Study of the deformation process in an equal-channel step matrix of a new design based on computer simulation

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Abstract. The paper presents the results of computer simulation of the deformation process in equal-channel step matrix, the distinctive feature of which is the location of intermediate channel at two angles to the input and output channels. Models with values of the inclination angle in the longitudinal direction (angle \( \alpha \)) of 135 degrees and inclination angles in the transverse direction (angle \( \beta \)) of 15, 25 and 35 degrees are considered. To study the stress-strain state, the following parameters were considered: equivalent strain (total strain intensity); equivalent stress (stress intensity), and the resulting deformation force. It was found that with an increase in the value of the angle \( \beta \), all the characteristics of the stress-strain state increase in their absolute value. When the angle \( \beta \) increases from 0 to 35 degrees, the equivalent strain increases by an average of 22÷25%. The analysis of the forces showed that when the value of the angle \( \beta \) increases, the deformation force increases at both stages, the nature of the increase is non-monotonic. The increase in force occurs sequentially by 10, 12 and 23 kN, which indicates the exponential nature of increase in force depending on the value of the angle \( \beta \). The maximum force value of 257 kN that occurs when using a matrix with angle of \( \beta=35^\circ \) exceeds the standard value for \( \beta=0^\circ \) by only 22%. Therefore, the best option for performing equal-channel step pressing with the flow of metal in 3 planes can be considered a matrix with angle \( \alpha=135^\circ \) and angle \( \beta=35^\circ \).

1 Introduction
Equal-channel angular pressing (ECAP) is one of the most well-known methods of severe plastic deformation, which allows obtaining bulk blanks with an ultrafine-grained (UFG) structure. This method has been known for more than 40 years [1] and is still being actively investigated [2-5]. Despite the fact that a number of new devices and technologies have already been developed [6-9], which are based on the principle of ECAP, the vast majority of these ideas have not been widely applied in industry. The reason for this is the disadvantages of ECAP inherent in most of the developed technologies: the relatively small size of the resulting blanks, the discreteness of the deformation process, and the need to implement a large number of deformation cycles to form the UFG structure. And if the first two disadvantages are successfully coped with by developing so-called "combined" processes [10-13], where the principle of continuous deformation of long samples operates, then the last disadvantage is quite difficult to overcome. Its essence lies in the fact that in order to obtain the UFG structure in the deformable material, it is necessary to ensure the implementation of high degrees of deformation for grain grinding. Based on this, to reduce the required number of deformation cycles, it is necessary to ensure an increase in the level of accumulated deformation in one pass. To do this, it is necessary to improve the design of the deforming tool.

Another effective way to increase the metal processing during ECAP is to turn the sample. In [14], this factor was thoroughly investigated: it was found that the most optimal method of edging is the BC route (90° edging along the longitudinal axis of the sample, i.e. changing the horizontal direction of deformation in the cross section to the vertical one).

The purpose of this work is to study the deformation process in an equal-channel step matrix of a new design, the distinctive feature of which is the location of the intermediate channel at two angles to the input and output channels, i.e. the deformation occurs not in the horizontal or vertical directions, but in both simultaneously (diagonal direction). In fact, the deformation in the matrix of this design is
conventional ECAP with partial edging of the sample. The diagonal movement of the metal in this matrix is shown in figure 1a.

Figure 1. Scheme of the channels design in the matrix with a metal flow in 3 planes

2 Models for research

4 matrix models were constructed in the KOMPAS program to simulate equal-channel step pressing using matrices with a metal flow in 3 planes. The first matrix had a "classical" equal-channel step structure, in which the direction of metal flow changed only in 2 planes. The other 3 matrices had a similar design to the first one, with the only difference that in them the direction of metal flow is carried out not in two, but in three planes. The channel junction angle in the longitudinal direction (angle α) in all matrices was assumed to be equal to 135 degrees, as the most optimal for equal-channel step pressing [15]. The angle of the channel junction in the transverse direction (angle β) in the first matrix was zero, in the other three matrices it was equal to 15, 25 and 35 degrees, respectively (figure 1b).

The initial blank had dimensions of 20 x 20 x 100 mm. A grid of finite elements evenly distributed over the entire volume of the workpiece was applied to this model. The average size of the final element was 1.3 mm, the number of nodes was 30699, and the number of elements was 96024. Steel AISI1035, heated to a temperature of 1100°C, was chosen as the material of the billet. The rheological properties of the material were taken from the Deform database. A non-isothermal type of calculation was chosen, i.e. in addition to the heat output to the tool, the workpiece also gave heat to the environment, the temperature of which was assumed to be 20°C. In an earlier study of equal-channel step pressing, it was found that the value of the friction coefficient in the matrix will depend on the required force required for the stable flow of the deformation process. To minimize its value, the value of the friction coefficient equal to 0.1 was taken.

To study the stress-strain state, the following parameters were considered: equivalent strain (strain intensity) and equivalent stress (stress intensity).

3 FEM simulation

The accumulation of equivalent strain occurs when the workpiece moves in the second and third channels of the matrix. In a matrix with an angle β = 0°, the distribution of equivalent strain, as in the first stage, is uneven (figure 2), zones of different strain values are clearly visible, the value of which varies in the range of 0.7÷1. As the value of the angle β increases, the distribution of the equivalent strain along the length of the workpiece becomes more uniform, and its numerical value increases. In a matrix with an angle β = 15°, the value of the equivalent strain at the second stage is 0.75÷1.07; in a matrix with an angle β = 25°, it is 0.85÷1.1; in a matrix with an angle β = 35°, it is 0.92÷1.22.
The equivalent stress distribution is located in two distinct zones: in the junction zone of the first and second channels and in the junction zone of the second and third channels (figure 3). In a matrix with an angle $\beta = 0^\circ$ in the docking zone, the value of the equivalent stress varies in the range of 180÷200 MPa. In the area of the channel junction, the value of the equivalent stress increases and is in the range of 420÷450 MPa. As the value of the angle $\beta$ increases, the numerical value of the equivalent stress increases. In a matrix with an angle $\beta = 15^\circ$, the value of the equivalent stress in the docking zone is 220÷250 MPa; in the area of the channel junction - 430÷470 MPa. In a matrix with an angle $\beta = 25^\circ$, the value of the equivalent stress in the docking zone is 260÷320 MPa; in the channel junction zone - 460÷490 MPa. In a matrix with an angle $\beta = 35^\circ$, the value of the equivalent stress in the docking zone is 290÷340 MPa; in the channel junction zone - 480÷500 MPa.

To complete the study, it is also necessary to evaluate the resulting deformation force, since an excessively large value of this parameter entails large energy costs and can lead to equipment failure. Graphs of the resulting force were constructed, one of which is shown in figure 4, the force values for the first and second stages of deformation were recorded on them. For convenience, the effort values were presented as a summary chart (figure 5).
Discussion of the obtained results

As can be seen from the data presented in figures 2-3, with an increase in the angle $\beta$, all the characteristics of the stress-strain state increase in their absolute value. Due to the absence of compression in ECA matrices as such, the growth of equivalent strain in this process occurs solely due to the implementation of the shear scheme on inclined planes connecting adjacent channels. Therefore, the key factor determining the resulting level of strain in a single pass is the value of the angle (in our case, the angles) of the inclination of these planes to the input and output vertical channels. When the angle $\beta$ increases from 0 to 35 degrees, the equivalent strain increases by an average of 22-25%.

Equivalent stresses have a similar distribution in both zones – with an increase in the angle $\beta$, this parameter increases. However, the change in the channel junction zones is smoother than in the docking zones. This is due to the fact that the channel junction zones, where shear deformations are actually implemented, have a rather small length compared to the lengths of the matrix channels. As a result, the
stress concentration in these zones occurs in strictly defined intervals, which is not the case for docking zones, the length of which can reach up to half the length of the channels.

As can be seen from the diagram, when the value of the angle $\beta$ increases, the deformation force increases at both stages. The increase in force occurs sequentially by 10, 12, and 23 kN, which indicates the exponential nature of the increase in force depending on the value of the angle $\beta$. The maximum force value of 257 kN that occurs when using a matrix with an angle $\beta=35^\circ$ exceeds the standard value for $\beta=0^\circ$ by only 22%. Therefore, a matrix with an angle $\alpha=135^\circ$ and an angle $\beta=35^\circ$ can be considered the best option for performing equal-channel step pressing using metal in 3 planes.

Based on this, we can conclude that the most optimal deformation scheme occurs when the angle $\beta$ increases, i.e. in a matrix with an angle $\beta=35^\circ$.

5 Conclusion

The paper presents the results of computer simulation of the deformation process in an equal-channel step matrix, the distinctive feature of which is the location of the intermediate channel at two angles to the input and output channels. Models with values of the angle of inclination in the longitudinal direction (angle $\alpha$) of 135 degrees and angles of inclination in the transverse direction (angle $\beta$) of 15, 25 and 35 degrees are considered. Analysis of the parameters of the stress-strain state and the resulting deformation force showed that the most optimal deformation scheme occurs when the angle $\beta$ increases, i.e. in a matrix with an angle $\beta=35^\circ$.

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