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Evaluation of the bars' multichannel angular pressing scheme and its potential application in practice

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ABSTRACT

Introduction. Deformation of low-plastic materials requires a high degree of compressive stress. This requirement is implemented, for example, in the process of *equal channel angular pressing* (*ECAP*). However, the products obtained by the *ECAP* method have a cross-section identical to the initial blank, which is one of the disadvantages of this method. The method of *nonequal channel angular pressing* (*NECAP*), in contrast to *ECAP*, makes it possible to change the shape of the initial blank towards closer to the shape of the finished product. However, the well-known *NECAP* device allows obtaining products only in the form of a thin strip of rectangular cross-section. Well-known devices for multichannel pressing of non-angular type also have a disadvantage — it is implemented only on horizontal type presses, where it is possible to receive long products on the workshop areas. **The aim of the work** is the evaluation of the bars' multichannel angular pressing scheme, combining a change in the shape of the initial workpiece in cross-section, as well as the accumulation of a high level of strain during deformation. **Research methods:** finite element modeling using the *DEFORM* software module. **Results and discussion.** The paper considers the scheme of the angular pressing process with the use of a device that allows, for example, to obtain magnesium bars with a diameter of d = 4.1 mm with the number of matrix channels n = 3 from a blank of round cross-section. The container of this device in its lower part has a rectangular groove where the matrix is inserted. Modeling of the process under study using a matrix with the axes of its channels located in the plane of the orthogonal axis of the container and, in the first variant, along the axis of a rectangular groove, and in the second variant, along the radius of the container, allowed us to estimate the distribution of the average stress. It is established that the metal of the blank in both variants of the deformation process is affected by compression stresses at a high level (–1,600 MPa). The assessment of the degree of deformation of the pressed bars allowed us to find out that at the initial stage of both process variants, the maximum strain degree can reach 2.6, and at the steady stage it reaches 5.0. It is established that in the case of the first variant of the matrix, the strain level along the length of the bars is lower than when using the second variant of the matrix. The difference reaches 20 %. By evaluating the distribution of the strain degree in the cross section of the pressed bars near the deformation site, it was found that in the case of the first variant of the matrix, the pressed bars of the first and third channels have an uneven dimensions, and the greater value of the strain degree is on the peripheral part of the rods from the side bordering the central bar. This difference in the strain degree reaches 20 %. When placing the second version of the matrix, this unevenness decreases to 12 %. Thus, in the case of using a matrix with the arrangement of the channel axes along the radius of the container, the strain degree is distributed more evenly compared to the strain degree when using a matrix with the arrangement of the channel axes along the axis of a rectangular groove.

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Introduction

In order to process low-ductile materials, it is often necessary to use the methods that provide a high level of compressive stresses [1–3]. For example, the authors of works [4–5] demonstrated that it is possible to deform low-ductile magnesium and its alloys on a par with ductile materials by means of compressive stresses achieved during *equal channel angular pressing* (*ECAP*) [6–8]. However, the *ECAP* devices have a drawback: the final product produced by this method has a cross section similar to the initial blank [9–11]. In addition, the final product has a short length due to the short length of the initial blank, which is limited by the friction conditions on the container wall. Besides, with a one-time application of the *ECAP* process, the final product demonstrates non-uniform deformed state [12].

In the case of *non-equal channel angular pressing* (*NECAP*), unlike *ECAP*, the change in the shape of the initial blank is implied by the process itself [13]. The NECAP device consists of a punch and a container resting its lower part on a plate, with a rectangular groove gap between the lower end of the container and the flat surface of the plate, which acts as a die. As a result of the metal flowing through the gap, a sheet stock is produced in the shape of a thin strip having a profile similar to the gap. It is not possible to obtain a different profile, which is a drawback of this device. However, there is a need for press products with round, square and other cross-sections. Thus, this device is limited in its manufacturing capabilities.

There are multichannel pressing devices of non-angular type, where the travel direction of a punch coincides (direct method) or does not coincides (indirect method) with the movement direction of the extruded profile during deformation [14–15]. However, these devices also have a drawback – it can be used only with horizontal presses, which ensure the acceptance of long products in the production areas, while on vertical presses the acceptance of such products is impossible. Therefore, in this case it is advantageous to use an angular pressing scheme, where the axis of the press is vertical and the axis of the pressed product is perpendicular to it. It is possible to place products produced by this method on a rack using, for example, additional tensioning devices for finished profiles [16].

Typically, the maximum permissible strain level during pressing is determined either by the ductility of the metal or by the load on the pressing tool. Unlike conventional structural analysis, where a permissible safety factor is limited to values between 5 and 10, a pressing tool often operates at the limit of its capabilities with a safety factor slightly higher than 1. In this case such a tool is used for one pressing cycle, in the next cycle it has to be replaced in the next cycle due to loss of shape. For example, this approach is used when pressing titanium, tungsten, molybdenum and other alloys. Due to the different thermomechanical processing parameters used for different alloys, the allowable strain degree turns out to be different. There are recommendations for the use of different elongation ratios under production conditions for different materials, e.g., 30 to 50 for bronzes, 60 to 100 for magnesium alloys. Thus, the maximum permissible elongation ratio for magnesium alloys is 100, which corresponds to a strain degree about $\ln(100) \cong 5$. This value will be taken into account in further calculations.

The purpose of this study is to evaluate the multichannel angular pressing of bars, which combines a change in the shape of the initial blank in the cross section, as well as the accumulation of a high level of strain during the deformation process.

To achieve this purpose, the following objectives are set:

1. To describe the design of the device for multichannel angular pressing of bars, including the die design features;

2. To build two variants of computer models for magnesium cold deformation by the method of multichannel angular pressing of bars with a diameter d = 4.1 mm with the number of matrix channels n = 3 (according to the first variant, the axes of the matrix channels are located along the axis of the rectangular groove; according to the second variant, the axes of the matrix channels are located along the container radius) and to run simulation with the aid of the *DEFORM-3D* software package;

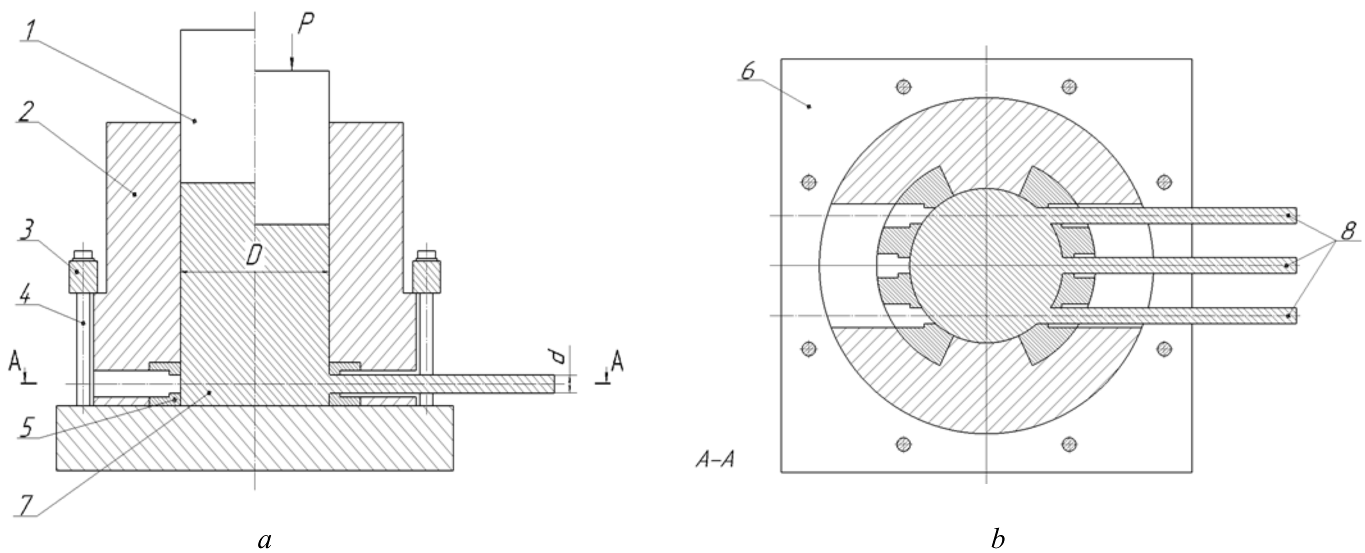
3. To analyze the stress-strain state of the metal using computer modeling for two die variants and, in particular, to compare the mean stresses, axial stresses, strain degree and strain rate.

Research methodology

We studied the design of the device for angular multichannel pressing (fig. 1), consisting of the following structural components: a punch *1*, a container *2*, a flange *3*, bolts *4* and a bottom plate *6*. The container *2* is connected to the plate *6* by means of the flange *3* and the bolts *4*. At the bottom of the container *2* (fig. 1, *a*) there is a rectangular groove located at an angle of 90° relative to the axis of the container *2* with diameter *D*. The die *5* is mounted in the groove, which in this case has three channels of an equiaxed shape. The shape of the channels of the die *5* is shown in fig. 1, *b*. The axes of these channels are located at an angle of 90° to the axis of the container and along the axis of the rectangular groove. It should be noted that the channels can be placed in another way, namely, along the radius of the container. At that, in the first positioning variant, the bars flow out of the dies in parallel rows; when implementing the second variant, the symmetry of the metal flow of the pressed rods relative to the center of the circumference of the container cavity is ensured. In this case, the channels have a circular shape in its cross-section. It should be noted that the channels can have a different cross-section, for example, a square, depending on the requirements of the consumer of the pressed products. Thus, the presence of a device for angular multichannel pressing among the structural elements ensures a change in the configuration of the cross section of the pressed product to the shape of the openings present in the die.

The use of a die with the number of channels $n > 2$ makes it possible to bring the pressing force values closer to the minimum possible values. From the theory of pressing it is known that the force is proportional to the natural logarithm of the elongation ratio, and with a larger number of channels the overall elongation ratio decreases. This becomes an important factor if it is planned to press metals with high strain resistance without heating. However, it should be taken into account that as the number of channels increases, the area of the contact surface at the level of the parallel lands of the die increases. The situation is complicated by the fact that this area is considered in the pressing force equation by introducing an elongation ratio as a co-multiplier, which is a significant value in pressing. Therefore, we have to apply the rule of minimizing the lengths of die parallel bands. Its length should provide the strength conditions with a small safety factor. When setting the problem, the length of the die parallel bands was assigned to 4 mm.

It should be specially noted that, unlike the conventional pressing, the axes of the die channels in this case are in a plane located at an angle of 90° to the axis of the container. This makes it possible to reduce the size of discard, which, in turn, leads to an increase in the product yield value.



a *b*

Fig. 1. The structure diagram of the device for angular pressing of bars round cross–section in the amount three:
a – the beginning of the process is reflected on the left half, the stationary stage of the process is reflected on the right half; *b* – the cross section A-A: on the left shows a matrix with the axes of the channels at an angle of 90° to the axis of the container and along the axis of the rectangular groove, with the display on the right of the same with the location of the bars

The equiaxial shape of the die channels ensures a uniform stress distribution in each macro-zone of deformation.

Fig. 1, *a*, *b* on the right shows a diagram of the device in question, showing the mutual position of the parts at the intermediate moment of deformation of the blank *7* to obtain the bars *8*.

It should be mentioned that this device is mounted and fixed on the press table, and the punch *1* (fig. 1, *a*) interacts with the press slide. The structural elements fastening the plate *6* with the table and the punch *1* with the slide are not shown in fig. 1.

Preparation for the pressing process of a cylindrical blank *7* with a diameter *D* is the application of a lubricant on its ends and side surface. The first step of the pressing cycle is the placement of the blank *7* into the container channel *2*. Further, the punch *1* is actuated by the press drive and lowered until it comes into contact with the upper end of the blank *7*. Fig. 1a, b on the left shows the relative position of the parts at this moment. At the next stage of the process, the punch *1* moves under the action of the press force *P*, while the lower end surface of the blank *7* gets deformed, and the main metal flows into the channels of the die *5*. This pressing cycle results in the production of three bars with a diameter *d*, the length of which depends on the size of the initial blank and the material strain degree.

The experiments on cold pressing of magnesium were carried out on a press with a nominal force of 10 MN [17] in the conditions of the scientific laboratory of the *Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences*. The nominal force of the press lifting cylinders was 2 MN. The nominal pressure of the power fluid was 32 MPa. The stroke of the moving crosshead was 1,000 mm. The maximum distance between the table and the moving crosshead was 1,800 mm.

The pressing tool assembly corresponded to the *non-equal channel angular pressing* method, and a die with a single rectangular channel of 40×1 mm was used. The punch was subjected to sufficiently high force during deformation and it was necessary to prevent its destruction, so the punch was made of steel *R18*. The choice of this grade is explained by its high fracture resistance and hardness. Steel *R18* was subjected to quenching in a vacuum chamber at 1,290 °C and triple tempering for 1 hour at a temperature of 550 °C. Such heat treatment resulted in a fairly high hardness value (64 HRC). Pressing was carried out from a container with a round cross-section consisting of two liners tightly inserted one into the other with interference fit. The inner liner, compared to the outer one, is made of stronger steel, since it takes up most of the pressure in the process. The inner diameter of the container was 40 mm.

The elongation ratio when producing a strip of 40×1 mm was $\lambda = \frac{\pi D^2}{4} / (bh) = 31$. It was revealed that with such technological parameters there is no damage to the press tooling. It was concluded that this technique is workable and the value of the elongation ratio $\lambda \le 31$ in the described deformation technique is acceptable.

When using the device in question, which includes a die, it is possible to produce bars (instead of strips) with a diameter *d* equal to the number of the die channels (*n*). In the example under consideration, $n = 3$. To calculate the diameter of the resulting bars, we determine the total cross-sectional area of the channels $F = n\frac{\pi d^2}{4}$ and calculate the elongation ratio using the Eq. (1):

$$\lambda = \frac{\frac{\pi D^2}{4}}{n\frac{\pi D^2}{4}} = D^2 / (nd^2). \tag{1}$$

Hence, the diameter of the resulting bars is calculated using the Eq. (2):

$$d^2 = D^2 / (\lambda n). \tag{2}$$

Thus, for $\lambda = 31$ and $n = 3$ we get $d = 4.1$ mm. This is the smallest diameter value at the specified elongation ratio and the number of die channels. Reducing the diameter may lead to exceeding the permissible stresses in the tool.

In order to verify the feasibility of angular pressing according to the proposed technique, two models of this process were built with the use of a die with the number of channels $n = 3$ and obtaining bars with a diameter $d = 4.1$ mm in the DEFORM 3D software package.

Fig. 2 shows two variants of the die design. The axes of the channels in both variants are at an angle of 90° relative to the container axis, however, in the first variant, the axes of the channels are located along the axis of the rectangular groove (fig. 2, *b*), and in the second variant, the axes of the channels are located along the radius of the container (fig. 2, *c*). For a more uniform metal flow from the die channels, it is recommended to have it placed at the same distance from each other.

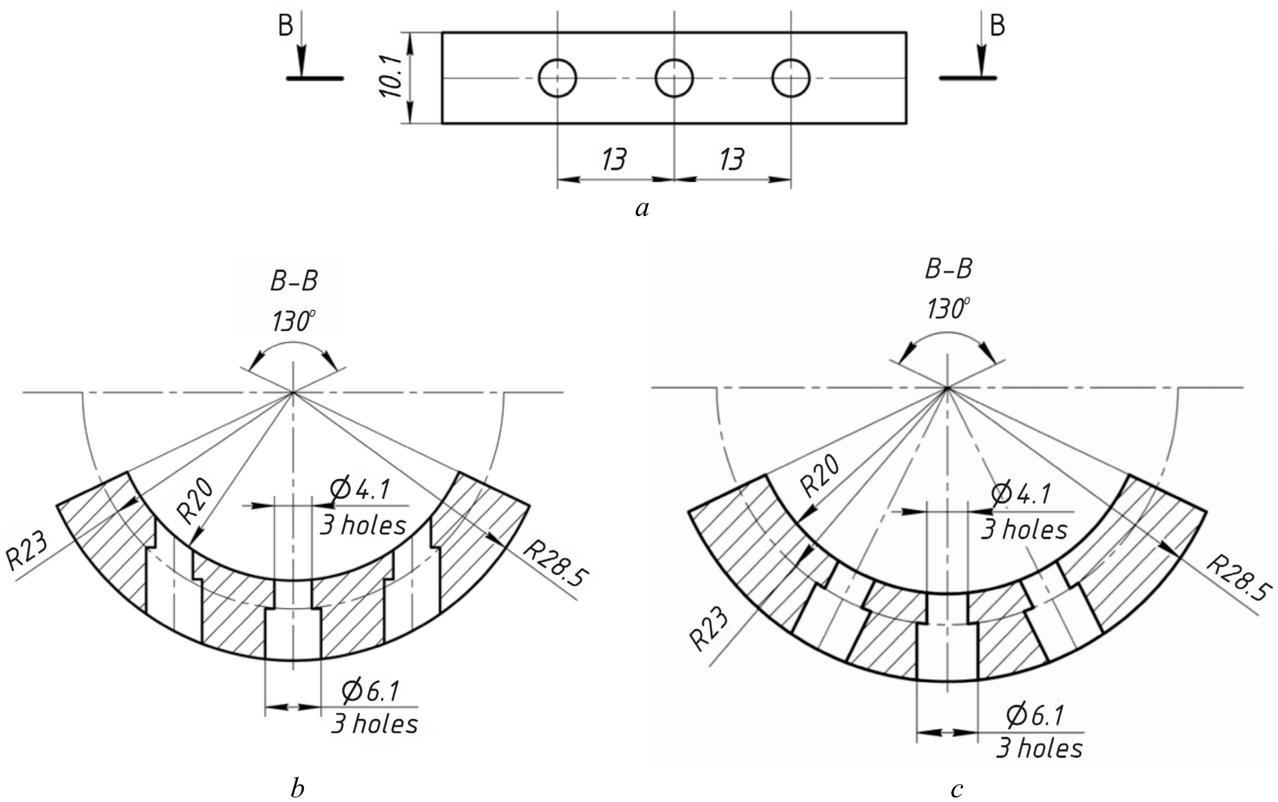


Fig. 2. The configuration of the die with a number of channels $n = 3$ for angular pressing of bars with a diameter $d = 4.1$ mm (*a*); the 1st variant of a die section (the axes of the channels are located along the axis of the rectangular groove) (*b*); the 2nd variant of a die section (the axes of the channels are located along the radius of the container) (*c*)

Magnesium of grade *Mg90* (GOST 804–93) was selected as a low-ductile metal of the blank.

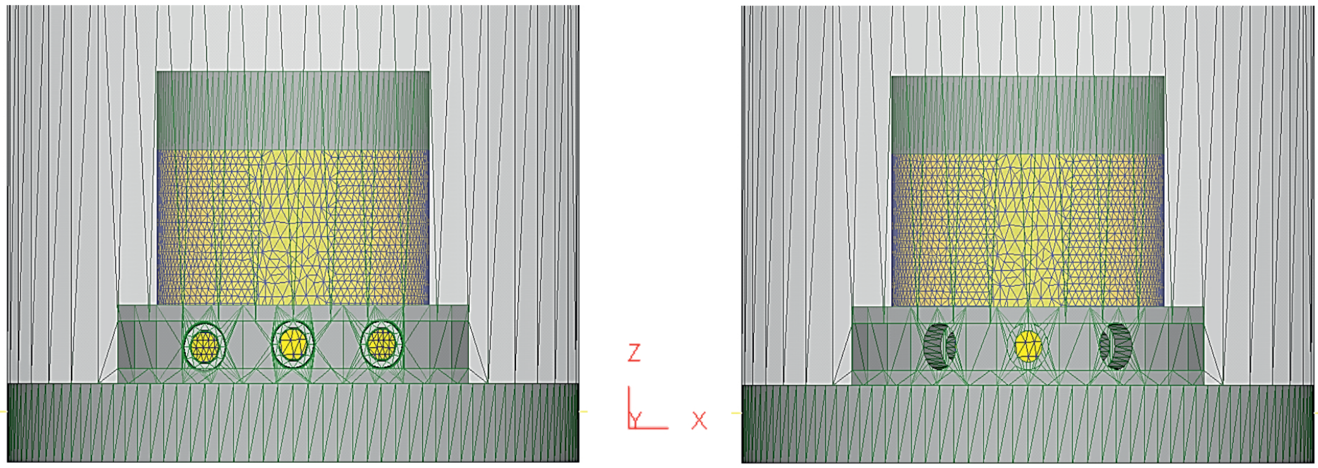
Magnesium is a metal with high specific strength, low density, high damping performance, biocompatibility, biodegradability, as well as chemical activity. These properties make it popular for the use in rocket and space equipment, aviation, automotive, medical and the oil industry [18–21].

Magnesium, as a material with a hexagonal close-packed (*HCP*) lattice, has a limited number of slip planes, which leads to its reduced ductility at room temperature [22–23]. However, hot deformation of magnesium, which increases the level of plastic properties [24], has disadvantages: oxidation of the surface of semi-finished products due to low corrosion resistance of magnesium, gas trapping within the metal volume [25], loss of the metal strain hardening effect, which allows increasing strength properties the final product, as well as an increase in energy costs for heating the blanks. Therefore, the possible approach is to carry out the processing in a cold state and to increase the ductility, for example, by increasing the level of compressive stresses [26–27]. It also means that a comprehensive compression scheme is implemented, in which compression stresses act along all three axes of the coordinate system. This is exactly the pattern that occurs in pressing processes.

The formulation of both variants of the problems consisted of entering data on physical and plastic properties of the blank metal, as well as in description of the shape of the deformation zone. The magnesium blank has a cylindrical shape (diameter D = 40 mm and height H = 42 mm). The boundary friction conditions are set by *Siebel* law (the friction coefficient is 0.2). The condition for stopping the calculation is set by the movement of the punch along the z-axis by 28 mm. In this case, a discard 14 mm high will remain in the container.

The computational formulation is described as follows: the deformable medium is ductile; the type of a task is isothermal (the temperature of the blank and the tool is 20 °C); the number of finite elements of the blank at the initial moment of time is 50,000; the tool is assumed as a rigid body.

Fig. 3 shows the initial assembly of the tool (the container is at this point is transparent) and the blank in the *XZ* plane for the two variants of the models: 1) when the die channel axes are positioned along the axis of the rectangular groove (fig. 3, *a*) and 2) when the die channel axes are positioned along the radius of the container (fig. 3, *b*).



a *b*

Fig. 3. The initial assembly of the tool (the container is currently transparent) and the blank in the *XZ* plane for the simulation option when using a die with the axes of the channels along the axis of the rectangular groove (*a*) and along the radius of the container (*b*)

Results and discussion

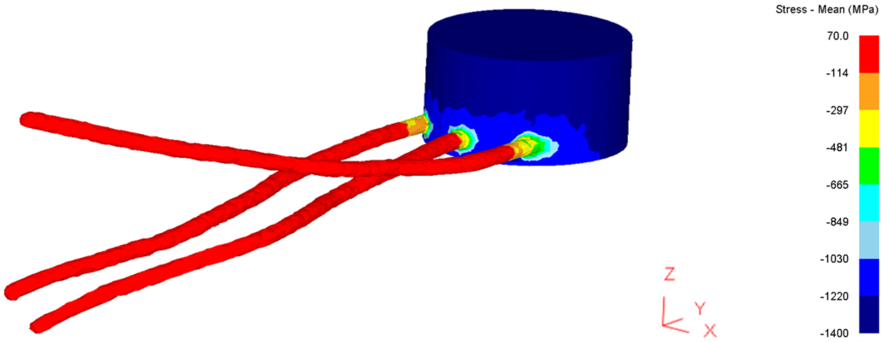
Fig. 4, *a* shows the result of solving the task in the form of mean stress distribution at the steady stage of angular pressing as the three-dimensional representation when using the die with channel axes arranged along the axis of the rectangular groove. Fig. 4b shows the same, only for the die channel axes arranged along the radius of the container.

It can be seen that the cylindrical blank in the process of deformation is under the action of mean (hydrostatic) compressive stresses at the level of –1,600 MPa. Thus, an all-round compression behavior is provided here, and the presence of high (modulo) values of the mean stress allows us to expect an increase in the level of ductility, which should prevent metal fracture.

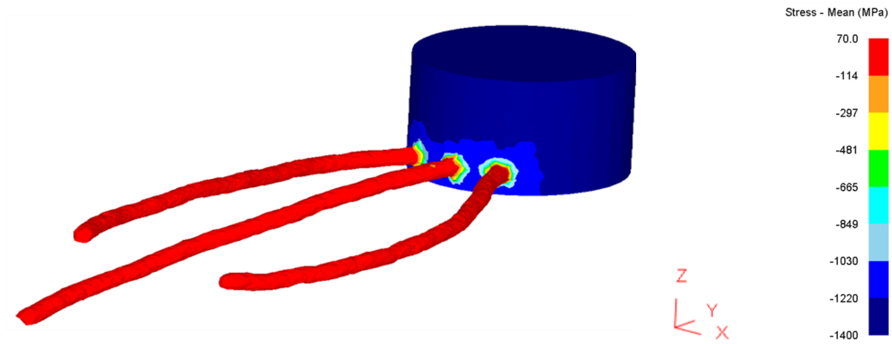
The pressure on the punch in this process is presented in fig. 5, *a* for the die channel axes arranged along the axis of the rectangular groove and in fig. 5, *b* for the die channel axes arranged along the radius of the container.

In this case, a reference point for the adequacy of the pressure on the punch can be the specific pressure on the punch during *NECAP* of a strip with a similar elongation ratio. It is known [28] that in this case it is equal to 1,300 MPa, which means that the value of 1,400 MPa obtained in this solution is quite probable.

Fig. 6, *a* shows the result of solving the problem in the form of regions of equal level of strain rate in the steady stage of angular pressing for the longitudinal section of the central bar in the *YZ* plane when using the die with the arrangement of the channel axes along the axis of the rectangular groove. Fig. 6, *b* shows the same, but for die channel axes arranged along the container radius.

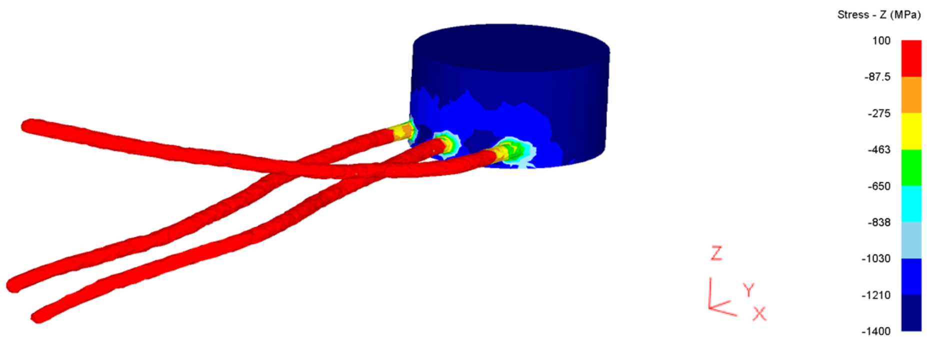


a



b

Fig. 4. Distribution of the mean stress in the stationary stage of the angular pressing process when the die channels are located along the axis of the rectangular groove (*a*) and along the radius of the container (*b*)



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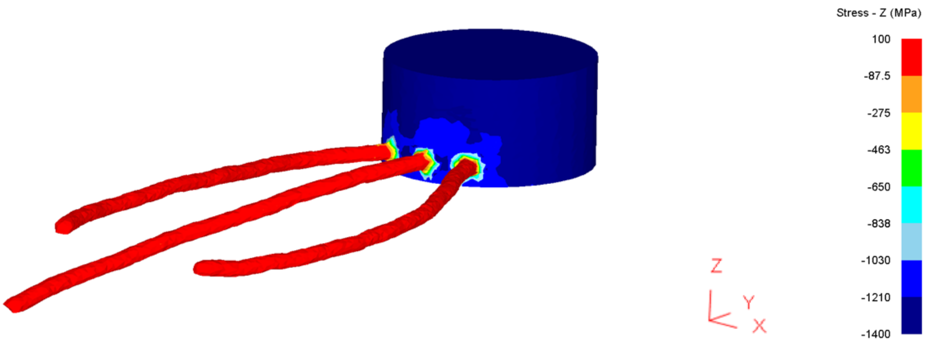


b

Fig. 5. Distribution of axial stresses in the stationary stage of the angular pressing process when the die channels are located along the axis of the rectangular groove (*a*) and along the radius of the container (*b*)

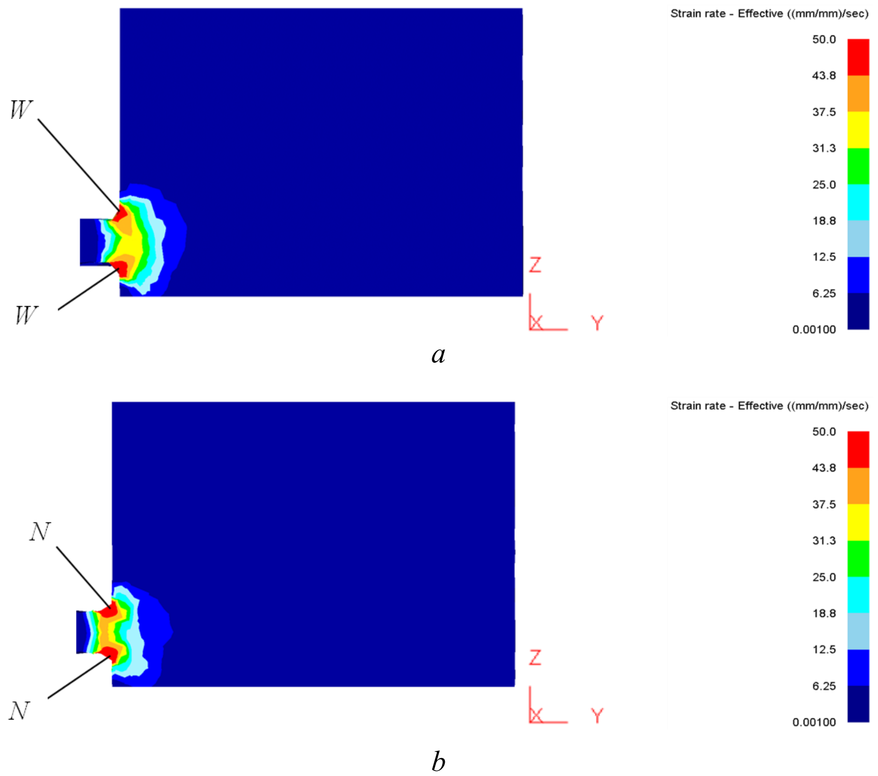


Fig. 6. Distribution of the strain rate (s^{-1}) in the longitudinal section of the central bar (*YZ* plane) when the axes of the die channels are located: along the axis of the rectangular groove (*W* is a maximum strain rate) (*a*); along the radius of the container (*N* is a maximum strain rate) (*b*)

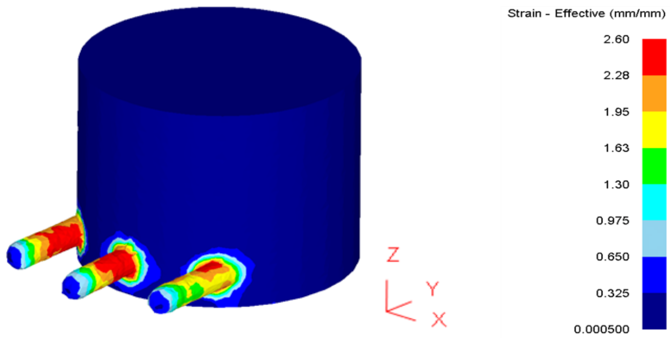
The strain rates in both variants increase as the metal approaches the die opening. The metal remaining in the container is a rigid zone. The maximum strain rates (*W, N*) occur in the zone of the highest shear strain when the direction of the metal changes, and its values are of equal level (50 s^{-1}).

Fig. 7 shows the initial moment of the blank deformation by angular pressing and the pressed bars with the strain field when the die channels are arranged along the axis of the rectangular groove (fig. 7, *a*) and along the radius of the container (fig. 7, *b*).

Here it can be seen that already at the initial stage of the deformation process in both variants there is a non-uniform distribution of the strain degree, with the highest strain degree of the outer bars in the first variant (fig. 7a) on its peripheral part on the side bordering the central bar. In this case, the difference in the strain degree over the diameter of the peripheral bar reaches 28 %, while in the central bar it does not exceed 10 %. In the second variant of the channel axes arrangement (fig. 4, 7), the difference in the strain degree over the diameter of all bars is not more than 10 %.

Fig. 8 shows the steady stage of angular pressing and the pressed bars as the three-dimensional representation with a strain field when the die channels are arranged along the axis of the rectangular groove (fig. 8, *a*) and along the radius of the container (fig. 8, *b*). It turns out that in both variants of the process the maximum strain degree can reach the value of 2.6 at the initial stage, before the stationary deformation zone is formed, and 5.0 at the steady stage. The strain degree in both variants reaches its maximum value at a considerable distance from the front ends of the bars. Thus, the front ends of the bars may be not sufficiently structured.

It is also worth mentioning that with the die channel axes arranged as per fig. 8, *a* the strain along the length of the bars is less than with the die channel axes arranged as per fig. 8, *b*. On average, the difference reaches 20 %. Besides, when the die channel axes are arranged along the container radius (fig. 8, *b*), it is apparent that the strain distribution along the length of the bars is more uniform as compared to pressing through the die with its channel axes arranged along the axis of the rectangular groove (fig. 8, *a*).



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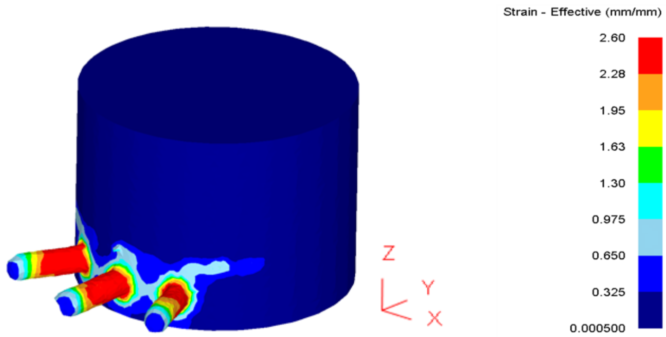
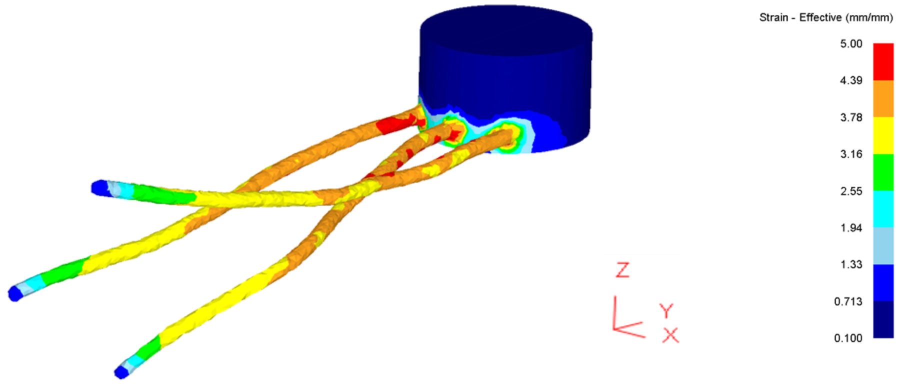


b

Fig. 7. Distribution of the strain in the initial stage of the angular pressing process with pressed bars when the die channels are located along the axis of the rectangular groove (*a*) and along the radius of the container (*b*)



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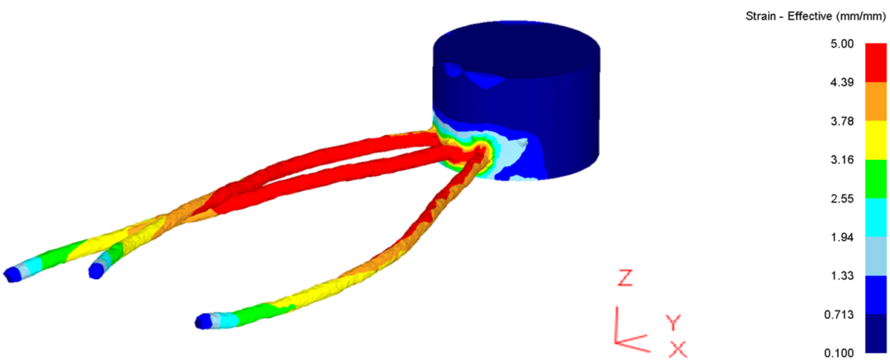
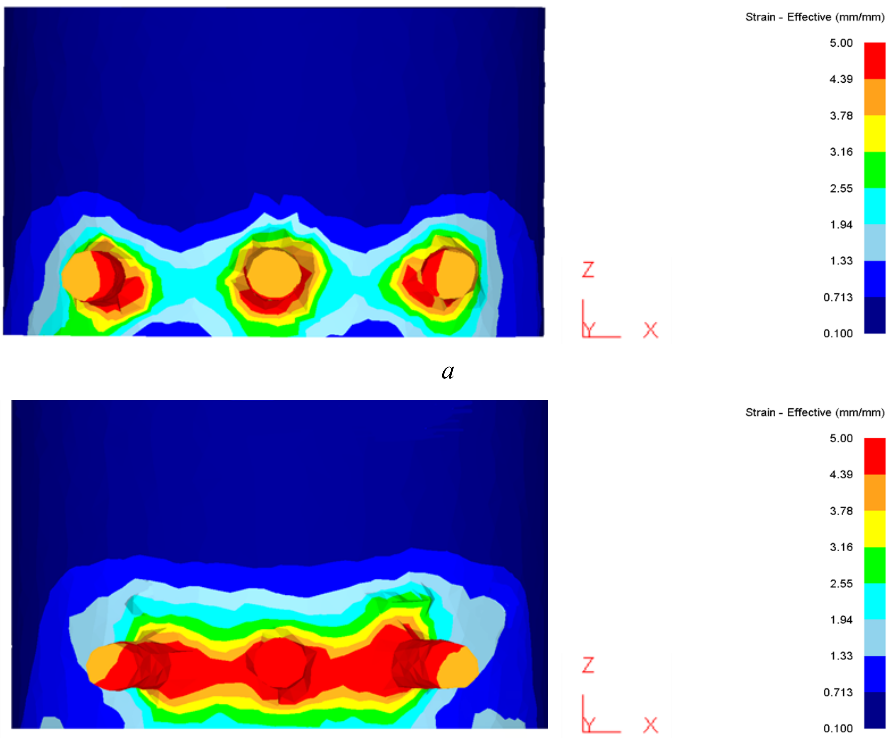


b

Fig. 8. Distribution of the strain of the pressed bars in the steady stage of the angular pressing process with the arrangement of the die channels along the axis of the rectangular groove (*a*) and along the radius of the container (*b*)

The 3D model allowed us to estimate the distribution of the strain over the cross-section of the pressed bars near the deformation zone (fig. 9, *a*, *b*). It is established that when the die channel axes are arranged along the axis of the rectangular groove (fig. 9, *a*), non-uniformity of strain distribution is not observed over the cross-section of the central bar. However, the pressed bars from the first and the third channels exhibit non-uniformity, with a larger degree of strain being on the peripheral part of the bars on the side bordering the center one. This difference in the strain degree reaches 20 %. This non-uniform strain distribution can be explained by the positioning of the axes of the channels. The axis of the center channel is positioned along the radius of the container, while the axes of the first and third channels are offset from the radius line out of necessity. This is what creates a non-uniform effect on bars. When the axes of the channels are arranged along the container radius, this non-uniformity is reduced to 12 %.



a

b

Fig. 9. Distribution of the strain in the steady stage of the angular pressing process in the cross section of the pressed bars in the *XZ* plane with the arrangement of the die channels along the axis of the rectangular groove (*a*) and along the radius of the container (*b*)

Conclusions

1. The structural diagramm of the device for angular multichannel pressing and particular features of the die are described. The device offers a wide range of manufacturing options due to the use of the die that allows to change the shape of the pressed product in cross-section into the shape given by the die opening. As a result, it is possible to produce bars of round, square and other sections.

2. The paper is focused on two variants of manufacturing magnesium bars with a diameter of $d = 4.1$ mm and a number of die channels $n = 3$ using the method of multichannel angular pressing. The first variant involves the die with its channel axes positioned along the axis of the rectangular groove, and the second variant involves the die with its channel axes positioned along the radius of the container. Computer simulation of these variants of the process is carried out with the *DEFORM-3D* software package.

3. The mean stress evaluation in the three-dimensional representation made it possible to establish that in both process variants, the cylindrical blank during deformation is under compressive stresses at the

sufficiently high level (–1,600 MPa). Thus, an all-round compression behavior is ensured here, and the presence of high (modulo) values of the mean stress allows to expect an increase in the level of ductility, which should prevent metal fracture.

4. In the first variant, the highest strain degree of the outer bars is observed at its peripheral part on the side bordering the center bar. In this case, the difference in the strain degree over the diameter of the peripheral bars reaches 28 %, while in the central bar it does not exceed 10 %.

5. In the second variant of the channel axes arrangement, the difference in the strain degree over the diameter of all bars is less than 10 %.

6. In both variants of the process, the maximum strain degree can reach a value of 2.6 at the initial stage and 5.0 at the steady stage, with the maximum strain degree achieved at a considerable distance from the front ends of the bars in both variants. Thus, the front ends of the bars may be not sufficiently structured.

7. It is established that when the die is used with the first variant of the channel axes arrangement, the strain level along the bar length is less than when the die channel axes are arranged according to the second variant. The difference reaches 20 % on average.

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Conflicts of Interest

The authors declare no conflict of interest.