IOP Conference Series: Materials Science and Engineering

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To cite this article: B Omranpour *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **194** 012047

Experimental and numerical analysis of HPTE on mechanical properties of materials and strain distribution

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Abstract. High Pressure Torsion Extrusion (HPTE) is a novel technique which has been recently introduced to the society of Nano-SPD researchers. HPTE exploits the deformation mechanics of HPT but in a larger scale using rod-shape samples and is capable of applying high values of strain to materials in one pass. This research aims to evaluate the effect of HPTE on mechanical properties of materials and also to study the effect of geometry of HPTE die on strain distribution in deformed samples by using Finite Element Method (FEM). Commercial pure Aluminium AA1050 was used for experimental work; and eccentric dies with parallel-misaligned channels were developed for evaluation by numerical modelling. Results of this research will help us better understand the effect of process parameters and also geometry of the die on materials.

Keywords: High Pressure Torsion Extrusion (HPTE); Die design; FEM; Eccentric dies

1. Introduction

Severe Plastic Deformations are very famous techniques in producing Ultra Fine-Grained materials (UFG) by imposing high strains on materials and subdividing original coarse grains into smaller subgrains. This reduction of grain size from micro-meters towards nanometers affects the mechanical properties of materials such as strength, hardness and ductility [1]. Basically in SPD processes, yield strength and hardness are improved, and ductility is reduced; although there are some reports about retaining ductility along with improving other mechanical properties [2].

High Pressure Torsion Extrusion, hereinafter called as HPTE, is a novel technique of Severe Plastic Deformation, introduced in 2015 [3] and has distinctive characteristics in deformation mechanism and properties. HPTE is composed of two separate upper and lower dies rotating relative to each other and a punch will extrude the sample through the die. HPTE approaches a combination of mechanisms of deformation including conventional High Pressure Torsion (HPT) [4] and Cyclic Expansion and Extrusion (CEE) [5] [6]. The major advantage of HPTE over HPT is the possibility of producing rod-shape samples, similar to ECAP; whereas in HPT, using a small disk with an average thickness of less than 1 mm restricts the applications to laboratory research [4] [7]. Plastic strain in this process is composed of torsion, expansion and extrusion (Figure1). Accumulated strain after one pass of HPTE can be calculated by the following equation:

$$\mathrm{E} = 2\ln\frac{\mathrm{D1}}{\mathrm{D0}} + 2\ln\frac{\mathrm{D1}}{\mathrm{D2}} + \frac{\omega\cdot \mathrm{R}\cdot \mathrm{D1}}{\sqrt{3}\cdot \mathrm{v}\cdot \mathrm{D2}} \qquad (1)$$

Where D0, D1, and D2 are diameters of inlet channel, deformation chamber and the outlet channel, respectively; ω is the rotational speed of the lower die, v is extruding speed and R is the desired distance from the center at the section of the sample. The first two terms of this equation correspond to expansion and extrusion, and the third term is referred to the plastic strain resulted by torsion [3].

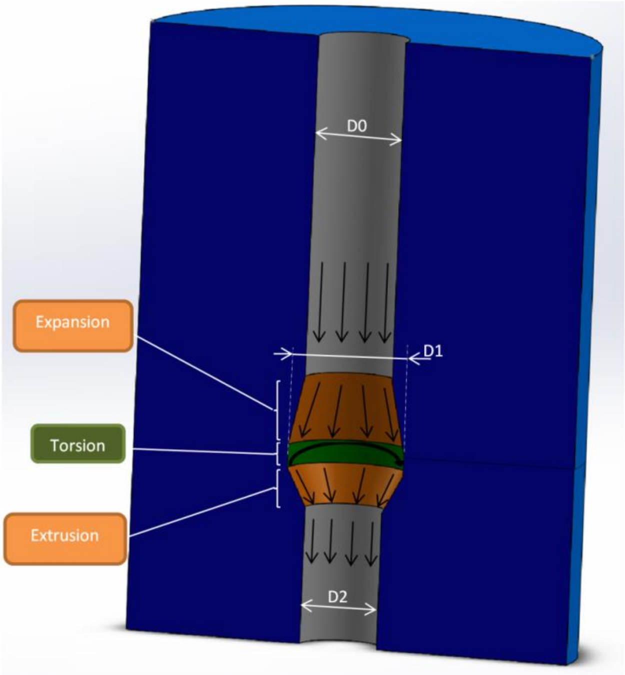


Figure 1. Schematic illustration of HPTE die

A key factor in HPTE die is concerned with the design of inner side of the die at the shear zone. Torsion at this zone is provided by rotating the lower die in order for twisting the workpiece and applying high amounts of shear strain to the specimen. Since the initial state of the material has a cylindrical shape, it is necessary to provide enough friction torque to prevent the materials from slippage. This issue is solved by using jutting surfaces inside the die. These jutting surfaces act as holding elements (resembling hexagon socket head cap screws) to constrain the material and apply torsion when the die is rotating (Figure 2.C).

This research in the first step tries to evaluate the effect of HPTE on mechanical properties of materials and in the second step, intends to propose a new design with eccentric channels using Finite Element Methods (FEM). Numerical modeling methods such as FEM are nowadays very common in metal forming processes either to study different aspects of a new technique or to optimize a process [8][9]. FEM as the most popular technique in numerical modeling is capable of assessing different parameters of a process including tool geometry, process conditions and materials properties [10]. The aim of simulation in this work is to devise a new design of HPTE die with eccentric channels towards manipulating strain distribution and adapting new properties in the materials. A theoretical concept of this idea firstly was introduced in an earlier work [3].

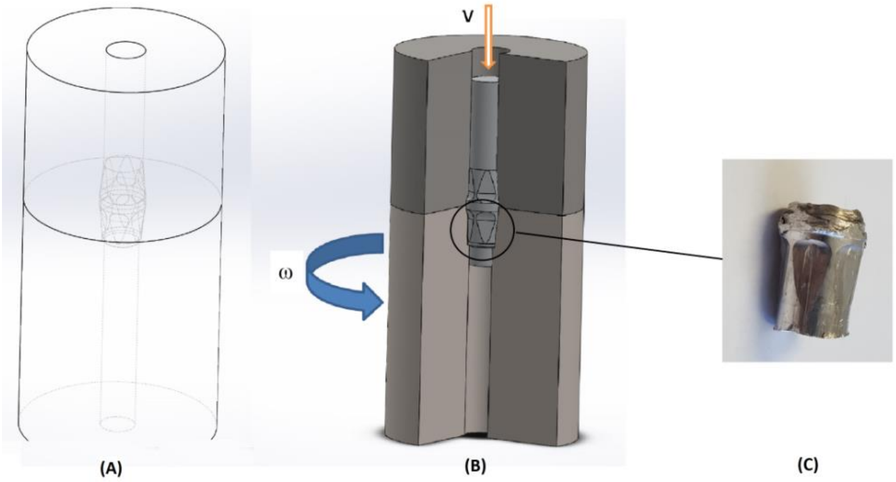


Figure 2. (A) Wireframe demonstration of HPTE die; (B) Process parameters of HPTE: Extruding speed, V and rotational speed, ω; (C) Small section of a workpiece extracted from the deformation zone of the die

2. Methodology

2.1. Experimental testing and evaluation

Processing of HPTE was performed on commercial pure Aluminium AA1050. Samples were prepared in the dimensions of 11.6 mm in diameter and 13.5mm in length. One specimen was considered as a reference and annealed at 350 ^{o}c for 30 minutes. Computer-controlled HPTE machine executed the process at room temperature with rotational speed of ω=1 rpm and extruding speed of V=7mm/min. Instant pressing force values together with extruding speed and rotational speed were monitored and recorded in real-time operating system to be used for validation of the simulations.

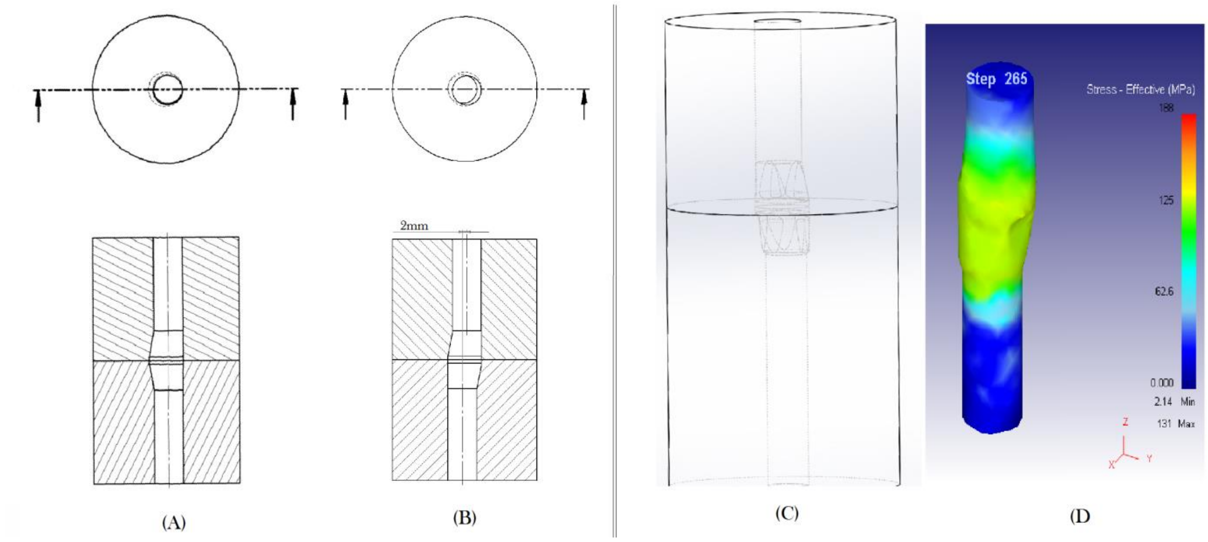
In order for mechanical testing of materials two testing methods of compression and hardness tests were conducted on the materials. A "SHIMADZU" universal testing machine performed the compression test on the samples with a compressive speed of 2 mm/min; Teflon sheet was used as a solid lubricant. Criterion of maximum length reduction of 66.67% (e=2/3) was established in the test. "Buehler Micromet-5104" tester applied micro-indentation at the cross section of the specimens on 11 points at regular intervals to measure Vickers hardness. Pressing load of 0.2 Kg.F with a dwell time of 15 seconds was conducted into all samples.

2.2. FEM simulations:

In this study, DEFORM-Ver.11 was implemented for simulation of the process. Assumptions of simulation rest on using the same extruding and rotational speed as in the experiments (ω=1 rpm, V=7mm/min), friction coefficient of 0.4, neglecting the deformation heating and considering the die as rigid body.

2.3. Scheme of the new design

First and foremost, an FEM simulation of the base die with the exact dimensions was carried out to verify the simulations; thereafter, a new design with eccentric channels was modeled. This new die includes two channels with the same diameters as the base die, but they are misaligned in parallel lines. Therefore there is an eccentricity between the upper and lower channels. At the beginning of the process, there is no eccentricity (Phi=0) (Figure 3.A) but after rotation, it gradually increases to the maximum value of 2mm when the lower die is rotated 180 degrees (Phi=180^{o}) (Figure 3.B).



(A) (B) (C) (D

Figure 3. HPTE die with eccentric channels: (A) At the beginning of the process, both upper and lower dies are perfectly aligned and there is no eccentricity; (B) Maximum eccentricity appears after 180° of rotation; (C) Wireframe illustration of HPTE die with eccentric channels; (D) Numerical modeling of the process

3. Results and discussion:

3.1. Mechanical testing

Following figures depict results of compression test and hardness test on the annealed and HPTE processed samples. Results of compression test are demonstrated in True stress-strain diagram in which yield strength of 44MPa as the initial case reached up to 141 MPa after processing.

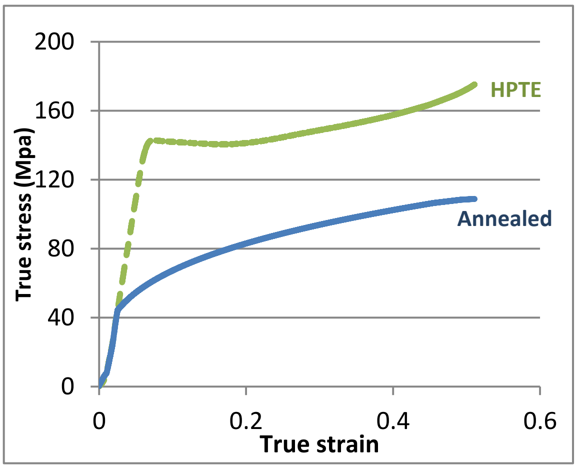


Figure 4. True stress-true strain diagram of HPTE processed and initial samples obtained by compression testing

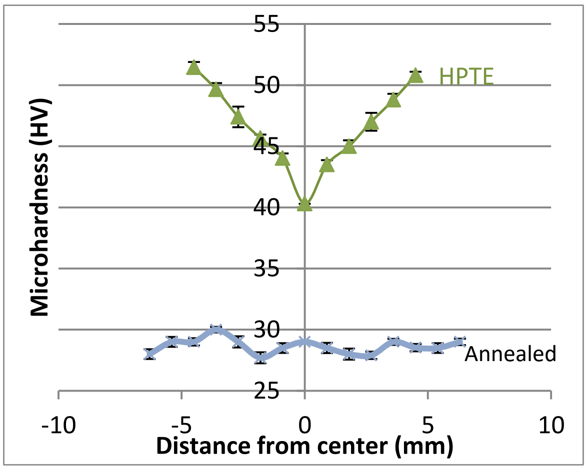


Figure 5. Results of Hardness testing

Results of hardness testing showed a sharp increase in hardness values after HPTE processing. One interesting point about this graph is that hardness distribution at the cross section of the samples is quite similar to that of HPT samples [11], that is to say lower values are located in the center and higher values are found near the periphery. The gradient of hardness varies from a minimum value of

40HV to the maximum value of 52 along the radius of the specimen, which implies a successful approach in improvement of mechanical properties of materials by means of HPTE.

3.2. Simulation results:

Simulated models were cut in the middle and then twenty nodes, evenly spaced apart, were selected from the cross section of the specimens.

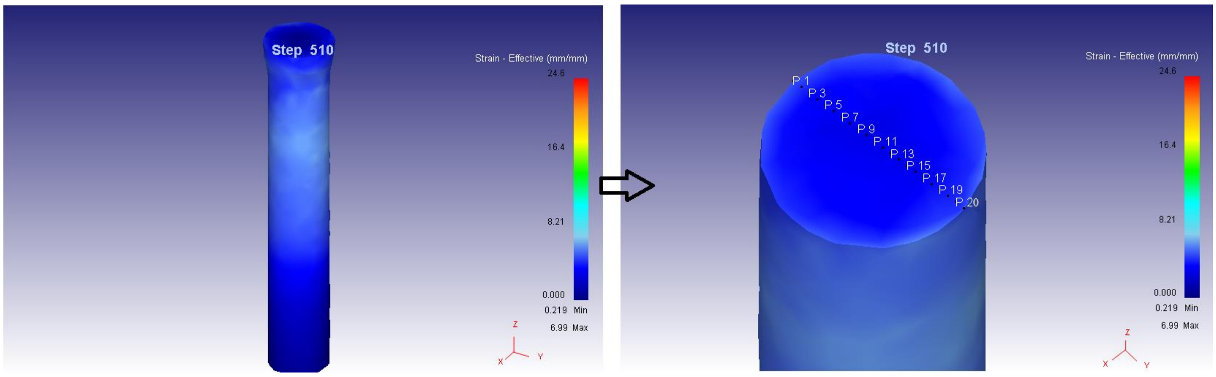
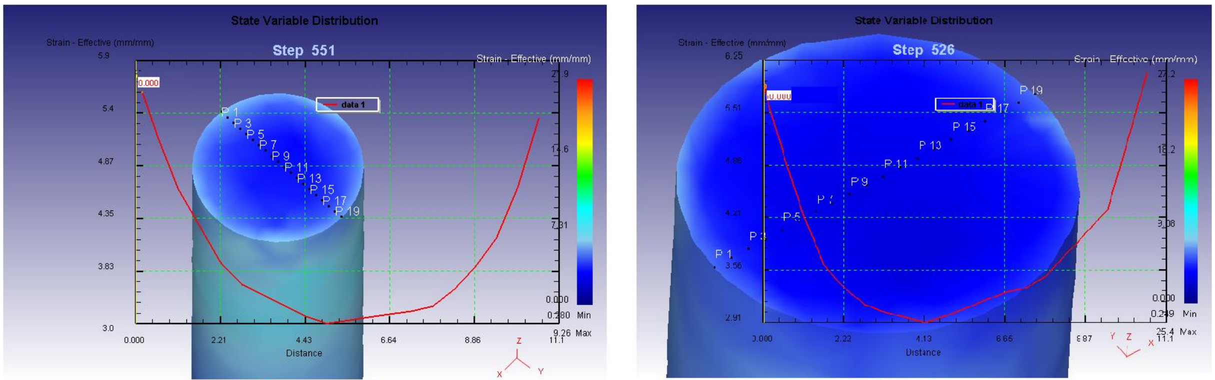


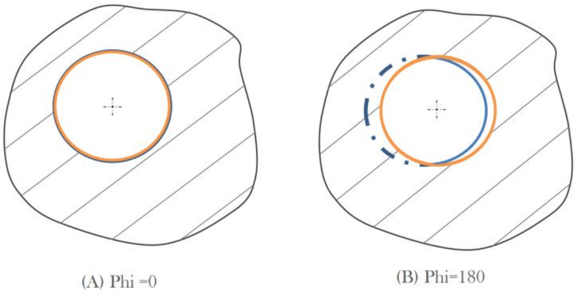
Figure 6. Selection of random nodes from the cross section of the models



(A) Base die (B) Eccentric die

Figure 7. Strain distribution diagrams within the specimens for the base die (A) and eccentric die (B)

Figure 7 shows distribution of effective strain applied to the materials after HPTE. In this figure, strain distribution varies from 3 to 5.5 in base die, while in the eccentric die this variation changes from 2.9 to 6.1. Based on the results, there is no big difference in the minimum level of strain in the central part of both samples. But maximum values of strain in those areas which are close to the periphery, slightly increased in the presence of eccentricity.



Firure 8. Cross section view of an eccentric die

(A) Both upper and lower channels are aligned; effective radius and nominal radius are equal.

(B) Eccentricity of two channels after rotation of the lower die at the phase of 180º; Effective radius in torsion is bigger that the nominal one

This phenomenon can be explained by considering the fact that strain in the central area of the specimens is mainly resulted from expansion and extrusion; and eccentricity does not really affect the strain at this area. On the other hand, at the outer parts of the specimen, when eccentricity reaches to its maximum value, effective radius at the deformation zone will be increased; and consequently strain which is caused by torsion will rise in value (Figure 8).

4. Conclusion

A new SPD process was evaluated and analyzed using Aluminium specimens. Mechanical properties of materials by two different methods of hardness testing and compression testing were studied. Moreover, some modifications in die design were proposed by implementing FEM. Based on the experimental results, after one pass of HPTE hardness values increased by 79% from an initial state of 29 HV to the final state of 52HV near the edge of the samples; and yield strength in compression test improved by 220% from an initial value of 44MPa to 141MPa.

According to the simulation results, the new die with eccentric channels showed a gradual increase in the level of strain near the periphery of the sectioned samples.

5. Acknowledgment

This project was sponsored in part by *Deutscher Akademischer Austauschdienst* (DAAD)- Germany and in part by *National Council of Science and Technology* (CONACYT)- Mexico. Technical and scientific support for running the compression test at CIDET-UANL is greatly appreciated.

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