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Kottapalli Venkatesh
Metallurgical engineering, JNTU JNTU-Gurajada Vizianagaram A.P, jntu vizianagaramVillage, Dwarapudi

Swami Naidu Gurugubelli
Metallurgical Engineering, JNTU JNTU-Gurajada Vizianagaram, A.P, jntu vizianagaramVillage, Dwarapudi

Srinivasa Prasad Katrenipadu
Mechanical Engineering, JNTU JNTU-Gurajada Vizianagaram, A.P, jntu vizianagaramVillage, Dwarapudi

M. Srinivas
Scientist E, DRDO, NSTL, Visakhapatnam, A.P, P6WP+8WM, New Road , N.A.D, Nad Junction

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The Effect of Processing Parameters on Structural and Mechanical Properties of 5083Aluminium Alloy Processed by a Novel Equal Channel Angular Rolling

Kottapalli Venkatesh[1,*], Swami Naidu Gurugubelli[2], Srinivasa Prasad Katrenipadu[3], M. Srinivas[4]

[1]Metallurgical engineering, JNTU-Gurajada Vizianagaram A.P, jntu vizianagaramVillage, Dwarapudi, Andhra Pradesh 535003 India

[2]Metallurgical Engineering, JNTU-Gurajada Vizianagaram, A.P, jntu vizianagaramVillage, Dwarapudi, Andhra Pradesh 535003 India

[3]Mechanical Engineering, JNTU-Gurajada Vizianagaram, A.P, jntu vizianagaramVillage, Dwarapudi, Andhra Pradesh 535003 India

[4]Scientist E, DRDO, NSTL, Visakhapatnam, A.P, P6WP+8WM, New Road , N.A.D, Nad Junction, Sanjevaya Nagar, Visakhapatnam, Andhra Pradesh 532007

*Author to whom correspondence should be addressed:
E-mail: kottapallivenkatesh323@gmail.com

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Abstract: The effect of case thickness and die channel angle on the mechanical properties and microstructure of AA 5083 alloy processed by a novel equal channel angular rolling (ECAR) process using copper as the case material has been evaluated and reported. The copper sheets of different thicknesses (0.5 mm, 1.0 mm, and 1.5 mm) were used as casing on both the sides of the AA 5083 alloy. ECAR was processed at room temperature on alloy sheets of different thicknesses (2 mm, 3 mm, and 4 mm) using different dies with variation in channel angles (90°, 105° and 120°) in A-Route.In the ECAR process, the 'A-route' refers to a primary pathway through which the sheet is passed between rolls. The subsequent passes of the work material were performed in the same direction without rotating the work material. Four passes were given for the sheets of different thicknesses and the structural and mechanical properties were evaluated after each pass. The Vickers hardness property of the alloy increased with an increase in case thickness up to 1mm and beyond that, the hardness decreased. The hardness of a 3.0 mm thick sheet with 1.0 mm copper casing produced by a die with channel angle 90° has enhanced by approximately 150% from the 1st pass to the 4th pass. The tensile strength and yield strength of the alloy were enhanced by 42% and 228% respectively, and the grain size was reduced from 60 µm to 0.71µm after the first pass and to 0.42 µm after the fourth pass. The mechanical and structural properties obtained for a 3mm thick sheet with a 1mm copper casing are much superior to those obtained for other sheets. The novel ECAR process using copper casing resulted in improved mechanical properties, grain refinement and structural homogeneity because of the lower coefficient of friction between copper and steel than between aluminum and steel.

Keywords: Aluminum; SPD- Severe Plastic Deformation; ECAR- Equal Channel Angular Rolling; Microstructure; Copper Casing; Fractographic analysis; COF- Coefficient of friction

1. Introduction

Aluminum alloy is considered a very attractive material for various applications in engineering, aerospace, marine, Defence and automobiles[1)]. The strength of materials increases in most of the metalworking processes, such as rolling, extrusion and drawing. However, for producing preferred properties or geometry for the material, these techniques may not be sufficient. Severe plastic deformation (SPD) techniques can be used to manufacture materials with better mechanical characteristics and ultrafine grain sizes. Equal channel angular pressing is a popular SPD technique, although it is not suitable for sheet goods due to its discontinuous nature. Equal Channel Angular Rolling (ECAR) is an SPD technique that may be applied to strip type and sheet type of metal sample to improve mechanical properties and reduce grain size[2,3)]. The

ECAR procedure involves connecting rollers with die at a particular channel intersection angle (Φ)[4]. The ECAR process significantly improves mechanical characteristics like as hardness, yield (YS) strength, tensile strength (TS), and at an expense of ductility[5]. This is due to strain hardening and deformation of the microstructure. Non-uniform strain distribution is imposed by the formation of a dead metal zone at the outer corners of the die, by which alloy structural homogeneity is affected[6]. Shaeri et al[7] noticed a significant gain in mechanical characteristics and uniform strain distribution when ECAP was performed on 7075 aluminum alloys with copper casings. Existing research has demonstrated that both ECAP (Equal Channel Angular Pressing) and ECAR (Equal Channel Angular Rolling) processes can significantly enhance the mechanical properties of materials. However, these processes often come at the cost of reduced ductility. The present study aims to improve the mechanical properties of the material while minimizing the loss in ductility. By performing the ECAR process with copper casing, this research seeks to strike a balance between strength and ductility, offering a promising advancement in material performance. Metal processing using ECAR dies with different channel angles resulted in substantial plastic deformation at several locations and strain levels[8]. Dissimilar Channel Angular Pressing (DCAP) yields severe plastic deformation (SPD)[9]. The surface residual stress reduces with each successive pass from one to three. These parameters are subject to the path chosen to pass the sample along the dies during the ECAR process[10]. ECAP, Equal channel angular pressing is the most effective of the existing severe plastic deformation (SPD) techniques for causing strain in bulk metals[11]. Thermo-mechanical processes are responsible for modifications in the microstructure features of the Al alloys. The heating and rolling processes alter the microstructure of the 6061 alloy and, consequently, its corrosion resistance and strength[12]. The improved mechanical characteristics are mostly due to both the finer microstructure and the large number of dislocations that may occur during ECAP[13]. Under the room temperature, Four passes of equal channel angular (ECA) pressing on as-solution-treated AlMgSi alloy resulted in a nanoscale microstructure with a grain size of approximately 0.5 μm[14]. Based on the Hall-Petch relationship, it is obvious that reducing grain size improves the strength of ECAE'd alloys[15]. The influence of several passes in ECAP and processing techniques (route of feeding) on the workability of pure aluminum was examined. ECAP was performed on aluminum specimens using a die with 90° channel angle[16]. Four passes of processing resulted in ultrafine-grained structure (UFG), with a recrystallized grain and Grain refinement and a high density of substructures demonstrate geometric grain subdivision[17]. Post ECAP first pass, approximately half of the grains indicated an ultrafine size[18].

In comparison with the pure copper condition, Ebrahi mi M. et al. evaluated both alloying and ECAP treatment effects on the corrosion behavior of Cu-Sn alloy[19]. The influence of several procedures (R+ECAP andR, ECAP) on progression of microstructure was investigated, as well as the influence of pressing method on rolling efficiency. The study demonstrates that ECAP led to a homogeneous grain arrangement[20].

In the year 2018, Varadala, A. B. et al. conducted SPD process on AA 5083 using copper as casing and discovered substantial increase in the Vickers hardness and tensile strength properties of the treated alloy with copper casing due to freshly produced submicron-sized grains in the homogenous structure[21]. Attarilar Shokouh, et al. has investigated the feasibility of using an apparatus to impose massive shear strains on sheet metal during the rolling process for the production of UFG metals and alloys[22]. M. Ebrahimi et al. (2022) have addressed the properties of magnesium alloys and their basic features in plastic deformation treated through cyclic extrusion compression (CEC), the impact of CEC-based processes on the microstructure and texture evolution and the grain refinement mechanisms are analysed through electron backscatter diffraction (EBSD) analysis[23]. M. Aali Majidabad et al. in 2023 has investigated mechanical properties and corrosion properties of Al5085 alloy by ECAP and found noticeable increase in the mechanical properties after every pass[24]. In 2020, A. Mahyudin et al., Studies were undertaken to explore the impact of areca fiber% on the mechanical properties[25]. Sathi, Brahmananda Reddy et al. has conducted wear experiments and studied at the structural features of the 5083 aluminiumcomposite reinforced with red mud and found that the production of submicron-sized grains greatly improved the hardness of the ECAPed composites, hence reducing the wear loss[26]. Senoz et al. in 2021 has examined the change in microstructural and hardness values AA7075 aluminum alloy after ECAP[27]. H. Sosiati et al. evaluated the effect of the fiber composition on the tensile characteristics of composites[28]. A. Mahyudin et al., has examined the mechanical properties of AA 5083 and found that there is significant increase in mechanical properties with increase in the reinforcement[29]. A new technology called ECAE with casing inserts the billet into a metallic or non-metallic capsule or casing[30]. Among the several Severe Plastic Deformation (SPD) techniques, equal channel angular extrusion is one of the most important for enhancing the mechanical characteristics of materials by generating ultrafine grains[31,32]. Panigrahi et al, observed that, along the transverse planes, maximum improvement in hardness and a uniform distribution[33]. AA 5083 is used as matrix material and observed different mechanical properties post SPD technique[34]. Aydın, M et al, Investigated mechanical properties and fatigue life of ECARed AA5083 aluminium alloy[35]. Because ECAP is a discontinuous process, deformation of sheets does not apply to it. A new SPD technique called equal channel angular rolling (ECAR), which is based on ECAP, allows sheets to undergo continuous shear deformation without seeing a significant change in thickness[36)].

Most of the SPD techniques are contributing for the grain refinement, microstructural changes and in obtaining product with improved mechanical properties. However, the techniques may not be sufficient for producing materials with preferred properties and geometry. In addition, the existing SPD techniques could able to improve the mechanical properties at the expense of ductility. The Novel ECAR technique with copper casing adopted in the present investigations could able to improve the mechanical properties without decreasing the ductility so much as compared to conventional SPD techniques.

Therefore, an attempt is made to process the 5083-aluminum alloy by equal channel angular rolling using copper casing of different thicknesses on either side of the alloy. The primary originality of this effort is to provide copper casing with different thicknesses on both sides of the work piece. In this method of ECAR, copper is used as the case material due to the lower (COF) coefficient of friction between steel and copper (0.18) than that between steel and aluminum (0.47 to 0.6). This leads to reduced deformation loads, improved mechanical properties and homogeneity throughout the geometry of the work piece. Other alloys may have higher friction characteristics and due to which the ductility may not be retained and may require higher deformation loads. Hence, copper casing is used in the present investigations. The effect of Cu case thickness and die channel angle on tensile strength, microhardness, and grain refinement is determined and reported.

2. Experimental procedure

2.1 Materials and methods

Research grade AA 5083 in soft 'O' grade condition is used as the work material and its chemical composition obtained by optical emission spectrometer is Si-0.12%, Fe-0.26%, Cu-0.08%, Mn-0.60%, Mg-4.53%, Cr-0.08%, Zn-0.05%, Ti-0.03% and remaining aluminum. The dimensions of the alloy sheet used and the thickness of the copper casing used in the present investigations are tabulated in Table 1.

Table 1. Geometry of work piece

Type of sheet	Dimensions of sheet in mm^3	Thickness of copper case in mm	Types of sheets with casing
Rectangular	2 x 15 x 600	0.0, 0.5, 1, 1.5	t_0, $t_{0.5}$, t_1, $t_{1.5}$
Rectangular	3 x 15 x 600	0.0, 0.5, 1, 1.5	t_0, $t_{0.5}$, t_1, $t_{1.5}$
Rectangular	4 x 15 x 600	0.0, 0.5, 1, 1.5	t_0, $t_{0.5}$, t_1, $t_{1.5}$

Smooth surface finish was obtained on the work samples to reduce the (COF) coefficient of friction during process of ECAR. The procedure was performed by providing copper cases with variation in thickness i.e., 0.5 mm, 1.0 mm and 1.5 mm placed on either side of the alloy. ASTM B918-01 standards are followed and after being annealed at a temperature of 450 °C and 400 °C each, AA 5083 and copper sheets were air-cooled for an hour to reduce any pre-existing residual stresses. Die sets of oil-hardened steel such as 90°, 105°, and 120° channel angles (Φ) were used in this ECAR work and are shown in Fig. 1.

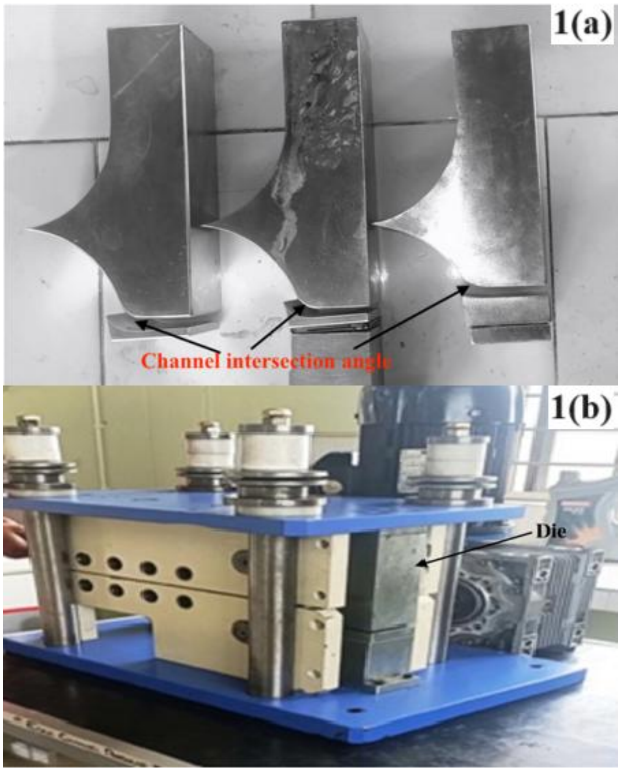

Fig. 1: (a) ECAR dies with 90°, 105° and 120° channel intersection angle (b) Die fixed to the rollers.

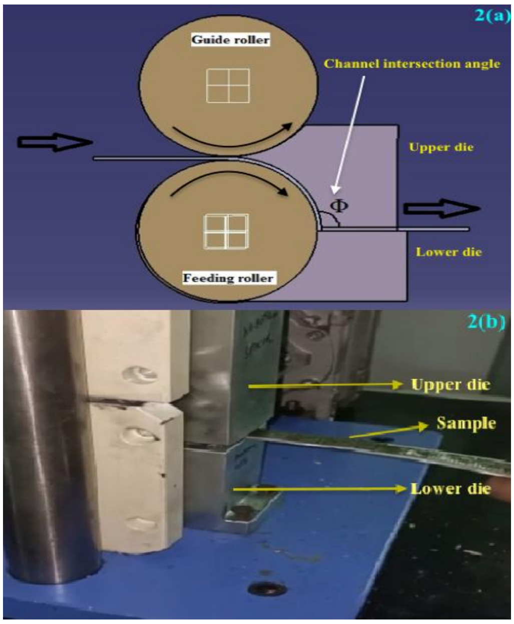

Fig. 2: (a) Schematic representation of ECAR (b) ECAR processing

The AA 5083 sheets, without Cu casing (t_0), and with Cu casing ($t_{0.5}$, t_1 and $t_{1.5}$) on both faces, were processed in route A up to four passes, at room temperature as shown in Fig. 2. The rolling speed of 2 mm/s was maintained during the ECAR process. The effective strain imposed on the material in every pass refines the grain size and the effective strain will be influenced by the channel intersection angle (Φ) and the number of passes (N). The effective strain is determined using the Iwahashi equation $\mathcal{E}_N = 0.863$.

The Vickers microhardness tests were conducted on ECAR processed work piece surfaces at 200 g of load for 15 seconds of dwelling time. Tensile tests were also conducted as per ASTM E8 standards using a 300DX Instorn machine under ambient conditions of 0.001s^{-1}. Tensile testing specimens, as shown in Fig. 2(b), were prepared using the wire-cut EDM process to avoid heat generation while cutting. The schematic representation of ECAR and the sample passing through the die is shown in Fig 2(a), respectively. Microstructures of deformed surfaces were obtained using Zeiss Neon 40 cross-beam FE SEM with 1.1 nm resolution and characterized.

3. Results and discussion

3.1 Vickers microhardness (HV)

The microhardness results produced on the ECAR-processed alloy without Cu casing (t_0) and with Cu casing ($t_{0.5}$, t_1, $t_{1.5}$) using dies with different channel angles of 90°, 105° and 120° are presented in Fig. 3, 4 and 5 respectively. The Vickers hardness property of the alloy increases as the number of passes increases and the observations are consistent with Shaeri et al.[7]. ECAR processing with copper casing yielded higher hardness measurements than that processed without casing. The hardness property of the alloy increased with an increase in case thickness up to 1 mm and beyond that, the hardness decreased. A comparable result was found with all channel angles and the effect is more predominant with 90° channel angle die. The hardness of a 3.0 mm thick sheet with 1.0 mm Cu casing worked using a 90°channel angle die was increased by nearly 150% from the first to the fourth pass. This is because of the development of ultra fine grain structure by processing the alloy with copper casing. The influence of copper case thickness on the hardness measurements of the alloy observed is almost negligible. A similar trend in the improvement of microhardness measures is observed in another study[5].

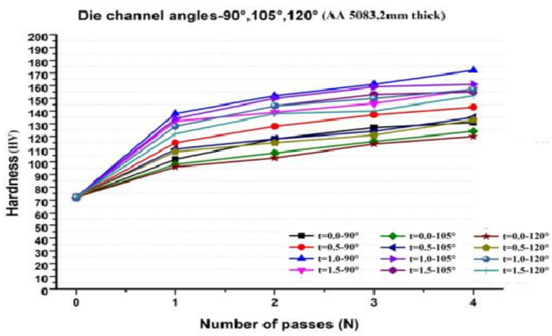

Fig. 3: The influence of Cu casing thickness and number of passes on microhardness of 2 mm thick AA 5083 processed with 90°, 105° and 120°die channel angle.

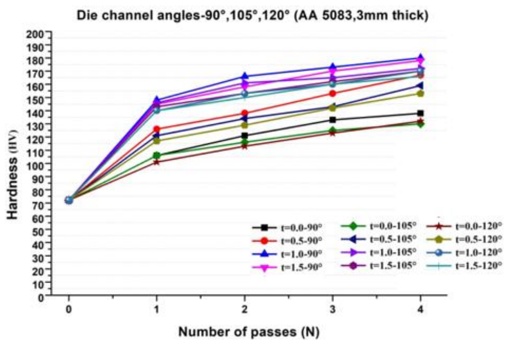

Fig. 4: The influence of Cu casing thickness and number of passes on microhardness of 3 mm thick AA 5083 processed with 90°, 105° and 120° die channel angle.

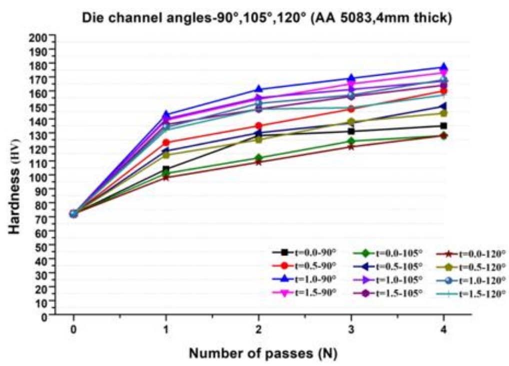

Fig. 5 The influence of Cu casing thickness and number of passes on microhardness of 4 mm thick AA 5083 processed with 90°, 105° and 120° die channel angle.

The hardness measurements obtained for the ECAR processed alloy in the present investigations are superior to those obtained in ECAP processed alloy. The comparison of such results is depicted in Table 2.

Table 2. Comparison of Microhardness of AA5083 with other SPD technique (ECAE).

No. of passes	Microhardness (VHN)					
	t=0 ECAE	t=0 ECAR	t=1 ECAE	t=1 ECAR	t=1.5 ECAE	t=1.5 ECAR
Before processing	72					
1st Pass	97	**106**	139	**148**	136	**145**
2nd Pass	113	**121**	158	**166**	150	**158**
3rd Pass	127	**133**	167	**173**	164	**170**
4th Pass	134	**138**	176	**180**	174	**178**

3.2 Tensile properties

The yield strength and tensile strength measurements obtained for AA 5083 before and after ECAR with and without copper casing are shown in Fig. 7-9. The tensile strength and yield strength are maximum for a 3mm sheet with a 1mm copper casing processed through a 90° channel angle die. The tensile strength of unprocessed AA5083 is 300 MPa and it has increased by 42% when ECAR is performed for four passes on a 3mm thick alloy with a 1mm copper casing through die with 90° channel angle. The tensile strength is also determined for the alloy processed through dies with different channel angles. Large elongated grains are disrupted up during the first pass of the ECAR, and as a result, sub-grains with relatively high dislocation densities are created. These sub-grains play an important function in strengthening metallic materials after the pass one. At this point, a high fraction of low angle grain boundaries is formed as the dislocation density in both the interior and exterior of the initial coarse grains rises. Even while the strength improvement persisted during the third pass, the rate of growth was slower than in the first pass. Additionally, strain hardening, which happens in materials because of plastic deformation, is a major factor in the rise in yield and tensile strength at the first pass.

However, the effect of channel angle on tensile strength is very little. The yield strength of unprocessed AA5083 is 115 MPa and it has been massively increased by 228% when ECAR is performed for four passes on a 3mm thick alloy with a 1mm copper casing through die with 90° channel angle. The yield strength is also determined for AA 5083 processed with different die channel angles. This large increase can be attributed to grain refinement and strain hardening. The increase in yield strength due to ECAR depends on the severity of the deformation, which, in turn, is influenced by the die angle. A 90° angle is likely optimizing the strain path for the alloy, leading to substantial hardening. The trend of test results observed in this study had more agreement with the report published by Varadala et al.[21], but was not applicable to sheet-type specimens. The stress-strain behavior of as-received alloy and ECARed alloy processed with a 90° channel angle is presented in Fig. 6.

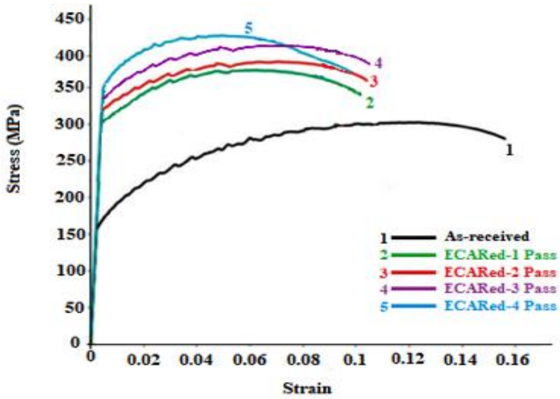

Fig. 6: Stress-Strain behavior of As-received and ECAR processed AA 5083 with 90°die channel angle.

However, the effect of channel angle on tensile strength is very little. The effect of copper case thickness on both tensile strength and yield strength was observed to be negligible. The size of the grains has a sound impact on their mechanical properties. Because of the wider grain boundary area, coarse-grain structured materials have lower hardness and strength than fine-grain structures do. The Hall-Petch correlation explains how grain size influences a material's mechanical properties[15].

$$\sigma_y = \sigma_o + k_{y*} d^{-1/2} \quad (1.1)$$

In this equation, d denotes the diameter of the grain, σ_o is the prime stress, and k_y represents material yield constant. Expression 1.1 shows that reducing grain size considerably increases material strength. The intriguing characteristic of grain refining piqued the interest of material scientists in developing ultrafine grain-structured materials.

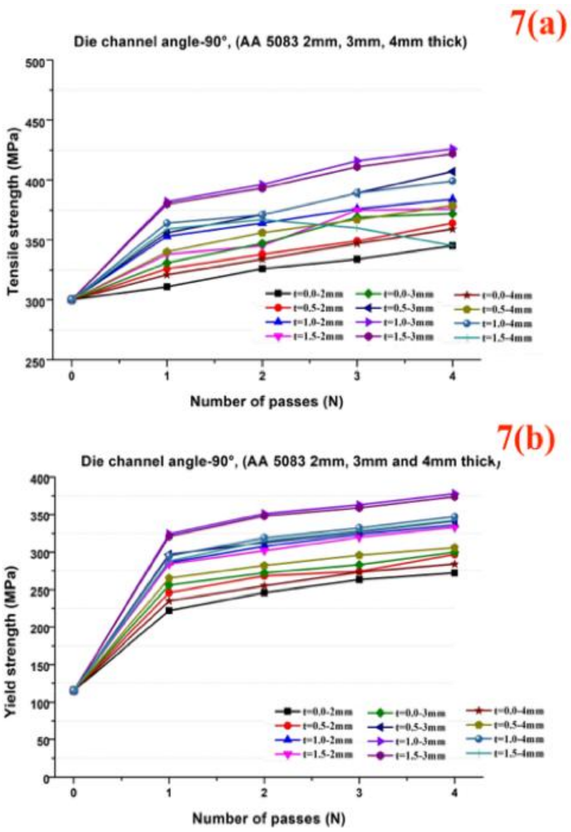

Fig. 7: Effect of no. of passes and Cu casing on tensile properties of 2 mm, 3 mm, and 4 mm thickness AA 5083, processed with 90° die channel angle (a)Tensile strength (b)Yield strength.

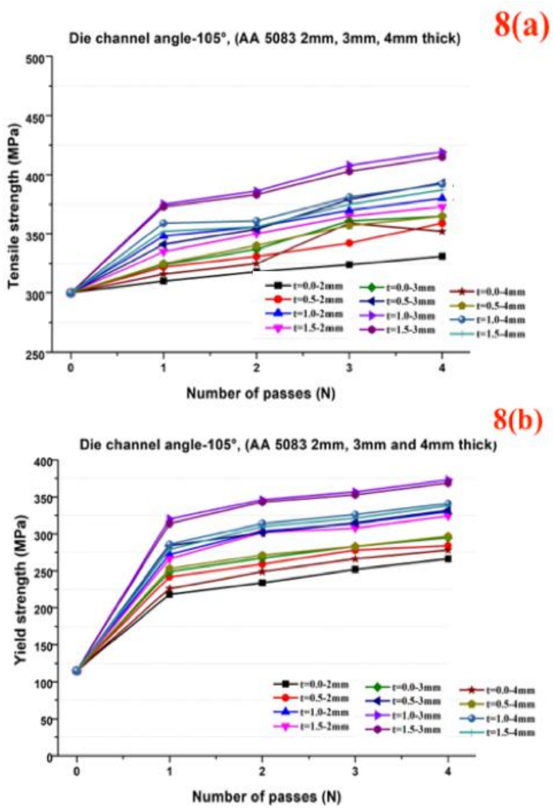

Fig. 8: Effect of no. of passes and Cu casing on tensile properties of 2 mm, 3 mm, and 4 mm thickness AA 5083, processed with 105° die channel angle (a)Tensile strength (b)Yield strength.

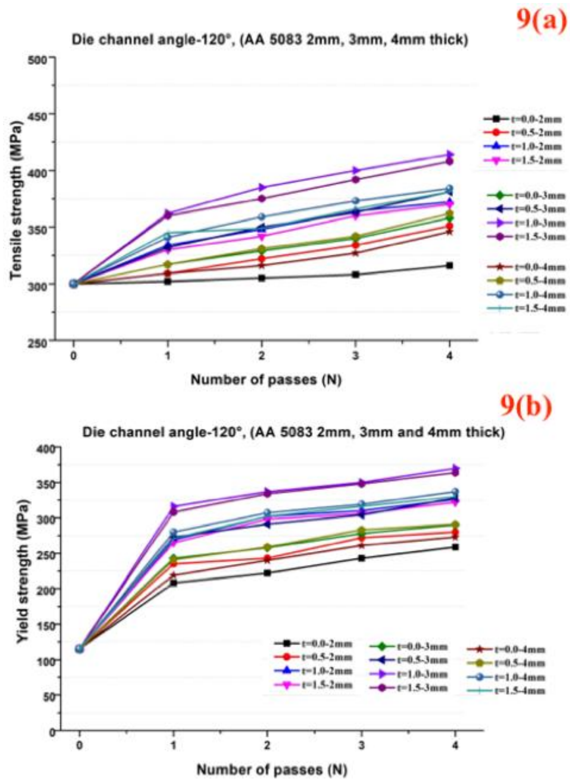

Fig. 9: Effect of no. of passes and Cu casing on tensile properties of 2 mm, 3 mm, and 4 mm thickness AA 5083, processed with 120° die channel angle (a) Tensile strength (b) Yield strength.

The ductility of the alloy processed with copper casing and through different dies is shown in Fig. 10. The ductility of AA5083 without processing is 12 and after processing without copper casing, it is 6.2 after the first pass and 5.0 after the fourth pass. There is a reduction in ductility of more than 50% due to ECAR processing. The ductility obtained for the alloy processed using copper casing of 1mm thickness is observed at 11 after the pass one and at 10 after the pass two. The ductility of the alloy is almost constant when ECAR is performed with copper casing. The addition of copper as casing considerably improves the mechanical properties of the produced alloy while not sacrificing ductility. This is owing to the lower COF between copper and steel over aluminum and steel. The preservation of ductility can be attributed to several mechanisms. First, the lubrication properties of copper reduce friction between the material and the die, which helps minimize the occurrence of excessive shear stresses. This results in a more uniform distribution of strain across the material. Additionally, the copper casing acts as a protective layer, preventing localized strain accumulation and thereby reducing the likelihood of crack formation. These combined effects help maintain the material's ductility while still improving its mechanical properties through the ECAR process.

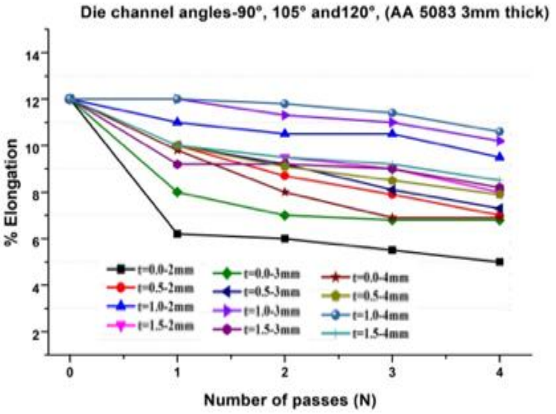

Fig. 10: Effect of no. of passes and Cu casing on % elongation for 3 mm thickness sheet processed with 90°, 105° and 120° die channel angles.

3.3 Grain refinement

The grain size of the alloy produced with ECAR is calculated using the line intercept method. The structural homogeneity and grain refinement are greater in sheet t_1 than in sheets $t_{0.5}$ and $t_{1.5}$. ECAR processing of the alloy with Cu casing has significantly increased homogeneity and grain refinement. The coefficient of friction between copper and steel is 0.18 and that between aluminum and steel is about 0.6. Due to the lower coefficient of friction, the dead metal zone in the deformation zone has been reduced and hence the grain refinement and homogeneity have increased. The maximum grain refinement has been observed in the alloy processed using 1mm thick copper casing compared to that with 0.5mm and 1.5mm thick copper casing. The 1mm thickness appears to strike the right balance. It’s thick enough to significantly reduce friction, promoting uniform deformation throughout the material. By ensuring the material experiences a more homogeneous shear strain distribution, the microstructure can undergo more effective grain refinement. The reduced friction also helps the material flow more freely, ensuring that it passes through the die without excessive resistance, thus facilitating the formation of finer grains throughout the specimen. Too-low copper casing might not be sufficient to reduce the coefficient of friction and too-high-thickness casing might cause reduced homogeneity in deformation. This might be the reason for the maximum grain refinement obtained in the processed alloy copper casing of 1mm thickness. It is also observed that the sheet processed using the 90° channel angle die with a resulted in significantly higher grain refinement than that processed through the dies with 105° and 120° channel angles. This is because the alloy processed through the die with a channel angle of 90° has experienced more effective strain than that processed through other dies.

The SEM structure of the unprocessed AA 5083 is presented in Fig. 11 and the average (mean) grain size of 60 µm is observed. The ECAR processing caused severe plastic strain at the die channel intersection angle and the coarse grains were refined to a few hundred nanometers.

Figure 12 depicts the FE-SEM microstructure of the ECARed alloy treated without copper casing in passes one through four. The average grain size decreases from 0.75 µm to 0.50 µm after the first and fourth passes, respectively. The decrease in grain size observed between the first and fourth passes is significantly less.

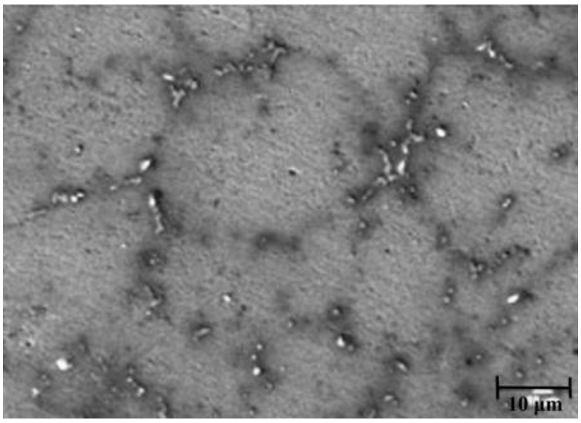

Fig. 11: Microscopic structure of FE-SEM of AA 5083 prior to ECAR.

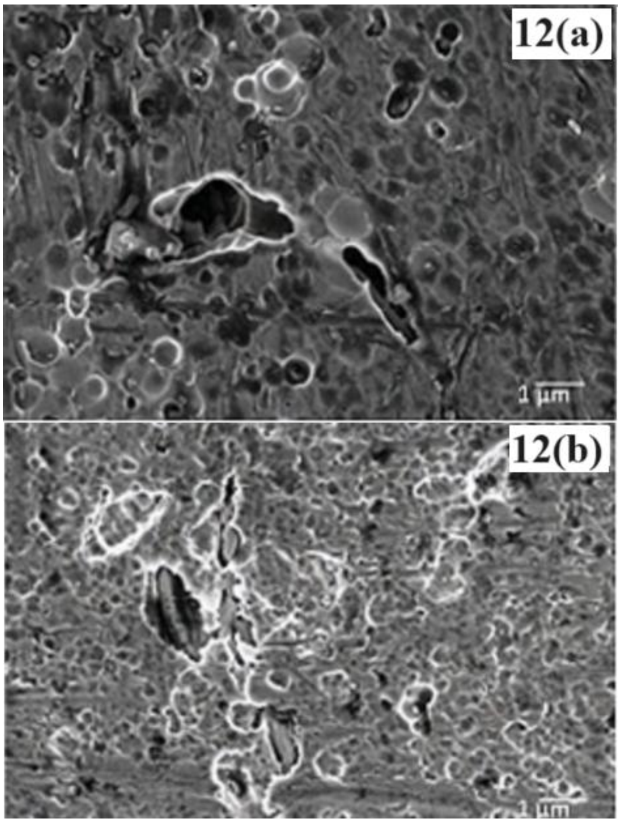

Fig. 12: Microscopic structure of FE-SEM of AA5083 without copper casing (a)After pass one and (b)After pass four.

The application of copper casing around the alloy during ECAR processing resulted in decreased microstructural flaws and greater structural homogeneity. The alloy processed without copper casing has larger dead metal zones, structural inhomogeneity, and microstructural defects. At the channel intersection, the empty space formed is filled by the copper and hence dead metal zone development is decreased in the processed alloy using copper casing and therefore the micro-structural defects. Figure 13 shows the FE-SEM structure produced after the first pass of ECAR processed with copper casing. The sheet type $t_{0.5}$ has produced 0.73µm equiaxed submicron-sized grains, as depicted in Fig. 13(a). The FE-SEM structures obtained for sheet types t_1 and $t_{1.5}$ show average grain sizes of 0.71 µm and 0.65 µm, respectively, as depicted in Fig. 13(b) and 13(c). Free flow of material is seen by the use of Cu casing, which hence results in a non-porous and dense structure.

Figure 14 shows the FE-SEM microstructure of the rolled 5083 alloy with varying thicknesses of copper casing after the fourth ECAR pass. For the sheet types $t_{0.5}$, t_1 and t1.5, the average (Mean) grain sizes are 0.46 µm, 0.42 µm and 0.46 µm correspondingly, as illustrated in Table 2. A noticeable decrease in mean grain size after pass one is observed for the ECAR of AA 5083 sheets with and without copper casing and after successive passes, marginal refinement is seen; the mean grain size and their respective standard deviations are presented in Table 3.

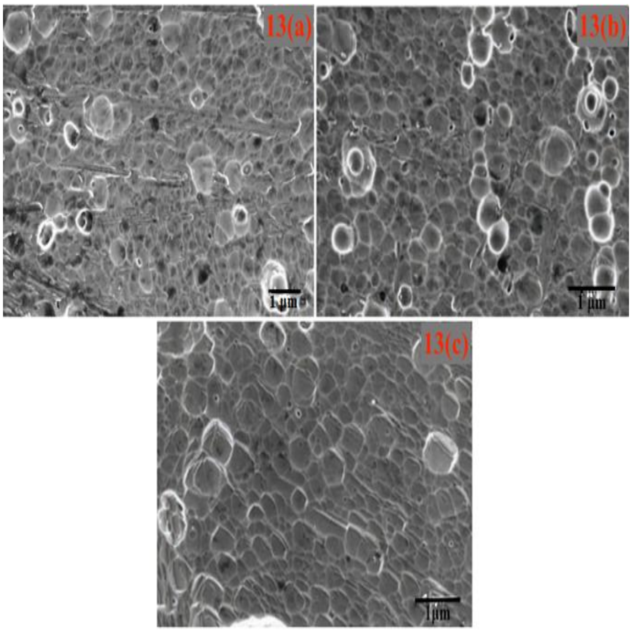

Fig. 13: FE-SEM Microscopic picture of AA 5083 upon one pass. (a) $t_{0.5}$, (b) t_1 and (c) $t_{1.5}$ for 3 mm thickness processed with 90° die channel angle.

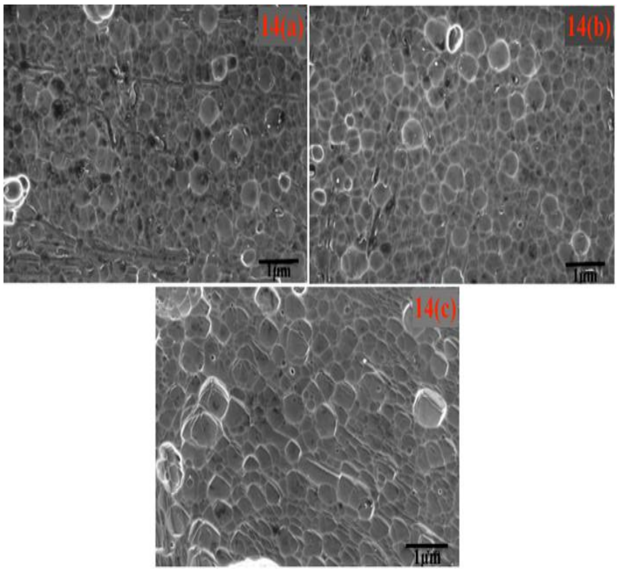

Fig. 14: FE-SEM Microscopic picture of AA 5083 upon fourth pass. (a)$t_{0.5}$, (b)t_1 and (c)$t_{1.5}$ for 3mm thickness processed with 90° die channel angle.

Depending up on the Hall-Petch relationship, Figure 15 shows the yield strength against $d^{-1/2}$ for the ECARed alloy processed with a 3mm thickness and a 90° die channel angle with copper casing ($t_{0.5}$, t_1 and $t_{1.5}$) and without copper casing (t_0) to study the impact of grain size on the rolled alloys.

Table 3. Effect of no. of passes and Cu casing on grain refinement (Mean) for 3mm thickness with 90° channel angle.

Sample type	**Average Grain size (Mean)(µm)**	**Standard deviation**
Before ECAR	60	± 5.94
3mm, $t_{0.0}$ Cu casing Pass 1	0.75	± 0.148
3mm, $t_{0.5}$ Cu casing Pass 1	0.73	± 0.135
3mm, $t_{1.0}$ Cu casing Pass 1	0.71	± 0.129
3mm, $t_{1.5}$ Cu casing Pass 1	0.72	± 0.134
3mm, $t_{0.0}$ Cu casing Pass 4	0.50	± 0.119
3mm, $t_{0.5}$ Cu casing Pass 4	0.46	± 0.109
3mm, $t_{1.0}$ Cu casing Pass 4	0.42	± 0.086
3mm, $t_{1.5}$ Cu casing Pass 4	0.46	± 0.102

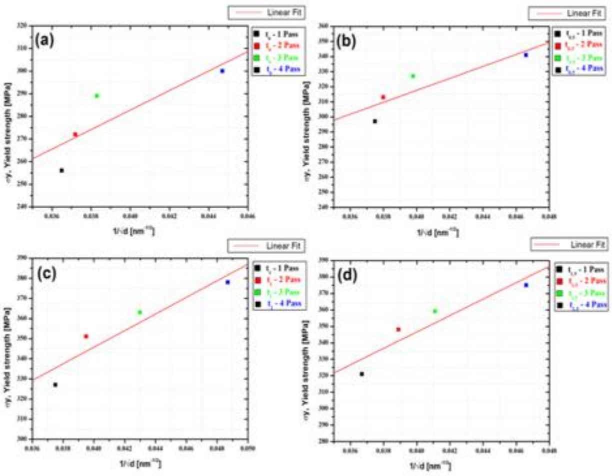

Fig. 15: Yield strength of ECAR processed AA 5083 (3 mm thick) after 1, 2, 3 and 4 passes as a function of the inverse square root of the average grain diameter.

As can be observed, the strength of the ECARed alloy increases as grain size decreases, which is consistent with the well-known Hall-Petch relationship (a positive slope in the yield stress against $d^{-1/2}$ plot). In this connection, the slope of the linear fit is considered as a Hall-Petch coefficient. Extracted Hall-petch coefficients (slope K, strengthening coefficient) are 4312.6, 3959.6, 4127.4 and 4992.4 Mpa-m$^{1/2}$ for samples type t_0, $t_{0.5}$, t_1 and $t_{1.5}$. A positive slope in all graphs (yield stress against $d^{-1/2}$ plot) indicates a high correlation coefficient for a linear fit, as shown in Fig. 15.

3.4 Fractographic analysis of tensile tested samples

SEM examination of the fracture surfaces of ECAR-processed (90° channel angle, 3mm thickness, 1mm Cu casing) tensile samples has been performed and the corresponding photographs are presented in Fig. 16. It is worth noting that the alloy processed without Cu casing possesses more dimples and fine cracks and the number of dimples and fine cracks have been reduced with the number of ECAR passes. However, the dimples and fine cracks are minimal for the alloy processed with Cu casing of 1mm thickness. This is due to the lower COF between the Cu casing and steel disc than between the aluminum alloy and steel die. As shown in the SEM pictures, the alloy processed without copper casing (90°1 pass and 90°4 pass) has a higher number of dimples and these pictures also show failure by void coalescence, as shown in Fig 16 (a) and (b). Whereas, the alloy processed with copper casing of 1mm thickness (90° 1pass and 90° 4pass) showed a very low number of dimples, cracks, and void coalescence, and there is no evidence of intergranular failure. The severely plastic-deformed samples have fewer pits, dimples and void coalescences when compared with the as-received sample. Severe plastic deformation influences the fracture mechanism of the material. In the as-received state, materials typically fracture through mechanisms like micro void coalescence or ductile rupture, where voids nucleate at grain boundaries or precipitates and grow, eventually coalescing to form cracks. However, after ECAR processing, the fine microstructure allows for more uniform strain distribution, reducing the formation of large voids or pits. The fracture surface is generally less rough, showing fewer dimples or pits compared to the as-received material. With ECAR, the material becomes more homogeneous, reducing the presence of defects such as inclusions, second-phase particles, or precipitates that would act as crack initiation sites in the as-received material. This further reduces the likelihood of pit formation or void coalescence.

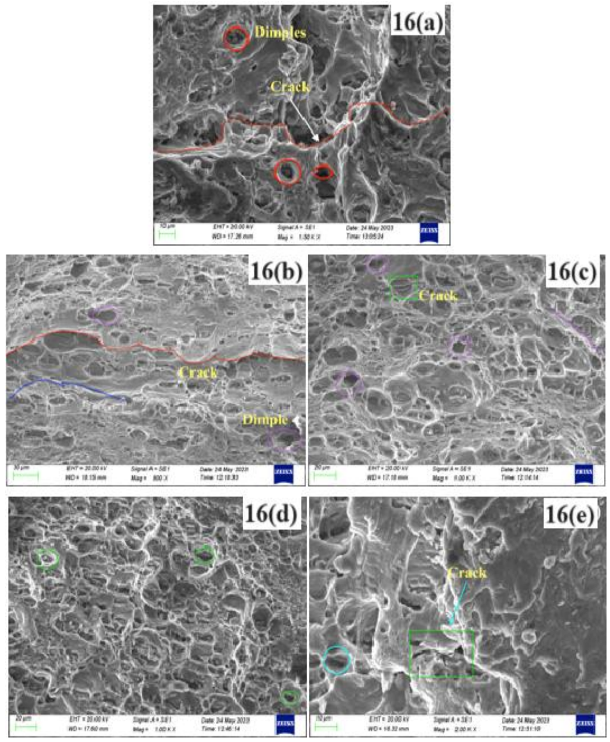

Fig. 16: Fractographic analysis of the tensile tested samples (a)As received sample, (b)90°-1 pass without copper casing, (c)90°-4 pass without copper casing, (d)90°-1 pass with copper casing, (e)90°-1 pass with copper casing.

4. Conclusions

The following conclusions are drawn from the present investigations.

ECAR processing with copper casing yielded higher hardness measurements than that processed without casing. The hardness property of the alloy increased with an increase in case thickness up to 1mm and beyond that, the hardness decreased. The hardness of a 3.0 mm thick sheet with a 1.0 mm copper casing, processed through a 90°channel angle die, has been enhanced by about 150% from the 1st pass to the 4th pass.

The yield strength (YS) and tensile strength (TS) property of the AA5083 alloy sheet of 3mm thickness are enhanced by 42% and 228%, respectively, when it is processed by ECAR using copper casing of 1mm thickness. The effect of copper case thickness and die channel angle on the yield strength and tensile strength of the alloy is observed to be very little.

Copper casing improves the mechanical characteristics of the produced alloy without sacrificing ductility. The initial mean grain size of the alloy before ECAR processing is 60 µm and it is reduced to 0.7 µm and 0.42 µm, respectively, after ECAR processing using a die with a 90°channel angle and a copper casing of 1mm thickness.

The strength of the ECARed alloy increases as grain size decreases, which is consistent with the popular Hall-Petch relationship (a positive slope in the yield stress against $d^{-1/2}$ plot) and indicates a high correlation coefficient for a linear fit. The ECAR processing using copper casing resulted in improved mechanical properties, grain refinement and structural homogeneity. This is because of the lower COF between copper and steel than between aluminum and steel.

Conflict of interest Statement

On behalf of all authors, the corresponding author declares that there is no conflict of interest.

References

1) Dursun T and Soutis C, "Recent developments in advanced aircraft aluminium alloys," Materials & Design,56:862–871(1980–2015). doi: 10.1016/j.matdes.2013.12.002
2) Lee JC, Seok HK, Han JH, et al., "Controlling the textures of the metal strips via the continuous confined strip shearing (C2S2) process", Materials research bulletin, 36, (5-6) 997-1004, (2001). doi:10.1016/S0025-5408(01)00557-8.
3) Lee JC, Seok HK and suh JY, "Microstructural evolutions of the Al strip prepared by cold rolling and continuous equal channel angular pressing," Acta Mater, 50, (16) 4005-4019 (2002). doi:10. 1016/S1359-6454(02)00200-8.
4) Djavanroodi F and Ebrahimi M, "Effect of die parameters and material properties in ECAP with parallel channels", Materials Science and Engineering, A527 (29–30) 7593–7599 (2010). doi: 10.1016/j.msea.2010.08.022
5) Azimi A, Tutunchilar S, Faraji G, et al., "Mechanical properties and microstructural evolution during multi-pass ECAR of Al 1100-O alloy", Mater design 42:388-394 (2012). doi: 10.1016/j.matdes.2012.06.035
6) Eviani AR and KarmiTaheri A, "The effect of dead metal zone formation on strain and extrusion force during equal channel angular extrusion," Computational Materials science 42(1) 14-20 (2008). doi:10.1016/j.commatsci.2007.06.001
7) Shaeri M, Djavanroodi F, Sedighi M, et al., "Effect of copper tube casing on strain distribution and mechanical properties of Al-7075alloy processed by equal channel angular pressing", Journal of Strain Analysis for Engineering Design, 48(8) 512–521 (2013). doi:10.1177/0309324713498234.
8) Keeler SP and Backofen WA., "Plastic instability and fracture in sheets stretched over rigid punches," ASM Trans Q, 56 (11) 25–48 (1963). doi: 10.1016/j.ijsolstr.2020.06.029.
9) Tan E, Kibar AA and Gur CH., "Mechanical and microstructural characterization of 6061 aluminum alloy strips severely deformed by dissimilar channel angular pressing", 62(4) 391-397 (2011). doi: 10.1016/j.matchar.2011.01.016
10) Mahmoodi M, sedighi M and Tanner DA., "Experimental study of process parameters effect on surface residual stress magnitudes in equal channel angular rolled aluminium alloys," Proceedings of the institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 228(12) 1592-1598 (2014). doi:10.1177/0954405414522449.
11) Esmailzadeh M., Aghaie-Khafri M., "Finite element and artificial neural network analysis of ECAP," Comput.Mater. sci., 63, 127-13 (2012). doi: 10.1016/j.commatsci.2012.05.075
12) Mariana X. Milagre, Margareth Franco, Frederico Genezini, Robert C. Wimpory, Fabiano Yokaichiya & Isolda Costa, "A correlation between microstructure and residual stress in the 6061 Al–Mg–Si alloy with different thermo mechanical process", SN Applied Sciences volume 2, Article number: 2106 (2020). doi: 10.1007/s42452-020-03945-y
13) Nashith A, Sanjid P, Shamsudheen M, Rasheeque R, Ramis M. K, Shebeer A. R, "Effect of Equal Channel Angular Pressing (ECAP) on Hardness and Microstructure of Pure Aluminum," International Journal of Materials Engineering, 4(3) 119-122 (2014). doi: 10.5923/j.ijme.20140403.08
14) J.-Y. Chang, A. Shan, "Microstructure and mechanical properties of AlMgSi alloys after equal channel angular pressing at room temperature," Mater. Sci. Eng. A (347) 165–170 (2003). doi:10.1016/S0921-5093(02)00577-4.
15) N. Hansen, "Hall-petch relation and boundary strengthening," Scr. Mater., 51(8) 801-806 (2004). doi: 10.1016/j.scriptamat.2004.06.002.
16) A. Sivaraman, Uday Chakkingal, "Investigations on workability of commercial purity aluminum processed by equal channel angular pressing," Journal of Materials Processing Technology 202 (1-3) 543–548 (2008). doi:10.1016/j.jmatprotec.2007.10.006.
17) El-Shenawy M, Ahmed MMZ, Nassef A, El-Hadek M, Alzahrani B, Zedan Y, El-Garaihy WH. "Effect of ECAP on the Plastic Strain Homogeneity, Microstructural Evolution, Crystallographic Texture

and Mechanical Properties of AA2xxx Aluminum Alloy’. Metals, 11(6) 938 (2021). doi:10. 3390/met11060938.

18) Romero-Resendiz, L.; Figueroa, I.A.; Reyes-Ruiz, C.; Cabrera, J.M.; Braham, C.; Gonzalez, G. “Residual stresses and microstructural evolution of ECAPed AA2017”. Mater. Charact., 152 44–57 (2019). doi: 10.1016/j.matchar.2019.04.007.
19) Ebrahimi, M.; Attarilar, Sh.; Shaeri, M. H.; Gode, C.; Armoon, H.; Djavanroodi, F., “An investigation in to the effect of alloying elements on corrosion behavior of severely deformed Cu-Sn alloys by equal channel angular pressing,” Archives of Civil and Mechanical Engineering, 19(3) 842–850 (2019). doi: 10.1016/j.acme.2019.03.009.
20) Xu, Q., Ma, A., Li, Y., Sun, J., Yuan, Y., Jiang, J., & Ni, C., “Microstructure evolution of AZ91 alloy processed by a combination method of equal channel angular pressing and rolling”. Journal of Magnesium and Alloys, 8(1) 192–198 (2020). doi: 10.1016/j.jma.2019.05.012
21) Varadala, A. B., Gurugubelli, S. N., &Bandaru, S., “Equal Channel Angular Extrusion of Al 5083 Alloy with Copper Shielding”, Emerging Materials Research, 7(3) 1–28 (2018). doi: 10. 1680/jemmr.18.00043
22) Attarilar, Shokouh; Ebrahimi, Mahmoud; Hsieh, Tsung-Hsien; Uan, Jun-Yen; Gade, Ceren. “An insight into the vibration-assisted rolling of AA5052 aluminum alloy: Tensile strength, deformation microstructure, and texture evolution”, Materials Science and Engineering: A 140489 (2020). doi:10.1016/j.msea.2020.140489.
23) Mahmoud Ebrahimi, Qudong Wang, Shokouh Attarilar, “A comprehensive review of magnesium-based alloys and composites processed by cyclic extrusion compression and the related techniques,” Progress in Materials Science, Volume 131 (16) 101016 (2023). doi: 10.1016/j.pmatsci. 2022.101016
24) Milad Aali Majidabad; Ali Reza Rezaei; Mohammad Reza Sabour; Ghader Faraji. “Mechanical properties and pitting corrosion behavior of Al5085 alloy processed via ECAP”, Journal of Ultrafine Grained and Nanostructured Materials, 56 (1) 42-49 (2023). doi:10.22059/jufgnsm.2023.01.05.
25) A. Mahyudin, S. Arief, H.Abral, M. Muldarisnu, M.P. Artika, “Mechanical Properties and Biodegradability of Areca Nut Fiber-reinforced Polymer Blend Composites”, Evergreen, 7(3) 366-372 (2020). doi:10.5109/4068618.
26) Sathi, Brahmananda Reddy, and Swami Naidu Gurugubelli. “The Effect of ECAP on Structural Morphology and Wear Behaviour of 5083 Al Composite Reinforced with Red Mud”, Evergreen, 10 (2) 774-781(2023). doi:10.5109/6792827.
27) Senoz, G.M.L.; Ozturk, D. “Investigation of Microstructural and Hardness Changes of AA7075 Alloy Processed By ECAP”, 9 1326–1338 (2021). doi: 10.21923/jesd.913992.
28) H. Sosiati, Y. A. Shofie and A. W. Nugroho, “Tensile Properties of Kenaf/E-glass Reinforced Hybrid Polypropylene (PP) Composites with Different Fiber Loading.” EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 5(2), 1-5 (2018). doi:10.5109/1936210.
29) A. Mahyudin, S. Arief, H.Abral, M. Muldarisnu, M.P. Artika, “Mechanical Properties and Biodegradability of Areca Nut Fiber-reinforced Polymer Blend Composites,” Evergreen, 7(3) 366-372 (2020). doi:10.5109/4068618.
30) Naseri R, Kadkhodayan M, ShariatiM, “An experimental investigation of casing efect on mechanical properties of billet in ECAP process”. Int J Adv Manuf Technol 90 (9–12) 3203–3216, (2017). doi:10.1007/s00170-016-9658-1.
31) El-Danaf EA, Soliman MS, Almajid AA, El-Rayes MM, “Enhancement of mechanical properties and grain size refinement of commercial purity aluminum 1050 processed by ECAP”. Mater SciEng, A 458(1–2) 226–234, (2007). doi: 10.1016/j.msea.2006.12.077.
32) Kucukomeroglu. T, “Effect of equal-channel angular extrusion on mechanical and wear properties of eutectic Al-12Si alloy”. Mater Des 31(2) 782–789 (2010). doi: 10.1016/j.matdes.2009.08.004.
33) A. Panigrahi, N. Scheerbaum, P. Chekhonin, J. Scharnweber, B. Beausir, M. Hockauf, S. Sankaran, W. Skrotzki, “Effect of back pressure on material flow and texture in ECAP of aluminum”, IOP Conf. Ser. Mater. Sci. Eng. 63 1–13 (2014). doi:10.1088/1757-899X/63/1/012153.
34) A. Kumar, A.K. Chanda, S. Angra, “Optimization of Stiffness Properties of Composite Sandwich using Hybrid Taguchi- GRA- PCA,” Evergreen, 8(2) 310-317 (2021). doi:10.5109/4480708.
35) Aydın, M. “High-cycle fatigue behavior of severe plastically deformed binary Zn–60Al alloy by equal-channel angular extrusion”. J. Mater. Process. Technol., 212 1780–1789 (2012). doi: 10.1016/j.jmatprotec.2012.03.027.
36) Park Jong-Woo, Kim Jin-Won, Chung Young-Hoon. “Grain refinement of steel plate by continuous equal-channel angular process.” Scripta Mater, 51 181–4 (2004). doi: 10.1016/j.scriptamat.2004.02.022.