DIE DESIGN PARAMETERS AND EFFECT OF BACK PRESSURE ON AA5083 THROUGH ECAPED TECHNIQUE

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Abstract. Techniques for severe plastic deformation are those that generate exceptionally high strains of plastic in one pass and mostly utilize shear stresses. Additional passes during the process may potentially result in higher strain values. Because die production is simple, equal channel angular processing is the most often used technique among SPD techniques. However, the strong notch effect limits the use of the dies and is often the cause of die failures such corner cracking. In order to eliminate die failures during the production of ECAP dies, a multi-element die design method was employed, which led to many passes of deformation of the 5083 Aluminium alloy specimen. Even though die arrangement and fastening still need work, dies can be used safely, corner cracking has never been observed. Bulk material with full density was created using pure aluminium particles and back pressure equal channel angular pressing at room temperature. The outcomes showed that the successful production of strong bulk materials from particles. The present samples show finer grains with an average size of roughly 10 µm after four passes. The sample's density neared the theoretical density of pure aluminium and was noticeably higher than that of materials that were subjected to ECAP without back pressure. It was suggested that the source of this phenomenon was the interaction of strain accumulation, shear deformation, and hydrostatic pressure. Grain dislocations are constantly moving towards the grain boundaries as a result of the mechanisms behind grain refinement.

Keywords: *ECAP, die design, separated dies, back pressure, AA5083 ultra fine grains*

Introduction

Severe plastic deformation processes are the best approach to obtain large strength improvements and, in particular, refine grain size, especially when using relatively basic dies and die arrangements (Valiev and Langdon, 2006). When employing very simple dies and die arrangements, severe plastic deformation procedures are the most effective way to achieve significant strength gains and, in particular, refine grain size (Azushima et al., 2008). *Figure 1* illustrates the basic die geometry and layout. In conventional ECAP applications, the diameters of the entrance and exit cross sections differ based on the available press loads, properties of the material, and frictional conditions. The cross sections are produced in a square configuration. By repeatedly deforming the specimen with identical channel dimensions, higher strain values can be produced. Equation 1 is used to get the average strain value achieved in a single pass (Singh et al., 2023).

$$\varepsilon = \frac{1}{\sqrt{3}}\left[2\left(\cot\left(\frac{\phi}{2}+\frac{\psi}{2}\right)\right)+\psi\operatorname{cosec}\left(\frac{\phi}{2}+\frac{\psi}{2}\right)\right] \qquad \text{Eq. (1)}$$

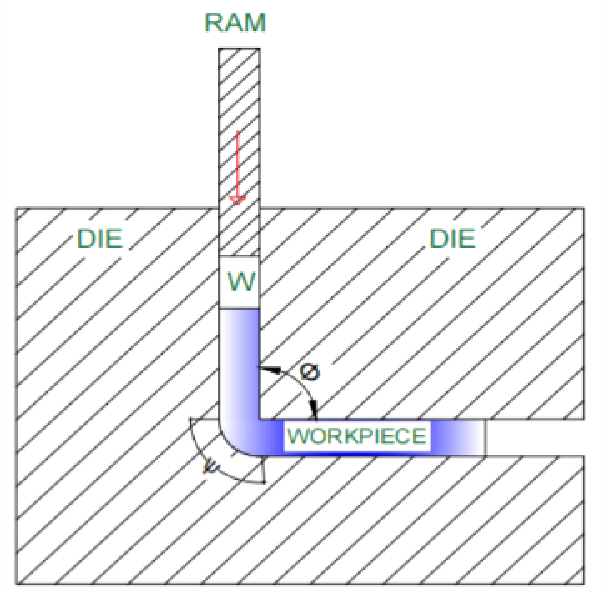

Figure 1. *Schematic diagram of ECAPed die with back pressure.*
Source: Singh et al. (2023a)

Diminishes to zero in the event that the channels lack curvature (*Figure 2*). Equation 2 provides the total strain after N passes in a more basic manner by accounting for N.

$$\varepsilon = \left(\frac{N}{\sqrt{3}}\right)\left[2\left(\cot\left(\frac{\phi}{2}\right)\right)\right] \qquad \text{Eq. (2)}$$

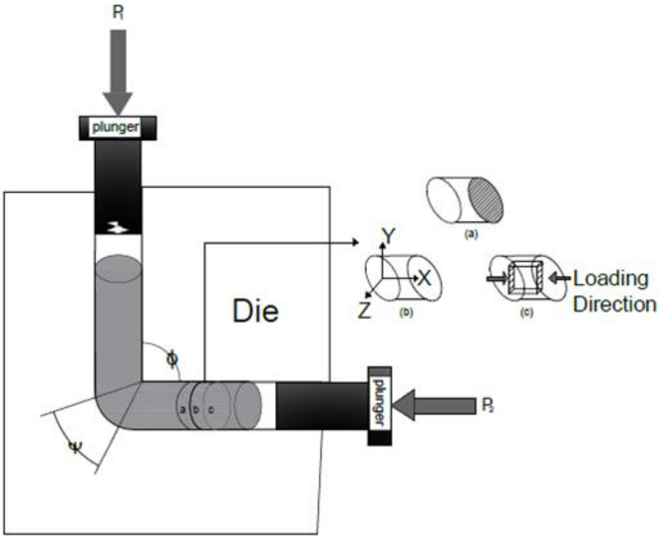

Figure 2. *ECAP technique with back pressure and plunger direction.*
Source: Singh et al. (2023b)

According to the second equation, many rounds of ECAP operations could result in extremely high equivalent strains. Higher back pressure (*Figure 3*) may be used in some circumstances to improve the workability of the treated material (Gur et al., 2008). Large shear stresses cause exceptionally high strains and strengthen the material during severe plastic deformation processes. They also dramatically lower the subject and technique used in nanostructure applications produce extremely fine granules. Several research (Balog et al., 2009) address the relationship between mechanical characteristics and grain size. But aside from the technical aspects that work well, there are certain problems with the ECAP dies. It takes high extrusion forces to raise overall stresses. Even with lubricants present, this raises the frictional forces between the material and the die walls. High overall load makes long punches less stable when buckling, hence high strength materials must be used in the design of the punch and die. Moreover, there is an exceptionally large concentration of stress at the die corners of square and rectangular cross sections, which causes cracking (Höppel et al., 2006). Numerous studies have been conducted on different die designs that assist material flow around corners, lower total loads and frictional effects, and combine conventional extrusion with an ECAP die (Pérez, 2004). Sometimes punches are made as tiny bits that are properly organized into dies to lessen the possibility of buckling. In certain instances, circular channel cross sections are created to reduce the notch effect and the ensuing crack formation.

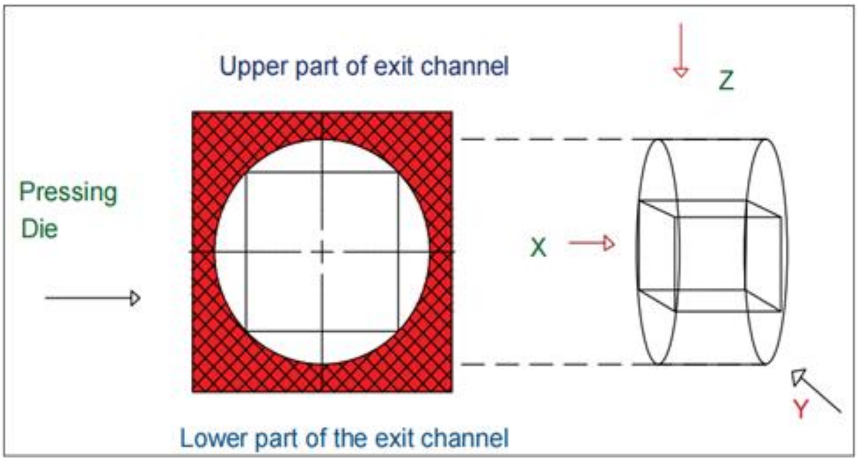

Figure 3. *A schematic diagram of the current angular pressing die with equal channels and ECAPed sample's planes that are sectioned off for observation.*
Source: Singh et al. (2024)

To lessen cracking at die corners, an alternate die design is suggested and used in the study that is being presented. To keep the four ECAP die parts together during the process, they are placed inside a die holder cylinder. There is no chance of the dies breaking because they have already been divided at the corners. Powder metallurgy and ceramic production have been used for a long time to synthesise particles with certain forms, sizes, and required performance characteristics in order to manufacture bulk materials (Singh et al., 2023b). It does not, however, involve extensive solidification processing and frequently leads to casting flaws and composition segregation, making it challenging to attain the desired theoretical hardness and density. Products of powder metallurgy have limited plastic deformation capabilities as compared to other dense materials. After processing, cracks are prone to forming, which makes it difficult to build up large effective strains or deformations. This has an effect on the microstructure refinement result, significantly reducing its toughness and strength. However, employing traditional powder metallurgy procedures to manufacture truly dense materials is challenging. In order to combine aluminium particles into extremely dense components, severe deformation techniques like extrusion-equal channel angular pressing (Mathieu et al., 2006), back pressure equal channel angular pressing, torsional-equal channel angular pressing and equal channel angular pressing have become more and more popular in recent years. ECAP-induced deformation works well to improve consolidation effects, increase relative density, and decrease porosity.

This approach has been employed to prepare particle-reinforced aluminum-based composite materials, particularly when the wrapped powder with sheath technique is applied. Strong particle contact and disruption of the surface oxide layer are assumed to result from the severe shear deformation in these processes. As a result, it is possible to create totally dense bulk materials and perform consolidation at room temperature (Wang et al., 2009). High pressure and forceful shearing are combined in a novel way called back pressure equal channel angular consolidation (BP-ECAC) to form bulk materials from particles. In earlier studies, back pressure equal channel angular pressing was used to consolidate micrometer-sized aluminium particles. The effective use of BP-ECAC in the production of aluminium matrix composites containing fine flyash particles results in ultrafine metal matrix composites as well as a considerable increase in efficiency, which lowers production costs. In the current study, bulk material was created at room temperature using pure aluminium particles and the BP-ECAP technique. A back pressure block was inserted into the ECAP mold's channel to increase hydrostatic pressure, which allowed for the creation of consistent shear within a vast volume of material. The aluminium powder was contained in a pure aluminium sheath. Effective bonding between particles, reaching full density, and producing finely grained structures were indicated by hardness tests (Yoon et al., 2007).

Materials and Methods

The aluminium melt atomization process was utilised to create the pure aluminium powder, which had an average particle size of roughly 35µm. Because of its face-centered cubic structure, 12 slip systems, and great plasticity, pure aluminium powder was chosen as the experimental material. ECAP deformation application leads to efficient deformation and fruitful consolidation (Balasundar et al., 2009). In order to generate sufficient strain for effective structure refinement during ECAP, a pure aluminium sheath was utilised. The sheath contained the pure aluminium powder, and the deformation process happened at the same time as the sheath. The barrier functioned as a sheath to stop contamination. Back pressure equal channel angular pressing (BP-ECAP) is an excellent choice for practical industrial applications because of these characteristics. The BE-ECAP mould consists of a punch, a sheath, and a die, as seen in *Figure 1*. The mould has a split structure, with the separating surface located close to the channel's edge, to facilitate a smooth sample extraction. To ensure the die has enough radial pressing force and prevent flash at the blank's parting surface, a Mo type taper fit is employed between the extruding die and the sheath. Samples of cuboids, 15 mm by 15 mm, were prepared for BE-ECAP analysis (Xu and Langdon, 2003). Using a die with and , where indicates the outer arc of curvature and indicates the inner arc. To ensure the die has enough radial pressing force and prevent flash at the blank's parting surface, a Mo type taper fit is employed between the extruding die and the sheath.

Experimental procedure

Prior to the experiment, a precise first compaction was achieved by compressing the pure aluminium powder inside a cylindrical aluminium sheath. To meet volume requirements, deformation zone distribution, and strength requirements, the thickness of the sheath must be considered. The extent of deformation in the bottom area is relatively little because of the unequal distribution of deformation in the deformation area. To guarantee that the powder deformation is uniform, an appropriate margin is maintained (Singh et al., 2024). To increase back pressure and prevent powder loss during pressing, a 5 mm thick gasket was constructed to protrude forward in the entrance channel. The microstructure of the material was examined using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The calibration procedure for the top-sectional plane Z, side-sectional plane Y, and cross-sectional plane X. Conventional metallography techniques were used to create a polished surface in order to permit SEM inspection. Then, for around 20 seconds, this surface was etched in a mixed acid solution containing 0.5% hydrofluoric acid, 1.5% hydrochloric acid, 2.5% nitric acid, and 95.5% water to disclose the grains (Matsuki et al., 2000). TEM research was done using an FEI-G20 at 200 kV. Thin foils for TEM analysis were made using punching discs with a 3 mm diameter. Next, utilising a Gatan691 plasma ion polisher, these foils underwent ion milling after being mechanically polished to 70µm. By using a 50g load and a loading time of 25 seconds, the Rockwell hardness test was used to evaluate the mechanical characteristics of the samples.

Die geometry and special considerations

The zero rounding off and perpendicular channel dies are the most popular ECAP dies because they provide the best grain refinement, are the easiest to machine, and can achieve around 115% equivalent strain in a single pass. In the investigation, this specific type of geometry was employed. The tube is 60 mm long and features machined cross sections that are 8 by 8 mm^2. The tempered AISI H13 hot work tool steel, which was used to create the die parts, is hardened to 50 HRC at 600 degrees Celsius due to the intense friction and high pressure in the channel area. Before testing, dies were polished after heat treatment (Senkov et al., 2005). Steel cutters with an 8x8 mm^2 high speed tool were used to cut the punches. Steel cutters with an 8x8 mm^2 high speed tool were used to cut the punches. The vertical groove at the bottom of the Number 1 section was then cut using a milling machine. The rectangular die components were rounded to a 28 mm diameter with a lathe after the channel machining. In the primary die assembly, each component was firmly inserted into a cylindrical hole with a wall thickness of 28 mm. The thick-walled cylinder and the remainder of the main assembly are fastened together to prevent the ECAP parts from likely moving vertically. *Figure 3* shows images of the components and the die assembly. Prior to every test, the die walls and specimen were lubricated. Due to a high blocking pressure between the die pieces and the holder, dies and the ECAPed specimen had to be removed from the die holder cylinder using ejector punches after the test was completed.

Results and Discussion

Al powder's microstructure evolution during BE-ECAP

Figure 5a shows the appearance and shape of pure Al powder produced by atomization. Equiaxed grains with an average size of around 35 µm and some coarse particles were still present in the pure Al particle. The morphology and visual depiction of pure aluminium powder produced by atomization are shown in *Figure 5a*. Along with some residual coarse particles, the equiaxed grains in the pure aluminium particles had an average size of roughly 35µm. Additionally, *Figure 5b* shows that the particles were asymmetrical, with most of the grains in each particle being equiaxed and averaging 6.36 µm in size. The contents of the powder as received were as follows: silicon (0.1%), iron (0.15%), copper (0.02%), oxygen (0.25%), aluminium (99.48%), and iron (0.15%). *Table 1* displays the powder's checked composition as it was received. Interestingly, the contents of Silicon (Si), Iron (Fe), Copper (Cu), and Aluminium (Al) match the typical contents of pure aluminium that is sold commercially. However, *Table 1* shows that the powder material had a greater oxygen concentration of 0.25wt%.The increased specific surface area of the aluminium particles as they were received was clearly responsible for this elevation's existence of surface oxide.

Table 1. *Percentages of weight for each chemical composition in the aluminium powder as received.*

Category	Percentage of weight (%)
Si	0.1
Fe	0.15
Cu	0.02
O	0.22
Al	99.48

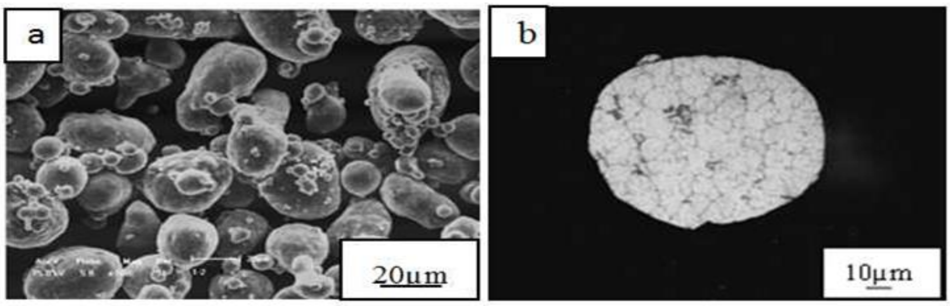

Figure 5. *The pure Al particles' as-received appearance and microstructure.*
Source: Matsuki et al. (2000)

Microstructure analysis following a single BE-ECAP process

The SEM pictures of the X and Y planes following a single room temperature BE-ECAP pass are shown in *Figure 6*. There were no visible pores and a strong connection between the particles. The closure of several micropores led to a significant increase in density. These results mostly agreed with those of earlier research (Gudimetla et al., 2018). When compared to the pure aluminium powder as received, the microstructure of the X plane does not change (*Figure 6a*). As seen in *Figure 6b*, the grains on the Y plane were considerably more refined and clearly elongated, with an average size of around 22.6µm, which was much smaller than the particles in their as-received state. It seems to be uniform, and the shear scars are clearly apparent. As previously mentioned, the findings show that during the start of the BE-ECAP process, the powder region did not make it to the front of the mold's corner. Due to the minimal degree of deformation in comparison to the sample as received, the pore morphology and powder matrix stayed unaltered. Due to severe shear deformation, the sample's microstructure and morphology significantly changed after the particles reached the corner area.

Mechanical interlocking and bonding consolidation were the outcome of the particles' movement, rotation, deformation, and fracture. This observation is consistent with earlier research findings (Gudimetla et al., 2015). *Figure 7* displays the TEM microstructure of the Y plane after a BE-ECAP pass. There was severe shear deformation between the particles, which caused the matrix structure to be significantly strained. This thus made it easier for the grains to develop multiple dislocations. A unique dislocation structure had typically formed inside the grains after a single BE-ECAP pass, and entangled dislocations were piled on top of one another to form a dislocation wall. Grain dislocations clearly travel in the direction of the grain boundaries, as Fig. 4a shows. Although the grain boundaries appear relatively blurry at the arrow point, more fully equiaxed subgrains (shown by the arrow in *Figure 7*) may be seen inside the local grains.

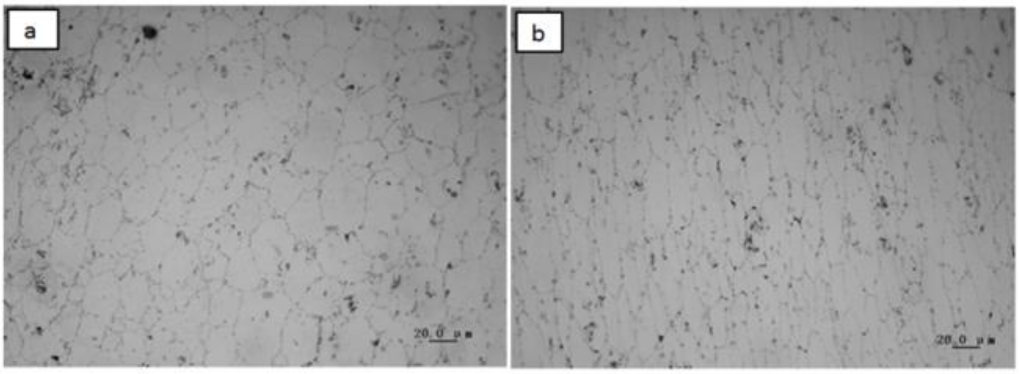

Figure 6. *The X and Y plane microstructures following a single BE-ECAP pass.*
Source: Senkov et al. (2005)

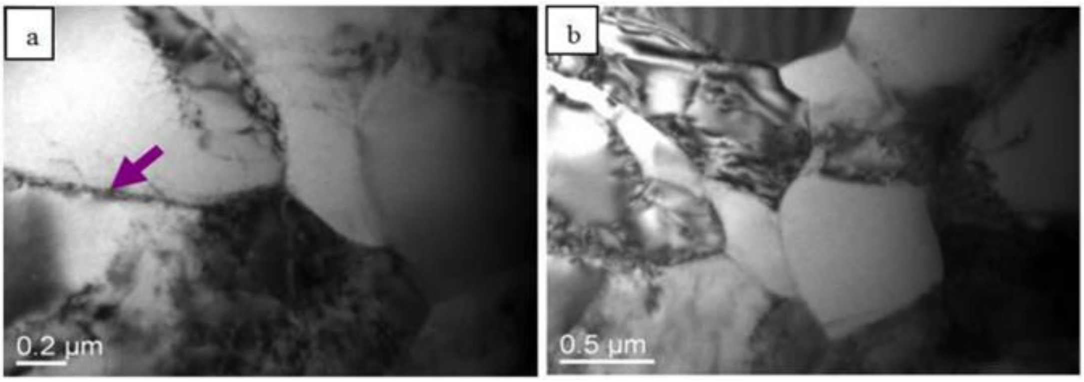

Figure 7. *Dislocation (a) and subgrain (b) morphology on the Y plane following a single BE-ECAP pass.*
Source: Gudimetla et al. (2015)

Microstructure analysis following two passes of BE-ECAP processing

TheThe SEM microstructure of the X and Y planes following two BE-ECAP passes is shown in *Figure 8*. Compared to the single pass prior, the X plane's microstructure is unchanged. However, the Y plane's microstructure continued to elongate, forming a structure resembling a band and displaying noticeable shear marks. However, additional elongation of the Y plane's microstructure resulted in a structure resembling a band and visible shear marks. *Figure 9* displays the TEM microstructure of the Y plane after two BE-ECAP passes. It can be observed when the shear strain increases, more dislocations occur, which makes it easier to refine the grains even more than in the first pass. A dislocation grid is formed as a result of the movement of dislocations, as seen in *Figure 9a*; the arrow in the figure indicates this. Within some of the grains, as seen in *Figure 9b*, sub-grains appeared, both fully formed and partially formed. They were not all the same size or shape, and there were no obvious dislocations. Accumulation of dislocations is still noticeable at the subgrain boundaries, with some of these boundaries appearing relatively flat.

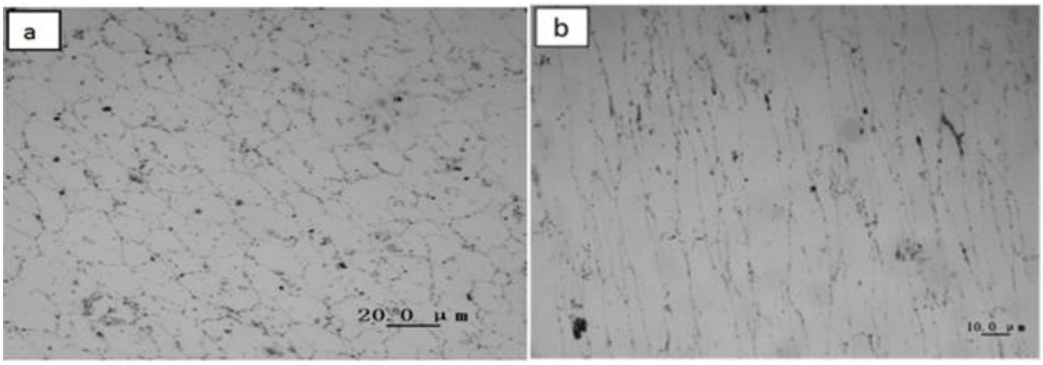

Figure 8. *After BE-ECAP for two passes, the microstructure of an X plane and a Y plane.*
Source: Gudimetla et al. (2015)

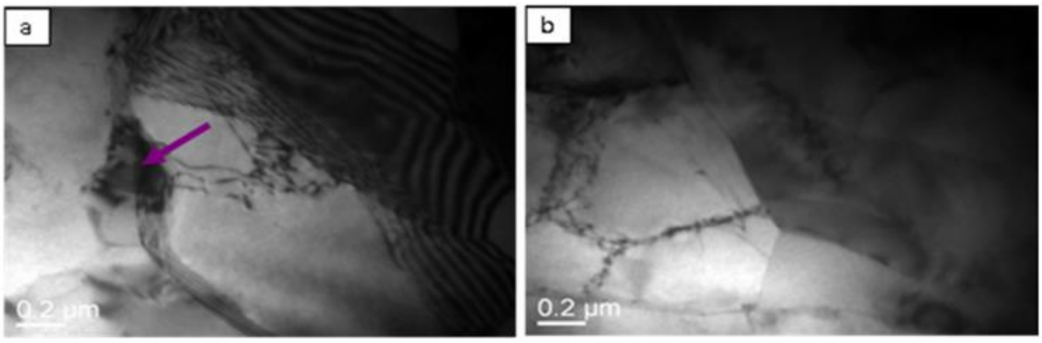

Figure 9. *The dislocation and b subgrain morphology on the Y plane following the BE-ECAP for two passes.*
Source: Wang et al. (2015)

Density and micro-hardness change with every pass

A lathe was used to remove the sample cover after each pass. The materials' densities were then calculated using the Archimedes principle on samples that had a volume of roughly 2 cm³ and were polished all over (Wang et al., 2015). Vickers hardness (HV) was measured in terms of mechanical qualities with a 50g load and a 25-second loading period. Ten distinct testing intervals were used to examine each material. The sample's density and HV values are shown in *Table 2*. With only one consolidation pass, the pure aluminium powder clearly underwent effective consolidation and densification, resulting in an increase of approximately 18.4% to a relative density of 97.0% and a micro-hardness of 38.6 HV. Afterwards, the BE-ECAP procedure helped to further improve and densify the material structure. But after four BE-ECAP passes, the relative density and micro-hardness increased at a slower rate, reaching 99.2% and 44 HV, respectively. This observation is consistent with earlier research findings. On the other hand, even after several passes, materials that underwent ECA deformation without back pressure were unable to reach their maximum density. According to the previously cited research, particles can be effectively bonded together at room temperature by undergoing severe shear deformation while under mild compressive stress (Jahedi and Paydar, 2010). With each BE-ECAP pass, the sample's density changed systematically due to displacement and deformation of the pure aluminium particles inside the container due to stress. The applied stress caused the powder to be shifted to fill the pores before the particles penetrated the mold's corner. The powder's arch bridge effect was broken, which caused the sample's density to rise quickly. When the particles arrived at the junction of the two channels, they experienced a considerable shear deformation. Some large particles were crushed once the powder's critical tension was exceeded, filling the spaces between the particles. Moreover, the metal particles' surface oxide coatings were ruptured by the shearing action, exposing newly cleaned surfaces. As a result, the sample's density increased even more, ensuring strong bonding between the particles. While the specimen's pores continued to close in the ensuing BE-ECAP passes, the degree of the rise in density was not as noticeable as it was in the initial pass. The sample's density grew closer to the theoretical density of pure aluminium after four BE-ECAP cycles. This illustrates the process's ability to provide a very positive powder compacting impact. Within the deformation zone, the metal experienced a considerable compressive stress due to the combination of the back pressure block's action and the particles' plastic deformation. This made the aluminium powder easier to consolidate and alloy.

***Table 2**. The sample's density and Vickers microhardness for each pass.*

Commercial pure Al	Density (g/cm^3)/Relative density (%)	HV (Kg/mm^2)
1st pass	3.69/107.0	49.7HV
2nd pass	3.72/108.1	52.3HV
3rd pass	3.73/108.5	13.2HV
4th pass	3.75/109.2	55HV

Conclusion

The study being presented aims to propose and develop an alternative die design that, when processing square cross-sectioned test items through ECAP, will stop corner cracking. Die holders were cylindrical, with dies consisting of four separate sections holding them together. There has been no sign of corner cracking on the divided dies. A few additional advancements in die layout and fixing are needed to shorten testing times and improve automation capabilities. The experiment's findings support the study's success and the safety of die use. The plastic deformation and consolidation of pure aluminium powder under hydrostatic pressure were aided by the application of back pressure. After the first pass through at room temperature, full density and robust bonding throughout the volume were achieved. The powder underwent severe shear deformation, filled holes, and underwent displacement throughout the consolidation process. When the powder was subjected to stresses greater than the critical stress, it began to deform, which caused the arch bridge effect to be disrupted. After four BE-ECAP passes, the sample's density increased and approached the theoretical density of pure aluminium due to the enhancement of the filled pores effect. After just one BE-ECAP pass, the grain saw significant refining, going from an as-received state of roughly ~35 µm to 10.62 µm. Even if the powder was further refined after several BE-

ECAP runs, the magnitude gains seemed to be quite modest. The BE-ECAP deformation process was identified as the mechanism for grain refining. Dislocations created within the grains as a result of this process moved constantly to the boundaries between the grains, where they accumulated, were entangled, and eventually destroyed. This resulted in a continuous breaking of grains and a significant refinement of the grain structure.

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Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

REFERENCES

[1] Azushima, A., Kopp, R., Korhonen, A., Yang, D.Y., Micari, F., Lahoti, G.D., Groche, P., Yanagimoto, J., Tsuji, N., Rosochowski, A., Yanagida, A. (2008): Severe plastic deformation (SPD) processes for metals. – CIRP Annals 57(2): 716-735.

[2] Balasundar, I., Rao, M.S., Raghu, T. (2009): Equal channel angular pressing die to extrude a variety of materials. – Materials & Design 30(4): 1050-1059.

[3] Balog, M., Simancik, F., Bajana, O., Requena, G. (2009): ECAP vs. direct extrusion-Techniques for consolidation of ultra-fine Al particles. – Materials Science and Engineering: A 504(1-2): 1-7.

[4] Gudimetla, K., Jampana, G.V., Kumar, S.R., Ravisankar, B., Kumaran, S. (2015): Effect of Equal Channel Angular Pressing on Densification Behavior of Al 5083 Alloy Powder. – In Materials Science Forum, Trans Tech Publications Ltd. 830: 63-66.

[5] Gudimetla, K., Kumar, S.R., Ravisankar, B., Prathipati, R.P., Kumaran, S. (2018): Consolidation of commercial pure aluminum particles by hot ECAP. – In IOP Conference Series: Materials Science and Engineering (Vol. 330, No. 1, p. 012031). IOP Publishing 330(1): 6p.

[6] Gur, H., Ogel, B., Atala, H., Bor, S., Tan, E. (2008): Aluminyum Alasimlarinin Asiri Plastik Deformasyon. – Islemleriyle Uretimi 97p.

[7] Höppel, H.W., Kautz, M., Xu, C., Murashkin, M., Langdon, T.G., Valiev, R.Z., Mughrabi, H. (2006): An overview: Fatigue behaviour of ultrafine-grained metals and alloys. – International Journal of Fatigue 28(9): 1001-1010.

[8] Jahedi, M., Paydar, M.H. (2010): Study on the feasibility of the torsion extrusion (TE) process as a severe plastic deformation method for consolidation of Al powder. – Materials Science and Engineering: A 527(20): 5273-5279.

[9] Mathieu, J.P., Suwas, S., Eberhardt, A., Toth, L.S., Moll, P. (2006): A new design for equal channel angular extrusion. – Journal of Materials Processing Technology 173(1): 29-33.

[10] Matsuki, K., Aida, T., Takeuchi, T., Kusui, J., Yokoe, K. (2000): Microstructural characteristics and superplastic-like behavior in aluminum powder alloy consolidated by equal-channel angular pressing. – Acta Materialia 48(10): 2625-2632.

[11] Pérez, C.L. (2004): On the correct selection of the channel die in ECAP processes. – Scripta Materialia 50(3): 387-393.

[12] Senkov, O.N., Senkova, S.V., Scott, J.M., Miracle, D.B. (2005): Compaction of amorphous aluminum alloy powder by direct extrusion and equal channel angular extrusion. – Materials Science and Engineering: A 393(1-2): 12-21.
[13] Singh, N., Agrawal, M.K., Saxena, K.K., Kumar, S., Prakash, C. (2024): Advancement and Influence of Designing of ECAP on Deformation and Microstructure Properties of the AA5083 under Thermal Effects. – International Journal on Interactive Design and Manufacturing (IJIDeM) 18(3): 1809-1827.
[14] Singh, N., Agrawal, M.K., Verma, S.K., Tiwari, A.K. (2023a): Impact design of die parameters on Severe plastic deformation during Equal channel angular pressing: An overview. – In E3S Web of Conferences, EDP Sciences 430: 16p.
[15] Singh, N., Agrawal, M.K., Verma, S.K., Tiwari, A.K. (2023b): A review on impact route process on AA5083 of back pressure through equal channel angular pressing. – Materials Today: Proceedings 6p.
[16] Valiev, R.Z., Langdon, T.G. (2006): Principles of equal-channel angular pressing as a processing tool for grain refinement. – Progress in Materials Science 51(7): 881-981.
[17] Wang, S., Liang, W., Wang, Y., Bian, L., Chen, K. (2009): A modified die for equal channel angular pressing. – Journal of Materials Processing Technology 209(7): 3182-3186.
[18] Wang, X.X., Min, H.E., Zhen, Z.H.U., Xue, K.M., Ping, L.I. (2015): Influence of twist extrusion process on consolidation of pure aluminum powder in tubes by equal channel angular pressing and torsion. – Transactions of Nonferrous Metals Society of China 25(7): 2122-2129.
[19] Xu, C., Langdon, T.G. (2003): Influence of a round corner die on flow homogeneity in ECA pressing. – Scripta Materialia 48(1): 1-4.
[20] Yoon, S.C., Quang, P., Hong, S.I., Kim, H.S. (2007): Die design for homogeneous plastic deformation during equal channel angular pressing. – Journal of Materials Processing Technology 187: 46-50.