FEM-SIMULATION ANALYSIS OF SPHERICAL CAVITY ECAP DESIGN AT DIFFERENT CHANNEL ANGLES

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Abstract

Equal-channel angular pressing (ECAP) is one of the main ways of refinement the structure of metals into a fine-grained and nanostructured state. Regardless the great prevalence and high knowledge of the method, the issues of optimization and improvement of the design and geometry of the working tool still relevant. A number of simulations of the geometry of the channels of the die with a spherical cavity of the junction of the channels were carried out in order to study the regularities of the stress strain state formed in the channel. The study was carried out for different angles of the junction of the die channels using the example of a zirconium alloy Zr-2,5%Nb. Due to the spherical cavity, a back pressure is formed, as a result of which the nature of the accumulation of deformation in the alloy changes. Using die with spherical cavity, it is possible to achieve a more complex of shear deformations scheme in comparison with the conventional method and to increase the treatment of metal in the axial zone of the billet. However, this type of ECAP is characterized by a more heterogeneous distribution of the accumulated strain in the cross section of the billet, as well as an increase in the pressing force in all cases.

Keywords: Severe plastic deformation, ECAP, finite elements, simulation

1. INTRODUCTION

Equal Channel Angular Pressing (ECAP) is among the most favored processes among various severe plastic deformation (SPD) techniques. This is due to the fact that the ECAP method offers a substantial effective strain and does not require a complicated and costly experimental setup [1-3]. The main outcome of ECAP processing is a significant change in the mechanical properties of materials, such as strength and duktility [3]. By completing several passes, it is possible to achieve significant grain grinding and increase the structural anisotropy of various metals and alloys, including magnesium, aluminum, and copper. [4-9].

The comparatively large sizes of the blanks and the wide range of processed materials make this method of severe plastic deformation attractive for areas such as biomedical and aerospace engineering, as well as other areas of engineering that require increased mechanical properties. Ultrafine-grained (UFG) materials produced by ECAP have potential applications in nuclear engineering as they can serve as durable materials capable of withstanding the harsh environments within nuclear reactors.

Despite the sufficient study and wide practical application of the method, there are still relevant questions regarding the optimization and investigation of the impact of the tool's geometry on the process, as well as opportunities for further improvement and adaptation of the process for specific materials and goals.

In previous studies, the authors investigated severe plastic deformation and examined the features of the structure formation process in zirconium alloys (E-110-1%Nb and E125-2.5%Nb) used for the manufacture of fuel rod claddings. The resulting ultrafine-grained (UFG) structure and its properties were thoroughly studied using the radial shear rolling method [10-11], and the prospects of using hot forging to eliminate defects in zirconium alloy ingots were demonstrated using FEM simulation [12]. Naturally, the next step is to study the development of the stress-strain state and the structure of zirconium alloys through ECAP to eliminate metallurgical defects in zirconium alloy ingots.

One of the geometric options for the ECAP channel is a design with a spherical cavity at the intersection of the die channels. The peculiarity of this design is the presence of a spherical cavity at the intersection of the die channels. Several publications have demonstrated the effectiveness of this method [13,14]. The advantage of using this die design is the resistance created by the spherical cavity, which improves the fillability of the die channels, creates a more complex stress-strain state, and has a favorable effect on the processing of internal inhomogeneities in the billet.

This work examines the patterns of formation and the influence of the intersection angle of the channels with a spherical cavity on the stress-strain state in the billet using finite element simulations.

2. SIMULATION DESIGN

The simulation was performed using the finite element method with the Deform3D software package. Three variations of ECAP with spherical cavity were modeled. The geometry used in the simulation was previously constructed using the Kompas 3D CAD software. The geometry of all objects used in the simulation, including the workpiece, punch, and three variations of the die, were exported in the *.STL format for further use in Deform3D. Drawings with dimensions and the geometry of the working tool (in section) are shown in **Figure 1.**

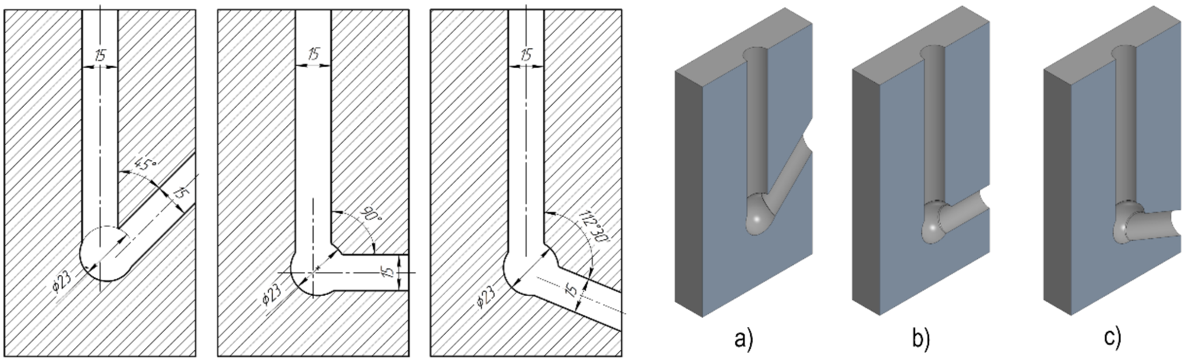

Figure 1 Drawings with dimensions and the geometry of the working tool

The workpiece is a cylinder with a diameter of 15 mm and a length of 100 mm made of the zirconium alloy E110. A finite element mesh with 50,000 elements was created for the workpiece. The mesh is the same for all pressing variants. The maximum and minimum element lengths were 0.6444715 mm and 1.28943 mm, respectively. The speed of the plunger pushing the workpiece was 5 $m \cdot s^{-1}$. The process was modeled as isothermal, with the workpiece temperature set to 20 °C. The working die and plunger were included in the simulation as rigid objects. To characterize the stress-strain state of the pressing process, the strain-rate and strain effective parameters were analyzed.

3. ANALYSIS OF THE OBTAINED MODEL AND PARAMETERS OF THE STRESS-STRAIN STATE OF THE PROCESS.

3.1 Strain rate of workpiece

The Strain-rate parameter shows the deformation occurring at a specific moment in time and corresponds to the deformation zone. The strain effective parameter corresponds to the accumulated deformation in the workpiece and its level can determine the level of metalworking. Also, graphs of the force applied to the working tool in the pressing direction were obtained. All the results obtained for the Strain-rate parameter are shown in **Figure 2.**

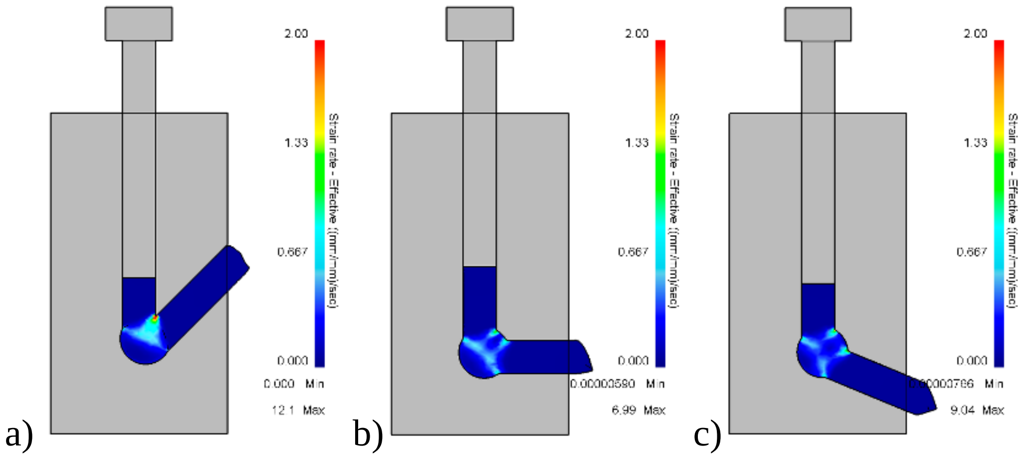

Figure 2 strain rate of three dies variants

In all cases, a complex deformation pattern develops. In variant a, maximum deformations occur and a highly concentrated deformation zone with a triangular shape is observed. Variants b) and c) have a more dispersed appearance, and the deformation zones' lines pass through the hypothetical diagonals between the intersection points of the channels and cavity.

3.2 Strain-Effective of workpiece

The distribution of the strain-effective parameter in the dies differs from the classical ECAP construction. In general, the studied type of ECAP is characterized by a higher degree of accumulated deformation. The concentrations of the highest values of the strain-effective parameter across the cross-section of the billet also have a different appearance. In the longitudinal section, a fairly good processing of the axial and adjacent zones with displacement can be observed. The strain pattern depends on the angle of the outlet channel relative to the inlet channel (**Figure 3**).

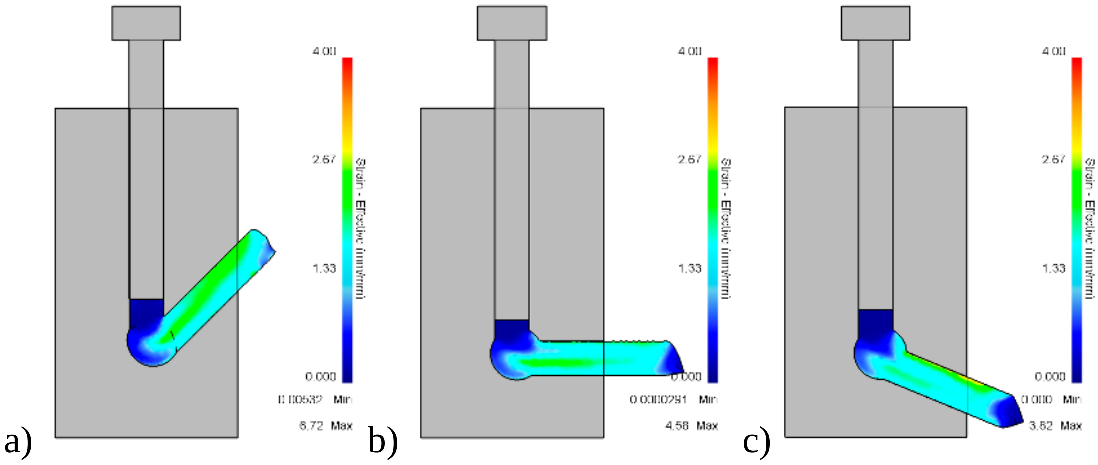

Figure 3 Strain-effective in workpiece longitudinal section.

However, in the cross section of the billet (**Figure 4**), highly symmetric concentrations of deformation can be seen relative to the pressing axis. The highest deformation zones are observed at an outlet channel angle of

45° (**Figure 4**). As the outlet channel angle increases, the distribution pattern of strain-effective changes - the highly concentrated zones become less intense and shift towards the upper surface of the billet. This is due to the complex geometry of the transition from a spherical void to a cylindrical channel.

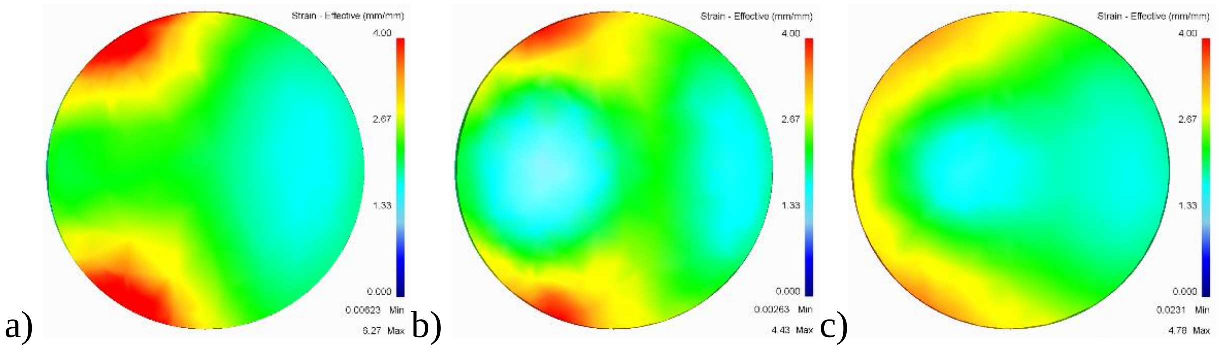

Figure 4 Strain-effective in workpiece cross section.

3.3 Load

Graphs of the force on the tool along the Z axis (parallel to the movement of the workpiece through the input channel) were obtained from the model. Graphs of the effort per tool are shown in **Figure 5**.

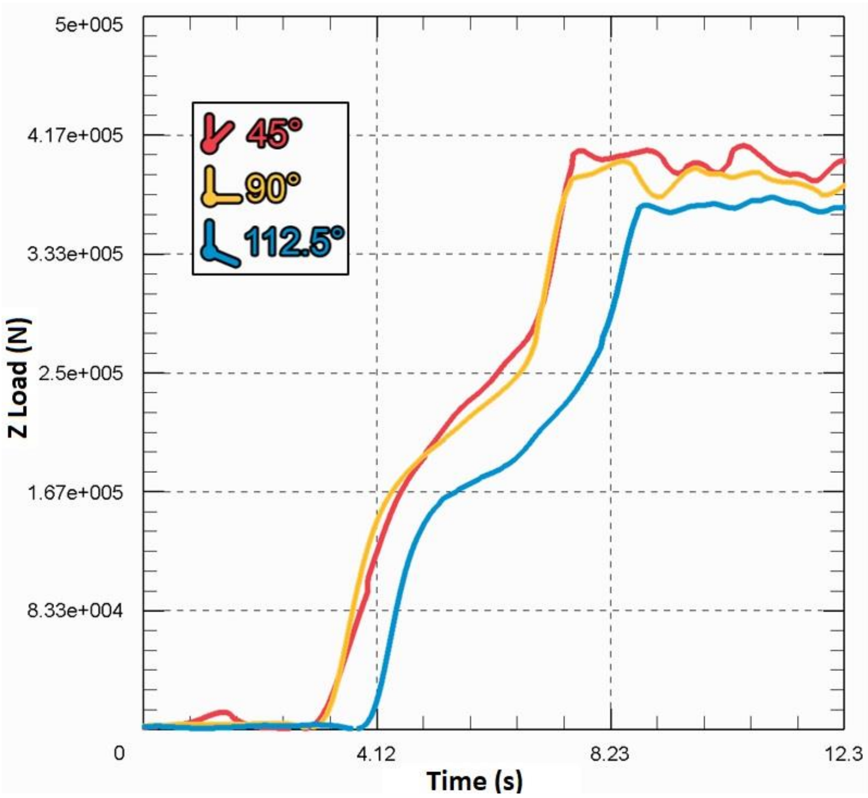

Figure 5 Load graphs for all variations of dies

The graphs of the tool load show a clear dependence of the force on the angle of the die. On average, the loads with this type of ECAP are greater than with the conventional scheme. The greatest load is observed at angles of 45° and 90° about 390,000 N. In the case of a die of 112.5°, the force is less - about 360,000 N.

The stepwise nature of the load increase is also noticeable. The "step" appears at the moment of filling the spherical cavity.

CONCLUSION

Despite the more favorable distributions of deformations in the workpiece resulting from ECAP with spherical cavity, the issue of the feasibility of the method remains relevant due to the need for high forces to be applied. This may be challenging to implement as high loads require high strength requirements for the working tool. To further study the process and conduct full-scale experiments, it is necessary to simulate the loading of the working tool to understand the necessary strength characteristics.

REFERENCES

[1] VALIEV, R. Z., LANGDON, T. G., & ZHU, Y. T. Fundamentals of equal channel angular pressing (ECAP) and its applications. *Progress in Materials Science*. 2006, vol. 51, no. 7, pp. 881-981. Available from: https://doi.org/10.1016/j.pmatsci.2006.11.001

[2] HORITA, Z., FUJINAMI, T., & NEMOTO, M. Development of ultrafine-grained metals and alloys by severe plastic deformation: Properties, processing and applications. *Materials Science and Engineering: A*. 2012, vol. 527, no. 1-2, pp. 62-76. Available from: https://doi.org/10.1016/j.msea.2009.12.063.

[3] ZHU, Y. T., LOWE, T. C., & VALIEV, R. Z. Advances in ultrafine-grained materials processed by severe plastic deformation: A review. *Materials Science and Engineering: A*. 2014, vol. 621, pp. 180-224. Available from: https://doi.org/10.1016/j.msea.2014.09.073.

[4] ESTRIN, Y., VINOGRADOV, A. Extreme grain refinement by severe plastic deformation: A wealth of challenging science. *Acta Materialia*. 2013, vol. 61, no. 3, pp. 782-817. Available from: https://doi.org/10.1016/j.actamat.2012.10.042.

[5] HUANG, X., LI, Y., LI, H., & LI, M. Grain refinement of magnesium alloy AZ31B by equal channel angular pressing: Microstructure, texture and mechanical properties. *Journal of Alloys and Compounds*. 2017, vol. 699, pp. 701-708. Available from: https://doi.org/10.1016/j.jallcom.2016.12.244.

[6] KNEZEVIC, M., DJURDJEVIC, M., & RAKIN, M. Equal channel angular pressing and its application in grain refinement of aluminum alloys. *Journal of Materials Engineering and Performance*. 2015, vol. 24, no. 10, pp. 3754-3764. Available from: https://doi.org/10.1007/s11665-015-1711-8.

[7] SHEN, Y. F., ZENG, S. M., CUI, Y. X., ZHENg, W. T., WANG, H., & Lu, J. Enhanced fatigue performance of a 6082 aluminum alloy processed by equal channel angular pressing. *Journal of Materials Science*. 2021, vol. 56, no. 6, pp. 4106-4119. Available from: https://doi.org/10.1007/s10853-020-05485-7.

[8] WANG, Y., XIA, J., YANG, H., QIU, Y., & LU, L. Microstructure evolution and tensile properties of Mg-9Al alloy processed by equal channel angular pressing. *Journal of Alloys and Compounds*. 2021, vol. 872, #159930. Available from: https://doi.org/10.1016/j.jallcom.2021.159930.

[9] YANG, X., WANG, H., HUANG, Z., XUE, F., ZHAO, W., CHEN, L., & WANG, Y. Mechanical properties and microstructure evolution of AZ31 magnesium alloy processed by equal channel angular pressing. *Journal of Materials Engineering and Performance.* 2022, vol. 31, no. 1, pp. 23-31. Available from: https://doi.org/10.1007/s11665-021-06007-5.

[10] ARBUZ, A., KAWALEK, A., OZHMEGOV, K., DYJA, H., PANIN, E., LEPSIBAYEV, A., SULTANBEKOV, S., SHAMENOVA, R. Using of Radial-Shear Rolling to Improve the Structure and Radiation Resistance of Zirconium-Based Alloys. *Materials*. 2020, vol. 13, no. 19, #4306. Available from: https://doi.org/10.3390/ma13194306.

[11] ARBUZ, A., KAWALEK, A., OZHMEGOV, K., PANIN, E., MAGZHANOV, M., LUTCHENKO, N., SHAMENOVA, R., YURCHENKO, V., Obtaining an Equiaxed Ultrafine-Grained State of the Longlength Bulk Zirconium Alloy Bars by Extralarge Shear Deformations with a Vortex Metal Flow. *Materials*. 2023, vol. 16, no. 3, #1062. Available from: https://doi.org/10.3390/ma16031062.

[12] BANASZEK, G., OZHMEGOV, K., KAWALEK, A., SAWICKI, S., Investigation of the Influence of Hot Forging Parameters on the Closing Conditions of Internal Metallurgical Defects in Zirconium Alloy Ingots. *Materials*. 2023, vol. 16, no. 4, #1427. Available from: https://doi.org/10.3390/ma16041427.

[13] ÖĞÜT, S., KAYA, H., KENTLI, A. et al. Applying hybrid equal channel angular pressing (HECAP) to pure copper using optimized Exp.-ECAP die. *Int. J. Adv. Manuf. Technol*. 2021, vol. 116, no. 11-12, pp. 3859-3876. Available from: https://doi.org/10.1007/s00170-021-07717-9.

[14] SEPAHI-BOROUJENI, S., FERESHTEH-SANIEE, F. Expansion equal channel angular extrusion, as a novel severe plastic deformation technique. *J. Mater. Sci.* 2015, vol. 50, no. 12, pp. 3908-3919. Available from: https://doi.org/10.1007/s10853-015-8937-9.