Investigation of simple shear extrusion steel mold and mechanical properties of nanostructured extruded samples of Al6061

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Abstract

The extrusion is used to produce samples with irregular cross-sections. In this process, the material is pressed along a straight extrusion channel using a special design. Simple shear extrusion steel mold was designed by Catia software. AISI 4140 and AISI D3 steel were used to make this mold and mandrel, respectively. The material of the mold and mandrel was selected based on the mechanical properties of steels and their application in industry. It is a new Sever Plastic Deformation (SPD) process to produce nanostructured material which is used to produce high strength material. The specimen dimensions remain unchanged. Results revealed that Simple Shear Extrusion (SSE) is superior compared to equal channel angular pressing (ECAP) in term of scrap material. They also concluded that strain and pressure distribution is more symmetric in specimen cross-section, in this method, which is an important advantage of SSE compared to other SPD processes. In this study, first, a SSE mold with specified form and dimensions, was fabricated. The cross-section of samples was square and the material was Al6061. After processing, the microstructure and mechanical properties of specimens, which were processed using different pass numbers, were investigated using tensile and impact tests, hardness evaluation, metallography. The results presented an improvement in the mechanical properties and microstructure. Due to finer grains, ductility of specimens was also improved in addition to an improvement in strength.

Keywords: AISI 4140 steel mold; AISI D3 steel mandrel; Sever plastic deformation; Simple shear extrusion process; Microstructure; Mechanical property.

1. Introduction

In recent years, investigation on manufacturing processes and mechanical properties of nanostructured materials was the subject of many researches, in the field of material science and engineering.

Sever Plastic Deformation (SPD) methods are interested to produce nanostructured materials without any impurity and porosity. The principles of SPD processes are increasing density of dislocations, forming dense dislocation wall, and achieving a nanostructure [1)]. The specimen which are produced via server plastic deformation are very important; because they have non-porous structure, they have good mechanical properties including high strength and ductility, and their dimensions are suitable for mechanical testing. All SPD processes are developing rapidly. They are in a transition period from laboratory to industry, based on different needs in various industries. In last decade, a broad investigation has been down to develop these processes, is in order to produce nanostructured metals excellent. Recently, many novel processes have been invented including Equal

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Channel Angular Pressing (ECAP) and extrusion in orbital equal channel with elliptical cross-section, among others. In ECAP, the grain size is reduced to nanoscale and mechanical and wear properties are improved exerting share stress to a specimen [2]. ECSEE is a new method of exerting high strain on a bulk material to modify the grain size without significant change in dimensions. In this study, normal and shear plastic strains in normal and shear planes were investigated [3]. It is presented that the mean plastic strain distribution, in ECAP is more uniform compared to SSE and the normal plastic strain in ECAP is higher compared to SSE while the shear plastic strain is almost same for both processes; although the work value is lower for SSE. The SSE was introduced in 2009 by Pardis and Ebrahimi. They also achieved equivalent plastic strains and compared them with those which are achieved in ECAP process. Any investigation on SSE will reveal novel information because it is a new process [4]. In each process, additional operations such as heat treatment and coating may be required. Metal forming processes are those that the base metal in the form of around or rectangular sheet, billet, or shaft is deformed to a designed form using plastic deformation [1]. Pardis and Ebrahimi[5] reported that during processing of material by SSE, there are four different routes affecting shear strain. They found that rotation of sample in SSE has a significant influence on plastic strain and relevant microhardness. Bagherpour et al. [6] studied twinning induced plasticity of steel imposed by two different SPD techniques namely SSE and ECAP. They found that single pass of ECAP leads to the segmented flow as a result of flow localization. Nevertheless, SSE successfully process twinning induced plasticity without any segmentation. Tork et al.[7] applied SSE for processing of magnesium alloy. They applied an extrusion process prior to SSE and analyzed different extrusion temperature on final microstructure of the sample. Results show that increase in extrusion temperature causes a coarser microstructure due to grain growth at higher temperature. Also, they have shown that pre-extrusion process significantly affects the microstructure after SSE. Bagherour et al. [8] developed analytical approach based on upper-bound theorem to study the simple shear extrusion process. They introduced a new parameter namely inclination angle and studied its effect on extrusion pressure. Bagherpour et al. [9] applied SSE for processing of copper. TEM analysis shows that the microstructure evolves from lamellar boundaries and elongated cells towards a more equiaxed homogeneous microstructure. Transmission electron microscopy (TEM) observations show that the dislocation density increases by increase in pass number up to 8 passes. While by further increase in pass number, the dislocation density is reduced due to fragmentations of grains. Nowadays, metal forming is an important manufacturing method. Therefore, more investigation on it, makes it possible to produce a specimen with higher quality. Metal forming is the science that investigates principles of deformation of ductile solids exerting a force. The types of molds that are used in SPD methods have certain structures and dimensions, along with the analysis of mold material is of special importance. In the simple shear extrusion method, due to the applied force and strain, it has a balanced and uniform structure in comparison with other methods of severe plastic deformation. For this purpose, AISI 4140 steel, which has good abrasion resistance, has been used to make the mold. Also, to prevent deformation and destruction under the press load, AISI D3 steel is used, which has acceptable hardness and strength. In this study, production of fine grain Al6061 using SSE process, which is a new server plastic deformation process, was investigated. First, the mold was designed and fabricated and then Al6061 samples were extruded for one or several passes. Then, the tensile strength, and the grain size were investigated. Compared to other server plastic deformation processes, this method yields samples with high mechanical properties and finds microstructure.

2. Sever plastic deformation

Sever plastic deformation is referred to a set of processes in which high mechanical load could be applied on a specimen without exerting any crack or failure. The interesting point is that, using server plastic deformation, not only the metallic strength increases but also any reduction in ductility is recovered and even improved. This is the main point which makes it different from other plastic deformation methods which is in result of nanostructure that is produced. Severe plastic deformation methods, based on the shape of the product, could be classified in three groups including bulk material, sheet, and pipe severe plastic deformation. Although, these processes are not different in term of microstructure changes and all of them include severe plastic deformation but they are different in term of distribution of strain and stress fields [1,10].

3. Simple shear extrusion (SSE)

This is a new method of severe plastic deformation which is used to produce nanostructured and high strength metals without any significant change in sample dimensions. In SSE, the sample is pressed in a straight channel whit a specified form [11]. The specimen is moved along channel and deformed gradually while its cross-section remains the same. In this study, the cross-section of samples was a square. The cross-section of the sample was a square, at the beginning of the channel, and was changed to a parallelogram with the maximum angle, in the middle of the channel, and was changed to a square again, at the end of the channel [12,13,14]. The specimen cross-section is a square, at the beginning, a parallelogram, in the middle, and a square, at the end, which is presented in Figure1.

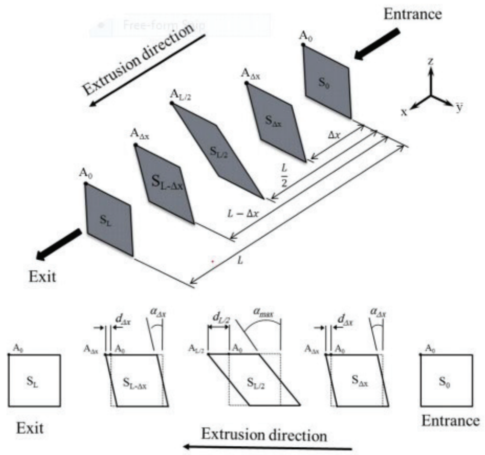
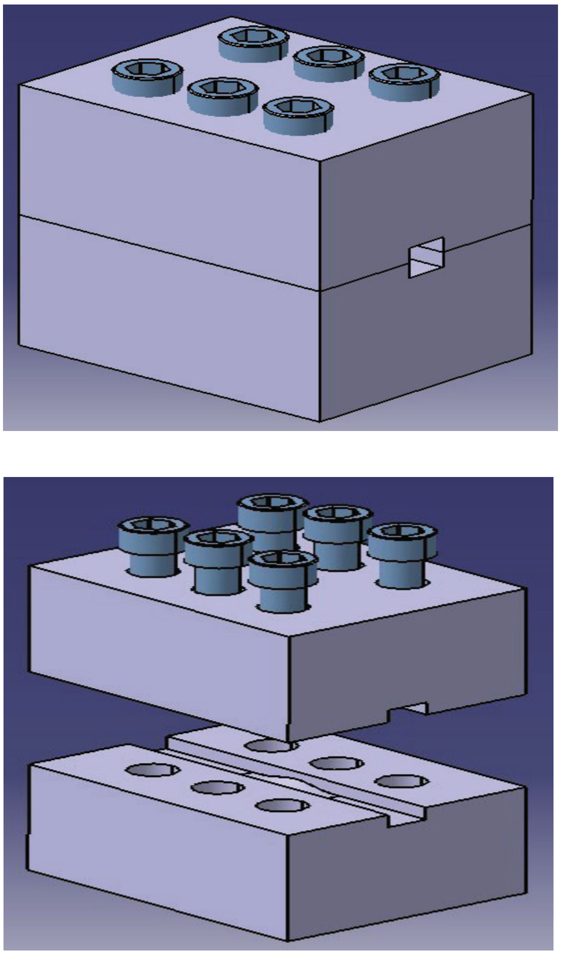


Fig. 1. Schematic illustration of the SSE process [4].

4. Designing and properties of the simple shear extrusion mold

In this study, a mold was designed and manufactured which was strong enough to carry the press load while maintaining ductility to avoid cracks. SSE mold was designed by Catia software and its dimensional size was based on similar industrial activities in the industry and in Mechanical Design and Shape environments, which are shown in Figure 2. Also, the design of the mandrel was done based on the applied load of the press machine and the form of the mold channel as shown in Figure 3. Machining of SSE steel mold was done first by the milling machine and the inner channel of the mold with the milling blade and then the spark machine was completed. Finally, drilling was done with a manual drill and mold assembly. The mold material was AISI 4140 which was selected based on mold, specimens, and press properties using Powermill software. The mold was hardened up to 50 RC. It was in the form of a cylinder which includes two symmetric parts. The design of the mold makes it necessary to use a fixture to perform the extrusion process. This is why that a holding shell was fabricated. The Channel cross-section is a square with dimensions of 15 mm × 15 mm. Figure 4 presents the mold. The mold angle was 45°.



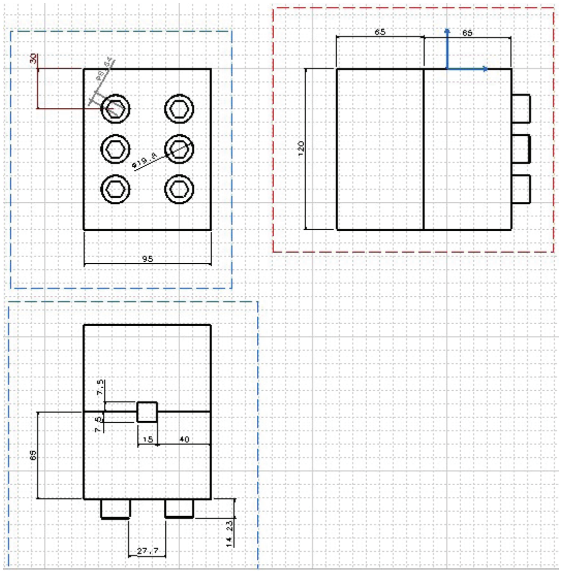


Fig. 2. SSE mold design by Catia software.

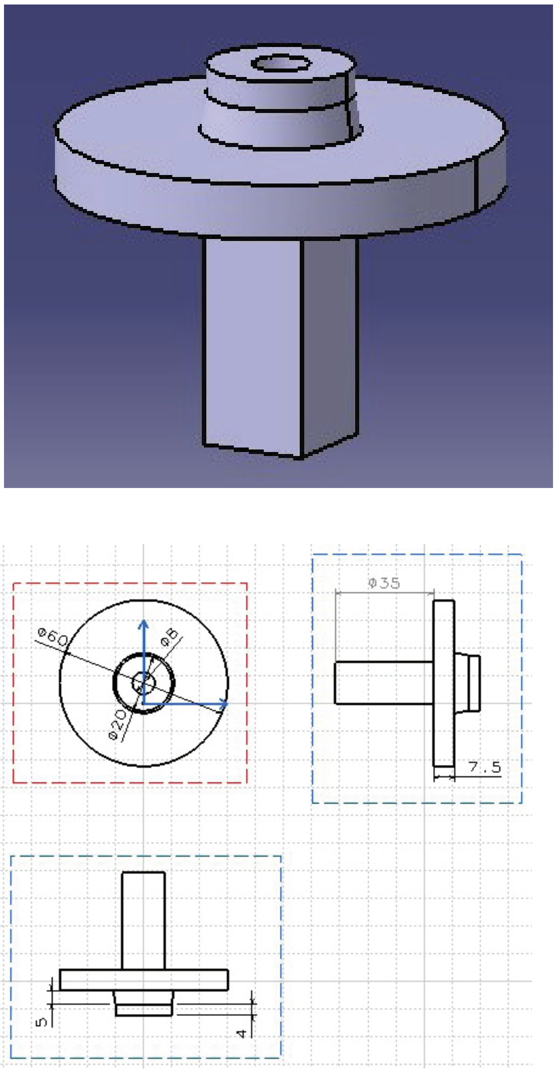


Fig. 3. Mandrel design by Catia software.

Fig. 4. Schematic illustration of inner part of the mold.

5. The sample preparation

Samples were made from Al6061. Al6061 is used in electrical industries due to its good electrical conductivity, in the thermal equipment because of its good thermal conductivity, and in order to its color and good ductility. Quantometry was used to validate the chemical composition of samples. Table 1, presents the chemical composition. Then, they were machined by milling machine to get dimensions of 15 mm × 15 mm × 60 mm. Then, the samples were annealed at 600 ° C for three hours to get high ductility.

The sample cross-section was a square with dimensions of 15 mm × 15 mm and its length was 60 mm. The dimensions were considered a little less than mold dimensions to achieve free assembly. The punch was fabricated with exact dimensions of the mold to eliminate the clearance which exerts a damage on the mold.

Table 1. Al6061 chemical composition (wt %).

S	Cu	Cr	Si	Ni	Fe	Mn	Al
None	Trace	0.01	0.01	0.01	0.005	0.01	98.3
Sn	Pb	Zn	Ag	Co	Be	P	
0.01	0.01	0.01	0.01	0.02	0.001	0.01	

6. Experiments

All specimens were fabricated according to the mentioned dimensions. An oil was used as a lubricant. Then, the mold was fixed under press and the punch was jointed to the spindle using the shell. The punch was moved with initial velocity of 1 mm/s and its final velocity was 3 mm/s, at the end of the process. It is important that the punch be located so that doesn't have any contact with mold which damages the mold. After a pass, the punch was returned and next specimen was located on the previous one. In the next step, the punch pressed both samples which moved previous specimen from deformation zone and the new one to deformation zone. It should be noticed that, in SSE, the strain is exerted gradually while it is focused in a specified zone, in ECAP [14]. Figure 5, present the processed specimen.

Fig. 5. The processed specimen.

7. Tensile test

ASTM B 557 M was used for tensile tests with speed of 0.12 mm/min. The exerted strain was 0.002. Figure 5 present the sample after test. As it is clear, processed samples properties are different from annealed ones. After The first pass, the yield and ultimate strengths of the sample were increased sharply while the ductility was decreased sharply. Grain and twin boundaries are barriers which prevent dislocations to move that result in higher strengths. The ultimate strength was increased from 189 to 254 MPa which presents the strengthening by 34%. It could be attributed to finer grains. According to Hall-Petch equation:

$$\sigma_y = \sigma_0 + KD^{-\frac{1}{2}} \qquad \text{Eq. (1)}$$

where σ_y is the yield stress, σ_0 is a materials constant for the starting stress for dislocation movement, K is the strengthening coefficient, and D is the average grain diameter. strength is a function of grain size. Therefore, the yield stress will increase by decreasing the grain size marked with the symbol D. The Hall-Petch effect is explained based on dislocation accumulation in grain boundaries. These accumulation results in stress concentration zones on grain boundaries which play an important role activating dislocation generating sources in neighbour grains and transferring them between grains. Therefore, for grain sizes more than 20 nm exert a limitation on this accumulation which limits dislocation distribution in the bulk.

In addition, due to lower accumulation defect of Al6061, samples are work hardened with high speeds. More passes don't affect mechanical properties of samples, significantly. Actually it reaches its highest level in the first pass which is reported for other plastic deformation processes, too. Figure 7 present the stress-strain diagram of processed samples.

8. Hardness test

ASTM E 92-72 involves was used to measure micro-hardness of samples in Vickers scale. A pyramid with square base and side angle of 136° is used as a penetrant, in this method, which is pressed whit a specified force on the sample. The hardness value is different in different zones of the sample due to non-uniform distribution of strain. In fact, the hardness could be considered as an index of strain distribution. KOOPA universal hardness testing machine was used. The force of 5 kg was applied for tests. The hardness was increased after first pass, significantly. Its changes were smooth in other passes. The diagram presents an increase in hardness by 27 Vickers from initial hardness of 71 Vickers. The hardness was

Fig. 6. A sample after tensile test.

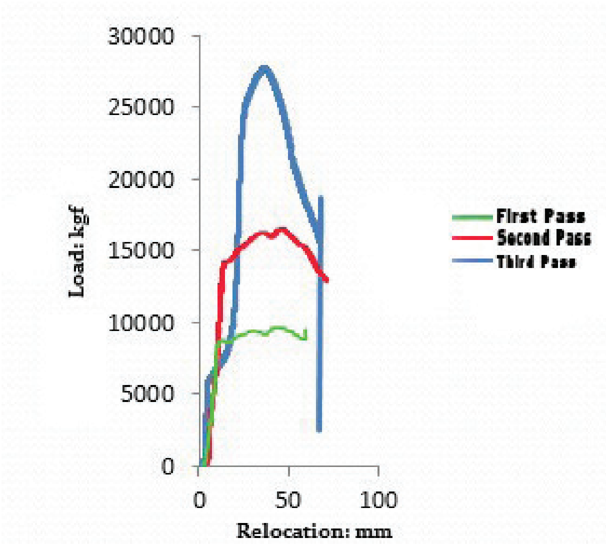


Fig. 7. Extruded Al6061 in the first, second and third passes.

increased by almost 73% and 57%, in the first and second passes, respectively. The increase in hardness in the next passes were negligible because it reached its high level in the first pass which is reported for ECAP and ARB processes, too. The hardness increases because of strain hardening or finer microstructure which could be explained using Hall-petch equation. The hardness results revealed with higher pass numbers, twin mode failure of samples increases and the distance between twins is decreased and dense strain is presented, as a result. Deformation because of twins in the second half of the channel results in reverse strain which hardens the material until its ultimate point. It should be mentioned that the dislocation density also increases after increase in hardness[15]. Table 2, present The mean hardness of annealed, one pass, and two pass processed samples.

Table 2. Hardness of each sample in its different surfaces.

The result from the Al6061 sample hardness by Vikers (HV)	
Annealed sample	71
First pass sample	111
Second pass sample	132

9. Impact test

In this test, the absorbed energy by a sample during failure is obtained from height difference of initial and final position of the pendulum. This is an index of ductility. According to the ASTM A370, the test sample is a part with a length of 55 mm. Its cross-section is a square with dimensions of 10 mm × 10 mm and it contains a groove with an angle of 45° and depth of 2 mm and a root radius of 0.25 mm. Figure 8, present a sample after the charpy impact test. As it is clear, the absorbed energy decreased from 132.6 to 70.7 j after one pass. As it discussed in microstructure of processed Al6061 samples, the surface of grain boundaries was increased significantly compared to annealed samples and according to the Hall-petch equation, the existence of grain boundaries results in brittle failure. Therefore, the absorbed energy in a sample with more grain boundary surface will be lower. This is important that, in the first pass, the absorbed energy before failure is significantly lower compared to annealed sample which is in result of higher hardness and brittleness of the sample. It should be mentioned that two and three pass processed samples were smaller than the standard sample and because of that performing the impact test was impossible.

Fig. 8. Sample after impact test.

10. Metallography

Samples were prepared according to the standard procedure. The etchant was a composition of 100 ml of H_2O, 50 ml of HCl, and 5 ml of $FeCl_3$. The microstructure of parent metal is presented in Figure 9 which is a homogenous microstructure with grain size of 74 µm. In the first and second passes of the SSE, the microstructure of samples was changed in shear plan and in longitudinal direction. As it could be predicted, the microstructure after first pass is completely different from parent material which was reported for other metal forming processes, too. Slipping and twining are two main mechanisms of deformation in metals. Slipping takes place because of slipping of edge and screw dislocations but twinning takes place when the slipping mechanisms are limited or in the presence of low accumulation defect.

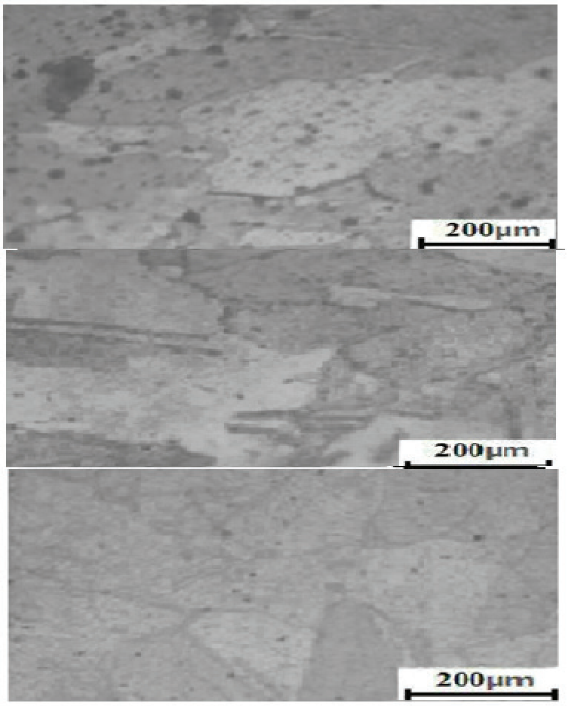


Fig. 9. Pictures of grain size samples annealed first pass and second pass metallography, respectively from left to right.

11. Conclusion

In this study, the simple share extrusion which is a new method to produce nano and very fine grain metals was investigated. First, mold parameters were investigated and the mold was designed and manufactured using that parameters. Samples were made from Al6061 which is an alloy with high thermal conductivity and is used in electrical industries and art. The chief results of this study was as follows:

- The ultimate strength of annealed sample was 148 Mpa which was increased to 214 Mpa in the sample which was processed in three passes.
- The mean hardness of annealed sample was 71 HV which was increased to 132 HV in the sample which was processed in two passes.
- The absorbed Energy before failure of annealed sample was 52/6 J which was decreased to 24/7 J in the sample which was processed.

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