 0, corresponds to the shear [10].

During calculation of Lode-Nadai coefficient were obtained the following results (figure 3). As expected, the results in the first three zones were completely identical. In the first zone during rolling present as a region of compression (\(\mu = 0.6\div0.9\)) and the area of tension (\(\mu = -0.6\div-0.8\)), which is the result of the peculiarities of the formation of the deformation zone during rolling, which includes areas of lag and advance. Similar results were obtained in the last area, when rolling in the second pair of rolls. In the second zone, in its entirety develops a compressive strain (\(\mu = 0.95\div1\)), which is a consequence of backpressure from the inclined channel matrix. In the third area when the passage of the workpiece through the channels of the matrix, in the deformable metal develop two types of deformation: compression (\(\mu = 0.6\div0.85\)) and shear (\(\mu = 0\div0.2\)), which is the most favorable scheme for the grinding of the original grain.

The most interesting are the values of Lode-Nadai coefficient obtained in the 4th zone, which characterizes the distance between the areas of the joints of channels in the matrix and rolling in the 2nd pair of rolls. Here the values of Lode-Nadai coefficient with horizontal and vertical rolls have significant differences. This is due to the kinetics and the forming of the workpiece in contact with the second pair of rolls. If you have a second pair of horizontal rolls, the billet gets re-compression in height, while the required amount of compression for a stable process flow is much less than in the first pair of rolls. As a result, the workpiece receives a significantly lower amount of widening. As a result, in the fourth area develop mainly tensile stresses (\(\mu = -0.6 \div -0.8\)), which is a negative factor.

In the case of vertical rolls at the exit of equal channel step matrix the billet gets a second compression in width, the value of which is commensurate with the compression in the first pair of rolls. As a
result, in the fourth area occurs backpressure from the rolls, thereby, tensile stresses are significantly reduced, until the appearance of zones of compression (μ=-0,3÷0,3).

4 Strain state

For analysis of the strain state was used indicator such as equivalent strain, which in some works is referred as intensity of deformation. This parameter allows to assess the common level of accumulated strain at any stage of the process.

Equivalent strain is determined by the formula

$$
\varepsilon_{EQV} = \frac{1}{3} \sqrt{\left(\varepsilon_1 - \varepsilon_2 \right)^2 + \left(\varepsilon_2 - \varepsilon_3 \right)^2 + \left(\varepsilon_3 - \varepsilon_1 \right)^2},
$$

where $\varepsilon_1$, $\varepsilon_2$, $\varepsilon_3$ - main strains.

In the study of this parameter were obtained results presented in figure 4. When comparing models with horizontal and vertical rolls, it was established that in the first four zones the values of equivalent strain are identical. This difference in values appears only in the last area, where due to the change in the direction of compression, in the vertical rolls significantly increases the level of processing, thus the value of the equivalent strain increased from 0.55÷0.8 in the horizontal rolls to 0.9÷1.15 in the vertical rolls.

![Figure 4. Equivalent strain.](image)

5 Conclusions

In this work was performed a comparative analysis of the efficiency of horizontal and vertical rolls in the "rolling-pressing" process. The comparison was performed based on the study of stress-strain state of both variants with the aid of computer simulation in the program DEFORM-3D based on the finite element method. For analysis of the stress state was used the Lode-Nadai coefficient, allowing you to determine which type of deformation is realized at a specific point – tension, compression or shear. For analysis of the strain state was used equivalent strain, which allows to estimate the common level of accumulated strain. In the comparative analysis of parameters of SSS was revealed that the use of vertical rolls at the exit from the matrix during "rolling-pressing" process, allows you to achieve a more favorable distribution of deformation along the entire length of the deformable workpiece.
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