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Microstructure evolutions and mechanical properties of tubular aluminum produced by friction stir back extrusion

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ABSTRACT

Aluminum tubes were successfully fabricated using a novel process of friction stir back extrusion (FSBE) known as one of the severe plastic deformation (SPD) routes. It was found that this process is capable to form a tube with a significant fine grained structure resulting from dynamic recrystallization phenomenon in the stirred area. Several regions were identified in the formed tube in which various microstructural evolutions occur, i.e. dynamic recrystallized (RX), static RX, and partially static RX zones along with extruded base metal. There was also no considerable change in the hardness and strength values of the formed tube with respect to those of the extruded base metal. However, elongation of the tube formed by FSBE process was higher than that of produced by other SPD methods. The results achieved from mechanical assessments were consistent with those obtained from microstructure examinations.

1. Introduction

During the last decade, interest on severe plastic deformation (SPD) has raised due to its capability of producing ultra-fine grained (UFG) structure in metals [1]. UFG materials exhibit superior physical and mechanical properties [2]. Several SPD methods have been introduced including equal channel angular pressing (ECAP) [3], accumulative roll bonding (ARB) [4], high pressure torsion (HPT) [5], cyclic extrusion compression (CEC) [6], and continuous repetitive corrugation and straightening (CRCS) [7]. However, studies on SPD of tubular-form metals are confined to processes of tube channel pressing (TCP) [8,9], accumulative spin-bonding (ASB) [10], high pressure tube twisting (HPTT) [11], and tubular channel angular pressing (TCAP) [12,13].

Among various methods for producing UFG materials, friction stir processing (FSP) has recently attracted growing attention [14,15]. The SPD resulting from stirring action of the process tool in the stir zone associated with the elevated temperature caused from friction between the surfaces of the process tool and the base metal as well as the deformation-induced heating leads to the dynamic recrystallization [16]. This phenomenon is responsible for forming UFG structures. Based on this process, a novel approach, i.e. friction stir back extrusion (FSBE), was developed by Abu-Farha [17] for creating tubes with fine-grained microstructure. In FSBE, a non-consumable rotating tool is plunged into the base metal round bar specimen constrained in the die. The combined rotational/axial motion of the rotating tool causes the stirred material to back-extrude as a tube. Abu-Farha [17] reported that this process is able to form tubular metals with fine-grained structure as it induces SPD at high temperature. For more details about FSBE process refer to [17].

Since traditional SPD processes are often carried out at ambient temperature, a relatively high load is needed for forcing the material to flow in the die. Moreover, rigidity of the equipment is also restricted. Considering these limitations, the size of SPD products is small and no routine industrial applications can be found [18]. Also, metals after SPD possess very low ductility in most cases [19]. However, it has been reported that UFG materials produced by FSP exhibit suitable ductility [20]. Hence, it is expected that tubular metals produced by FSBE process, as a method based on FSP, show more elongation than those produced by common SPD processes for tubes such as TCP and HPTT. In addition, although FSBE process is carried out at ambient temperature, frictional heat as well as heat induced by deformation in the FSBE process leads to facilitate material flow in the die. As a result, the load needed to accomplish FSBE process may be remarkably less than that needed for common SPD and cold extrusion processes for tubes.

Given the widespread applications of the tubular metals in aerospace, automobile and petroleum industries, and the limited data regarding FSBE process (despite its expected advantages), it seems that further studies on this process is necessary. Hence, the aim of present work is to investigate in more detail the microstructural evolutions and mechanical properties of tubular aluminum formed by FSBE process.

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2. Experimental procedures

In this work, round bars of an aluminum alloy with the nominal weight composition of Al–2.8 Si–1.99 Fe–1.16 Cu–0.01 Mg–3.12 Zn and the diameter of 20.7 mm were used as the starting material. FSBE process was utilized to form tube from as-received round bars. The schematic illustrations of the stirring tool and the die used in this study are presented in Fig. 1(a) and (b), respectively. The stirring tool for conducting FSBE process was prepared from H13 tool steel with the diameter of 17 mm. Moreover, an extruding die made of DIN 1.2344 (AISI H13) steel including an overall central cavity with the diameter of 21 mm, resulted in the clearance of 2 mm from outer surface of the stirring tool, was used. To ease the upward material flow during FSBE process, the hole was created by 3 passes of wire cut technique leading to a fine surface finish. Also, surface of hole was lubricated by MoS_2-suspension prior to FSBE process to facilitate the specimen extraction after the process. It should be pointed out that according to Fig. 1(b), a two-part die was used in this study in a different design from the two halves die employed by Abu-Farha [17].

For conducting the process, first, the initial round bar with a height of 50 mm was inserted into the die cavity. Then, stirring tool with rotation speed of 1600 rpm was driven downwards against the specimen with axial feed rate of ~40 mm/min. The mentioned process parameters were selected in the light of the primary experiments and the research carried out by Abu-Farha (rotation speed of 2000 rpm and axial feed rate of 120 mm/min) [17]. However, due to the limitation of our FSP machine, it was not possible to set the rotation speed of 2000 rpm; so, the rotation speed of 1600 rpm was used and to create the sufficient heat for softening of the material, the lower axial feed rate of 40 mm/min was employed. However, it is worthy to note that the rotation speed was chosen high enough that the material could be soften easily. The higher rotation speed can make material flow easier as a result of more heat input applied during FSBE process; but it should be considered that this can lead to the more grain growth and decrease in the mechanical properties of the formed tube in addition to the sticking between the material and the processing tool [21] as well as more energy consumption. Also, axial feed rate was considered as high as needed for material flow at the clearance between the rotating tool and die wall. The lower axial feed rate can cause to apply excessive heat input corresponding to more grain growth and decrease in the mechanical properties. On the other hand, high values of axial feed rate may lead to the high processing vertical forces, which may exceed the equipment limits [21]. When the tool tip reached to the height of 10 mm from the bottom surface of the die cavity, the tool was retracted while maintaining its rotational speed. During the FSBE process, thermal profile was measured by setting the thermocouple in the hole located at the center of cylinder height and had a 1.5 mm distance from the die cavity, as shown in Fig. 1(b) and (c). Finally, the processed sample was extracted from the die by separating the bottom plate of the die and tapping at the bottom side of the specimen.

For microstructural examinations, the cross section of the formed tube (Fig. 2) was prepared by standard grinding and polishing procedures. Then the sample was electroetched by a solution of 4.5 ml HBF_4 + 200 ml distilled water at voltage of 20 V. In addition, Vickers microhardness test, along two lines of AA′ and BB′ shown in Fig. 2, was performed by a load of 50 g applied for 15 s. Step sizes used for acquired microhardness data along paths of AA′ and BB′ were 100 μm and 200 μm, respectively with the start point which had 100 μm distance from the inner surface of the processed tube. To evaluate the mechanical properties of the formed tube, tensile test was carried out. For comparing mechanical properties of the formed tube with those of the starting material, the round bar was machined to create a tube with similar shape of the sample fabricated by FSBE process. In other words, in order to be able to compare the flow stress curves of the base material and the processed sample and to eliminate the shape effect of the tensile test specimen on the mechanical behavior during tensile test, the same geometry and dimensions were used for tensile test specimens. Three tensile test specimens were machined from each tube according to ASTM: E8-M with gauge length of 32 mm (Fig. 3).

3. Results and discussion

The thermal profile measured during FSBE process is shown in Fig. 4. As depicted, the peak temperature during FSBE process is about 390 °C. As previously described, the thermocouple is preplaced at the height of 50 mm where the top surface of the initial bar is located. When rotating tool reaches the surface of the bar, the temperature rises as a result of frictional and plastic deformation heat. The increase in the temperature continues until the rotating tool passes the thermocouple location during its retracting. Since the rotating tool is continuously in contact with the processed tube, frictional heat can progressively enhance the temperature. It should be pointed out that the acquired temperature profile cannot be considered as a representative of the heat cycle in any region of the specimen, particularly the area beneath the rotating tool. However, a relatively same thermal profile can be experienced at any region in the wall of the processed tube with different peak temperature [22].

3.1. Microstructure

Fig. 2 shows the macrograph of the specimen after FSBE process indicating the part of the base bar from which the tube was made

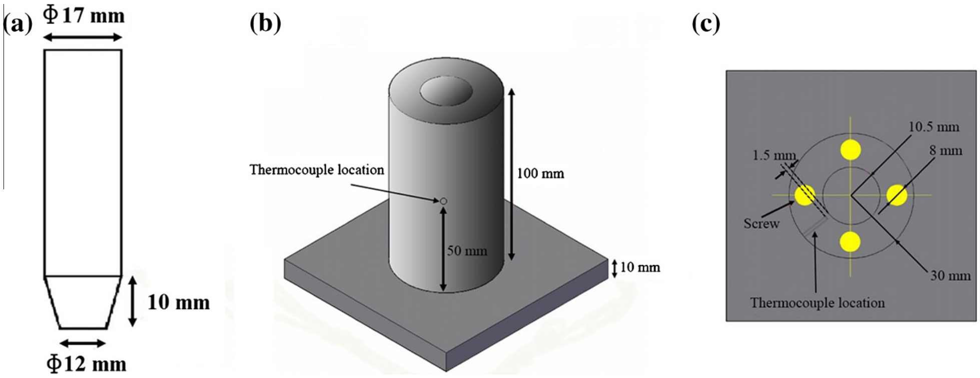

Fig. 1. The schematic illustrations of (a) the FSBE tool, (b) and (c) the general and bottom view of the die, respectively.