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Effect of ECAP Routes on Mechanical Properties and Microstructure of AA6061-T4 Recycled Chips

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HIGHLIGHTS

- Tensile strength increased substantially by around 67% for route BC, while for route C, it rose by about 50%
- Strength improved significantly, reaching 265MPa and 238MPa for routes BC and C after four passes
- Results showed route BC is most effective for generating UFG materials to refine grains from recycled AA6061-T4 chips
- ECAPed samples with tensile strength rising 67% for route BC and 50% for route C
- Micro-hardness increased 67% after four passes to 79.36 HV, while for route BC, it reached 62.82 after two passes

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ABSTRACT

Aluminum alloy finds strong suitability in automotive, sporting, goods aerospace, and weight reduction industries. Its blend of lightweight attributes and robust strength make it well-suited for crafting lightweight components and structures while upholding overall strength and performance standards. In this research, AA6061-T4 alloy chips underwent a recycling process involving hot extrusion followed by Equal Channel Angular Pressing. The influence of various routes and varied numbers of cycles on microstructure and mechanical characteristics were examined utilizing a die featuring angles of 90° and 20°. Two routes, BC and C, were scrutinized, and the outcomes displayed significant enhancements in properties for the recycled chips after the hot extruded and ECAP techniques. After the fourth run, route BC exhibited a maximum Ultimate tensile strength of 265 MPa, peak yield strength of 149 MPa, and an elongation to failure of 46%. Meanwhile, the corresponding values for route C were 238 MPa, 136 MPa, and 41%, respectively. For two routes, BC and C, every pass led to elevated strength and hardness while also contributing to increased elongation to failure. The microstructures and mechanical characteristics of the ECAPed samples surpassed those of the extruded sample. The routes and pass numbers substantially impacted the microstructures and mechanical properties of the solid-state recycled AA6061-T4 alloy chip specimens. Scanning electron microscopy pictures showcased a honeybee-type pattern following ECAP through route BC, signifying the final stages of grain refinement. At the same time, the initial sample exhibited a fracture tendency with a mix of brittleness and ductility.

1. Introduction

Aluminum alloy is widely employed across diverse industries and is recognized for its balanced strength, heat treatability, weldability, formability, resistance to corrosion, encompassing machinability, exceptional characteristics, and lightweight properties. Its affordability further contributes to its popularity among aluminum manufacturing entities. This alloy has extensive usage in furniture manufacturing, irrigation applications, agriculture fitting production, marine structures pipe, aerospace, and automotive [1]. The demand for aluminum is projected to sustain its upward trajectory owing to its favorable attributes, encompassing elevated strength, lightweight nature, exceptional conductivity, and corrosion resistance. In contrast to conventional aluminum recycling techniques involving remelting, solid-state recycling through plastic deformation presents noteworthy advantages. These advantages encompass diminished expenses, reduced power consumption, and a streamlined operational process [2]. The elongated, slender, and spiral configuration of aluminum chips renders the conventional remelting recycling approach unfavorable due to notable metal waste. Furthermore, additional losses are incurred at each successive treatment phase, leading to a maximum recovery of only fifty-four percent of the materials through traditional re-melting and recycling procedures [3]. Several scientists [4] have acknowledged the exceptional plastic deformation achieved via hot extrusion when contrasted with alternative methods. The capacity to subject compressed chips to substantial plastic deformation renders it

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a compelling and promising avenue for recycling. In its present characterization, Severe Plastic Deformation (SPD) encompasses any metal-forming technique that employs elevated hydrostatic pressure to induce substantial strain within a bulk solid.

This process leads to remarkable grain refinement while maintaining negligible alterations in overall dimensions [5,6]. New approaches to severe plastic deformation have been developed, including high-pressure torsion (HPT) [7], multi-directional forging (MDF) [8], cyclic extrusion compression (CEC) [9], accumulative roll bonding (ARB) [10], dissimilar channel angular pressing (DCAP) [11], equal channel angular pressing (ECAP) [12], among others. Severe plastic deformation (SPD) technologies such as ECAP and torsion straining have proven particularly advantageous among these techniques for producing ultrafine-grained materials.

Equal channel angular pressing stands as one of the most extensively employed severe plastic deformation methods for enhancing the strength of lightweight alloys. The SPD technique is introduced as an effective method for enhancing material strength by converting coarse grains into structures characterized by ultrafine-grained (UFG) morphology [13]. In addition, Duflou et al. [14] researched the ecological influence of the Solid-state recycling (S.S.R.) technique to produce net-form items with little to no pollution while seeking to extend the solid-state recycling process to produce goods suitable for producing other commodities. The growing significance of S.S.R. by extrusion or different techniques starting with solid-state chips has been encouraged by Wan et al., [3]. Additional prior investigation about enhancing solid-state recycling within extrusion employing frictional-stir extrusion by Baffari et al., [15]. Extrusion or other techniques that started with "solid-state" chips have increased the relevance of solid-state recycling. Maziarz et al., [16]. An investigation examined composites' morphology and mechanical features through TCAP at 350°C, 400°C, and 450°C. The finding yielded a composite with a matrix comprising equiaxed grains of varying sizes contingent upon the process temperature and particles measuring around 1μm in diameter exhibiting a twinned structure. The process of dynamical recrystallization significantly influenced the specimens, hardness, leading to a decrease in hardness levels.

Employing a die with the optimum design factors, the mechanical properties of the AA6063 alloy were examined both before and after the ECAP technique by Agarwal et al., [17]. An examination was conducted by applying a die via an angle die with two intersected channels at 90 and 20 degrees. Tensile strength rose with each run, but elongation was marginally reduced, as indicated by the stress-strain graph.

The study focused on analyzing the influence of morphology in AA5083 alloy following equal channel angular pressing treatment conducted at both room temperature and elevated temperatures by Baig et al., [18]. After undergoing three runs, strength increased to 251 MPa at a temperature of 250°C. The study delved into investigating the deformation behavior of a magnesium alloy by Gautam et al., [19]. The findings indicated that as grain refinement occurs, there is an increase in yield strength while ultimate compressive strength (UCS) and strain to failure witness a decrease. The grain size significantly influences the strain-hardening behavior at ambient temperatures. The morphology of the AA6060 alloy revealed the presence of a fragmented grain structure, according to Lefstad et al., [20].

Applying a die via an angular with two channels crossing at 90° and 20.2° degrees, the investigation was carried out through the BC route. Effects of combined ECAP and HPT processes on received material tribology characteristics, mechanical properties, and morphology improvement by Ibrahim et al., [21]. The findings indicated an upward trend in tensile strength and a decreased elongation as the number of ECAP passes and HPT revolutions increased. This behavior was attributed to grain refinement. Furthermore, the dominant mode of tensile fracture, across all samples, was found to be shear fracture with a decline in the shear angle evident with greater imposed strain. The dimple size exhibited a significant decrease, with an increase in the number of ECAP passes and HPT revolutions corresponding to the decrease in grain size. The tensile properties of AA6063 alloy were improved by Abioye et al., [22]. Extruding set A of the samples' billets into the die once was how the procedure was performed. According to the research, aluminum alloys are always strengthened by using ECAE. After four cycles, the elongation to failure (twenty-nine percent) and the Young Modulus 11GPa were recorded.

Surprisingly, Kadir et al. [23] applied hot compact (homogenization) to AA6061 recycled aluminum alloy chip and aluminum powder samples prior to extrusion at different preheating temperature periods extending from twenty minutes to six hours. AA6061 alloy chips were recycled by Taha et al., [24]. Using a die with a 90° angle. The hardness increased to 85 HV after combining extrusion with ECAP for six cycles, as observed. Investigation revealed that the sample grain sizes significantly diminished by 5, 3.28, and 2.46μm during the 2, 4, and 6 runs. Structural evolution, mechanical, and physical features of samples made of AA6061 alloy. The effects of extruded ratio and extruded temperatures were examined by Abd et al., [25]. Samples with ER12.8 and ET at ET500°C show better mechanical characteristics than the original ones. The last twenty years have seen a rise in the significance of hot extrusion as a technique for reutilization, which culminated in the most recent efforts by Liang et al., [26].

Gronostajski et al. [27] claim that a specific amount of Ɛ is necessary to remove layers of oxide from chip surfaces and produce a clean surface of metal to improve the bond. Investigation of the effects of cracking plane orientations on the test of fatigue cracking development rates and fracturing resistance of AA6063 by Kazemi et al., [28]. A die with 90° and 22° angles was employed for the study. The outcomes demonstrated a significant enhancement in UTS, increasing to 209 MPa, and a reduction in the average grain size from 45μm to approximately 230nm after undergoing four cycles. Aluminum and Magnesium alloy types are extensively utilized in applications in structure owing to their remarkable mechanical features and amalgamation of lightweight attributes. Many sectors of industries, including furniture, automobiles, plumbing, and other products, commonly use AA6061 alloy water for agricultural purposes [29].

ECAP has proven to be an efficient method for refining bulk metal and converting coarse grain structures into materials with excellent mechanical properties. As a result, it has been utilized in the solid-state recycling of aluminum machining chips to produce products with enhanced characteristics. One area that shows promise is the combination of hot extrusion followed by ECAP at ambient temperature, which has demonstrated more effective results due to the improved morphology of the materials.

Additionally, this approach requires less energy than a higher-temperature version of the same process to create high-strength materials. However, there is a lack of experimental investigations in this specific area based on the authors' knowledge. In order to build upon existing studies, the selection of ECAP process factors for the present investigation, along with their impact on mechanical properties and morphology, was carefully considered to yield the most desirable outcomes from the study.

2. Experimental

2.1 Equipment and Material

Figure 1 and 2 illustrates the arrangement and setup used for the experimental work. This study employed the industrially available AA6061 alloy. Physical characteristics, mechanical properties, and chemical composition are detailed in Tables 1 and 2 Chemical analysis utilizing quantometry examination. According to ASTM E1251-17, this standard practice outlines the procedures for evaluating the performance of optical emission spectrometers (OES) used in quantitative chemical analysis. It is a valuable resource for ensuring the reliability and accuracy of chemical composition analysis using quantometry with (OES) instruments, particularly in the context of metallic materials.

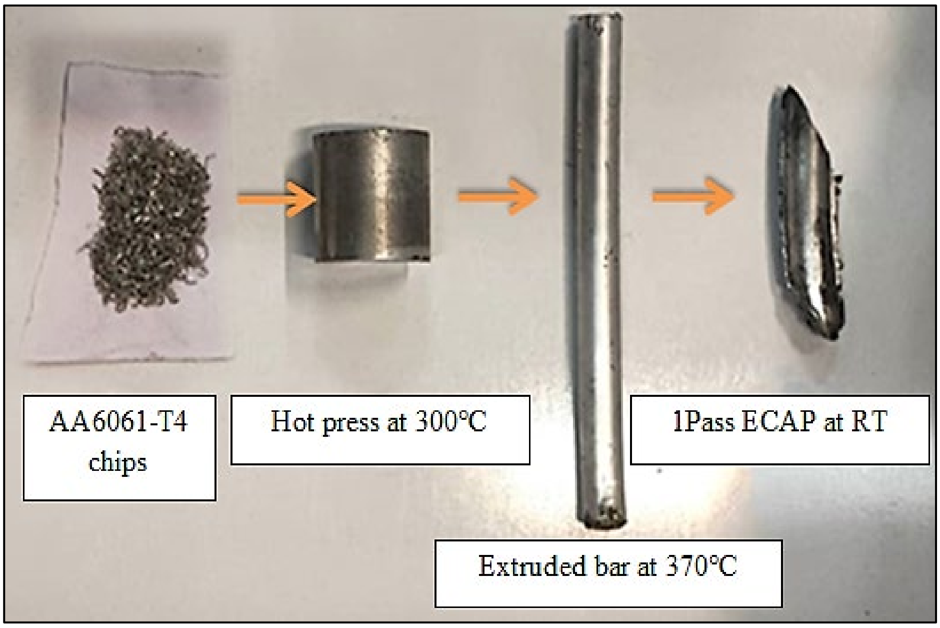

Figure 1: Demonstrated various configurations of the experimental work setup

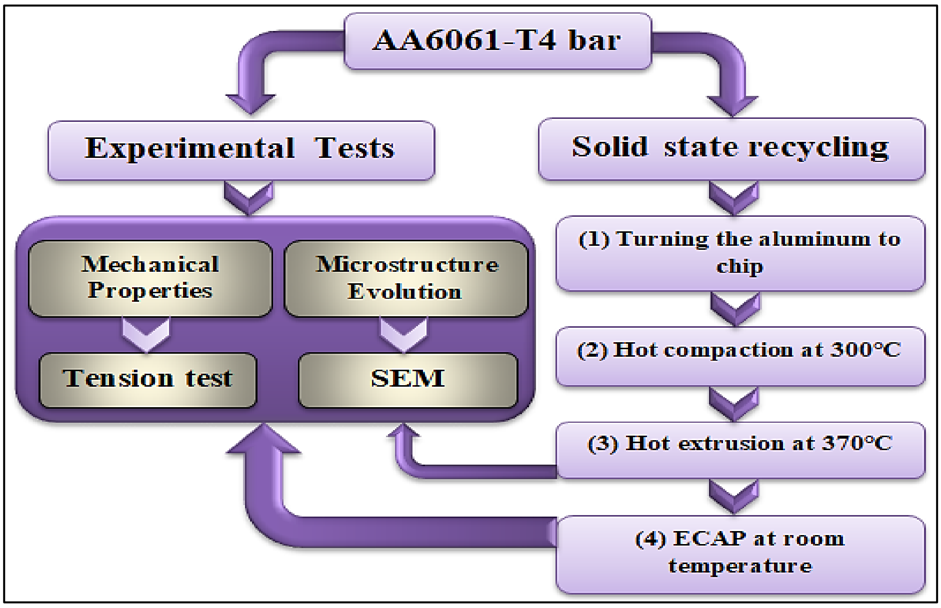

Figure 2: Experimental diagram

Table 1: Chemical Compositions of AA6061-T4 aluminum alloy

	Chemical Compositions									Base
Elements	**Mg**	**Si**	**Fe**	**Cu**	**Mn**	**Cr**	**Zn**	**Ti**	**Other s**	**Al**
%Min %Max [1, 30]	0.8 1.2	0.4 0.8	- 0.7	0.1 5 0.4	- 0.1 5	0.0 4 0.3 5	- 0.2 5	- 0.15	- 0.15	95.8 98.6
AA6061-T4	0.92	0.6 0	0.2 6	0.2 3	0.1 5	0.1 2	0.0 3	0.013	0.115	97.562

Table 2: Mechanical Properties of AA6061-T4 aluminum alloy [1,30]

Property	AA6061-T4
Tensile Strength	250 MPa | 36000 psi
Yield Strength	110 MPa | 16000 psi
Micro hardness	81.66 HV
Elongation	27%
Density	2.70 g/cc | 0.0975 lb/in³

2.2 The Experimental Work

In the current study, the original bar stock was dry-turned to create AA6061-T4 alloy chips. The machining process utilized the subsequent cutting parameters, a cutting speed of 88 m/min, a depth of cut set at 1mm, and a feed rate of 1mm/rev [25]. The chips underwent compaction at a temperature of 300°C. The compacted sample possessed dimensions of Ø=45x 80mm, and a compressive force of 200 bar was applied during this stage. Subsequently, extrusion was conducted at 370°C through a cone-shaped die with an extrusion ratio of 9 (approximately ε=2). This process was carried out using a horizontal hydraulic press with a capacity of 200 tons and a speed of 10mm/s, while the extrusion compressive force was maintained at 100 bar. As a result, intermediate items with a diameter of Φ 15mm were successfully produced. Hot extrusion, characterized by intense compressive and shear forces at elevated temperatures, strengthened the compacted recycled material chips [31]. Cylindrical samples with a diameter of Ø 15mm and a length of 60 mm designed as billets were machined from the extruded samples.

The ECAP process was carried out using a two-part divided die configuration, as illustrated in Figure 3 (a,b). The die material employed was tool steel, chosen for its suitability in reducing process time as it doesn't require bolts. The channels within the die intersected at an angle of Φ = 90°, while the outer corner angle was Ψ = 20°. To optimize grain refinement and enhance mechanical properties, the process was conducted through two selected routes: BC and C. These routes were chosen based on recommendations, as shown in Figure 4 (a,b). Equal Channel Angular Pressing was implemented on billets with dimensions of Ø15 x 50mm. The procedure ensured a consistent strain of approximately 1.05 in each successive run. Samples were subjected to significant simple shear strains [32]. The study explored the control of varying numbers of passes (1,2,4) using different routes at ambient temperature, as depicted in Figure 4. Among these routes, Route BC was identified as the most efficient for creating ultrafine-grained (UFG) materials with consistent morphology. The process involved employing a vertical hydraulic press (Model CH-250x250) with a 100-ton capacity operating at a pressing speed of 10mm/min [33]. In this process, for each pressing stage, molybdenum disulfide (MoS_2) was employed as a lubricant due to its low coefficient of friction and also known for its high-temperature stability. Using MoS_2 in the ECAP process helps reduce friction, wear, and heat generation, improving process efficiency, product quality, and extended tool life.

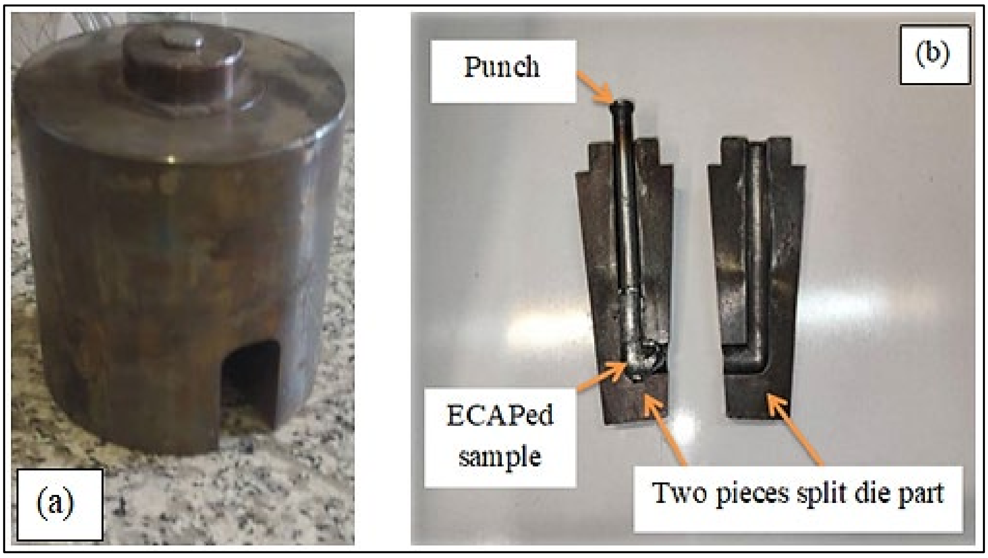

Figure 3: Display the ECAP Die (a) demonstrating the ECAP Die (b) showcasing the two –piece split die component

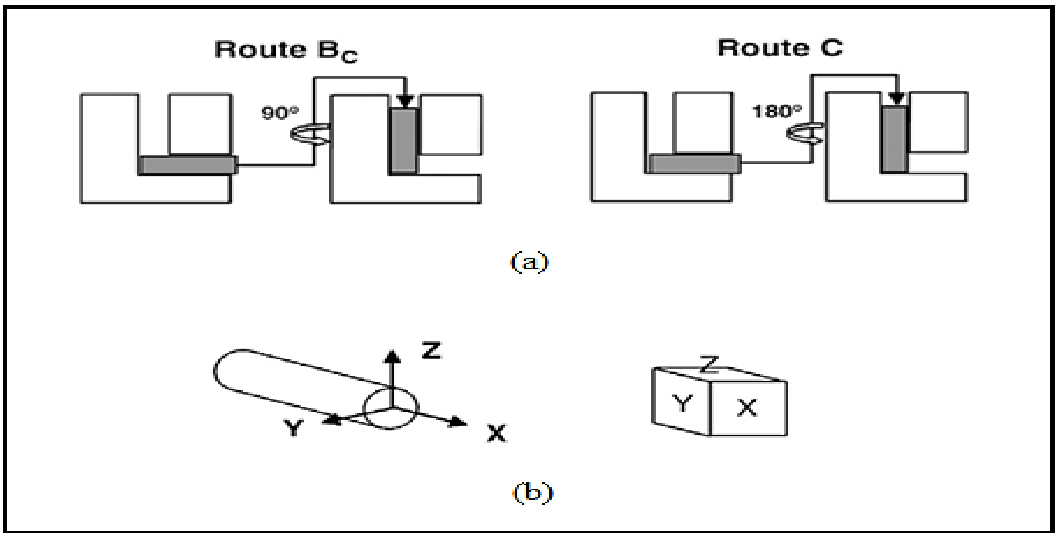

Figure 4: Depiction of (a) Schematic representation of ECAP routes BC and C inducingrotations around the longitudinal axis X of the billet by +90° and 180°respectively (b) Orientation of X, Y, and Z axes (on the left) and planes (on the right) [34,35]

The procedure of ECAP was implemented on billets with 4 cycles at RT. During the process, samples were pressed at a speed of 10mm/s. Utilizing a vertical hydraulic press of 100 tons. According to ECAP technology, plastic strain levels are around 1.05 in each cycle [36]. The samples were subjected to a larger simple shear strain [28]. The final products are shown in Figure 5 (a-e).

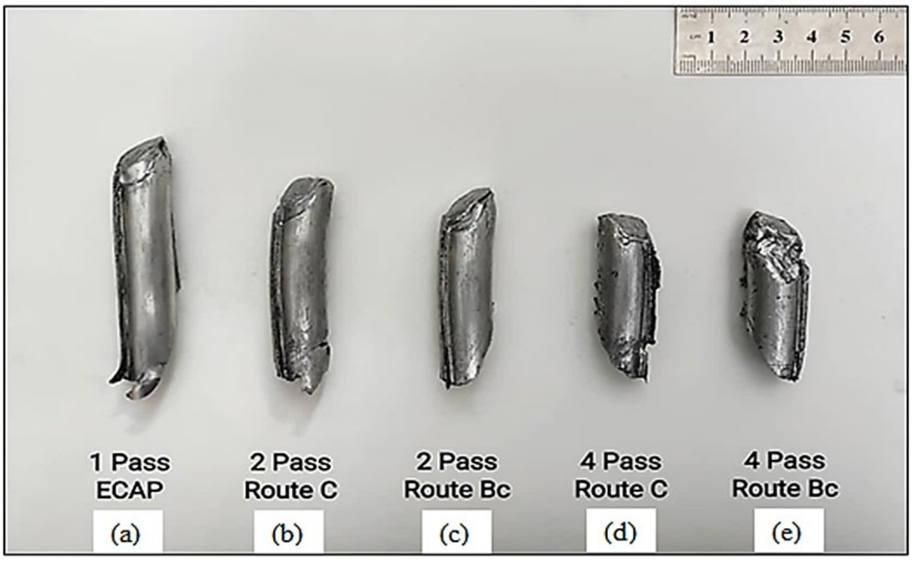

Figure 5: Final products of solid-state recycling of AA6061-T4 alloy recycled chips

3. Results and Discussion

The study involved conducting tests on recycled industrial AA6061-T4 chips. These chips were subjected to a process of hot extrusion followed by ECAP using two routes. The subsequent sections of this work elaborate on the outcomes and conclusions drawn from this experiment.

3.1 Routes Influence on Tensile Strength

All specimens, including the original extruded and ECAPed AA6061-T4 specimens, had their tensile characteristics evaluated using a universal machine (SANTAM STM-50). All specimens were precisely sectioned using an electro-discharge machining EDM wire cutting apparatus, as depicted in Figure 6. Specimens with a tapered configuration were then obtained, featuring a 3mm thickness and a 5mm gauge length. These samples had been clipped along the lengthwise orientation aligned with the extrusion direction, as illustrated in Figure 7 (a,b). Conforming to the ASTM E8/E8M-16 standards, the sub-sized tensile specimens adhered to specifications for a 5mm gauge length, 3mm width at the reduced section, and around 3mm thickness [37].

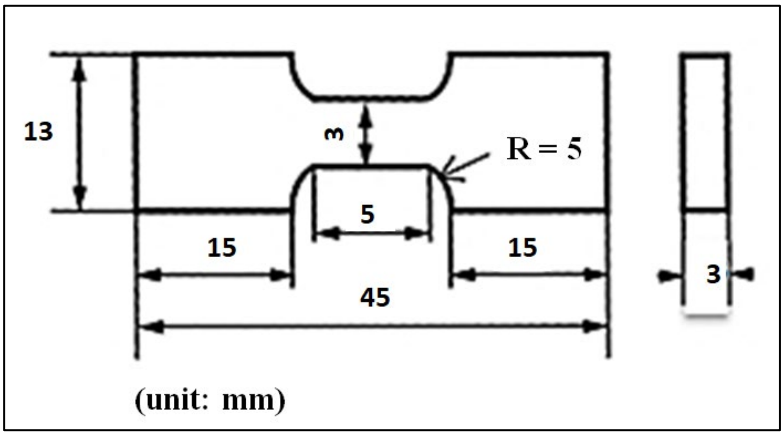

Figure 6: The dimensions of the tensile test samples are expressed in (mm)

Figure 7: Representation of tensile specimens (a) specimens before tensile testing (b) specimens after tensile examination

Tables 3 and 4 list the mechanical properties of AA6061-T4 prior to and following processing. Extruded specimens had 33% elongation and 159 MPa 105 MPa accordingly. With an increasing cycle number, there is a noticeable rise in both the YS and UTS numbers. After undergoing four passes, the UTS of this specimen demonstrates an enhancement to 265 MPa while the yield strength improves to 149 MPa, accompanied by a remarkable elongation of 46%. While the alloy's strength improves with an increase in the number of runs, there is also a corresponding enhancement in the extent of elongation, which increases from 33 percent to 46 percent. This phenomenon can be attributed to the effects of SPD processing and its consequent strengthening through material deformation. It has been deduced that the amplified strength observed in the alloy as a result of the ECAP procedure primarily stems from the grain refinement process [18]. Following a solitary ECAP pass, there is a notable reduction and refinement in the grain size. Moreover, the phenomenon of partition becomes evident within specific grains and along grain boundaries, and it becomes more pronounced as a consequence. Additionally, twinning plays a crucial role in altering the yield strength (YS), which acts as a barrier against dislocation glide and contributes to enhanced characteristics. Consequently, the increase in YS is influenced by the grain refinement and the interplay of twinning and dislocation motion. Notably, it becomes evident that elongation is reduced after reaching a critical pass. Generally, the ductility of materials tends to decrease post-twinning. This decline in elongation can be attributed to the innate malleability of metals, while the advancement of partitioning does not significantly impact microstructure refinement.

Table 3 illustrates that through route BC pressing, the ultimate tensile strength (UTS) undergoes a substantial enhancement from 159 MPa to 265 MPa after undergoing four passes, marking a remarkable improvement of 67%, as shown in Figure 8 (a). This enhancement in strength can be attributed to the grain refining process, which is facilitated through repeatable passes. In contrast to the extruded specimen, results indicate UTS rose even after just a single pass using route BC. Furthermore, as depicted in Table 4, the implementation of route C pressing results in a significant enhancement in UTS, escalating from 159 MPa to 238 MPa after undergoing four passes, indicating an impressive improvement of 50%, as shown in Figure 8 (b). This strengthening effect can be attributed to the process of grain refinement facilitated by many runs. Additionally, it demonstrated that material strength experienced an exceptional increase following four passes, exhibiting a notable disparity in contrast to the extrusion one. Strengthening resulting from the movement of dislocations and refinement of grains [38] was influenced by the heightened density of dislocations due to strain strengthening. Severe plastic and cold deformation alter the tensile properties of metallic strength subjected to SPD. During the initial pass, there was a marked rise in UTS and yield strength, albeit accompanied by a rapid reduction in elongation. The subsequent passes in this process yield an incremental increase in strength, fundamentally attributed to the evolving structures within the grains. Consequently, YS rates of enhancement and elongation decrease with successive passes, which are lower than the effects observed with the initial run.

Table 3: Mechanical properties of AA6061-T4 before and after ECAP using Route BC

Condition, Route BC	Average hardness (HV)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation %
As Received	81.66	250	110	27
Extruded	47.55	159	105	33
1-pass	61.16	209	135	13
2-pass	62.36	232	138	22
4-pass	79.36	265	149	46

Table 4: Mechanical properties of AA6061-T4 before and after ECAP using Route C

Condition, Route C	Average hardness (HV)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation %
As Received	81.66	250	110	27
Extruded	47.55	159	105	33
1-pass	61.16	209	135	13
2-pass	68.34	182	115	12
4-pass	86.06	238	136	41

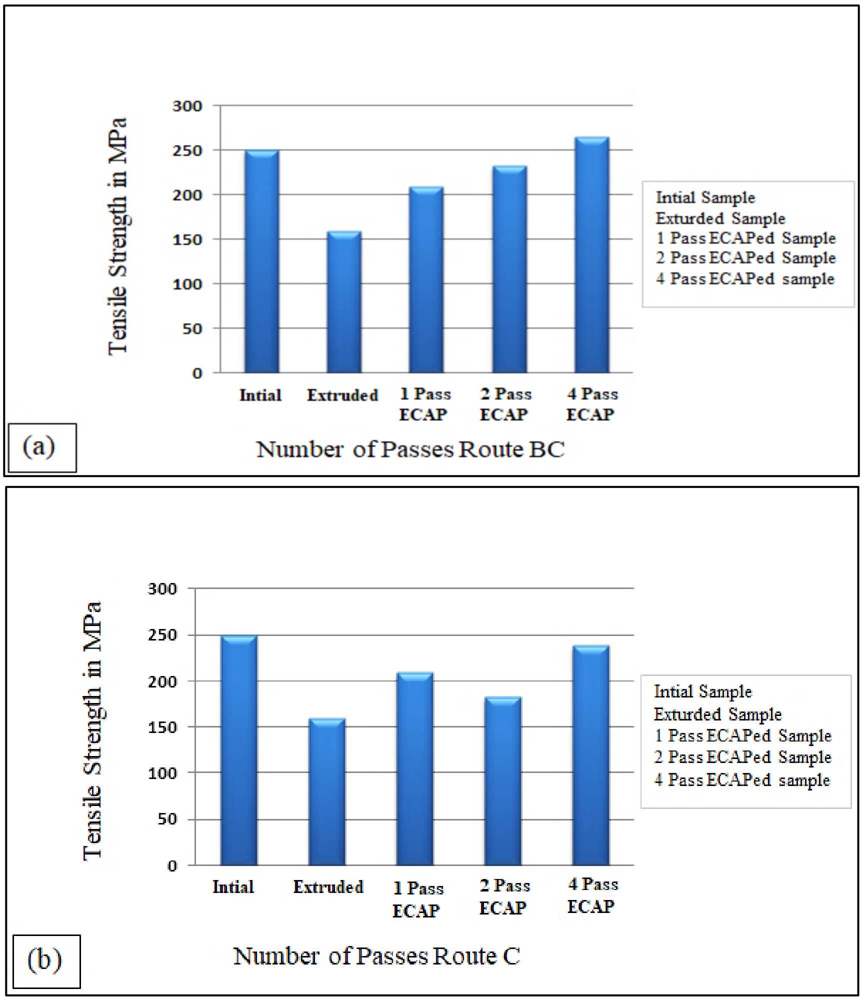

Figure 8: (a) Variation of tensile strength with ECAP using Route BC, (b) Variation of tensile strength with ECAP using Route C”

3.2 Impact of Routes on Hardness

Tables 3 and 4 revealed a clear correlation between hardness and YS, with an elevation in YS aligning with a rise in micro-hardness. Following a single run, the YS measured 135 MPa, accompanied by a recorded hardness of 61 HV. After implementing 4 cycles through route BC, the YS escalated to 149 MPa, and the significance hardness surged to 79 HV, as shown in Figure 9 (a). Likewise, for four runs utilizing the same path C, the yield behavior elevated to 136 MPa, accompanied by an increased number of 86 HV, as shown in Figure 9 (b).

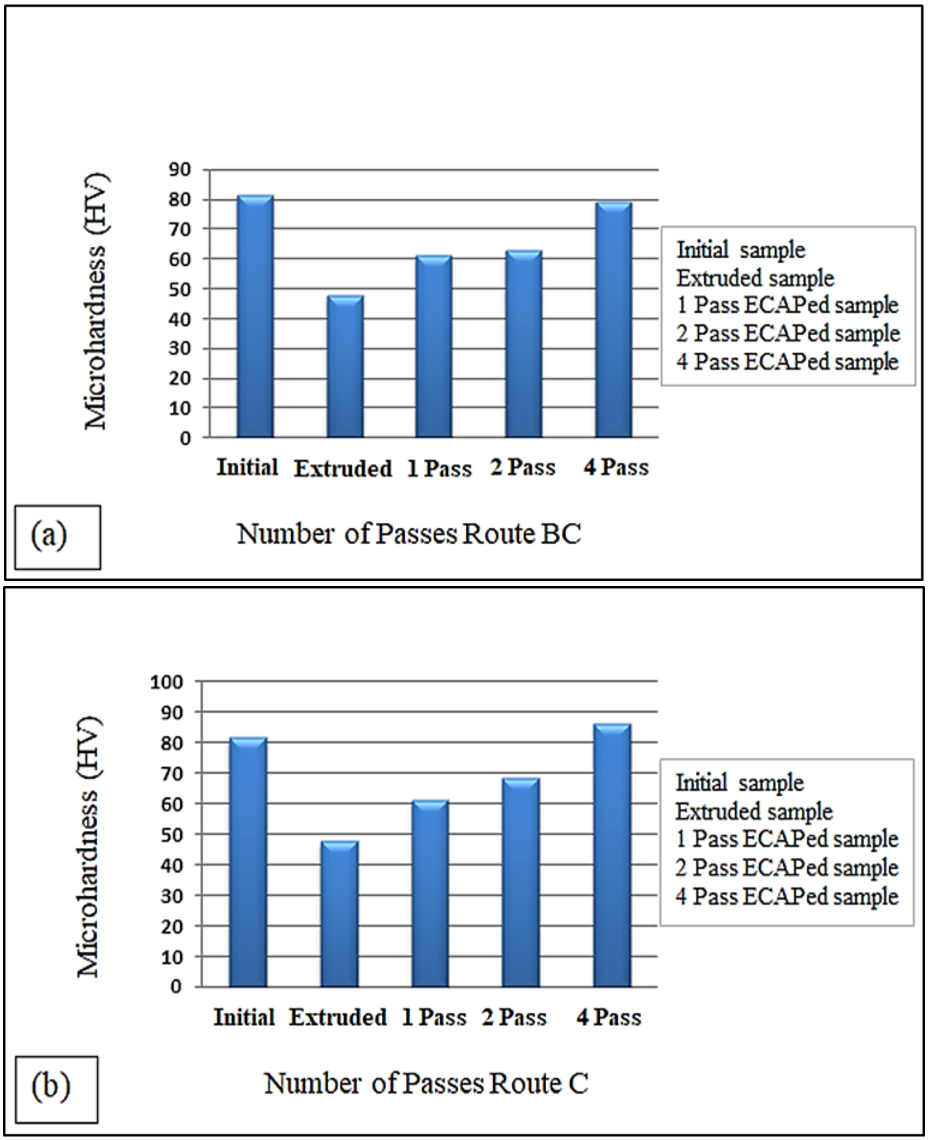

Figure 9: (a) Variation of Hardness with ECAP using Route BC, (b) Variation of Hardness with ECAP using Route C"

3.3 Routes Influence on Microstructures

The fracturing mechanisms of the fractured tension specimens have been further investigated. A 3-by-3-millimeter tip was made for each of the three separate specimens in addition to the initial specimen received to aid in this inspection. Structural testing is conducted using a SEM machine. A comprehensive analysis of the fracture properties of recycled AA6061-T4 alloy samples was carried out by examining fracture surfaces through scanning electron microscopy.

Throughout the tensile tests at various stress levels, 250 MPa, 159 MPa, 238 MPa, and 265 MPa, fractured areas of the initial specimen extruded in 4-runs C and the 4-runs BC samples were subjected to investigation. Observations revealed the fractures exhibited a ductile mode of propagation. Figure 10 presents the fractography images illustrating distinct fracture tendencies in recycled material alloy samples as captured by scanning electron microscopy (SEM).

Figure 10 (a) depicts the specimen as received, which has a mixed ductile-brittle fracture trend. In contrast, Figure 10 (d) depicts a specimen after four passes through route BC, demonstrating a honeybee-type structure. This structural pattern indicates the final stages of grain refinement, implying enhanced malleability and explaining the heightened uniformity of the specimen.

Furthermore, Figures 10 (b) and 10 (c) display the sample subjected to extrusion and the 4th specimen with route C, respectively. Both images illustrate specimens that display a ductile fracture tendency. Upon reaching the fourth pass of ECAP, the initial coarse grains began transforming into structures characterized by dislocation tangles, which considerably impacted the evolution of fracture crack behavior. The capability of cracks to propagate along dislocation walls and the boundaries of dislocation tangles leads to a modification in crack propagation direction within the larger grains. Fracture trans-granularly manifested zones of shear deformation formed within the planar region, while intergranular fracturing emerged across High-Angle Grain Boundaries (HAGBs) within the granular region [39].

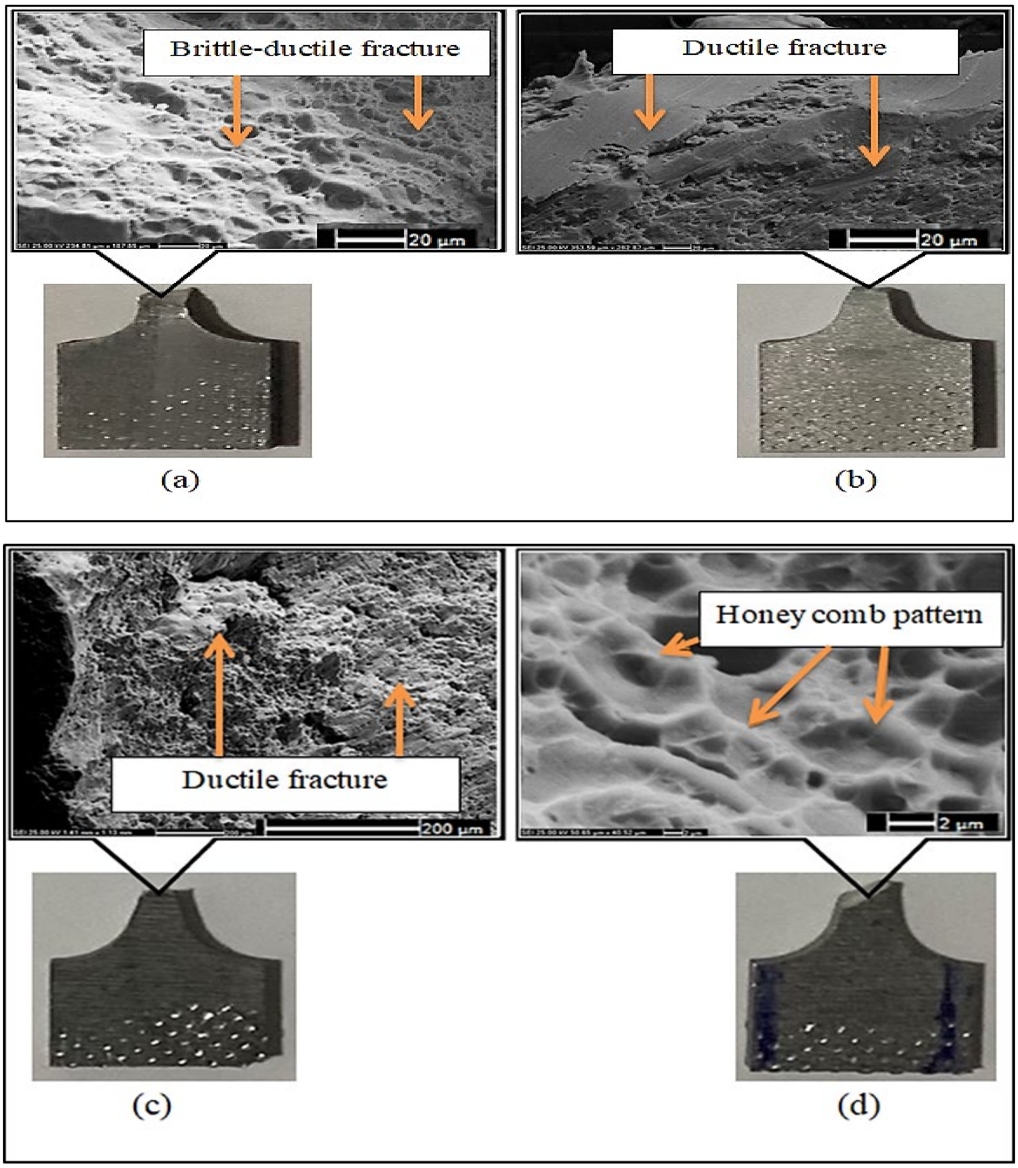

Figure 10: Different fractured specimens were seen using SEM (a) Received material brittle-ductile fracture, (b) Extruded sample, (c) 4th route C ECAP specimen, and (d) 4th route BC ECAP specimen displaying shear rupture”

The escalation in the HAGBs proportion led exclusively to the propagation of intergranular fractures following the completion of four ECAP passes. Corresponding findings were documented for UFG AA6063 and AA6061 alloys after undergoing four ECAP runs [28]. On the surface morphology of UFG materials, additional secondary cracks were also observed running parallel to the HAGBs, indicative of intergranular cracking. Despite the fact that the four-pass pressing process of the AA6061 alloy negated the fracture enhancement observed after the two-pass ECAP, the high fracture strength of the AA6061 aluminum alloy in this investigation remained intact. The outcomes of the present investigation showcased that the highest efficacy of fractures was attained by exposing AA6061-T4 to a sequence of 4th runs via the BC route. Most fracture examples conducted on processed samples have consistently exhibited this behavior, owing to the strength enhancement ECAP substantially elevating the materials' resistance against fracture. Conversely, grain refinement augments resistance against the development of fracture cracks by curbing the intensity of extrusion-induced expansions, primarily due to reduced dislocations within slip bands. In materials treated with ECAP, the pathway for crack propagation is simplified, reducing the propensity for crack advancement. Consequently, enhancing both strength and ductility plays a pivotal role in bolstering fracture resistance.

A comparison between the previous and current studies in terms of ultimate tensile strength, elongation to failure, and micro-hardness as tabulated in Table 5.

Table 5: Comparisons between the previous studies with the current study in terms of ultimate tensile strength, elongation to failure, and micro-hardness

Material	Ultimate tensile strength (MPa)	Elongation to failure %	Micro-hardness (HV)	Route	Φ	Ψ	Year	Methodology	Ref.
AA6061	-	10.9	-	BC	90°	30°	2018	as-cast condition ECAP	[40]
AA6063	-	26	-	BC	-	-	2019	As a received ECAP	[22]
AA6063	120	9.42	-	BC	90°	5°	2019	As a received ECAP	[41]
	176	10.95		C					
AA3030 Al-Mn-Fe-Si	240	-	70	-	90°	-	2020	Plates as a received I-ECAP	[42]
AA6061	245	11.9	84	-	90°	20°	2021	Boron carbide composite ECAP at 500 °C	[43]
AA6063	250	-	80	BC	120 °	30°	2021	As received ECAP at 250 °C	[44]
			85	C					
AA8176 Al–Fe alloy	186	10.5	-	BC	90°	90°	2021	As a received heat-treated at 540 °C ECAP	[45]
AA6061-T4	265	46	79.6	BC	90°	20°	2023	S.S.R AA chips hot extrusion followed by ECAP at RT	-
	238	41	86	C					

4. Conclusion

Commercial aluminum-grade AA6061-T4 chips were recycled using hot extrusion followed by SPD processing using both routes BC and C through the ECAP die with a 90° channel angle and 20° corner angles. The results are concluded as follows:

1) UTS demonstrated a notable escalation with an increasing number of passes. Following four passes via ECAP, route BC and route C achieved 265 MPa and 238 MPa, respectively.
2) The findings highlighted that Route BC proved to be the most efficient pathway for generating UFG materials characterized by a uniform microstructure. Moreover, the recycling of AA6061-T4 alloy chips was found to be conducive to achieving grain refinement.
3) Examination of the fractured surfaces using scanning electron microscopy (SEM) revealed honeybee-type patterns (indicative of high ductility) after ECAP via route BC. In contrast, the initial specimen exhibited mixed brittle-ductile fractures.
4) The fractured sample subjected to "ECAP," particularly the Route BC sample, displayed a fracture pattern reminiscent of shear rupture resulting from tensile forces. This fracture behavior was attributed to the grain morphology and the presence of elongated dislocation cells.

Author contributions

Conceptualization, A. Shahab and R. Mohammed; methodology, A. Shahab and R. Mohammed; validation, A. Shahab; investigation, R. Mohammed; resources, R. Mohammed; writing—original draft preparation, R. Mohammed; writing—review and editing, R. Mohammed; visualization, R. Mohammed supervision, A. Shahab; project administration, A. Shahab and R. Mohammed. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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