

Effects of equal-channel angular pressing and equal-channel multi-angular pressing on the microstructure and mechanical performance of aluminum strips

Elshafey Ahmed Gadallah

elshafeya@yahoo.com

Department of Mechanical, Faculty of Technology and Education, Suez University, P.O.Box: 43221, Suez, Egypt <https://orcid.org/0000-0002-8222-3018>

Mohamed Ibrahim Abd El Aal

Mahmoud Omar Abd Elrady

Abdelkarim Yousif Mohamed

Hossam Hemdan El-Fahhar

Research Article

Keywords: Equal-Channel Angular Pressing (ECAP). Equal-Channel Multi-Angular Pressing (ECMAP). Aluminum strips. Microstructure. Tensile and hardness properties

Posted Date: September 24th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10977427/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Effects of equal-channel angular pressing and equal-channel multi-angular pressing on the microstructure and mechanical performance of aluminum strips

Elshafey Ahmed Gadallah ^{1,*}, Mohamed Ibrahim Abd El Aal ², Mahmoud Omar Abd Elrady ³, Abdelkarim Yousif Mohamed ¹, Hossam Hemdan El-Fahhar ¹

¹ Department of Mechanical, Faculty of Technology and Education, Suez University, P.O.Box:43221, Suez, Egypt

² Mechanical Engineering Department, College of Engineering in Wadi Addawaser, Prince Sattam bin Abdulaziz University, Wadi Addawaser, 18734, Saudi Arabia

³ Jushi Egypt for Fiberglass Industry S.A.E. The Third Sector of North-West Gulf of Suez Economic Zone, Ain Sokhna, 8130114, Suez, Egypt

*Corresponding author Elshafey Ahmed Gadallah (Gadalla EA.); Department of Mechanical, Faculty of Technology and Education, Suez University, Suez, Egypt; Elshafey.Gadallah@ind.suezuni.edu.eg

Abstract

The Al-1050 strips were processed using ECAP and ECMAP up to 3-passes to investigate their effectiveness in grain-refinement and property-enhancement. The microstructures demonstrated a significant reduction in the average grain size of the annealed material after processing, resulting in a heterogeneous microstructure composed of both fine-grained and coarse-grained regions. Submicron and nanosized grains were successfully generated following both ECAP and ECMAP processes. The refined microstructures led to substantial improvements in tensile properties, where the UTS and σ_y increased by 93.62% and 20.68%, respectively, after 3-ECAP passes, while corresponding increases of 128.53% and 30.52% were achieved after 3-ECMAP passes. The fracture surface morphology revealed a progressive reduction in dimple size with increasing numbers, reflecting the influence of grain-refinement on the deformation and fracture behavior of the processed strips. Hardness measurements further confirmed the strengthening effect induced by SPD. ECAP exhibited superior hardening efficiency compared with ECMAP, achieving maximum hardness increases of 63.35% and 52.33% in the longitudinal and transverse directions, respectively, after 3-passes, whereas ECMAP produced corresponding increases of 54.09% and 41.38%. These findings demonstrate the effectiveness of both processes for tailoring the microstructure and mechanical performance of Al-1050 strips, with ECAP providing the highest hardening response under the investigated conditions.

Keywords Equal-Channel Angular Pressing (ECAP). Equal-Channel Multi-Angular Pressing (ECMAP). Aluminum strips. Microstructure. Tensile and hardness properties.

1 Introduction

The use of various metals and alloys is an important part of the growth and expansion of technological applications. The most often utilized ferrous alloys are steel and cast iron. Aluminum alloys and other materials are also frequently employed due to their useful technical qualities, which mandate their specialized applications [1]. The mechanical properties of aluminum are well-suited to the needs of major industries such as aerospace, automotive, and construction. These properties are influenced by its purity, plasticity, and thermal characteristics. Key features include low density, excellent machinability through severe plastic deformation (SPD) and casting, high corrosion resistance, along with electrical

and thermal conductivity. Additionally, aluminum offers unique aesthetic potential and a combination of lightweight and high strength. These attributes are crucial for meeting both current and future demands in these industries.

Recently, the enhancement of material properties has piqued the interest of materials scientists, such as high strength, wear resistance, ductility, plasticity, and wear and corrosion resistance. The ultra-fine grain (UFG) and nano-crystalline (NC) materials are produced by SPD techniques [2], which are considered a progressing direction of research in nano-science and nano-technology [3]. Thus, cold plastic deformation results in a metallographic structure composed of elongated grains, causing the material to harden, reduce its plasticity, and become brittle. Consequently, the possibility of metal breakage during subsequent deformation is high [3, 4]. Therefore, before undergoing another cold plastic deformation, the hardened state must be removed through annealing, which restores a structure with uniform grains, reduces hardness, and eliminates internal tensions. Different SPD processes are widely used such as; multi-directional forging (MDF) [2, 5], accumulative roll-bonding (ARB) [6], twist extrusion (TE) [7], high-pressure torsion (HPT) [8], equal channel angular pressing (ECAP) [4, 9] and equal channel multi-angular pressing (ECMAP) [10, 11]. Among these various processes, ECAP and ECMAP stand out as particularly attractive processing techniques. Several reasons make the ECAP and ECMAP the most applicable SPD process as following, low set-up costs, relatively high productivity rate, ease of fabrication, large sizes of specimens, simple equipment required in performing the process, it can be done on different types of materials and the homogeneity of the processed samples is better than any other SPD process [12]. The ECAP and ECMAP imposes SPD by forcing a billet through one and two channels of identical cross-sections intersecting at an angle, generating intense shear strain while preserving the billet dimensions. Between passes, the billet may be rotated according to route A (0°), Route Bc ($+90^\circ$), Route Ba ($\pm 90^\circ$), or Route C (180°). The selected route significantly influences strain accumulation, grain refinement, and mechanical properties, with such as route A, can produce finer grains, lower dislocation densities, and an improved strength-ductility balance after multi-pass processing at RT [4, 13].

The ECAP and ECMAP are effective SPD techniques capable of producing substantial grain refinement, resulting in enhanced hardness and mechanical properties [14]. Owing to the distinct channel geometries and strain paths imposed by ECAP and ECMAP, variations in grain fragmentation, strain homogeneity, and strengthening processes are expected. However, these effects have not been rigorously studied for Al-1050 strips. Although ECAP has been widely studied for bulk Al alloys and commercially pure Al, investigations on thin pure Al are limited. Furthermore, the microstructural development and mechanical properties of strip products treated by ECMAP have received very little study, especially under processing circumstances comparable to those utilized in ECAP. Furthermore, no systematic comparison between ECAP and ECMAP for aluminum strips under identical processing conditions has been reported, and the impact of die arrangement on grain refinement, strain distribution, hardness development, and tensile behavior has not been well investigated. Therefore, there is a need for a comprehensive investigation to determine how the one-and-two die designs affect the microstructural evolution and mechanical performance of Al-strips, providing guidance for selecting the most efficient

processing route for industrial applications [10, 15, 16], while there are insufficient literature reports on specimens with a thin rectangular cross-section. Table 1 lists the abbreviations used in the study.

To address this gap, the present work provides a systematic comparison between ECAP and ECMAP processing of pure aluminum strips under identical deformation conditions. Particular attention is given to grain refinement behavior, tensile properties, hardness evolution, and fracture characteristics after multiple-passes. The results provide insight into the influence of die configuration on the processing-microstructure-property relationships of thin aluminum strips.

The objective of this study is to investigate and compare the effects of ECAP and ECMAP processing on the microstructural characterization and mechanical properties of aluminum (Al-1050) strips.

2 Materials and Experimental Work

2.1 Materials

A commercial Al-1050 strips with a 5 mm width was provided by Trading Company for Insulation Thermal and Acoustical, Egypt. The Al-1050 strips were cut into (130 mm) length x (20 mm) width x (5 mm) thickness strips. The chemical composition of the received Al-1050 strips illustrated in Table 2. It consists mainly of Al (99.76%) strips with slight amounts of Cu, Fe, Si, Zn, Mn, Mg, Ti, and V [17], before the ECAP and ECMAE processes, Al-strips were recrystallized through annealing at 350 °C, followed by furnace cooling to RT.

2.2 Experimental Work

The experimental program included the preparation of commercially pure aluminum strips, fabrication of ECAP and ECMAP dies, and processing of the strips through different deformation passes. The processed strips were subjected to different numbers of passes, followed by tensile and hardness testing to evaluate their mechanical properties. Microstructure Characterization before and after the ECAP and ECMAP processes were investigated using different types of microscopes (Fig. 1). shows a flow chart of the experimental work.

The different parts of the ECAP and ECMAP dies, as shown in Fig. 2a and b. The ECAP die geometry parameters include channel angles and angles curvature ϕ_1 of 122° and ψ_1 of 15° respectively (Fig. 2a). The ECMAP die geometry parameters include channel angles and angles curvature $\phi_{1,2}$ of 165° and 150° respectively, and $\psi_{1,2}$ of 15° and 30° respectively (Fig. 2b). The lubricant molybdenum disulfide was used to reduce the friction during the ECAP and ECMAP process of Al-1050 strips specimens [18-20]. The commercial Al-1050 strips specimens pressed up to 3-passes at RT using a 200 tons universal testing machine (model UH-1000k Ni SHIMADZU Corporation, Japan) press, at a speed of 1 mm/s (Fig. 2c). The imposed strain per pass was ~0.61 of the ECAP and ECMAP dies, as calculated by equation (1) [21, 22].

$$\bar{\epsilon}_{\text{ECMAP}} = \sum_{i=1}^3 \left[\frac{2 \cot(\phi_i/2 + \psi_i/2) + \psi \operatorname{cosec}(\phi_i/2 + \psi_i/2)}{\sqrt{3}} \right] \quad (1)$$

Where N, Φ and ψ are the number of passes, channel and curvature angles, respectively.

A commercial Al-1050 strips was processed through the ECAP and ECMAP up to 3-passes through route A at RT. The ECAP and ECMAP were carried out using a die manufactured from H13 cold work steel and hardened to 52 HRC.

Microstructural characterization of Al-1050 strips before and after the ECAP and ECMAP processes was performed using Scanning Electron Microscopy (SEM; model XL30SFEG, Philips, Tokyo, Japan). The ECAP and ECMAP specimens were prepared as follows, mounting the samples, followed by grinding, polishing with an alumina solution, and etching with 2.5% HBF solution, 20V/3-5 min [23].

All specimens of Al-1050 strips after undergoing ECAP and ECMAP processes, were shaped into dog bone tensile specimens using a wire-cutter. The dimensions of these specimens (Fig. 3), adhere to the ASTM E8 standard. Tensile testing was performed at RT using an Instron machine (model 4208-002) with a 300 kN capacity and a strain rate of 3×10^{-3} . Each condition was tested three times for reliability. The fracture surface morphology was examined using (SEM; model-Quanta FEG 250, FEI Company, Hillsboro, OR USA).

The Vickers hardness of the Al-1050 strips was distributed in aluminum strips along the longitudinal and transverse pressing directions in the before and after ECAP and ECMAP processing, as shown in Fig. 4a and b. The stripe longitudinal and transverse pressing directions were prepared carefully in the pressing direction by grinding followed by polishing. A hardness tester machine (model HWDV-75, TTS Unlimited, Osaka, Japan) was employed to measure hardness, applying a load of 100 gf for 15 s. The holding time before and after the ECAP and ECMAP processes was measured along specimens in the pressing direction of both longitudinal and transverse pressing directions, with a 0.5 mm interspacing between measurement locations. Different reading at the same position for each specimen in the pressing direction of both longitudinal and transverse pressing directions were used to calculate the average hardness and plotted to show the hardness distribution in each case. Additionally, the total hardness value in each case was represented by the average of all hardness test points, as shown in Fig. 4a and b.

3 Results and Discussion

3.1 Microstructure characterization of the ECAP

The microstructure of annealed and severely deformed samples using ECAP technique compared in Fig. 5. Three distinct zones distinguished in the annealed sample that are grain growth zone, recrystallized zone and mixed zone (Fig. 5a). The grain growth in the annealed zero pass sample may be due to over annealing caused by excessive time or temperature. On the other hand, fine grains are seen that grain refinement of the deformed material, especially after the first and second passes.

After the 1-pass of ECAP strip submicron and nano size grains are formed (Fig. 5b). Also grain refining down to (1-10) micron grain size is observed. Moreover, elongated grains are observed after the second pass this may be due to the high deformation energy after repeating of passes (Fig. 5c). On the other hand, grain fragmentation is highly observed after the third pass of ECAP process this is may be due to high energy non-equilibrium state after sever deformation that may be resulted from high dislocations within the grains [24], so the grains prefer to minimize the surface energy (Fig. 5d).

The grain size distributions as illustrated in Fig. 6a-d, demonstrated the reduction of the grain size range after the ECAP processing. The grain size range decreased from $0 < d \leq 8 \mu\text{m}$ in the annealed strip to $0 < d \leq 4 \mu\text{m}$, $0 < d \leq 4 \mu\text{m}$, and $0 < d \leq 2.4 \mu\text{m}$ after 1, 2, and 3-passes of ECAP, respectively. Additionally, the grain size distribution became more uniform, contributing to the enhancement of mechanical properties, as discussed in the following sections. Notably, the microstructure of the Al-1050 strips post-ECAP processing consisted of a mixture of micro and ultrafine grain sizes, which can improve tensile strength and hardness while preserving a sufficient degree of ductility, as previously noted in various severely deformed materials [25, 26].

3.2 Microstructure characterization of the ECMAP

The microstructure of ECMAP samples after different passes as seen in Fig. 7b-d. Grain growth was observed after the 1 and 2-passes. To explain the mechanism of grain development, a picture of how grain growth happens throughout the several stages of the ECMAP process, coupled with the different regions of the pressing die.

Figure 8 shows the visualization of microstructure development during one pass of ECMAP technique. Dynamic recrystallization begins after the first angle during part II of the pressing die. Due to the high mechanical energy the growth of the recrystallized grains, start after pressing the sample through the second angle inside part III in the die leading to the formation of coarse microstructure in some regions of the pressed sample. During the second pass of ECMAP process the previously grown grains start to fragment when the previously deformed sample passing through the first angle inside part II of the pressing dies (Fig. 9). The third pass of ECMAP process has a pronounced effect on grain refining where a large amount of grain fragmentation carried out Fig. 10. Moreover, fibrous random structure and cleavages resulted after ECMAP 3-passes condition and a probable cracking of the structure detected (Fig. 11). The grain size was refined to create a more uniform nanocrystalline structure with large-angle boundaries and a more even distribution of precipitates. This may be due to the severity of forces that faced the samples after 3-passes and a large amount of strain engendered.

Figure 12a-d shows that the grain size range decreases after ECMAP processing. Initially, the range of the grain size raised from $0 < d \leq 8 \mu\text{m}$ in the annealed strip to $0 < d \leq 9 \mu\text{m}$ after the 1-pass of ECMAPed, then decreased to $0 < d \leq 6 \mu\text{m}$ and $0 < d \leq 5.5 \mu\text{m}$ after 2 and 3-passes, respectively. The grain size distribution became good homogenized, enhancing mechanical properties [27].

3.3 Mechanical Properties

3.3.1 Tensile properties

Figure 13 shows stress-strain curves of the Al-1050 strips and the influence of ECAP and ECMAP processes of Al-1050 on the strength and elongation. It was noticed that the ultimate tensile strength (UTS) of the Al-1050 strips have been enhanced from 73.69 MPa at the annealed situation to (105.28 and 78.21 MPa), (123.46 and 85.51 MPa) and (142.68 and 88.93 MPa) after the ECAP and ECMAP processing up to 1, 2, and 3-passes respectively, as shown in Fig. 14a and b. Where, the yield strength (σ_y) values are observed to increase from 58.39 MPa before the ECAP and ECMAP process. The yield

strength in the case of route “A” has continued to increase to (96.98 and 67.12 MPa), (115.13 and 72.27 MPa) and (133.44 and 76.21 MPa) after the ECAP and ECMAP processing up to 1, 2 and 3-passes respectively, as shown in Fig. 14a and b. But, it is noted that with the increase of the number of passes the difference between the values of UTS in the case of the two processes ECAP and ECMAP of route “A” is increased. The same behavior is also observed that increases in the UTS values of ECAP process in comparison with UTS values of ECMAP process. Then, the difference in UTS value is found to increase with the increase of the number of ECAP passes with comparison number of ECMAP passes and reaches ~27, 38 and 53 MPa after 1, 2 and 3-passes, respectively. Similar, trend of the difference between the values of the UTS in the case for both ECAP and ECMAP process of route “A” was observed in the case of Al and Al alloys [10, 28]. Yield strength has the same behavior that obtained in the case of the UTS, as it is found to be increase drastically after the first pass and then increase with the increase of the number of ECAP passes with comparison of the number of ECMAP passes. Similar, behavior of the proof strength was obtained in the previous work [24, 28-32].

The elongation (%) is noted for both ECAP and ECMAP processes to decrease drastically with the increased number of passes of the Al-1050 processed by route “A”, as shown in Fig. 14a-b. It can be noted that the elongation (%) is observed to decrease from 14.49% before the ECAP and ECMAP passes to (10.16 and 9.13%), (9.31 and 7.97%) and (8.04 and 7.49%) after 1, 2 and 3-passes, respectively. Then, the elongation % is noted to decrease continuously with a lower rate with the increase of the number of passes up to 3-passes in both ECAP and ECMAP processes by route “A”. The elongation % decrease after the ECAP and ECMAP is due to the grain size decrease, grain refinements, and strain hardening during the cold deformation of the Al-1050. Similar observations of the elongation decrease were also notated in the case of aluminum processed by ECAP and previous works [33-36]. The elongation of the Al-1050 after three passes was higher or even near to that of Al bulk specimens deformed by ECAP [33, 37] and previous works [34, 38], (see in Figs. 13 and 14). The increase of both UTS and σ_y can explain by the grain refinement that occurred after ECAP and ECMAP in line with the Hall-Petch relationship [39, 40]. As the UTS and σ_y can be obtained depending on the grain size through equation (2) [4, 39, 40].

$$\sigma_y = \sigma_0 + k_y d^{1/2} \quad (2)$$

Where σ_0 and k_y are the friction stress and a constant of yielding, respectively [39, 40].

Ln true stress (σ)/Ln true strain (ϵ) plots further revealed an increase in the strain-hardening exponent (n-values) from 0.19156 of the annealed Al-1050 strips to 0.19345, 0.39381, and 0.14097 after 1, 2, and 3-passes ECAPed respectively (Fig. 15), whereas the corresponding values after ECMAP processing were 0.32587, 0.37911, and 0.22289 (Fig. 16), indicating that SPD significantly altered the work-hardening behavior of the Al-1050 strips specimens, with ECAP producing a more pronounced strengthening effect than ECMAP.

The observations of the improvement of the tensile strength after the ECMAP of the Al-1050 strips were similar to those observed for Al bulk and sheet specimens deformed by ECAP [21, 41, 42], cyclic extrusion compression (CEC) [43], and accumulative roll-bonding (ARB) [44]. Therefore, the grain size refinement through SPD processing is effective in increasing the tensile strength of Al-1050 alloy

through different processes [45-47]. Interestingly, the percent increase in strength of the ECAP and ECMAP Al-1050 was near to those noted of Al bulk, strips and sheet specimens processed by different methods [37, 45-47].

3.3.1.1 Fracture surface

The fracture surface of the annealed Al-1050 strips and the processed specimens that went through the ECAP process are shown in Fig. 17a-d. Every specimen demonstrates the ductile fracture feature (Fig. 17a), the Al-1050 strips have large dimples prior to the ECAP treatment, indicating that the specimen has exceptional ductility. Following the execution of ECAP passes, there were more dimples overall, and they varied in size and fineness. This illustrates how the ductility progressively declines as the number of ECAP passes, as shown in Fig. 17b-d, which is consistent with the findings of (Fig. 5). This is explained by the flour grains that are treated in the ECAP procedure [48, 49].

Tensile specimens' fracture surfaces are depicted in Fig. 18a-d both before and after ECMAP processing for up to 3-passes. For every specimen, it is discovered that the fracture zone has a significant number of equiaxial dimples, suggesting a typical ductile fracture. There are little holes at the bottom of the dimples, which are where fractures first start. Impurities most likely caused the holes. The dimples in the fracture zone of the specimens that underwent ECMAP processing in a single pass are primarily large and deep (Fig. 18b). There are also several small and shallow dimples, and when the ECMAP pass increases, the distribution of dimples changes significantly. When the specimens were extruded through the ECMAP process for up to two passes (Fig. 18c), the dimples were shallower and more evenly distributed. The size of the dimples in the various specimens decreased after up to three passes (Fig. 18d).

On the other hand, demonstrate that the number of ECMAP passes and the route taken also affect the size and distribution of dimples on tensile fracture surfaces after three passes of ECMAP. Furthermore, it is well known that materials' ductility was greatly reduced and their uniform elongation dropped during ECMAP, indicating a major reduction in their work-hardening capacity. Consequently, shallower dimples are created because there is insufficient time for the dimple to mature and combine with the surrounding dimples. Dimple size reductions similar to this have been observed following ECMAP processing of a variety of materials [50]. Nonetheless, the current study observed more substantial deep dimples in comparison to aluminum specimens that underwent alternative deformation techniques [46, 48, 49].

3.3.2 Hardness results

The effect of ECAP and ECMAP processing on the hardness distribution of the Al-1050 strips is presented in Fig. 19. Hardness measurements were performed along both the longitudinal and transverse directions using a constant spacing of 0.5 mm between adjacent indentation points, as illustrated in Figs. 4a and b. The measurements were obtained for the strips in their annealed condition and after ECAP and ECMAP processing.

The hardness was found to increase after ECAP and ECMAP processing of the Al-1050 specimens along both the longitudinal and transverse directions of compared to the annealed strip specimens, as shown in Fig. 19a and b. The hardness of the unprocessed aluminum strip was 23.85 HV and increased

progressively with increasing numbers of ECAP and ECGAP passes, indicating substantial strain hardening and microstructural refinement induced by SPD [17, 51-53]. For the ECAP strip, the average hardness measured in the transverse direction increased to 29.91, 33.61, and 36.33 HV after 1, 2 and 3-passes, corresponding to improvements of 25.41, 40.92, and 52.33%, respectively, relative to the unprocessed state (Fig. 19a). In the longitudinal direction, the hardness increased further to 31.16, 34.18, and 38.96 HV, representing increases of 30.65, 43.31, and 63.35% after 1, 2 and 3-passes, respectively. For the ECGAP strip specimens, the transverse hardness increased from 25.75 HV and after the ECGAP 1-pass to 31.71 HV and 33.72 HV after the 2, 3-passes, corresponding to increases of 7.97, 32.96, and 41.38%, respectively, compared with the annealed state (Fig. 19b). Similarly, the longitudinal hardness increased to 28.64, 32.71, and 36.75 HV after 1, 2, and 3-passes, representing increments of 20.08, 37.15, and 54.09, respectively. Comparing both processing routes, ECAP produced higher hardness values than ECGAP at all deformation stages in both directions, with the difference becoming more pronounced after the 3-passes.

Specifically, the longitudinal hardness after 3-passes reached 38.96 HV for ECAP compared with 36.75 HV for ECGAP, whereas the transverse hardness reached 36.33 HV and 33.72 HV, respectively. Furthermore, the longitudinal direction consistently exhibited higher hardness than the transverse direction for both ECAP and ECGAP processes, suggesting a stronger accumulation of deformation-induced defects and grain refinement along the principal material flow direction. The hardness enhancement is attributed to the continuous accumulation of dislocations, grain subdivision and leading to the development of an UFG structure. Similar behavior has been widely reported for commercially pure aluminum processed by ECAP, where repeated passes resulted in significant hardness increases due to severe grain refinement and dislocation strengthening [4, 54, 55] demonstrated that SPD can reduce the grain size of pure Al to the submicrometer range, thereby enhancing hardness through the combined effects of Hall-Petch grain-boundary strengthening and increased dislocation density [56]. The continuous increase in hardness observed after the 3-passes indicates that microstructural refinement was still progressing and that hardness saturation had not yet been reached, which is consistent with previous studies on UFG aluminum produced by ECAP and related SPD techniques [56]. Previous research has shown a strong link between the interior microstructures of the material and the results obtained from microhardness measurements [57-60].

4 Conclusions

The present study can be summarized into the following conclusions:

The ECAP method is a first die with a 122° channel angle and a 15° curvature angle, and the ECGAP method is a second die with 165° and 150° channel angles 15° and 30° curvature angles, and a pressing rate of 1 mm/s of Al-strips up 3-passes was performed successfully.

The microstructure investigation reveals that the ECAP process is a more efficient method than ECGAP for microstructure refinement. After 3-passes, ECAP achieved a greater grain refinement effect, reducing the grain size range from $0 < d \leq 8 \mu\text{m}$ to $0 < d \leq 2.4 \mu\text{m}$, compared with $0 < d \leq 5.5 \mu\text{m}$

for ECMAP. This indicates the superior effectiveness of ECAP in producing fine-grain structures, whereas ECMAP resulted in a comparatively coarser but more homogeneous microstructure.

The yield strength and UTS have risen by (97.17 and 23.77%) and (93.62 and 20.68%), respectively, after the ECAP and ECMAP up to 3-passes. In addition, there is about a 44.51 and 48.31% reduction in elongation after 3-passes of the ECAP and ECMAP processes, respectively.

In the annealed specimens, there was a noticeable ductile fracture with deep dimples and a clear necking zone. However after using ECAP and ECMAP, grain refinement occurred, which reduced the size and depth of the dimples.

ECAP exhibited superior hardening efficiency compared with ECMAP for Al-1050 strips, resulting in higher hardness values in both longitudinal and transverse directions after all processing passes. After three passes, the longitudinal hardness increased from 23.85 HV to 38.96 HV for ECAP (63.35% increase) compared with 36.75 HV for ECMAP (54.09% increase), while the transverse hardness reached 36.33 HV (52.33% increase) and 33.72 HV (41.38% increase), respectively, confirming the greater capability of ECAP to promote strain hardening and microstructural refinement.

Acknowledgements The authors are grateful to the Science, Technology & Innovation Funding Authority (STDF) in cooperation with the Egyptian Knowledge Bank (EKB).

Author Contribution Gadalla EA, Abd Elrady MO, Mohamed AY, El-Fahhar HH, and Abd El Aal MI: Writing-review & editing, Writing-original draft, Visualization, Validation. Gadalla EA, Abd Elrady MO, Mohamed AY, and El-Fahhar HH: Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Gadalla EA, Abd Elrady MO, Mohamed AY, El-Fahhar HH, and Abd El Aal MI: Writing-review & editing, Resources, Project administration, Methodology. Gadalla EA, Abd Elrady MO, Mohamed AY, El-Fahhar HH, and Abd El Aal MI: Writing-review & editing, Writing-review & editing.

Funding This study was funding provided by the Science, Technology & Innovation Funding Authority (STDF) in cooperation with the Egyptian Knowledge Bank (EKB). The funding was provided by STDF (Egyptian Knowledge Bank).

Data Availability The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication All of the authors mentioned in the manuscript have agreed for authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.

Conflicts of interest/Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

References

1. Pop LD (2019) Research on the Optimal Regime of Recrystallization in 1050 Aluminium Alloy. *Procedia Manufacturing*. 32:4-7, doi:<https://doi.org/10.1016/j.promfg.2019.02.175>.
2. Wang C, Li F, Wang L, Qiao H (2012) Review on modified and novel techniques of severe plastic deformation. *Science China Technological Sciences*. 55(9):2377-2390, doi:10.1007/s11431-012-4954-y.
3. Langdon TG (2007) The principles of grain refinement in equal-channel angular pressing. *Materials Science and Engineering: A*. 462(1):3-11, doi:<https://doi.org/10.1016/j.msea.2006.02.473>.
4. Valiev RZ, Langdon TG (2006) Principles of equal-channel angular pressing as a processing tool for grain refinement. *Progress in Materials Science*. 51(7):881-981, doi:<https://doi.org/10.1016/j.pmatsci.2006.02.003>.
5. Valiev RZ, Estrin Y, Horita Z, Langdon TG, Zechetbauer MJ, Zhu YT (2006) Producing bulk ultrafine-grained materials by severe plastic deformation. *JOM*. 58(4):33-39, doi:10.1007/s11837-006-0213-7.
6. Rahmatabadi D, Shahmirzaloo A, Hashemi R, Farahani M (2019) Using digital image correlation for characterizing the elastic and plastic parameters of ultrafine-grained Al 1050 strips fabricated via accumulative roll bonding process. *Materials Research Express*. 6(8):086542, doi:10.1088/2053-1591/ab18c3.
7. Faregh SSH, Hassani A (2018) Stress and strain distribution in twist extrusion of AA6063 aluminum alloy. *International Journal of Material Forming*. 11(2):175-184, doi:10.1007/s12289-017-1340-0.
8. El Aal MI, El-Fahhar HH, Mohamed AY, Gadallah EA: Influence of High-Pressure Torsion Processing on the Tribological Properties of Aluminum Metal Matrix Composites. In: *Materials*. vol. 16; 2023.
9. Gadallah EA, Ghanem MA, Abd El-Hamid M, El-Nikhaily AE (2014) Effect of tin content and ECAP passes on the mechanical properties of Cu/Sn alloys. *Am J Sci Technol*. 1:60-68, doi: 10.21608/PSERJ.2014.46801.
10. Keshtiban PM, Bashirzadeh F (2019) Experimental Investigation of Multi-pass ECGAP Process. *Transactions of the Indian Institute of Metals*. 72(1):239-244, doi:10.1007/s12666-018-1477-7.
11. Beloshenko VA, Konstantinova TE, Matrosov NI, Spuskanyuk VZ, Chishko VV, Gajda D, Zaleski AJ, Dyakonov VP, Puźniak R, Szymczak H (2009) Equal-Channel Multi-Angle Pressing Effect on the Properties of NbTi Alloy. *Journal of Superconductivity and Novel Magnetism*. 22(5):505-510, doi:10.1007/s10948-009-0448-y.
12. Valiev RZ, Islamgaliev RK, Alexandrov IV (2000) Bulk nanostructured materials from severe plastic deformation. *Progress in Materials Science*. 45(2):103-189, doi:<https://www.sciencedirect.com/science/article/pii/S0079642599000079>.
13. Gadallah EA, El-Fahhar HH, Abd El Aal MI, Bassyouni M, Abdel Aziz SM, Metwaly EM (2026) Equal-channel angular pressing of copper rods: Comparative study of microstructure and hardness at different angles. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*. 0(0):09544089261472971, doi:10.1177/09544089261472971.
14. El-Danaf EA, Soliman MS, Almajid AA (2010) Effect of deformation path change on plastic response and texture evolution for 1050 Al pre-deformed by ECAP and subsequently plane strain compressed. *Materials Science and Engineering: A*. 527(10):2547-2558, doi:<https://doi.org/10.1016/j.msea.2010.01.003>.
15. Faraji G, Mosavi Mashhadi M, Joo S-H, Kim H (2012) The role of friction in tubular channel angular pressing. *Rev Adv Mater Sci*. 31:12-18.

16. Wang G, Song D, Zhou Z, Liu Y, Liang N, Wu Y, Ma A, Jiang J (2021) Developing high-strength ultrafine-grained pure Al via large-pass ECAP and post cryo-rolling. *Journal of Materials Research and Technology*. 15:2419-2428, doi:<https://doi.org/10.1016/j.jmrt.2021.09.085>.
17. Gadallah EA, Abd El Aal MI (2025) Severe plastic deformation of Al strips through equal multi and single channel angular pressing. *Scientific Reports*. 15(1):5642, doi:10.1038/s41598-025-88185-z.
18. Abd El Aal MI, Gadallah EA (2022) Parallel Tubular Channel Angular Pressing (PTCAP) Processing of the Cu-20.7Zn-2Al Tube. *Materials*. 15(4), doi:10.3390/ma15041469.
19. Abd El Aal MI, El-Fahhar HH, Mohamed AY, Gadallah EA (2022) Influence of Parallel Tubular Channel Angular Pressing (PTCAP) Processing on the Microstructure Evolution and Wear Characteristics of Copper and Brass Tubes. *Materials*. 15(9), doi:10.3390/ma15092985.
20. Gadallah EA, El-Fahhar HH, Ahmed MMZ, El-Sayed Seleman MM, Alzahrani B, Alamry A, El-Aty AA, El-Shrief E (2024) Experimental study and finite element modelling of pure copper tube fabrication via the Parallel Tubular Channel Angular Pressing (PTCAP) Process. *Materials Research Express*. 11(7):076504, doi:10.1088/2053-1591/ad37a4.
21. Zahari ZS, Awang Sh'ri DN, Abu Hassan MAH, Wan Harun WS (2019) Effect of ECAP die angle to the microstructure and mechanical properties of bulk nanostructured Al-6061. *IOP Conference Series: Materials Science and Engineering*. 469(1):012054, doi:10.1088/1757-899X/469/1/012054.
22. Keshtiban PM, Zadshakouyan M, Faraji G (2016) Friction Study in Equal Channel Multi Angular Pressing: Load Curve and Ring Compression tests. *Transactions of the Indian Institute of Metals*. 69(9):1793-1800, doi:10.1007/s12666-016-0840-9.
23. Vega MCV, Piva BH, Bolmaro RE, Ferrante M, Kliauga AM (2014) The texture development of ECAP processed AA1050 aluminum, before and after a final anneal: effect of the initial texture. *IOP Conference Series: Materials Science and Engineering*. 63(1):012152, doi:10.1088/1757-899X/63/1/012152.
24. Horita Z, Fujinami T, Nemoto M, Langdon TG (2001) Improvement of mechanical properties for Al alloys using equal-channel angular pressing. *Journal of Materials Processing Technology*. 117(3):288-292, doi:[https://doi.org/10.1016/S0924-0136\(01\)00783-X](https://doi.org/10.1016/S0924-0136(01)00783-X).
25. Hajizadeh K, Ejtemaei S, Eghbali B, Kurzydowski KJ (2020) Microstructure and Mechanical Properties of 1050 Aluminum after the Combined Processes of Constrained Groove Pressing and Cold Rolling. *Physics of Metals and Metallography*. 121(1):72-77, doi:10.1134/S0031918X20010081.
26. Wei G, Peng X, Liu J, Hadadzadeh A, Yang Y, Xie W (2015) Microstructure evolution and mechanical properties of Mg-9Li-3Al-2Sr alloy in change channel angular pressing. *Materials Science and Technology*. 31(14):1757-1763, doi:10.1179/1743284715Y.0000000002.
27. Keshtiban PM (2020) Microstructural Evolutions During the ECMAP Process Using the Die with Optimum Geometrical Parameters. *Metallography, Microstructure, and Analysis*. 9(4):596-602, doi:10.1007/s13632-020-00664-z.
28. El-Danaf EA, Soliman MS, Almajid AA, El-Rayes MM (2007) Enhancement of mechanical properties and grain size refinement of commercial purity aluminum 1050 processed by ECAP. *Materials Science and Engineering: A*. 458(1):226-234, doi:<https://doi.org/10.1016/j.msea.2006.12.077>.
29. García-Infanta JM, Zhilyaev AP, Cepeda-Jiménez CM, Ruano OA, Carreño F (2008) Effect of the deformation path on the ductility of a hypoeutectic Al-Si casting alloy subjected to equal-channel angular

pressing by routes A, BA, BC and C. *Scripta Materialia*. 58(2):138-141, doi:<https://doi.org/10.1016/j.scriptamat.2007.09.018>.

30. El-Danaf EA (2008) Mechanical properties and microstructure evolution of 1050 aluminum severely deformed by ECAP to 16 passes. *Materials Science and Engineering: A*. 487(1):189-200, doi:<https://doi.org/10.1016/j.msea.2007.10.013>.
31. Reihanian M, Ebrahimi R, Tsuji N, Moshksar MM (2008) Analysis of the mechanical properties and deformation behavior of nanostructured commercially pure Al processed by equal channel angular pressing (ECAP). *Materials Science and Engineering: A*. 473(1):189-194, doi:<https://doi.org/10.1016/j.msea.2007.04.075>.
32. Wang JW, Duan QQ, Huang CX, Wu SD, Zhang ZF (2008) Tensile and compressive deformation behaviors of commercially pure Al processed by equal-channel angular pressing with different dies. *Materials Science and Engineering: A*. 496(1):409-416, doi:<https://doi.org/10.1016/j.msea.2008.05.041>.
33. Valder J, Rijesh M, Surendranathan A (2012) Forming of tubular commercial purity aluminum by ECAP. *Materials and Manufacturing Processes*. 27(9):986-989.
34. Babaei A, Mosavi Mashhadi M (2014) Characterization of ultrafine-grained aluminum tubes processed by Tube Cyclic Extrusion–Compression (TCEC). *Materials Characterization*. 95:118–128, doi:[10.1016/j.matchar.2014.06.013](https://doi.org/10.1016/j.matchar.2014.06.013).
35. Faraji G, Roostae S, Seyyed Nosrati A, Kang JY, Kim HS (2015) Microstructure and Mechanical Properties of Ultra-fine-Grained Al-Mg-Si Tubes Produced by Parallel Tubular Channel Angular Pressing Process. *Metallurgical and Materials Transactions A*. 46(4):1805-1813, doi:<https://doi.org/10.1007/s11661-015-2740-8>.
36. Zhilyaev AP, Torres MJ, Cadena HD, Rodriguez SL, Calvo J, Cabrera J-M (2020) The Effect of Pre-Annealing on the Evolution of the Microstructure and Mechanical Behavior of Aluminum Processed by a Novel SPD Method. *Materials*. 13(10):2361.
37. Manna R, Mukhopadhyay NK, Sastry GVS (2012) Strengthening Behavior of Bulk Ultra Fine Grained Aluminum Alloys. *Materials Science Forum*. 710:241-246, doi:[10.4028/www.scientific.net/MSF.710.241](https://doi.org/10.4028/www.scientific.net/MSF.710.241).
38. Poojitha V, Raghu T, Pandurangadua V (2019) Microstructure evolution and mechanical behaviour of pure aluminium and aluminium alloys processed through constrained groove pressing. *Materials Today: Proceedings*. 18:2335-2344, doi:<https://doi.org/10.1016/j.matpr.2019.07.017>.
39. Hall EO (1951) The Deformation and Ageing of Mild Steel: III Discussion of Results. *Proceedings of the Physical Society Section B*. 64(9):747-753, doi:[10.1088/0370-1301/64/9/303](https://doi.org/10.1088/0370-1301/64/9/303).
40. Naik SN, Walley SM (2020) The Hall–Petch and inverse Hall–Petch relations and the hardness of nanocrystalline metals. *Journal of Materials Science*. 55(7):2661-2681, doi:[10.1007/s10853-019-04160-w](https://doi.org/10.1007/s10853-019-04160-w).
41. Illgen C, Bohne B, Wagner MFX, Gruber M, Volk W, Frint P (2021) Facing the Issues of Sheet Metal Equal-Channel Angular Pressing: A Modified Approach Using Stacks to Produce Ultrafine-Grained High Ductility AA5083 Sheets. *Advanced Engineering Materials*. 23(9):2100244, doi:<https://doi.org/10.1002/adem.202100244>.
42. Sadasivan N, Balasubramanian M, Rameshbapu BR (2020) A comprehensive review on equal channel angular pressing of bulk metal and sheet metal process methodology and its varied applications. *Journal of Manufacturing Processes*. 59:698-726, doi:<https://doi.org/10.1016/j.jmapro.2020.10.032>.

43. Richert M, Hubicki R, Łebkowski P (2022) Perspectives of Microstructure Refinement of Aluminum and Its Alloys by the Reciprocating Extrusion (Cyclic Extrusion Compression-CEC). *Materials (Basel)*. 15(11), doi:10.3390/ma15114006.
44. Jiang L, Ruano OA, Kassner ME, Pérez-Prado MT (2007) The fabrication of bulk ultrafine-grained zirconium by accumulative roll bonding. *JOM*. 59(6):42-45, doi:10.1007/s11837-007-0077-5.
45. Salamati M, Tamimi S, Moturu S, Sivaswamy G, Qarni M, Rosochowski A (2017) Microstructure and mechanical properties of Al-1050 during incremental ECAP. *IOP Conference Series: Materials Science and Engineering*. 194(1):012009, doi:10.1088/1757-899X/194/1/012009.
46. Magalhães DCC, Cintho OM, Sordi VL, Kliauga A (2022) Improved tensile properties in heterostructured 1050/7050 Al sheets produced by accumulative roll bonding. *Journal of Materials Research and Technology*. 17:2014-2025, doi:https://doi.org/10.1016/j.jmrt.2022.01.151.
47. Soliman MS, El-Danaf EA, Almajid AA (2012) Enhancement of static and fatigue strength of 1050 Al processed by equal-channel angular pressing using two routes. *Materials Science and Engineering: A*. 532:120-129, doi:https://doi.org/10.1016/j.msea.2011.10.072.
48. Soliman MS, El-Danaf EA, Almajid AA (2012) Effect of Equal-Channel Angular Pressing Process on Properties of 1050 Al Alloy. *Materials and Manufacturing Processes*. 27(7):746-750, doi:10.1080/10426914.2012.663150.
49. Eskandari MJ, Asadabad MA, Tafrishi R, Shafyei A (2016) Evolution of Nanostructure in Al 1050 Sheet Deformed by Cryo-cross-rolling. *Journal of Materials Engineering and Performance*. 25(4):1643-1649, doi:10.1007/s11665-016-1971-1.
50. El Aal MIA (2020) The influence of ECAP and HPT processing on the microstructure evolution, mechanical properties and tribology characteristics of an Al6061 alloy. *Journal of Materials Research and Technology*. 9(6):12525-12546, doi:https://doi.org/10.1016/j.jmrt.2020.08.099.
51. Wroński M, Wierzbowski K, Malik R, Wroński S, Wojtas D, Baczmański A, Tarasiuk J (2021) Microstructure Characteristics of ECAP Processed 1050 Aluminum After Deformation and 5 Years Later. *Metals and Materials International*. 27(8):2720-2731, doi:10.1007/s12540-020-00817-3.
52. Abd El Aal MI, El-Fahhar HH, Mohamed AY, Gadallah EA (2022) The Mechanical Properties of Aluminum Metal Matrix Composites Processed by High-Pressure Torsion and Powder Metallurgy. *Materials*. 15(24):8827, doi:https://www.mdpi.com/1996-1944/15/24/8827.
53. Derakhshan JF, Parsa MH, Jafarian HR (2019) Microstructure and mechanical properties variations of pure aluminum subjected to one pass of ECAP-Conform process. *Materials Science and Engineering: A*. 747:120-129, doi:https://doi.org/10.1016/j.msea.2019.01.058.
54. Iwahashi Y, Wang J, Horita Z, Nemoto M, Langdon TG (1996) Principle of equal-channel angular pressing for the processing of ultra-fine grained materials. *Scripta Materialia*. 35(2):143-146, doi:https://doi.org/10.1016/1359-6462(96)00107-8.
55. Horita Z, Fujinami T, Nemoto M, Langdon TG (2000) Equal-channel angular pressing of commercial aluminum alloys: Grain refinement, thermal stability and tensile properties. *Metallurgical and Materials Transactions A*. 31(3):691-701, doi:https://doi.org/10.1007/s11661-000-0011-8.

56. Zhilyaev AP, Langdon TG (2008) Using high-pressure torsion for metal processing: Fundamentals and applications. *Progress in Materials Science*. 53(6):893-979, doi:<https://doi.org/10.1016/j.pmatsci.2008.03.002>.
57. Qiao XG, Starink MJ, Gao N (2009) Hardness inhomogeneity and local strengthening mechanisms of an Al1050 aluminium alloy after one pass of equal channel angular pressing. *Materials Science and Engineering: A*. 513-514:52-58, doi:<https://doi.org/10.1016/j.msea.2009.01.051>.
58. Xu C, Furukawa M, Horita Z, Langdon TG (2005) The evolution of homogeneity and grain refinement during equal-channel angular pressing: A model for grain refinement in ECAP. *Materials Science and Engineering: A*. 398(1):66-76, doi:<https://doi.org/10.1016/j.msea.2005.03.083>.
59. Xu C, Horita Z, Langdon TG (2007) The evolution of homogeneity in processing by high-pressure torsion. *Acta Materialia*. 55(1):203-212, doi:<https://doi.org/10.1016/j.actamat.2006.07.029>.
60. Xu C, Xia K, Langdon TG (2007) The role of back pressure in the processing of pure aluminum by equal-channel angular pressing. *Acta Materialia*. 55(7):2351-2360, doi:<https://doi.org/10.1016/j.actamat.2006.11.036>.

List of Figure

Fig. 1 Flow chart of the experimental work.

Fig. 2 Process of experimental pressing: (a) ECAP technique; (b) ECMAP technique; (c) hydraulic press equipment for achieving ECAP and ECMAP process.

Fig. 3 Geometry and dimensions of tensile test specimens in the unprocessed condition, and after ECAP and ECMAP processed conditions.

Fig. 4 Schematic illustration of the hardness (HV) distribution in aluminum strips along: (a) longitudinal; (b) transverse compression directions in the unprocessed condition and after ECAP and ECMAP processing [17].

Fig. 5 SEM micrographs illustrating the microstructural characterization of the aluminum strips in the unprocessed condition and after ECAP passes: (a) unprocessed specimen; (b-d) after ECAP 1, 2 and 3-passes.

Fig. 6 Grain size distribution of aluminum strips in the unprocessed condition and after ECAP processing: (a) unprocessed specimen; (b-d) after ECAP 1, 2 and 3-passes.

Fig. 7 SEM micrographs illustrating the microstructural characterization of the aluminum strips in the unprocessed condition and after ECMAP passes: (a) unprocessed specimen; (b-d) after ECMAP 1, 2 and 3-passes.

Fig. 8 Visualization of the development of the microstructure during the different stages of the ECMAP press mold after 1-pass.

Fig. 9 Visualization of the development of the microstructure during the different stages of the ECMAP press mold after 2-passes.

Fig. 10 Visualization of the development of the microstructure during the different stages of the ECMAP press mold after 3-passes.

Fig. 11 Formation of cleavage structure and cracks after SPD of Al-1050 strips using 3-passes ECMAP technique.

Fig. 12 Grain size distribution of aluminum strips in the unprocessed condition and after ECMAP processing: (a) unprocessed specimen; (b-d) after ECAP 1, 2 and 3-passes.

Fig. 13 True stress-strain curve of Al-1050 strips in the unprocessed condition, and after ECAP and ECMAP processing.

Fig. 14 Effect of SPD on the tensile properties of Al-1050 strip specimens processed: (a) ECAP process; (b) ECMAP process.

Fig. 15 Ln true stress-strain plots of Al-1050 strips before and after ECAPed up to 3-passes.

Fig. 16 Ln true stress-strain plots of Al-1050 strips before and after ECMAPed up to 3-passes.

Fig. 17 SEM micrographs of aluminum strip fracture surfaces in the unprocessed condition and after ECAP passes: (a) 0 pass; (b) 1-pass; (c) 2-passes; (d) 3-passes.

Fig. 18 SEM micrographs of aluminum strip fracture surfaces in the unprocessed condition and after ECMAP passes: (a) 0 pass; (b) 1-pass; (c) 2-passes; (d) 3-passes.

Fig. 19 Average hardness of aluminum strip specimens in the longitudinal and transverse directions before and after (a) ECAP passes; (b) ECMAP passes.

Figure captions

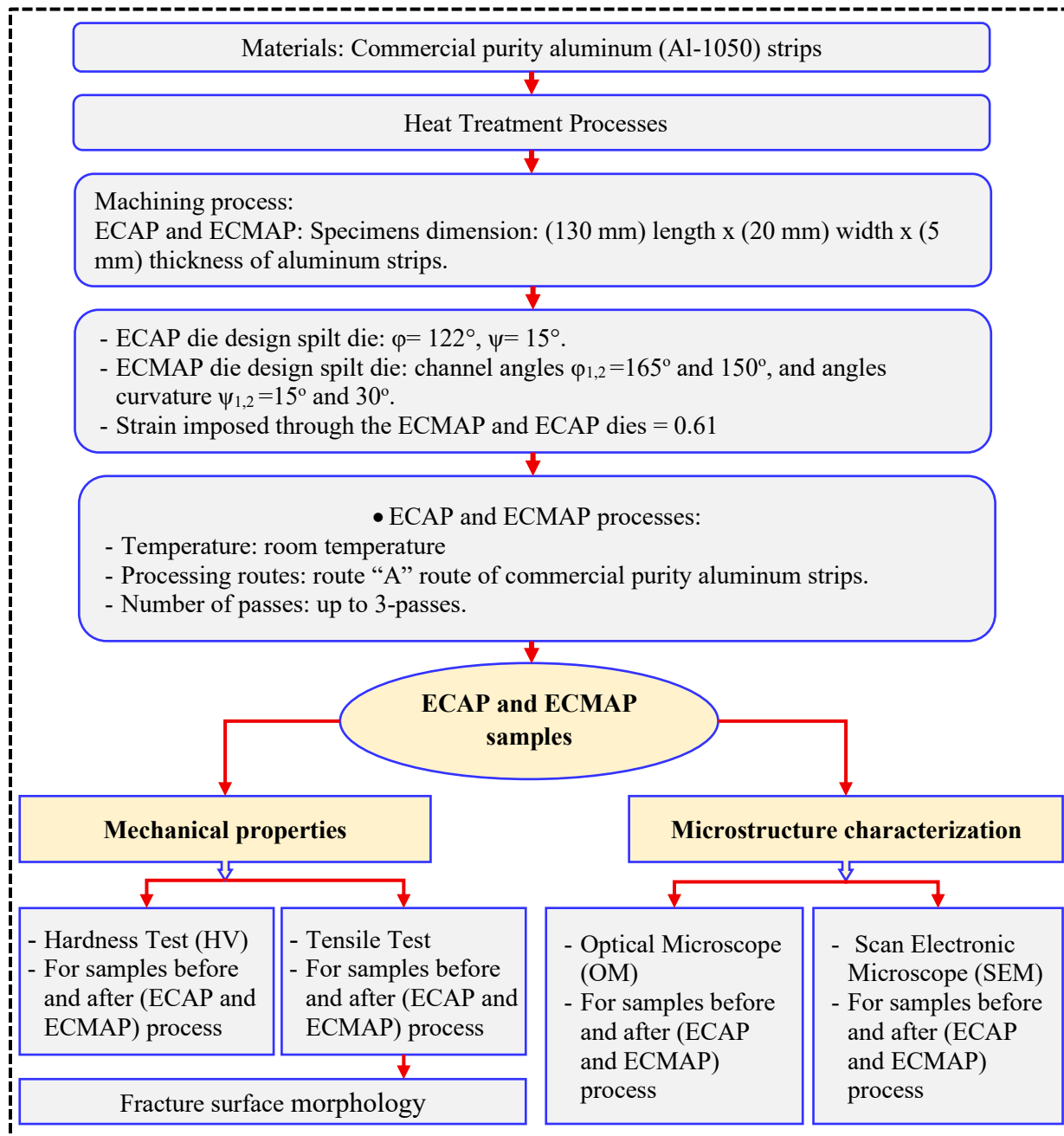


Fig. 1 Flow chart of the experimental work.

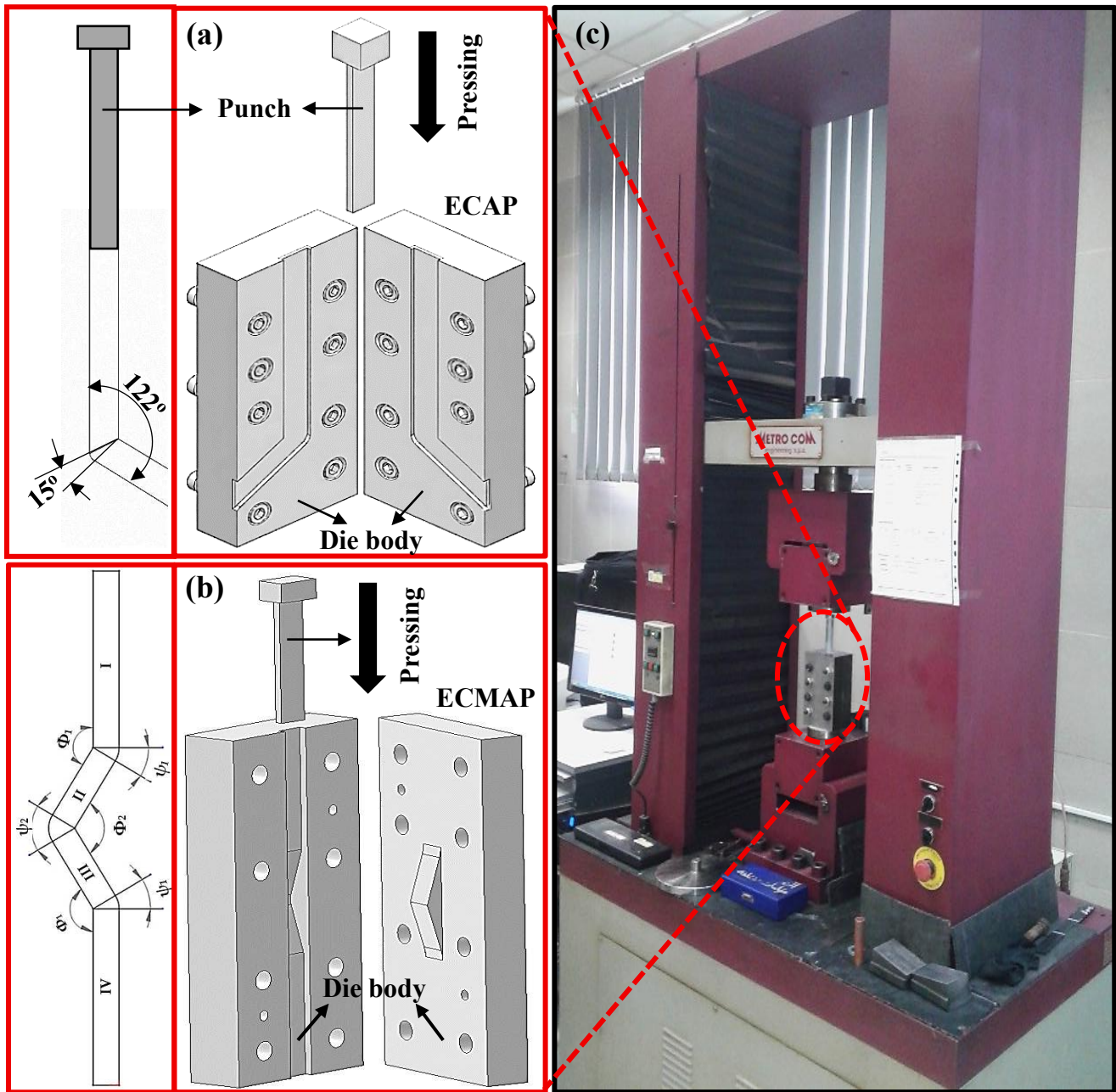


Fig. 2 Process of experimental pressing: (a) ECAP technique; (b) ECMAP technique; (c) hydraulic press equipment for achieving ECAP and ECMAP process.

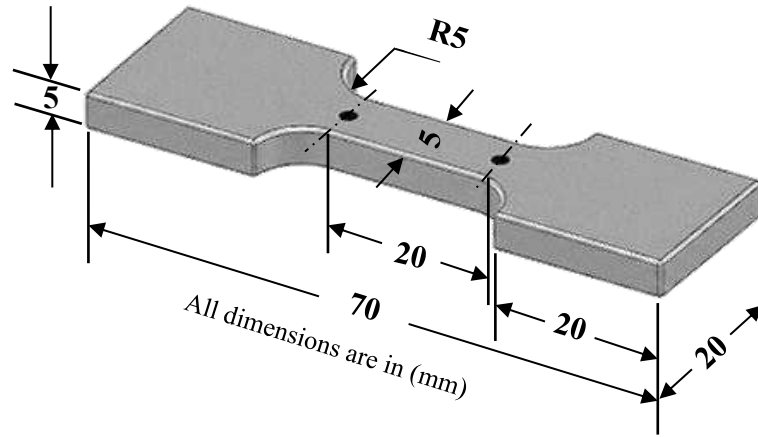


Fig. 3 Geometry and dimensions of tensile test specimens in the unprocessed condition, and after ECAP and ECMAP processed conditions.

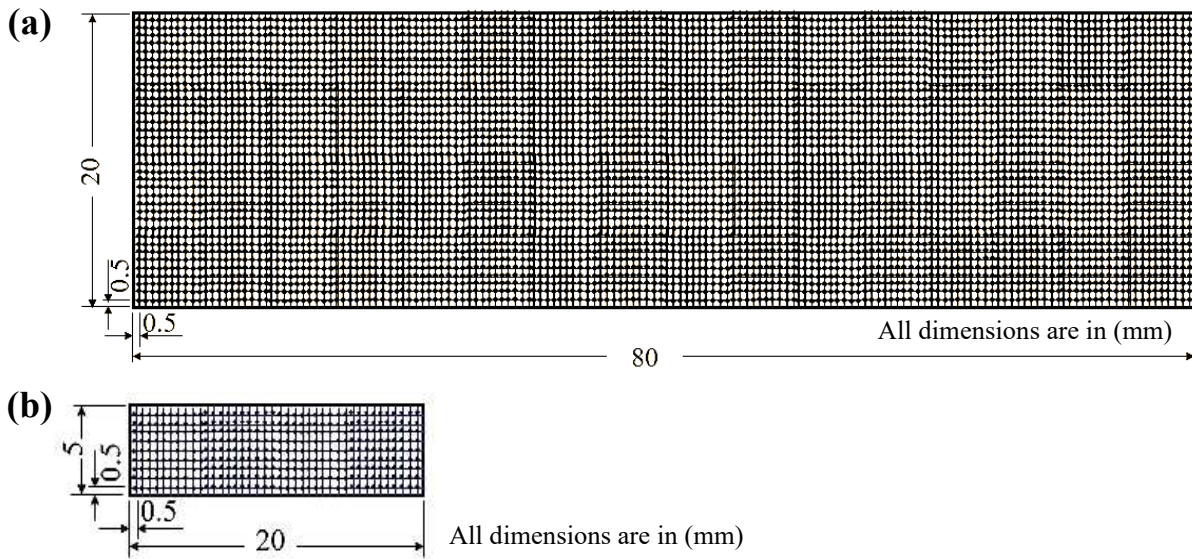


Fig. 4 Schematic illustration of the hardness (HV) distribution in aluminum strips along: (a) longitudinal; (b) transverse compression directions in the unprocessed condition and after ECAP and ECMAP processing [17].

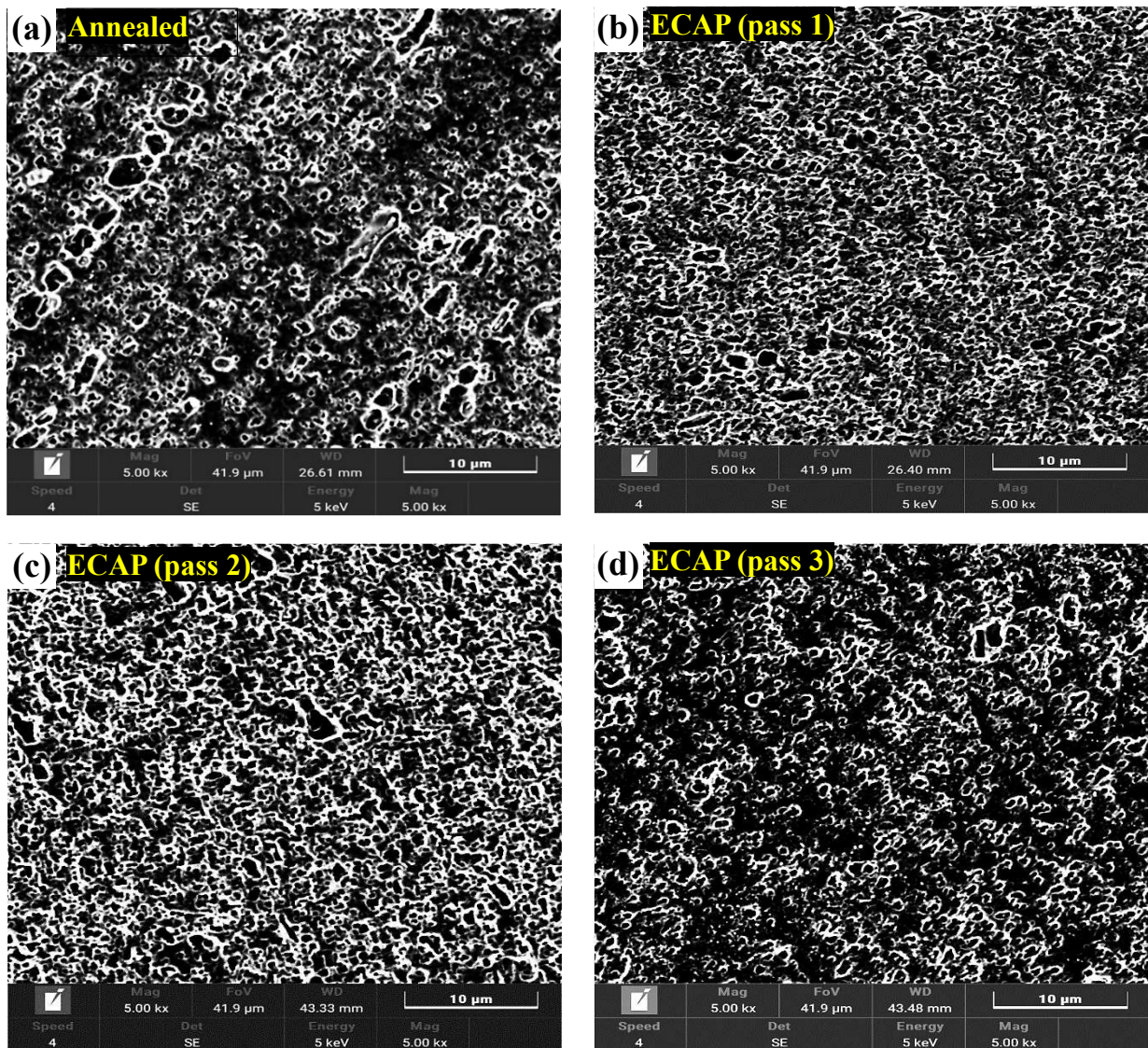


Fig. 5 SEM micrographs illustrating the microstructural characterization of the aluminum strips in the unprocessed condition and after ECAP passes: **(a)** unprocessed specimen; **(b-d)** after ECAP 1, 2 and 3-passes.

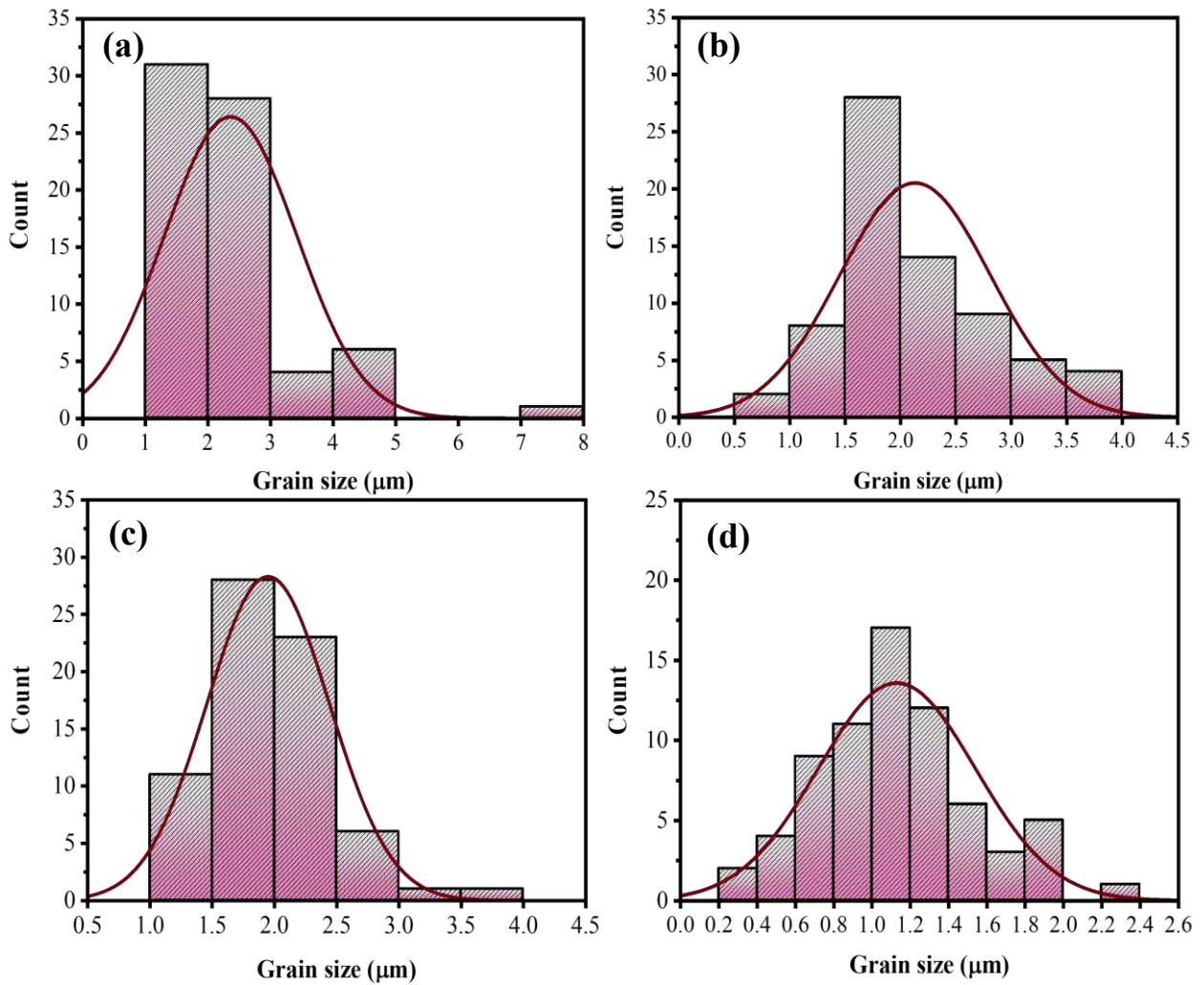


Fig. 6 Grain size distribution of aluminum strips in the unprocessed condition and after ECAP processing: **(a)** unprocessed specimen; **(b-d)** after ECAP 1, 2 and 3-passes.

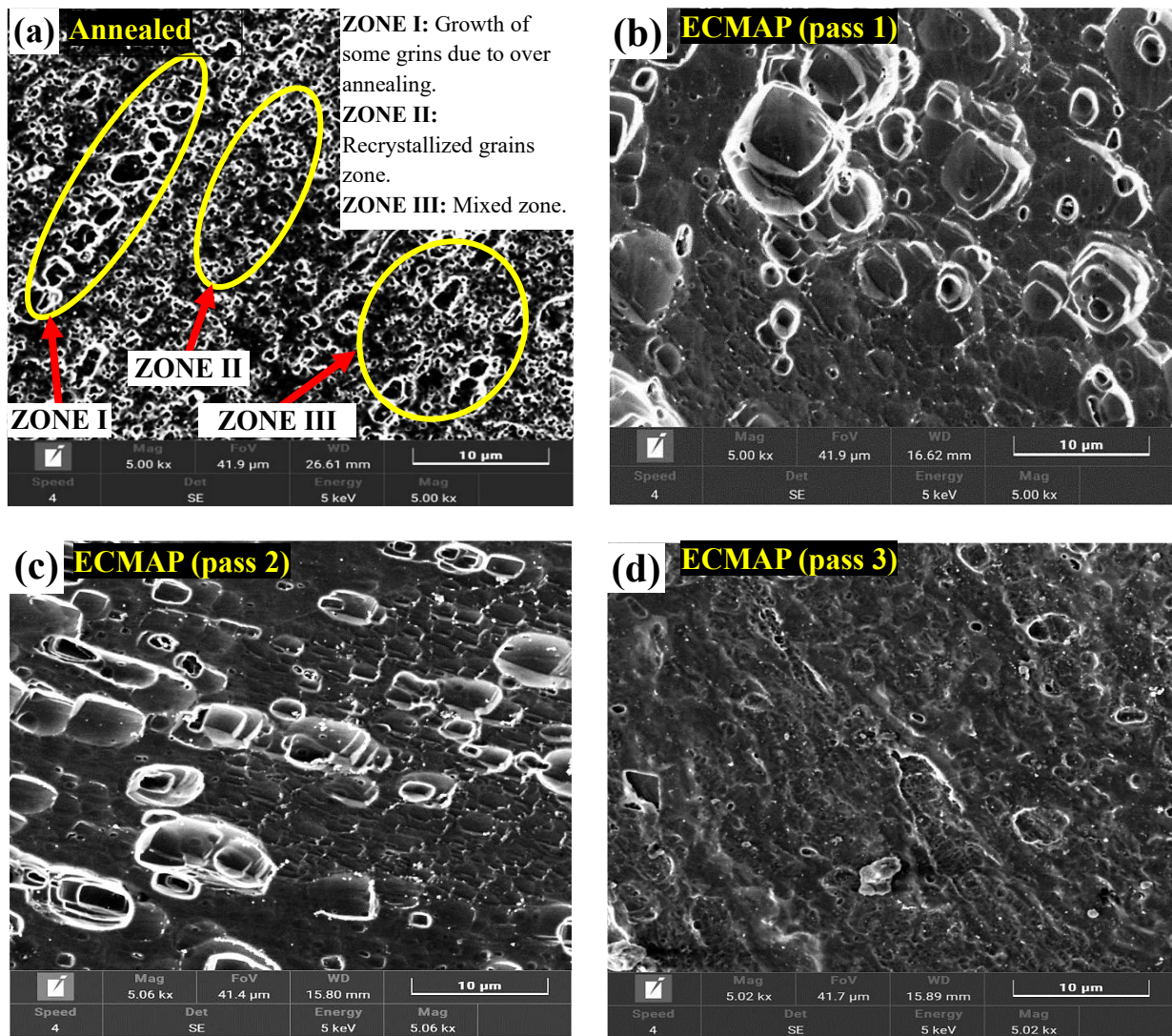


Fig. 7 SEM micrographs illustrating the microstructural characterization of the aluminum strips in the unprocessed condition and after ECMAP passes: **(a)** unprocessed specimen; **(b-d)** after ECMAP 1, 2 and 3-passes.

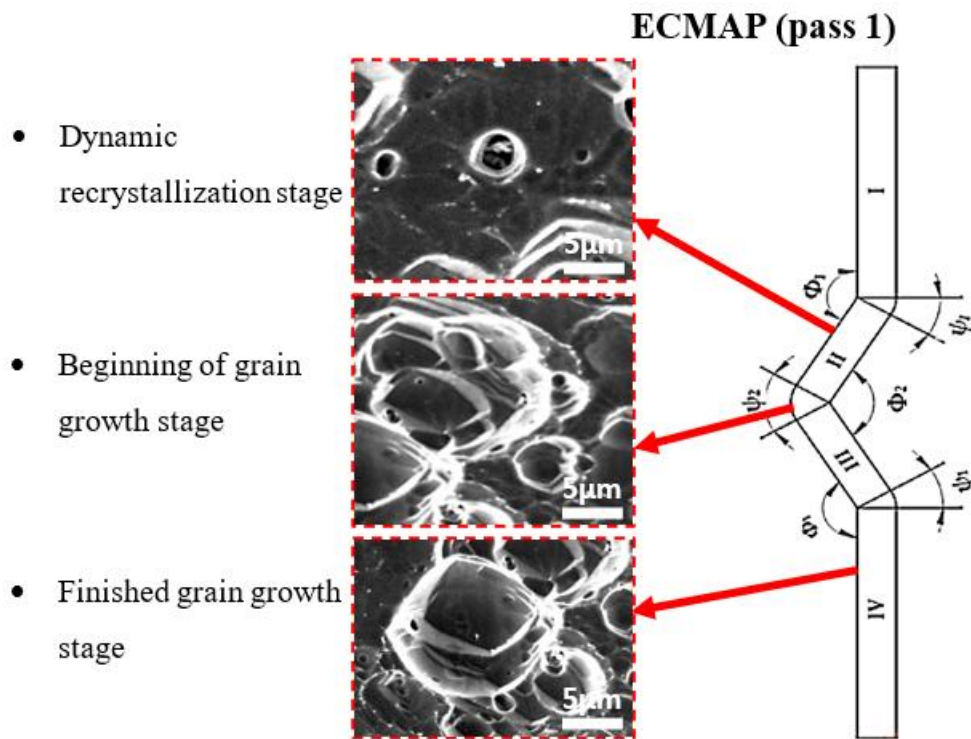


Fig. 8 Visualization of the development of the microstructure during the different stages of the ECMAP press mold after 1-pass.

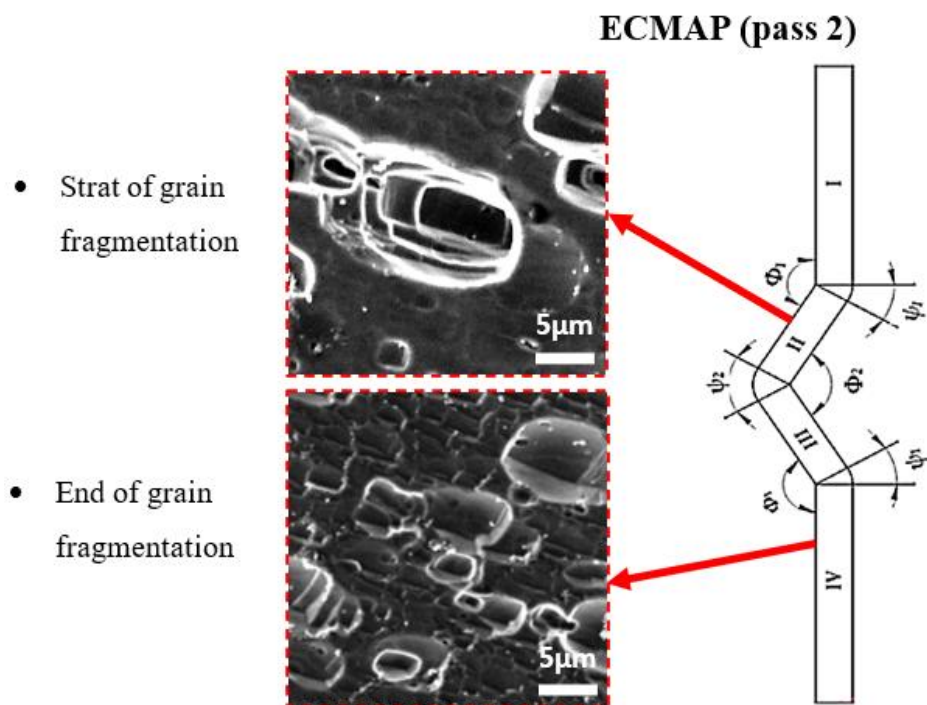


Fig. 9 Visualization of the development of the microstructure during the different stages of the ECMAP press mold after 2-passes.

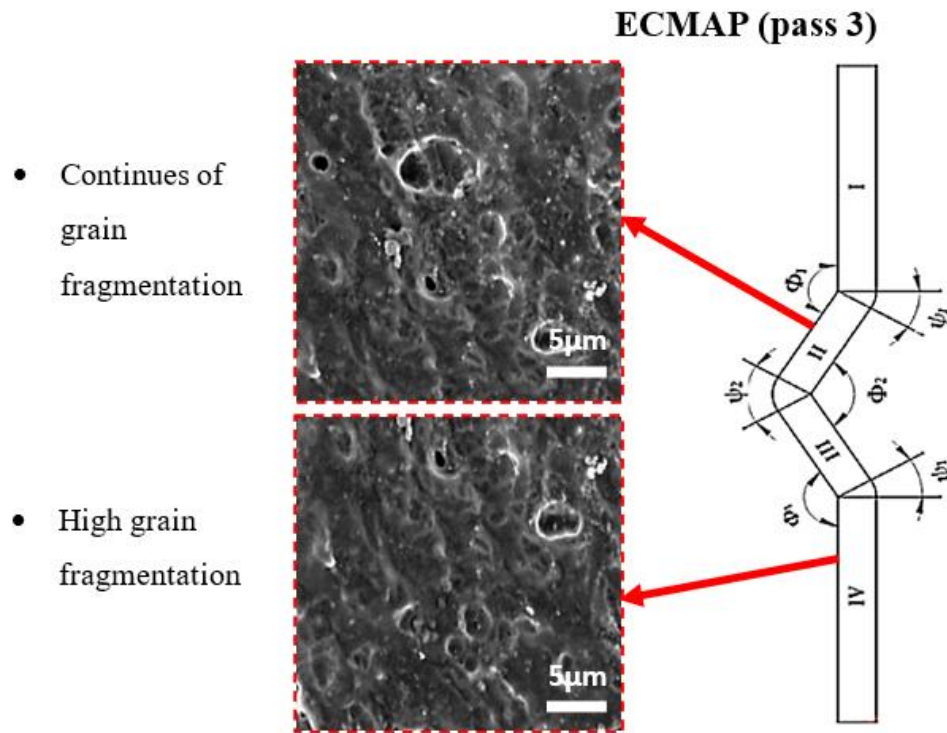


Fig. 10 Visualization of the development of the microstructure during the different stages of the ECMAP press mold after 3-passes.

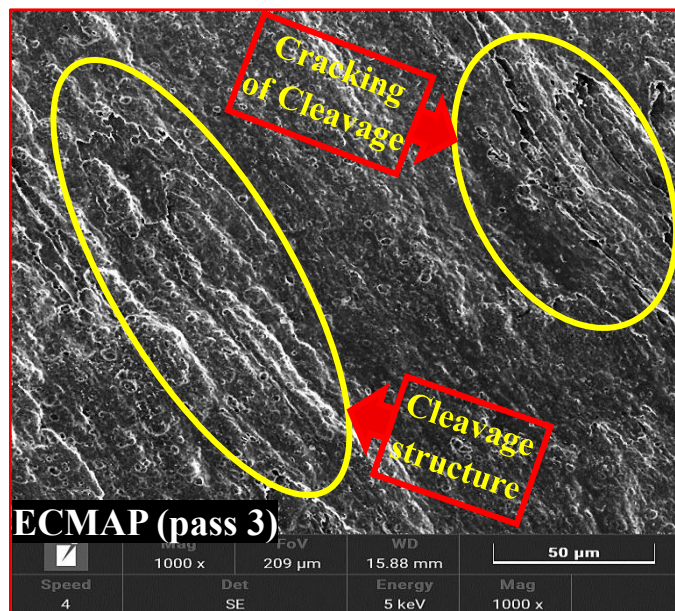


Fig. 11 Formation of cleavage structure and cracks after SPD of Al-1050 strips using 3-passes ECMAP technique.

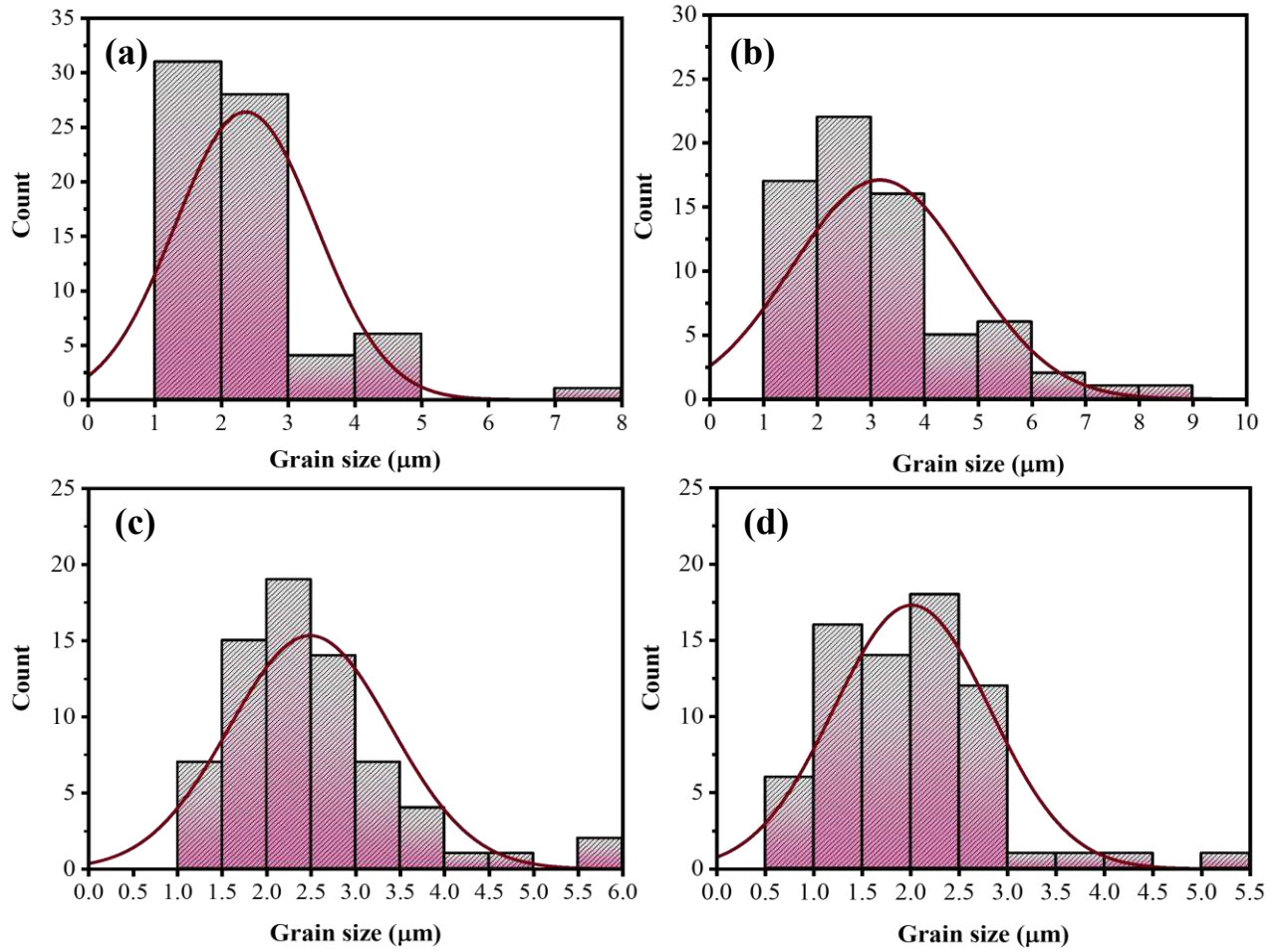


Fig. 12 Grain size distribution of aluminum strips in the unprocessed condition and after ECAP processing: (a) unprocessed specimen; (b-d) after ECAP 1, 2 and 3-passes.

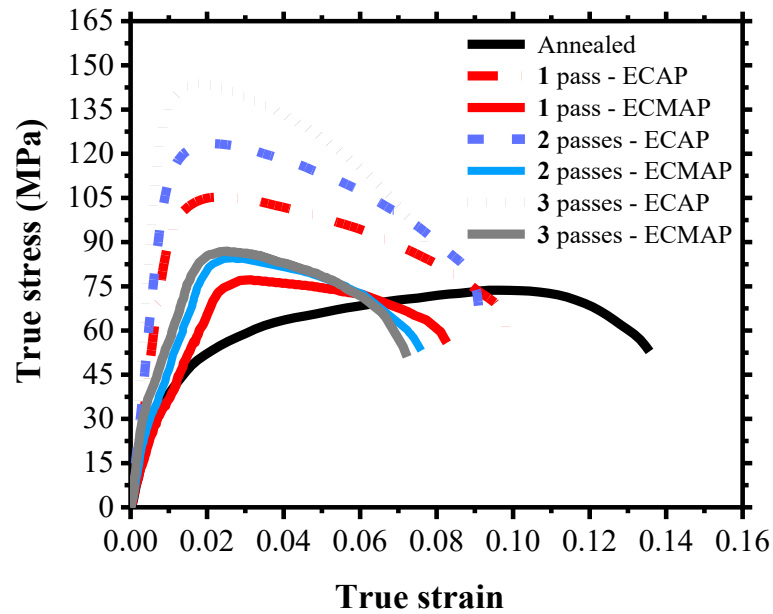


Fig. 13 True stress-strain curve of Al-1050 strips in the unprocessed condition and after ECAP and ECAP processing.

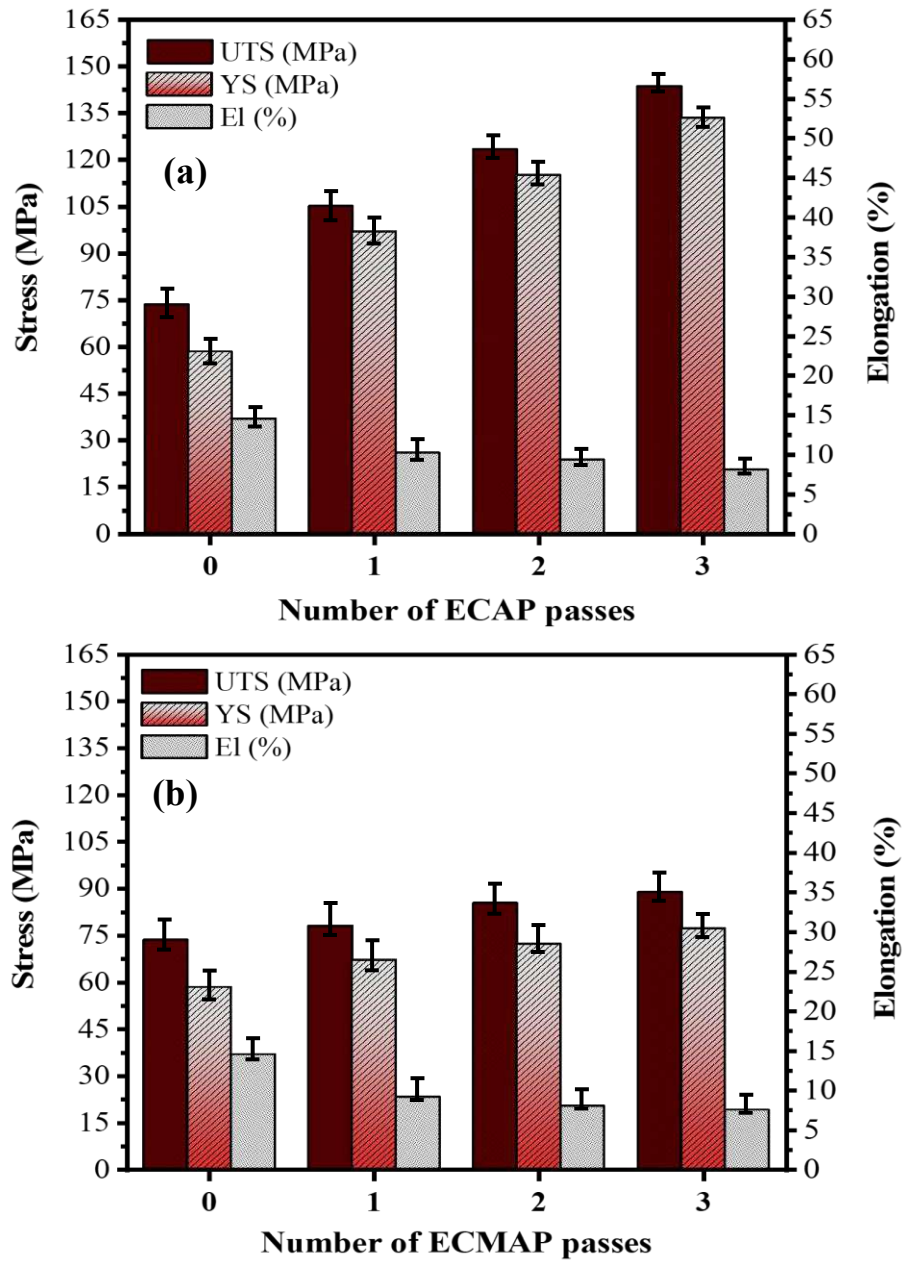


Fig. 14 Effect of SPD on the tensile properties of Al-1050 strip specimens processed: (a) ECAP process; (b) ECMAP process.

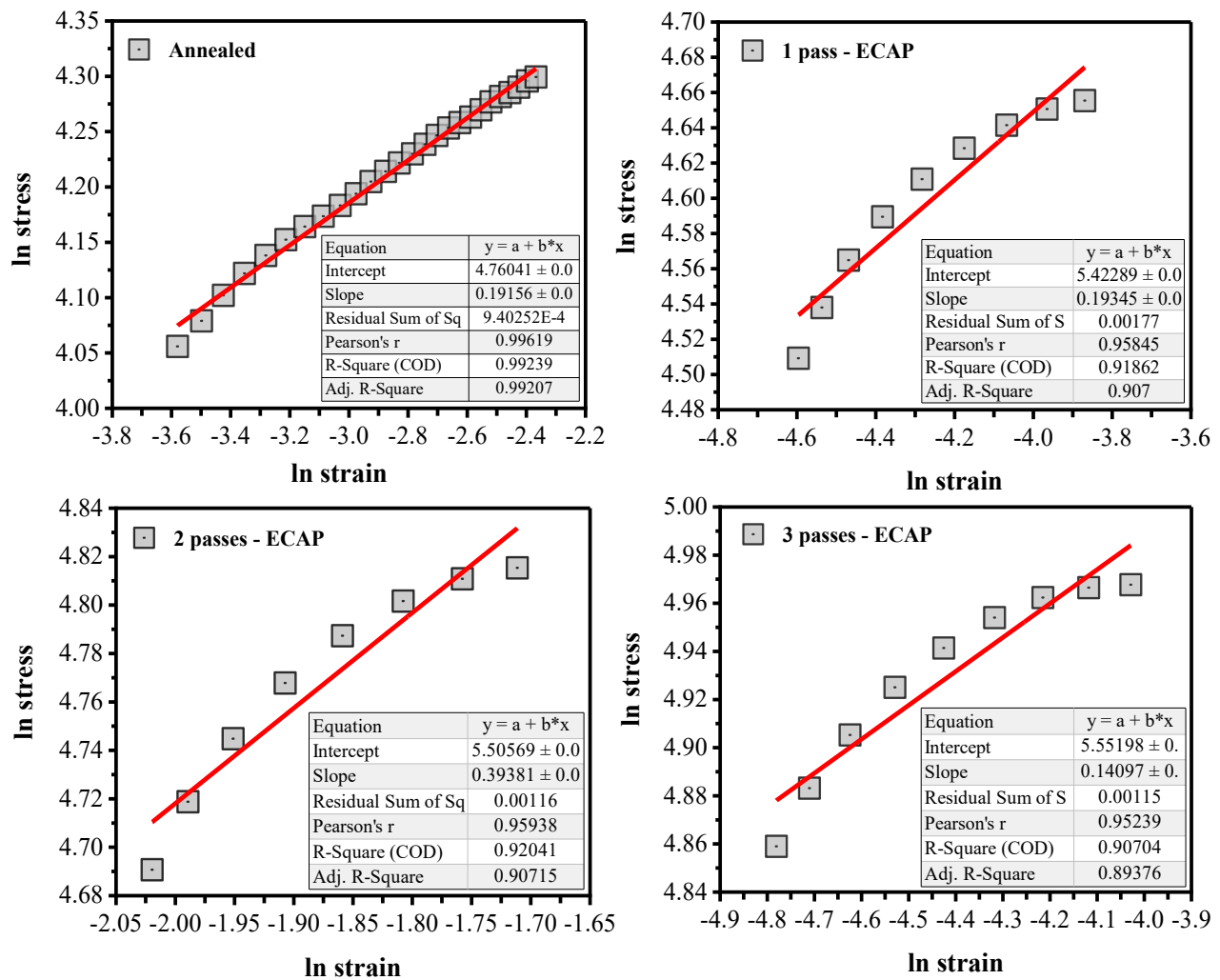


Fig. 15 Ln true stress-strain plots of Al-1050 strips before and after ECAPed up to 3-passes.

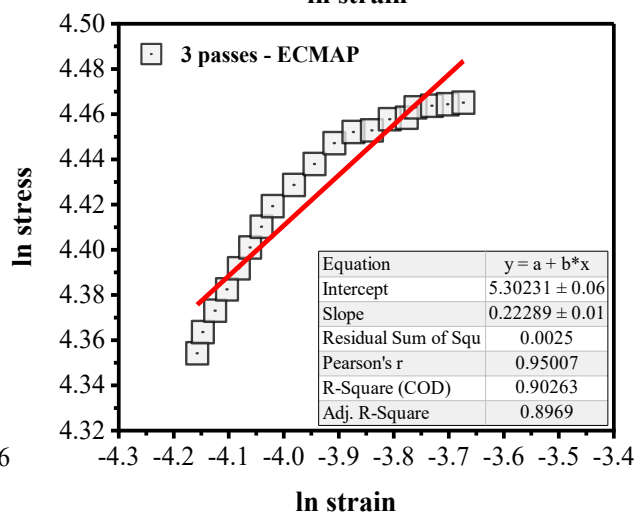
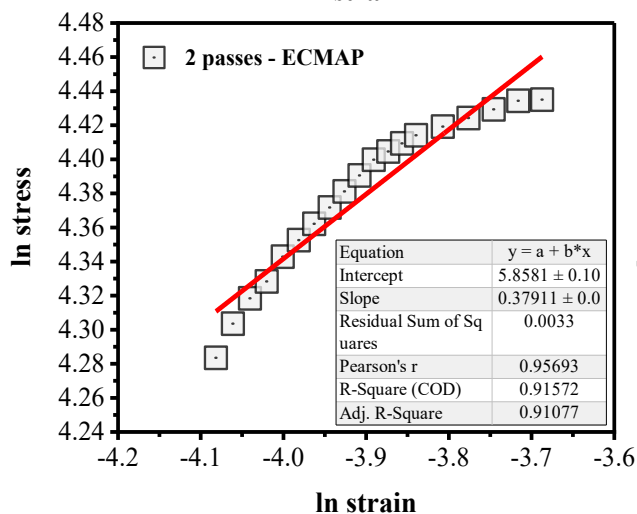
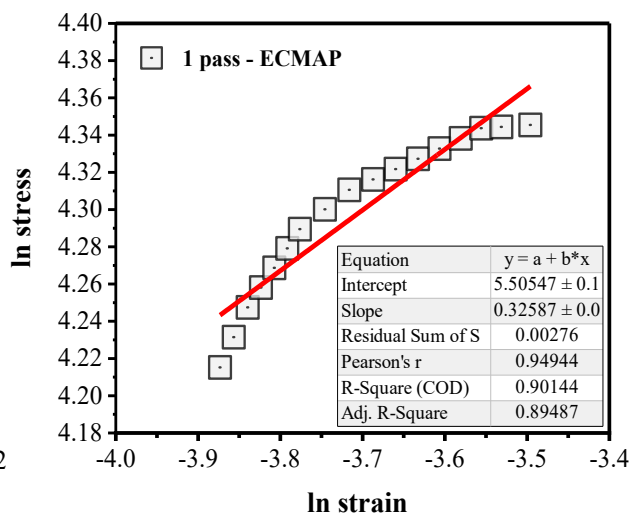
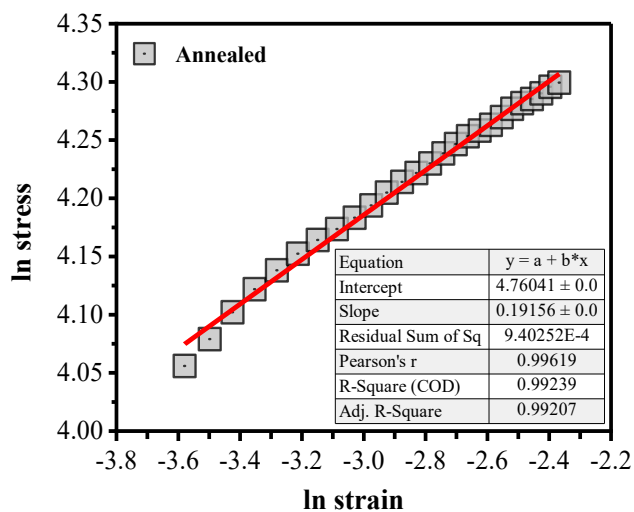


Fig. 16 Ln true stress-strain plots of Al-1050 strips before and after ECMAPed up to 3-passes.

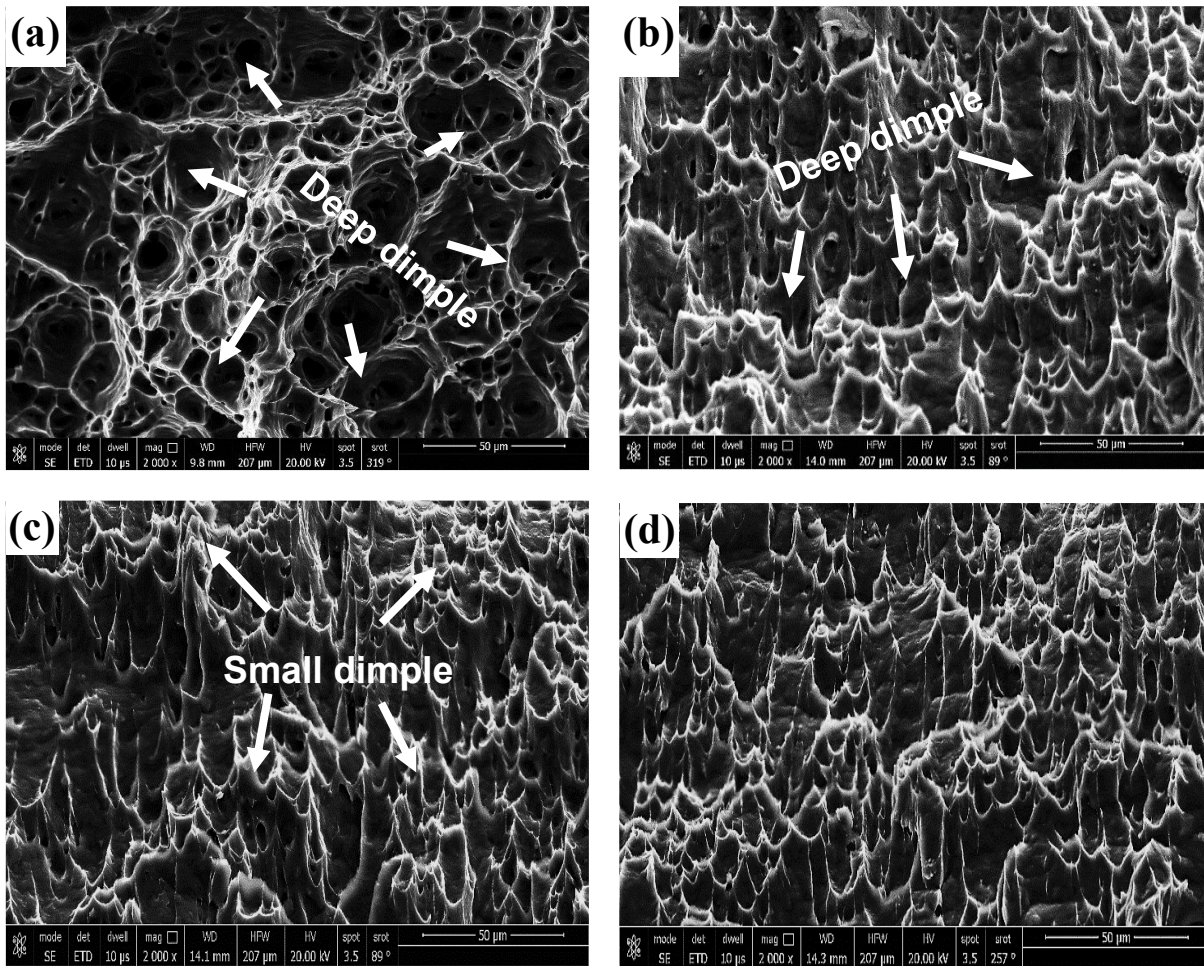


Fig. 17 SEM micrographs of aluminum strip fracture surfaces in the unprocessed condition and after ECAP passes: (a) 0 pass; (b) 1-pass; (c) 2-passes; (d) 3-passes.

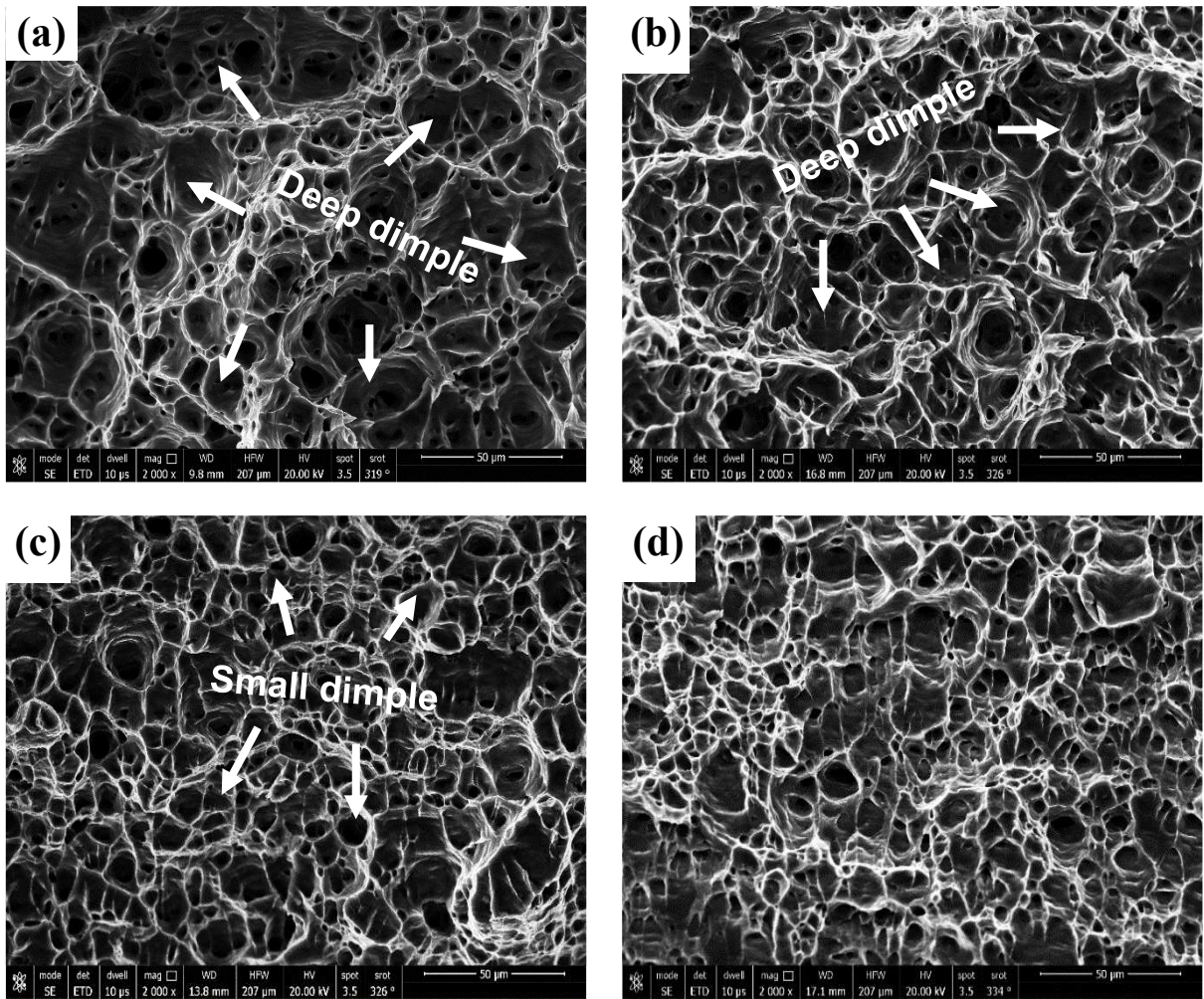


Fig. 18 SEM micrographs of aluminum strip fracture surfaces in the unprocessed condition and after ECTMAP passes: (a) 0 pass; (b) 1-pass; (c) 2-passes; (d) 3-passes.

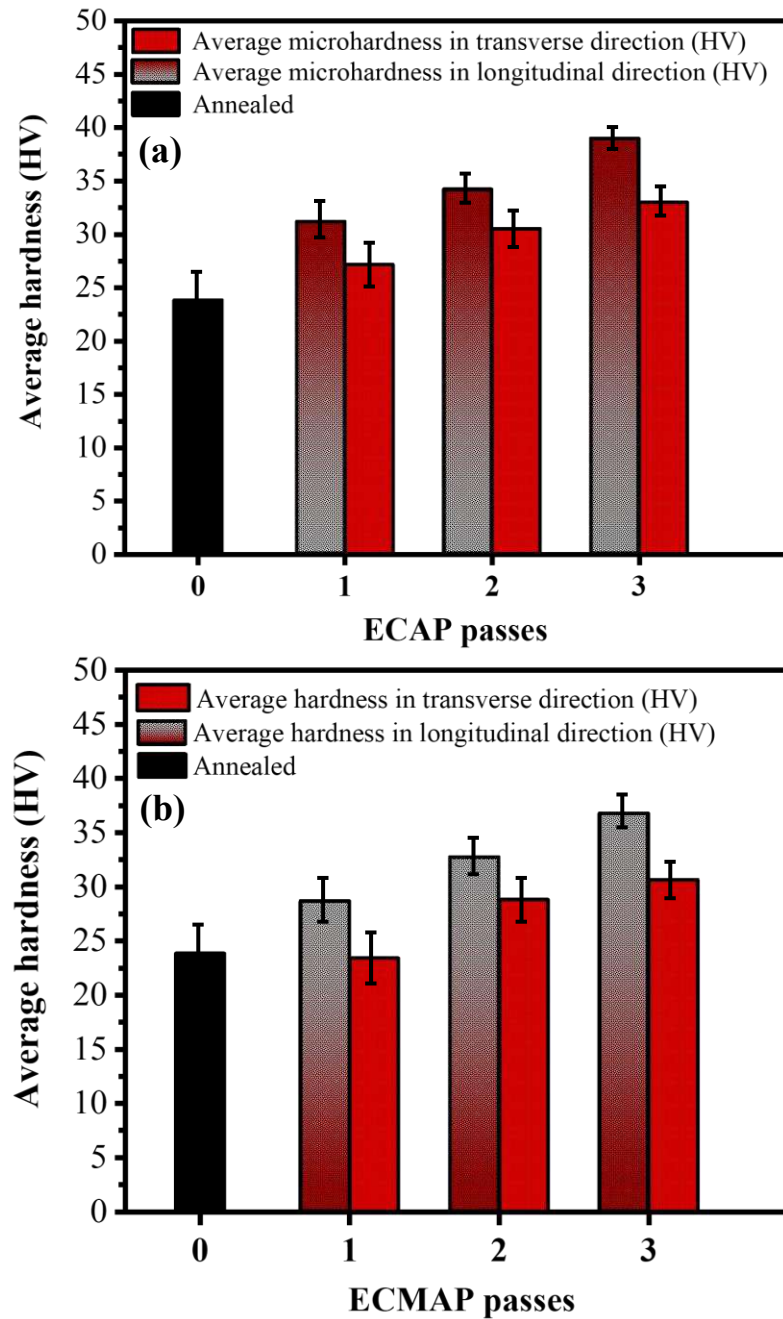


Fig. 19. Average hardness of aluminum strip specimens in the longitudinal and transverse directions before and after (a) ECAP passes; (b) ECMAP passes.

List of Table

Table 1 Symbols and abbreviations.

Table 2 Chemical composition of Al-strips (wt.%) [17].

Table captions

Table 1 Symbols and abbreviations.

H13	Cold Work Steel
ϕ	Channel Angle
ψ	Curvature Angle
$^{\circ}\text{C}$	Degree Celsius
ε	Equivalent Strain
MoS_2	Molybdenum Disulfide
σ_y	Yield Strength
ASTM	American Society for Testing and Materials
ARB	Accumulative roll-bonding
CEC	Cyclic Extrusion Compression
CNC	Computer Numerical Control
EBS	Electron Backscatter Diffraction
ECAP	Equal Channel Angular Pressing
ECMAP	Equal-Channel Multi-Angular Pressing
HPT	High Pressure Torsion
HV	Vickers Hardness
MDF	Multi Directional Forging
mm	Millimeter
MPa	Megapascal
NC	Nanocrystalline
OM	Optical Microscope
RT	Room Temperature
s	Second
SEM	Scanning Electron Microscopy
SPD	Severe Plastic Deformation
TE	Twist Extrusion
UFG	Ultra-fine Grain
UTS	Ultimate Tensile Strength
μm	Micrometre

Table 2 Chemical composition of Al-strips (wt.%) [17].

Si	Fe	Cu	Zn	Mn	Mg	Ti	V	Al
0.037	0.09	0.051	0.018	0.019	0.012	0.005	0.008	Bla.