Computer Simulation of the Metal Deformation Process in an Equal Channel Step Matrix with Additional Backpressure

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Abstract. Theoretical studies of the process of round cross-section billets pressing in equal-channel step matrices of various designs by modeling are carried out. It was found that the backpressure created by the narrowing of the matrix channels has a favorable effect on the stress-strain state of the metal, which in turn allows for better processing of the structure of the deformable metal. It is also found that when using an equal-channel step matrix with narrowing channels, the deformation force increases, which cannot be attributed to the positive sides of these matrix designs. It was found that the most optimal results were obtained when using an equal-channel step matrix with a narrowing of the intermediate channel.

1. Introduction

The development of technologies for the production of ferrous and non-ferrous metals and alloys with ultrafine-grained (UFG) structure by severe plastic deformation methods has been an actual direction of modern materials science for more than a decade. It is metals and alloys with an ultrafine-grained structure that are considered as promising structural and functional materials of the next generation, since most of these materials in this structural state have unique properties.

One of the most effective methods for obtaining UFG materials with severe plastic deformation is equal-channel angular pressing [1–6], and, in particular, pressing in an equal-channel step matrix [7–11]. At the same time, it is known from [11–19] that one of the main favorable factors affecting the possibility of obtaining an ultrafine-grained structure with a smaller number of pressing cycles is backpressure. One of the ways to create a backpressure during metal pressing in an equal-channel angular matrix is to narrow the output channel of the matrix [20–21]. In the process of metal pressing in an equal-channel step matrix, in contrast to the angular matrix, the backpressure is created due to the presence of a second junction of the matrix channels. Additional backpressure during compression in an equal-channel step matrix can be achieved, as well as in angular compression, by narrowing the channels of the matrix. There are several possible options:

- narrowing only the output channel of the matrix;
- narrowing of the intermediate (inclined) channel of the matrix;
- gradual narrowing of the intermediate channel and then the output channel of the matrix.

2. FEM-models

This work is devoted to the theoretical study of the deformation in an equal-channel step matrix with additional backpressure based on the simulation of these processes in the Deform software.
package, in order to determine the optimal design of an equal-channel step matrix, which allows creating the most favorable stress-strain state for obtaining metal with an ultrafine structure at lower energy costs.

For these studies, drawings of equal-channel step matrices with different channel diameters were developed. It was based on an equal-channel step matrix with a channel diameter of 15 mm, which was built in the “Kompas” software package. Also, equal-channel step matrices of the following designs were built:

- matrix with a narrowing of the intermediate (inclined) channel of the matrix from 15 mm to 13 mm;
- gradual narrowing of the intermediate channel of the matrix from 15 mm to 14 mm, and then the output channel of the matrix from 14 mm to 13 mm;
- narrowing the output channel of the matrix from 15 mm to 13 mm.

For all four matrices the following identical conditions were set: the length and diameter of the workpiece were 100 mm and 15 mm respectively, workpiece material was AISI 1016 steel, the mesh of the billet contained 25000 elements, the temperature of the billet was 1100°C, the temperature of the die was 200°C, the heat transfer coefficient was 0.7; the coefficient of friction was 0.25; pressing speed was 5 mm/s.

3. Simulation results

To identify the effect of the construction of an equal-channel step matrix on the stress-strain state of the metal at different values of the diameters of the matrix channels, the following indicators of the stress-strain state were determined: equivalent strain and equivalent stress.

Thus, as a result of modeling the pressing of blanks in an equal-channel step matrix of different designs, equivalent strain distributions were determined (Figure 1). It is found that in all matrices, the largest equivalent strain is realized in the second intermediate channel and in the third output channel, but to different degrees. Thus, in a matrix with the same channels, intensive equivalent strains are realized only in a small area on the inner side of the inclined and output channels, in the same area this parameter reaches the maximum value (Figure 1, a). In an equal-channel step matrix with narrowing only the output channel of the matrix, this area increases and also appears from the outside (Figure 1, d). In the matrix with narrowing sloping channel matrix from 15 mm to 13 mm (Figure 1, b) and in the matrix, with a gradual narrowing of the first intermediate channel matrix from 15 mm to 14 mm, and then the output channel of the matrix from 14 mm to 13 mm (Figure 1) in the output channel due to the additional backpressure the zone of intensive equivalent strain occupies almost the entire volume of the workpiece.

If we consider the value of the equivalent strain in volume of the deformable metal, during the pressing of the workpiece in the matrix channels with the same average value on a sloping plot is 0.5–0.7; and in the output channel, by passing the metal through a second junction of the channel matrix the mean value of the equivalent strain grows to 1.2 to 1.3. In the matrix with the only narrowing of the output channel value in the second channel is 0.7–0.9; and in the output channel is 1.3–1.5, and in some places reaches 2. In a matrix with a narrowing of the inclined channel of the matrix from 15 mm to 13 mm and in a matrix with a gradual narrowing of the intermediate channel of the matrix from 15 mm to 14 mm, and then the output channel of the matrix from 14 mm to 13 mm, the values of equivalent strain are almost identical. With the expense of creating additional backpressure by narrowing the channel matrix according to the schemes in the second channel strain increases significantly, and is run from 0.7 to 2.0; and the third channel value of the runway is reduced and the strain has a value from 1.6 to 2.0.

The nature of the equivalent stress distribution shows that the highest value in all matrices is realized in the joints of the matrix channels, while the most uniform distribution of equivalent stresses is observed when using an equal-channel step matrix with a narrowing inclined channel (Figure 2b) and in a matrix with a gradual narrowing of the inclined channel first, and then the output (Figure 2c).
Figure 1. Distribution of equivalent strain during pressing in an equal-channel step matrix of various designs: a – matrix with 15 mm channels; b – narrowing of the intermediate (inclined) channel from 15 mm to 13 mm; c – gradual narrowing of the intermediate channel from 15 mm to 14 mm, and then the output channel from 14 mm to 13 mm; d – narrowing of the output channel from 15 mm to 13 mm.

When using an equal-channel step matrix with a narrowing inclined channel, the highest equivalent stress is 250 MPa, and the average equivalent stress on the inclined section is 200–220 MPa (Figure 2b). In the output channel, the equivalent stress is reduced to a minimum. When using an equal-channel step matrix with a gradual narrowing of the inclined channel first, and then the output channel, the maximum value also reaches 250 MPa, on the inclined section it is equal to 200–215 MPa, in the output channel due to a smooth narrowing of the channel, the equivalent stress is gradually reduced from 190 MPa to 150 MPa (Figure 2c). When using an equal-channel step matrix without narrowing, the maximum stress reaches 200 MPa, on the inclined section, the equivalent stress is in the range of 130-180 MPa, in the output channel, the equivalent stresses are reduced to a minimum as well as in the equal-channel step matrix with a narrowing inclined channel (Figure 2a). In an equal-channel step matrix only with the narrowing of the output channel, the equivalent stress reaches 230 MPa, on the inclined section it has a large run–up and is 140–215 MPa, and in the output channel, due to the narrowing of this channel, a more uniform
distribution is observed, and the run–up is reduced to 20 MPa, i.e. in this section, the equivalent stress is already 130–150 MPa (Figure 2d).

**Figure 2.** Distribution of equivalent stresses during pressing in an equal-channel step matrix of various designs: a – matrix with 15 mm channels; b – narrowing of the intermediate (inclined) channel from 15 mm to 13 mm; c – gradual narrowing of the intermediate channel from 15 mm to 14 mm, and then the output channel from 14 mm to 13 mm; d – narrowing of the output channel from 15 mm to 13 mm.

Analysis of the effect of the design of an equal-channel step matrix on the deformation force showed that any narrowing of the matrix channels leads to an increase in the effort spent on pressing compared to pressing in the matrix without narrowing (Figure 3). The greatest effort is observed when using an equal-channel step matrix with a gradual narrowing of the first intermediate channel of the matrix from 15 mm to 14 mm, and then the output channel of the matrix from 14 mm to 13 mm. The maximum pressing force in this equal-channel step matrix reaches 151 kN (Figure 3c). The deformation process in an equal-channel step matrix with a narrowing of the output channel of the matrix from 15 mm to 13 mm also requires significant energy consumption (Figure 3d). When using this matrix, the pressing force reached 120 kN. When using a matrix with a narrowing of the inclined channel of an equal-channel step matrix, the pressing force is not much higher than the pressing force in an equal-channel step matrix without a narrowing (Figure 3a, b). So if you are using angular equally channel step matrix with narrowing sloping channel matrix from 15 mm to 13 mm the stress is equal to 91 kN, and the use of a matrix with a channel 15 mm pressing force is equal to 81 kN.
Figure 3. Graphs of the pressing force: a – matrix with 15 mm channels; b – narrowing of the intermediate (inclined) channel from 15 mm to 13 mm; c – gradual narrowing of the intermediate channel from 15 mm to 14 mm, and then the output channel from 14 mm to 13 mm; d – narrowing of the output channel from 15 mm to 13 mm.

4. Conclusions
In the course of the theoretical study of the pressing process of round cross-section billets in equal-channel step matrices of various designs by modeling in the “DEFORM” software package, it was found that the backpressure created by the narrowing of the matrix channels has a favorable effect on the stress-strain state of the metal, which in turn allows for better elaboration of the structure of the deformed metal. But the analysis also showed that when using an equal-channel step matrix with narrowing channels, the deformation force increases, which cannot be attributed to the positive sides of these matrix designs. Therefore, only the choice of rational parameters of the matrix design will allow you to obtain a metal with an ultra-fine-grained structure due to the uniform distribution of deformation and stress over the entire volume of the deformed metal and its intensive processing at low energy costs. In our case, the best results were obtained when using an equal-channel step matrix with a narrowing of the intermediate (inclined) channel of the matrix.

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