STUDY OF THE EFFECT OF EQUAL-CHANNEL ANGULAR PRESSING ON THE CLOSURE OF CASTING DEFECTS IN ZIRCONIUM ALLOYS

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ABSTRACT

In this study, the effectiveness of the Equal Channel Angular Pressing (ECAP) method for closure of casting defects in the zirconium alloy Zr - 1 % Nb, widely used in nuclear power engineering, was studied. A FEM simulation of ECAP processing of a workpiece with an artificially created through defect with a diameter of 5 mm in matrices from different angles of the junction of the die channels was carried out (45°, 90°, 135°). The simulation was verified on a 135° die. The results showed that after two passes, the defect was practically eliminated, the remaining residual crack had a width of only 10 - 25 mm, which indicates the high efficiency of the method. Microstructural analysis revealed a significant grinding of grains to sizes 1 - 8 mm and an increase in the hardness of the material from 145 HV to 171.5 HV. The data obtained confirm the potential of the ECAP method for improving the microstructure and mechanical properties of zirconium alloy ingots.

Keywords: zirconium alloy, equal channel angular pressing (ECAP), defect closure, final element method (FEM).

INTRODUCTION

Modern nuclear power engineering places high demands on the quality and safety of operation of nuclear reactor parts, especially fuel assemblies made of zirconium alloys [1, 2]. Fuel element plugs are one of the most critical elements of the core, which requires the use of exclusively defect-free parts of the ingot [3]. However, existing technologies for processing zirconium ingots do not allow efficient use of the entire volume of material, leaving a significant substandard part [4]. This leads to a decrease in the ingot utilization rate and an increase in the cost of production [5].

Plastic deformation of ingots is an important processing step aimed at eliminating casting defects such as pores and microcracks, as well as improving the mechanical properties of the material [6]. Traditional methods of plastic deformation used in industry include rolling [7] and forging [8]. Rolling is widely used due to high productivity and the possibility of large-scale processing of large workpieces. However, its main drawback is the uneven distribution of deformation over the section of the ingot [9, 10]. The greatest degree of plastic deformation is concentrated in the surface layers, whereas the central zone experiences significantly lower stresses, which reduces the efficiency of closing internal pores and defects [6].

Forging allows you to achieve a higher degree of deformation and better cover internal defects compared to rolling, but it also has its limitations. It can lead to uneven effects on the material and cause new defects, such as cracks, with insufficient process control [11, 12]. The high temperatures at which hot rolling and forging are carried out contribute to grain growth and a decrease in the density of the dislocation structure, which negatively affects the strength characteristics of the finished product [13].

Thus, for tasks requiring uniform processing of the material throughout the entire volume - such as the production of highly responsible parts for nuclear reactors - rolling and forging have limited capabilities to eliminate casting defects. This necessitates the use of more effective methods of plastic deformation, such as Severe plastic deformation (SPD) [14 - 16].

The possibility of obtaining ultrafine-grained structures by means of SPD (ECAP method) is shown by Segal [17, 18]. Further research in this area was continued by Valiev and his colleagues [14, 19], who demonstrated the effectiveness of SPD to improve the mechanical properties of various materials, including zirconium alloys. SPD allows to significantly grind the grain structure of the material, which leads to an increase in strength, hardness and wear resistance without significantly reducing plasticity [20, 21].

Intensive plastic deformation is mainly used to create an ultra-fine-grained structure of the material, rather than for processing ingots. However, SPD can also be effective for cast materials, since high shear deformations contribute to the closure of casting pores [22]. The multiple shear deformations characteristic of this method minimizes thermal effects such as grain growth, improving the mechanical properties of the material and preventing the appearance of new defects.

One of the most promising SPD methods is ECAP [18]. This method has been widely recognized due to its ability to significantly improve the microstructure of materials due to significant plastic deformations without changing the initial geometric dimensions of the workpiece. In the ECAP process, the workpiece is repeatedly passed through a mold with an angular channel, which provides intensive shear deformation [15]. This makes it possible to achieve a high degree of deformation without changing the shape and size of the product, which is an important advantage when processing expensive materials such as zirconium alloys [20]. Unlike traditional methods, ECAP ensures uniform distribution of deformation over the entire volume of the workpiece, which theoretically can help close defects in the central zones.

However, the ability of ECAP to effectively eliminate casting pores and microcracks still remains an insufficiently studied area, because researchers mainly concentrate on refining ordinary structures into a nanoscale state [23]. There is insufficient data in the literature on the process of closure of casting defects when using ECAP, especially in relation to zirconium alloys. Understanding these processes is critical for expanding the application of ECAP in industry and improving the efficiency of materials use.

In this paper, we aim to investigate the possibility of closing casting defects such as pores and microcracks when using ECAP on zirconium alloys. To do this, we use finite element computer modelling techniques to analyse the metal flow during ECAP. This will allow us to determine the optimal process parameters that contribute to the effective closure of defects.

Conducting this research will not only deepen the fundamental understanding of the processes of deformation and closure of defects in metals, but also contribute to the development of technologies for the manufacture of critical parts for nuclear energy. This is of great practical importance, given the high requirements for safety and reliability in this area [5].

EXPERIMENTAL

The main objective of the study was to study the conditions for closing a defect with a diameter of 5 mm in a zirconium alloy using the ECAP method. To achieve this goal, two methods were used: computer simulation of the ECAP process using Deform 3D software and a real experiment with real samples. Computer modelling made it possible to analyse the metal flow and material behaviour and predict the effectiveness of defect closure under various process parameters. A real experiment involving two passes through the die and subsequent microstructural analysis using scanning electron microscopy (SEM) provided empirical data on defect behaviour and changes in the grain structure of the material.

Blanks made of zirconium alloy grade Zr - 1 % Nb(E110), widely used in nuclear power due to its high corrosion properties and low neutron capture cross section, were used for the study. The blanks had a rectangular cross-section measuring 30 × 20 mm and a length of 50 mm. A 5 mm through hole was created on the side surface of each workpiece, simulating a large casting defect. The location of the defect perpendicular to the longitudinal axis of the workpiece complicated the conditions for its closure during deformation, which made it possible to evaluate the effectiveness of the

ECAP method for eliminating such defects. Size of defect was chosen based on previous work with forging [24] and radial shear rolling [25].

First, the Finite Elements Simulations of the ECAP process of the workpiece described above using the Deform 3D software was carried out. Numerical experiments were carried out to simulate the pressing of blanks in dies with channel junction angles of 45°, 90° and 135°. The geometry of the dies corresponded to experimental conditions: rectangular channels with a size of 30 × 24 mm. The simulation made it possible to analyse the metal flow, the temperature distribution and the efficiency of closing defects under various process parameters. The simulation was carried out in several passes before the defect was closed.

The DEFORM 3D program was used to simulate the ECAP process in matrices with different channel junction angles using the finite element method. The channel geometry of the three matrices was identical and corresponded to the cross section of the workpiece 24 x 30 mm. The key difference was in the different values of the channel junction angle. Angles of 90, 135 and 45 degrees were used for modelling. The through defect in the workpiece was represented as a cylindrical hole with a diameter of 5 mm, made symmetrically in the center of the workpiece with a length of 50 mm (Fig.1).

Zirconium alloy with 1 % niobium was chosen as the material of the workpiece. Since this alloy is not present in the internal database of DEFORM materials, the rheological properties of the workpiece material were taken from the work [27]. The finished model of the Zr - 1 % Nb alloy for DEFORM is available in [26]. The initial temperature of the workpieces was set to 530°C [27], as this temperature is optimal for enhancing the deformation behaviour of the zirconium alloy during the ECAP process. At this temperature, the material exhibits improved plasticity and reduced flow stress, facilitating more efficient grain refinement. Additionally, the die temperature was maintained at 200°C to further improve formability, as suggested in the article [28].

The following technological parameters were used in computer modelling: the material of the workpiece was assumed to be isotropic and elastically plastic; the material of the matrices and the punch was assumed to be rigid; the type of finite elements was a tetrahedron; the number of FE - 18150 nodes, the number of FE - 83766; the coefficient of condensation of FE in the defect zone is 5 (i.e., the volume of elements in the defect zone was 5 times less than in the rest of the workpiece); deformation was carried out at an ambient temperature of 20°C; the

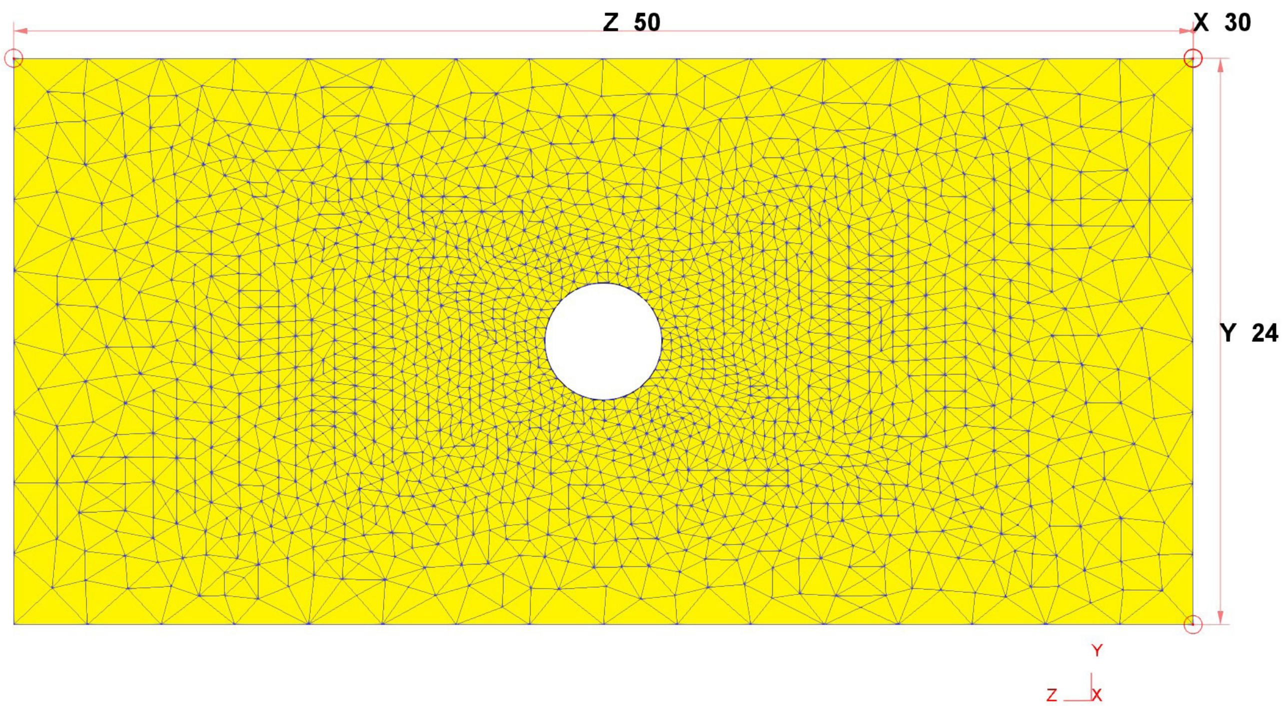

Fig. 1. A model of a workpiece with a through defect.

heating temperature of the workpiece before pressing was 530°C; the calculation type was non-isothermal; the heat exchange coefficient of the workpiece with the tool was W m^{-2} $°C^{-1}$; the heat exchange coefficient of the workpiece with the environment was 20 W m^{-2} $°C^{-1}$; when calculating the contact interaction of the workpiece and the rolls, the Siebel friction was set, the friction coefficient at the contact of the workpiece with the matrices was assumed to be 0.12 (which corresponds to a polished surface with a low level of roughness and with the use of lubricant); the movement speed of the punch was 10 mm s^{-1}.

The calculation was carried out by a direct iterative method using a sparse die solver for a higher level of convergence at each step. The calculation used a time interval to maintain high accuracy - 1 step was equal to 0.1 s.

For experimental verification, the model with the highest channel junction angle - 135° was chosen as the most difficult from the point of view of defect closure. The die for the experiment was made of tool steel and had a rectangular channel with a size of 30 × 24 mm. The channel surfaces were polished and lubricated with high-temperature graphite grease to reduce the coefficient of friction and prevent jamming.

Before the experiment, the workpieces were heated in an electric Nabertherm LH-30/14 furnace to a temperature of 530°C for one hour to ensure uniform temperature distribution over the volume. The die was preheated to a temperature of about 200°C using a gasoline burner. Heating of the die made it possible to reduce the temperature gradient between the workpiece and the tool, reducing thermal stresses, tightening of the workpiece and the likelihood of cracking during deformation. The temperature of the die was controlled using the FLIR-T540 thermal imaging camera, which provided accurate control and visualization of the temperature field.

To move the workpieces through the die channel, pushers made of aluminium alloy with a size of 30 × 24 × 50 mm were used. Pressing was carried out on a hydraulic press with a maximum force of 1500 kN. The deformation rate was maintained within 5-10 mm s^{-1} to ensure quasi - static conditions and prevent rapid cooling of the workpiece. The experiment included two consecutive passes of the workpiece through the die channel. After the first pass, the workpiece was rotated 180° around the longitudinal axis. This rotation changed the orientation of the previously deformed areas relative to the direction of deformation during the second pass, contributing to a more uniform distribution of accumulated deformation over the volume of the workpiece. Then the workpiece was pressed through the die again using a new aluminium pusher.

The temperature of the die and the workpiece was constantly monitored using a thermal imager to ensure stable deformation conditions. During pressing, visual control of the process was carried out, paying attention to possible deviations or defects.

After completing two passes, the workpieces were cooled to room temperature in air. Metallographic analysis was performed to assess the condition of the defect and study the microstructure of the material. The samples were subjected to mechanical grinding up to the P2500 grain size and subsequent electrochemical polishing on the Stuers Lectropol 5 apparatus. For a detailed study of the structure and assessment of the presence of residual defects, scanning electron microscopy (SEM) was used on a Zeiss Crossbeam 540 microscope, using back-reflected electron diffraction (EBSD) using a NordlysNano Oxford Instruments detector. The EBSD method allowed to obtain information about the crystallographic orientation of grains, grain size and the presence of texture in the material after deformation. The EBSD analysis was performed for an area of 37.5 x 28.1 μm (magnification x3000), with a step size of 36 nm at an accelerating voltage of 30 kV. The resolution of the received EBSD cards is 1024x768 pixels.

Finite elements simulation

To analyse the process of closing a through defect, it is most rational to consider the picture of metal flow rates in the central zone of the workpiece. When moving in a vertical channel, the vector velocity pattern looks like this (Fig. 4) - the entire workpiece moves evenly through the die channel at a speed of 10 mm s^{-1} due to pushing with a punch.

1) A model with a 45° channel junction angle

In a model with a 45° channel junction angle, the change in metal flow begins when the rounded joint is filled (Fig. 3a). At this point, a local braking zone appears on the rounding, resulting in a sharp decrease in speed. At the same time, the remaining volume of the workpiece receives a slight lateral displacement

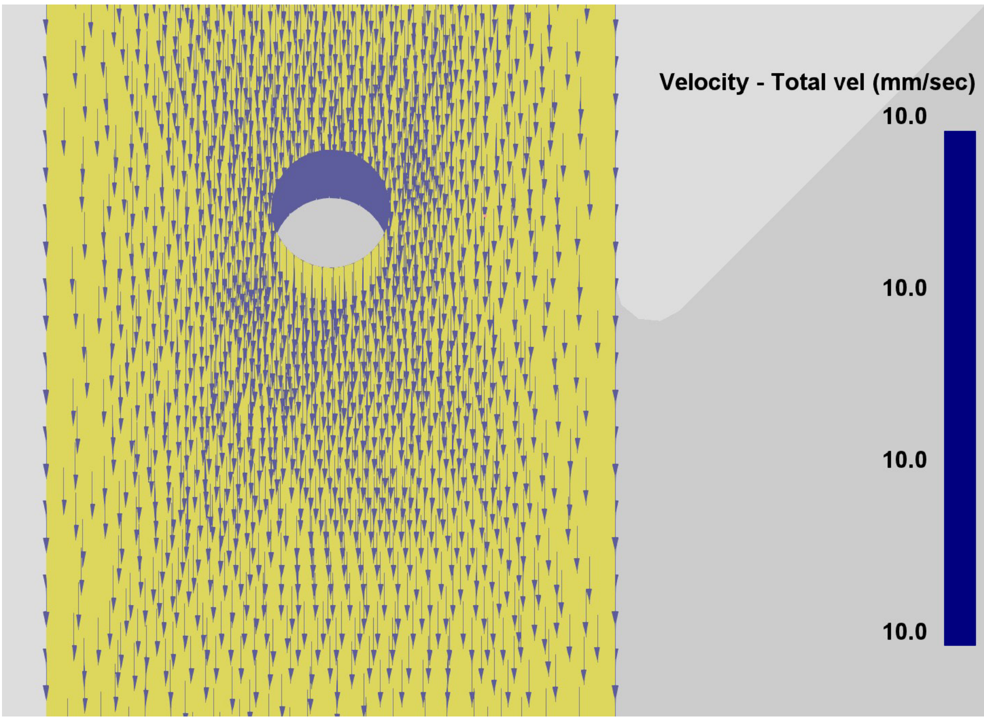

Fig. 2. Vector picture of velocities when moving in a vertical channel.

towards the free cavity of the channel. After the rounding zone is filled, the workpiece is pressed and the metal flows in a direction parallel to the inclined face of the channel (Fig. 3b). At this point, the entire volume of the workpiece is divided into 4 zones: in the first zone, located in the vertical channel, the initial velocity of 10 mm s^{-1} is maintained. The central second zone is separated from the first by a line connecting the upper corner of the junction of the channels with the local braking zone (zone 3), here the velocity value not only decreases, but there is also a strong turbulence of the flow vectors towards the free cavity. As a result, the through hole begins to flatten due to the difference in velocity in height, taking the shape of an ellipse with a height of about 4 mm. There is a free zone 4 at the lower end of the workpiece, the flow velocity in which is almost identical to the velocity in zone 1.

When the workpiece reaches the third face of the channel (Fig. 3c), a new local braking zone appears. As a result, the flow of metal in the channel intersection zone slows down significantly. The continued movement of the punch leads to the intensification of compression of the defect in the central zone, the height of which decreases to 1.5 mm, and then, as the metal fills the second inclined face, to 0.5 mm (Fig. 3d). After that, the last stage of deformation in this die begins - filling the output channel, because of which the metal flow vectors begin to rise up (Fig. 3e). With the steady process of pressing into the output channel, the defect is finally closed (Fig. 3e).

2) A model with a 90° channel junction angle

In the model with a 90° channel junction angle, the metal flow change also begins when the rounded joint is filled (Fig. 4a), where a local braking zone is formed. After filling the rounding zone, the front end of the workpiece rests against the perpendicular wall of the channel, due to which a large zone of vector velocity displacement is formed in the volume of the workpiece, which is located on the diagonal line of the junction of the channels at 45°. As a result, the through hole begins to flatten in height, taking the shape of an ellipse with a height of about 3 mm. After overcoming this zone, the metal changes the flow direction by 90° from the initial one (Fig. 4b). Passing through the velocity separation line, the hole receives the combined effect of both compression deformation from the punch and shear

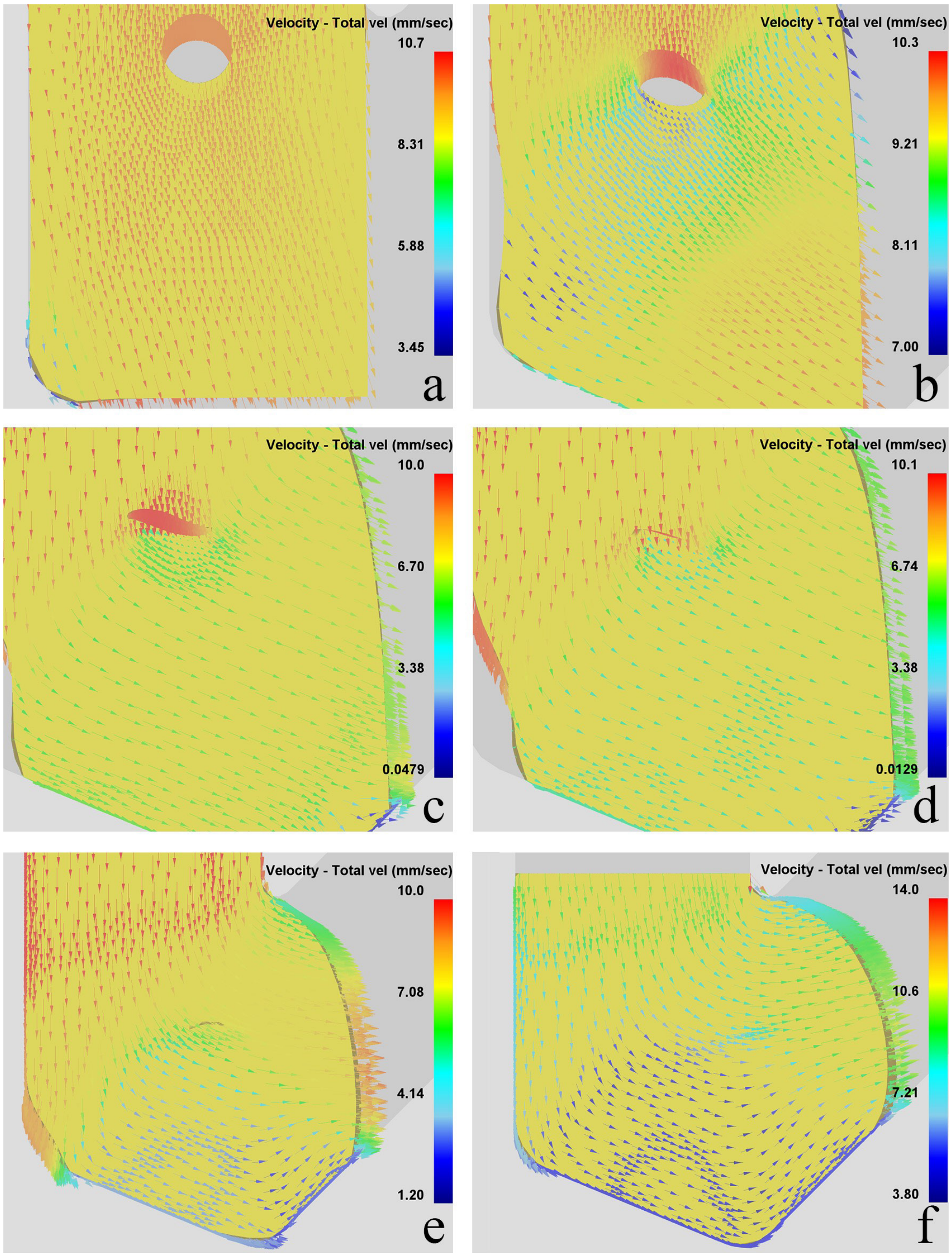

Fig. 3. The stages of closing a through defect in a model with a 45° channel junction angle.

deformation. At this point, the defect is intensively closed (Fig. 4c - d). When exiting the transit zone and obtaining a flow direction parallel to the output channel, the defect is finally closed (Fig. 4e - f).

3) A model with a junction angle of the die channels of 135°

In the model with the junction angle of the die channels of 135°, as in previous models, the change in metal flow also begins when the rounded joint is filled (Fig. 5a), where a local braking zone is formed. At the same time, almost immediately the front end of the workpiece receives a vector offset parallel to the output

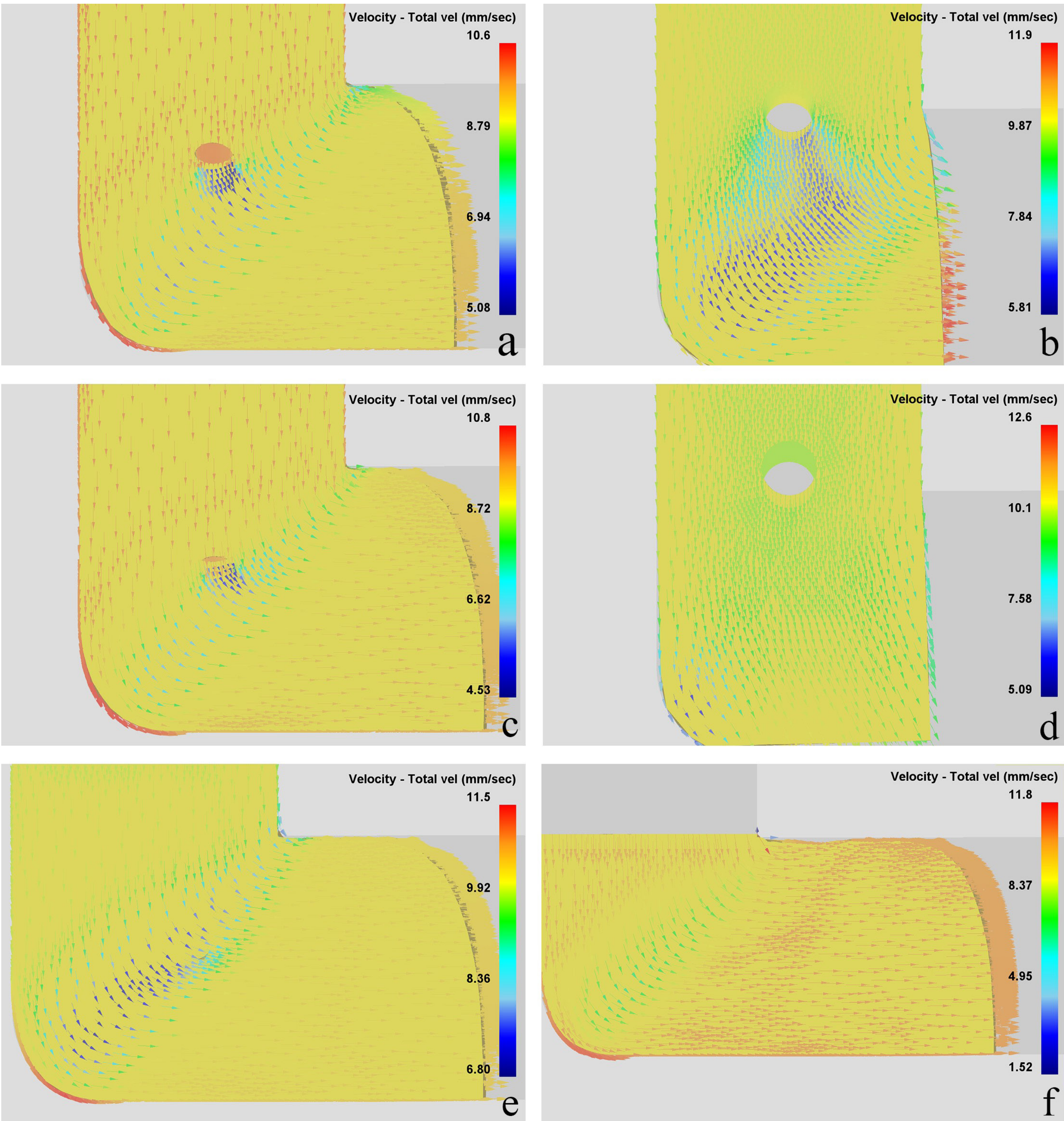

Fig. 4. The stages of closing a through defect in a model with a 90° channel junction angle.

channel due to a sufficiently large value of the channel junction angle (Fig. 5b). At the moment of leaving the rounding zone and the beginning of metal movement along the inclined wall of the channel, the through hole, as in the previously considered models with smaller joint angles, begins to flatten. However, due to a significant decrease in the level of back pressure, the degree of flattening in this case is insignificant. The greatest degree of closure occurs when passing through the transit zone, which is characterized by a diagonal line connecting opposite corners in the channel junction area (Fig. 5c - d). After passing through this zone, the defect is almost

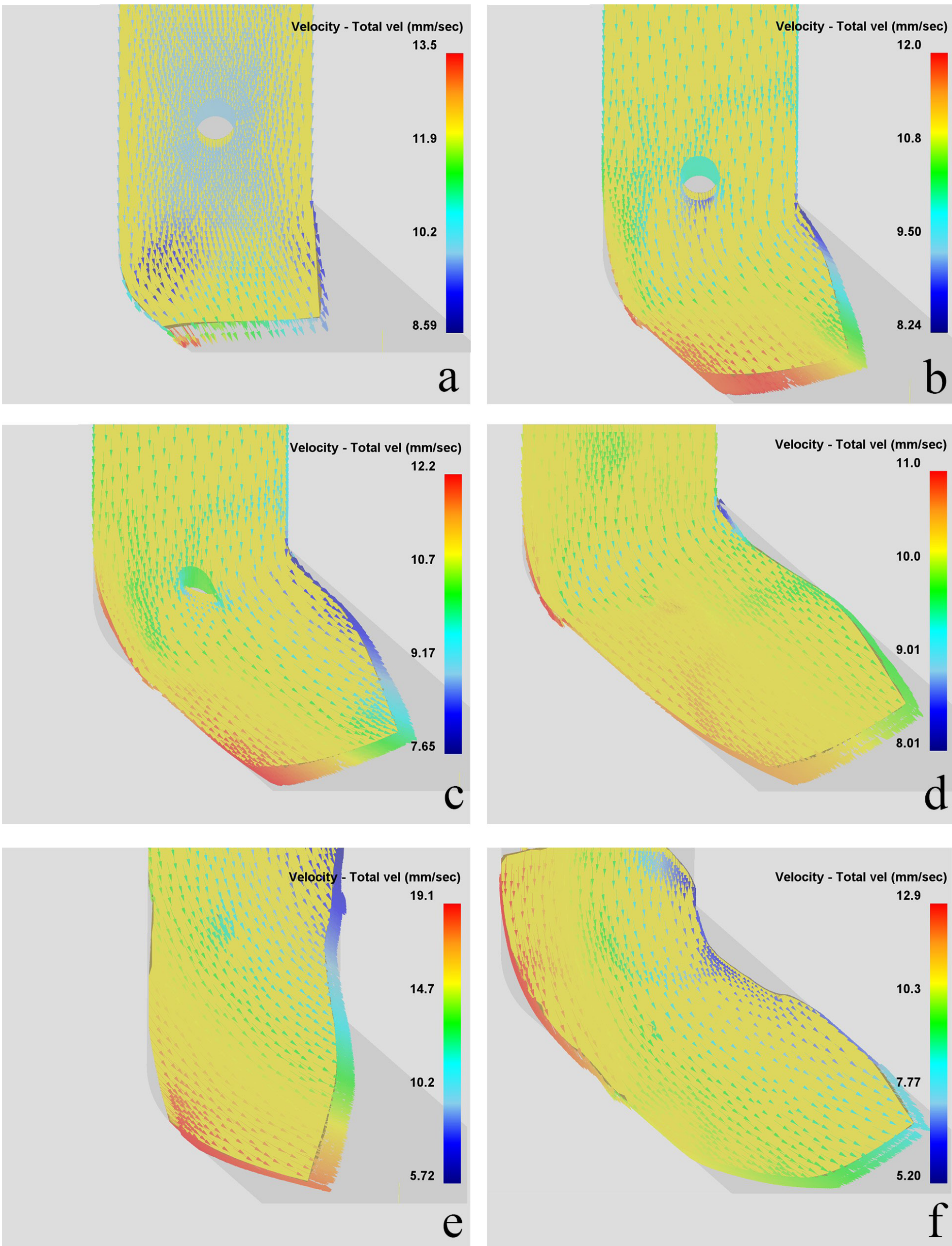

Fig. 5. The stages of closing a through defect in a model with an angle of junction of the channels of the die of 135°.

completely closed, flattening to a height of 0.5 - 0.6 mm. In the future, when moving in an inclined channel, the defect does not close. Therefore, for complete closure, a second deformation cycle was carried out, after which the defect finally closed (Fig. 5e - f).

The results of the simulation indicated that the defect is completely closed after two passes. Based on this data, a decision was made to conduct an experiment with real samples to confirm the results of the theoretical modelling and obtain practical data supporting the conclusions drawn from the simulations. This experiment not only allowed for the verification of the accuracy of the calculations but also demonstrated the effectiveness of the method in practice.

Verification of the model by a real experiment

Based on the results of computer modelling, it was decided to conduct an experiment to evaluate the effectiveness of the ECAP method in closing casting defects. The simulation showed that reducing the angle of intersection of the die channels from 135° to 90° and 45° leads to an increase in the equivalent degree of deformation in the material, which contributes to more effective closure of defects.

Therefore, a die with an angle of 135° was chosen for experimental verification. This choice is since at an angle of 135°, the degree of deformation is minimal among the angles considered. If it is possible to achieve the closure of a large defect under these conditions, then when using matrices with smaller angles (90° and 45°), providing more intense deformation, the closure of the defect will be even more effective. This allows us to confirm the effectiveness of the ECAP method in the least favourable conditions and extrapolate the results to matrices with higher degrees of deformation.

Since, during the simulation, it was shown that the closure of the defect occurs in 2 passes, it was also decided to conduct the experiment in 2 passes on a similar workpiece under similar conditions. After pressing, a microstructural analysis of the material and an examination using scanning electron microscopy (SEM) were performed. The results of the experiment showed that after two passes through the die with an angle of 135°, the defect was successfully closed. The appearance of the workpiece after one and two passes with the evolution of defect closure is shown in Fig. 6.

Microstructural analysis revealed a homogeneous grain structure with no visible signs of residual defects. This indicates that even with the minimum degree of deformation provided by the 135° die, the ECAP method is effective for eliminating casting defects in zirconium alloys.

Thus, the experimental data obtained in combination with the simulation results confirm that the use of matrices with smaller channel intersection angles (90° and 45°), providing a higher degree of deformation, will lead to even more effective closure of defects. This opens new opportunities for the industrial application of the ECAP method in improving the structural characteristics of the E110 alloy and eliminating casting defects.

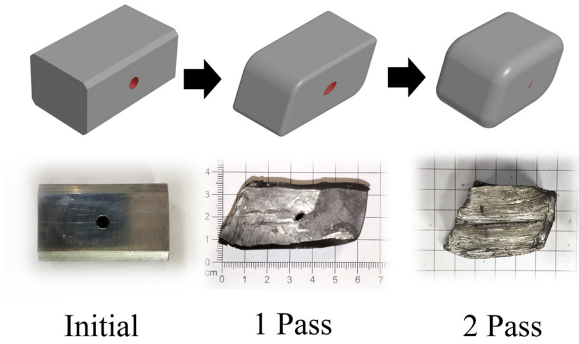

Fig. 6. Evolution of defect closure during the pressing process.

RESULTS AND DISCUSSION

After the first pass through the die (Fig. 7), the defect underwent only partial deformation. Its shape has changed: it has shrunk vertically and stretched along the direction of deformation, but the edges of the defect have not fully joined. The preservation of significant residual voids and non-welded areas is explained by the insufficient degree of accumulated deformation and stresses in the material at this stage of the process.

The image obtained using scanning electron microscopy (SEM) after the second pass through the die shows that the initial large defect was almost eliminated (Fig. 8). However, in its place there was a residual crack with a width of 10 to 25 μm. This crack extends along the entire length of the zone of the former defect, which indicates an incomplete completion of the brewing process.

The second pass through the die led to an active convergence of the edges of the defect due to more intense plastic deformation. Under the influence of accumulated stresses and elevated temperatures, the edges of the defect were partially welded, which significantly reduced its size. However, the presence of a residual crack with a width of 10 - 25 mm indicates localized stresses and difficulties in completely closing defects of this size solely due to plastic deformation. Probably, the remaining crack is the result of a microscopic mismatch of the edges of the defect or local inhomogeneities in the properties of the metal.

The presence of this residual crack indicates that additional heat treatment may be required to eliminate

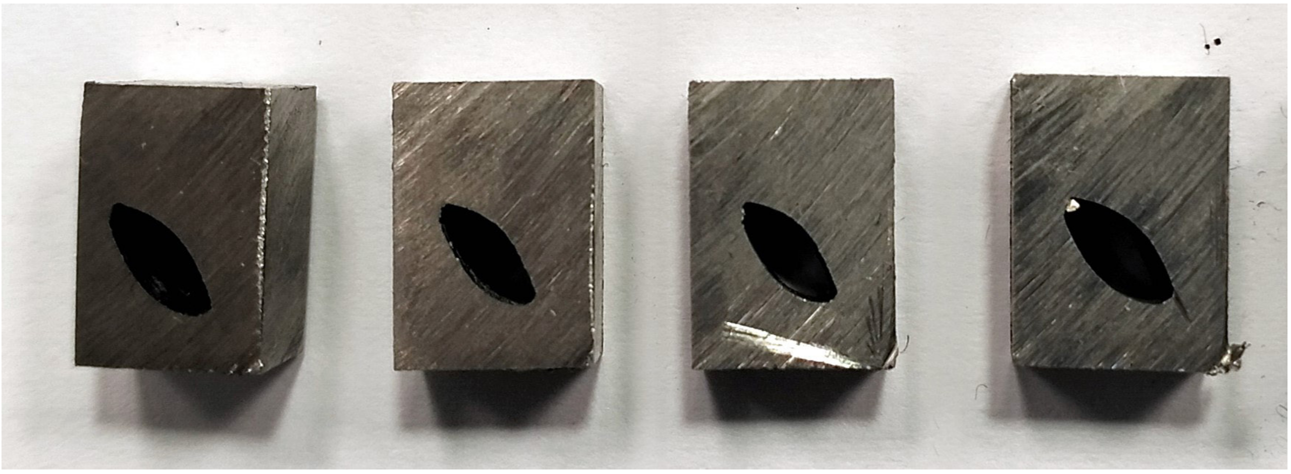

Fig. 7. Defect cross sections after 1 pass.

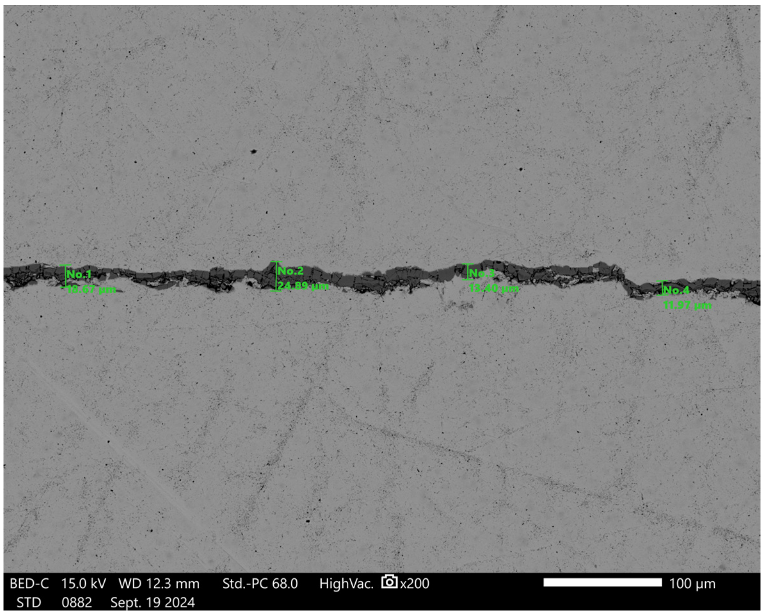

Fig. 8. residual crack after 2 pressing passes.

such defects in zirconium alloys to relax residual stresses. Alternatively, you can change the deformation parameters, for example, increase the number of passes or use a die with a smaller channel intersection angle to increase the intensity of deformation. Despite this, even with the current process parameters, the crack size was significantly reduced compared to the initial diameter of the defect, which demonstrates the high efficiency of the ECAP method for solving such problems. Based on the data obtained, it is recommended to conduct at least three passes for complete brewing of large defects.

The hardness measurement showed a change in this indicator after deformation. The initial hardness of the E110 alloy was about 145 HV, which corresponds to the reference data for this material. After the first pass through the die, the hardness increased to 158.9 HV, which may be due to the processes of dynamic recrystallization and grinding of the grain structure, leading to changes in internal stresses and an increase in hardness. After the second pass, the hardness increased to 171.5 HV, which indicates further hardening of the material due to the accumulation of dislocations and additional grinding of grains to sizes 1 - 8 mm. The change in hardness is associated with complex processes

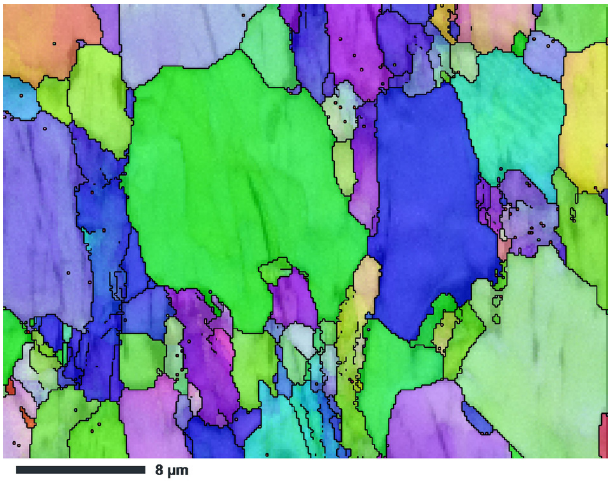

Fig. 9. EBSD map after passing 1 step in pressing.

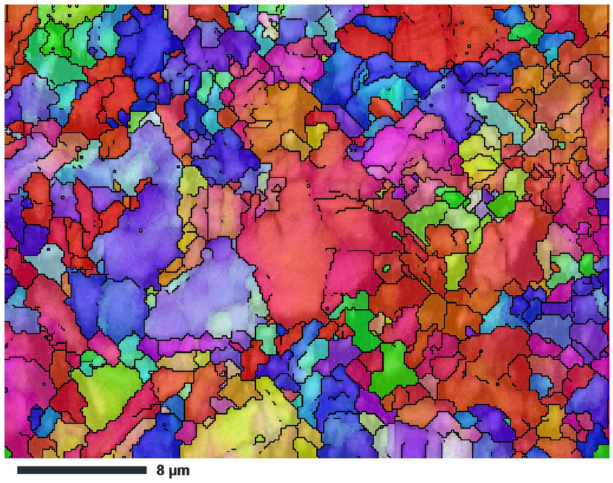

Fig. 10. EBSD zirconium map after passing 2 steps in pressing.

of plastic deformation, recrystallization and structural transformations in the material.

Microstructural analysis after the first pass showed that the grain structure remains relatively large, with individual grain sizes up to 20 mm. Nevertheless, there is already a noticeable change in the shape of the grains, which indicates the beginning of the processes of their grinding and plastic deformation. The EBSD map of the sample that has been pressed in 1 pass is shown in Fig. 9.

After the second pass (Fig. 10), the grain structure underwent significant changes. There was a significant grinding of the grains to sizes of the order of 1 - 8 mm. This grinding is due to the intense shear deformation characteristic of the ECAP process and contributes to the improvement of the mechanical properties of the material, such as strength and ductility. Reducing the grain size also enhances the recovery and recrystallization processes, which can further close microcracks and increase the uniformity of the material.

In general, the analysis shows that two passes through the die with an angle of 135° significantly reduce the size of the initial defects in zirconium alloys, although their complete closure is not achieved. The presence of a residual crack indicates the need to optimize the technological parameters to increase the efficiency of the process. An increase in the number of passes or the use of matrices with smaller channel intersection angles (which increases the equivalent degree of deformation) can contribute to the complete closure of defects.

In addition, additional heat treatment after deformation can help in the relaxation of residual stresses and the completion of welding processes at the microstructural level. Such measures will improve the structural integrity of zirconium alloys and expand the possibilities of their application in critical areas where high performance characteristics are required.

Thus, the ECAP method demonstrates a high potential for effective closure of casting defects and improvement of the microstructure of zirconium alloys. Further research in this direction may be aimed at optimizing the process parameters and studying the impact of additional technological operations on the quality of the resulting material.

CONCLUSSIONS

The conducted study confirmed the effectiveness of the ECAP method for eliminating casting defects in the zirconium alloy Zr - 1 %Nb. Using computer modelling and a physical experiment with real workpieces, it was possible to show the closure of a large defect with a diameter of 5 mm. After two passes through the die with a channel junction angle of 135°, the defect was almost eliminated, only a minimal residual crack with a width of 10 - 25 mm remained, which demonstrates the high potential of the ECAP method in closing casting defects.

The ECAP method is effective for reducing the size of casting defects in zirconium alloys. After two passes through the die with a channel junction angle of 135°, the initial defect with a diameter of 5 mm was significantly reduced, although a residual crack remained. This demonstrates the ability of the method to significantly improve the structural integrity of the material even with minimal deformation parameters. The successful reduction of the defect size confirms the possibility of using ECAP to improve the quality of workpieces with large casting defects without the need for complete processing or rejection of the material.

The junction angle of the die channels significantly affects the efficiency of defect closure. Computer modelling has shown that reducing the channel junction angle from 135° to 90° and 45° leads to an increase in the equivalent degree of deformation, which contributes to more effective closure of defects. At smaller angles, more intense shear deformation occurs, the degree of accumulated deformation increases, which accelerates the processes of welding the edges of the defect and contributes to its complete closure. This indicates the possibility of optimizing the process by selecting the appropriate angle of the die for specific tasks.

Microstructural changes contribute to the improvement of the mechanical properties of the material. After the second pass through the die, a significant grinding of the grains to sizes 1 - 8 mm was noted. Such grinding of the grain structure is caused by intense plastic deformation and contributes to an increase in the strength and plasticity of the material. The fine-grained structure improves the material's resistance to crack development and increases its resistance to external loads, which is especially important for materials used in nuclear power.

An increase in the hardness of the material confirms the hardening due to deformation. The hardness of the alloy increased from the initial 145 HV to 171.5 HV after the second pass through the die. This is due to the accumulation of dislocations and the grinding of the grain structure, which leads to the hardening of the material. The increased hardness improves the wear resistance and durability of the alloy, expanding its operational capabilities under high loads and temperatures.

The presence of a residual crack indicates the need to optimize the technological parameters of the ECAP process. Despite a significant reduction in the size of the defect, its complete closure was not achieved. To completely close the defects, it is recommended to increase the number of passes through the die, which will allow a greater degree of deformation to accumulate and contribute to the complete welding of the edges of the defect. Alternatively, using matrices with a smaller channel junction angle can increase the strain rate. Additional heat treatment after deformation can contribute to the relaxation of residual stresses and the completion of welding processes at the microstructural level.

The ECAP method has a high potential for industrial applications in improving the quality of zirconium alloys. Improving the microstructure and mechanical properties of the E110 alloy expands the possibilities of its use in nuclear power and other critical areas where high reliability and performance of materials are required. The use of ECAP can increase the competitiveness of manufactured materials and reduce the costs associated with the rejection and processing of defective workpieces.

This study provides valuable insights for the nuclear energy industry by demonstrating the effectiveness of the ECAP method in reducing large casting defects in zirconium alloys. The ability of ECAP to minimize or nearly close defects like cracks enhances the structural integrity of materials used in nuclear reactors. This is particularly useful for ensuring the reliability and durability of fuel rods in extreme operational conditions. As a result, the findings show that ECAP can help improve the quality and lifespan of critical components in nuclear applications.

Further research is needed to optimize the process and increase its efficiency. The conducted research lays the foundation for future work on optimizing ECAP parameters, including studying the influence of the number of passages, channel junction angle, deformation rate and process temperature. It is also important to explore the possibility of combining ECAP with other processing methods, such as heat treatment, to maximize the improvement of material properties. The development of recommendations and techniques for the industrial implementation of ECAP will facilitate the widespread use of this method in the production of high-quality zirconium alloys.

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