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

S.S. Jamali, G. Faraji,* K. Abrinia

School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran 11155-4563, Iran

1. Introduction

Extrusion is one of the main metal forming processes having industrial applications for producing different parts with various shapes. 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 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 producing 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 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. MoS2 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, \( R_1 = 12 \) mm, \( R_0 - H = 3 \) 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 MoS2 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 \( 2.5 \times 10^{-3} \) 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].

### 3. Results and discussion

Fig. 2 shows AZ91 workpieces in the forms of unprocessed initial as-cast AZ91 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.

#### 3.1. Microstructure

Fig. 3(a) shows a cross section of the workpiece parallel to the longitudinal axis during the process. The microstructure of the initial as-cast AZ91 is shown in Fig. 3(b), which contain large grains of \( \alpha \) phase embedded within conjunct nets of \( \beta \) phase. \( \alpha \) phase is a typical dendritic structure with a significant amount of Mg, and \( \beta \) phase (characterized by bright colors in Fig. 3(b)) contains \( \text{Mg}_17\text{Al}_12 \) intermetallic, that is brittle and hard phase [12,19]. The dark regions around the grain boundaries are \( \alpha \) eutectic phase with a higher amount of Al than \( \alpha \) phase. Fig. 3(c) and (d) shows the microstructure of AZ91 after RFE (zone “c” shown in Fig. 3(a)). Since large effective...
strain applied to the specimen at 300 °C, dynamic recrystallization, and equiaxed grains occurs [18]. According to the figures, the RFE process could significantly refine the microstructure. The grain size was refined from an initial value of ~150 µm to ~3 µm after RFE process.

The material flow of the regions of “a”, “b” and “c” (Fig. 3(a)) are shown in Fig. 4(a), (b) and (c), respectively. Material flow into the radial and direct channels create elongated grains. Due to high compressive stress, elongation rate near the mandrel is more than other regions [20]. Fig. 3(e) and (f) shows the microstructures related to the regions “a” and “b” (Fig. 3(a)), respectively. Compressive deformation mode is applied to specimen before entering into the radial channel, so there is no effect on grain refinement shown in Fig. 3(e). Comparison of the microstructures of Fig. 3(b) and (e) show that low amount of intermetallic Mg17Al12 is partially dissolved in α eutectic phase [19]. Fig. 3(f) shows the microstructure of AZ91 in the radial channel. Elongated grains, distribution of β phase in α phase and some unrecrystallized zones are observed in this figure.

Fig. 3(c) shows the microstructure of the region labeled “c” in Fig. 3(a). Dynamic recrystallization and finer grains observed in the forward channel as a result of large effective plastic strain and process temperature. From Fig. 3(b) and (e) it is clear that the grain size had a high dependence on the effective strain level applied to the AZ91 alloy [12,21,22].
3.2. Microhardness

Microhardness changes of the AZ91 alloy during RFE process were shown in Fig. 5. Fig. 5(a) displays the microhardness of the sample cross sections at parallel and perpendicular to axis directions compared to the initial value. RFE processing causes microhardness increase to 88 Hv from the initial value of 52 Hv. Also, the increasing of the microhardness is almost similar in both parallel and perpendicular to axis cross sections. Fig. 5(b) shows microhardness values at regions labeled in Fig. 3(a). With increasing of the plastic strain, the microhardness is increased during the process. It can be said that in magnesium alloys having hexagonal closed packed (hcp) crystal structure with a limited number of slip systems [23], hardness has a strong dependency on the grain size. Also, the grain refinement is affected by the value of effective strain that plays an important role in the microhardness enhancement [12,15]. Fig. 5(c) and (d) shows microhardness changes in the across length and thickness of the tube. The value of fluctuations in the microhardness curve is less than ten percent. These fluctuations are related to the brittle phase (Mg17Al12) in the grain boundaries and unrecrystallized zones in the microstructure which have different hardness values. Fluctuations in the microhardness curves are also affected by the non-uniform distribution of grain size [12]. Microhardness of the tube has good homogeneity in the across length of the tube. Due to the existence of a higher fraction of elongated small grains in the inner wall of the tube (Fig. 4(a–c)), the microhardness is greater than that in the outer wall.

3.3. Tensile property

True stress-strain curves of unprocessed AZ91 alloy and processed tube are shown in Fig. 6. The yield strength (YS), ultimate tensile strength (UTS) and elongation (EI) were increased significantly. Tensile property variations are shown in Table 1. YS, UTS, and elongation were increased about 3.2, 2.6 and 2 times compared to the initial value, respectively. For engineering and industrial applications combination of higher strength and elongation simultaneously is demanded. Distribution of the intermetallic Mg17Al12 phase and also the grain refinement caused improvement in the mechanical properties of AZ91 alloy [15,20]. Due to the distribution of the intermetallic Mg17Al12 phase, reducing the size of grains and formation of equiaxed grains, both strength and ductility were increased in comparison with the unprocessed sample. As is pointed out, RFE is a combined method of producing large seamless tube and material flow along the radial, and forward channels causes large effective strains which cause grain refinement and improvement of mechanical properties in the final tube in comparison with the unprocessed state. Table 2 shows YS, UTS, and ductility of RFE processed tube compared with those from SPD methods for AZ91 alloy. As shown, relatively higher strength and ductility was achieved from RFE process as compared with that from equal channel angular pressing (ECAP) which is one of important SPD methods. At the same time, the strength and ductility are a bit lower than that from TCAP process [24]. A negligible more strength may be attributed to the higher compressive stress in TCAP process compared to RFE, which leads to a saturated mean grain size of about 1 µm. Though, the resulting properties from RFE are higher
Fig. 5. (a) Microhardness changes of AZ91 alloy before and after RFE process, (b) Microhardness values in the different positions (shown in Fig. 3(a)), (c) microhardness vs. distance from RFE processed tube end, and (d) changes in microhardness along the tube thickness.

Table 1
Mechanical properties of AZ91 alloy initial specimen and final tube.

<table>
<thead>
<tr>
<th>Sample</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As received</td>
<td>73</td>
<td>123</td>
<td>3.9</td>
</tr>
<tr>
<td>RFE processed</td>
<td>235</td>
<td>325</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Fig. 6. True stress versus true strain of unprocessed and final tube after RFE process at room temperature.

Table 2
YS, UTS, and ductility of RFE processed tube in comparison with those from hot extrusion and SPD methods at 300 °C.

<table>
<thead>
<tr>
<th>Processing method</th>
<th>Effective strain rate (S⁻¹)</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>Ductility (%)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFE</td>
<td>3.58</td>
<td>10⁻⁴</td>
<td>235</td>
<td>325</td>
<td>7.7</td>
</tr>
<tr>
<td>TCAP</td>
<td>2.67</td>
<td>2*10⁻⁵</td>
<td>245</td>
<td>–360</td>
<td>7.2</td>
</tr>
<tr>
<td>TCEC</td>
<td>1.92</td>
<td>5*10⁻⁴</td>
<td>184</td>
<td>292</td>
<td>7.5</td>
</tr>
<tr>
<td>ECAP</td>
<td>–</td>
<td>5*10⁻⁴</td>
<td>205</td>
<td>–300</td>
<td>6</td>
</tr>
<tr>
<td>Hot extrusion</td>
<td>–</td>
<td>–</td>
<td>330</td>
<td>9</td>
<td>[25]</td>
</tr>
</tbody>
</table>

than that of as cast state but the properties are similar to those of hot extruded AZ91 [25].

3.4. FEM

Fig. 7(a–c) show the effective strain contours at different stages of RFE process. As is shown in Fig. 7(a) severe deformation occurs at the material when flows into the radial channel and the material experiences a higher amount of strain in the area near the mandrel. According to the Fig. 7(b) and (c), when the material flows into the forward channel, the severe plastic deformation is applied. Due to high compressive stresses on the inner walls of the tube, the value of effective strain imposed in these regions is more than other areas. Fig. 8(a) the change of effective strain at the selected nodes of p1-p5 (shown in Fig. 7(d)). As is seen, the effective strain in the inner wall of the tube is more than other regions. When moving to the outer wall, the effec-
could be seen in the sample processed by conventional extrusion in comparison with that by RFE. Fig. 8(a) and (b) shows the history of strain variation of selected nodes (Fig. 7d and e) during the RFE and conventional extrusion processes, respectively. As shown in all the selected nodes, the strain level in RFE processed sample is higher than that in conventional extruded one. It is well known that higher effective strain leads to more grain refinement and strength improvement [26]. However, as shown in Fig. 8(a), an average effective strain of about 3.58 in RFE process is achievable. Such a high amount of effective strain has not been already reported at the end of the first pass of any SPD processes. As an example, for TCAP [12], PTCAp [13] and also TCEE [15] which are suitable SPD processes for the tubes, the average effective strain values are 2.67, 3.24 and 1.92, respectively. Meanwhile, these SPD methods are useable for initial tubes, but the RFE process is used for the unprocessed billets.

![Fig. 7](image)

**Fig. 7.** (a), (b), and (c) effective plastic strain contours at different stages of RFE, (d) the selected nodes in the specimen, before and after RFE process.

The effective strain is reducing so there would be some inhomogeneity through the cross section of the tube. This issue appeared in the microstructure of the material seen in Fig. 4(b–d). Elongation of material and grain refinement in the inner wall of the tube and regions close to the mandrel are more than others because of applying large effective strain [15]. This issue is also validated by microhardness variation shown in Fig. 5(d). Generally, with increasing of the compressive stresses in the regions of deformation, as the value of effective strain increases, grain refinement, and mechanical properties are improved.

Fig. 7(e) shows the effective strain contour of the tube processed by conventional extrusion. As shown, relatively lower plastic strain
Fig. 8. Effective plastic strain curves correspond to selected nodes of (a) RFE (Fig. 7 (d), (b) conventional extrusion processed samples (Fig. 7 (e), and (c) path plot of the effective plastic strain through the thickness of the processed tube via RFE and conventional extrusion processes.

Fig. 9. FE calculated local plastic strain rate variation of five selected nodes p1-p5 (Fig. 7. (d)) versus punch displacement during RFE.

Prior mechanical properties in final tubes while less force is needed compared to a conventional extrusion process.

Fig. 10. Experimental and FEM calculated force versus ram displacement during the RFE process.
Fig. 11. FEM calculated force versus ram displacement for RFE and conventional extrusion processes.

4. Conclusions

AZ91 alloy tubes were produced by RFE method at 300 °C, and mechanical and metallurgical properties were investigated. Following results could be concluded:

- RFE is a suitable process for producing larger seamless tubes from small billet.
- About 50% lower force is needed compared to the conventional extrusion process.
- The average effective strain of 3.58 was achieved.
- Large strain applying at high temperature caused dynamic recrystallization and dissolved Mg17Al12 phase.
- Significant grain refinement was achieved and the grain size reduces to ~3 μm from the initial size of 150 μm.
- Yield strength, ultimate strength, and microhardness were increased about 3.2, 2.6 and 1.5 times compared to the initial value, respectively.
- Though, the resulting properties from RFE are higher than as cast state but are similar to those of hot extruded AZ91.
- Dynamic recrystallization and equiaxed grains have increased elongation up to 2 times, compared to the initial value for AZ91 alloy.
- Simultaneous improvement of strength and ductility was obtained.

References