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Numerical and experimental studies of the plastic strains distribution using subsequent direct extrusion after three twist extrusion passes

S.A.A. Akbari Mousavi*, Sh. Ranjbar Bahadori, A.R. Shahab

School of Metallurgy and Materials Engineering, University College of Engineering, University of Tehran, P.O. Box 11155-4563, Tehran, Iran

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ABSTRACT

In this investigation, simulation of three consecutive clockwise twist extrusion for commercially pure aluminum samples at ambient temperature with and without subsequent direct extrusion is presented. The influences of 50% reduction on strains distribution are analyzed on the specimen middle transverse cross-section. The results show that performing subsequent direct extrusion after twist extrusion increases the shear strain magnitude in the center of the specimen. High shear strain results in more grain refinement in the center regions in contrast to the corner ones. Few experiments were also carried out to validate the numerical findings. Furthermore, examination of microstructure evolutions and mechanical properties for the commercially pure aluminum samples were conducted using SEM, microhardness and tensile tests. The study shows that adding direct extrusion to the twist extrusion process alleviates the mechanical heterogeneity due to producing more intensified strains in the center regions than in the corner ones.

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1. Introduction

Nowadays, severe plastic deformation (SPD) methods are of great importance in order to produce ultrafine-grained materials [1]. Twist extrusion (TE) is one of the most unprecedented technique among the SPD methods, developed in recent years [2–4]. In this process a square-section billet is pressed into the twisted channel of the extrusion die. The schematics of the twist extrusion product and the twist extrusion die are shown in Fig. 1. In all of SPD methods, heterogeneity of strains distribution is considered as the most significant barrier against commercialization. Choosing a modifying trend needs an analytical evaluation of strains mode occurring during deformation by means of numerical finite element methods. Some numerical investigations of TE were reported in the previous publications, implied on heterogeneity of strains along the length and across the samples cross-section [5–8]. As a case in point, 50% cold rolling after three passes of TE was employed as an efficient tool which reduced the mechanical heterogeneity and resulted in more grain refinement [9,10].

It is of great scientific interest to find a method to solve or reduce the problem of heterogeneity of strains distribution in the SPD methods. Heterogeneity of strain distribution is one of the significant barriers against commercialization. In the present study, it was attempted to reduce the heterogeneity of strains distribution by employing post direct extrusion process after three clockwise twist extrusion passes. Therefore, in the first part of the work, numerical analysis were carried out to investigate the strains distribution across the middle transverse cross-section of commercial pure aluminum with and without employing a subsequent conventional direct extrusion (DE) after three clockwise twist extrusion passes. The numeral outcomes show that performing the post direct extrusion not only increases the strain values but also decreases the heterogeneity of strains distribution throughout the transverse section, considerably. The experimental data validates the simulation results in regard to the grain refinement and strength properties.

2. FEM details

In this study, a high purity aluminum sample with the cross-section of $18 \times 28\,\text{mm}^2$ and the length of 80 mm was used. ABAQUS 6.5 was selected as the finite element software [11]. The isometric view of the partial discretized model of the sample is shown in Fig. 2. Furthermore, this figure shows the elements number of 29, 32,159 and 352 positioned on the middle transverse cross-section of the sample. The elements of 29, 32 and 352 have been located at three corners and the element of 159 has been located at the center of the cross-section. The elements of 29 and 159 are the representatives of the corner and the center of the mentioned cross-section for further references. These elements were selected since the maximum and minimum of the strains are occurred at these elements [5]. Three guides, three TE dies and one DE die were used to adjust the setup for three accumulated passes of TE and 50% subsequent DE as

* Corresponding author. Tel.: +98 21 82084096; fax: +98 21 88006076.
E-mail address: akbarimusavi@ut.c.ir (S.A.A. Akbari Mousavi).

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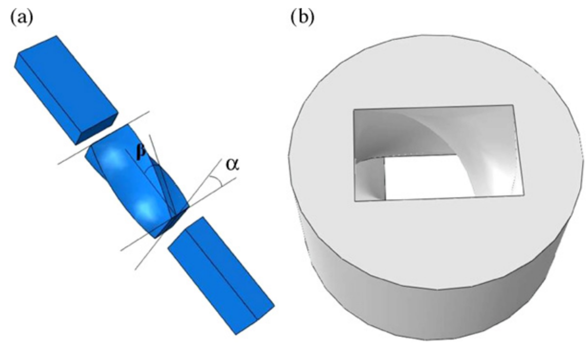

Fig. 1. Schematic of (a) the product and (b) the twist extrusion die.

shown in Fig. 3. The lengths of the first guide, both the second and third guides, TE dies and DE die were 70 mm, 20 mm, 25 mm and 30 mm, respectively. The TE die channel had a rectangular cross-section of $18 \times 28\,\text{mm}^2$ with a clockwise twist angle of 90° and the twist die slope of 60°. Ram speed was 3 mm/s and the friction coefficient between the die and sample surface was chosen to be 0.01. The dies, the ram and the guides were modeled as rigid solid type and therefore no material properties were assigned to them. The dynamic temperature–displacement explicit procedure was used for the finite element analysis.

In the Abaqus software, the plastic strain tensor is defined with output variable of PE. Hence, the normal and the relative tangential (shear) displacement components during the deformation are expressed as plastic strain components: PE11, PE22, PE33, PE12, PE13 and PE23, respectively. The first three terms are related to the normal plastic strain components which are in the directions normal to the planes *A*, *B* and *C*, respectively (see Fig. 2). PE12, PE13 and PE23 are the shear plastic strain components which are parallel with the planes *C*, *B* and *A*, respectively. Moreover, the equivalent plastic strain defined with PEEQ variable. The distribution of normal plastic strains of PE11, PE22 and PE33 and also shear plastic strains of PE12, PE13 and PE23 were considered at the corner and the center of the middle transverse cross-section after three passes of TE with and without subsequent DE.

The Johnson–Cook material model [11,12] was used (Eq. (1)) to describe the behavior of the material during the deformation. The

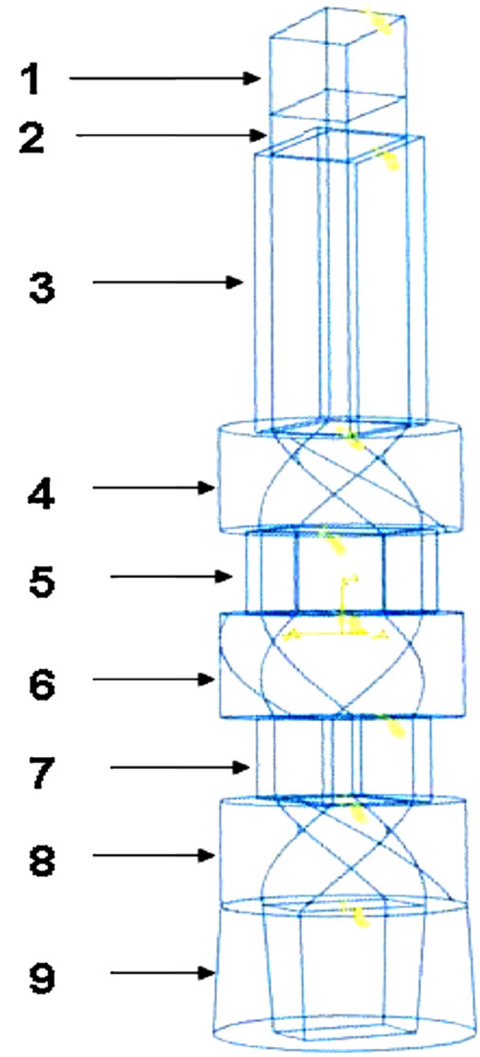

Fig. 3. Schematic of three twist extrusion passes + direct extrusion setup: (1) the ram, (2) the billet, (3) the first guide, (4) the first TE die, (5) the second guide, (6) the second TE die, (7) the third guide (8) the third TE die and (9) the DE die.

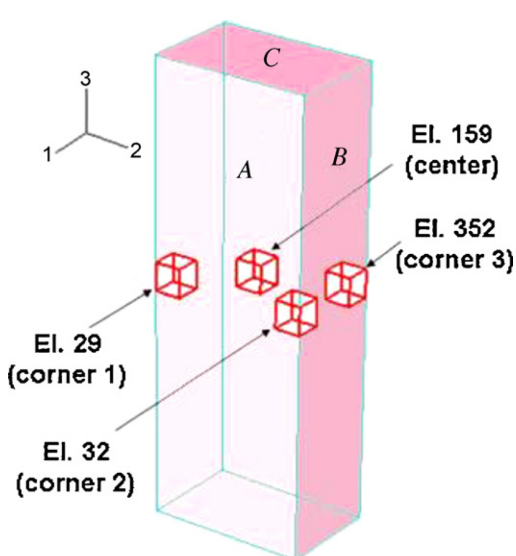

Fig. 2. Partial discretized sample model with elements number of 29 (corner 1), 32 (corner 2), 159 (corner 3) and 159 (center) on the middle transverse cross-section.

Johnson–Cook constitutive equation is defined as:

$$\bar{\sigma} = [A + B(\bar{\varepsilon}^{pl})^n]\left[1 + C\ \ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0}\right)\right](1 - \hat{\theta}^m) \quad (1)$$

where $\bar{\sigma}$ is the yield stress at nonzero strain rate, $\bar{\varepsilon}^{pl}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}^{pl}$ is the equivalent plastic strain rate for $\dot{\varepsilon}_0 = 1.0\,\text{s}^{-1}$ and *A*, *B*, *C*, *n* and *m* are the material parameters measured at or below the transition temperature, $\theta_{\text{transition}}$. The material constants were determined from straining tests performed in tension or torsion. The Johnson–Cook parameters for pure aluminum are presented in Table 1 [13].

$\hat{\theta}$ is the non-dimensional temperature defined as

$$\hat{\theta} \equiv \begin{cases} 0 & \text{for } \theta < \theta_{\text{transition}} \\ \theta - \theta_{\text{transition}}/\theta_{\text{melt}} - \theta_{\text{transition}} & \text{for } \theta_{\text{transition}} \le \theta \le \theta_{\text{melt}} \\ 1 & \text{for } \theta > \theta_{\text{melt}} \end{cases} \quad (2)$$

Table 1
Johnson–Cook model parameters for pure aluminum [8].

A (MPa)	*B* (MPa)	*n*	*C*	*m*	T_m (K)
80	120	0.73	0.008	1.7	933

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