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# Influence of twist extrusion process on microstructure and mechanical properties of 6063 aluminum alloy

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ABSTRACT

In this study, aluminum alloy 6063 was severely deformed by twist extrusion (TE) technique and its mechanical properties, before and after TE, was investigated using a die with the twist line slope of $\beta = 30°$. It was revealed that large strains imposed on the material by this advanced method of severe plastic deformation (SPD) led to a nano-scale ultra-fine microstructure and to an enhancement of the mechanical properties. The more passes of TE the finer grained microstructure was produced. Also with increasing the number of TE passes, yield strength, ultimate tensile strength and hardness increased, while after relative reduction of uniform elongation and elongation to failure by intermediate passes they remained almost unchanged. Therefore, both the strength and ductility of the material were improved when deformed by twist extrusion.

## 1. Introduction

In recent years manifestation of severe plastic deformation (SPD) methods in material science has shed light on new prospects in achieving a unique combination of high strength and ductility [1] as well as attaining ultrafine-grained materials with improved properties. SPD is a family of metal forming techniques that use extensive hydrostatic pressure to impose a very high strain on bulk solids, producing exceptional grain refinement without introducing any significant change in the overall dimensions of the sample [2]. Several different SPD techniques are now available; these include high-pressure torsion (HPT) [3], equal channel angular pressing (ECAP) [4], multi-directional forging (MDF) [5], accumulative roll-bonding (ARB) [6], repetitive corrugation and strengthening (RCS) [7], spread extrusion (SE) [8], simple shear extrusion (SSE) [9] and twist extrusion (TE) [10,11]. Each process has unique properties determining its use in research and practice. The fine grained materials deformed by SPD procedures have much higher structural efficiency in comparison with their coarse-grained counterparts. However, cost effectiveness of the SPD methods itself is still of big concern. Therefore, development of new SPD methods to tackle cost problem is of importance.

Twist extrusion (TE) is known as one of rather newly developed SPD methods which comply with strain accumulation and intense grain refinement to nano-scale sizes while the procedure is comparatively inexpensive. The key idea in TE is based on pressing out a pseudo-prismatic specimen through a die with a longitudinal profile consisting of two prismatic regions separated by a twisted part. Each cross-section of a billet undergoes severe shear deformations at the distorted region such that first, it is twisted by being deformed at a given angle in one certain direction, and then is re-twisted at the same angle in the opposite direction. TE is performed under high hydrostatic pressure in the center of deformation. The pressure is created by applying backpressure to the specimen when it exits the die [12]. It is possible to produce more isotropic and homogeneous deformation by turning the samples 90° in each consecutive deformation or alternatively, make the use of consecutive clockwise–anticlockwise–clockwise twists. This matter is very important for electronic and magnetic materials. A comparison between TE and the two most widely used SPD methods, ECAE and HPT, reveals that firstly, TE provides some advantages over ECAE such as the ability to extrude the hollow parts and the rectangular cross-sections [1]. Secondly, HPT involves order of magnitude higher pressures than in any other SPD process which provides attainment of uniquely high strains and formation of ultrafine grained structures. However, application of HPT is limited to laboratory conditions due to small size of the samples [13]. Several SPD schemes were proposed to deal with this problem. These schemes could realize torsion under pressure in sufficiently large specimens. The problem was resolved with the introduction of SPD processes that combine extrusion with torsion (twist extrusion). TE has a large potential for grain refinement and microscale homogenization of metals due to the characteristic deformed state of the samples during the extrusion, as mentioned. The sample size for TE is limited by two factors: the aspect ratio (length/diameter) has to be smaller than a critical value to avoid bending of the press plunger during extrusion and the plunger has a limited travel distance [13]. In TE, twisting of the specimen occurs

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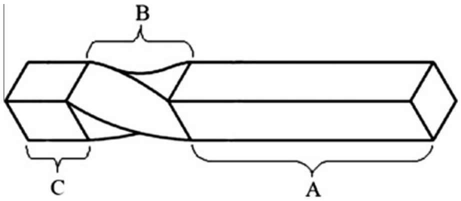

**Fig. 1.** Input and output sections and guides for twist extrusion die: (A) input guide with length of 80 mm, (B) twisted channel with length of 37.73 mm, and (C) output guide with length of 30 mm.

due to the special form of the extrusion die, while in torsion extrusion and shear extrusion method, it is realized by twisting the die around the container. Fig. 1 is a sketch of twist extrusion path. Since the main dimensions of the work-piece remain unchanged when it exits the die, it is possible to repeat the operation as much as required for achieving the higher levels of plastic deformation and providing with the conditions of controlling the microstructure and properties of the material.

In the present research, microstructural evolution of 6063 aluminum alloy which was severely deformed by twist extrusion, and grain refinement behavior of the material due to accumulated strains were studied. The effect of number of TE passes on strength, ductility and hardness of the alloy were also investigated.

## 2. Materials and experimental procedures

The material used in this study, 6063 aluminum alloy, was received in the form of extruded round rod of 90 mm diameter and 700 mm length with the chemical composition as indicated in Table 1. The rod was directly extruded at 400 °C to be deformed to a rectangular billet of 8.4 m length with a cross-section of 14.6 × 14.6 mm. After cooling the billet to room temperature, it was cut to smaller pieces of 65 mm. Because the samples were work hardened, they needed to be fully annealed before performing the tests to make sure that the resultant microstructural evolution and mechanical properties would exclusively be obtained from TE processes. Therefore, the specimens were annealed at 413 °C for 3 h, and then furnace cooled to 260 °C at the rate of 10 °C/h and finally, cooled down in air to ambient temperature. The samples were then wrapped with Teflon tape and also silicon sprayed to reduce friction. Then, they were inserted into the input guide of the twist extrusion die being pushed to the distorted channel using a steel plunger with speed of 1.1 mm/s. Unlike significant effect of billet axial rotations between ECAP passes [14,15], the billet rotations between TE passes have no effect on the plastic flow. This is due to the axial symmetry of the process.

The interior view of the twist extrusion die of 15 × 15 mm cross-section with a twist line slope of $\beta = 30^\circ$ in the counter-clockwise direction is shown in Fig. 1. In order to apply a back pressure on the sample, the output channel was built steeped. This channel, itself, acted as a direct extrusion die. Thus, after the specimen passed the twisted channel, entered a straight passage of 30 mm length during which its cross-section changes from 15 × 15 mm to 14.6 × 14.6 mm.

To investigate the microstructural changes in the material due to twist extrusion through micrography, the samples were prepared by cutting them from the cross-section perpendicular to the axial direction of the extruded billets. The microstructural evolution was then studied in the central and lateral regions of the cross-section using scanning electron microscopy (SEM). The hardness test samples were also cut from the cross-section perpendicular to the extrusion direction. Hardness testing was performed on the points across cross-section diameter with 1 mm intervals from one corner to the other.

**Table 1**
Chemical composition of the 6063 aluminum alloy used.

| Element | Mg | Si | Fe | Cu | Mn | Cr | Zn | Ti |
|---|---|---|---|---|---|---|---|---|
| Weight percent | 0.707 | 0.585 | 0.350 | 0.084 | 0.100 | 0.020 | 0.110 | 0.038 |

## 3. Results and discussion

### 3.1. Microstructural evolution

Koch and his co-workers [16] in qualitative and quantitative analyses performed by both high resolution electron microscopy (HREM) and X-ray diffraction showed that in the materials deformed through severe plastic deformation (SPD), intense elastic stresses occur in vicinity of grain boundaries due to the presence of crystal defects, especially high dislocation density. Experimental results indicated that in the materials with lower recovery rates (lower atomic stacking fault energy), the final grain size become smaller and a homogeneous microstructure is achieved if severe plastic deformation is performed sequentially [17,18]. Since the 6063 aluminum alloy is a solid solution strengthened material and its alloying elements may reduce the rate of recovery by impeding dislocations glide and retarding their movement to achieve a relatively homogeneous ultra-fine microstructure, it is necessary to repeat the SPD operations several times. To better compare grain refinement in various passes of TE, the mean grain sizes at the central and lateral regions of the cross-section of the samples, before and after the process, were measured (Table 2). In addition, fine particles may be precipitated in the 6063 aluminum alloy during the twist extrusion. The recent research of Sheng et al. [19] revealed that the precipitates can appreciably contribute to the microstructure refinement. Mechanisms of such strain induced precipitation have widely been studied by many authors on aluminum alloys [20–22]. Chandler and Bee [21] in a research on an Al–Mg–Si alloy observed that cyclic loading had induced the formation of precipitates on dislocations. They found that the dislocation density increased at first but later decreased although cyclic hardening continued. It was suggested that this was due to the progressive immobilization of dislocation sources as cycling proceeded.

Fig. 2 illustrates SEM image of cross section of the material prior TE with coarse distinct grains. As seen in Figs. 3 and 4, by increasing the number of passes, the microstructure became more fine-grained in the lateral regions of cross-section compared to the central regions. The microstructure was therefore, more homogenized in the lateral regions of the cross-section than the central regions. This is the evidence that the lateral regions undergo larger strains compared to the central regions [23], that is, strain value in radial direction increases from the center of the cross-section towards the edge (Fig. 5). The true strain values in different parts of the cross-section were obtained using the relationship:

$$\varepsilon = \ln\left(\frac{d_0}{d_1}\right)^2 \tag{1}$$

**Table 2**
Mean grain size at central and lateral regions of the samples at various passes.

| Sample state | | Annealed | 1 Pass | 2 Passes | 4 Passes | 8 Passes | 16 Passes |
|---|---|---|---|---|---|---|---|
| Mean grain size (μm) | Center | 11 | 8.1 | 3.2 | 1.3 | 0.86 | 0.16 |
| | Edge | 11 | 4.4 | 1.9 | 0.89 | 0.62 | 0.13 |