Original Article

Microhardness distribution and finite element method analysis of Al 5452 alloy processed by unconstrained high pressure torsion

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Abstract
High pressure torsion (HPT) is one of the successful and efficient methods of severe plastic deformation (SPD). In this research, disk-shaped specimens of aluminum alloy were exposed to high pressure and torsion, which are the key factors of HPT. Simultaneously applying high pressure and torsion causes shear strain and thus enhancement of mechanical properties such as microhardness. In order to understanding the behavior of local deformation on disks after HPT, the process has been simulated by using finite element analysis method in ABAQUS/Explicit software. Results of simulation showed that by increasing applied pressure and number of turns, more effective strain would be applied to the disks. By comparing results of experiment and simulation, it was concluded that there is a region in the middle of the disk that has higher microhardness value in comparison to other regions, which is caused by more strain that was applied to it. Also, dimensions and equivalent plastic strain (PEEQ) obtained in experiments and simulations are compared. It was observed that expected dimensions and PEEQ of simulations are in good agreement with experimental results.

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1. Introduction

Nowadays production of bulk ultra-fine grained (UFG) materials by using severe plastic deformation (SPD) is an established procedure [1–3]. This is explained by the fact that reducing the grain sizes down to submicron or nanometer scale provides many technological advantages and enhances the mechanical and physical properties to a significant level [3]. So in the last decade, bulk nano-structured materials produced by SPD have been investigated intensively [4]. The most popular SPD methods are currently equal channel angular pressing (ECAP), high pressure torsion (HPT) and accumulative roll bonding (ARB) [5]. All of these methods impose high strains but in practice the largest strains are applied by HPT and in comparison to other available SPD procedures, HPT processing gives the smallest grains [6–9] and the highest fraction of high-angle grain boundaries [8,9]. At present, bulk solids with nano-scale

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microstructures in a wide range of pure metals, alloys, intermetallics and composites have been successfully produced by using the HPT process [10,11]. There are three different types of HPT, which are defined as constrained, quasi-constrained and unconstrained HPT process. In the constrained HPT the disk is placed within a depression in the lower anvil so that any lateral flow is prevented. Under quasi-constrained conditions, the disk is placed within depressions on the inner surfaces of the upper and lower anvils so that there is some limited outward flow during the torsional straining. In unconstrained HPT the anvils are flat and the material flows outwards during processing. In cases that applied pressure and number of turns are relatively less than required value, this method can be used [10,12].

Fig. 1 shows the unconstrained HPT process schematically. In the HPT process plastic deformation is performed in two steps: (1) applying pressure, (2) applying torsion at constant pressure. During the process, a high hydrostatic pressure is supplied by the contact of the two anvils, and the surface frictional forces deform the specimen by shear while rotating the lower anvil [13–15].

Several different approaches have been employed to convert the shear strain into an “equivalent strain”, which has led to considerable confusion in the literature; to solve this problem Jonas et al. [16] concluded that only the Von Mises equivalent stresses and strains should be employed in the description of HPT results. The equivalent Von Mises strain, \( \varepsilon_{eq} \), imposed in HPT is given by the following simple equation:

\[
\varepsilon_{eq} = \frac{2 \pi Nr}{h \sqrt{3}}
\]

(1)

where \( N \) is the number of turns of torsional straining, \( r \) is the distance measured from the center of the disk, and \( h \) is the initial height (or thickness) of the specimen [10,12].

Based on the rigid-body assumption in Eq. (1), it is reasonable to anticipate that the strain in HPT is inhomogeneous and varies linearly from zero strain at the disk center to a maximum at the outer edge of the disk [17]. Also, most metals tend to give results that are reasonably consistent. Specifically, the hardness is initially higher at the edge of the disk and lower in the center, but the hardness of center increases until ultimately there are similar hardness values throughout the disk [18].

Many researches regarding to quasi-constrained HPT process have been carried out on Al alloys to examine microhardness evolution. For example, research on commercially pure aluminum Al-1050 alloy by Kawazaki et al. [19], Al-2024 alloy by Vafaei et al. [3], Al-6063 alloy by Das et al. [20], Al-7075 alloy by Sabbaghianrad et al. [21] under applied pressures 6, 2.5, 2 and 6 GPa, respectively, and 5 turns. They showed that the microhardness values saturated about 240–250 Hv throughout the disks. Also, a study on high purity aluminum (99.99%) followed by 6 GPa pressure and 20 turns shows saturated microhardness of around 60 Hv throughout the disk [14]. Currently, only limited information is available about the microhardness of 5XXX series aluminum alloys processed by HPT. Bazarnik et al. [9] claimed that after 10 turns, microhardness was reasonably homogeneous across the disk with a saturation value of about 240 Hv. Despite the great interest to carry out the HPT process and studies on microhardness evolution in HPT disks, limited information is available about microhardness distribution across unconstrained HPT of disks.

Because the mechanical properties of the deformed material are directly related to the amount of plastic deformation, i.e. the imposed strain, understanding the phenomenon associated with the strain development in severe plastic deformation processes is very important [22]. So far, studies on simulation of constrained HPT and quasi-constrained HPT have been conducted, but there is lack of information about simulation of unconstrained HPT process. For example, Jahedi et al. showed a new method of HPT termed as high pressure double torsion (HPDT) that leads to larger plastic strain and as a result more efficient refinement than standard HPT; and they concluded that predictions of the dimension of specimen by finite element analysis (FEA) in good agreement with experimental values [23,24]. For these reasons, in this research, disks of aluminum AA 5452 alloy were subjected to unconstrained HPT process and effects of two parameters, number of turns (N) and applied pressure (P), were investigated. Also, finite element analysis of unconstrained HPT was done by ABAQUS/Explicit software and finally the simulation predictions were compared with experimental results.

2. Methods

2.1. Preparation of materials

An AA 5452 aluminum alloy rod with a diameter of 15 mm and composition of 2.7% Mg, 0.61% Mn, 0.27% Fe, 0.11% Cr, and 0.21% Si was used in this research. Initial material was annealed at 345 °C under a soaking time of 2 h. The annealed rod was then cut to a thickness of 3 mm perpendicular to the extrusion direction in order to prepare the specimen for the experiment. Then the disks were polished to achieve a flat and smooth surface. The unconstrained HPT process was performed on the disks under pressures of 1.5, 1.86, 2.7 and 3.3 GPa, and number of turns was 0.5, 1 and 2.
For the microhardness tests, the rough surface of the disks after HPT process were polished and smoothened. The microhardness test was done by BUHLER digital microhardness device, MMT-7 model by weight of 25 g. The measurements were carried out on 12 different diameters by angular distance of 15°, where the test step size was set 0.5 mm along diameter from center to surface of disk.

### 2.2. Simulation

The isothermal FEM analysis of unconstrained HPT process was executed by using three-dimensional (3-D) elasto-plastic commercial ABAQUS/Explicit software. Dimensions and properties of specimen were introduced to software according to conditions of the experiment. At this stage, the SI units (mm) were utilized. To enter the mechanical properties of the material into the software, the AA 5452 alloy was subjected to tensile test according to the ASTM E8 standard. The obtained data of this test was introduced into the software. The boundary conditions were considered in two steps for simulation; the step (1) was associated to applying pressure and the step (2) was related to applying torsion. In step 2, the bottom anvil makes a rotational movement about Y axis and in this stage different numbers of turns are applied to specimen through movement of the anvil. In the step 1, pressure is applied to reference point of the top anvil and anvil’s movement is toward negative-Y axis, however, the bottom anvil is fixed and immobile. In the step 2, which is related to applying torsion, the bottom anvil moves about the Y axis and number of turns is applied to disk by moving the bottom anvil. Also, in this step for maintaining the pressure on disk and reducing the disk height due to applied pressure, displacement of the top anvil is free toward Y axis. The coefficient of friction between top anvil and surface of specimen was considered 0.25 and coefficient of friction between bottom anvil–disk interface was considered 0.275 [24]. For applying pressures of 1.5, 1.86, 2.7, and 3.3 GPa according to conditions of the experiment, forces of 266,560, 329,280, 478,240 and 580,160 N, respectively, were applied to reference point of top anvil. In order to mesh the specimen, the eight node linear brick elements (C38DR) were used and for meshing the rigid parts of process – top and bottom anvil – the R3D4 type of meshing was utilized. By precise inspection of the results of simulation, we found out that 4968 meshes for specimen and 2520 meshes for each of the anvils were enough to reveal the local deformation behavior of the HPT process. Large deformation is applied to induce torsions in the specimen which in turn leads to distortions of meshes during the simulation of the HPT process, so, the Adaptive mesh was used in simulation.
3. **Results and discussion**

3.1. **Effect of the number of turns on microhardness**

As it can be seen in Fig. 2, microhardness curves are plotted in condition of constant applied pressure (P) for investigating the effect of the number of turns (N). Fig. 3 shows average microhardness curve as a function of the number of turns at constant applied pressure of 1.5, 1.86 and 2.7 GPa. As for Figs. 2 and 3 it is found that by enhancement of N, overall microhardness values are increased in three conditions. Maximum microhardness value in P = 2.7 GPa, N = 2, was recorded as 252.5 Hv. According to Figs. 2c and 3 it can be seen that at higher applied pressure, increasing rate of microhardness values was reduced with increasing number of turns. In other words, according to Fig. 3, the increasing rate of average microhardness in range of 0.5–1 turn increased and in range of 1–2 turn decreased, so it could result in occurrence of strain hardening and increasing the density of dislocations due to applying large deformation.

3.2. **Effect of the applied pressure on microhardness**

Fig. 4 shows microhardness variations at the applied pressures of 1.5, 1.86, 2.7 GPa, (and 3.3 GPa in Fig. 4c) at the constant number of turns. According to Fig. 4, it can be found that by increasing the pressure, in all conditions overall microhardness values are increased. According to Fig. 4b, it is revealed that because applied pressures were close to each other and the center of the disk had less shear deformation than the peripheral areas of the disk, microhardness values in the center of disk are so close at P = 1.5 GPa and P = 1.86 GPa. As for Fig. 4c, it can be seen that by enhancement of P to 3.3 GPa at N = 2, overall microhardness values are increased due to saturation of microstructure and occurring intensive strain hardening.

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**Fig. 3** – Variation of average microhardness as a function of number of turns at constant pressure values.

**Fig. 4** – Microhardness across disk diameters of the Al-5452 alloy at constant number of turns (a) 0.5 turn, (b) 1 turn and (c) 2 turns at different applied pressure of 1.5, 1.86, 2.7 GPa and 3.3 GPa (only for Fig. (c)).
Fig. 5 shows average microhardness values as a function of the applied pressure at constant  \( N = 0.5, 1 \) and 2 turn(s). According to Fig. 5, it can be seen that in the range of 1.5–1.86 GPa the increasing rate of average microhardness increased and in range of 1.86–2.7 GPa it decreased, so it could lead to occurring strain hardening and increasing density of dislocations tangle due to severe imposed deformation.

### 3.3. Development of microhardness distribution at unconstrained HPT processing

Fig. 5 shows contour of the microhardness distribution in the Al-5452 alloy over the disk surface in contact of bottom anvil, after unconstrained HPT processing for different intended conditions. For understanding the effect of number of turns on microhardness distribution, by comparing Fig. 6a and b at constant \( P = 1.5 \) GPa, it is shown that by increasing the number of turns from 0.5 to 2, the range of microhardness in the middle region at the surface of the disk have raised from range of 140–160 Hv to 180–200 Hv. Also, at \( P = 2.7 \) GPa and by
increasing number of turns from 0.5 to 1 then to 2, it is revealed that the microhardness values of the middle region have raised from range of 180–200 Hv to 200–220 Hv and then reached to 220–240 Hv, Fig. 6c–e. Also, in order to understand the effect of applied pressure on microhardness distribution, at constant \( N = 0.5 \), we found out that by enhancing \( P \) from 1.5 GPa to 2.7 GPa, the range of microhardness at middle region of disk increased from 140–160 Hv to 180–200 Hv (see Fig. 6a and c). By comparing Fig. 6b, e and f at constant \( N = 2 \) and by increasing pressure from 1.5 GPa to 2.7 GPa and then 3.3 GPa it is shown that the microhardness of middle region increased from range of 180–200 Hv to 220–240 Hv and then approximately remained constant, with this exception that the area of region possessing value of 240 Hv extended and finally the microhardness distribution at the middle region became more uniform.

### 3.4. Equivalent plastic strain at unconstrained HPT processing

Fig. 7 represents the results of simulated equivalent plastic strain (PEEQ) distributions on Al-5452 alloy disks after different \( P \) and \( N \), according to experimental conditions. The PEEQ distributions investigated at section 1 (tool contact interface) and 2 (thickness section) of sample. By comparing Fig. 7a and b at constant applied pressure, \( P = 1.5 \) GPa, with experimental conditions of \( N = 0.5 \) and 2, respectively, it is deduced that by increasing \( N \), the amount of PEEQ increased at both sections and its maximum value increases from 0.839 to 0.905. Similar results, at constant \( P = 2.7 \) GPa and \( N = 0.5, 1 \) and 2, can be found that at both sections by increasing \( N \), the amount of PEEQ increases and maximum value grows from 2.505 to 2.844 and finally reaches to 2.963, Fig. 7c–e. By considering the above mentioned results it is concluded that by increasing the \( N \), the amount of PEEQ increases throughout the disk.

At constant \( N = 0.5 \) and applied pressures of 1.5 GPa and 2.7 GPa, it is shown that by increasing pressure, the amount of PEEQ increases and maximum PEEQ grows from 0.839 to 2.505 (see Fig. 7a and c). Also, from Fig. 7b, e and f, which are at constant \( N = 2 \) and \( P = 1.5, 2.7 \) and 3.3 GPa, respectively, by increasing HPT pressure, the amount of PEEQ increases and maximum value grows from 0.905 to 2.963 and then reaches to 4.223. Regarding to above results, it is concluded that by increasing applied pressure, the amount of PEEQ increases throughout the disk. In section 1, surface of disks contacts with the upper anvil, by increasing \( P \) and \( N \), the equivalent plastic strain distributions were almost unchanged throughout the disks. This could be due to fixed upper anvil in the
second step of HPT processing which applies torsion. At Section 2, PEEQ's value at central and inner segments of disk is equal with its value at the surface of the middle segment at \( P = 1.5 \) GPa. But by increasing \( P \) from 1.5 to 2.7 and 3.3 GPa, at middle segment of disks, PEEQ's value become greater than PEEQ's value at central and inner segment of the disks. This could be due to applying the torsion on the surface of the disks, which is the result of applying greater pressure.

Microhardness and equivalent plastic strain distribution on lower surface of disks, which are in contact with bottom anvil and transfer the torsion on the disk, are essential for understanding plastic deformation behavior and other mechanical properties. Also, because of limited information about microhardness and PEEQ's distribution in unconstrained HPT process, it is necessary that overall behavior of materials in respect to microhardness, PEEQ, microstructure and their evolution completely and clearly explained. Fig. 8 shows PEEQ's evolution at the bottom surface of HPT's Al-5452 alloy disks. As can be seen, between central and peripheral region of the disks, there is a region with higher imposed strain in comparison to other regions of the disks. Therefore, experimental and simulation results reveal that because of applying intense strain in this region, its microhardness becomes higher than other regions.

Fig. 9 shows counter of PEEQ distribution in the Al-5452 alloy at first step (after pressurizing and before twisting of sample) unconstrained HPT processing. At this step, it can be seen middle region of the disk has highest imposed strain. With starting step 2 (applying torsion) and progress the process, areas which are far from ring-shaped region, because placed at sticking zone of disks, material flow between both of anvil’s surface and thus low strain is subjected to them. This
phenomenon makes difference between results of unconstrained HPT and quasi-constrained HPT. In quasi-constrained HPT there is a gap between the top and bottom anvils so the friction between the specimen and the anvils and the depression walls in the anvils prevents the sample from flowing significantly through the gap at least in the early step of the process [25]. Thus, returned stress is engendered and applied to edge of the disks. That is why in the quasi-constrained HPT’s disks; microhardness and strain values at the edge are higher than in center and other region. However, as discussed above, the experimental and simulation results illustrated that the microhardness and equivalent plastic strain at the middle regions of the disks are higher than other region.

3.5. Comparing the experimental and simulation results

According to Table 1 that shows disks diameter and thicknesses values as predicted by FEA and experiments, it can be seen that the experimental and simulations results are in good agreement. By increasing N and P deviation of experimental and simulations results increased. Deviation from forecasted and experimental results may also be due to distorting mesh effects and/or coupling effects between tribological and rheological behaviors of the specimen material and/or the low efficiency of HPT apparatus at higher applied pressure.

In a research that was done on commercially pure aluminum (AA1050) by Jahedi et al. [24], a specimen with a rectangular cross section was subjected to a pressure of 600 MPa and a half-turn rotation. The amounts of twisting after the half-turn rotations of the HPT were measured. The amount of twisting around the central axis was 14.2°. In this research, a disk was subjected to 1.5 GPa, and by this fact that at the first step, material flows between two anvils then cross-sectional area increased. Therefore, actual applied pressure at commence of step 2 decreased to about 884 MPa. We used this result and calculated that if N = 0.5 and the amount of twisting were 14.2°, therefore, the effective N value would be equal to 0.039. Based on experimental results in Table 1, values of r and h are equal to 10 mm and 1.7 mm, respectively. By using values in Eq. (1), the calculated amount of equivalent strain is about 0.83. On the other hand, the amount of PEEQ obtained from simulation result for P = 1.5 GPa and N = 0.5 was equal to about 0.81. Therefore, theory and simulation results with good approximation are close together.

4. Conclusions

By increasing N at constant P, from 0.5 to 1 and 1 to 2 turns, overall microhardness values raised throughout the disks. Maximum microhardness value for P = 2.7 GPa and N = 2 was recorded as 252.5 Hv. By increasing P at constant N, from 1.5 GPa to 1.86 GPa and 1.5 GPa to 2.7 GPa overall microhardness values increased. Also, by enhancing the N and P, growing rate of average microhardness decreased.

According to contour of microhardness and PEEQ distribution, their values at the middle regions of the disks are higher than that of other regions. At P = 1.5 GPa, by increasing N from 0.5 to 2, microhardness range at middle region of the disk surface has been raised from 140–160 Hv to 180–200 Hv and amount of PEEQ was increased and its maximum value was increased from 0.839 to 0.905. At constant P = 2.7 GPa and N = 0.5, 1 and 2, the microhardness values of middle region have been raised from range of 180–200 Hv to 200–220 Hv and then reached 220–240 Hv and amount of PEEQ was increased and maximum value was raised from 2.505 to 2.844 and finally reached 2.963. At constant N = 2, by increasing P from 2.7 GPa to 3.3 GPa, microhardness of the middle region approximately remained constant, with this exception that the area of region possessing value of 240 Hv was extended and finally the microhardness distribution at middle region became more uniform and maximum PEEQ raised from 2.963 to 4.223.

Also, Specimen dimensions predicted by FEM analysis and experimental results were in good agreement, at P = 1.5 GPa and N = 0.5, theoretical and simulation PEEQ values equal to 0.83 and 0.81, respectively, were close to each other with good approximation.

Conflicts of interest

The authors declare that they have no conflict of interest.

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REFERENCES