Journal of Ultrafine Grained and Nanostructured Materials
https://jufgnsm.ut.ac.ir
Vol. 52, No.1, June 2019, pp. 32-42
Print ISSN: 2423-6845 Online ISSN: 2423-6837
DOI: 10.22059/JUFGNSM.2019.01.04

Investigation on the Deformation Behavior and Strain Distribution of Commercially Pure Aluminum after Circular Simple Shear Extrusion

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Recieved: 20 January 2019; Accepted: 25 March 2019

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ABSTRACT

Circular simple shear extrusion process was introduced as a new geometry for simple shear extrusion technique to fabricate ultrafine-grained materials. Similar to the simple shear extrusion method, this process is also based on direct extrusion, and the samples deform in a simple shear manner. In this investigation, the simulations were carried out using the commercial finite element code ABAQUS/Explicit and the process was performed experimentally on commercially pure aluminum (AA1050) samples. Besides, the optimized length of the deformation channel was measured, 26 mm using the commercial simulation package DEFORM 3D. The effects of back-pressure and processing routes on deformation behavior and hardness homogeneity were studied in the simulation and experiment. Uniaxial compression test, X-ray diffraction, and Vickers microhardness test were performed on the samples to determine the mechanical and microstructural properties. The experimental results were in good agreement with the ones obtained by simulation. It was found that in the practical approach with the absence of back-pressure, route D had the most homogeneous distribution of strain in the cross-section and throughout the length of the samples. The results of compression and microhardness tests showed that the mechanical properties of the samples were improved compared to the annealing state. Also, a significant reduction in crystallite size can be seen in the XRD results leading to an average crystallite size of 103 nm after 10 passes.

Keywords: *Circular Simple Shear Extrusion, Severe Plastic Deformation, Finite Element Analysis, Mechanical Properties.*

1. Introduction

Severe plastic deformation (SPD) processes have been considered by many researchers for the production of bulk nanostructured and submicrometer metals and alloys. This method of deformation can be applied to bulk materials or materials in sheet form and has certain advantages that can alter the grain size of the material samples without changes in their chemical composition and their shape [1,2]. The materials produced by severe plastic deformation can be tailored to have superior mechanical properties, and because of their large dimensions, they can perform various types of mechanical tests that are necessary for their use in the industry. Among the various SPD processes, equal channels angular pressing (ECAP) [3,4], high pressure torsion (HPT) [5], accumulative roll bonding (ARB) [6], constrained groove pressing (CGP) [7] and twist extrusion (TE) [8] are known for producing ultra-fine grain materials. The simple shear extrusion (SSE) process is a professional SPD technique which was developed by Pardis and Ebrahimi in 2009 [9]. This method is based on direct extrusion, and in comparison to the ECAP, it has the advantages of having a symmetric and uniform distribution of the strain in the sample's cross-section, less amount of waste material and less processing load [9]. Besides, in the ECAP process, all deformation occurs in the junction of two channels; therefore, the total strain occurs in a narrow region and within a short period of time [3], while in the SSE process, due to a longer deformation zone, the strain is applied gradually to the material, and thus the strain rate in this method is much lower than that of the ECAP. This feature makes it possible to use this method for materials with limited workabilities, such as TWIP steel [10] and materials with an HCP crystalline structure such as magnesium and its alloys, even at room temperature [11]. These materials have a limited number of slip systems [2], thus while applying large strains in a short amount of time results in segmentation, the SSEed samples do not experience such a thing.

In 2018, a new design for a simple shear extrusion process was introduced by Ebrahimi et al. [12, 13], named circular simple shear extrusion (CSSE). They showed that due to the circular geometry of this new process, the required processing load, the extrusion pressure, the maximum principal stress, and the contact pressure are less than those in the conventional SSE. This leads to a longer service life of this process. Moreover, they concluded that the CSSE process needs a lower amount of back-pressure to fill the outlet cross-section of the die in comparison to the SSE. CSSE was presented for workpieces with a circular cross-section. Since the circular cross-section is a favorable shape in most industrial applications, the CSSE process has great potential in the industrial application.

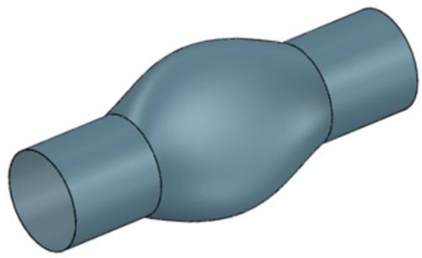
The main objective of this work is to process commercially pure aluminum by circular simple shear extrusion at room temperature and investigate the effects of back-pressure, processing routes and the different number of passes on the mechanical properties and deformation homogeneity of the samples. The evaluation of the crystallite size of the processed samples through CSSE had been done using the XRD analysis. Also, the optimized length of the deformation channel of this process was calculated using the finite element analysis.

2. Materials and Methods

2.1. Deformation Behavior during Circular Simple Shear Extrusion

As previously mentioned, the circular simple shear extrusion process is a new design for the simple shear extrusion method. It is based on direct extrusion, and the material deforms in a simple shear manner. The schematic view of the die and the sample's cross-section during deformation in the CSSE method is shown in Fig. 1.

In this method, the material undergoes simple shear, while its cross-sectional area remains constant. As can be seen in Fig. 1, the initial circular cross-section of the sample gradually deforms into an elliptical shape at the center of the deformation channel and then it will return to a circle with the initial dimensions. The distortion angle reaches its maximum value (α_{max}) at the middle of the



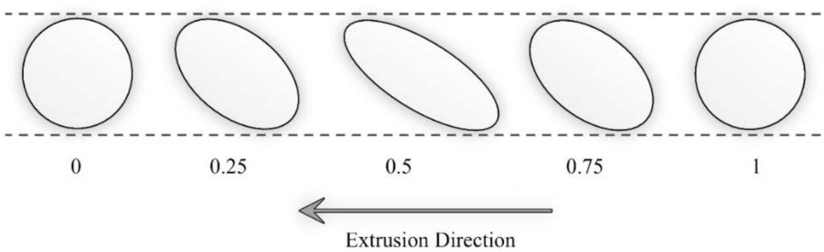


Fig. 1- (a) Schematic design of CSSE's deformation channel and (b) the geometry of the material's cross-section during deformation.

deformation channel and then gradually reduces to zero through the second half of the channel (Fig. 2). Therefore, after one pass of the process, a total shear strain of $\gamma = 2\tan(\alpha_{max})$ will be applied to the specimen.

The geometry of the deformation channel in the circular simple shear extrusion process requires a special design in order to fabricate the die used in the process. The design specifications of the deformation channel can be found in the previous work [12].

2.2. Experimental Procedures

Cylindrical specimens having a circular cross-section with a diameter of 10 mm and a length of 50 mm were machined out of commercially pure aluminum (AA1050). They were then annealed at a temperature of 450 °C for 2 hours and furnace cooled to room temperature, having a fully annealed homogeneous structure with an average grain size of 160 μm. In order to reduce friction, the specimens were wrapped in Teflon and oil before beginning the process. The process was carried out using a screw press of 20 tons and a speed of 0.2 millimeters per second, and the specimens of passes 1 to 10 were prepared in order to study their mechanical properties.

The Vickers microhardness test with a load of 25 g, the rate of 0.2 gs^{-1} and 15 s dwell time was used in order to measure the hardness on the cross-section of the samples and the central points of different lengths. Due to the small size of the samples processed by this method, it is very difficult to prepare specimens for the uniaxial tension test. Thus the uniaxial compression test was used to study the strength of the samples at different passes. The samples used in this test were 8 mm in height and 6 mm in diameter.

The CSSE process was performed without applying any back-pressure. But in order to investigate the effect of back-pressure on the properties of the samples, two cylindrical specimens with a diameter of 10 mm and a length of 30 mm were machined out of commercially pure copper and were placed in front of the aluminum sample in the die entrance. Since copper has more strength than aluminum, the presence of two copper samples in front of an aluminum one provides enough amount of back-pressure needed to fill the die completely. The double compression test [14] was also used to estimate the mean strain value after the first pass of the process. Although this test was originally presented as a method to evaluate the material's strain hardening exponent, it can also be used to measure the amount of pre-strain in the sample processed by CSSE.

X-ray diffraction analysis was carried out to calculate the average crystallite size of the samples according to the modified Williamson-Hall method using dislocation contrast factor. In order to model the diffraction peak profiles in the presence of the strain anisotropy, the average dislocation contrast factor, was calculated for the studied material according to the Ungar procedure [15]. The specimens used in this method were 4 mm in thickness from different passes plus the annealed sample and the sample with a back-pressure. In order to make a better comparison,

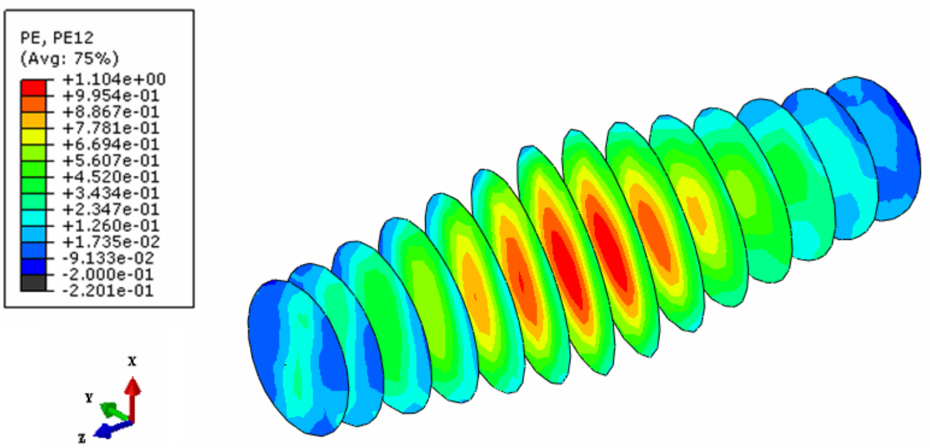


Fig. 2- Shear strain distribution in the sample's cross-section throughout the deformation channel.

all of the samples were cut of the same section perpendicular to the extrusion direction. The XRD operation was performed with a scan rate of 0.05 degree per second and the angle 2θ was considered between 30 to 105 degrees using Cu Kα beam.

2.3. Finite Element Analysis

The 3D simulations were carried out using commercial finite element code ABAQUS/Explicit to investigate the deformation behavior of the material in this process. The die and punch were assumed as discrete rigid bodies, and the sample was chosen to be a deformable aluminum alloy with the stress-strain relation of $\sigma = 106\varepsilon^{0.347}$ MPa which was experimentally obtained from performing the uniaxial compression test on the annealed sample with a height of 15 mm and diameter of 10 mm. The ram speed and the dimensions of the samples, the die and the punch were considered according to the experimental setup. The friction factor at the interface between the surface of the die and samples was determined as m = 0.1 using barrel compression test [16, 17], which was converted to a friction coefficient of $\mu = 0.047$ [18] to be applied in the simulations. In order to mesh the parts, 8-node linear triangular prism elements (C3D8R) [19] were used to mesh the specimens, and 4-node bilinear rigid quadrilateral elements (R3D4) [19] were used for the die and the punch.

In order to optimize the length of the deformation channel in CSSE process, dies with different lengths of deformation channel, from 16 to 30 mm have been designed and used in the simulations carried by commercial finite element software DEFORM-3D V.11 [20]. The reason for using this software was its ease of use and faster analysis runtime in comparison to most FEM programs such as ABAQUS. Therefore, 3D simulations of systems with different deformation lengths were conducted by DEFORM-3D. The workpiece has meshed into 31000 elements and the dies and the punch were modeled as rigid surfaces in this analysis.

3. Results and Discussion

By considering the same boundary conditions such as friction, the modified length can be measured by comparing the required processing loads obtained from the results of the simulations of dies with different lengths. As can be seen in Fig. 3, the die with the deformation length of 26 mm needs the least required force at steady state stage; therefore, it is the best choice for CSSE process. Due to the less frictional surfaces in the CSSE's die, this length is a little higher than the 24.5 mm which was calculated for the SSE process.

Fig. 4 shows the image of the sample's cross-section before and after the process with and without back-pressure. As can be seen, without having an adequate amount of back-pressure, the sample's cross-section did not fully return to its initial shape and did not completely fill the outlet section of the deformation channel. Actually, without the backpressure, the material prefers to flow to the front instead of filling the die. Because the sample front is a free surface that the material can easily flow to that side. Therefore, the length of the samples after the process will increase by about 15%, while in the sample with back-pressure the cross-section is completely restored to its initial state with a small increase (below 5%) in the total length

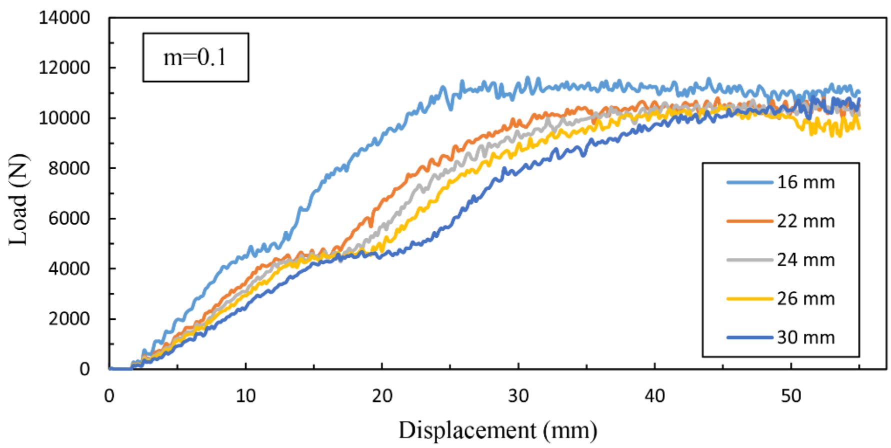


Fig. 3- The load-displacement curve obtained from simulations of the CSSE process with different deformation channel lengths.

of the samples. The need for an adequate amount of back-pressure is also reported in other methods of severe plastic deformation, including the simple shear extrusion (SSE) and twist extrusion (TE) [8].

The effect of applying different amounts of back-pressure on the shape of the back-end cross-section of the samples at the outlet section of the deformation channel is shown in Fig. 5. As shown, by applying a back-pressure of 100 MPa, the sample completely returns to its initial dimensions, which, as previously reported, [13], CSSE needs lower back-pressure to completely fill the die in comparison to SSE (150 MPa).

Four different processing routes (A-D) have been proposed [21] for SSE technique which can also be used in CSSE process. Each of these routes results in different strain paths which would affect the structural homogeneity, mechanical properties, texture, and the microstructure of the materials processed by this method. It has been reported that routes C and D, due to a 90° rotation of the sample about its main axis, result in a more homogeneous strain distribution than routes A and B. By considering the material flow in the simulation results, route D is practically the best option for CSSE process without applying back-pressure. Because, this route has the advantages of route C and a 180° rotation of the sample about an axis normal to the extrusion direction between each consecutive pass which provides a uniform strain distribution in the cross-section and throughout the length of the specimens in the absence of back-pressure.

In Fig. 6, the distribution of the equivalent strain (PEEQ) on the sample's cross-section in the outlet of the die along the dashed line is shown for two systems: with and without back-pressure. As shown, the greatest amount of strain is located at

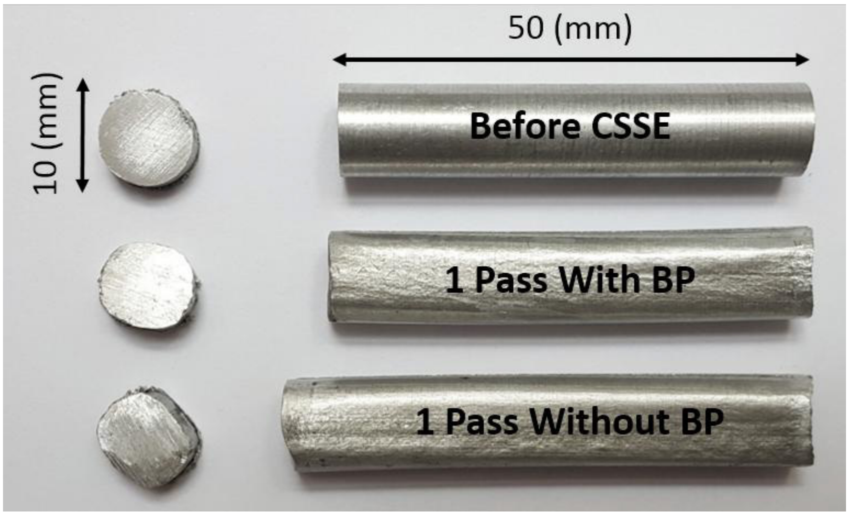


Fig. 4- Cross-section of samples with and without back-pressure plus the annealed one.

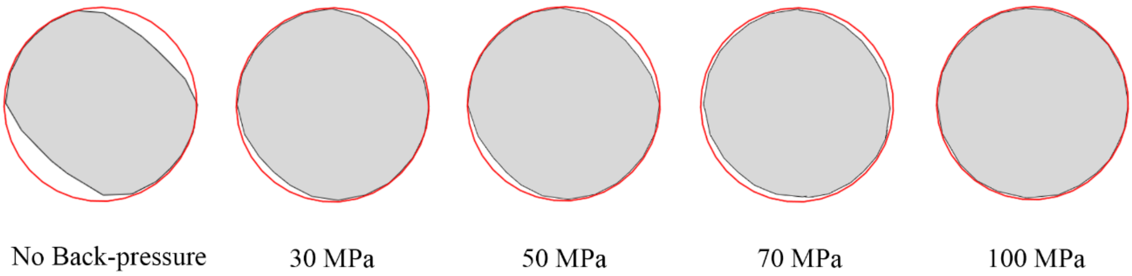


Fig. 5- Effect of different amounts of back-pressure at the sample's cross-section obtained by FEM.

the center of the cross-section of the specimens and it decreases while approaching the edges. It should be noted that as the amount of back-pressure increases, the strain value and its homogeneity also increase.

Fig. 7 illustrates a sectioned view of the equivalent strain distribution in the sample's cross-section after the process. As can be seen, the sample with 100 MPa of back-pressure has a higher value of strain with more homogeneity, and it has completely returned to its initial dimensions in comparison to the sample with no back-pressure. Fig. 8 shows the distribution of the equivalent strain (PEEQ) at the center of the cross-section throughout the sample's length after one pass of deformation. Due to the absence of back-pressure, the strain value in the second half of the specimen is less than what was expected. The higher value of the equivalent strain at the second half of the samples can be due to the existence of the first half which creates some amounts of back-pressure for the rest of the sample. Besides, the smaller diameter

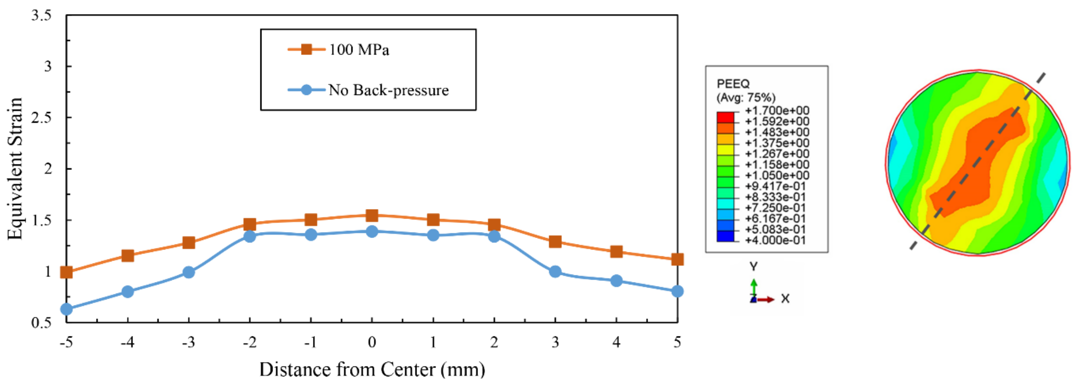


Fig. 6- the distribution of the equivalent strain (PEEQ) on the cross-section of the sample after CSSE.

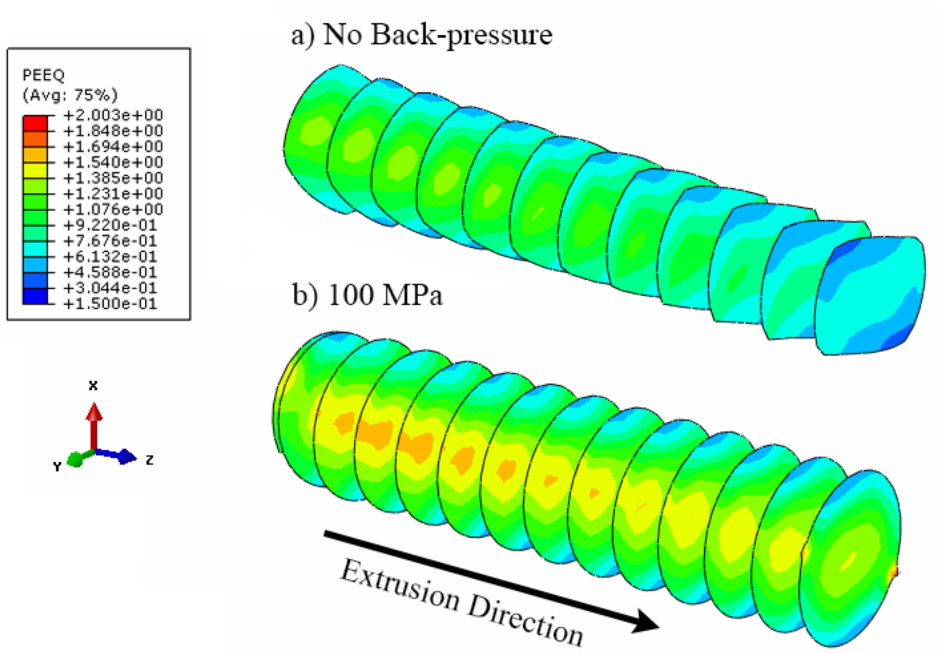


Fig. 7- Sectioned view of equivalent strain in processed samples with a) 0 MPa and b) 100 MPa of back-pressure.

of the outlet of the deformation channel and the deformed sample in the outlet channel of the die will increase the amount of the back-pressure.

By knowing the material work hardening exponent (n = 0.347) and performing the double compression test [14], the mean strain value in the first pass samples with and without back-pressure was measured experimentally. As expected, the mean value of the strain in the sample with the back-pressure (ε_{avg}^{exp} = 0.93) is higher than that of the sample with no back-pressure (ε_{avg}^{exp} = 0.84). The mean value of the strain has also been calculated from the simulation results which are (ε_{avg}^{sim} = 0.91) in the no back-pressure system and (ε_{avg}^{sim} = 0.99) in the sample with 100 MPa back-pressure.

Fig. 9 shows the distribution of Vickers microhardness on the sample's cross-section along the dashed line shown in Fig. 6. The test was performed on the samples after being processed by one pass of CSSE with and without back-pressure plus the sample at the annealed state.

As shown in Fig. 9, by performing one pass of CSSE, the average hardness value of Hv 30 (the annealed state) reaches about 51 Hv, as expected. The results of the hardness distribution are in agreement with the strain distribution predicted

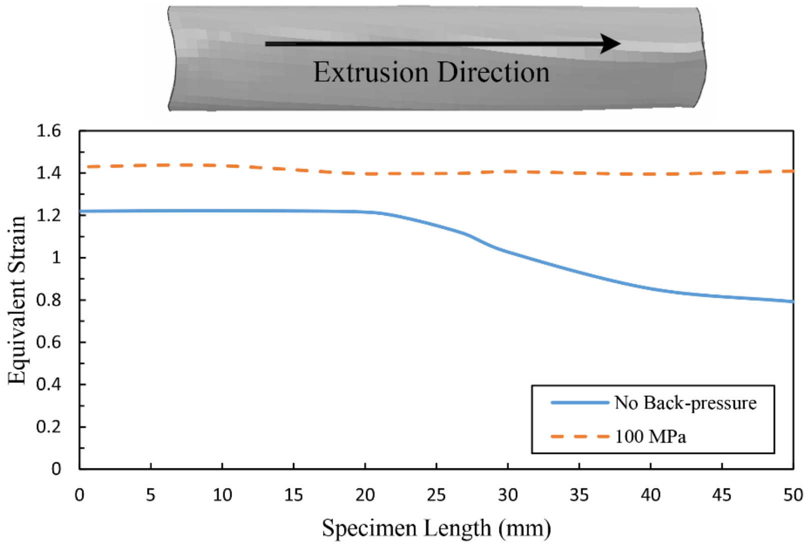


Fig. 8- The equivalent strain (PEEQ) distribution curve throughout the sample's length after the process.

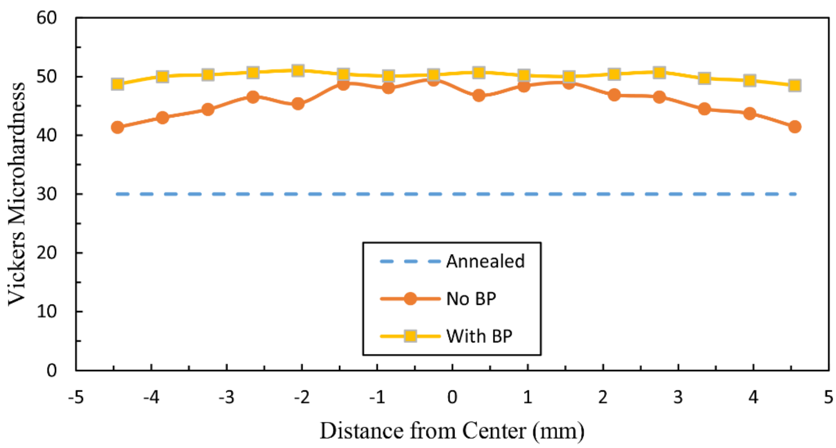


Fig. 9- Hardness distribution on the cross-section of the annealed sample and samples after one pass of CSSE with and without back-pressure.

by the simulation, which is symmetrical with the highest value in the center of the cross-section. In addition, the hardness values and its distribution over the cross-section, are comparable with those reported for other SPD processes like ECAP [22] and HPT [23].

The hardness distribution on the cross-section of the samples processed with a different number of passes of CSSE is plotted in Fig. 10. Due to the 90° rotation of the samples about the extrusion axis in route D, the hardness distribution is more homogeneous and uniform at the cross-section in comparison with those of the 1 pass samples. Moreover, after 9-passes of the process, the hardness values decrease slightly. Such behavior has also been reported in other methods of severe plastic deformation [24].

Figs. 11 and 12 show the distribution of Vickers microhardness throughout the length of samples processed with and without back-pressure and samples with a different number of passes of CSSE. By comparing the results of Figs. 10 and 12, it can be concluded that route D has the most homogeneous distribution of hardness on the cross-section and throughout the samples in this process, which makes it the best choice in the systems without back-pressure. However, it is expected that by applying the adequate amount of back-pressure the routes C and D have the same distribution of hardness in the samples.

By performing a uniaxial compression test on the processed samples, it is observed that after

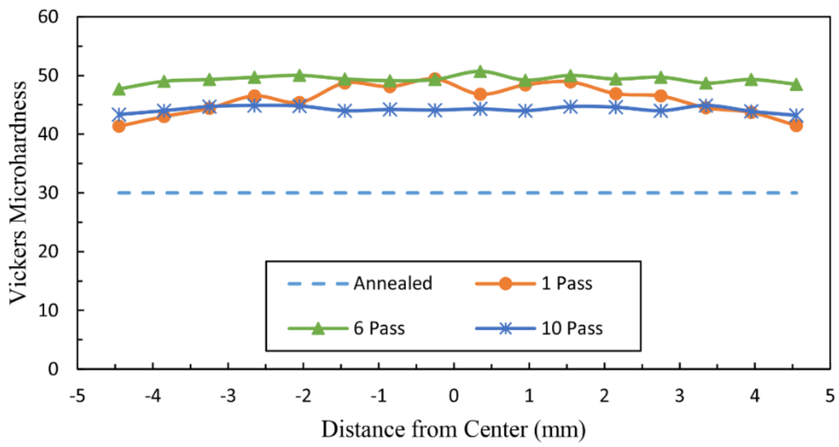


Fig. 10- Hardness distribution on the cross-section of samples with different passes of route D.

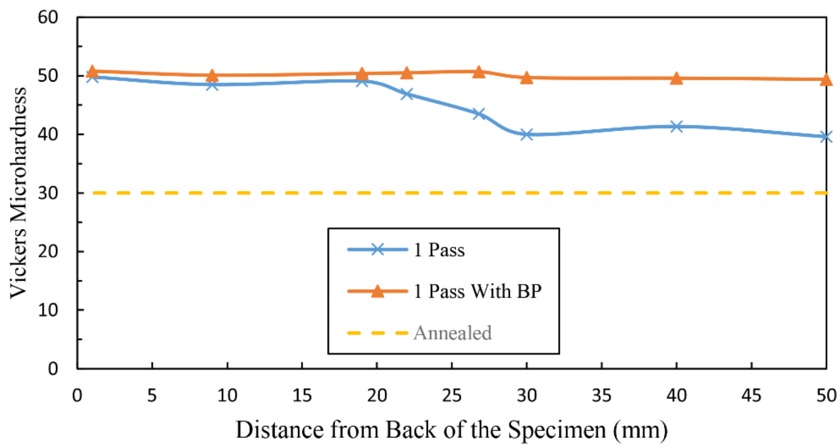


Fig. 11- Distribution of hardness in the length of the specimens with and without back-pressure.

performing even one pass of the CSSE process, the strength of the samples increases compared to the annealing state. However, by performing more passes of CSSE, no particular increase in the strength of the samples is observed. Saturation of dislocation in the higher numbers of CSSE passes is the main reason for the decline in work-hardening rate process that can be observed after four passes of CSSE. Generally, in severe plastic deformation processes, the work hardening rate of the processed samples is low due to the saturation of dislocation density. In order to investigate the rate of the work hardening of the samples after the process, the compression test was performed on the first pass with and without back-pressure and its results were compared with those of the annealed state. In Fig. 13, the true stress vs the true strain curve of these three samples is plotted. As shown, the samples do not work-harden significantly and behave like ideally plastic material.

Fig.14 represents the X-ray diffraction (XRD) patterns of the 10^{th} passed processed sample and the annealed one. As can be seen, the intensity of planes {111} and {220} are significantly increased after the CSSE process in comparison to the annealed sample. On the contrary, the intensity of the {200} planes decreased. This indicates that the shear deformation in the samples, causing a change in their texture after being processed with CSSE.

The modified Williamson-Hall method using the average contrast factor of dislocations are adequate for modeling the X-ray peak profiles in the presence of strain anisotropy [15]. The average size of the crystallite cells was calculated using the integral breaths of diffraction peaks of the samples processed with different passes of CSSE. In Fig.

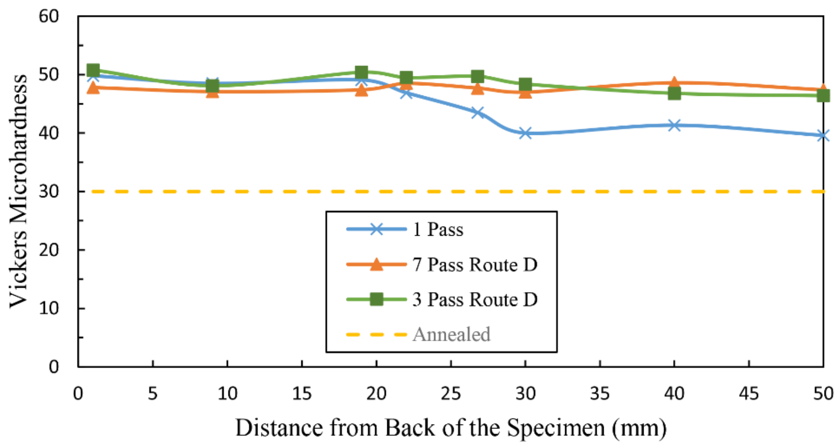


Fig. 12- Distribution of hardness in the length of the specimens at different passes.

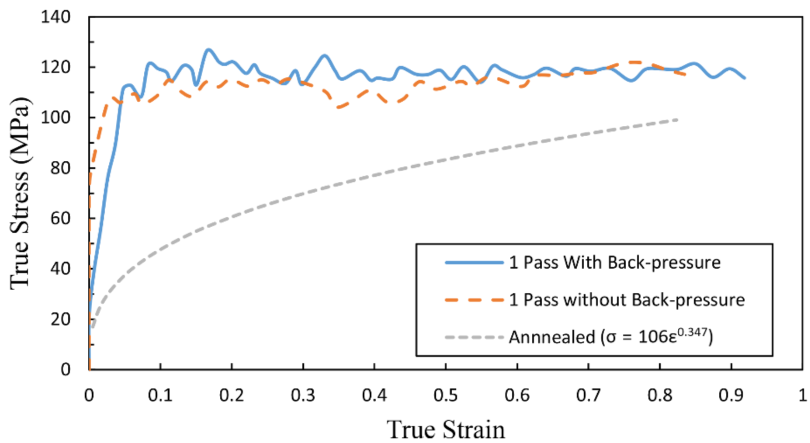


Fig. 13- True Stress Vs True Strain curve of the samples with and without back-pressure.

15, the graph shows the average crystallite cell size versus the number of passes. As it was fairly documented before [25], by imposing strain to the specimens, a high number of dislocations are generated and distributed throughout the grain. These dislocations will then rearrange themselves into dislocation cells. During deformation, more dislocations are generated and the number of dislocation cells increases, which forces them to get smaller, developing misorientation and forming subgrains. Therefore, the crystallite size decreases drastically in the first three passes of the CSSE. By applying more passes of this process, additional deformation causes an increase in the sub-grain misorientation angle rather than decreasing the crystallite size. Thus, after four passes, the decreasing rate of the crystallite size reduces, which can be seen in Fig. 15. In this way, the new grains form as a result of the increase in the misorientation of the sub-grains and transformation of low angle grain boundaries (LAGBs) to high angle grain boundaries (HAGBs) at sufficiently large strains. It is also observed that the initial microstructure, with an increasing number of passes, gradually reaches a size below the micrometer.

4. Conclusions

In this research, the mechanical properties of

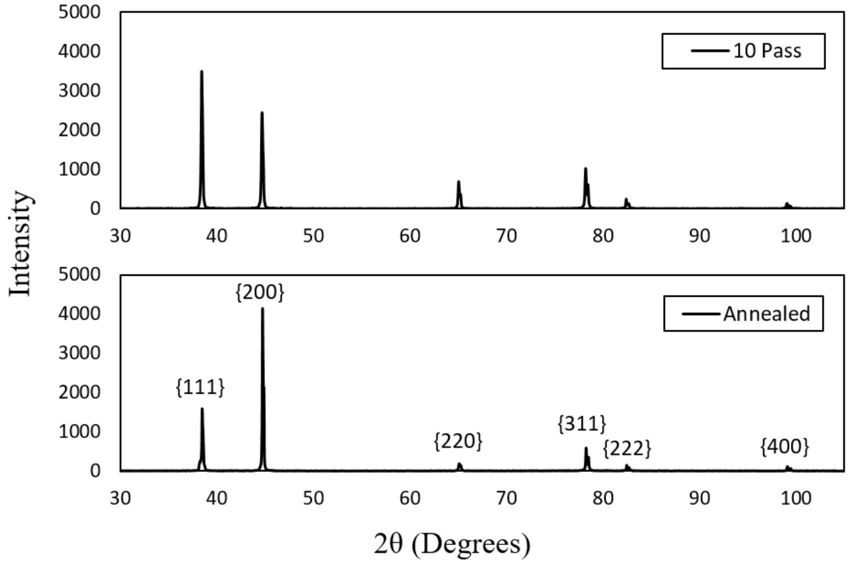


Fig. 14- XRD patterns of the 10th pass processed and annealed samples.

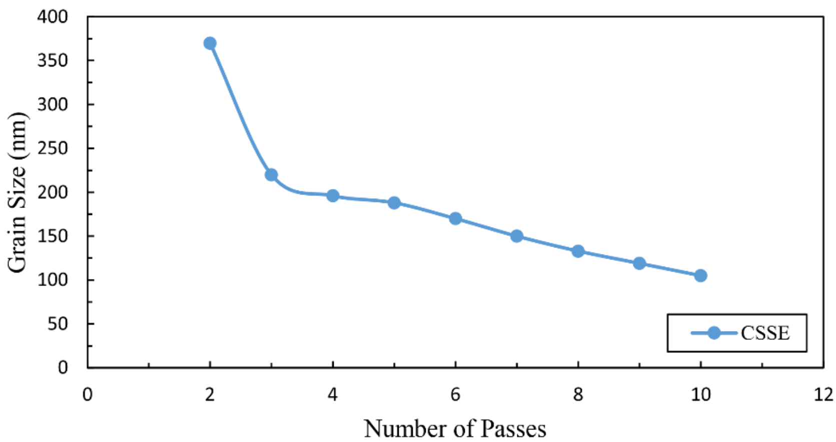


Fig. 15- Crystallite Size Vs Different Number of passes of the CSSE process.

the commercially pure aluminum (AA1050) after the circular simple shear extrusion process were investigated experimentally and the process was simulated by finite element method. The hardness distribution, the compression test, and XRD analysis have been carried out on the specimens processed by CSSE with different passes and different routes. The results are summarized as follows:

1. By observing the distribution of strain in the cross-sectional area and throughout the length of the samples, it was determined that among the four different routes, the route D, practically, produces the most homogeneous distribution of the strain and hardness in the cross-section and throughout the length of the samples.

2. Average strain with and without back-pressure was calculated by finite element method, ε_{avg}^{sim} =0.99 and ε_{avg}^{sim} =0.91 respectively, which are in good agreement with of the ones measured experimentally by double compression test, ε_{avg}^{exp} = 0.93 and ε_{avg}^{exp} = 0.84 respectively.

3. Results of X-ray diffraction analysis indicates that with increasing the number of passes in the CSSE process the crystallite size reduces. Therefore, after performing 10 passes of the process, the size of the crystallite cell decreases to about 103 nm.

Acknowledgments

The authors appreciate Shiraz University for financial support (grant number 96-GR-ENG-15) and research facilities used in this work.

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