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To cite this article: Ayat Fadhil et al 2021 J. Phys.: Conf. Ser. 1973 012103

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Design Parameters for Equal-Channel Angular Pressing (ECAP) Via Numerical Approach

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Abstract. A numerical approach utilizes to investigate the optimal die design parameters of the ECAP technique. The Deformation behavior and strain distribution are affected by die geometry and processing parameters. were analyzed and evaluated. In addition, the influence of the inner channel angle (ICA) and the outer channel angle (OCA) on the behavior of plastic deformation during ECAP process also studied using a finite element technique. The numerical investigation implemented over a range of die angles (90°, 110° , and 135°) with inner corner radius (0, 3, 4, 5, and 8 mm) with their corresponding values considered for the outer corner radius (0, 10, 12, 14, 15 and 20 mm). The results obtained regarding the force required, maximum stress, maximum strain, and equivalent stress evaluated over a range for die inner angle radius and die outer angle radius. These results show that the size of the inner and outer curvature radii has a big effect on deformation homogeneity of the billet. had an influence on both the quantity and distribution of effective strain. With the increment of inner and outer curvature radii, the effective strain value decreased in the deformation regions. Moreover, the optimum conditions in terms of strain distribution and homogeneity of billet are associated with a radius of the inner fillet of 4 mm and radius of outer corner of 12 mm. The impacts on the von Mises strain and the press force. The optimal compromise between applied force and von Mises strain balances small press forces and high von Mises strain and homogeneity indices.

Keywords: Equal Channel angular pressing, Finite element analysis, Severe plastic Deformation, FEM, ECAP.

1. Introduction

Severe plastic deformation (SPD) is one of the techniques possessing excellent grain structure used to modify conventional the rough grain of metals and alloys to ultrafine metals and alloys -grain (UFG). SPD-induced structural alterations are as follows: Metals' mechanical qualities have improved, as have

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Journal of Physics: Conference Series	1973 (2021) 012103	doi:10.1088/1742	-6596/1973/1/012103

their yield stress and hardness. The processes relevant to the achievement of the operational objectives to produce the ultra-fine grain structure are equal-channel angular pressing (ECAP) and high-pressure torsion (HPT) [1]. Equal Channel Angular Pressing ECAP is now the most widely used SPD procedure. One of the essential advantages of the ECAP is that enforces high plastic strains without changing the crosssection of bulk materials, allowing it to pass several times to transfer the most significant amount of pressure into the granules as required [2]. During the ECAP. Into two intersecting channels of identical shape sample is inserted. The cross-sections containing die channel angle (Φ) and an outer corner angle (Ψ). Figure 1,Displays a schematic diagram for die widely used in the ECAP method.



Figure 1. (a) Schematic of a ECAP die (b) ECAP with the channel angle (Φ) and outer arc angle (Ψ) [4-5].

Many parameters effect on ECAP process. The main parameter controlling deformation uniformity is angle Ψ , described by the inner and outer curvature radii (R and r, consecutively). the main importance of the die channel geometry in controlling the microstructural changes of the material as well as the mechanical behavior and the hardening effect and imposes the strain homogeneity and flow affect the mechanical properties and microstructural of deformed materials [3]. only a few papers investigate the impact of curvature radii r and R. (Tyagi et al. 2020) [4]. has concluded that using 3D FEM simulation is done on ECAP process using DEFORM-3D software on different channel angles such as 90°, 105°, 120° and 135° and corner angles such as 0°, 10°, 20° and 30°. The observed results, it was found that the shear strain decrease with increase in channel and corner angle.. While (Ghazani and Moslemi 2018) [5] the effect of the ECAP die's inner corner radius on strain distribution and material flow characteristics, the results indicated that increasing the inner corner radius results in a reduced corner gap and a narrow deformation zone. The damage factor is greater in the top sections of the sample than in the lower areas.

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As a result, the pressing force was increased by increasing the inner corner radius. (Jabur 2020) [6] studied the effect of the outer corner radius on the action of ECAP The results affirm a significant effect of die geometry on pressing force and equivalent plastic strain as channel angle and outer corner radius increase. The equivalent plastic strain and pressing force decrease. (Abioye et al. 2017) [7] Found the outer corner angle has a substantial impact on strain homogeneity and is, therefore, one of the most critical parameters studied by simulations ,it was recommended that it is more economical to extrude at an outer angle between 22.5° and 45° as a relatively higher effective strain will be induced. [8] (Zhang 2017) The greater radius of the inner fillet, the less effective the strain, to both inner and outer corners. This attribute to the mitigation ,extruded of the billet compression stress in shear deformation zone (Hans Raj et al. 2018) [9]. It is inferred from the FEM findings that, for all materials, the ECAP dies with an outer arc angle of 30° and a radius of a fillet of 5 mm; Without any strain cumulation, the deformation is significantly more homogenous. If the angle of the corner increases, the strain is more evenly scattered throughout the specimen, and the highest strain concentration moves from the bottom to the top layer.

The equivalents ECAP's Von Mises strain was computed using the equation, where N is the number of passes. (Iwahashi, 1996) [10]:

The current study used numerical simulations on ECAP to estimate the influence of the die's whole shear deformation zone, particularly the inner angle radius and outer angle radius, on the homogeneity of the strain of the ECAP-processed billet. FE simulations obtained on different ECAP dies of $\Phi = 90^{\circ},110^{\circ},135^{\circ}$ with varying values for the inner corner angles are r (0, 3, 5, 8) their corresponding average value for the outer corner angles are R (0, 10, 15, 20 mm) respectively. The relevance of studies relating die geometry with the above characteristics resides in the fact that heterogeneous deformation leads to heterogeneous grain size distribution. The discussion of the results here obtained will show that the influence of the R–r geometry on the deformation homogeneity, is quite substantial.

2. Methodology

In this study, the Ansys software utilizes to perform the modeling and simulation of the ECAP procedure. The Finite Element Analysis (FEA) involved in this technique evaluates the die design parameters of the ECAP process seeking the optimal parameters to be adopted in manufacturing the die. The work material selected is Aluminum alloy, cast, A,356.0, and the subsequent cross-sectional area to be extruded with extreme plastic deformation properties is to be square. The SPD properties determine by the die angle since strain rates vary with the die angle. The more acute the die angle, the better the mechanical properties, and the more obtuse the die angle, the lower the extrusion load needed. 90°, 110°, and 135° angle. The die model design performs by Solidworks software. Commercial software ANSYS 2020 R1 to assess the effect of ICA inner corner angles and OCA outer corner angles. The die was made up of two channels that intersected at an angle, Φ , the inner corner angles (r) and outer corner angles (R) were both changeable in the system for numerical simulation. The billet was square samples of 10 mm × 10 mm and 70 mm in length. Figure 2 demonstrates the first mesh systems used in the ECAP simulations of several types ICAs and OCAs. Six of the die geometries with varying ICA values were evaluated. r =0 (sharp corner), 3, 4, 4 and 5 mm, corresponding outer corner angles values of 0, 10,12, 14, 15, and 20 mm, for angle $\Phi = 90^{\circ}$.



Figure 2. The Initial mesh for ECAP simulations with varying outer and inner corner angles for angle 90°.

Meshing schemes were used in all simulations to handle broad strains and account for flow localization. There are approximately 4529 initial elements via calculations with varying the number of elements. The total number of elements to be adequate to convey local strain rate deformation.

3. Results and Discussion.

The results obtained regarding the force required, maximum stress, maximum strain, and equivalent stress evaluated over a range of die inner angle radius and a range of die outer angle radius are present in this section. In the following Figures (3-5), the obtaining results of simulation demonstrate as follows, as shown the specified values taken for the inner corner angles are (0, 3,4, 5, and 8 mm) while their corresponding values considered for the outer corner angles are (0, 10,12,14, 15 and 20 mm) respectively.



Figure 3. equivalent elastic strain across for different of inner corner angles, outer corner angles in the flow planes of samples processed through ECAP dies of varying angle 90°.

Figure 3 displays the equivalent elastic contours of strain with varying angles at the inner and outer corners show in the middle of deformation zone. As the inner corner angles and outer corner angles increase, the generation of equivalent strain is increased near the inner corner of the deformation zone, resulting in lower strains towards the deformed samples' outer corner. demonstrated the strain distribution was controlled by the outer corner angle. In Figure 3a, With an radius of the inner fillet of 3 and an radius of the outer fillet of 10 mm, strain showed as a descend distribution and grew from top to bottom of the billet. In Figure 3d, eanf f , It has been shown that the effective strain in the billet's outer corner was considerably reduced, which was observed found by Patil et al. [16]. Thus, strain inhomogeneity would be displayed. By increasing the radius of the inner fillet, the strain distribution becomes less homogeneous. [11].



Figure 4. equivalent elastic strain across for different of inner corner angles, outer corner angles in the flow planes of samples processed through ECAP dies of varying angle 110°.



Figure 5. equivalent elastic strain across for different of inner corner angles, outer corner angles in the flow planes of samples processed through ECAP dies of varying angle 135°.

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Moreover, in this Figure 4, It is easily shown that the max equivalent elastic strain across for different inner corner angles and outer corner angles reduced with the increment of ICA and OCA. So also strain inhomogeneity would be displayed in bigger inner and outer corner angle .In Figure 4a,b and c, which shows an radius of the inner fillet of 0 and n radius of the outer fillet of 0 mm, The strain was distributed in a gradient pattern and rose from the top to the bottom of the billet. In Figure 3 d,e and f It can be noticed that the effective strain in the billet's outer corner was substantially lowered ,while in Figure 5, the same behavior was found recording resulted in equivalent strain for a wide range of exterior corner angle and Inner corners angle so in the three angles the maximum value of equivalent strain it gives in r=4, R=12 mm.





(c)

Figure 6. Average, (a) maximum stress (b) equivalent stress (c) maximum strain across for different of inner corner angles, outer corner angles in the flow planes of samples processed through ECAP dies of varying angles 90°,110°,135°.

As shown in Figure 6, the effect of the inner corner angles and outer corner angles value the maximum stress, equivalent stress maximum stress investigated over averring value for the die channel angle 90°,110° and135°. The channel angles were the (a) it is readily evident that the maximum stress decrease, with an increment of inner corner angles in the 110° and 135° die angle for the outer corner angle it has been closed to same behaved. While angle 90° shows highs and lows for the inner corner angle with r= 4 and 5 mm, the practical stress values range from 3705.7 to 2656.4, whereas with r = 3 and 8 mm, the effective stress values are below the above range in the inner corner 4and 5 mm. The same behavior obtains with R= 12,14 and 15 mm for practical stress values in the outer corner angle. The greater the outside radius, the lower the maximum stress and the wider the stress distribution. The added inner radius reduces the maximum stress and spreads the stress distribution more.so Maximum stress development occurs during deformation, in current work the deformation gragin is increes as the inner corner angles and outer corner angles decrease, Niu et al. discovered a similar trend of stress growth during ECAP processing in their numerical simulation and discovered that the largest stress development occurred near the deformation zone. [12]. While for the effect of ICA and OCA were considerable effect on (b) equivalent stress for die angle 90°, 110° when in angle 135° was insensitive. (c) maximum strain across a broad range of inner corner angles, outer corner angles indicates that when the inner and outer corner angles increased, the average maximum strain reduced steadily. The distinction between average and maximum strain at the three inner corner angles are minimal with r = 3, 4, and 5 mm as compared to r = 0and 8 mm, also outer corner angles, the average of max strains is minuscule with R = 10.12 and 14 mm compared to r = 0, and 20 mm. Similar results were also reported by Tyagi et al. in ECAP simulation research When the outer corner angle is increased, the strain is reduced. [4]. The results observed at the inner corner angles and outer corner angles were 0 gives the max strain, stress, and equivalent stress but is very unfavorable because it gives max values of pressing force; these findings were consistent with [13].

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While The bigger inner corner angle ICA r=8 mm and OCA R=20 mm in ECAP dies, the effective strain would be smaller, which was also found by Zhang results the bigger the inner fillet radius, both on the inner and outside corners. That attributable to the relieving impact of the compression stress on extruded billet in shear deformation zone [14-15]. Therefore, It would be able to achieve flow and strain homogeneity. with r=4, R=12 because it gives the best value of max strain, stress, equivalent stress, and force. It is of an appropriate value compared to other values of the force.



Figure 7. Average force across for different of inner corner angles, outer corner angles in the flow planes of samples processed through ECAP dies of varying angle 90°,110°,135 °.

To find out how channel and corner angles effect on the extrusion load, In general, when the billet slides, the load increases. The initial rapid increase in load signifies the billet has reached the die channels' corners and, after attaining its maximum value, the load progressively decreases and stabilizes. The load curve fluctuates during the process, and this variation can be related to a change in contact friction between the die. Therefore, during the actual extrusion process, adequate the die channel's lubrication can greatly minimize energy consumption and extrusion load, resulting in a longer mold life. For the present study, in Figure 7, the magnitude of the inner corner angles and outer corner angles of the die angles significantly affect the force required in die with 90°, 110° angle while is It decreases slidly in 135° angle die. The relationship affirms, as an outer and inner channel radius increases, the pressing force decreases Similar to Jabur[6]. found the At the smallest channel angle, the maximum of extrusion load was attained. 90° at r=0 and R=0 Similar findings have also been reported. by Tyagi et al. The channel and corner angle have an impact on the extrusion load. The maximum extrusion load was attained at the smallest channel angle, 90°. [4].

4. Conclusions

In this work, the effect of ECAP dies outer corner angle. Inner corner angle showed a substantial effect on the strain homogeneity and flow, Simulations with ECAP dies of various inner radius were performed, exterior radius s, r=(0, 3, 4, 5 and 8) and R=(0,10,12,14,15 and 20) correspond with a channel angle of $\Phi = 90^{\circ},110^{\circ}$ and 135° .

The following are the conclusions:

1. the radius of the outer fillet and the radius of the inner fillet had an have an effect on the distribution of the effective strain . monitoring strain homogeneity and flow are feasible with smaller inner and outer corner radius.

2.Increased outer and inner corner radius s cause greater principal stresses in the region of deformation, resulting in inflow and strain heterogeneity.

3. The average maximum strain and stress reduced significantly as the increased in inner corner radius and outer corner radius.

4. The optimization die structure for Aluminum alloy, cast, A,356.0 billet with r = 4, R=12 is acceptable in finite element simulations because it gives the best value of max strain, stress and, equivalent stress and strain homogeneity was found that

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