Effects of process parameters on microstructural evolution and properties of AZ61 alloy during hot extrusion

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Abstract. Extrusion testing of AZ61 alloys were conducted at deformation temperatures of 300°C to 410°C and extrusion ratios of 3, 10 and 16 respectively to optimize the process parameters. The experimental results show that deformation process parameters significantly affect microstructures and properties. Optical microscope observation shows that grains are refined greatly during hot extrusion and the mechanical properties are improved with increasing the extrusion ratio. For AZ61 alloy, the optimal extrusion temperature is 370°C. When deformation temperature increases, more slip systems participate in the plastic deformation, which leads to the decrease of the cleavage surface. After severe plastic deformation, a remarkable improvement of ductility of AZ61 alloy has been found. The ductile fracture mechanism is gradually dominant instead of brittle fracture with increasing the extrusion ratio.

1. Introduction
Magnesium alloys are widely used due to a series of advantages, such as the biological compatibility, the specific strength and stiffness, excellent process performance and corrosion resistance [1-3]. Due to the close-packed hexagonal structure and fewer slip systems, the magnesium alloy always exhibits low strength and limited ductility when produced by the traditional casting process and semi-solid process [4, 5]. Therefore, some plastic deformation process, such as extrusion, forging, and rolling has been applied for obtaining the high-quality products of magnesium alloy [6-16].

In this work, the extrusion process of AZ61 alloy was implemented under different deformation parameters. Based on the analysis of microstructures and mechanical properties, the optimal parameters for extrusion has been chosen, which provides the guide for its application in practice.

2. Experimental procedures
The as-cast AZ61 alloy with chemical composition (wt.%) of Mg-5.93Al-0.66Zn-0.3Mn-0.14Si was used for extrusion test. The cylinder samples with a diameter of 40 mm and height of 60 mm were cut first and then homogenized at the temperature of 400°C for 12 hours followed by furnace cooling.

After homogenization, the samples were extruded according to the given scheme. A schematic drawing of extrusion process was shown in figure 1. The extrusion process was carried out at

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temperatures of 300°C, 350°C, 370°C, 390°C, and 410°C and extrusion ratio of 3, 10, and 16 respectively. Before the extrusion process, die was lubricated with MoS₂ and preheated. The die temperature was below 20°C compared with extrusion temperature. After the extrusion tests, the samples were mechanically polished and eroded in a solution including distilled water of 192 ml, oxalic acid of 4 ml and nitrate of 4 ml. Hardness was tested by HVS21000 type digital microhardness tester.

3. Experimental results and discussion

3.1. Homogenization process for AZ61 alloy

Figure 2 shows the XRD pattern of AZ61 alloy, which is mainly composed of the primary α-Mg and secondary eutectic Mg₁₇Al₁₂.

Figures 3(a) and 3(b) shows the microstructure of the as-cast AZ61 alloy and the microstructure after homogenization at temperature of 400°C for 12 hours respectively. In figure 3, the white structure represents α-Mg phase while the black is the eutectic Mg₁₇Al₁₂ phase. From figure 3(a), grains have a characteristic of coarse and dendritic structure with the average size of about 200 μm. The grain boundary is not clear. After homogenization, the morphology and the size of grain vary apparently as shown in figure 3(b).

3.2. Effect of deformation temperatures on microstructures and mechanical properties

Optical photomicrographs for AZ61 alloy at different deformation temperatures are shown in figure 4. It can be observed in figure 4(a) that the phenomenon of dynamic recrystallization appears when deformation temperature is lower than 300°C. Meanwhile, the microstructures consist of partially
recrystallized grains and coarse primary grains. From figure 4(b), the coarse primary grains at deformation temperature of 350°C are gradually replaced by dynamic recrystallization grains. The distribution of grains tends to be more homogeneous when the deformation temperature increases. In figure 4(c), the microstructures of samples extruded at deformation temperature of 370°C are fully recrystallized. As shown in figures 4(c) and 4(d), the recrystallized grains coarsen gradually with increasing of deformation temperature.

![Microstructures of AZ61 alloy at different extrusion temperatures](image)

**Figure 4.** Microstructures of AZ61 alloy at different extrusion temperature(a) 300°C; (b) 350°C; (c) 370°C; (d) 390°C; (e) 410°C.

Figure 5(a) shows the strength of samples extruded at different extrusion temperatures. It can be seen from the curve that tensile strength increases with increasing of deformation temperature when extrusion temperature is lower. Tensile strength reaches optimal value at extrusion temperature of 370°C. When the extrusion temperature is above 370°C, the strength of AZ61 alloy decreases.

Effects of extrusion temperatures on the elongation for AZ61 alloy are illustrated in figure 5(b). It can be found that elongation is low at temperatures lower than 300°C and increases gradually with
increasing of the deformation temperature. The elongation of AZ61 alloy reached 12% at extrusion temperature of 350°C and then decreases quickly when the deformation temperature increases above 370°C.

**Figure 5.** Curves of the mechanical properties vs. deformation temperatures for AZ61 alloy (a) strength; (b) elongation.

Compared figure 4 with figure 5, it can be concluded that the ideal mechanical properties are attributed to refined grains. The sample keeps finer and equiaxed grains at deformation temperature of 370°C and exhibits optimal strength and plasticity. In other words, for AZ61 alloy, the optimal extrusion temperature is 370°C.

3.3. Effect of extrusion ratio on microstructure and mechanical properties of AZ61 alloy

**Figure 6.** Microstructures of AZ61 alloy at different extrusion ratio (a) extrusion ratio of 3; (b) extrusion ratio of 10; (c) extrusion ratio of 16.

Figure 6 shows the optical photomicrographs of AZ61 alloy at different extrusion ratio. From figure 6,
it may be noted that dynamic recrystallization occurs and the grains become finer and equiaxed when the extrusion ratio increases. In other words, the microstructure of AZ61 alloy can be effectively refined by means of hot extrusion process.

Figure 7 illustrates the changing of the strength and elongation of AZ61 alloy with the extrusion ratio. It is clear that the strength and elongation increase gradually with increasing of the extrusion ratio when extrusion ratio is less than 10. When the extrusion ratio gets to 16, ultimate strength and elongation reach the ideal value of 345 MPa and 14% respectively.

Figure 7. Curves of the mechanical properties vs. extrusion ratios for AZ61 alloy (a) strength; (b) elongation.

Effect of extrusion ratio on the strength and elongation of AZ61 alloy is mainly related to extrusion parameter and characteristics of microstructures. When extrusion ratio is higher, grain refinement is enhanced, which leads to improvement of the mechanical property.

Figure 8. SEM morphology of AZ61 alloy at different extrusion parameters (a) 300 °C at extrusion ratio of 3; (b) 370 °C at extrusion ratio of 3; (c) 410 °C at extrusion ratio of 10; (d) 410 °C at extrusion ratio of 16.
3.4. SEM observation for fracture morphology

The SEM fracture morphology of AZ61 alloy after extrusion under different process parameters is shown in figure 8. At low temperature in figure 8(a), the cleavage surface and dimples, which are taken as mixed-rupture characteristics of brittle fracture and ductile features, can be seen on fracture surfaces. With increasing of deformation temperature, more slip systems participate in the plastic deformation, which leads to decreasing of the cleavage surface. Then, many fine dimples can be observed as shown in figure 8(b).

The number and depth of dimples increase apparently with increasing of extrusion ratio as shown in figures 8(c) and 8(d). The tear ridge of dimple is very small and uniform, which is typical characteristics of ductile features. Therefore, the remarkable improvement of ductility of AZ61 alloy can be obtained after severe plastic deformation. The ductile fracture mechanism is gradually dominant instead of brittle fracture with increasing of extrusion ratio.

4. Conclusions

The microstructure and mechanical properties for AZ61 alloy are affected by process parameters of extrusion temperature and extrusion ratio. Due to dynamic recrystallization, grain refinement has been enhanced, which is helpful to the improvement of mechanical property of AZ61 magnesium alloy. With increasing of the extrusion ratio, grains have been refined apparently and ultimate strength and elongation increase greatly as well. Then, the ductile fracture mechanism is gradually dominant instead of brittle fracture with increasing of extrusion ratio. So, it is necessary to extrude at high extrusion ratio to obtain ideal mechanical property of AZ61 alloy. It can be concluded that the optimal extrusion temperature for AZ61 alloy is 370°C.

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