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Computation on new deformation routes of tube channel pressing considering back pressure and friction effects

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ABSTRACT

Three deformation routes for recently invented severe plastic deformation (SPD) method named tube channel pressing (TCP) have been introduced in this paper. The effects of routes, back pressure and friction have been investigated on deformation behavior of commercially pure (CP) aluminum tubes. Utilizing finite element analysis provides a broader understanding of these effects through different deformation routes. Due to the large values of strains accumulated in TCP, modified Estrin–Tóth–Molinari–Brechet (METMB) constitutive model has been employed in finite element analysis program to consider a realistic flow stress of the material in TCP. Employing experimental procedures confirms the accuracy of the analysis.

1. Introduction

Investigation into the micro-structural evolution of ultrafine-grained (UFG) materials has been surged tremendously in recent 20 years [1,2]. Utilization of severe plastic deformation (SPD) methods has provided a convenient approach for producing these UFG materials [3]. UFG materials exhibit outstanding characteristics especially mechanical properties [4,5]. Several SPD methods have been proposed so far such as equal-channel angular pressing (ECAP) [6], high pressure torsion (HPT) [7], accumulated roll bonding (ARB) [8] and cyclic extrusion compression (CEC) [9]. However, studies on SPD of tubular form of materials are limited to high pressure tube torsion (HPTT) [10] and tube channel pressing (TCP) [11].

In the previous research carried out by the authors [11], the applicability and capability of TCP in order to reduce the grain size and improve the strength of commercially pure (CP) aluminum tube have been studied. Nevertheless, this method has not yet been studied thoroughly. Various factors such as number of pressing passes, die design, different deformation routes, friction and back pressure have considerable effects in mechanical properties and microstructure of materials produced by SPD techniques, which have been considered in detail, for ECAP [3,4,12,13]. Among the aforementioned factors, applying back pressure has been revealed to provide several advantages such as feasibility for exerting SPD methods on low-ductility materials [14], reaching to a finer microstructure [15,16], development of smaller size of equiaxed dislocation cells [17] and increasing of uniform deformation and deformation to failure, due to augmentation of strain rate sensitivity [18].

Friction has significant effects on the strain distribution, die filling and shearing characteristic of the material processed by different SPD methods [19]. It reveals that applying friction between the die/sample interface leads to more accumulated strain and less strain homogeneity in the cross section of the material processed by ECAP [20,21].

Different deformation routes have been introduced by Segal for ECAP [22]. It has been shown that employing various deformation routes activates different slip systems, which leads to diverse mechanical and micro-structural properties in materials processed by various methods such as ECAP [23], twist extrusion (TE) [24], and Simple Shear Extrusion (SSE) [25]. In this study, three different routes for processing the tube by TCP have been introduced, and the effects of back pressure and friction are investigated on each of these deformation routes using finite element method (FEM), ABAQUS/Explicit program.

Moreover, in order to simulate the mechanical behavior of severely deformed materials which have been processed by TCP method to high accumulated strain, it is essential to consider its constitutive equation that can predict materials responses. In this regards, an empirical relation [26] achieved from a Modified Estrin–Tóth–Molinari–Brechet (METMB) [27] constitutive model is taken into account and its result is fed into the FEM.

2. Deformation routes in TCP

The procedure of TCP is based on pressing a tube through the channel which has a neck zone in its middle (Fig. 1). Through

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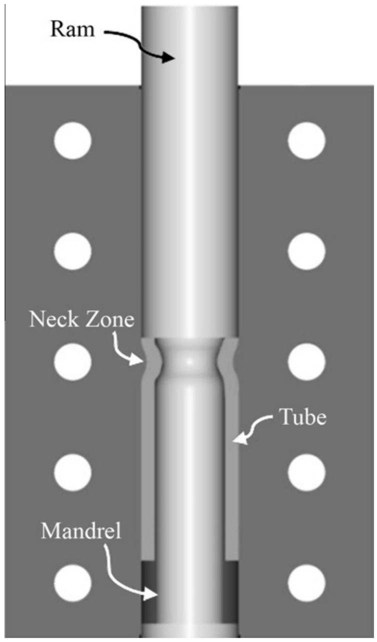

Fig. 1. Schematic of Tube Channel Pressing die.

passing the tube into the neck zone, outer and inner diameters of the tube are reduced to 23.5 mm and 15.4 mm, respectively, and after passing the neck zone, they are expanded into their initial dimensions, i.e. 26 mm and 19 mm, respectively. However, the cross section of the tube remains constant throughout the process.

As shown in the previous work carried out by the present authors [11], the deformation in the neck zone is mainly in shear mode, where two opposing shear modes of deformation operate subsequently leading to a homogeneous mode of deformation with less disturbed meshes.

Three different TCP routes have been introduced in Fig. 2. Employing these deformation routes result in various strain distributions and different shearing characteristics in the tube. The route R (which denotes reversible) was experimentally examined in the previous work [11]. In this route, after finishing the first pass, the die rotates 180°, and the second pass is performed like the first pass (Fig. 2a). The route A (like route A in ECAP) [4] is carried out by passing the tube through the die and expelling it from the end of the die. Then, in the second pass the tube is fed again from the top of the die like the first pass (Fig. 2b). As shown in Fig. 2c, the route I (which denotes inverse) consists of two die designs. The first one is the same as shown in Fig. 2a and b. But, the second one has a bulging deformation zone, with similar degrees and curvatures in the deformation zone as the first one. In route I, the first and second dies are used for the first and the second passes, respectively. In the second die, through passing the tube into the bulging zone, outer and inner diameters of the tube are increased to 29.5 mm and 22.6 mm, respectively, and after passing the bulging zone, they are reduced into their initial dimensions.

3. Experimental materials and procedure

CP aluminum (Al 1100) tube samples of 70 mm long, and with outer and inner diameters of 26 mm and 19 mm were prepared, respectively. Samples were annealed at 623 K for 3 h and then sprayed with MoS_2 lubricant to reduce the friction between the interaction of die and sample.

In this study, TCP was carried out with a 500 kN semi-automatic hydraulic pressing machine at the ram speed of 1 mm/s and room temperature. The load–displacement diagram has been obtained from the computer-controlled pressing machine.

In order to verify the results achieved from FEM simulation, the tubes were cut longitudinally. The longitudinal cross section was examined by stereographic microscope after polishing and etching with Poulton reagent [28]. Three microscopic images were taken from different regions of the processed tube in route R after 5 TCP passes.

4. Finite element analysis

Axisymmetrical finite element analysis of TCP has been carried out using commercial program, ABAQUS/Explicit, by choosing 4-node bilinear axisymmetric quadrilateral elements (CAX4R) for a tube, and assigning an analytical rigid characteristic for both of the die and ram. The dimension of TCP die in analysis is identical to experimental geometry, and a friction coefficient (μ) of 0.05 is utilized with respect to the presence of a hydrostatic pressure in the die/sample interface in which promotes lubrication [29]. In account of severe strains accompanied with higher TCP passes, mechanical properties of the CP aluminum in higher strains must be utilized in order to obtain more realistic results. For this reason, mechanical properties of CP aluminum in higher strains i.e. up to 6, were retrieved from METMB constitutive model [26]. This model is based on the dislocation densities in the cell interiors and cell walls and tracking their evolutions during deformation process. According to this model, dislocation densities in the cell interior and cell walls are considered by these equations, respectively [26,27]:

$$\dot{\rho}_c = \frac{\alpha^* \dot{\gamma}_w \sqrt{\rho_w}}{\sqrt{3}b} - \frac{6\beta^* \dot{\gamma}_c}{bd(1-f)^{1/3}} - k_c \dot{\gamma}_c \rho_c \left(\frac{\dot{\gamma}_c}{\dot{\gamma}_0}\right)^{\frac{-1}{n_c}} \quad (1)$$

$$\dot{\rho}_w = \frac{\sqrt{3}\beta^* \dot{\gamma}_c (1-f)\sqrt{\rho_w}}{bf} + \frac{6\beta^* \dot{\gamma}_c (1-f)^{2/3}}{bdf} - k_w \dot{\gamma}_w \rho_w \left(\frac{\dot{\gamma}_w}{\dot{\gamma}_0}\right)^{\frac{-1}{n_w}} \quad (2)$$

where ρ_c and ρ_w are the dislocation densities in cell interiors and cell walls, and $\dot{\gamma}_c$ and $\dot{\gamma}_w$ are resolved strain rates in cell interiors and walls, respectively. $\dot{\gamma}_0$ is a reference shear strain rate, b is the magnitude of Burgers Vector, f is the volume fraction of cell walls and α^*, β^*, k_c, k_w, n_c and n_w are the model constants. Finally, d is the average cell diameter which is indirectly related to the total dislocation density in the Holt's relation [30]:

$$d = \frac{K}{\sqrt{\rho_{tot}}} \quad (3)$$

where K is the cell size coefficient and ρ_{tot} is the total dislocation density.

The contribution of hydrostatic pressure on the activation energy in the ECAP process has the form of [27,31]:

$$\left(p + \frac{\sigma_y}{\sqrt{3}} \cot\left(\frac{\Phi}{2}\right)\right)\Omega \quad (4)$$

where p is the magnitude of back pressure, σ_y is the yield strength of the material, Φ is the angle of two intersecting channels and Ω presents the atomic volume. Hence, the form of Eq. (2) in the presence of back pressure is modified to an Arrhenius-type equation [27]:

$$\dot{\rho}_w = \frac{\sqrt{3}\beta^* \dot{\gamma}_c (1-f)\sqrt{\rho_w}}{bf} + \frac{6\beta^* \dot{\gamma}_c (1-f)^{2/3}}{bdf} - k_w \dot{\gamma}_w \rho_w \times \exp\left(-\frac{\left(p + \frac{\sigma_y}{\sqrt{3}} \cot\left(\frac{\Phi}{2}\right)\right)\Omega}{n_w k T}\right) \left(\frac{\dot{\gamma}_w}{\dot{\gamma}_0}\right)^{\frac{-1}{n_w}} \quad (5)$$

The intrinsic pressure originated from the die curvatures (Φ = 158, 136 and 158° [11]) in the second term of Eq. (4) without any applied back pressure ($p = 0$) in TCP processing of CP