A novel combined severe plastic deformation method for producing thin-walled ultrafine grained cylindrical tubes

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ARTICLE INFO

Article history:
Received 28 November 2014
Accepted 20 December 2014

Keywords:
Severe plastic deformation
Thin-walled tube
AZ31
Microstructure
Grain boundaries
Nanocrystalline materials

1. Introduction

Various severe plastic deformation (SPD) techniques have received much attention in recent years due to their efficient in improving properties of metallic materials [1]. In all SPD processes, the intense shear plastic strain is applied to the specimen and results ultrafine-grained (UFG) materials. Due to the Hall–Petch equation, materials with finer grain sizes exhibits higher yield strength. Equal channel angular pressing (ECAP) [2], accumulative roll bonding (ARB) [3], high pressure torsion (HPT) [4], and cyclic extrusion compression (CEC) [5] are successful SPD methods suitable for deforming bulk materials. Despite the need of high strength tubes for a wide range of industrial application, few SPD methods have been proposed for deforming tubular components. Many studies were done in recent years. Mohebbi and Akbarzadeh [6] developed accumulative spin bonding (ASB) inspired from ARB process to manufacture UFG tubes. Tóth et al. [7] proposed a high pressure tube twisting (HPTT) method. This method applies a high hydrostatic stress, but there is a large strain inhomogeneity through the radial direction. Faraji et al. [8,9] proposed tubular channel angular pressing (TCAP) as an effective method. Recently, they developed parallel tubular channel angular pressing (PTCAP) based on TCAP for producing UFG and nanostructure tubes [10,11]. Among these processes, the PTCAP has several advantages compared to other methods. It needs lower process load, in addition, there are a superior strain and hardness homogeneity through the thickness and length direction [10].

In all SPD methods for tubular components, there is a limitation that cannot be used for thin-walled tubes. Because, as the thickness of the tube is reduced, the most of the processing load is the friction force and so the friction is the main obstacle, and the SPD process is technically difficult to perform. In order to facilitate the SPD process for thin-walled tubes, the present work introduces a combined tube backward extrusion (TBE) and PTCAP method as a suitable process for producing nanostructured and UFG thin-walled cylindrical tubes. To investigate the applicability of this new combined SPD approach, an AZ31 magnesium tube is processed.

2. Principles of the process

This new combined method consists of two stages of PTCAP and TBE processes. First, the PTCAP process is applied to the thick tube and then the TBE process is consequently applied to reduce the thickness. The PTCAP process consists of two half cycles shown schematically in Fig. 1. In the first half cycle, the first punch presses the tube material into the gap between mandrel and die including two shear zones to increase the tube diameter (Fig. 1(a)). Then the tube is pressed back using the second punch in the second half cycle, decreasing the tube diameter to its initial value (Fig. 1(b)). In the next step, the TBE process shown schematically in Fig. 1(c) is applied to the UFG PTCAP processed tube. In this stage, the punch presses the tube to reduce its thickness. The equivalent strain

A novel severe plastic deformation (SPD) process entitled combined parallel tubular channel angular pressing (PTCAP) and tube backward extrusion (TBE) is proposed for producing thin-walled ultrafine-grained (UFG) tubes. In this new combined SPD approach, the PTCAP and TBE processes are consequently applied to the tube material in which a severe plastic strain is applied to produce a UFG thin-walled tube. This technique was performed on an AZ31 magnesium tube, and a remarkable grain refinement was achieved. The results showed that this method could easily produce a high strength thin walled tube. The microhardness increased significantly to 70 HV after the process from an initial value of 38 HV.

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http://dx.doi.org/10.1016/j.matlet.2014.12.107
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achieved from the $N$ passes of PTCAP stage can be estimated via
the following equation [10]:

$$\varepsilon_{\text{PTCAP}} = 2N \left\{ \sum_{i=1}^{N} \left[ 2 \cot \left( \frac{\phi_1}{2} + \frac{\psi_i}{2} \right) + \psi_i \csc \left( \frac{\phi_1}{2} + \frac{\psi_i}{2} \right) \right] \right\} + \frac{2}{\sqrt{3}} \ln \frac{R_1}{R_f}$$

(1)

where $R_1$, $R_2$, $\phi$ and $\psi$ were shown in Fig. 1(d). With assuming the uniform deformation, the following equation can be used for the equivalent strain in the TBE stage of the combined process:

$$\varepsilon_{\text{TBE}} = \ln \frac{A_0}{A} = \ln \frac{R_0^2 - r_f^2}{R_0^2 - r_0^2}$$

(2)

where $t_1$ and $t_2$ are shown in Fig. 1(d). The total equivalent strain at the end of the combined process is equal to the sum of Eqs. (1) and (2):

$$\varepsilon_{\text{tot}} = 2N \left\{ \sum_{i=1}^{N} \left[ 2 \cot \left( \frac{\phi_1}{2} + \frac{\psi_i}{2} \right) + \psi_i \csc \left( \frac{\phi_1}{2} + \frac{\psi_i}{2} \right) \right] \right\} + \frac{2}{\sqrt{3}} \ln \frac{R_1}{R_f} + \ln \frac{R_0^2 - r_f^2}{R_0^2 - r_0^2}$$

(3)

Fig. 1. Schematic of the combined process; (a) the first and (b) the second half cycles of PTCAP and (c) TBE and die parameters of (d) PTCAP and (e) TBE stages.

The total equivalent accumulative plastic strain after PTCAP (1.6) and TBE (1.2) considering the parameter used in this study is about 2.8.

3. Experimental procedures

The material used in this study was an AZ31 magnesium alloy. Tubular samples of 20 mm in outer diameter, 2.5 mm in thickness and length of 35 mm were prepared. The PTCAP and TBE dies were manufactured from hot-worked tool steel and hardened to 55 HRC. Die parameters for PTCAP and TBE stages were shown in Fig. 1(d) and (e), respectively. Die parameters are as following: the channel angles $\phi_1 = \phi_2 = 150^\circ$, the angle of the curvature $\psi_1 = \psi_2 = 0^\circ$, $r_0 = 15$ mm, $R_0 = 15$ mm, $r_f = 9.25$ mm, $r_0 = 15$ mm, $R_0 = 15$ mm and $r_f = 9.25$ mm. In TBE process, the thickness of the tube is reduced from the initial value 2.5 mm to 0.75 mm (extrusion ratio is 70%). The PTCAP and TBE processes were performed at the ram speed of 10 mm/min at 250°C. The MoS$_2$ lubricant was sprayed on the specimens and dies to reduce the friction. All the samples were cut along the axial direction and microstructural and microhardness investigations were done in this cross section at the point near the middle of the thickness.
samples were mechanically polished and then etched for 5 s using a solution of 140 ml ethanol, 4.2 g picric acid, 10 ml acetic acid and 10 ml distilled water. Microstructure evolution was conducted by optical microscopy (OM). The HV microhardness testing was performed using with a load of 100 g applied for 10 s.

4. Results and discussion

Fig. 2 shows OM micrographs of the microstructure and the grain size distribution of the as-received and processed samples via different routes. The average grain size of as-received tube (Fig. 2(a)) is ~33 µm, as it can be seen from the histogram the grains are not uniformly distributed. The grain size is varied from 6 µm to 76 µm. After PTCAP process (τ = 1.6) (Fig. 2(b)), the grain size decreases to ~14.5 µm. TBE process (τ = 2) (Fig. 2(c)) results in a grain size of ~4.5 µm. After combined PTCAP and TBE processes (τ = 1.6 and 2) (Fig. 2(d)), the grain size is further reduced to ~3 µm.
average grain size is reduced to ~14.5 μm, and the microstructure is relatively more uniform. The grain size was affected by accumulated strain. Faraji et al. reported that the grain size of the material could be refined and completely homogeneous by increasing the number of passes [10]. The mean grain sizes were dramatically affected by severe strain in TBE process in which a high extrusion ratio (70%) is applied (ε = 1.2). Consequently, the mean grain size is significantly refined to ~4.5 μm for TBE processed tube (Fig. 2(c)). After combined process of PTCAP+TBE process (ε = 2.8) the grain size refined to below ~3 μm (Fig. 2(d)). It is obvious that after combined process, the fine grained material was achieved. The HCP structure of magnesium needs elevated forming temperatures to allow better formability. Thus, temperature plays an important role in a variation of the grain size during plastic deformation of magnesium alloys [12,13]. Tan et al. reported that the optimum temperature to achieve finer grains and homogeneous microstructure is 250 °C [14] which is identical the current experiment temperature. During plastic deformation, grain refinement is caused by dynamic recrystallization (DRX) at high temperature [12]. As depicted in Fig. 2(c) and (d), by increasing the strain, finer dynamic recrystallized grains develop to cover all the original microstructure. Subgrains are first formed in the adjacency of grain boundaries as deformation progresses during DRX. Then, Subgrain structure form over the whole volume and also subgrain boundary misorientation angle increases and then, low angle grain boundaries transform to high angle counterparts [14]. As depicted in Fig. 3, the microhardness of as-received tube increases from ~38 HV to ~50 HV after just PTCAP process. For directly TBEed of as-received tube, it is ~58 HV. After combine PTCAP+TBE process, it remarkably increases to ~70 HV. Magnesium alloy exhibits a high dependency of hardness to the grain size due to the limited number of slip system [15]. Thus, a superior increase in hardness of the PTCAP+TBEed tube is due to the severe grain refinement.

True stress–strain curves of the samples at room temperature were shown in Fig. 4. As shown, after PTCAP process the ductility was slightly increased, and the strength was decreased. This result is in good agreement with the work done on AZ31 alloy in ECAP by Xia et al. [16]. After PTCAP+TBE process, an intense plastic deformation is imposed to the tube and results in a remarkable increase of the strength. As discussed in the previous section, UFG material is achieved after PTCAP+TBE process. Thus, a high dislocation density and a large fraction of fine grain cause a significant increase in yield and ultimate strength. Chen et al. [17] reported that as the extrusion ratio is increased, the mechanical properties of magnesium alloy improved effectively. As depicted, because of grain refinement and more homogeneous structure, the strength for PTCAP+TBE processed sample is higher than the TBE sample directly from as-received tube.

5. Conclusions

In this study, a combined SPD process is introduced suitable for producing thin-walled UFG tubes. The effect of this process on grain refinement, mechanical properties and microhardness of AZ31 was successfully investigated, and following conclusions could be made:

- A fine grained thin-walled tube with the thickness of 0.75 mm was produced.
- A formula is proposed for a total equivalent strain, and it is 2.8 at the end of PTCAP+TBE process.
- A remarkable grain refinement could achieve from ~33 μm for as-received tube to below ~3 μm after the combined process.
- The Vickers microhardness was significantly increased from the initial value 38 HV to 70 HV due to the grain refinement after the combined process.
- Yield and ultimate strengths were remarkably increased.

Acknowledgements

The authors would like to acknowledge the University of Malaya for providing the necessary facilities and resources for this research. This research was fully funded by the Ministry of Higher Education, Malaysia with the high impact research (HIR) grant number of HIR-MOHE-16001-00-D00001. This work was financially supported by Iran National Science Foundation (INSF).

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