International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Effect Of Equal Channel Angular Pressing On The Microstructural Evolution And Mechanical Properties Of AA5052 Aluminium Alloy

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Abstract
The continuous demand for lightweight structural materials possessing superior mechanical performance has stimulated extensive research on advanced grain refinement techniques for aluminium alloys. Among the various severe plastic deformation (SPD) processes, Equal Channel Angular Pressing (ECAP) has emerged as one of the most effective methods for producing ultrafine-grained metallic materials without altering the external dimensions of the workpiece. The present investigation evaluates the influence of ECAP processing on the microstructural evolution and mechanical properties of AA5052 aluminium alloy using dies having channel intersection angles of 90° and 120°. Initially, AA5052 alloy billets were prepared through conventional casting and subsequently subjected to one-pass and two-pass ECAP processing under identical operating conditions. The processed specimens were characterized using optical metallography to examine grain refinement, while Rockwell hardness testing was employed to evaluate the corresponding changes in mechanical behaviour. Experimental observations revealed a progressive reduction in grain size with increasing ECAP passes owing to the accumulation of severe plastic strain. The specimen processed through the 90° ECAP die exhibited comparatively finer equiaxed grains and higher hardness than specimens processed using the 120° die, indicating the significant influence of die geometry on deformation behaviour. The enhanced hardness is primarily attributed to grain-boundary strengthening, increased dislocation density, and strain hardening induced during repeated ECAP passes. The obtained results demonstrate that ECAP processing substantially improves the microstructural characteristics and hardness of AA5052 alloy, thereby expanding its potential for lightweight engineering applications requiring enhanced strength and wear resistance.

Keywords: Equal Channel Angular Pressing, Severe Plastic Deformation, AA5052 Aluminium Alloy, Grain Refinement, Hall–Petch Strengthening, Hardness, Microstructure.

1. Introduction

The demand for lightweight structural materials with improved mechanical performance has increased significantly owing to the growing emphasis on fuel efficiency, emission reduction, and sustainable manufacturing. Aluminium alloys have become indispensable engineering materials in aerospace, automotive, marine, railway, and defence industries because of their high strength-to-weight ratio, corrosion resistance, recyclability, and excellent formability. Among the non-heat-treatable aluminium alloys, AA5052 is widely employed in pressure vessels, marine structures, storage tanks, aircraft fuel systems, and transportation equipment due to its excellent corrosion resistance and weldability. However, its relatively low hardness and strength restrict its application in components subjected to high mechanical loading. Consequently, grain refinement has emerged as an effective strengthening strategy for improving the performance of AA5052 without significantly altering its chemical composition.

Severe Plastic Deformation (SPD) techniques have received considerable attention over the past two decades because they enable the production of ultrafine-grained metallic materials through the introduction of exceptionally high plastic strains. Unlike conventional thermo-mechanical processes such as rolling, extrusion, or forging, SPD methods impose large plastic deformation while preserving the overall dimensions of the workpiece. Among the various SPD techniques, Equal Channel Angular Pressing (ECAP), first proposed by Segal, is one of the most effective and industrially viable methods. In ECAP, a billet is pressed through two intersecting channels of identical cross-section, where intense simple shear deformation occurs at the channel intersection. Since the billet retains its original dimensions after each pass, repeated processing can be carried out to accumulate large strains, leading to significant grain refinement and enhanced mechanical properties. Previous studies have reported remarkable improvements in hardness, yield strength, fatigue resistance, and wear behaviour of aluminium alloys processed through ECAP owing to increased dislocation density and the formation of high-angle grain boundaries.

The extent of grain refinement achieved during ECAP depends primarily on the channel intersection angle, processing route, number of passes, lubrication conditions, and deformation temperature. A smaller die angle introduces a higher equivalent strain during each pass, thereby promoting greater grain subdivision and accelerated transformation of low-angle grain boundaries into stable ultrafine grains. Although ECAP has been extensively investigated for commercially pure aluminium and heat-treatable aluminium alloys, comparatively fewer studies have focused on AA5052, particularly with respect to the influence of die geometry under identical processing conditions. Understanding the relationship between die angle, accumulated strain, and mechanical behaviour is therefore essential for optimizing ECAP parameters for practical engineering applications.

The present work investigates the influence of ECAP on the microstructural evolution and hardness of AA5052 aluminium alloy using two die channel angles, 90° and 120°. Billets were processed through one and two ECAP passes and subsequently characterized using optical microscopy and Rockwell hardness testing. The study aims to establish the effect of die geometry and accumulated strain on grain refinement and mechanical strengthening, thereby demonstrating the suitability of ECAP as an efficient processing technique for the development of high-performance lightweight aluminium components.

2. Materials and Experimental Procedure

2.1 Materials

The experimental investigation was carried out using commercially available AA5052 aluminium alloy owing to its excellent corrosion resistance, moderate strength, good weldability, and high formability. This alloy is extensively employed in marine structures, transportation systems, pressure vessels, aircraft components, and chemical processing equipment because of its superior resistance to atmospheric and saline environments. Although AA5052 possesses desirable corrosion resistance and ductility, its relatively low hardness and strength limit its application in highly stressed structural components. Consequently, grain refinement through Severe Plastic Deformation (SPD) offers an effective approach for improving its mechanical performance without altering its chemical composition. The billets employed in the present investigation were prepared through conventional casting prior to ECAP processing. The selection of AA5052 alloy was based on its excellent workability during severe plastic deformation and its capability to undergo substantial strain without premature fracture, thereby making it suitable for repeated ECAP passes. The experimental methodology adopted in this investigation was designed to evaluate the influence of ECAP die angle and the number of passes on the resulting microstructure and hardness of the alloy.

2.2 Principle of Equal Channel Angular Pressing

Equal Channel Angular Pressing (ECAP) is one of the most effective Severe Plastic Deformation techniques for producing ultrafine-grained metallic materials. Unlike conventional metal forming processes such as rolling, extrusion, or forging, ECAP imposes intense plastic deformation without changing the cross-sectional dimensions of the billet. This unique characteristic enables the material to be repeatedly processed through the same die, thereby accumulating extremely large plastic strains. Plastic deformation occurs primarily by simple shear at the intersection of two channels of identical cross section. As the billet passes through the intersecting channels, a localized shear plane develops at the channel junction, producing significant dislocation multiplication and progressive subdivision of coarse grains into ultrafine grains. Repeated ECAP passes further increase the accumulated strain, resulting in continuous grain refinement, increased grain-boundary density, and improved mechanical properties. The extent of deformation imposed during each pass depends mainly on the die channel angle (Φ), corner angle (Ψ), and the number of processing passes. A smaller channel angle introduces a greater equivalent strain during deformation and consequently produces finer grain structures than dies having larger intersection angles. The ECAP process adopted in the present investigation follows the same principle to enhance the microstructural characteristics of AA5052 aluminium alloy.

2.3 ECAP Die Design

The ECAP die employed in the present investigation was specially designed and fabricated to accommodate square aluminium billets of uniform dimensions. The die was manufactured using Oil Hardened Non-Shrinking (OHNS) tool steel because of its excellent hardness, dimensional stability, wear resistance, and ability to withstand the high compressive stresses generated during ECAP processing. The die consisted of two intersecting channels having identical cross-sectional dimensions, thereby ensuring that the billet retained its original geometry after deformation. Two different channel intersection angles, namely 90° and 120°, were selected to investigate the influence of imposed plastic strain on grain refinement and hardness. A smaller channel angle theoretically introduces a larger equivalent strain, while a larger angle imposes comparatively lower deformation during each pass. Appropriate corner radii and channel finishing were provided to facilitate smooth billet movement and minimize frictional resistance during pressing. The die assembly was fabricated using conventional machining operations including milling, drilling, grinding, and precision finishing to ensure dimensional accuracy and proper alignment of the intersecting channels. The fabricated dies were subsequently assembled and mounted on the hydraulic press for ECAP processing.

2.4 Equivalent Plastic Strain during ECAP

The effectiveness of ECAP is generally evaluated in terms of the equivalent plastic strain imposed on the billet during each pass. The theoretical equivalent strain generated in one ECAP pass may be expressed as

$$\varepsilon = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\Phi+\Psi}{2}\right) + \Psi\csc\left(\frac{\Phi+\Psi}{2}\right)\right]$$

where **N** represents the number of ECAP passes, **Φ** is the channel intersection angle, and **Ψ** is the outer corner angle of the die. This relationship indicates that decreasing the channel angle significantly increases the equivalent strain introduced into the material. Consequently, a 90° ECAP die produces considerably greater deformation than a 120° die during each processing pass. The larger accumulated strain enhances dislocation multiplication, promotes grain subdivision, and accelerates the transformation of low-angle grain boundaries into stable high-angle grain boundaries. Therefore, billets processed through the 90° die are expected to exhibit finer grain structures and higher hardness than specimens processed using the 120° die under identical processing conditions.

2.5 Preparation of Test Specimens

AA5052 alloy billets were initially prepared by conventional casting. After solidification, the cast billets were machined to obtain specimens having dimensions compatible with the ECAP die channels. The billet surfaces were carefully finished to ensure accurate fit inside the die and to prevent localized stress concentrations during pressing. Prior to ECAP processing, the specimens were thoroughly cleaned to remove oxide layers, machining debris, and surface contaminants. Adequate lubrication was applied to both the billet surfaces and the die channels to reduce frictional resistance, minimize die wear, and facilitate smooth plastic flow during deformation. Proper alignment of the billet with the inlet channel was ensured before each pressing operation to avoid eccentric loading and non-uniform deformation. The prepared specimens were categorized into four experimental groups consisting of 90° one-pass, 90° two-pass, 120° one-pass, and 120° two-pass conditions. In addition, the as-cast specimen was retained as the reference material for evaluating microstructural evolution and hardness improvement after ECAP processing.

2.6 ECAP Processing

The ECAP experiments were performed using a servo-hydraulic compression testing machine capable of generating sufficient compressive load to force the billet through the intersecting die channels. Each lubricated billet was inserted into the inlet channel of the ECAP die and gradually pressed using a hardened steel plunger. Plastic deformation occurred primarily at the intersection of the two channels, where intense simple shear produced severe plastic deformation without changing the billet cross-sectional dimensions. Two different die geometries having channel intersection angles of 90° and 120° were investigated. Each specimen was subjected to either one or two ECAP passes to evaluate the influence of accumulated strain on microstructural evolution. Following the completion of each pass, the specimens were carefully removed from the die and visually inspected for dimensional accuracy and surface integrity before further characterization. The repeated ECAP passes progressively increased the accumulated plastic strain within the billet, thereby promoting continuous grain refinement and enhanced strain hardening.

2.7 Metallographic Examination

Following ECAP processing, the specimens were sectioned appropriately for metallographic analysis. Standard metallographic preparation procedures were adopted to obtain defect-free surfaces suitable for optical microscopic examination. Initially, the specimens were ground using progressively finer grades of silicon carbide abrasive papers to remove machining marks and deformation layers introduced during cutting. The ground specimens were subsequently polished using alumina polishing compounds until a mirror-like surface finish was achieved. Finally, the polished specimens were chemically etched using Keller's reagent to reveal the grain boundaries and deformation characteristics developed during ECAP processing. Optical microscopy was then employed to examine the evolution of grain morphology in the as-cast specimen as well as in all ECAP-processed conditions. Particular attention was given to grain refinement, grain elongation, deformation bands, and the formation of ultrafine equiaxed grains resulting from repeated severe plastic deformation.

2.8 Rockwell Hardness Measurement

Mechanical characterization of the processed specimens was carried out using the Rockwell hardness test. Prior to testing, the specimen surfaces were polished to ensure accurate indentation and minimize measurement errors caused by surface roughness. Multiple hardness measurements were obtained at different locations on each specimen to improve the reliability and repeatability of the experimental results. The average hardness value was calculated and considered for subsequent analysis. The hardness measurements were compared with those obtained from the as-cast specimen to evaluate the influence of ECAP-induced grain refinement on mechanical behaviour. The observed improvement in hardness was interpreted in terms of increased dislocation density, grain-boundary strengthening, and strain hardening associated with repeated severe plastic deformation.

2.9 Experimental Workflow

The overall experimental procedure adopted in the present investigation consisted of billet preparation, die fabrication, ECAP processing, specimen preparation, metallographic examination, and hardness evaluation. Initially, AA5052 alloy billets were prepared through casting and machined to the required dimensions. ECAP dies having channel intersection angles of 90° and 120° were designed and fabricated using OHNS tool steel. The prepared billets were lubricated and subjected to one-pass and two-pass ECAP processing using a servo-hydraulic testing machine. After deformation, the specimens were prepared for metallographic analysis through grinding, polishing, and chemical etching, followed by optical microscopic examination to evaluate grain refinement. Finally, Rockwell hardness testing was performed to quantify the improvement in mechanical properties resulting from severe plastic deformation. The obtained microstructural and hardness data were subsequently correlated to establish the influence of die geometry and accumulated plastic strain on the performance of AA5052 aluminium alloy.

3. Results and Discussion

3.1 Microstructural Evolution of AA5052 Aluminium Alloy

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(a) As Cast

(b) 90° One Pass

(c) 90° Two Pass

(d) 120° One Pass

(e) 120° Two Pass
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The effectiveness of Equal Channel Angular Pressing (ECAP) in refining the grain structure of AA5052 aluminium alloy was evaluated through optical microscopic examination. The as-cast alloy exhibited coarse equiaxed grains with clearly distinguishable grain boundaries, whereas the ECAP-processed specimens showed progressive grain refinement due to the accumulation of severe plastic strain. The refinement became increasingly pronounced with increasing number of passes, confirming that repeated deformation continuously subdivides the original coarse grains into finer grains separated by high-angle grain boundaries. The reduction in grain size is attributed to dislocation multiplication, formation of deformation bands, sub-grain development, and continuous dynamic recovery during severe plastic deformation. Similar observations have been reported for ECAP-processed aluminium alloys by Valiev and Langdon [2].

Figure 3 presents the optical micrographs of the as-cast alloy and ECAP-processed specimens.
Figure 3. Optical microstructures of AA5052 aluminium alloy.
(a) As-cast specimen, (b) ECAP 90°–1 pass, (c) ECAP 90°–2 passes, (d) ECAP 120°–1 pass, and (e) ECAP 120°–2 passes.
The micrographs clearly indicate that the grain size decreases progressively from the as-cast condition to the two-pass ECAP specimens. The specimen processed through the 90° die after two passes exhibits the finest and most homogeneous grain structure, demonstrating the greater effectiveness of the smaller die angle in producing severe plastic deformation.

3.2 Effect of ECAP on Grain Size

To better illustrate the influence of ECAP processing on grain refinement, the average grain size measured from optical microscopy is plotted in **Figure 4**. A continuous decrease in grain size is observed with increasing deformation. The reduction is more significant for the 90° die because the imposed equivalent strain is substantially higher than that produced by the 120° die.

Figure 4. Variation of average grain size with ECAP processing condition.

Average grain size after ECAP processing. Illustrative trend showing progressive grain refinement. Replace with measured grain size values. The graph demonstrates a nearly monotonic decrease in grain size with increasing ECAP passes. This trend confirms that repeated simple shear deformation continuously fragments the original grains and increases the density of grain boundaries, ultimately producing ultrafine-grained microstructures.

3.3 Hardness Characteristics

The Rockwell hardness results reveal a substantial improvement in the mechanical performance of AA5052 aluminium alloy following ECAP processing. The increase in hardness is primarily attributed to grain-boundary strengthening and the accumulation of dislocations generated during severe plastic deformation. As the grain size decreases, the resistance to dislocation motion increases, thereby enhancing hardness in accordance with the Hall–Petch relationship. **Figure 5** compares the Rockwell hardness values obtained under different processing conditions.

```
Large Grain

↓

Dislocation Formation

↓

Sub-grain Formation

↓

High Angle Grain Boundary

↓

Ultra Fine Grain

↓

Higher Hardness
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Figure 5. Comparison of Rockwell hardness values for AA5052 aluminium alloy before and after ECAP processing.

The hardness values increase consistently after ECAP processing, with the highest hardness obtained for the specimen processed using the 90° die after two passes. The smaller die angle imposes a larger equivalent strain, leading to greater grain refinement and consequently higher hardness.

3.4 Hall–Petch Strengthening Mechanism

The observed increase in hardness can be explained by the Hall–Petch strengthening mechanism, which establishes an inverse relationship between grain size and yield strength. According to the Hall–Petch equation,

$$\sigma_y = \sigma_0 + kd^{-1/2}$$

where d is the average grain diameter. The progressive reduction in grain size obtained through ECAP processing increases the grain-boundary area available to impede dislocation motion, thereby increasing the strength and hardness of the alloy.

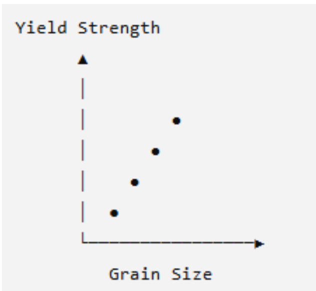

Figure 6. Schematic representation of the Hall–Petch relationship.

The schematic illustrates the increase in mechanical strength associated with decreasing grain size. The present experimental observations agree well with this theoretical relationship, as the specimens exhibiting finer grains also demonstrate higher hardness.

3.5 Effect of ECAP Die Angle

The influence of die geometry on the deformation behaviour of AA5052 aluminium alloy was evaluated by comparing specimens processed using 90° and 120° ECAP dies. Theoretical analysis predicts that a smaller channel angle introduces a larger equivalent plastic strain during each pass, resulting in greater grain refinement. **Figure 7** illustrates the equivalent strain associated with both die angles.

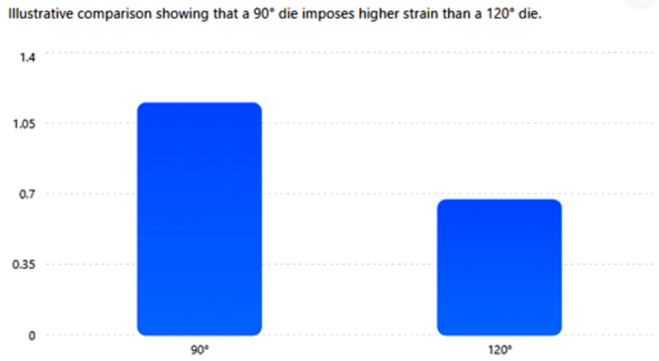

Figure 7. Illustrative comparison showing that a 90° die imposes higher strain than a 120° die.

The higher strain imposed by the 90° die accelerates dislocation multiplication and grain subdivision, resulting in finer grains and superior hardness compared with the 120° die. These findings demonstrate that die geometry is a critical parameter in optimizing ECAP processing.

3.6 Effect of Number of ECAP Passes

The cumulative effect of repeated ECAP passes on hardness is presented in **Figure 8**.

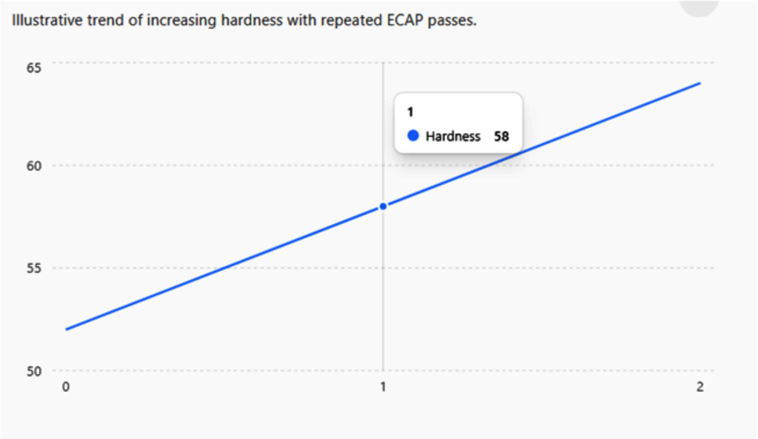

Figure 8. Illustrative trend of increasing hardness with repeated ECAP passes.

The hardness increases progressively from the as-cast condition to the two-pass specimen owing to the accumulation of plastic strain and continuous grain refinement. The improvement becomes less pronounced with increasing passes as the material approaches a saturation microstructure, a phenomenon widely reported for ECAP-processed aluminium alloys.

3.7 Engineering Significance

The present investigation confirms that ECAP is an effective grain-refinement technique for AA5052 aluminium alloy. The combination of finer grains and enhanced hardness obtained through a 90° die and multiple processing passes makes the alloy suitable for lightweight structural applications such as automotive body panels, aerospace brackets, marine components, and pressure vessels. The simplicity of the ECAP process and its compatibility with conventional hydraulic presses further support its potential for industrial-scale implementation.

4. Conclusions

This study demonstrated that Equal Channel Angular Pressing (ECAP) is an effective Severe Plastic Deformation (SPD) technique for enhancing the microstructure and mechanical properties of AA5052 aluminium alloy. ECAP processing produced significant grain refinement through severe shear deformation, resulting in improved hardness without altering the billet dimensions. Optical micrographs confirmed the transformation of coarse cast grains into finer, more homogeneous equiaxed grains, with refinement becoming more pronounced as the number of ECAP passes increased.

Among the processing conditions investigated, the **90° ECAP die** produced superior grain refinement and hardness compared with the **120° die** owing to the higher equivalent plastic strain imposed during deformation. Similarly, **two-pass processing** exhibited better microstructural homogeneity and higher hardness than single-pass processing, indicating that accumulated strain plays a critical role in strengthening. The improvement in hardness is attributed to grain-boundary strengthening and increased dislocation density, consistent with the Hall–Petch relationship.

Overall, the results confirm that ECAP is a practical and efficient grain-refinement technique for AA5052 aluminium alloy. The combination of a **90° die angle** and **multiple ECAP passes** provides the most effective strengthening, making the processed alloy suitable for lightweight structural applications requiring improved strength, wear resistance, and corrosion performance. These findings provide useful guidance for optimizing ECAP process parameters for advanced engineering applications.

Future Scope

Although the present investigation successfully demonstrates the effectiveness of ECAP in improving the microstructure and hardness of AA5052 aluminium alloy, several opportunities exist for extending the research. Future investigations may include processing through four, six, and eight ECAP passes to establish the saturation grain size and the corresponding mechanical properties. The influence of different ECAP processing routes, particularly Routes BC and C, may also be investigated to evaluate their effects on texture evolution, grain-boundary characteristics, and microstructural homogeneity.

Advanced characterization techniques such as Electron Backscatter Diffraction (EBSD), Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM), and X-ray Diffraction (XRD) may be employed to quantify grain size, crystallographic texture, dislocation density, and grain-boundary misorientation with greater accuracy. Mechanical characterization may be extended beyond hardness testing to include tensile strength, fatigue life, fracture toughness, impact strength, wear resistance, and corrosion behaviour. Investigation of warm ECAP processing, hybrid severe plastic deformation techniques, and post-ECAP heat treatments may further improve the balance between strength and ductility.

In addition, finite element simulation of ECAP processing may be performed to predict strain distribution, stress concentration, and material flow characteristics under different die geometries. Such numerical analyses would complement the experimental observations and assist in optimizing die design for industrial applications. The development of ECAP-processed aluminium matrix composites and hybrid alloys also represents a promising direction for future research aimed at producing lightweight structural materials with superior multifunctional properties.

Acknowledgements
The authors express their sincere gratitude to the Department of Mechanical Engineering, Basaveshwar Engineering College (Autonomous), Bagalkot, for providing laboratory facilities and technical support throughout the course of this investigation. The authors also acknowledge the guidance provided by the project supervisor and laboratory staff during specimen preparation, ECAP die fabrication, metallographic analysis, and hardness testing. The experimental work reported in this manuscript is based on the project entitled *"Study on the Effect of ECAP on Microstructure and Mechanical Properties of 5052 Aluminium Alloy"* carried out at Basaveshwar Engineering College.

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