EVALUATION OF THE STRAIN RATE AND THE DEVELOPMENT OF THE DIE CORNER GAP IN EQUAL CHANNEL ANGULAR PRESSING: AN OVERVIEW

Nagendra Singh[1], Manoj Kumar Agrawal[2], Sanjeev Kumar Verma[3], Rajhans[3] Ashish Kumar Tiwari[4]

[1]Research Scholar, Department of Mechanical Engineering, GLA University, Mathura, UP, India-281406

[1]Assistant Professor, Department of Mechanical Engineering, Institute of Engineering and Technology, Khandari Campus, Agra, UP, India-282002, singh.mech2008@gmail.com

[2]Associate Professor, Department of Mechanical Engineering, GLA University, Mathura, UP, India-281406 manoj.agrawal@gla.ac.in

[3]Department of Mechanical Engineering J. S. University Shikohabad UP, India- 283135, sanjeev0085@gmail.com
kumar.rajhans2015@gmail.com

[4]Junior Technical Superintendent (JTS), advanced Centre for Materials Science, IIT Kanpur, UP India-208016
ashishtr@iitk.ac.in

*Corresponding Author: singh.mech2008@gmail.com

Abstract

The constitutive behaviour of rate-sensitive materials, the flow stress evolution and dislocation density, the generation of deformation heat, and other aspects of plastic deformation are all influenced by strain rate. A geometric method was used to assess the workpiece material strain rate during ECAP. The outcomes were contrasted with those of finite element studies performed on a model made of perfect plastic with different sizes of mesh. The obtained formula for the strain rate agrees with the finite element method's findings in a fair amount of detail. When using ECAP, the strain rate rises with falls with die channel angle, die corner angle, and workpiece and width punch speed . For analytical calculations of the distortion, thermal, and behaviour of material microstructural development during ECAP, the relationship derived can be applied. During ECAP process of materials, a die inner corner gap is typically discovered. It was determined how the corner gap development and deformation behaviour of the strain-hardening material and the nearly perfect plastic material. The strain hardening behaviour and the workpiece regional flow velocity in the deforming zone, the mechanism of corner gap generation is discussed. To more accurately predict the tension during ECAP, from the die corner angle to the workpiece arc curvature, the corner angle must be changed.

Keywords: Strain Hardening, ECAP, Finite Element Analysis, Die internal corner gap

1. Introduction

In the recent decades, the development of metal micro-structures during plastic deformation has been extensively studied. It is widely acknowledged that typical sub-grain/cell size decreases with strain when metals deform at normal temperature[1]. Deformation processing is thus a potential technique for metal grain refining. The ultrafine-grained materials' distinctive physical and mechanical characteristics can be seen in the SPD processed materials, However, they also possess a variety of benefits over nanostructured materials produced using conventional techniques, such as powder processing. The ECAP process, one of many SPD techniques, includes running a sample through a die that contains *intersection* of any *two channels* with similar rummage that meet at a specific angle, causing substantial shear plastic deformation in a deforming layer of a workpiece. Multiple forging, torsion straining, accumulated roll bonding, and equal-channel angular pressing are additional SPD techniques[2]. Because it can repeatedly run the operation while keeping the workpiece original cross section, resulting in massive, complete dense samples with ultrafine grains. Both the analysis of the procedure itself and the comprehension of the fundamental characteristics of the ECAP metals have advanced significantly.

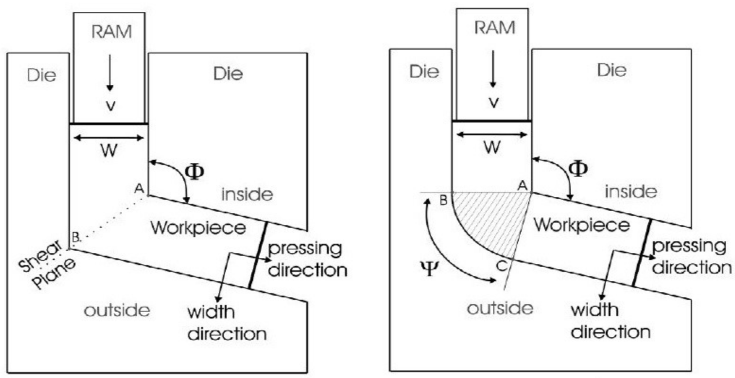

Figure 1. ECAPed Processed with Channel angle ϕ and Corner angle $\psi = 0$ and $\psi > 0$ [13].

The oblique angle ϕ where two channels with equal cross sections converge Explain using the ECAP principle. Regarding the workpiece, three perpendicular directions the pressing direction, breadth direction, and thickness direction are introduced.

The terms "inside part" and "outside part" refer to the portions of the specimen that flow close to the internal corner and external corner of the die, respectively. As in the case of pure torsion, the ideal circumstances deformation mode in ECAP is "simple shear" in Figure 1. The primary distinction between ECAP and contortion or other methods for plastic deformity, which makes Equal Channel Angular Pressing is that deformity takes place right next to the plane, specifically the shear Zone, which is located at the junction of the dual channels[3]. The ECAP sample deformity is relatively localized. In a rectangular workpiece with width and length is no strain along the thickness direction because it is perpendicular to directions of plane strain condition. As a result, the rectangular specimens' deformity during the ECAP procedure is now two dimensional. The true deformity characteristics, in contrast to the ideal situation of Figure 1 are inhomogeneous because of frictional effects, an incomplete filling of the die, a bent die corner.

2. Literature Review:

2.1 Corner angle and Channel Angle formation

The angle subtended by the arc curvature is known as corner angle of die ψ, and it varies $\psi = 0$ to $\psi = \pi - \phi$ degrees. When the die corner angle is not zero due reduced shear zone in the outer part of the workpiece develops because the outer half of the workpiece travels along a shorter path within the main deformity zone[4]. The degree of plastic deformity is strongly correlated with the micro-structures and mechanical characteristics of the deformed materials, it is crucial to have a grasp of the phenomena connected to the development of stress and strain. By subjecting materials with a gritty texture to Equal channel angular pressing it is possible to create high-quality ultrafine-grained materials. To evaluate the plastic deformity behaviour of work parts during Equal Channel Angular Pressing, numerous theoretical attempts have been performed, such as strain studies that take geometrical factors into account, using the self-consistent velocity field method, together with the finite element approach and upper bound theory (FEM). To the author's knowledge, the majority of earlier studies did not consider the impact of strain rate during Equal Channel Angular Pressing.

Materials behaviour during construction, such as density of dislocation, flow stress, and thermal growth brought on by deformity of plastic are in fact determined by the strain rate during plastic deformation[5]. The pressing speed in ECAP affects the microstructure of pure aluminium and an alloy of aluminium and 1% magnesium. FEM simulation that pressing speed and strain rate sensitively affect the homogeneity of the deformation during ECAP. Although strain rate plays a significant role in plastic deformation processes, little experimental data or theoretical estimation exists for ECAP. The effective strain rate for ECAP was calculated using finite elements, although the reliability of these estimates is in doubt given the mesh size scheme that was employed. A quick parametric analysis still requires an approximately analytical solution. In order to comprehend the properties of material and optimize the design of process, it is important to establish a simplified quantitative formulation to during Equal Channel Angular Pressing, estimate the workpiece strain rate. The workpiece material strain rate during ECAP is examined based on a geometric analysis[6]. To evaluate the correctness of the suggested formulation, The FEM outcomes of a fictitious non-dimensional model material are contrasted with the estimated strain rate values.

Many ultrafine grained materials have distinct physical and mechanical properties. The use of extreme plastic deformation techniques has been the subject of intensive study recently. There are also a number of advantages to using materials that have undergone extreme plastic deformation over nanostructured materials produced using other processes using powder forms. Moving a workpiece through a die with two intersecting channels with identical cross sections that meet at a predetermined angle is one of many ways to cause severe plastic deformation. This causes a thin layer of the workpiece to undergo large simple shear plastic deformation[7]. Its capacity to produce huge, A lot of research has been done recently on producing totally dense samples with ultrafine grain sizes by repeating the process while retaining the original cross-section of the workpiece. Analysis has demonstrated that the relationship between and represents the similar strain ε after one pass, where the angle of corner ψ is defined as the angle that the curvature of the arc occupies lies between $\psi = 0$ and $\psi = \pi - \phi$. It is given by the relationship,

$$\varepsilon = \frac{1}{\sqrt{3}}\left[2\cot\left(\frac{\psi}{2}+\frac{\phi}{2}\right)+ +\psi\cos ec\left(\frac{\psi}{2}+\frac{\phi}{2}\right)\right] \quad (1)$$

The equivalent strain decreases with the corner angle ψ in accordance with Eq. (1), as depicted in Fig. 2. It has been discovered that, while the channel angel $\phi = 90^0$ is set at, raising the corner angle from $\psi = 0^0$ to $\psi = 90^0$ results in a decrease in the maximum effective strain during ECAP to the lowest effective strain of 0.907. It should be emphasised that due to the gap that forms between the workpiece and the die, the angle of corner ψ_D utilised to be an Curvature of the workpiece in an arc ψ_w. If the workpiece fully engulfs the die as shown in Figure 2. Due to the space between the die and the specimen, the angle of corner the specimen ψ_w would be greater than that of the die ψ_D. Using the die angle of corner ψ_D is underestimated[8].

The specimen's corner angle was the similar as the die and there was no corner gap. Intriguingly, the results of 4340 steel show that the ram speed affects the the development of the corner gap. For instance, development of the corner gap at ram speeds of less than 25 mm/s^{-1}, as opposed to the ram speeds of B2.5 mm/s^{-1}. This shows that the generation of corner gaps is influenced by both the type of material used and the deformation circumstances[9]. One of the key factors in the corner gap development during ECAP is the workpiece materials' hardening behaviour. Based on a thorough comparison of the variations in material characteristics and deformation circumstances between two scenarios[10].

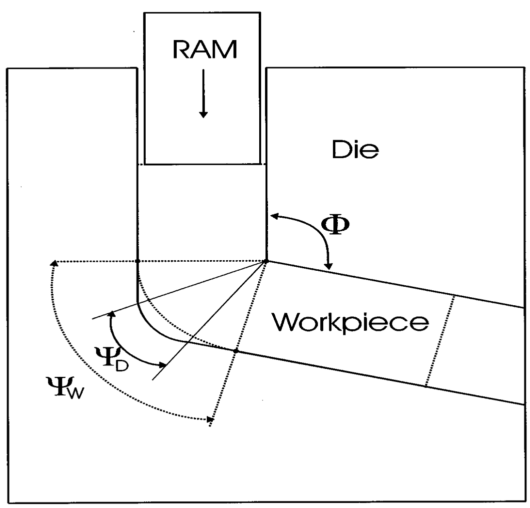

Figure 2. Equal Channel Angular Pressing method without a corner gap and with a corner gap between the die and the workpiece [23].

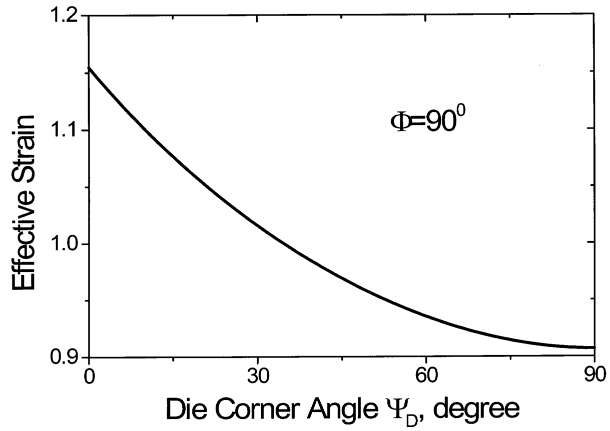

Figure 3. Relationship between effective strain and angle of corner [23].

Recognizing the corner gap phenomena and its relationship to strain development is crucial for a good ECAP die design. Because the amount of deformation and strain induced directly affect the mechanical properties of the pressed material[11]. There have been some recent research on the use of the finite element approach for the analysis of deformation during ECAPed. The creation of the die corner gap, particularly in relation to the qualities of the material, hasn't been covered in great detail, nevertheless. In forming die corner gaps during Equal Channel Angular Pressing and to examine the impact on the strain building up in the workpiece[12].

2.2 Strain Rate Model for Equal Channel Angular Pressing

The relationship illustrated by equation 1 is a frequently used equation for the equivalent strain created in the workpiece after one ECAP pass. The angle of die corner ψ and the angle of channel ϕ both result in a reduction in the equivalent strain[13]. When the angle of channel is fixed as $\phi = 90^0$. Figure 2 shows the variations in effective strain between a channel angle and a corner angle. It is clear that the die corner angle ψ has less of an impact on the strain during ECAP compared to the angle of channel ϕ . The "deformation time" or "dwell time" of the sample inside the deformity region is another parameter value that needs to be established[14]. The limited zone in the area where the two channels intersect is where the deformation during ECAP takes place. Deformation takes place right next to the plane, or in the shear plane, which is located where the two channels converge in figure 3.

The material travels through MDZ more quickly at the inner corner zone of the workpiece than at the outer corner zone. The material flows at various rates between the inside and exterior of the workpiece[15]. In other words, as you get further away from the inside corner, the speed in MDZ increases. The outcomes of the FEM will support this. Due to the uneven velocity within the MDZ, it is necessary to specify either the average speed or the average deforming time.

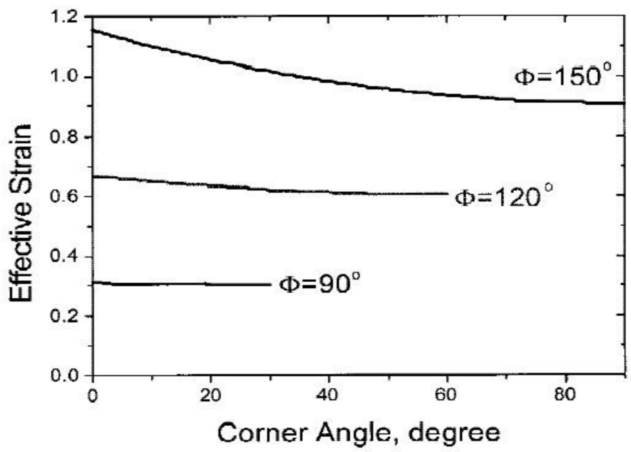

Figure 4. Angle of channel and angle of corner with strain [13].

A line parallel to curve $GG^{'}$ in Fig. 1 represents the geometric centre of the MDZ (b). Given that MDZ is an arc geometrically, W where is the width of the workpiece and diameter, the distance between point A at the inner corner and the curve $GG^{'}$ is $W/\sqrt{2}$ [16].

The strain rate equation during ECAP can be created by given equation,

$$\varepsilon = \frac{1}{\sqrt{3}}\left[2\cot\left(\frac{\psi}{2}+\frac{\phi}{2}\right)+ +\psi\cos ec\left(\frac{\psi}{2}+\frac{\phi}{2}\right)\right]\frac{\sqrt{2V}}{\psi W} \quad (3)$$

The angle of corner tends to infinity as it approaches zero. Even if the die corner angle is zero, Due of the shear plane limited breadth, the material cannot entirely fill the die[17]. It was noted that a number of variables. Instead of the die, material properties affect the angle of corner and the deforming workpiece.

3. Finite Element Analysis

Isothermal two-dimensional plane strain FEM simulations for the ECAP process were performed using the industry-standard elasto-plastic finite element programme ABAQUS. Experimental and theoretical evaluations show that modest pressing speed can satisfy the isothermal criterion. With dies of $\psi = 0^0$, 45^0 and 90^0, it was determined that this number of pieces was adequate to represent local deformity of the sample. In order to eliminate the influence of strain rate and strain hardening on the behaviour of deformation and concentrate the analysis on purely geometric factors, A fictitious model material that behaves in an elasto-perfect-plastic way was used for the computations[18]. A 0.02 mm/s constant ram speed was mandated. It was expected that there would be no rubbing of the specimen against the die channel inside, which would imply a frictionless environment. Despite the fact that the impact of friction was not considered in the current study and effect of the ECAP process to be the main point of attention. Friction is a crucial process parameter. This slows the surface material's flow and causes shear strain is greater at the workpiece lower zone and bottom shear strain at its top zone. Two different types of materials were used to examine the effects of strain hardening on the growth of the die corner gap. It is clear that an alloy's strain hardening is minimize in comparison to another alloy's. A fixed ram speed of 1 mm/s was mandated. To account for significant stresses and potential for localising flow during simulation, all simulations used automatic remeshing[19]. It was anticipated that there would be no friction between the specimen and the channel inside, or that there would be zero friction.

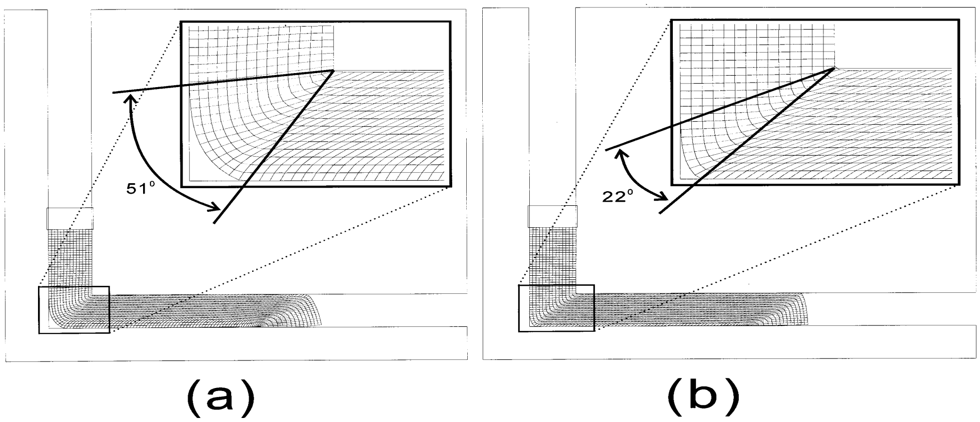

Figure 5. Schematic diagram of strain hardening and quasi-perfect plastic materials AA5083 through grid distortion [23].

4. Results and Discussion

There are two gaps between the die and the workpiece in the computed results for the coarse mesh of 0.6 mm. the distance in the die exit channel between the billet top and it. The size of the corner gap, on the other hand, is lower for fine mesh estimate does not account for the exit channel gap. Too-coarse mesh analysis is unable to accurately represent full die filling[20]. In materials that undergo strain hardening and the corner gap develops while in materials that undergo rate sensitivity and exit channel gap develops during the frictionless ECAP process of $\phi = 90^0$, $\psi = 0^0$ with the fine mesh $\phi = 135^0$, $\psi = 0^0$, and, the workpiece surface produced and this extended LSZ is distinctive of the round corner die ECAP process. The exit channel gap in Figure 4 is caused by a higher bending effect in round corner dies than in 45 degree[21]. The workpiece corner angles are larger than the die corner angles regardless of zero degree.

Both situations result in the gap development in the exit channel, however the round corner die's are greater than the sharp corner die's because of the stronger bending effect. Evidently, a large channel angle die produces less shear strain during ECAP than a small one[22]. Another thing to keep in mind is die corner gaps not only lessen shear deformation overall but also amplify strain inhomogeneity. Figure 5 displays the calculated effective strain rate distributions at the ECAP steady states. It is augean to detect between the deforming zone and the undeforming region since deformation happens within the MDZ as well as before and after it, and the boundary separating them is hazy[23].

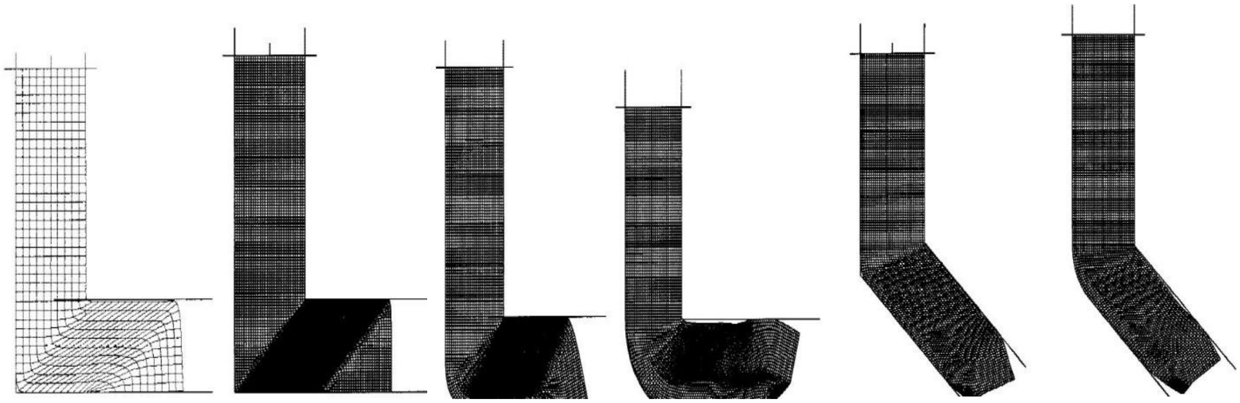

Figure 6. Deformed Geometry through ECAPed Processed [13].

It is easier to see the maximum strain rates across the shear plane as well as the strain rates along the centre curve[24]. It can be deduced that finite element analyses using coarse mesh systems cannot accurately represent the local deforming behaviour because a mesh only captures the averaged values within an area of one element shown in figure 6. While estimating the values in the low deformed zone, coarse elements overestimate the values of strain and stress. When the die corner angle is zero, the strain rate is rather uniform throughout the deforming zones along the line AB. Regionally high strain rates are present close to the inner corner point, and they gradually decrease as one advances from the inner corner toward the point[25]. Because a high strain rate increases the flow stress of rate-sensitive materials while also enhancing the heat generated during plastic deformation. With increasing distance from the inner corner and strain rate would fluctuate, which would have more complicated impacts on the inhomogeneity of deformation[26].

It is obvious that the behaviours of the strain hardening and quasi-perfect plastic materials when filling die corners are very different. In AA5083, the corner gap between the workpiece and the die is significant and it is less so in materials that exhibit minimal strain hardening behaviour. The corner gap is projected to completely disappear for real perfect plastic materials with 0% hardening rate. Even though the die corner angle ψ was 0°, and workpiece does not exactly match the die's corner shape[27]. It is not necessary for the high strain development in the workpiece to have a sharp die corner angle. The gap of corner on the side of entry is longer than the corner gap on the side of exit. This can be attributed to the asymmetry of the deformation strain and the loading conditions in regard to the central shear plane. The stress distribution that has formed in the workpiece can be used to explain the mechanism of die corner gap creation. For the non-hardening material, the workpiece fills the die corner as the ram presses[28]. For the strain hardening material, the interior of the workpiece within the deforming zone experiences more severe deformation and is harder than the exterior of the deforming zone. The exterior of the workpiece, which experiences less deformation and is softer than the interior can flow to the exit channel more quickly. The bottom surface of the finished workpiece formed of the strain hardening material displays less shear distortion than the non-hardening workpiece because the outside surface of the strain hardening workpiece travels less distance than the outside surface of the non-hardening workpiece[29].

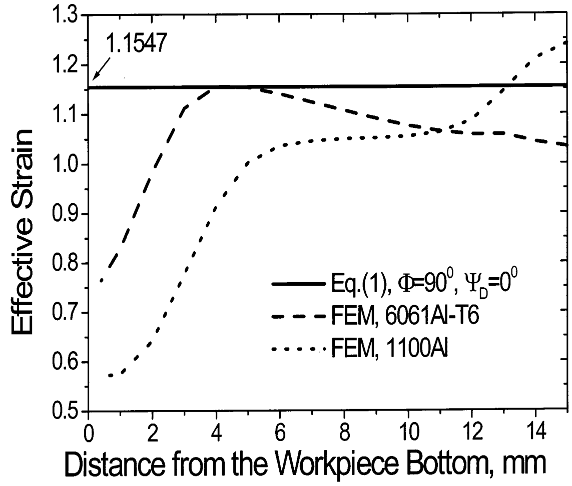

Figure 7. Schematic diagram of curves depicting strain distribution along the workpiece stable region [23].

Figure 7 shows the effective strain distributions along the workpiece's path normal to the pressing direction[30]. For both strain hardening and non-hardening materials, the workpiece exhibits low strain due to the formation of corner gaps and bottom portions. It should be noted that the generation of corner gaps increases the internal strain of the workpiece while decreasing the external strain. As a result, the strain distribution has a less uniform shape with wider corner gaps. These strain numbers and the average effective strain values from the FEM are more in agreement. It is preferable to use the workpiece's arc curvature rather than the die corner angle[31]. Due to the fact that the die corner gap is dependent on how materials respond to strain hardening and optimal ECAP die design may change depending on the material of the workpiece. Although it is anticipated that the material with the higher strain hardening behaviour will produce a larger die corner gap in the first pass, the size of the corner gap decreases over the course of further passes since the hardening rate normally decreases as total strain increases. Finite elements are being used to model the gap formation as well as the dead zone formation based on the process conditions[32].

5. Conclusion

In relation to the typical effective strain rate during Equal Channel Angular Pressing, an analytical formulation was put out. Increasing the channel angle and die corner angle results in a reduction in strain rate. The corner angle has a far greater effect on the strain rate than the channel angle due to the expanded primary deforming zone and shorter deforming time. The results of the finite element analysis support the strain rate equation's validity[33]. The influence of mesh size was also covered. In order to effectively analyse the local deformation behaviour using finite elements, corner gap formation is necessary[34]. Corner gap formation overstates the strain and stress values in the low deforming zone and understates the values in the highly deformed zone. It was discovered that the greater strain hardening rate material forms wider corner gaps because the workpiece softer exterior in the deforming region passes through the strain hardening material more quickly[35].

Reference:

[1] Kim, Hyoung Seop. "Evaluation of strain rate during equal-channel angular pressing." Journal of materials research 17.1 (2002): 172-179. https://doi.org/10.1557/JMR.2002.0026.

[2] Kim, Hyoung Seop, Min Hong Seo, and Sun Ig Hong. "On the die corner gap formation in equal channel angular pressing." Materials Science and Engineering: A 291.1-2 (2000): 86-90. https://doi.org/10.1016/S0921-5093(00)00970-9.

[3] Sevillano, J. Gil, Paul Van Houtte, and Etienne Aernoudt. "Large strain work hardening and textures." Progress in materials science 25.2-4 (1980): 69-134. https://doi.org/10.1016/0079-6425(80)90001-8.

[4] Junaidi Syarif, Amro Altoyuri, Intan Fadhlina Mohamed, Equal channel angular pressing of single crystal aluminum: a molecular dynamics simulation journal of materials research and technology 2022;17:888-897. https://doi.org/10.1016/j.jmrt.2022.01.061.

[5] Williams JC, Starke EA. Progress in structural materials for aerospace systems. Acta Mater 2003;51:5775-99. https://doi.org/10.1016/j.actamat.2003.08.023.

[6] Suryanarayana C. Structure and properties of nanocrystalline materials. Bull Mater Sci 1994;17:307-46. https://doi.org/10.1007/BF02745220.

[7] Sekar P, Sanna N, Desai V. Enhancement of resistance to galvanic corrosion of ZE41 Mg alloy by equal channel angular pressing. Mater Corros 2020;71:571-84. https://doi.org/10.1002/maco.201911337.

[8] Murata Y, Nakaya I, Morinaga M. Assessment of strain energy by measuring dislocation density in copper and aluminium prepared by ECAP and ARB. Mater Trans 2008;49:20-3. https://doi.org/10.2320/matertrans.ME200707.

[9] Larsen PM, Schmidt Sø, SchiØtz J. Robust structural identification via polyhedral template matching. Model Simulat Mater Sci Eng 2016;24. https://doi.org/10.1088/0965-0393/24/5/055007.

[10] Vijay Reddy K, Pal S. Structural evolution and dislocation behaviour during nano rolling process of FCC metals: a molecular dynamics simulation based investigation. J Appl Phys 2019;125:095101. https://doi.org/10.1063/1.5085750.

[11] A.I. Alateyah, Mohamed M. Z. Ahmed, Majed O. Alawad d, Sally Elkatatny, Yasser Zedan, Ahmed Nassef, W.H. El-Garaihy, Effect of ECAP die angle on the strain homogeneity, microstructural evolution, crystallographic texture and mechanical properties of pure magnesium: numerical simulation and experimental approach journal of materials research and technology 2022;17:1491-1511 https://doi.org/10.1016/j.jmrt.2022.01.088.

[12] Segal VM. Materials processing by simple shear. Mater Sci Eng, A Jul. 1995;197(2):157-64. https://doi.org/10.1016/0921-5093(95)09705-8.

[13] Kim, Hyoung Seop. "Evaluation of strain rate during equal-channel angular pressing." *Journal of materials research* 17.1 (2002): 172-179. https://doi.org/10.1557/JMR.2002.0026.

[14] Nagasekhar AV, Tick-Hon Y, Li S, Seow HP. Effect of acute tool-angles on equal channel angular extrusion/pressing. Mater Sci Eng, A Nov. 2005;410(411):269-72. https://doi.org/10.1016/j.msea.2005.08.043.

[15] Shaeri MH, Salehi MT, Seyyedein SH, Abutalebi MR, Park JK. Characterization of microstructure and deformation texture during equal channel Angular pressing of AleZneMgeCu alloy. J Alloys Compd Nov. 2013;576:350-7. https://doi.org/ 10.1016/j.jallcom.2013.05.182.
[16] Alkorta J, Gil Sevillano J. A comparison of FEM and upperbound type analysis of equal-channel angular pressing (ECAP). J Mater Process Technol Nov. 2003;141(3):313-8. https://doi.org/10.1016/S0924-0136(03)00282-6.
[17] Fan GD, Zheng MY, Hu XS, Xu C, Wu K, Golovin IS. Improved mechanical property and internal friction of pure Mg processed by ECAP. Mater Sci Eng, A Oct. 2012;556:588-94.
[18] del Valle JA, Carre~no F, Ruano OA. Influence of texture and grain size on work hardening and ductility in magnesiumbased alloys processed by ECAP and rolling. Acta Mater Sep. 2006;54(16):4247-59. https://doi.org/10.1016/j.actamat.2006.05.018.
[19] El-Shenawy, M., Mohamed MZ Ahmed, Ahmed Nassef, Medhat El-Hadek, Bandar Alzahrani, Yasser Zedan, and W. H. El-Garaihy. "Effect of ECAP on the Plastic Strain Homogeneity, Microstructural Evolution, Crystallographic Texture and Mechanical Properties of AA2xxx Aluminum Alloy." *Metals* 11, no. 6 (2021): 938.
[20] Leiter, H. "Nanostructured materials: basic concepts and microstructures." Acta Mater 48 (2000): 1-6. https://doi.org/10.1016/S1359-6454(99)00285-2.
[21] Nagendra Singh, Dr. Manoj Kumar Agrawal, Sanjeev Kumar Verma, and Ashish Kumar Tiwari et al. "A Review on Effect of Stress and Strain Distribution on the AA5083 With Respect to Different Channel Angle of ECAP." International Research Journal on Advanced Science Hub 4.3 (2022): 57-66. http://dx.doi.org/10.47392/irjash.2022.013
[22] Azushima, Akira, et al. "Severe plastic deformation (SPD) processes for metals." CIRP annals 57.2 (2008): 716-735. https://doi.org/10.1016/j.cirp.2008.09.005.
[23] Kim, Hyoung Seop, Min Hong Seo, and Sun Ig Hong. "On the die corner gap formation in equal channel angular pressing." Materials Science and Engineering: A 291.1-2 (2000): 86-90. https://doi.org/10.1016/S0921-5093(00)00970-9.
[24] Erol Akata, Huseyin. "Application of separated die design to production of ECAP dies." Advanced Materials Research. Vol. 445. Trans Tech Publications Ltd, 2012. https://doi.org/10.4028/www.scientific.net/AMR.445.120.
[25] Beyerlein, I. J., R. A. Lebensohn, and C. N. Tome. "Modeling texture and microstructural evolution in the equal channel angular extrusion process." Materials Science and Engineering: A 345.1-2 (2003): 122-138. https://doi.org/10.1016/S0921-5093(02)00457-4.
[26] Sanusi, Kazeem O., Oluwole D. Makinde, and Graeme J. Oliver. "Equal channel angular pressing technique for the formation of ultra-fine grained structures." South African Journal of Science 108.9 (2012): 1-7. https://hdl.handle.net/10520/EJC127477.
[27] Segal, V. M. "Materials processing by simple shear." Materials Science and Engineering: A 197.2 (1995): 157-164. https://doi.org/10.1016/0921-5093(95)09705-8.
[28] Bagherpour, E., et al. "An overview on severe plastic deformation: research status, techniques

classification, microstructure evolution, and applications." The International Journal of Advanced Manufacturing Technology 100.5 (2019): 1647-1694. https://doi.org/10.1007/s00170-018-2652-z.
[29] Abd El Aal, Mohamed Ibrahim, and M. M. Sadawy. "Influence of ECAP as grain refinement technique on microstructure evolution, mechanical properties and corrosion behavior of pure aluminum." Transactions of Nonferrous Metals Society of China 25.12 (2015): 3865-3876. https://doi.org/10.1016/S1003-6326(15)64034-1.
[30] Sklenicka, Vaclav, et al. "Equal-channel angular pressing and creep in ultrafine-grained aluminium and its alloys." Aluminium Alloys-New Trends in Fabrication and Applications (2012): 3-45. https://doi.org/10.5772/51242.
[31] Samsudin, M. H. M., Denni Kurniawan, and Fethma M. Nor. "Strain distribution equal channel angular pressing of magnesium alloy at 90^0 and 120^0 corner angles." Procedia Manufacturing 2 (2015): 230-235. https://doi.org/10.1016/j.promfg.2015.07.040.
[32] Ebrahimi, M., F. Pashmforoush, and C. Gode. "Evaluating influence degree of equal-channel angular pressing parameters based on finite element analysis and response surface methodology." Journal of the Brazilian Society of Mechanical Sciences and Engineering 41.2 (2019): 1-12. https://doi.org/10.1007/s40430-019-1597-y.
[33] Kamaruddin, Akmalia Shahira, and Mohd Nizam Katimon. "Simulation study on the material stress distribution respect to different angle of ECAP." Research Progress in Mechanical and Manufacturing Engineering 2.2 (2021): 433-441. http://publisher.uthm.edu.my/periodicals/index.php/rpmme.
[34] Eivani, A. R., et al. "Simulation of deformation and fracture initiation during equal channel angular pressing of AZ31 magnesium alloy with covered tube casing." Journal of Materials Research and Technology 12 (2021): 1913-1923. https://doi.org/10.1016/j.jmrt.2021.03.096.
[35] Mousavi, Seyed Elias, et al. "Effect of the equal channel angular pressing route on the microstructural and mechanical behavior of Al-5086 alloy." Materialia 4 (2018): 310-322. https://doi.org/10.1016/j.mtla.2018.10.007.