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Evaluation of mechanical and metallurgical properties of AZ91 seamless tubes produced by radial-forward extrusion method

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A B S T R A C T

Radial forward extrusion (RFE) is a suitable method for producing large diameter seamless tubes with superior properties from smaller cylindrical billets. Material flow along the radial and forward channels causes large effective strains and consequently improved mechanical and metallurgical properties of the final tube. In this study, isothermal RFE process was applied to a commercial AZ91 magnesium alloy at 300 °C, and the mechanical properties and microstructure evolution were examined. Due to severe plastic deformation at 300 °C, dynamic recrystallization occurs, and equiaxed grains were formed. The grain size was reduced to $\sim 3\ \mu m$ from the initial value of $\sim 150\ \mu m$. Yield and ultimate strength were increased by 3.2 and 2.6 times compared to the initial values, respectively. Though, the resulting properties from RFE are similar to those of hot extruded AZ91. Besides, elongation was increased up to 2 times after the RFE process. Microhardness was also increased to 88 Hv from the initial value of 52 HV. Good homogeneity of effective strain and microhardness in the longitudinal section was observed while force requirement is dramatically reduced compared to the conventional extrusion. The RFE process seems to be a very promising extrusion process for producing fine-grained seamless tubes.

1. Introduction

Extrusion is one of the main metal forming processes having industrial applications for producing different parts with various shape. There are several basic categories of extrusion process including forward (direct), backward (indirect) and radial (lateral). Combined extrusion process is a combination of two or three of these processes. Some methods of combined extrusion are double backward extrusion [1], backward forward extrusion [2–5], radial backward extrusion [6,7], radial forward extrusion [8–10] and forward backward radial extrusion [11]. These processes have the capability of producing complex components through one stage. Porthole extrusion and piercing extrusion could be used for producing hollow extruded samples from light metals such as aluminum and magnesium alloys. Of them, piercing extrusion could be used for producing seamless tubes. Though seamless tubes could be produced using conventional extrusion process, this method may not produce high strength fine-grained tubes. In the last few years, several methods based on severe plastic deformation (SPD) were provided to improve the mechanical properties of the tubes via grain refinement. Tubular channel angular pressing (TCAP) and parallel tubular channel angular pressing (PTCAP) processes were introduced by Faraji et al. [12,13]. The tube channel pressing (TCP) process was introduced by Zangiabadi et al. [14] and tube cyclic expansion extrusion (TCEE) was developed by Babaei et al. [15]. These methods can be used only for ready tubes previously been produced by extrusion or drawing processes. The current authors developed a novel plastic deformation method of new backward extrusion which is combined radial and backward extrusion suitable for processing of high strength tubes from cylindrical billets [16,17]. Similarly, the combination of radial and forward extrusion method applies an intense plastic deformation to the material. This is capable of producing seamless tubes with superior properties from a small billet. Also, producing large diameter tubes from smaller cylindrical billets is another feature of RFE process. Lee et al. [8] simulated RFE process by finite element method (FEM) and investigated the effect of geometrical parameters on the required force. Ebrahimi et al. [9] used an analytical approach to evaluate the impact of geometrical parameters and friction. Limited experimental studies were conducted on RFE process for producing seamless tubes emphasizing on microstructure and mechanical properties. Considering the need for high strength tubes in a broad range of industrial applications, RFE has the capability of producing them by only a single step. Experimental work considering the mechanical and metallurgical characterization of tubes processed by RFE process was found to be rare in the literature.

This paper proposes RFE as a suitable process for producing

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high strength and fine-grained seamless tubes. To demonstrate the applicability of this method, microstructure and mechanical properties of AZ91 magnesium alloy was investigated.

2. Experimental and FEM procedures

A schematic of RFE process is shown in Fig. 1(a). Unprocessed billet constrained by the mandrel and the outer die is extruded into the annular gap until it reaches the tube outer diameter. Then, the material is extruded 90° annular channel and the tube forms around the mandrel. In the present work, AZ91 magnesium alloy with a composition of Al 9.1 wt%, Zn 0.68 wt%, Mn 0.21 wt%, S 0.085 wt%, Cu 0.0097 wt%, and Mg bal. was employed. The unprocessed billet with 20 mm diameter and 30 mm length were machined from as-cast ingots. Radial-forward extrusion die, punch, mandrel, and other components were manufactured from H13 hot-worked tool steel and hardened to 55 HRC. MoS_2 Lubricant was sprayed on the specimen and die to reduce the friction [18]. Geometrical parameters for RFE were shown in Fig. 1(b). Die parameters are as following: $R_0=10$ mm, $R=15$ mm, $R_i=12$ mm, $R_d=H=3$ mm and $R_m=0$. The process was conducted at 10 mm/min pressing speed at 300 °C in the isothermal state after applying the MoS_2 spray lubricant on the billet and die surfaces. To do so, an electric heater was used around the die during processing to certify isothermal forming condition. Also, a thermocouple was installed near the initial billet that measured the temperature during processing. So, the temperature of the billet is kept constant during the process. The temperature variation during the process was kept at 300 ± 5 °C. Microhardness of the samples was measured at both cross sections of parallel and perpendicular to the tube axis with a load of 200 g applied for 10 s Tensile properties of the processed tubes were investigated using the tensile test at room temperature. Gauge length, gauge width, gauge thickness, radius length of grip section and width of grip section of the tensile test samples were 13 mm, 4 mm, 3 mm, 3 mm, 45 mm, 13 mm, respectively. Microstructural investigations were also carried out with general metallographic methods. FEM method was used to investigate the deformation behavior of the specimen in RFE process. Due to the symmetry of the process, Deform-2D simulation was used. The geometrical dimensions of the specimen and die component in the simulation of the process were considered to be the same as an experiment. Mechanical properties of AZ91 alloy also were obtained through a compression test at a strain rate of 2.5×10^{-1} at 300 °C. The stress-strain curve extracted from the compression test at 300 °C (identical to the RFE process) was used in the simulations. Whereas the RFE test was done in isothermal condition and relatively low speed of 10 mm/min, so the temperature variation effect during the process was neglected in FE simulations. 1400 elements with four nodes were employed in the model. Also, an automatic remeshing method was employed to adapt the imposed large strain and increased the accuracy of the results. All components of the die set were modeled as rigid parts, and the Coulomb friction coefficient was assumed to be 0.05 [13].

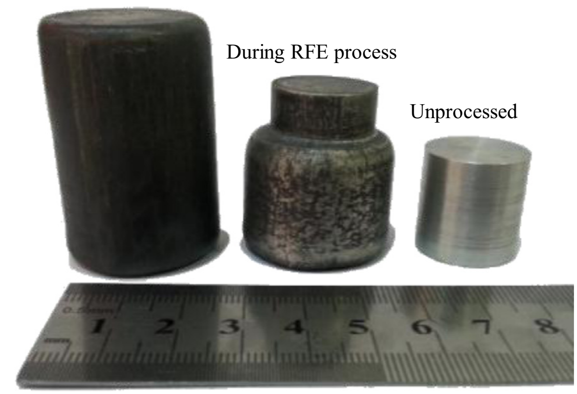

Fig. 2. An AZ91 workpiece from the initial unprocessed billet before the process, during the process and at the end of RFE process.

3. Results and discussion

Fig. 2 shows AZ91 workpieces in the forms of unprocessed initial unprocessed billet, during the process and final processed tube at the end of RFE process. As indicated in Fig. 2, an unprocessed billet in the RFE process becomes to a seamless tube with a larger diameter.

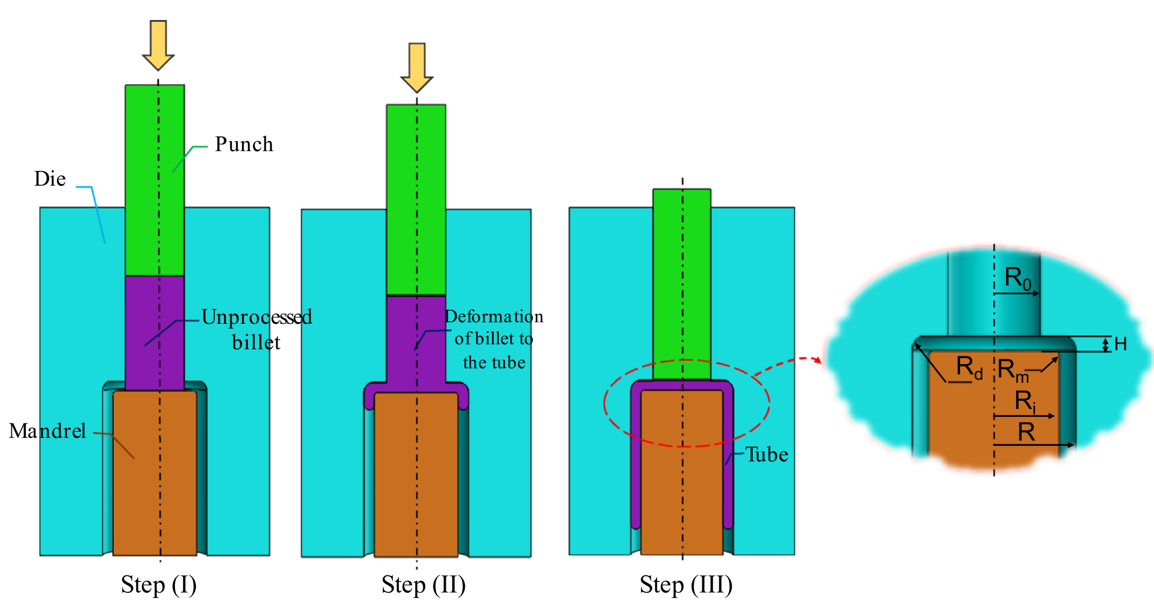

Fig. 1. Schematic of RFE process and die parameters.