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Prediction of hardness distribution during SPD process based on FEM simulations: case study of ECAP and HPT processes

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Abstract

3D finite element method (3D FEM) simulations of equal channel angular pressing (ECAP) and high-pressure torsion (HPT) of Al6061-T6 alloy were carried out and analyzed. 3D FEM results were correlated and compared with those obtained experimentally and theoretically through different mathematical equations. Furthermore, the hardness was estimated using the FEM strain and theoretical strain. The simulations and experimental results were in high conformity with each other. The ECAP load—displacement curves, the HPT load-time curves, and peak loads of FEM and experimental results were close to each other. FEM simulations provided clear strain distribution maps in different planes that fully explain the plastic deformation characteristics and homogeneity in the ECAP and HPT processes. FEM effective strain results have high reliability with a slight deviation from those theoretically estimated through the mathematical equations. The hardness distribution and the strain contours maps were in good agreement, confirming the quality of the FEM results. Hardness values calculated based on FEM effective strain indicate a deviation range of 0.96%—8.8% from experimental results that support the reliability of the FEM results. Microstructure results support hardness increase because of the effect of the grain refinement after ECAP and HPT processing.

1. Introduction

The Al6061 aluminum alloy, with its superior properties, enables it to be a good choice in different applications. The Al6061 aluminum alloy’s capability to be weldable, hot and cold deformed, and high corrosion resistance makes it used extensively in various fields such as building construction, transportation, and electrical applications [1]. The Al6061 alloy mechanical properties can be improved through heat treatment and fabrication of Al6061 metal matrix composites (MMCs), as previously noted [2–6].

The severe plastic deformation (SPD), used extensively in the production of nano, ultrafine-grained (UFG), and MMCs of the Al6061 alloy samples using different processes, especially equal channel angular pressing (ECAP) and high-pressure torsion (HPT). Various previous works were interested in the ECAP of Al6061 alloy [7–9]. The earlier studies about the HPT of the Al6061 samples and composite were mainly interested in studying the microstructure evolution and the hardness of the samples [10–15]. Recently some previous works concerned with the ECAP of the Al6061-T6 alloy [16, 17].

The high cost of the SPD processing experimental work makes the finite element simulation (FEM) is the best choice in studying the deformation behavior of the materials processed by SPD processes with low cost and high accuracy. FEM simulations performed accurately to analyze the plastic deformation [18], the tracing of the corner gap formation [19], and the investigation of the deformation mechanism and homogeneity [20–23] during the ECAP by two (2D) and three (3D)-dimensional (FEM).
On the other hand, the FEM simulations of the HPT process started with great efforts by Kim HS [24]. The HPT process FEM simulations were concerned with studying the plastic deformation behavior [25–28]. Although, the early works of the FEM simulations of the HPT process were concerned with using unconstrained die types [24, 25]. Recently, the interest shifted to the FEM of the HPT process using a quasi-constrained die type [26–29].

Nevertheless, the FEM simulations of HPT in previous works were performed under one revolution and a pressure of 2 GPa [25, 26]. These limited processing conditions were related to the complexity of the FEM simulation process due to the reduction in the sample volume during remeshing process. Moreover, the occurrence of a high distortion of the FEM mesh elements increases the remeshing steps and reduces the accuracy of the results [26]. Interestingly, the authors who justified the difficulty of using high pressures during the FEM of the HPT process already utilized a pressure of 5 GPa and 5 revolutions in different previous works [26–29].

Regarding the previous observations, the FEM of the HPT process under applying high pressure and the number of revolutions can be performed considering the following. Using a thicker sample with a larger diameter can decrease the sample volume reduction due to the flash formation. Increasing the sample thickness from 0.8 to 1.5 mm allows the increase of the applied pressure from 2 to 6 GPa, during FEM of HPT [26, 28]. Furthermore, using a finer mesh with smaller element sizes helps use high pressure and a high number of revolutions. Where element size affects the accuracy of FEM results as it influences problem convergence, simulation time, and penetration between die and sample. Therefore, using a fine mesh with smaller element sizes could improve results that combined with a decrease in the penetration between the die and samples. However, using fine mesh increases the simulation time [30]. Nevertheless, we cannot consider the long computing time as a problem with the presence of high-performance, robust, advanced workstation computers. Moreover, using a fine mesh with a short simulation time can be achieved by considering the remeshing techniques such as adaptive meshing and mesh to mesh solution mapping. Furthermore, careful adjustment of the remeshing criteria that is helpful in reach convergence of the problem correctly.

Figure 1. Schematic diagram of Al6061-T6 alloy processing by ECAP and HPT and the deferent experimental procedures.
Interestingly, recently the FEM of the HPT of Al 6061 alloy was performed effectively under high pressure using a thicker sample and very fine mesh [31]. However, the recent study [31] did not consider the correlation between the FEM and experimental results or predicting the experimental results based on the FEM results. Moreover, the previous work [31] ignores the investigation of the strain distribution and the deformation homogeneity in different planes (investigate the strain distribution only in the plane perpendicular to the pressing direction in the ECAP and HPT processes). Furthermore, the lack of interest in tracing the load-time behavior during the previous works of the FEM of the HPT process [24–29, 31] is one of the primary motivations for the current study.

Therefore, due to the few previous works concerned with correlating and predicting the experimental results depending on FEM results of the ECAP and HPT processing of Al 6061 alloy, the current study was performed to achieve the following objectives:

1. Prove the effectiveness of using the deform 3D to simulate the ECAP and HPT processes under conditions similar to those used in the actual experimental work.

2. The prediction of the ECAP and HPT processes load-displacement and load-time curves, respectively.

3. Investigate the plastic deformation strain distribution and homogeneity of Al6061-T6 samples deformed by ECAP and HPT in different planes.

4. Reach a recommendation about the most accurate equation in calculating the imposed strain during the ECAP and HPT processes.

5. Finding a correlation between the FEM results with the experimental results (hardness and microstructure).

2. Experimental work

Al6061-T6 alloy, with the analysis shown in table 1, was used in the current study. The ECAP was conducted successfully up to 4 passes at room temperature and speed of 1 mm s$^{-1}$ by route Bc [16, 17] for cylindrical samples with a diameter and length of 10 and 90 mm [16, 17, 23], as shown in figure 1. More details about the ECAP die can be found in previous work [23, 31]. Disc shape samples with a thickness of 1.5 mm and used as HPT samples. HPT process performed under a pressure of 9 GPa up to 10 revolutions at room temperature and rotational speed of 1 rpm, as shown in figure 1.

Samples with a diameter of 10 mm and thickness of 15 mm, were machined from the as-received and the steady-state zone of ECAPed samples. Microhardness measured in the X-Z plane across the base of disk shape samples, as shown in figure 1. Furthermore, some of the disk-shaped and HPTed samples were sectioned like half of a cylinder (half disk shape) to measure microhardness in the X-Y plane, as shown in figure 1. The microhardness samples were prepared in such a way previously mentioned [31–33]. The microhardness was measured on the X-Z and X-Y planes using a Mitutoyo microhardness tester equipped with a Vickers indenter under an applied load of 100 gf and dwell time of 15 s. The microhardness measurements were recorded on the surface of each disk following a regular grid pattern with a spacing of 0.5 mm. The hardness test was repeated three times for each case, and the average of the three measurements in the same position in the X-Z and X-Y planes was used in plotting the color-coded contour maps. Moreover, the average of the total measurements was taken as the average microhardness value of each condition. The standard deviation of the microhardness measurements obtained was used as a deformation inhomogeneity index.

The tensile test of the as-received and ECAPed up to 1, 2, and 3 passes samples was performed under a strain rate of $8.33 \times 10^{-3}$ s$^{-1}$ to obtain the true stress–strain curve those needed in the 3D FEM process. Tensile test was performed using a UNITECH Micro-load system Universal Testing Machine. A wire-cut electrical discharge machine was used to make Micro-tensile test samples with gauge length, width, and thickness of 2, 1, and 0.9 mm, respectively.

The microstructure observations of the different samples were carried out to trace the grain size and distribution using scanning electron microscopy (SEM) with electron backscatter diffraction (EBSD). 3D Total Analysis System (Dual Beam FIB) equipped with EBSD (Link EDAX system) and associated software (OIM4.5) was used. The EBSD specimens were prepared by grinding, followed by polishing with alcohol and diamond.

| Element | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Others | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|--------|-----|
| Amount (Wt.%) | 0.4–0.8 | Max. 0.7 | 0.15–0.4 | Max. 0.15 | 0.8–1.2 | 0.04–0.35 | Max. 0.25 | Max. 0.15 | 0.05 | Bal |

Table 1. Chemical composition of the Al6061-T6 alloy.
paste suspensions to mirror-like surfaces. The specimens were further polished using mixtures of colloidal silica and ethanol for 1 h \[33\]. More details of the EBSD samples preparation and the selected parameters used in the samples’ scanning were presented in previous work \[33\]. All of the microstructure observations were performed in the plane perpendicular to the pressing direction in the ECAP and HPT processes (X-Z plane), as shown in figure 1.

### 3. Finite element simulation

Rigid-viscoplastic 3D FEM simulations were performed to obtain the load-displacement, load-time, and effective strain distribution during the ECAP and HPT of Al6061-T6 alloy using DEFORM-3D V.10.0 \[22, 23, 34\]. The ECAP and HPT samples and dies shown in figure 2 were draw and uploaded to the simulation program that has the capability of reading, checking, and even fixing their geometry. The ECAP and HPT samples were considered rigid plastic bodies. The ECAP and HPT samples materials properties were provided in the form of the flow stress equations extracted from tensile curves shown in figure 3 \[31\], as follows:

\[
\sigma = k\varepsilon^n
\]

(1)
Where \( \sigma, k, \varepsilon, \) and \( n \) are the flow stress, strength coefficient, effective tensile strain, and strain hardening exponent. ECAP and HPT samples meshed into 150000 four-node elements, which consider enough or higher than those used previously in the FEM of ECAP [19–23] and HPT [24–28].

The ECAP simulation process performed for multiple passes using the batch-type method [22, 35], that the material characteristics and the mesh with all the geometry, stress, and strain data for the first step in any new pass was interpolated from the last step in the previous pass [22]. An ECAP die with an inner arc angle \( \Phi = 90^\circ \) and an outer arc angle \( \Psi = 15^\circ \) was described as a rigid body. The ECAP sample top nodes received the displacement in the direction of the punch movement after the tolerance between them was automatically detected. Speed of 1 mm s\(^{-1}\) was applied in the Y-axis direction, as shown in figure 2. The interference depth between punch and sample was limited to 0.7 mm with conducted the ECAP using route Bc [16, 17].

The upper and the lower dies are considered rigid bodies in the simulation of the HPT process. The HPT upper die moves with a speed of 0.1 mm s\(^{-1}\) until being in contact with the lower die, then the pressure of 9 GPa, (load of \( 72 \times 10^3 \) kg) applied gradually. After the pressure reaches its target value, the lower die starts to rotate under a rotational speed of 1 rpm up the required number of revolutions around the Y-axis. The tolerance between the dies’ inner walls and the sample was automatically detected (the tolerance value was 0.0002 mm). ECAP and HPT simulations were performed under a friction coefficient (COF) and the temperature of 0.12 and 20 °C [23]. Automatic remeshing was activated when the elements became too distorted.

### 4. Results and discussion

#### 4.1. ECAP FEM results

#### 4.1.1. ECAP load—displacement curves

Figure 4(a) shows FEM and experimental load-displacement curves of ECAPed samples processed up to 1, 2, and 4 passes. Both experimental and FEM loads gradually increased from zero in the first 20 mm. The load then ramps and reaches approximately its maximum value and followed by steady-state load value up to the stroke end, as previously noted in the ECAPed Al-1080 and Al-1070 [23, 35]. The load-displacement curves of the different ECAPed samples have similar behavior, with a noticeable increase in the peak load value that combined with increasing the ECAP number of passes, as shown in figure 4(b). The load-displacement behavior in the current study can be explained, as previously noted, depending on the effect of the die geometry, especially the outer die angle (\( \Psi \)) value [23, 35]. Where, \( \Psi \leq 40^\circ \) (\( \Psi = 15^\circ \) in the current study), revealed a high peak load value and ramp area followed by a steady-state one [23, 35].
Figure 4(b) shows the peak load values of the load-displacement curves during the ECAP up to 4 passes. The experimental peak load values were 40.2, 50.4, and 68 kN after the ECAP up to 1, 2, and 4 passes, respectively. The FEM peak load values were close to the experimental one of 43.9, 54.8, and 75.1 kN noted after 1, 2, and 4 passes, respectively. The difference between the experimental and the FEM peak load values ranged from 8.6% to 9.3%. Therefore, it can be noted that the FEM and experimental results of the ECAP process were so close to each other. The deviation between the peak load FEM and the empirical results of the ECAP noted in the current study was acceptable and even smaller than that stated previously [36–38].

Interestingly the deviation in ECAP peak load not only occurred between the experimental and FEM results but also noted even between the 2D and 3D FEM results [38]. The difference between the experimental, 2D and 3D FEM results is due to the difference FEM conditions such as mesh size, coefficient of friction, sample size, and the FEM simulation method 2D or 3D.

4.1.2. ECAP effective strain distribution

Effective strain distribution of ECAPed samples processed up to 4 passes in the mid-span of the steady-state zone in the X-Z plane is shown in figures 5(a)–(c) [31]. The effective strain was increased from bottom to top of the sample after one pass with an average of 1.13, which is close to the value of 1.08 obtained from equation (2) [39].

\[
\varepsilon_{\text{ECAP}} = N \left[ \frac{2 \cot \left( \frac{\Phi}{2} + \frac{\Psi}{2} \right) + \Psi \cosec \left( \frac{\Phi}{2} + \frac{\Psi}{2} \right)}{\sqrt{3}} \right]^{\frac{2}{3}}
\]

(2)

Where \( N, \Phi, \Psi \) are the number of passes, inner, and outer arc angles, respectively. The strain distribution pattern noted after one pass was similar to those previously noted [20–22].
The strain distribution becomes more homogenized after the ECAP to 2 passes, as shown in figure 5(b) [31]. Around 75% of the sample area has an average effective strain of 2.11, which is located between the average strains of 2.26 and 2.16 obtained by FEM and equation (2), as shown in figure 6(b). Interestingly, up to 2 passes, the difference between the average strain values calculated by equation (2) and FEM did not exceed 4.3%, as shown in figure 7. After four passes, the strain distribution becomes homogenous, where 81% of the sample area was covered with a strain value near that of 4.79, as shown in figures 5(c) [31] and 6(c). Interestingly the difference between the FEM strain and that calculated based on equation (2), after four passes, is 8.8%, as shown in figures 6(c) and 7. Therefore, equation (2) can be the most reliable equation to calculate the ECAP strain with close results to FEM simulations. Further, prove about the effectiveness of equation (2) can be supported by the comparison with the ECAP average effective strain calculating based on equation (3) that recently introduced [40].

\[
\begin{align*}
g_{\text{ECAP or HPT}} & = \sqrt{\frac{4}{3} \left[ \ln \left( \sqrt{\gamma_{\text{ECAP or HPT}}} + 1 \right) \right]^2 + \frac{\tan^{-1} \gamma_{\text{ECAP or HPT}}}{3}^2} \\
\end{align*}
\] (3)

Where \(\gamma\) is the shear strain imposed during the ECAP or HPT in the case of ECAP \(\gamma_{\text{ECAP}}\) obtained through equation (4) [39].
The difference between the strain values obtained through FEM and those calculated based on equation (3) were 22.1, 21.2, and 50.2% after 1, 2, and 4 passes, as shown in Figure 7. Therefore, it can be noted that the Iwahashi Y equation (2) [39] is the most effective equation for calculating ECAP average effective strain with the slightest deviation from the FEM results.

Interestingly, the deviation between the average FEM effective strain and the strain value calculated based on equation (2) after ECAP to 1 to 4 passes was in the range of 4.3%–8.8%, which is smaller than previously noted [21, 38, 41, 42]. The deviation between average FEM effective strain and that calculated based on equation (2) in the present work was smaller than that of 21.7, 11.3, 43.2–117, and 7.8%–53.8% noted after the ECAP simulation of Al, Ti, AZ31, and IF steel using Deform 3D and 2D under different conditions [21, 38, 41, 42]. The high accuracy of the simulation process of the ECAP in the present work is due to using a fine mesh with 150000 four-node elements and the batch-type method.

The strain inhomogeneity index values calculated based on the standard deviation of the FEM strain values decreased from 3.21 after one pass to 2.47 and 2.01 after two and four passes, as shown in Figure 8(a). Therefore, the increase of the ECAP number of passes increases the deformation homogeneity, as previously noted after

\[
\gamma_{ECAP} = N \left[ 2 \cot \left( \frac{\Phi}{2} + \frac{\Psi}{2} \right) + \Psi \csc \left( \frac{\Phi}{2} + \frac{\Psi}{2} \right) \right]
\]  

(4)

Figure 6. Effective strain distribution histograms through the X-Z plane of the samples processed by ECAP up to (a) 1 pass (b), 2 passes (c) 4 passes, and processed by HPT under 9 GPa up to (d) 1, (e) 5, and (f) 10 revolutions.
ECAP of Al and Ti [22, 43]. The increase of the deformation homogeneity is due to reducing corner gap size and using route Bc. The deformation homogeneity improvement with the increase of the ECAP number of passes also proved by tracing the strain values variation along the line passed from bottom to top of the sample, as shown in figure 8(b). The slope of the strain distribution line decreased from 0.11 after one pass to 0.06 and 0.012 after two and four passes. This observation indicates that the values of the strain from the bottom to the top become stable. Moreover, the difference between the strain values appears as a straight line parallel to the X-axis.

Figure 9 shows the effective strain distribution in the X-Y plane of the ECAPed samples. The strain was increased from bottom to top after the first pass, as shown in figure 9(a). Then the deformation homogeneity increased as noted after 2 and 4 passes. Deformation homogeneity increased was confirmed through the following two observations, as shown in figure 9. First, effective strain values variation range from the bottom to top of the sample was decreased obviously with the number of passes. Second, the increase of the sample area covered with effective strain near to that obtained through equation (2). The close results of the strain distribution and deformation homogeneity in the X-Z and X-Y planes confirm the effectiveness of the FEM simulation of the ECAP process.

4.2. HPT FEM results

4.2.1. HPT load-time curves

The experimental and FEM load-time curves of the HPT process under 10 revolutions and applied pressure of 9 GPa are shown in figure 10. The experimental load increases gradually and takes around 5 s to reach its target value before the lower die rotates for 10 revolutions, as shown in figure 10(b). Interestingly, the FEM load-time curve of the HPT process has the same behavior as the experimental curve. However, the FEM load-time curve did not include any lag between the load and the time until the pressure reaches its target value, as shown in figure 10(c). The difference noted between load-time behavior in the start part of the experimental and FEM results can be explained by the overall mechanical efficiency of the HPT machine parts. Even with the difference noted between the HPT experimental and FEM load–time curves, the deviation in peak load values between them did not exceed 0.16%, as shown in figure 10(d). Therefore, the closeness between the experimental and simulation results of load behavior and peak load confirms the effectiveness of the 3D FEM process in the current study.
4.2.2. HPT effective strain distribution

Figures 5 [31] and 6(d)–(f) show the strain patterns of the HPTed samples in the X-Z plane. The different HPT samples indicate the same strain distribution features. In all cases, strain increases from the sample center to its edge. However, increasing the number of revolutions decreases the difference between strain values between the sample center and the edge.

The HPT sample’s FEM effective strain distribution was in agreement with those previously noted of the HPTed samples processed under different conditions [25, 26, 28, 29, 44]. Interestingly, 33, 62, and 84% of the samples were covered with strain values near the FEM average effective strain of 2.66, 4.22, and 5.73 after HPT to 1, 5, and 10 revolutions.

Figure 11 shows the comparison between the FEM effective strain variation from the center to the samples edge and its average values with those calculated depending on the mathematical equation (3) [40], (5) [45, 46], and (7) [46, 47].

\[
\varepsilon_{HPT} = \left( \frac{2}{\sqrt{3}} \right) \ln \left[ 1 + \frac{\gamma^2_{HPT}}{4} \right]^{\frac{1}{2}} + \frac{\gamma_{HPT}}{2}
\]

(5)

Where \(\gamma_{HPT}\) is the shear strain imposed in the HPT process in both equations (3) and (5) that can be calculated from equation (6) [46, 48] as follows.
Where \( N_1, r, \) and \( h_0 \) are the number of revolutions, HPTed sample radius, and initial thickness, respectively.

In another case, the effect of the decrease of the sample initial thickness \( h_0 \) on the effective strain during the HPT process was considered using equation (7) \([46, 47]\).

\[
\varepsilon_{\text{HPT}} = \ln\left(\frac{2\pi N_1 r h_0}{h^2}\right)
\]  
(6)

Where \( h \) is the final thickness of the HPTed sample.

Strain patterns obtained from the equations (3), (5), (7), and the FEM have the same features after the HPT processing, as shown in figure 11. After one revolution, the FEM strain values were relatively close to those of equations (3), (5), and (7), as shown in figure 11(a). The same results also noted after processing up to 5 and 10 revolutions, as shown in figures 11(b) and (c). Although strain patterns obtained from equations (3), (5), and (7) were similar to that of the FEM. The FEM strain distribution was closer to equation (7), especially under HPT processing up to a higher number of revolutions. Figure 7 shows the deviation of the FEM effective strain from that calculated based on equations (3), (5), and (7). The difference between the FEM and equations (3), (5), and (7) average strains was in the range of 6.8–13.1, 7.5–13.2, and 7.9%–10.9% after 1, 5, and 10 revolutions, respectively. Although equations (3), (5), and (7) confirms the accuracy of the FEM in the prediction of strain.
imposed in the HPT process. However, equation (7) is more reliable in calculating the imposed strain in the HPT process, as previously confirmed [48].

The high reliability of equation (7) observed in the current study can explain as follows. First, most of the previous works were interested in using equation (8) [46, 49] in calculating the effective strain during the HPT process.

\[
\varepsilon_{\text{HPT2}} = \left[ \frac{2 \pi N r}{h_0 \sqrt{2}} \right]
\]

(8)

However, the previous comparison between equations (5) and (8) [40], and present comparison between equations (3), (5), (7), and (8) shown in figure 12 indicated that equation (8) could apply up to 4 revolutions [26–29]. Nevertheless, increasing the sample radius and the number of revolutions increases the value of the shear strain. So the deviation between the strain obtained by equation (8) and other equations becomes obvious. Second, equations (3), (5), and (7) can consider reliable according to the previous observation that recommended using them in calculating high imposed shear strains with values more than 0.8. On the other hand, equation (8) is limited to calculating shear strains values less than 0.8 [46]. Finally, equation (7) is more

Figure 10. (a)–(c) Experimental and FEM simulations load-Time curves and (d) peak load of the samples processed by HPT under pressure 9 GPa up to 10 revolutions.
reliable, as it developed to include the effect of the decrease in HPTed sample thickness and so the influence of the pressure.

The FEM strain maps of HPTed samples in the X-Z plane further confirmed by strain maps in the X-Y plane, as shown in figure 13. The strain patterns noted in the X-Y plane were in agreement with those of the X-Z plane, as shown in figures 5(d)–(f) and 13. The pattern in the X-Y plane was approximately constant through the sample thickness. So the top surface in the X-Z plane can be representative of any other position along the axis Y. Interestingly, the effective strain distribution of the HPTed samples in X-Y and X-Z planes shown in figures 5 and 13 indicates a decrease in the size of the low strain area in the sample center with increasing the number of revolutions. Consequently, inhomogeneity indexes decrease (so the deformation homogeneity increase) from 4.8 after one revolution to 4.2 and 2.27 after 5 and 10 revolutions, as shown in figure 8(a).

### 4.3. Microhardness distribution and results

#### 4.3.1. Microhardness distribution of the ECAP samples

Figure 14 [31] shows the color-coded microhardness maps of the different ECAPed samples in the X-Z plane. The as-received sample has a homogeneous microhardness distribution in the X-Z and X-Y planes with an average microhardness of 122.2 Hv and an inhomogeneity index of 1.02, as shown in figures 14(a), 15(a), (b), and 16(a).

The microhardness distribution becomes non-homogeneous after the ECAP for one pass, where the microhardness increases from the bottom to top with a low microhardness area in the bottom and occupied 25% of the sample, as shown in figure 14(b). With a further increase in the ECAP number of passes, the microhardness distribution becomes more homogeneous, as shown in figures 14(c), (d), and 15(b). The increase

![Figure 11. Effective strain distribution along the sample diameter in the X-Z plane of the samples processed by HPT under an applied pressure of 9 GPa and (a) 1, (b) 5, and (c) 10 revolutions.](image-url)
of microhardness homogeneity is due to the effect of the backpressure that decreases the corner gap size [7, 22, 31, 50]. The average microhardness of the ECAP samples increases from 122.2 Hv to 141.05 Hv after one pass, then to 149.15 Hv and 155.3 Hv after two and four passes, as shown in figure 15(a). The microhardness values of ECAPed samples in the present work were higher or near those of 77.9–161 Hv of the ECAPed Al6061 and Al6061-T6 alloys processed up to 8 passes [7, 8, 17].

The microhardness distribution results in the X-Z plane confirmed by tracing the microhardness distribution in the X-Y plane. Although the microhardness distribution of the as-received sample in the X-Y plane was homogeneous, as shown in figure 16(a). However, after the ECAP up to one pass, the microhardness distribution becomes non-homogeneous, as shown in figure 16(b). Then the microhardness distribution in the X-Y plane becomes more homogeneous with increasing the number of passes, as shown in figures 16(c) and (d). The microhardness distribution features in the X-Y plane in the current study were similar to those previously observed of the ECAPed Al6061 alloy [31, 50]. The average microhardness values in the X-Y plane were 143.79, 147.16, and 159.98 Hv after 1, 2, and 4 passes, which were close to those noted in the X-Z plane. Interestingly, the FEM strain and microhardness distribution maps of the ECAP samples in the X-Z and X-Y planes agreed with each other, as shown in figures 5(b)–(d), 10, 14(b)–(d), and 16.

4.3.2. Microhardness distribution of the HPT samples

Figure 17 [31] shows the increase of the microhardness from the sample center to its edge with the presence of a low hardness area at the HPTed sample center in the X-Z plane. Interestingly the low microhardness area diameter was decreased with increasing the number of revolutions due to the increase of the strain imposed according to equation (7), as shown in figure 17.

The increase of the HPTed samples microhardness distribution homogeneity in the X-Z plane with increasing the number of revolutions was noted through the following notes. First, around 50 and 81% of the sample area has microhardness values in the range of 155–170 Hv, which is close to the average microhardness of the HPTed sample shown in figure 15(a). Second, the difference between the microhardness in the sample center and edge decreases from 45 Hv after one revolution to 42 and 26 Hv after 5 and 10 revolutions. Finally, the inhomogeneity index decrease from 15.42 to 12.3 and 7.15 after 1, 5, and 10 revolutions, as shown in figure 15(b).

The hardness distribution in the X-Z plane of the HPTed samples in the current study was compatible with the results previously noted of HPTed Al6061 and Al-Mg-Si alloys [10–13]. Increasing the number of
revolutions from one revolution up to 10–20 revolutions decreases the diameter of the low hardness area in the center and the hardness difference between center and edge from 20 mm and 20 Hv down to 10 mm and 5 Hv \([12, 13]\). Therefore, through a detailed comparison with the previous results \([10–13]\), a higher hardness with a high degree of homogeneity can be reached through the HPT processing under 9 GPa and ten revolutions.

The microhardness distribution maps in the X-Z plane were congruent with those of the X-Y plane, as shown in figures 17 and 18. The microhardness distribution through the X-Y plane appears as an extension of that noted in the X-Z plane. Furthermore, the microhardness distribution becomes more homogeneous with increasing the number of revolutions, as shown in figure 18. Moreover, the average microhardness values in the X-Y plane of 145, 147.4, and 164 Hv were close to those noted in the X-Z plane of 146.65, 153.76, and 165.37 Hv after 1, 5, and 10 revolutions, respectively, as shown in figure 15(a). Interestingly, in both X-Z and X-Y planes, the microhardness and strain distributions were in good agreement.

### 4.4. Microstructure evolution and correlation with FEM and hardness results

Figure 19 [31] shows the EBSD microstructure observations of the ECAP and HPT samples. The grain size decreased from 18.2 \(\mu m\) in the as-received case down to 0.55, 0.46, and 0.28 \(\mu m\) after ECAP to 1, 2, and 4 passes respectively, as shown in figures 19(a)–(d). Furthermore, the grains continuously evolved into equiaxed grains due to the increase of the imposed strain with the increasing number of passes. Moreover, increasing the ECAP number of passes decreases the grain size range, as shown in figures 20(b)–(d). Therefore, increasing the imposed strain that combined the increase of the number of passes, as noted in figures 5(a)–(c) and 7 through the FEM results and theoretical equation (2), leads to the grain refinement and the evolving the microstructure into equiaxed grains.
The ECAPed to 4 passes grain size of 0.28 \( \mu m \) was near or even smaller than that of 0.28 and 0.5 \( \mu m \) ECAPed Al6061 alloys \([7, 8]\). Therefore, the higher hardness noted in the current study relative to the previous one \([7, 8]\) can be related to the smaller grain size. The decrease of the average grain size and range can be related to the imposed effective strain and so the microhardness.

The HPT processing decreasing the grain size from 18.2 \( \mu m \) in the as-received case down to 0.43, 0.36, and 0.2 \( \mu m \) after one, five, and ten revolutions, as shown in figures 19(e)–(g). The HPT sample’s grain sizes were smaller by 22%–30% than the ECAPed samples due to the relatively higher strain imposed during the HPT, as shown in figure 20. The grain size noted after one revolution was lower than that of 0.7, and 0.702 \( \mu m \) that noted after HPT up to one revolution and pressure of 6 GPa of Al-6061 and Al-Mg-Si alloys \([12, 13]\). Moreover, the grain size of 0.36 \( \mu m \) of the HPTed sample processed to five revolutions was near that of 0.12–0.58 \( \mu m \) obtained after HPT of Al6061, Al-Mg-Si, Al6061-O, and Al6061-T651 samples \([10, 12–14]\). Moreover, the HPT processing up to ten revolutions and 6 GPa of Al-Mg-Si alloy produces an average grain size of 0.25 \( \mu m \) \([13]\).

The increase of the imposed strain decreases the grain size range and size and consequently increases the microhardness of the ECAPed and HPTed samples. The increase of the ECAP number of passes to 1, 2, and 4 passes increases the hardness by 15.2%, 21.8%, and 27.3%, respectively. On the other hand, increasing the HPT number of revolutions up to 1, 5, and 10 revolutions increases the hardness by 20, 25.5, and 33.6%, respectively. The increase of the hardness after the SPD processing via ECAP and HPT can be explained by the high dislocation density and refined grains obtained due to the grain size refinement during the severe plastic deformation noted through EBSD microstructure observation, as shown in figures 19 and 20. The increase of the Al6061 sample hardness after the ECAP and HPT processing results from the grain refinement, as shown in figures 19 and 20, according to the Hall–Petch relation shown in equation (6) \([51, 52]\), that correlates the hardness of a material H with its grain size:

\[
H = H_0 + K_d d^{-1/2}
\]  

(9)
Where $d$ is the grain size, and $H_0$ and $k_H$ are constants. Moreover, the increase of the dislocation density also contribute to the increase of hardness $H$ and strength $\sigma$ after HPT processing according to the Taylor equation (7) [53, 54].

\[
\sigma = \sigma_0 + \alpha \frac{M G b}{\rho} \frac{1}{2}
\]

Where $\alpha$ is a constant, $G$ is the shear modulus, $b$ is the length of the Burgers vector of dislocation, $M$ is the Taylor factor, and $\rho$ is a dislocation density. The increase of the dislocations density during ECAP and HPT processes (through increasing the number of passes and revolutions) can be observed by the increase of the non-indexed
data areas (black areas), as shown in figure 19 [33]. The non-indexed data regions on the well-prepared sample surface in EBSD images are the points where the collected Kikuchi diffraction patterns do not produce accurate data because the pattern quality is too poor to analyze due to highly distorted regions (due to the severe plastic deformation) [33]. Similar observations of the increase of the hardness after the ECAP and HPT of the Al6061 alloys were also observed in previous works [7, 8, 10–13, 17, 31]. Interestingly, the hardness of the HPTed samples was higher by 17%–57% than that of the ECAPed samples, as previously noted [7, 8, 10–13, 17, 31]. As a higher strain imposed during the HPT samples relative to that imposed in the case ECAP samples, as shown in figures 5–7 produces smaller grain sizes, as shown in figures 19–20 and so higher dislocations density revealed higher hardness in the case of the HPTed samples.

4.5. Correlation between the strain and the microhardness results

The previous sections indicated an agreement between the strain and the microhardness distribution results, as shown in figures 5, 9, 13, 14, 16–18. Therefore, the need for the correlation between the strain and the microhardness is required. So the FEM strain can be used in predicting the microhardness of the samples deformed plastically. Different studies were concerned with predicting Vickers microhardness of the materials deformed by plastic and severe plastic deformation [23, 55–57]. The microhardness of the ECAP and HPT processed samples were calculated depending on the average FEM and the calculated strains obtained from equations (2), (3), (5), and (7) in the X-Z plane using the following equation (11) [55]:

\[
Hv_{\text{calculated}} = ck(\varepsilon_e + \varepsilon_0)^n
\]

Figure 16. Microhardness distribution contours maps through the X-Y plane of the (a) as-received and processed by ECAP up to (b) 1 pass, (c) 2 passes, and (d) 4 passes Al6061-T6 samples.

Where, Hv calculated, c, k, εe, ε0, and n, are calculated Vickers microhardness depend on the effective plastic strain obtained from FEM and equations (2), (3), (5), and (7), constraint factor [46], strength coefficient, representative strain, effective strain (obtained from FEM or equations (2), (3), (5), and (7)), and strain hardening exponent, respectively. The representative strain calculations were explained in detail by Tekkaya A E et al [56]. A representative strain with a value of 0.11 was used in the current study [23, 56, 57]. Figure 7 shows the different strain values used in calculating the ECAPed and HPTed sample’s microhardness. Moreover, the constraint factor c calculated through equation (12) [55]:

\[
Hv_{\text{calculated}} = ck(\varepsilon_e + \varepsilon_0)^n
\]
Where $HVi$ and $\sigma e$ [48, 55] are the microhardness of the Al6061-T6 alloy and the representative stress obtained from equation (13) [55]:

$$\sigma e = k \varepsilon_c^n$$

The constraint $c$ factor value calculated based on equation (12) in the current study and is equal to 3.3, that’s value consider close to that used previously [23, 55, 56].

The experimental microhardness values and those calculated based on the FEM and equations strains were close to each other, as shown in figure 15. The difference between the experimental and calculated microhardness values of the ECAPed samples was less than 10%. The difference between the calculated and experimental microhardness of the ECAPed samples processed from 1 up to 4 passes was 1.06%–7.15%. It can note that the calculated microhardness based on the FEM results of ECAPed samples has a more negligible difference from the experimental results than that calculated based on equations (2) and (3). This observation indicated that the high reliability and effectiveness of using the FEM results. Furthermore, the difference between the predicted microhardness values based on equation (2) and the experimental one was smaller than equation (3). Therefore, equation (2) is the most proper equation for calculating the strain of the ECAP process.

The effectiveness of using the FEM strain in calculating the microhardness was also noted in the HPTed samples. The difference between the experimental average microhardness of the HPTed samples and those calculated based on the FEM, equations (3), (5), and (7) strain was in the range of 0.96–8.8, 1.27–9.46, 1.3–9.43, and 0.57–9.32, respectively. This observation confirms the effectiveness of using FEM strain in calculating the microhardness of the HPTed samples with narrower differences range from the experimental results than using equations (3), (5), and (7), as shown in figure 15. Furthermore, it can note that equation (7) can consider the

![Figure 17. Microhardness distribution contours maps through the X-Z plane of the Al6061-T6 sample processed by HPT under the pressure of 9 GPa up to (a) 1, (b) 5, and (c) 10 revelations. Reprinted from [31] Copyright (2020), with permission from Elsevier.](image-url)
most proper equation to calculate the imposed strain in the HPT, and so the prediction of the microhardness of
the HPTed samples.

Although the difference between experimental and calculated microhardness increased with the increase of
the number of passes and revolutions, the max value of the difference was less than 10%. This observation
confirms the effectiveness of using equation (11) in estimating the microhardness of both the ECAP and HPT
samples based on the values predicted based on the strain values obtained by FEM, equations (2), (3), (5), and (7).
Interestingly the present results confirm the previous works about the effectiveness of equation (11) in
predicting the hardness of the metals after the deformation deformed by different methods [23, 55, 56].

5. Conclusions

In the present work, the following conclusions were obtained:

1. 3D FEM of ECAP and HPT processes were carried out successfully under the actual experimental
conditions that reduce the efforts and the time consumed needed in the actual practice of the ECAP and
HPT processes.

2. 3D finite element method (3D FEM) simulations provide an accurate prediction of peak load and strain
imposed during the ECAP and HPT processes with a small margin of error due to the accurate simulation
conditions selected and fine mesh used.

Figure 18. Microhardness distribution contours maps through the X-Y plane of the Al6061-T6 sample processed by HPT under the
pressure of 9 GPa up to (a) 1, (b) 5, and (c) 10 revelations.
3. The current study provides a recommendation with verification using the FEM results about the most reliable equations in calculating the effective strain imposed during the ECAP and HPT processing.

4. The microstructure investigation proved the effect of the imposed strain increase on the grain refinement degree, consequently increasing the deformed samples’ microhardness and deformation homogeneity.

5. The microhardness values of ECAP and HPT samples were predicted efficiently depending on the FEM and mathematical equations strain with a margin of error less than 10% from the experimental results. Therefore the current study can be helpful in estimating the hardness of the plastically deformed materials theoretically that reduce the need for the experimental tests.

Figure 19. Color-coded orientation map images of (a) as-received, (b)–(d) processed by ECAP up to 1, 2, and 4 passes and (e)–(g) processed by HPT under 9 GPa and 1, 5, and 10 revolutions Al6061-T6 samples. Reprinted from [31] Copyright (2020), with permission from Elsevier.
Data availability statement

No new data were created or analysed in this study.

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Figure 20. The grain size distribution of (a) as-received, (b)–(d) processed by ECAP up to 1, 2, and 4 passes and (e)–(g) processed by HPT under 9 GPa and 1, 5, and 10 revolutions Al6061-T6 samples.
Mater. Res. Express 8 (2021) 086521
M1 Abd El Aal

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