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Deformation Behaviour of the Billet and Tooling Design on AA5083 through Equal Channel Angular Pressing With Effect of Back Pressure

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Abstract

Equal channel angular pressing is an emerging method applied to subject materials to significant plastic strains while maintaining the original shape of the billet. Researchers have discovered that the level of strain attained through equal channel angular pressing is influenced by factors such as the angle of die, friction conditions, and the implementation of back pressure. These variables significantly impact the microstructure and the irregularity of strain within the billet being processed. The strain distribution is most consistent and closely resembles that of a simple shear deformation. This results in a consistent rotation of material along a constant strain path at the ends of the billet. As a result, the sizes of grain of AA5083 are submicrometer reduced range. The submicrometer grains in AA5083 exhibited considerable stability up to annealing temperatures of approximately 210 ^{0}C. Moreover, these fine-grained structures were retained in AA5083 even when subjected to annealing temperatures as high as 300 ^{0}C. After undergoing equal channel angular pressing by a single passage, the ultimate tensile stress of each alloy increased while the elongation to failure decreased accordingly. The metal flow during equal channel angular pressing is influenced by various factors. The tooling configurations used in the study included a "simple" design, which lacked moving of channel members, and a "complex" design featuring a sliding bottom floor. The non-uniform flow occurred not only near the head and tail of the pressing but also in other regions of the billet.

Keywords: *AA5083; Back Pressure; Ultrafine grain size; Deformation Behaviour, Flow Behaviour.*

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INTRODUCTION

For a considerable period, it has been recognized that subjecting metallic alloys to extreme plastic strains offers considerable advantages. These advantages encompass refining improving and microstructure the mechanical properties of the materials. Submicron grain structures of Bulk materials with can be produced by SPD. Traditional processes such as wire drawing involve continuously reducing one or more than one dimensions of the material thro
ugh strain, making it challenging to attain very high strains ($\varepsilon > 5$) except in the case of foils or filaments, which have limited practical uses. In recent times, several techniques for severe deformation have emerged, enabling the deformation of metallic alloys to extremely high plastic strains while maintaining nearly unchanged overall dimensions at ambient temperatures. Among these techniques, ECAP is recognized as one of the most straight forward deformation technique, characterized by a predominantly simple shear process under ideal circumstances, enabling the development of diverse microstructures. Moreover, the scalability of the technique

allows for the production of sizable material pieces [1]. ECAP stands out as one of the most efficient processes currently accessible for the severe deformation of bulk materials, catering to both research endeavors and industrial applications.

Fig. 1 provides a schematic representation of the ECAP process. In ECAP, a billet is subjected to compression as it is pushed through a die that has two channels that have the similar cross-sectional and meet at an angle 2ϕ. The billet is compelled to completely occupy the die channels, while the corner of the die is designed to be sharp. As the billet passes through the die, an element within it experiences a sudden shearing effect upon crossing the junction line between the two channels [2]. The extent of this shearing displacement is determined by the die angle. In such situation the shear strain magnitude denoted as can be calculated using Equation 1.

$$\gamma = 2\cot\phi \tag{1}$$

Here, represents half of the angle that is created internally between the two channels. Consequently, the Von-Mises effective strain per pass can be expressed as indicated in Equation 2.

$$\gamma = \frac{2}{\sqrt{3}}\cot\phi \tag{2}$$

It is important to note that the aforementioned analysis represents an idealized scenario and does not consider the influences of factors such as rounded die corner and friction or incomplete billet filling within the die.

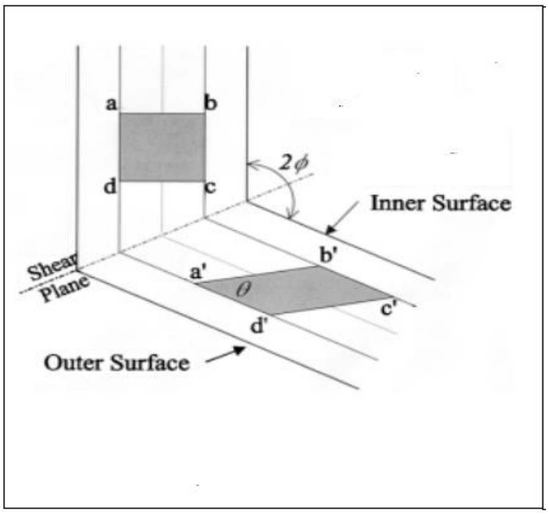

Fig. 1: Provides visual representations of the ECAP processes [3].

The sample ends behaviour when it enters the shear plane first causes the deformed billet to be uneven. The primary cause of this is the billet's partial filling of the die corner as a result of friction. In order to estimate the shear strain in such cases where the deformity zone spreads through an arc, it is important to consider these factors. According to the analysis, in certain circumstances, the deformation becomes more intricate and the highest attainable shear strain is constrained by Equation 1 [4].

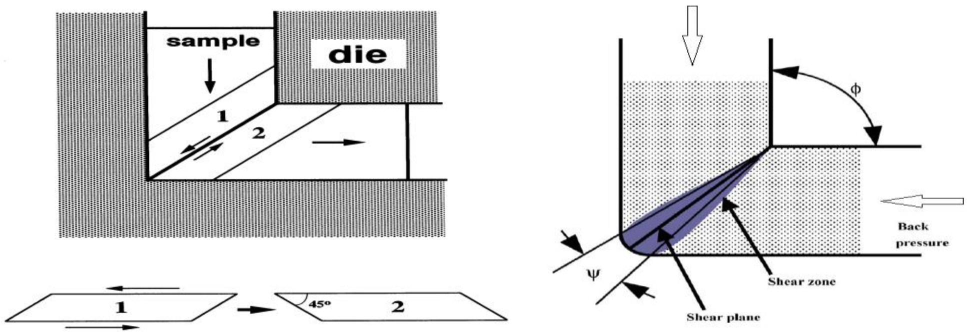

Fig. 2: Shearing plane within the die of ECAP Process and Back Pressure [5].

In real-world applications, a minimum die angle limits the strain every pass, resulting in a maximum effective strain of 1.18. As a result, multiple repeated pressing cycles are necessary to achieve high strains. It is a common misconception that multiplying Equation 2 by the quantity of pressing cycles will yield the overall strain after a number of cycles mentioned in Fig. 2. However, as no actual data has been offered to support it, this assumption lacks experimental support. It is standard procedure to rotate the billet about its axis between pressing cycles during ECAP processing. This rotational movement facilitates the development of diverse microstructures within the material. However, it should be noted that this rotation can result in cyclic redundant strains occurring with each full rotation 360^0. A consistent strain path keeps the shearing effect from building up, which causes the billet to lengthen with each pass [6]. In ECAP, the geometry of the billet remains relatively unchanged after the initial pressing cycle, despite undergoing multiple subsequent pressings through the die. It implies that additional deformations must take place within the ECAP process to ensure the billet's dimensions remain constant.

Fig. 3 depicts the fundamental concept of ECAP, where a sample is subjected to compression by a die consisting of two channels that cross close to the centre of die. This configuration results in the sample undergoing deformation of shear, as mentioned in the schematic illustration in Fig. 3. Which is perpendicular to the samples longitudinal axis and y-plane & z-plane, which are similar to the side and top surfaces of the pressed sample respectively at the point when it emerges from the die. The angle ϕ at which the two channels intersect is what essentially determines how much strain is created in a single rotation of the die. In practical terms, when the angle of intersection $\phi = 90^0$ is such that the channels meet at a right angle, the strain imparted during a single pass, regardless of the specific value of ψ [7].

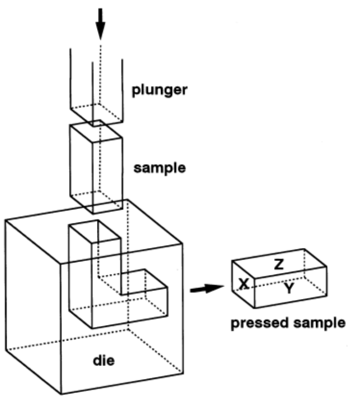

Fig. 3: ECAP system, showing the x-planes, y-planes and z-planes with respected direction [8].

It is evident that a more comprehensive examination of the deformation characteristics of the workpiece during ECAP is necessary for two primary reasons: firstly, to better comprehend the processes that lead to the development of sub-micron grain formations, and secondly, to successfully apply the method as a commercial process for ultra-high strain alloy deformation. The research primarily concentrates on investigating the influence of angle of die and friction on the deformity behavior of a material with strain hardening properties throughout one extrusion cycle. ECAP is a manufacturing process created to severely deform a material cross-section while preserving its original dimensions [9]. By putting the substance passing via a die that has two equal-sized channels, this deformation is accomplished simply by shearing it., intersecting at a specific angle ϕ. ECAPed capacity to reduce a materials substance passing via a die or even nanoscale range is a significant advantage. A die with an internal angle of $\phi = 90^0$ is the most efficient way to achieve uniform microstructures with ultrafine grains. ECAP has a number of benefits over traditional powder metallurgy techniques, including the possibility to apply it to bulk samples made via ingot metallurgy. This eliminates concerns related to residual porosity that may arise in other techniques. Two important advantages result from reducing the grain size to the submicrometer region. The reduction of the grain size to the submicrometer range has two significant advantages. According to the Hall-Petch connection, it results in an increase in especially at low temperatures, while maintaining or minimally affecting overall tensile strength and ductility. While the potential of equal channel angular pressing for industrial applications is widely acknowledged, there are relatively few reports available that discuss the ECAP of commercial aluminum alloys. Subsequently, the samples that underwent ECAP were subjected to testing at high temperatures.

EXPERIMENTAL MATERIALS AND PROCEDURE

Selection of Materials

Table 1: Chemical Compositions of AA5083 in Weight Percent and Annealing Condition for 1 hr at 320 ^{0}C air cool [10].

Alloy	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Al**
5083	0.08	0.21	0.02	0.58	1.154	0.06	<0.01	-	bal

Every ECAP experiment was run at 200 ^{0}C room temperature and composition of AA5083 shown in Table 1. A solid die was employed, It comprised two circular cross-section channels that intersected at an angle of $\phi = 90^0$, accompanied by a curve on the outside at the point where the channels meet. It has been established that for these specific angles associated with channel intersection angle of $\phi = 90^0$, the sample undergoes an equivalent strain of ~1 on each pass through the die [11]. A speed of about 19 mm/s was used for the pressings, utilizing MoS_2 as a lubricant.

After the ECAP process, The obtained rods were cut parallel to their longitudinal axes, resulting in small disks with a thickness of ~ 0.4 mm. To assess the thermal stability of the microstructures obtained through ECAP, these discs went through an hour-long process of temperature variations for static annealing. The maximum temperature reaching 300 ^{0}C. The evaluation of microstructures and grain sizes was used TEM. The properties materials of each alloy were assessed in their as-pressed state by fabricating at temperatures range from 120 ^{0}C to 320 ^{0}C.

Equal Channel Angular Pressing Procedure

The creation of materials with tiny grain sizes and a consistent microstructure is the main goal of the ECAP process. The outer corner shape follows a parabolic pattern, with different ratios for d_v and d_h, resulting in varying overall curvature depending on the specific ECAP conditions, like Mold Shape Forced Corner (MSFC), Natural Corner (NC) and Fig. 4 illustration of a Back Forced Corner.

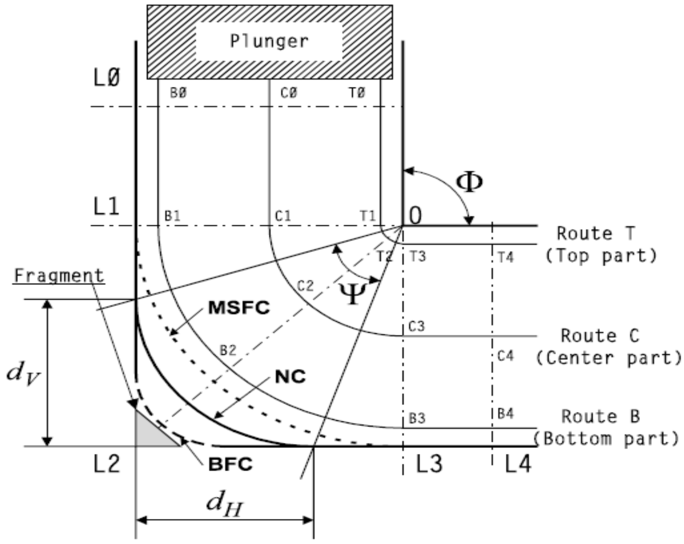

Fig. 4: The Condition of the Corner During the ECAP Procedure [12].

The natural corner refers to the billets outer corner shape when there is no friction, back pressure, or deformation brought on by the mould. Conversely, the mold shape forced corner arises when the corner's radius exceeds that of the natural corner. This increased radius causes extra deformation in the billet, thereby reducing the overall plastic deformation on its outer part.

Deformation Analysis of Experimental Procedure

To obtain accurate plastic strain values, experimental strain measured were made to interpret the deformation of the billet in detail. The symmetric plane of the ECAP die was meant to be the division line. It has a viewpoint perpendicular to the perspective plane shown in Fig. 5. There was a separation gap 90^0 in between the exit and entrance channels on the particular ECAP mould that was used.

The bent billet and the warped grids as a result of the ECAP procedure are shown in Fig. 6. A comparison was made between the grid shapes before and after passing through the mold corner. Due to the severe deformation in certain areas, the grids became elongated and thin, making it difficult to tell where the warped grids borders should be shorter length proved difficult and the measurement error was relatively more sensitive in thinner sections. To simplify the measurement and strain calculation, grid area was thought to remain consistent during the ECAP procedure. The sizes of the distorted grids were measured based on the images obtained.

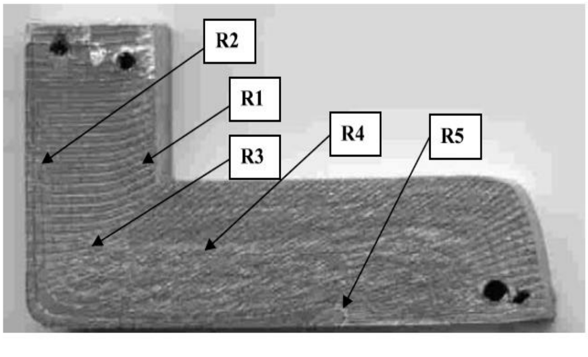

Fig. 5: A Pure Aluminium Sample that is Partly Distorted With Distorted Square Grids in the Centre Plane Undergoing ECAP with ($\psi = 0^0$, when $\phi = 90^0$) [13].

The sample was covered in lubricant made of molybdenum disulfide., and the pressing speed was set at around 19 mm/s. The ECAP process involved passing the sample through each of the five distinct shear planes within the die.

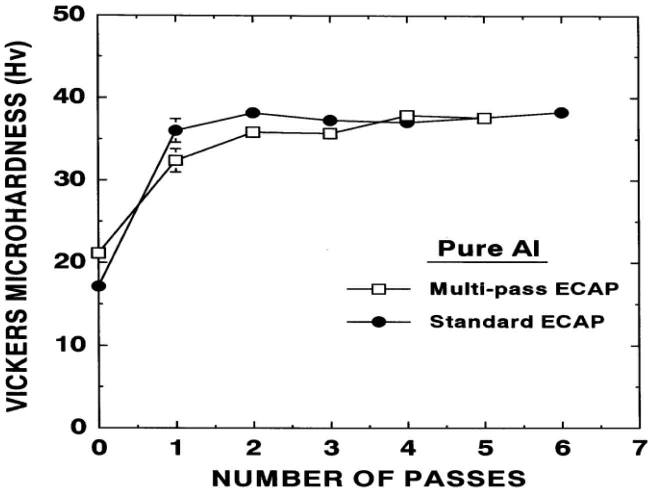

Fig. 6: Number of Passes for Two Different Types of Samples [14].

Finite Element Modeling

To investigate the influence of various factors on local stresses and strains in isothermal ECAP, finite element modeling was employed. The analysis focused on different combinations of material properties, tooling characteristics, and process variables. Considered was a fictitious workpiece material that exhibited three separate stress-strain behaviours as flow softening, rigid and perfectly pliable and strain hardening as shown in Fig. 7. Simulations were run with a range of 0.02 and 0.30 for the rigid fully behaviour of plastic constitutive. The deformation process required high flow stresses due to the complex tooling with corresponding channel sizes $2\phi = 90^0$. The FEM results were further validated by comparing them with previous observations of ECAP samples made from heated isostatically and cast pressed near-gamma titanium aluminide AA5083. These experiments also utilized a complex die with specific dimensions of $2\phi = 90^0$. Because intermetallic materials limited have much ductility, such as titanium aluminide, lubrication was applied to the bottom slider, resulting in higher back-pressure during the ECAP process.

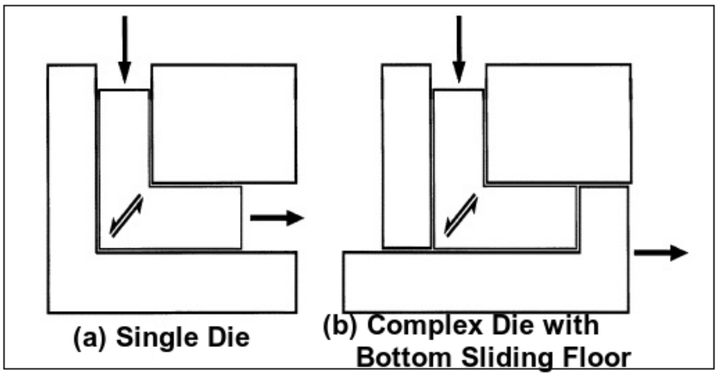

Fig. 7: Geometry of ECAP Tooling with Simple Die and Complex Die with Bottom Sliding Floor [15].

EXPERIMENTAL RESULTS

Experimental Deformation for Equal Channel Angular Pressing

The experimental setup consisted of an ECAP rig with two dies featuring specific angles between the channels for entry and exit of $2\phi = 90^0$ and 120^0. The pressing process was carried out using a hydraulic ram, which maintained a constant extrusion rate of 14 mm/min. The temperature was maintained at approximately 40 0C. To look into a billet's distortion after a single pass, AA5083 samples with scribed grids were utilized. These samples represented billets that undergo work hardening during the ECAP process. The samples were divided along their centre to produce the grids and the resulting center plane was meticulously mechanically and polished scribed to form a square grid with a pitch of 0.6 mm. These collets were fitted over the reduced diameter sections of the billet ends. However, during pressing, it was observed that the billets, being split along the symmetrical plane and die constraints, did not require the collets to remain intact. The collets mainly served the purpose of holding the two halves together during insertion into the die [16]. The split samples exhibited a nearly identical shape change compared to a solid rod, demonstrating that the deformation behaviour was not considerably affected by the splitting process.. To facilitate the study of metal flow behavior at the opposite end of the billet. There was no need for a collet at the other end because some samples might deform with just one collet.

The pressing of all split billets took place at room temperature, without monitoring the heat generated from the plastic deformation. Three distinct pressing conditions were investigated as (i) a "low friction" situation (ii) a "high friction" scenario (iii) a "low friction" condition along with the application of back-pressure. The "low friction" setup involved the use of a meticulously polished die, along with lubrication of the sample using polytetrafluoroethylene tape and spray. To apply back-pressure a constant opposing force of 8 kN was employed on the extruded end of the billet through the secondary ram. The applied back-pressure of 32 MPa corresponded to approximately 73% of the yielding strength of the commercially AA5083 material.

The two friction conditions were labeled as "low" and "high," although the specific values of coefficient of friction were not precisely found. Split specimens were partially extruded into the die, allowing for the investigation of grid distortion within the deformation zone situated at the billet's midpoint. To assess strain distribution in the deformed billets, grid element displacement was gauged at designated points. The existence of collets at the split sample's extremities had negligible influence on deformation when contrasted with a solid sample, and it had no impact on the measured strains within the billets' central areas.

Finite Element Simulation

Metal forming was used to perform finite element simulations of the ECAP technique, aiming to validate the data obtained from the deformed grids. The modeling process involved the use of a die with 120^0a specific geometry and two different friction coefficients denoted as between the die and the billet sliding surfaces were represented, $\mu = 0.002$ and $\mu = 0.6$. The coefficients were selected with the aim of approximating the friction experienced during the deformation of the divided samples under the aforementioned high and low friction conditions [17]. The die's inner corners were sharp and devoid of any fillet radius. The outcomes derived from this model were compared to prior finite element simulations that employed a similar 90^0 and 120^0 approach but utilized a different die with friction coefficients of $\mu = 0$ and $\mu = 0.28$.

To assess how the ECAP process impacted the uniformity of the resulting microstructures, samples were extracted from various regions within specific billets. These stages encompassed ultimate electro-polishing subsequent to mechanical polishing. Additionally, orientation mapping was performed on specific zones of a room temperature deformed billet composed of

AA5083. This mapping was executed utilizing electron back-scatter diffraction assessment with a 0.08 µm step size, covering regions measuring 40.5 µm by 18.5 µm.

Analysis of Billet Behaviour and Deformation Zone

A representative image of the central plane of a split specimen after deformation, along with its corresponding finite element analysis, the finite element mesh used was not the one shown in the grid. It functions as an overlay grid similar to the experimental scribed grid and is used to visualize the distribution of stresses.

These comparisons were specifically focused on the central segment of the billet, where the distribution of strain is relatively even. The objective of this study was to verify the claimed homogeneity of strain for shear in ECAP procedure and assess the accuracy of shear strain per pass predictions. This particular image corresponds to the low friction case of the die. In Fig. 8 only the traces of every second grid line are shown for better readability corresponding to the 90^0 and 120^0 dies, respectively. To obtained from the high friction case with the die, not all grid lines could be distinctly observed due to the extensive deformation of 90^0 experienced by this billet.

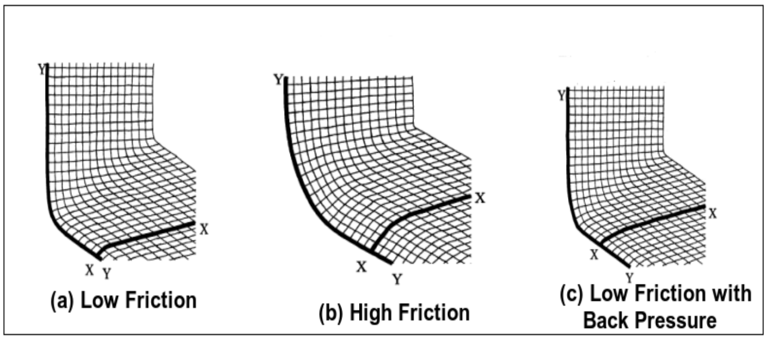

Fig. 8: The Pressing Conditions Measured through (a) Low Friction, (b) High Friction, and (c) Low Friction with Back Pressure [18].

When there is less friction and back pressure is present externally, the deformed samples exhibit a relatively sharp outer corner, indicating more uniform shearing across the width of the billets. In contrast, with low friction and no back-pressure depends on outer corner of the billets has a larger radius, showing that the die corner in both dies is not fully filled. A greater amount of the sample width has not been sheared equally. Die angle often results in a smaller deformation zone, in particular mentioned in Fig. 9. The high friction of die, and the grid lines curve backward on the top surface of the billet as a result of prevented sliding, leaving a visible thin layer on the surface. The sample deformed under the two circumstances that produced the least consistent shear at effect of back pressure in the die and low friction externally . This sample also has the sharpest external corner and the smallest deformation zone obtained at 90^0.

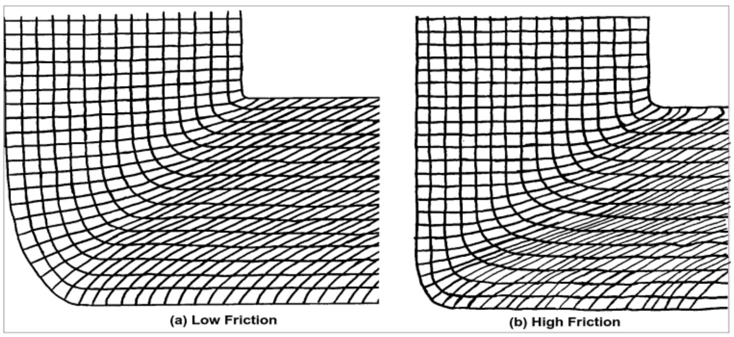

Fig. 9: These Traces Correspond to Two Different Conditions at (a) Low Friction and (b) High Friction [19].

The identical material properties and approach have previously been utilized for finite element simulation of deformation in Equal Channel Angular Pressing mentioned Fig. 10. Employing friction conditions of $\mu = 0$ and $\mu = 0.25$ both low and high magnitudes. These findings suggest that analogous outcomes are observed when using more acute die angles shown in Table 2.

Table 2: Comparison of the Estimated Strains and Shear Strains Measured from the Billets Uniform Region at Angle of Die for Various Condition [20].

Angle of Die (Degree)	Pressing Conditions	Calculated shear strain	Measured shear strain
120^0	Lower fiction	1.25	1.15
120^0	Higher friction	11.25	1.2
120^0	Lower friction +35 MPa back pressure	1.25	1.25
90^0	Lower fiction	2.2	1.9
90^0	Higher friction	2.2	2.05

The middle sections of the billet, which have undergone uniform deformation resemble the findings of measurements made using the scribed grids [21]. resemble the findings of measurements made using the scribed grids. When higher friction is present for all die angles 120^0, the inhomogeneous zone's breadth is decreased. In the scenario of the die model, once the maximum level is attained, the shear strain maintains a uniform distribution up to the inner surface. These findings indicate marginally elevated magnitudes in the case of high friction, attributed to the narrower deformation zone. When employing more acute die angles, there is a noticeable rise in the maximum shear strain under increased friction conditions. Nevertheless, when the die angle is subsequently decreased to $120^0$and 90^0, the shear strain displays a minor decline near both the inner and outer surfaces of the billet. This trend becomes more distinct with greater friction levels. This behaviour is in line with the results from the scribed grids, which show that friction on the inner die 90^0 wall prevents sliding, which reduces shear strain near the surface in the die.

The finite element models, however, exhibit this behaviour to a greater extent. The outcomes from the finite element analysis exhibit slightly greater magnitudes of maximum shear strains in comparison to the recorded values. Additionally, the impact of different friction levels on the outer surface is less conspicuous in the simulations than in the actual experiments. The use of straightforward 4-noded quadrilateral elements is probably a more logical explanation for the errors found. These elements do not handle bending conditions effectively due to their straight sides leading to shearing at the integration points and potentially causing an overly rigid response. Using second-order elements would be more suitable for accurately modeling bending behavior. It continued to capture the patterns witnessed in the recorded grids and generate almost indistinguishable overall alterations in the deformed billets' shapes. Upon a more thorough analysis of the grids situated close to the outer surface of the deformed specimens, it becomes clear that the grid components undergo elongation while traversing the deformation zone, subsequently undergoing compression upon exit.

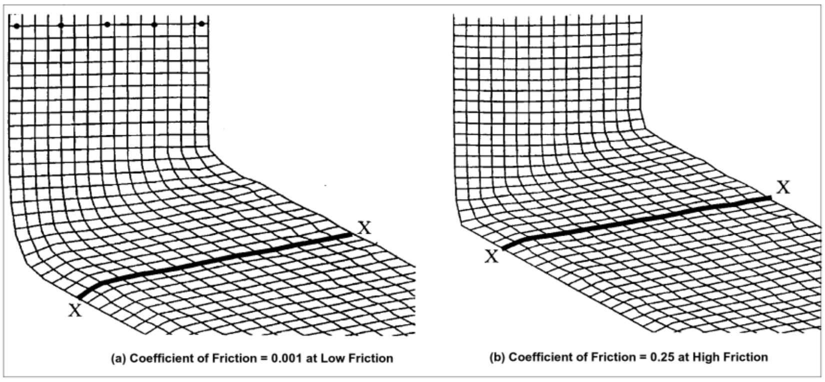

Fig. 10: Die Under Two Different Friction Conditions as (a) Low Friction at $\mu = 0.021$and (b) High Friction at $\mu = 0.35$ [22].

The finite element model $120^0$of the dies effective strains are provided as a function of time. To capture the measured of strains, five specific points along the center of the billet are selected as it traverses through the die. initial moment when corresponds to the completion of the billet's passage by the deformation zone. Fig. 11 shows optical images of this event in a single pass, low friction, no back-pressure deformation of an AA5083 alloy sample. On the inner surface of the specimen an elongated grain structure has formed as a result of the distortion caused by shear strain. At the outer surface, where tensile strain predominates and shear strain is minimal grains have remained relatively undistorted. These observations highlight that the current analyses are inadequate for predicting the shear strain in ECAP processing an arc-shaped deformation zone is present. This is due to the non-uniform distribution of strain throughout the billet, and the assessments fail to consider the influence of tensile strain. The findings show that the central part of the billet has a strain distribution, which undergoes uniform deformation is strongly influenced by factors such as die angle, friction and effect of back pressure.

The strain becomes more uniform when the deformation zone is significantly from the values predicted by Eq. (1). The presence of partial bending in the billet leads to an uneven distribution of strain across a significant portion of its width, reaching up to 42% with the 120^0 die. Hence, Eq. (1) represents an upper limit that can only be attained under ideal circumstances. The analysis reveals that die with a rounded internal corner promote billet bending, resulting in reduced homogeneity of deformation and lower shear levels. In addition to friction and die angle, the width of the deformation zone is influenced by the work hardening rate of the material. A narrower deformation zone brings it closer to an idealized state for an elastic-plastic solid.

Multiple Pass Deformation Behaviour

In ECAP, it is often necessary to subject billets to multiple pressing through the die, resulting in very high strain levels. However, the use of scribed grids to observe material flow becomes challenging when multiple pressing cycles are involved, as the grids become indiscernible [23]. To overcome this limitation, an alternative approach was adopted. In certain ECAP processing routes, the billet is rotated between each pressing, causing the shear strain to cyclically reverse. Conversely, when the pressing cycles are completed with the billet oriented consistently, the shear strain progressively increases with each repetition of the process. Even though it may appear counter intuitive for a body to keep its shape while being subjected to a growing single shear, when the billet orientation is maintained after the initial pressing cycle, it has been found, its dimensions remain relatively unchanged during subsequent repeated extrusions. To better comprehend why the billet exhibits this nearly invariant shape under a constant strain path in ECAP in Fig. 11.

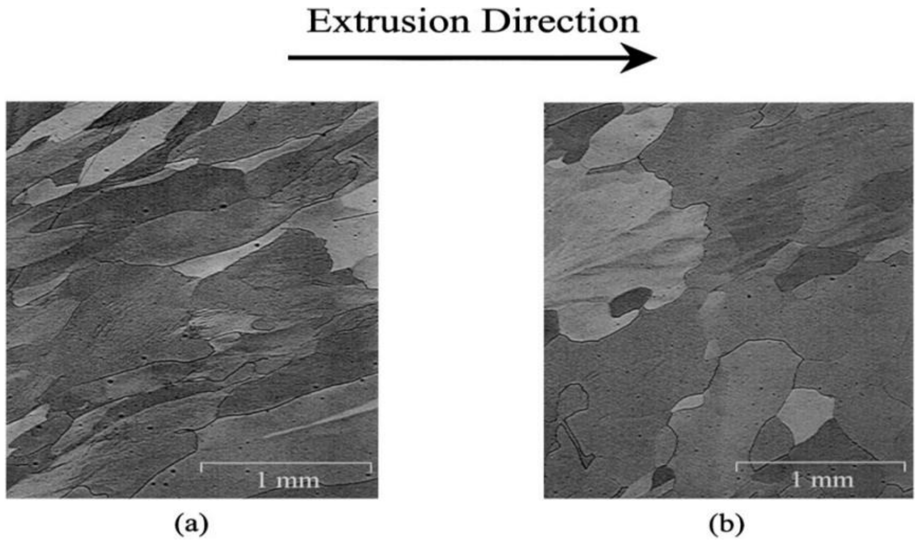

Fig. 11: Underwent Deformation at Room Temperature Without Application of Back Pressure and Under Low Friction Conditions [24].

The comparison of Fig. 12 demonstrates that the predicted and observed behaviors show a high level of agreement. This indicates that the finite element prediction, which assumes no friction fits the split sample's real deformation under low friction conditions quite well. The right-hand corner of the billet experiences the least amount of deformation during pressing as a result of the effective transit of the billet through the deformation zone before to being placed in the die 120^0. As the sample corner moves forward the material trailing behind it experiences shearing forces, which result in the pushing of the non deformed billet corner side and reason rotation at 90^0. The rotation is nearly complete, with the billet end almost reaching a full rotation, as indicated in the diagram. Fig. 12 illustrates a similar cross-section of an aluminum-magnesium (Al–0.13% Mg) solid billet after undergoing 15 pressing cycles through the 120^0 die. Each pressing cycle is represented by the presence of faceted surfaces at the end of the billet, as marked by the arrows. In subsequent pressing, the corner begins to move backward along the bottom surface.

The distortion progresses to the middle of the billet, where it is often thought to be rather consistent. This behavior becomes more evident when deforming a billet that contains a signed wire embedded forward its length. The starting condition of the signed wire prior to distortion, as well as its positions after undergoing two and five pressing cycles through a die, while maintaining a consistent billet orientation. A similar process also takes place at the opposite end of the billet, where the top corner rotates in reference to the central portion of the billet rather than being sheared. However, this end undergoes deformation from the pressing ram in addition to rotation. Even while following a constant strain path, the ECAP process has the inherent ability of the shear to adjust itself inside the given billet dimensions.

EXPERIMENTAL DISCUSSIONS

Effect of Rotation on Specimen

Rotating the material around the ends of the billet significantly contributes to the creation of macroscopic variations within the billet. In contrast, the local deformation structure may not be as pronounced because the variations in strains that an element encounters while moving around the billet's ends are expected to be relatively minor compared to the substantial shear strains produced during ECAP. To assess the effect of rotation on the local deformation structure, theoretical shear strain as a result was 17.3. For this operation, a die $120^0$with high friction conditions was used at room temperature.

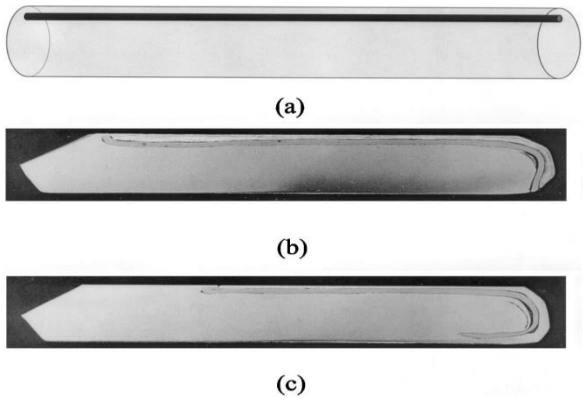

Fig. 12: Displays Cross-Sectional Views of Billets Featuring Copper Wire Markers Through the 120^0 die [25].

Two microstructure samples were collected from different locations near the end of the deformed billet for analysis. The first specimen was taken from the billets upper half, where uniform shear deformation of the material had taken place. The second specimen was taken from the lower portion, where the material had returned to the shear zone after completing a full revolution around the billet end. The samples were then investigated using an Electron Backscatter Diffraction system attached to a high-resolution field emission gun scanning electron microscope. The resulting maps depicting the orientation distribution are presented in Fig. 13. Table 3 includes the X and Y directions and summarises the study of the electron backscatter diffraction data. It is important to note that the white lines denote low angle boundaries ($> 15^0$ and $< 15^0$). Compared to the grains in the material exposed to uniform shear, the grains in the material that has experienced rotation about the billet end are less elongated and slightly bigger. The material after completing its rotation around the billet end.

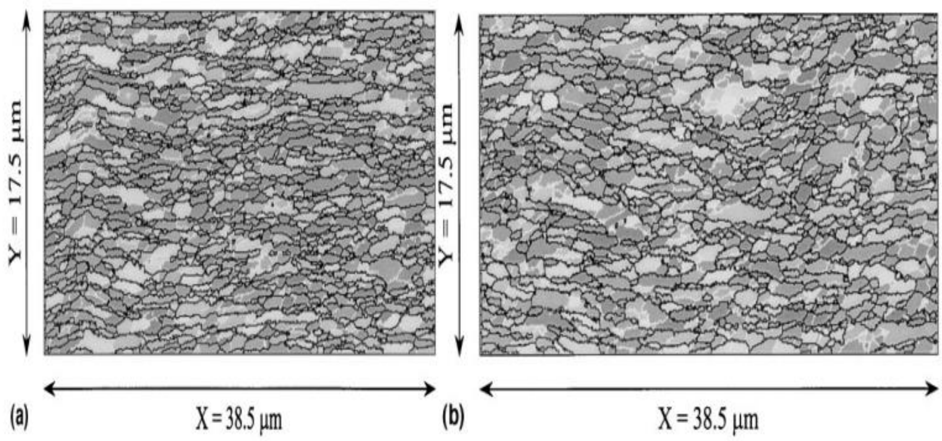

Fig. 13: Displays High-Resolution EBSD Maps, which have been Cleaned, Capturing regions Near the End of the Billet [26].

Table 3: Description of Various Deformation Parameters [27].

Deformation Zone	**X-direction**	**Standard Deviation**	**Y-direction**	**Standard Deviation**	**Grains Sampled**	**Map Statistics**
	Grain statistics (μm)					EBSD patterns

						indexed in percentage
(i)	0.83	0.62	1.96	2.24	1024	72
(ii)	0.97	0.79	1.96	2.11	828	68
	Sub-grain statistics (μm)					High angle boundaries in percentage
(ii)	0.68	0.50	1.18	1.06	2300	70
(ii)	0.86	0.68	0.94	0.82	2105	68

To achieve a comparable level of shear strain, approximately three pressing cycles using a die would be required. Which has just recently returned to the shear zone, suffered a shear strain of around 18.4. Compared to the lesser shear strain of about 14.4 experienced by the former. The rotation of material around the specimen end can cause the progressive assimilation of microstructurally different regions into the centre section of the billet, even if it's possible that the variation in the deformation structure in this case isn't particularly significant.

Effect of Back Pressure

Efficient fabrication procedures are indeed crucial in ECAP studies to achieve fine-grained billets with improved microstructure. Various various processes have been researched to enhance the homogeneity and anisotropy of the material during each mold passage, while reducing the number of required passes. The mould wall was the sole thing holding the billet in place, which made it difficult to produce uniform deformation [28]. The specific areas where the EBSD orientation maps were obtained can be identified in Fig. 14. By applying hydrostatic pressure to the billet, the back-pressure helps to ensure more uniform plastic flow throughout the material. By implementing back-pressure, all the deformed areas of the billet can achieve strain values exceeding one, indicating significant plastic deformation. This implies that both the shape change of the driving plunger (used for pushing the billet) and the back pressing plunger (used for applying hydrostatic pressure) contribute to the improved productivity of the ECAP process. Overall, the inclusion of back-pressure in the ECAP fabrication procedure allows for better control over the deformation process, leading to more uniform and efficient production of fine-grained billets.

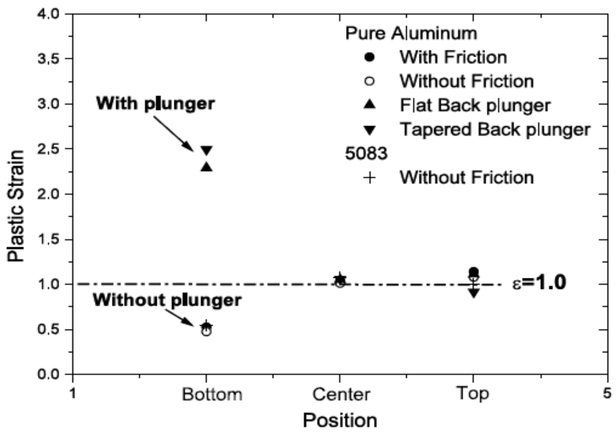

Fig. 14: Compare Various Routes of Equal Channel Angular Pressing for AA5083 [29].

Incorporating a back pressing plunger into the ECAP process can exert a noteworthy influence on how the billet undergoes deformation. In the absence of the back pressing plunger, the lower section of the billet may encounter limited deformation primarily because of the limitations imposed by the mold walls alone. When employing the back pressing plunger, a fresh constraint is introduced at the outer mold corner, thereby influencing the deformation pattern.

Consequently, the strain in the lower segment of the billet rises to a level of 2.5. Although this strain value suggests non-uniform deformation, it's crucial to emphasize that the extent of strain can be managed by modifying the back-pressure. By reducing the back-pressure, it is possible to achieve more uniform deformation throughout the billet. Finding the optimal conditions for the ECAP process involves studying and determining the appropriate combination of parameters such as back-pressure, temperature, strain rate, and the number of passes. By carefully adjusting these process parameters, it is possible to achieve a balance between uniform deformation and the desired microstructural characteristics. Experimental studies and numerical simulations can help in identifying the optimal conditions for the ECAP process, taking into account the specific material properties and desired outcomes.

Billet Corner Shape Index

Fig. 15 illustrates that the deformed billets display corner shapes resembling a parabolic curve and the dimensions of these corner shapes are influenced by alterations in material characteristics and frictional conditions. The inherent parabolic shape of the corners implies, that the moulds design to featuring a circular corner with a radius larger than that of the NC can impact the deformation characteristics. Regarding the Multi-Segment Flange Contact case, it is not analyzed in this study as it yields worse results compared to the case with a sharp corner. This suggests that a sharp corner configuration is more favorable for achieving desired deformation behavior and plastic strain distribution in the ECAP process. Overall, these findings emphasize the importance of considering the corner gap, material properties, and friction conditions in the design and optimization of the ECAP process to control deformation and achieve the desired corner shape and plastic strain distribution in the billet.

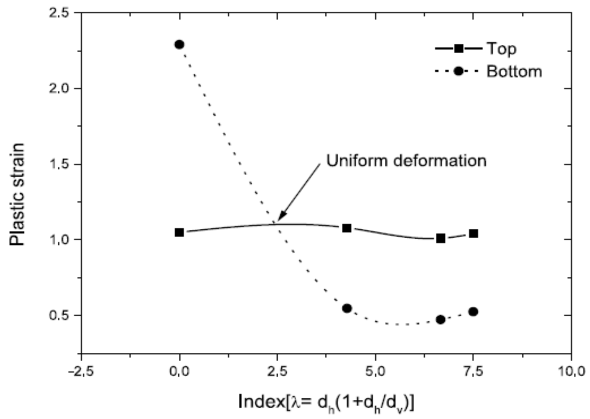

Fig. 15: Corner Shape Index for Homogeneous Plastic Strain Distribution [30].

The index guideline for attaining consistent deformation in the ECAP process was found to be 2.5 based on the analysis that was done. To achieve consistent material flow, the corner shape index for plastic strain was evaluated in Fig. 15 to determine the ideal index value. It was found that the plastic strain values remained close to 1.0 and that the centre portion of the billet was not sensitive to the local geometries of the ECAP mould. However, the bottom part of the billet exhibited strong dependence on the index value. Index values ranging from 4 to 7.5 resulted in a bottom part strain of approximately 0.5, indicating non-uniform deformation. However, when the index value was decreased to less than 4, the bottom of the billet began to experience more strain. The billet deformed uniformly with a strain value of about 1.0 at an index value of 2.5.

The research reveals that keeping the index value at 2.5 during the ECAP process can result in uniform deformation and a good distribution of plastic strain across the billet. This information can serve as a valuable guideline for achieving optimal conditions and improved process control in ECAP. Based on the analysis and observations conducted, it is evident that achieving a uniform billet deformation with an index value of 2.5 in real-world ECAP applications requires careful consideration and adjustment of several factors [31]. The factors that should be taken into account include material properties (such as flow behavior, strain rate sensitivity, and temperature sensitivity), loading rate, temperature, back pressing pressure, friction between the billet and mold, mold corner shape, back-pressure, and the shape of the back pressing plunger.

CONCLUSIONS

By examining the deformation behavior within an ECAP die using techniques such as scribed grids, finite element analysis, and microstructural analysis, it becomes apparent that the attained strains and their consistency rely significantly on factors like the die angle, frictional circumstances, and the application of back-pressure. When performing ECAP under ideal circumstances a sharp die corner and back-pressure are used. This effect becomes more pronounced with larger die angles exceeding a certain threshold, resulting in less overall shear strain than would be anticipated from a single simple shear. This phenomenon can be attributed to the material's rotation around each end of the specimen in the shear direction. This phenomenon can lead to non-uniformity within the central section of the billet, especially when subjected to high levels of strain. The primary regions where non-uniformities in deformation are prominent are at the beginning and end sections of the extruded billets. Utilizing "complex" tooling featuring a movable floor and applying substantial back-pressure effectively prevents the billet from detaching or separating from the surface of the bottom die. The degree of tensile damage can be mitigated by elevating the back-pressure in intricate tooling setups. In situations involving materials with flow softening characteristics, enlarging the radius of the front leg can also contribute to this reduction in damage. Materials with high strength demonstrated more consistent deformation in contrast to materials with lower strength. This consistency is advantageous for maintaining quality control in the ECAP process. The gap at the corners of the billet is influenced by a range of factors, encompassing material characteristics, temperature, friction, and the application of back-pressure. The deformed billets display corner shapes resembling a parabolic curve, and the dimensions of these shapes change in response to variations in both the material used and the applied back-pressure.

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