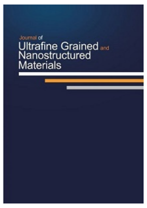

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Experimental and Finite Element Analyses of the Hydrostatic Cyclic Expansion Extrusion (HCEE) Process with Back-Pressure

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ABSTRACT

It is generally known that severe plastic deformation processes with back pressure not only apply higher hydrostatic stress and more deformation compared to what a regular process can apply to a workpiece but also prevent surface defects in the workpiece during the process. Hydrostatic cyclic expansion extrusion (HCEE) was developed recently for processing long ultrafine-grained metals and alloys. This process applies relatively higher hydrostatic pressure and prevents the formation of defects at the same time dramatically decreases the processing load by eliminating the friction. However, increasing the compressive hydrostatic pressure leads to enhance the mechanical properties by minimizing the initiation and propagation of defects. So, back pressure may be considered as a solution. In this paper, first, morphological investigation of HCEE processed aluminum without back pressure is conducted. Second, the plastic deformation behavior of the aluminum sample during this recently introduced process for producing longer samples with different external back pressures is investigated using the finite element method. The homogeneity within the workpiece was analyzed in terms of contours, path plot, and statistics of strain distribution under different conditions regarding back pressure. The simulation results shed some lights on the optimum design of HCEE for homogeneous and large severe plastic deformation.

Keywords: *Severe plastic deformation, Hydrostatic Cyclic Expansion-Extrusion, Finite element, Grain refinement.*

1. Introduction

Researcher's attempts have continued to reach Nano-grained (NG) and ultrafine-grained (UFG) materials in industrial scale. Severe plastic deformation (SPD) is one of the methods which approximate scientists to reach this purpose. The most common SPD techniques for processing bulk materials are equal channel angular pressing (ECAP) [1, 2], cyclic extrusion compression (CEC) [3], accumulative roll bonding (ARB) [4, 5], and high-pressure torsion (HPT) [6, 7]. However, in those processes, by increasing the length of the workpiece, friction force increases sharply; while the deformation part of the total force is constant, so the total force increases dramatically. Thus, the punch deforms, yields or buckles under high forces; so, the process cannot be completed. ECAP-confirm [8], reciprocating extrusion [9], incremental high-pressure torsion (SIHPT) [6] hydrostatic tubular cyclic expansion extrusion (HTCEE) [10] have been devised to produce long length UFG materials. HCEE process has more advantage than other similar processes including applying more strain rate, decreasing the heat of deformation zone and preventing dynamic recovery, applying more internal hydrostatic pressure and so on.

Also, hydrostatic extrusion (HE) [11, 12] has the same benefits, but due to a reduction in the size of diameter, this process is confined to apply large strain. So, HCEE process takes advantage of continuing processes and hydrostatics pressure. Unlike the great advantage of HCEE process, this method applies non-uniform strain which causes to produce non-uniform properties.

Back-pressure (BP) system has main role in CEC [13] and ECAP [14] to apply more uniform strain distribution. The higher hydrostatic pressure may cause a significant difference in defect storage, and this could be critical for some highly non-equilibrium ultra-fine grained materials. For the improvement of the ECAP and CEC process, back pressure was introduced to the exit channel of a die which helps to obtain a uniform strain distribution inside of the workpiece and to prevent defect formation on the surface of the workpiece. In the SPD community, back pressure is regarded as the remedy to prevent defects during SPD processes and to achieve uniform plastic deformation. However, despite that most of the experimental research posed successful results, only a handful of numerical approaches have been carried out for the processing and flow behavior of the materials in the process with back pressure [14-16].

CEE is invented to simplify the CEC process by eliminating the back pressure system. The inventors of CEE claimed that this process has the internal pressure and eliminate the needs of back pressure system in CEC. However, the investigations showed that conventional CEE and HCEE processes did not reach suitable strain uniformity. So, external back pressure can be a positive factor to reach better properties.

The present study aims to develop HCEE process by applying back pressure system for producing long length UFG material with uniform properties. In this paper, finite element analysis (FEA) was carried out to investigate the effects of back pressure on the strain distribution of HCEE process.

2. Principles of BP-HCEE

A schematic of HCEE process with back pressure system is shown in Fig. 1. The main difference between HCEE with back pressure system and prevalent HCEE process is on using of back pressure system at the end of the exit channel. As a result, the pressure load applies to the opposite direction of the sample's movement. As can be seen in Fig. 1a, like the HCEE process a hydraulic fluid, which is sealed by PTFE polymeric seal, fills the space between the initial billet and the primary pressure container. The sequences of HCEE process with back pressure are shown in Fig. 1. At first, the initial billet is located into the die, and then the hydraulic fluid is poured into the chamber of the die. Bottom punch is immobile and causes the billet to fill the deformation zone. In the second stage, the initial billet is forced to move down by the pressurized fluid to reach the bottom of the punch. The billet will be expanded to fill the die cavity. In the third stage, the bottom punch is detached, and the fluid filled into the exit channel and sealant is lied. Back pressure system has to be applied behind of the sealant and control the pressure. After continuing the upper punch movement, the first pass is completed after transferring the billet through the chamber. To perform the other passes, the die rotates 180°, and the process is repeated the same as before. This technique can be done to achieve a required number of passes without getting out the sample from the die.

3. Experimental and FEM procedures

In this study aluminum alloy 1050 was investigated. The diameter of the samples is 10 mm with the length of 100 mm. They were annealed at the temperature of 350 ºC for 2 hours and cooled in the furnace [17]. The die and its components were manufactured from hot worked tool steel and hardened to 55 HRC. Geometric die parameters are D = 14 mm, d = 10 mm, , L = 1 mm, r = 3 mm and α = 60° as shown in Fig.1. The process was conducted using a hydraulic press at a ram speed of about 5 mm/min. Microstructure of the HCEE-processed rod was investigated using electron back-scattered diffraction (EBSD) and optical microscopy (OM). The outer portion of surfaces of the HCEE-processed samples were polished to obtain mirror-like surfaces for accurate EBSD measurements. After polishing using silicon carbide papers (sandpapers) of 180, 400, 600, 800, and 1200 grits in order, 3 and 1 μm alcohol-based diamond suspensions and 0.04 μm colloidal silica suspension were used to produce the mirror-like surfaces. In addition, a field emission gun scanning electron microscope (JEOL 7100F FEGSEM) equipped with an EBSD camera (EDAX TSL) was operated at 20 kV and ~ 26 nA is used for EBSD data collection.

Finite element simulations were carried out using commercial software Abaqus\Explicit to investigate deformation behavior of material during HCEE. Regarding the symmetry of the process, the analysis was conducted in the form of axisymmetric 2D [18]. Geometric dimensions and mechanical properties were selected according to the die parts and specimen and the same as experimental conditions. The specimen and die parts were selected as deformable and rigid respectively. The billet material was modeled with 6012 nodes and linear quadrilateral elements of type CAX4R. Friction situations between die and sample are defined in two sections. In contact between die and fluid, simulation is considered frictionless, and where die and sample have contact, friction is considered 0.1. The criterion of strain homogeneity needs to be defined for effective evaluation. The strain in the area is tabulated according to the strain homogeneity index H which can be calculated as where is the effective strain, is the maximum effective strain, is the area populated by the effective strain and is the total investigated area.

$$H = \sum \left(\frac{\varepsilon_i}{\varepsilon_0} \frac{A_i}{A_o} \right) \quad \text{(eq. 1)}$$

4. Result and discussion

Although the CEE is invented to eliminate needs for back pressure, which is an inevitable factor during CEC, due to some problems occurred during CEE process, the presence of back pressure seems to be a positive factor. The first problem is the probability of existing empty regions during CEE due to incorrect choice of mold parameters. The second problem is that some regions of processed samples are faced with tensional stresses so that cracks can be easily made during the process. The third problem is the CEE's limitation for processing of brittle metals like magnesium. This paper aims to illustrate the effects of applying backpressure to the recently developed method of HCEE process by finite element method which can solve the problems above. The aluminum sample which is processed by HCEE in one pass without application of back pressure is illustrated in Fig. 2. As it is shown, by implementation of this method, longer and better samples can be easily produced compared to the conventional CEE. The maximum length/diameter (L/D) of the sample which can be processed via CEC or CEE is below 5 [19]; in the other hand, by using hydraulic fluid, L/D ratios of greater than 10 can be easily achieved. As it is shown in Fig. 2, the surface in the one pass processed side of the sample is better due to the frictionless characteristic of HCEE process. Using fluid pressure to produce samples, plays a major role in HCEE process. Also, it affects the method's load during the process and decreases it due to the existence of hydrostatic pressure and eliminating the friction effect [20].

The OM microstructure of the as-received aluminum with an average grain size of ~50 μm is illustrated in Fig. 3. Furthermore, the microstructure of the one pass processed sample

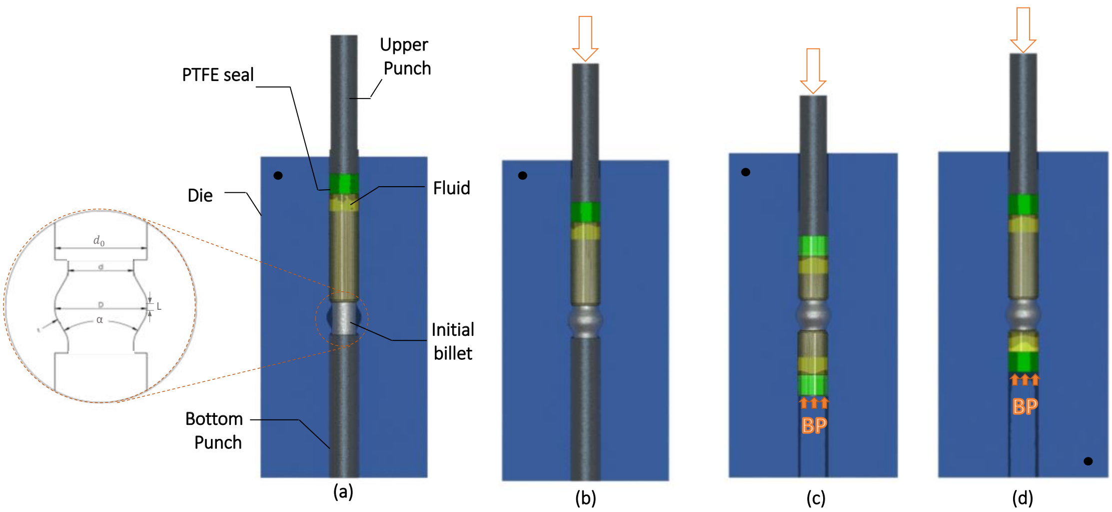

Fig. 1- Sequences of the BP-HCEE process (a) stage 1, (b) expansion stage, (c) first cycle HCEE processing, and (d) second cycle HCEE processing, (e) die parts.

is illustrated in the Euler EBSD micrograph of Fig. 4. As it is shown, sub-grains are formed, and the average size of the sub-grains decreases to an approximate grain size of 0.76 μm at the mid-radius of the cross-section. Also, grains with high angles are relatively formed. Large plastic deformation under hydrostatic compressive stresses causes severe reduction of grains and sub-grains sizes and change their orientation. At first, the geometrical shape of grains changed, and subsequently, grain subdivision appeared [21, 22]. As shown in EBSD micrograph of Fig. 4, variation in the grain sizes is detectable. One of the important factors which cause these variations is inhomogeneous applying of strain during the process [23]. On the other hand, one of the best ways to homogenize the strain values in different parts of samples during the CEE is applying the back pressure. Also, applying back pressure helps to process difficult-to-work metals and prevent crack generation and failure during the processes [24, 25]. So, metals can be deformed at lower temperatures without cracking, resulting in a finer grain structure.

Fig. 5 illustrates counters and path plot of equivalent plastic strain by inserting of different value of back pressure (0, 10, 30, 50, 100 MPa) during the HCEE process. It can be seen that longitudinal strain distribution does not have any variation. However, in the lateral direction, inhomogeneity is seen. The section of material with a very low strain in the front of the workpiece is due to that part of the material being outside the shear zone right from the beginning of the CEE process. As for the end portion, the material has very low strains because it has not applied complete CEE process on this portion of the workpiece. Therefore, it is recommended that a minimum length equaling the width or diameter of a workpiece should be discarded for both front and end regions to obtain a final workpiece with steady strain lengthwise. Also, the length of steady strain region in the longitudinal section can be increased with a longer workpiece, and the length of a workpiece should be preferable at least five times its width or diameter. Also, the presence of strain inhomogeneity in the lateral direction can be attributed to the flow path of the workpiece through the shear plane and friction. Since the workpiece is pressed, the process

Fig. 2- Aluminum sample during HCEE without back pressure from the unprocessed zone to the processed zone.

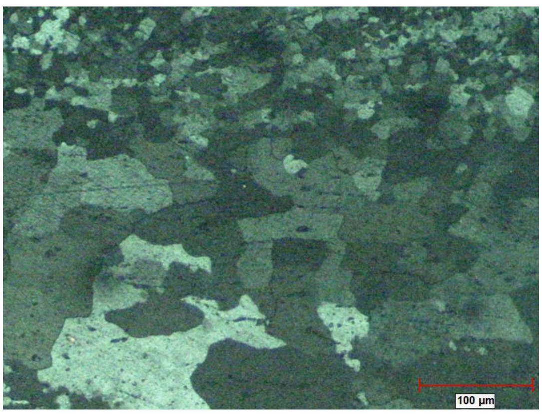

Fig. 3- OM micrograph of the as-received annealed Al 1050.

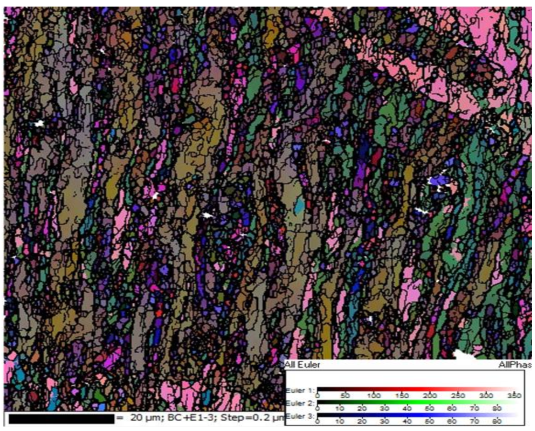

Fig. 4- EBSD micrograph of the one pass microstructure HCEE processed sample without back pressure.

dictates that the outer part of the workpiece closer to the die outer surface moves slower and travels a longer distance than the middle part of the workpiece. As a result, the lower strain found in the middle part of the workpiece is due to the lower velocity and the earlier exit of the material from the shear zone than the outer part [26]. According to Fig. 5-a, when the back pressure is zero, strain distribution along the lateral path (path A-B) is inhomogeneous. As it is shown, at this state, the value of strain at the middle of the sample is about 0.3; it reaches the value of 2 at the outer radius. By applying back pressure of 10 and 30 MPa, the homogeneity of strain distribution improves. In the state, in which 10 MPa back pressure is applied, in path A-B the value of strain at the middle is 1.7 and

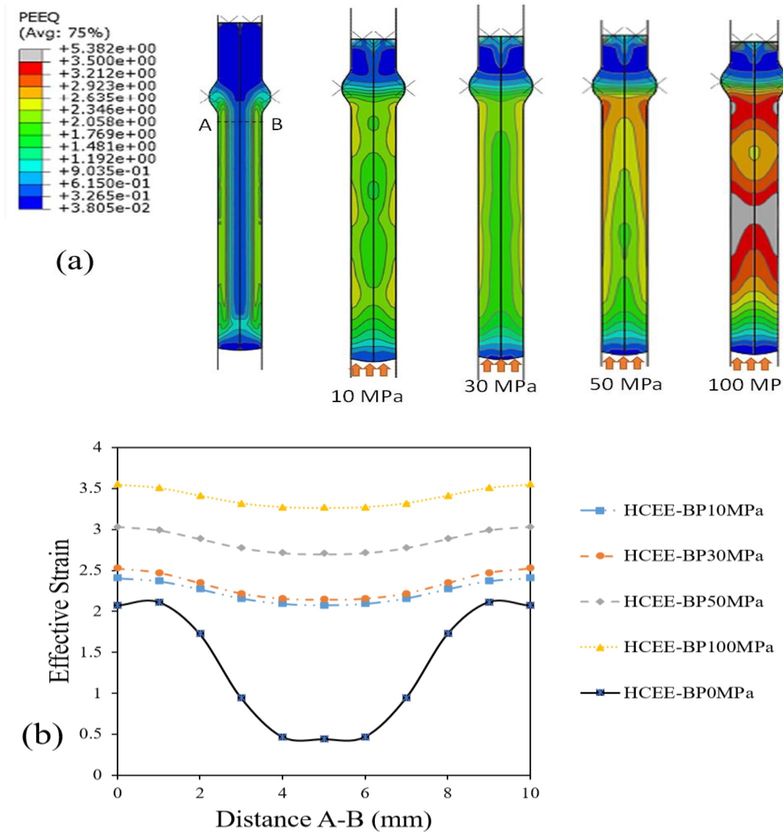

Fig. 5- (a) Strain Counters of HCEE with different back pressure values of 0, 10, 30, 50 and 100 MPa (b) Effective strain diagram in different back pressures in path A-B .

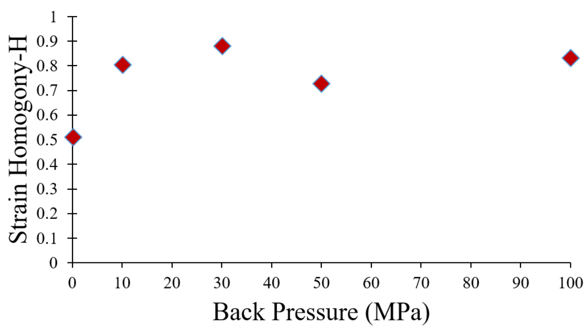

Fig. 6- Strain homogeneity index for different back pressures during HCEE.

in the outer part is 2.2. In the case of applying 30 MPa, the value at center and outer part are 2.3 and 2.6, respectively. So, it is illustrated that the strain distribution becomes more and more uniform. Also, by applying back pressure the values of strains which are inserted to the workpiece increases, which helps further in the generation of ultrafine grained samples. By insertion of 50 MPa back pressure, the values of strain along path A-B in the center and outer radius are 2 and 3, respectively. So the homogeneity of strain distribution decreases. It can be concluded that increasing of back pressure may improve the uniformity of strain to some extent and there may exist an optimum value for back pressure. For Further investigation of this issue, the homogeneity index of H, which consider all deforming areas by using the strain data in the longitudinal and transverse sections shown in Fig. 5-a, is introduced in equation 1. By implementing this equation and calculating the homogeneity index for various states, a diagram of Fig. 6 is achieved. This figure shows the homogeneity index for different back pressures during HCEE. As it is illustrated, for the back pressure value of 30 MPa, maximum homogeneity achieved which is about 90%. For the other states of back pressure, the homogeneity index is lower which further indicates and proves that there is the optimum value of back pressure for providing maximum strain uniformity. For the state, which there is no back pressure, the homogeneity index is only 50%. This shows that the HCEE without external back pressure is not very appropriate process and external back pressure must be inserted during the process to reach better strain homogeneity and grain size distribution and elevated properties. Also, the maximum force required for each state of processes is reported in Table. 1. Due to main reduction in friction forces during the process by using the hydraulic fluid, the max ranges of force for processing is between 3 and 6 tons in different back pressures. Also, applying back pressure increases the requiring force for the process.

5. Conclusion

The uniformity of plastic strain distribution in a workpiece after HCEE with a different value of external back pressure was studied using finite element software ABAQUS in 3D. Although, During the HCEE, the internal back pressure due to nature of the process is inserted, the presence of external back pressure helps to improve the characteristic of processed metals. The EBSD micrographs of Aluminum processed by HCEE showed that grain size during the HCEE is decreases dramatically and grain with high angles are generated. However, there is no good uniformity between the grain sizes which is mainly due to the inhomogeneity of strain distribution. The results of the simulation of HCEE process by back pressure shows that inserting external back pressure helps to reach a more uniform strain structure which is a more important factor for better grain size distribution. Also, inserting external back pressure helps to increase the value of strain in materials which also leads to smaller and better sub-grains. The calculation of strain homogeneity index shows that there is an optimum value for back pressure in reaching the more uniform strains and only increasing of back pressure is not the appropriate way. The homogeneity index in the state which there is no back pressure is only 50%. By applying

Table 1- Maximum force required for HCEE processing of Aluminum in different back pressures

Back pressure (MPa)	Max. force during HCEE (KN)
0	31
10	31.5
30	38.5
50	40
100	60

back pressure of 30 MPa, the strain homogeneity index of 90% is achieved.

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