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SIMULATION OF THE FORGING PROCESS WITH AN ADDITIONAL MACRO-SHIFT IN "DEFORM" SOFTWARE PACKAGE

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ABSTRACT

The paper presents the results of computer simulation of the process of forging round blanks in the strikers of the new design. It is shown that the use of a radial joint of the faces has a favorable effect on the stress distribution along the entire length of the metal-tool contact. The analysis of models with different angles of inclination of flat faces showed that the best option is to use strikers with an angle of 30°, since in this case a fairly extensive distribution of strain over the cross section occurs in the workpiece with a significantly lower deformation force than when using strikers with an angle of 0°. The analysis of the technological parameters influence on the microstructure evolution showed that the most optimal workpiece heating temperature is 1000°C, while all 3 variants of the punch speed can be recommended for the implementation of this process in practice.

Keywords: forging, broaching, shear deformation, computer modeling, stress-strain state, force, microstructure evolution.

INTRODUCTION

The production intensification, implementation of technical reconstruction based on the introduction of advanced technological processes, improving the quality and increasing new types of metal products is still an urgent task for the metallurgical, mechanical engineering and other industries. At the same time, despite the rapid development of metallurgical processes for the production of semi-finished products aimed at improving the smelting, casting and crystallization modes, a significant improvement in the properties of any cast metal, ensuring its wide application in modern mechanical engineering, is achieved by hot metal forming. The main arguments for the use of hot metal forming, namely forging, are next: providing the necessary shape and dimensions as close as possible to the configuration and dimensions of the part with the least labor costs; elimination of defects in the cast structure; improvement of the quality by converting the cast structure into a deformed one; distribution of the properties in the volume of forging and workpiece according to the law that satisfies the operation of this part at the manufacturing stage by plastic deformation.

In traditional metal forming operations, to improve the quality of the metal by grinding the structure to a fine-grained state, it is necessary to significantly change the size of the workpiece, which leads to significant energy and labor costs. The technical solution of these problems is based on the implementation of shear and alternating deformations [1]. Therefore, in order to process the cast structure to obtain a high-quality metal with a homogeneous or directionally textured fine-grained structure in the entire volume of the workpiece, it is necessary to build the technological process of deformation that sufficient shear and alternating deformations occur in the entire deforming volume [2].

Previously, this was most often achieved by increasing the total compression of the ingot or the initial billet. Now, to solve this problem, a number of new forging processes and tools for their implementation have been developed [3 - 11], which allow implementing additional shear or alternating deformations in addition to the usual compression during the deformation process.

In the work [12], the technology of broaching blanks was developed, which allows to implement intensive shear deformation of the workpiece over the entire volume of metal, and a forging tool for its implementation was proposed – lock strikers (Fig. 1(a)). This technology showed very good results, which consisted in improving the quality of the metal of forgings by obtaining a more uniform and fine-grained structure and better welding of internal defects when forging in this tool compared to forging using the current technology in flat strikers. At the same time, this effect is achieved with a smaller forge coefficient, which allows reducing energy consumption for the production of high-quality forgings [13]. But at the same time, this technology has its own small drawbacks, and one of them is that this technology is mainly applicable for forging of only rectangular cross-section billets and due to the angles available in this design, small concentrators of additional tensile stresses still appeared.

Therefore, this tool was improved so that it is possible to use it for forging round billets, and to avoid the occurrence of even small concentrators of tensile stresses. At the same time, the design of this tool (Fig. 1(b)) will allow for more significant alternating deformations throughout the entire volume of the deformed workpiece.

a) b)
Fig. 1. Tools for broaching: a - with an angular joint; b - with a radial joint

The implementation of the deformation process in the tool is carried out in 2 stages (Fig. 2). Between the first and second stages, the workpiece is subjected to 90-degree edging. In this case, the workpiece is subjected to two types of deformation at the first and second stages:

1) upsetting, which is caused by the movement of one striker towards another;

2) simple shift that occurs in the transverse direction of the workpiece when it is deformed by the inclined working surfaces of the strikers.

It is known from the work [14] that the quality of workpieces is significantly affected by the stress-strain state (SSS) that occurs in the metal during its deformation. At the same time, during the metal deformation, the resulting SSS is influenced by a number of factors that can be conditionally divided into three groups: the geometric factor (most often the shape of the tool), the kinematic factor and the temperature factor.

The aim of this work is to study the influence of geometric factors (the construction shape of a new forging tool, as well as the inclination angle of the striker faces shown in Fig. 1(b)) on the stress-strain state of the metal. In addition, the influence of kinematic and temperature factors on the deformation force and the microstructure evolution was studied.

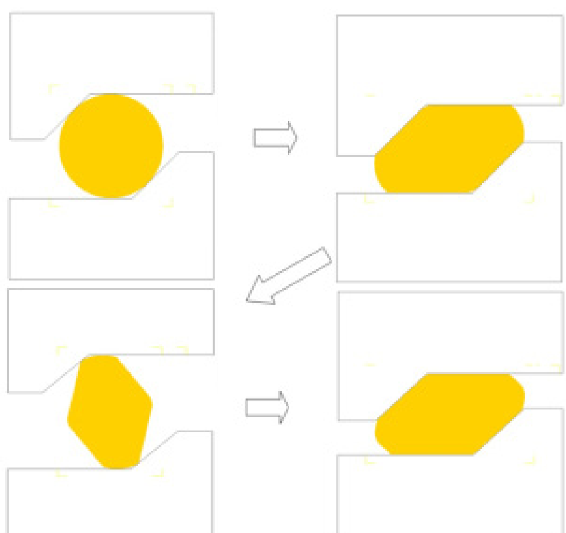


Fig. 2. Scheme of forging (broaching) of blanks in strikers of a new design.

EXPERIMENTAL

Computer simulation

Computer simulation of the forging process with an additional macro-shift was carried out using the Deform software package. $7CrMn_2WMo$ steel was chosen as the billet material. The initial billet had a diameter of 45 mm. The deformation was carried out at a temperature of 1000°C. A non-isothermal calculation type was set for the simulation. The vertical speed of the upper striker was 1 mm/sec. When the workpiece came into contact with the strikers, the value of the friction coefficient was set to 0.25. An absolute tetrahedral grid was built on the blank, condensed on the surface for better rendering of the round shape. The minimum size of the element was set to 0.3 mm, the maximum size of the element was set to 0.6 mm, the parameters for the grid remesing were set by default.

For process investigation the following parameters were chosen, which reveal the stress and strain states in the most detail: equivalent strain, average hydrostatic pressure, damage criterion.

Equivalent strain is a characteristic of the strain state, which allows us to assess the level of metal processing [15]. Its value is determined by the formula:

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

where ε_1, ε_2, ε_3 - main strains.

Average hydrostatic pressure is a characteristic of the stress state, which allows estimating the stress level taking into account the sign, i.e. the magnitude of the tensile and compressive stresses [15]. The value of this parameter is determined by the formula:

$$\sigma_{AV} = \frac{\sigma_1+\sigma_2+\sigma_3}{3}, \quad (2)$$

where σ_1, σ_2, σ_3 - main stresses.

Damage criterion is a value that determines the consumption of the plasticity resource. This characteristic is important from the point of view of the possible formation of various defects.

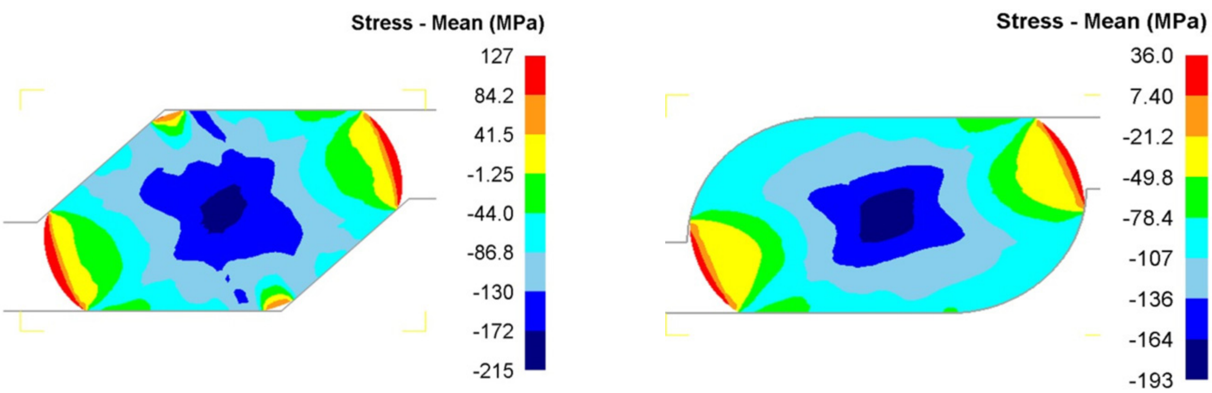
To calculate the damage to the metal, the Cockcroft-Latham criterion equation is used by default [15]:

$$D = \int_0^{\varepsilon_{EQV}} \frac{\sigma_1}{\sigma_{EQV}} d\varepsilon \quad (3)$$

where: σ_1 - main (tensile) stress; ε_{EQV} - equivalent strain; σ_{EQV} - equivalent stress.

During the computer simulation, the influence of the faces angle of the strikers, as well as kinematic and temperature factors on the resulting deformation force and the microstructure change was studied. The value of 60 microns was taken as the initial grain size. When analyzing each model, the study of the selected parameters was carried out after the completion of the second stage of deformation (Fig. 2).

At the first stage of simulation, the stress state was compared when using the striker constructions shown in Fig. 1, during which the influence of the joint shape of the internal faces was studied. It was found that when using strikers with an angular joint (Fig. 3(a)), a region of tensile stresses of up to 80 MPa occurs in this zone. This effect is negative from the point of view of further deformation with the edging of the workpiece. The highest values of tensile stresses occur in the lateral zones, where there is no contact with the strikers and barrel formation occurs. When the workpiece is edged at 90°, these areas become in contact with the strikers and then large compressive stresses are created here, which annihilate the negative effect of the stretching



a) b)

Fig. 3. Average hydrostatic pressure in strikers with different types of joints: a - with an angular joint; b - with a radial joint.

action. But the considered metal zones from the area of angular joints after edging become contactless. As a result, tensile stresses also occur here during the subsequent deformation cycles. Therefore, these areas are potentially dangerous from the point of view of the occurrence of surface cracks.

The proposed design of the strikers (Fig. 3(b)) creates a more uniform stress state over the entire length of the contact surface due to the radial joint of the faces. It is clearly seen that no areas of tensile stresses arise in this case, and the general level of the stress state is characterized by the action of only compressive stresses in the range of -90 to -100 MPa.

At the same time, it is necessary to note another important distinguishing feature of these two constructions. In both cases, symmetrically arranged non-contact zones are formed at the deformable workpiece, where tensile stresses prevail. However, due to the change of the angular joint of the faces to a radial, the level of tensile stresses is significantly reduced from 120 to 35 MPa. This is a consequence of the change in the nature of the metal flow in these lateral areas. In both cases, the inclined faces of the strikers create a certain level of backpressure, which increases with an increase in the amount of compression. But if in strikers with an angular joint the increase in backpressure is linear, then in strikers with a radial joint it has a continuous increase until the metal touches the area of the striker that characterizes the horizontal position of the radius of rounding – here the amount of backpressure is the maximum possible. Based on this comparative analysis, it was concluded that it is advisable to use strikers with a radial joint of the faces.

Further, the influence of the inclination angle of a flat face on the stress-strain state was studied. For this purpose, models with an inclination angle of 15, 30 and 45 degrees were built. When considering the above parameters, in order to identify the most rational design of the strikers, it is necessary to introduce criteria for optimal values. The following criteria were adopted:

- equivalent strain – “more is better”;
- average hydrostatic pressure - “more is better” for the compressive stresses level;
- damage criterion - “less is better”;
- deformation force - “less is better”;
- grain size - “less is better”.

The analysis of the equivalent strain (Fig. 4) showed that in all cases the highest level of strain occurs in the central part of the workpiece ($\varepsilon \approx 4,5$), and the nature of the strain distribution has the form of a forging cross. At the same time, it is noted that the most intense level of strain develops in strikers with an angle of inclination of a flat face of 0°, covering most of the cross-section of the workpiece. This is a consequence of the action of normal stresses perpendicular to the movement of the punch over a sufficiently large length of metal contact with the strikers. As the angle increases, the level of normal stresses decreases, which, theoretically, should lead to a decrease in the deformation force. At an angle of 15°, the zones of strain development are the narrowest, an angle of 30° gives a picture of the strain distribution similar to strikers with an angle of 0°. An increase in the angle to 45° leads to a concentration of strain mainly in the central zone of the workpiece, significantly reducing it in the surface areas.

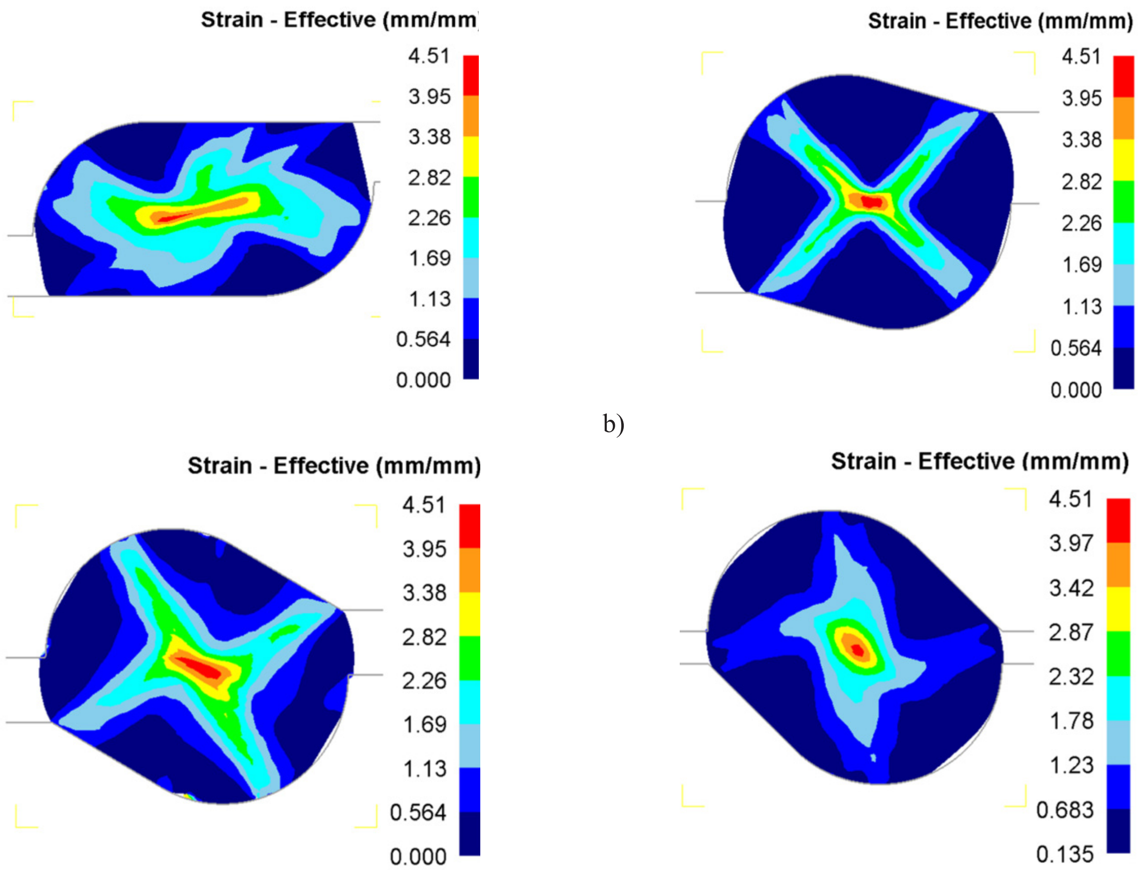
Based on the accepted optimality criterion of the equivalent strain “more is better”, the following sequence was identified in ascending order: 45° → 15° → 30° → 0°.

The analysis of the average hydrostatic pressure (Fig. 5) showed that a sufficiently favorable stress state is created in all designs of the strikers, since in all cases the level of compressive stresses significantly exceeds the level of tensile ones. The nature of the stress distribution is similar in all models – compressive stresses act along the entire perimeter of the workpiece, except for areas free from contact with the tool - tensile stresses prevail here due to the free flow of metal.

At the same time, it is noted that the most intense level of compressive stresses develops in strikers with an inclination angle of a flat face of 0°, since here the level of normal stresses acting perpendicular to the contact plane is the maximum. With an increase in the value of the angle of inclination of the flat faces, the level of normal stresses decreases, as a result, the value of compressive stresses decreases from -784 to -479 MPa.

Based on the accepted optimality criterion of the average hydrostatic pressure “more is better” for the level of compressive stresses, the following sequence was identified in ascending order: 45° → 30° → 15° → 0°.

The analysis of the damage criterion (Fig. 6) showed that the distribution of this parameter over the section of the workpiece has a similar character



a) b) c) d)

Fig. 4. Equivalent strain in strikers with different inclination angles of a flat face: a - 0°; b - 15°; c - 30°; d - 45°.

to the distribution of the equivalent strain, which is a consequence of the integral dependence of the fracture on the strain, as well as the value of the equivalent strain as the upper limit. However, the value of the fracture criterion depends not only on the value of the equivalent strain, but also on the value of the average hydrostatic pressure.

In strikers with an angle of inclination of a flat face of 0°, a damage level of 0.585 occurs. Given that this version of the strikers with horizontal faces can be considered a classic version, this damage value was taken as the basic one. In accordance with this, in other models, this damage value was set on a dimensional scale for the convenience of comparative analysis. Based on the accepted optimality criterion "less is better" for the damage criterion, the following sequence was identified in descending order: 0° → 45° → 30° → 15°.

The analysis of the microstructure evolution (Fig. 7) showed that in all cases, the nature of the grain grinding area has a shape similar to the distribution of equivalent strain and damage criterion, i.e. the shape of a forging cross. In all variants, the grain grinding area covers most of the cross-section of the workpiece. At the same time, the initial grain is crushed most intensively in strikers with an inclination angle of a flat face of 0°. Based on the accepted optimality criterion "smaller-better" for the grain size, the following sequence was identified in descending order: 15° → 45° → 30° → 0°.

The obtained graphs of the deformation forces (Fig. 8) confirm the previously stated hypothesis - the greatest values of the force occur when deforming in strikers with an angle of 0°, with an increase in the inclination angle of the flat faces, the force decreases from 710 kN to 202 kN. Based on the accepted optimality criterion "less is better" for the deformation force, the following sequence was identified in descending order: 0° → 15° → 45° → 30°.

For a more visual comparative analysis, the extreme values of all determined parameters were summarized in Table 1. Also, the optimality indicators presented in conditional points were summarized in this table.

Thus, the most optimal option would be to use strikers with an angle of 30°, since in this case there is

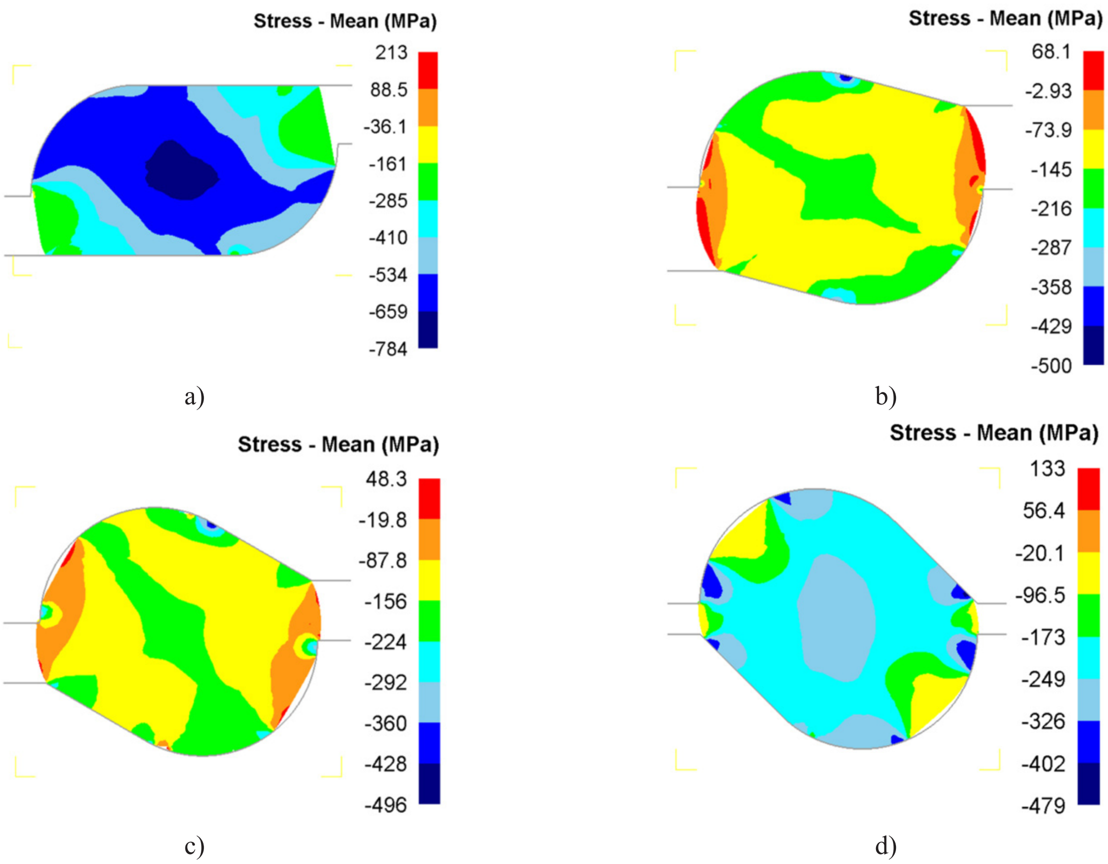


Fig. 5. Average hydrostatic pressure in strikers with different inclination angles of a flat face: a - 0°; b - 15°; c - 30°; d - 45°

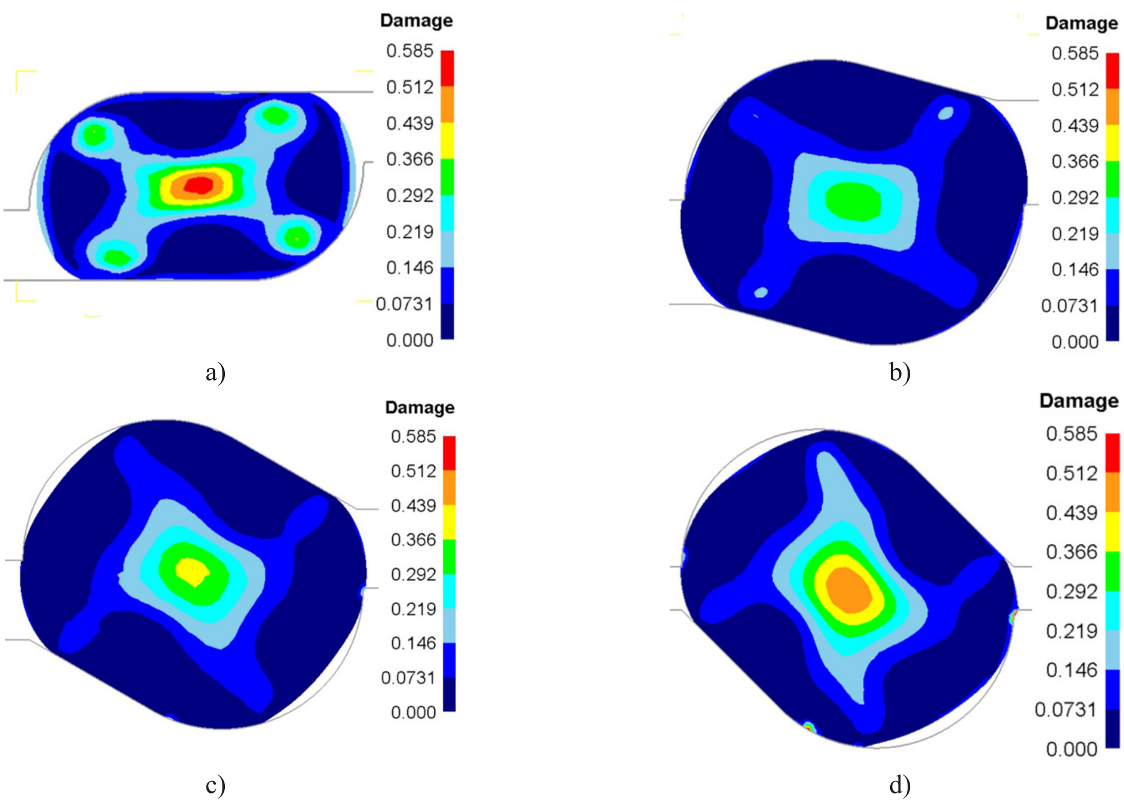


Fig. 6. Damage criterion in strikers with different inclination angles of a flat face: a - 0°; b - 15°; c - 30°; d - 45°

Table 1. Extreme values of the determined parameters and optimality scores.

	0°	15°	30°	45°
Equivalent strain	4,51	4,16	4,37	4,02
Compressive stresses	-784 MPa	-500 MPa	-496 MPa	-479 MPa
Damage criterion	0,585	0,354	0,372	0,486
Grain size	11 µm	28 µm	13 µm	20 µm
Force	710 kN	402 kN	202 kN	285 kN
Optimality level				
Equivalent strain	++++	++	+++	+
Compressive stresses	++++	+++	++	+
Damage criterion	+	++++	+++	++
Grain size	++++	+	+++	++
Force	+	++	++++	+++
Total scores	14	12	15	9

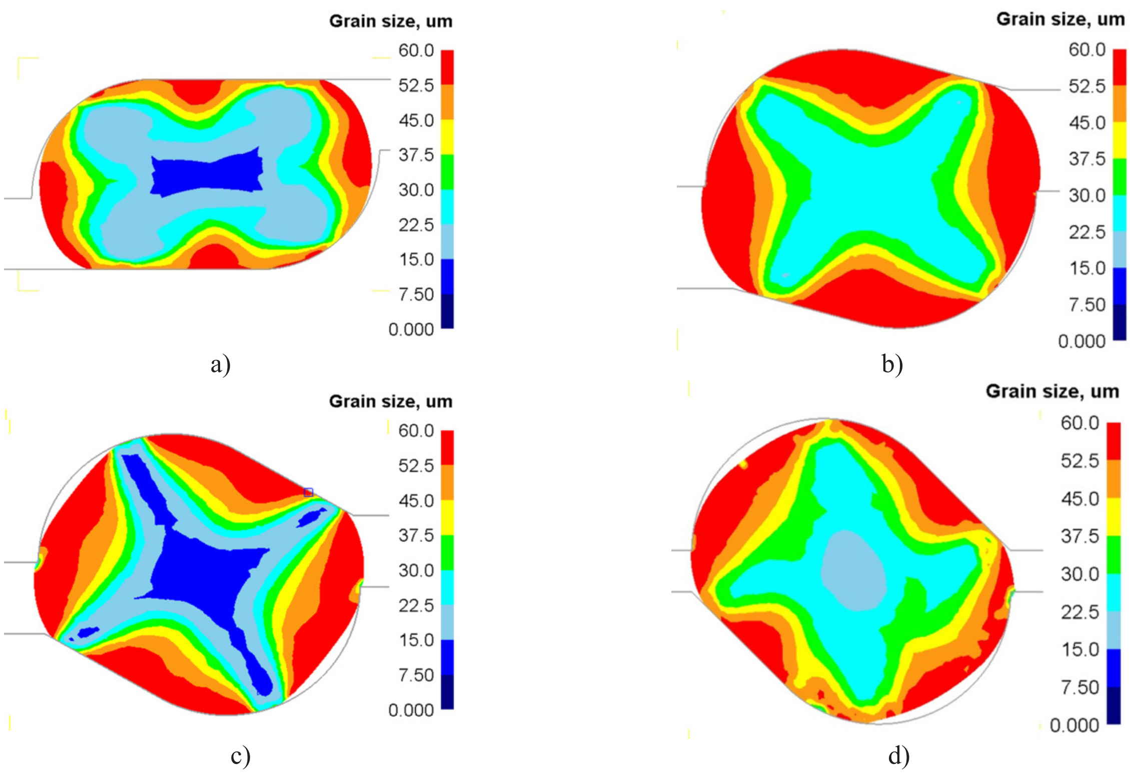


Fig. 7. Grain size change in strikers with different inclination angles of a flat face: a - 0°; b - 15°; c - 30°; d - 45°.

a fairly extensive distribution of strain across the cross-section in the workpiece (the second in terms of cross-section coverage after strikers with an angle of 0°) with a significantly lower deformation force and damage level. The result is the second most intense level of grain grinding.

For further analysis of the influence of the technological parameters in the new strikers on the microstructure evolution, it was decided to use strikers with an inclination angle of flat faces of 30°. The temperature of metal heating and the speed of the punch movement were chosen as variable parameters, since

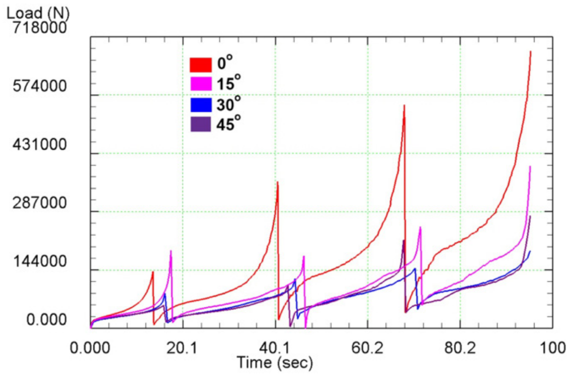


Fig. 8. Deformation force.

the values of these parameters are easy to change in real conditions. The resulting model is shown in Fig. 6(b) at a temperature of 1000°C and the upper striker speed of 1 mm/s was taken as the base model. As a result, to study the influence of the technological parameters in new strikers on the microstructure evolution, the following models were additionally constructed:

- with heating temperatures of the workpiece up to 1200°C and up to 800°C;

- with upper striker speeds of 0.1 mm/s and 10 mm/s.

Fig. 9 shows the results of calculating the change in grain size for various technological parameters. When considering models with different values of the heating temperature, it was found that this parameter has a very significant effect on the grinding intensity of the structure. When the heating temperature increases to 1200°C, the grain grinding intensity decreases significantly, which is the result of an increase of static and dynamic recrystallization. When the heating temperature decreases to 800°C, on the contrary, the intensity of structure grinding increases significantly. This is due to the fact that for steel 5HV2S, the temperature of the beginning of recrystallization is 775 °C (point AC1). Heated to 800°C, the workpiece gradually cools down, bypassing the AC1 point, as a result, the recrystallization processes are completely suppressed.

When considering models with different values of the upper striker speed, it was found that this parameter affects the intensity of structure grinding, although not as significant as the heating temperature. When the upper striker speed increases to 10 mm s^{-1}, the intensity of grain grinding decreases, and when the upper striker speed decreases to 0.1 mm s^{-1}, the intensity of structure grinding increases. This phenomenon is also associated with recrystallization processes. The recrystallization intensity depends on the workpiece temperature, the intensity of change of which depends on the strain rate.

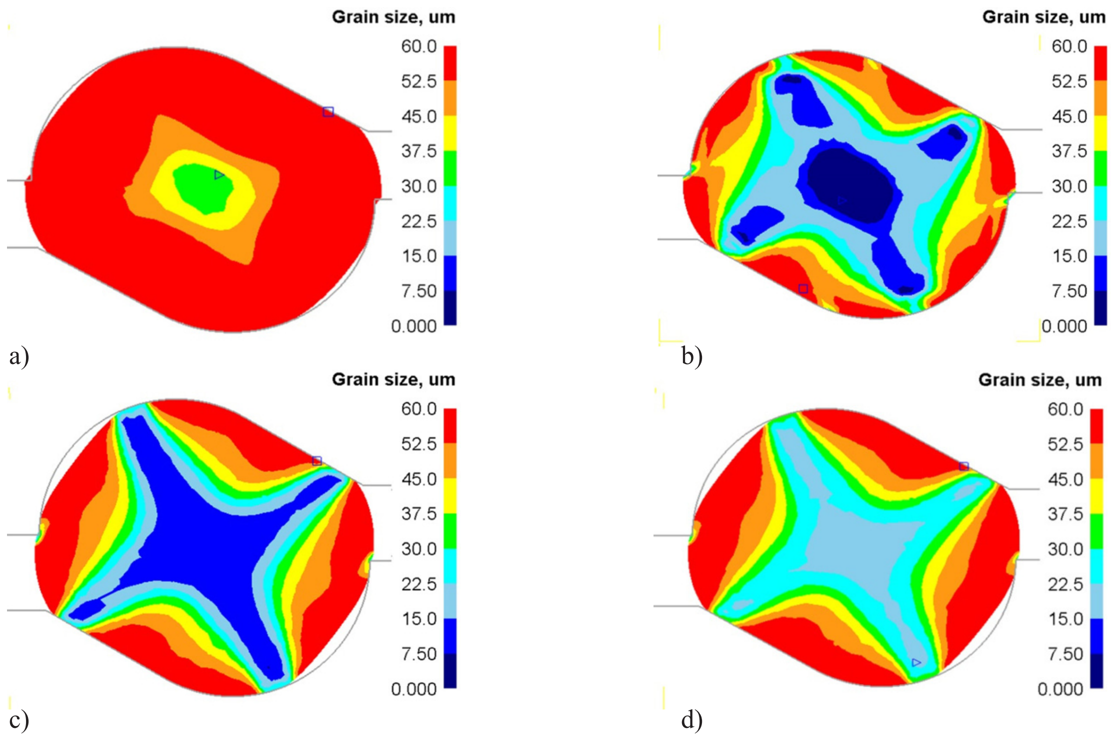


Fig. 9. Grain size change in models with different technological parameters: a - at 1200°C; b - at 800°C; c - at 0,1 mm s^{-1}; d - at 10 mm s^{-1}.

Table 2. Grain size and deformation force in models with different technological parameters.

	Base model	At 1200 °C	At 800 °C	At 0,1 mm/s	At 10 mm/s
Grain size	13 μm	36 μm	6 μm	10 μm	19 μm
Force	202 kN	164 kN	495 kN	278 kN	185 kN

At a reduced upper striker speed, the total duration of the deformation process increases. As a result, the workpiece has time to cool down more, which affects the level of grain grinding. At an increased strain rate, the intensity of cooling of the workpiece decreases, which leads to a decrease in the level of grain grinding.

Based on the data obtained, the most optimal conditions from the point of view of the final grain size are the heating temperature 800°C and the upper striker speed 0.1 mm s^{-1}. However, in order to approve these parameters, it is necessary to evaluate the resulting deformation forces in the models under consideration, since this parameter is critical at the stage of implementation of the developed technology. Summary data on grain size and deformation force are presented in Table 2.

It can be seen that despite the minimum grain size obtained, the option of lowering the heating temperature of the workpiece to 800°C is not optimal, since in this case, due to cooling and lowering the plasticity of the metal, the force level increases almost 2.5 times compared to the basic level. At the same time, all three options for the upper striker speed can be recommended for the implementation of this process in practice. The key factor in choosing the speed here will be the rated power of the pressing equipment. With a sufficient margin of safety, it is desirable to conduct the deformation process at reduced deformation rates, which will lead to additional grinding of the initial grain.

CONCLUSIONS

The paper presents the results of computer simulation of the forging process of round-section blanks in the strikers of a new design. It is shown that the use of a radial joint of the faces has a favorable effect on the stress distribution along the entire length of the metal contact with the tool. The analysis of models with different inclination angles of flat faces showed that the most optimal option is to use strikers with an angle of 30°. In this case, a fairly extensive strain distribution across the cross-section occurs in the workpiece, a high level of compressive stresses with a significantly lower deformation force and damage level than when using strikers with an angle of 0°. The analysis of the influence of technological parameters on the microstructure evolution showed that both considered parameters (upper striker speed and heating temperature) affect the structure grinding intensity, while the influence of the heating temperature is more significant. The most optimal heating temperature of the workpiece in terms of grain size and the resulting force is the base value of 1000°C, while all three options for the speed of movement of the punch can be recommended for the implementation of this process in practice.

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