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Influence of extruding temperature and heat treatment process on microstructure and mechanical properties of three structures containing Mg-Li alloy bars

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ABSTRACT

The Mg-Li alloy bars with density of 1.38 g/cm^3 as well as ultimate tensile strength of 329.2 MPa were fabricated. Simultaneously, an industrial process with convenience and low cost was developed. In the cast alloys, hcp-Mg was transformed gradually into bcc-Li with increasing Li content. During extruding at different temperatures, the dynamic recrystallization (DRX) in Mg-8Li-5Al-2Zn-0.5Y was weaker than Mg-5Li-5Al-2Zn-0.5Y and Mg-11.4Li-5Al-2Zn-0.5Y due to the mutual limitation between hcp-Mg (α) and bcc-Li (β). In the annealing process, abnormal grain growth in Mg-11.4Li-5Al-2Zn-0.5Y was found at 573 K, and a kind of regular dendritic structure was discovered in the coarse grains at 593 K. Additionally, a sort of solid solution strengthening behavior in bcc-Li was observed and enhanced remarkably the alloy strength (increased by ~160 MPa in maximum). Through controlling cooling velocity, a precipitation behavior could be achieved in the alloys. Through mathematical modeling with high accuracy, the relationships among microstructural evolution and alloy properties in the solid solution and precipitation processes were quantitatively analyzed and determined.

1. Introduction

Owing to its low density, high specific strength, good damping capacity, good formability and high energetic particle penetration resistance, Mg-alloys has attracted numerous attentions from the fields of aviation, aerospace, automobile, weapon industries, 3 C electronic components, etc. [1–5]. Nevertheless, shrinkage porosity, micro-porosity, poor corrosion resistance, poor thermal stability and low strength restrict its widespread applications in the national economy [6]. According to the Mg–Li phase diagram, when Li content is below 5.7%, the alloy consists of α-Mg phase. When the Li content is in the range from 5.7% to 10.3%, the alloy is composed of α-Mg and β-Li phases [6,7]. When Li content is more than 10.3%, the single β-Li phase exists in the alloy [8]. The Li addition reduces the axis ratio c/a of Mg crystal lattice, which makes a great contribution to improving the plastic deformation ability of Mg alloy due to activating more potential non-basal slip systems [9]. Addition of Al element could be acted as a catalyst for the solid solution and precipitation strengthening, and Zn addition could improve effectively the formability of Mg alloy due to its hcp structure identical to Mg. Thus, alloying of Al-Zn element is more popular with many researchers.

From the previous reports, many researchers almost concentrated on improving the mechanical properties of alloy, such as alloying strengthening [10–14], solid solution strengthening, ageing strengthening [15], equal channel angle pressing (ECAP) [16,17], extruding [18] and rare earth addition [19], etc. Thereby, they have accomplished some positive results. However, it has few reports on the industrial process with convenience and low cost as well as the semi-continuous casting process without vacuum protection for Mg-Li alloy. In the previous studies, we adopted alloying strengthening of low content and continuous warm rolling process to gain the sheets with good overall properties [20].

In this work, the fabrication method with convenience and low cost and theory study on novel high-strength super-light Mg-Li alloys were investigated.

2. Experimental procedures

This investigation involved the Mg-5Li-5Al-2Zn-0.5Y, Mg-8Li-5Al-2Zn-0.5Y and Mg-11.4Li-5Al-2Zn-0.5Y alloys. The chemical composition of the three alloys is listed in Table 1. The experimental materials used in this work were high pure Mg, Li, Al, Zn ingots (99.9%) and Mg-

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Table 1
Chemical composition of three alloys (wt%).

Designed composition	Actual composition
Mg-5Li-5Al-2Zn-0.5Y	Mg-4.58Li-4.65Al-1.91Zn-0.39Y
Mg-8Li-5Al-2Zn-0.5Y	Mg-7.83Li-4.86Al-1.89Zn-0.42Y
Mg-11.4Li-5Al-2Zn-0.5Y	Mg-11.26Li-4.73Al-1.94Zn-0.36Y

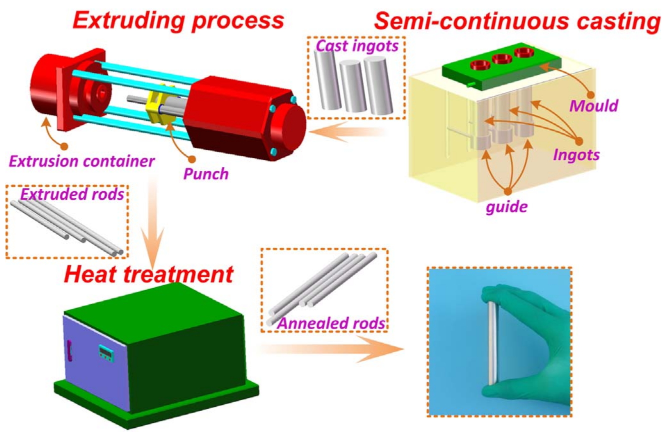

Fig. 1. Preparation diagram of Mg-Li alloy bars.

Table 2
The densities of the as-extruded alloys.

As-extruded alloy	Density (g/cm^3)
Mg-5Li-5Al-2Zn-0.5Y	1.61
Mg-8Li-5Al-2Zn-0.5Y	1.53
Mg-11.4Li-5Al-2Zn-0.5Y	1.38

25%Y master alloy. The alloys were melted in a resistance furnace with a graphite crucible under the protective atmosphere of SF_6 gas. Meanwhile, the covering flux was used to separate the melt from the air. At last, the original ingots were prepared by the semi-continuous casting process. After machined and homogenized, the ingots with size of Φ 48 mm × 110 mm were extruded into the rods at four temperatures (473 K, 503 K, 553 K and 623 K). The extrusion ratio was set as 17:1. Considering the requirement of material properties, the extruded rods were annealed at different temperatures for 24 h (553 K, 573 K and 593 K). Then the rods were cooled at different velocities (water quenching and 270 K/min, 4.5 K/min, 1.12 K/min and 0.32 K/min). The preparation diagram of Mg-Li alloy bars is shown in Fig. 1. The densities of the three extruded alloys are listed in Table 2.

The microstructural observation was performed by an optical microscope (OM) and a scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). The phase identification was analyzed by X-ray diffraction (XRD) using Cu K_α radiation. The tensile tests were performed on a universal testing machine at room temperature with initial strain rate of 1.4 × 10^{-3} s^{-1}. The tensile specimen size was in accordance with the standard of GB/T 228–2002. The Vickers hardness (HV) test was used to measure microstructure hardness with the loads of 25 g.

3. Results and discussion

3.1. Microstructure of as-cast and as-extruded alloys

Fig. 2 shows the microstructures and XRD patterns of the as-cast alloys. With increasing Li content (see Fig. 2a, c and e), the strong peak of hcp-Mg was gradually translated into that of bcc-Li. It illustrated that the addition of Li element influenced the lattice arrangement of Mg crystal. When Li content was 5%, the alloy was mainly composed of α-Mg phase, as shown in Fig. 2a and b. However, with Li increasing to 8%, the matrix primarily consisted of dual phase of hcp + bcc (α + β), as shown in Fig. 2c and d. When Li content was added to 11.4%, the single β-Li phase was predominant within the matrix, as shown in Fig. 2e and f. This structure transformation produced by Li addition would certainly generate the unusual properties. The reason of this structure transformation was that, in the solidification process, the increasing number of Li atoms resulted in the preferential nucleation of bcc structure whose nucleation rate might be faster than that of Mg structure.

Fig. 3 shows the microstructures of the Mg-xLi-5Al-2Zn-0.5Y alloys extruded at different temperatures (x = 5, 8 and 11.4). In Mg-5Li-5Al-2Zn-0.5Y, there existed a small amount of recrystallized grains in the range of 473–503 K (see Fig. 3a and d), indicating that the dynamic recrystallization behavior has taken place, in which the subgrains were gradually formed through atomic accumulation with assistance of increasing dislocation channels produced by deformation. The formation of recrystallized grain was attributed to the grain boundary diffusion. In the period of dynamic recrystallization, the subgrain boundary with small angle was transformed gradually into the ordinary grain boundary with big angle, which gave rise to the nucleus formation at the proper temperature. At 553 K (see Fig. 3g), the grain growth could be observed, which further illustrated the grain boundary diffusion became faster than before because the relatively high temperature could accelerated the atomic migration within the shorter time during the extruding process. The mean grain size at 553 K was measured as 5.5 µm. The grain growth at extruding temperature of 623 K was more obvious and the mean grain size was measured as 16.1 µm, as shown in Fig. 3j.

At 473 K, the α-Mg and β-Li phases of Mg-8Li-5Al-2Zn-0.5Y were apparently elongated and well distributed along the extrusion direction, as shown in Fig. 3b. It indicated that the addition of Li element improved apparently the alloy plasticity, implying that the deformation process became more amenable. During extruding at 503–553 K (see Fig. 3e and h), the dynamic recrystallization behavior has taken place in the β-Li phase, wherein the fine recrystallized grains at 553 K was measured as 6.2 µm. At 623 K, the recrystallized grain size in β-Li phase did not reveal the obvious increase, as shown in Fig. 3k. This could be explained that, during isothermal extruding, α-Mg atoms were aggregated around the region with high distortion energy. Meanwhile, its nucleation and subgrain combination were exhibited gradually along with the atomic diffusion, which promoted the dynamic recrystallization of the α-Mg phase. Thereby, the grain growth in α-Mg phase limited the development of β-Li grains.

In Mg-11.4Li-5Al-2Zn-0.5Y, the clear β-Li grain boundary could be observed in the range of 473–503 K (see Fig. 3c and f). At 553 K, the coarse grains generated by dynamic recrystallization emerged in the matrix. Simultaneously, the mean grain size was measured as 8.5 µm, as shown in Fig. 3i. When extruding temperature was 623 K, the grain size increased intensely to 65.4 µm, as shown in Fig. 3l. It illustrated that, in the extruding process, the dynamic recrystallization phenomenon became more obvious without the limitation of α-Mg phase. In this way, under the condition of continuous high dislocation density, the atomic diffusion and nucleation become more rapid than the dual-phase alloy.

Fig. 4 shows the XRD patterns of the Mg-xLi-5Al-2Zn-0.5Y alloys extruded under different temperatures (x = 5, 8 and 11.4). With increasing temperature, the phase category and amount did not revealed the marked variation in the extruding process, indicating that the extruding temperature would not affect the phase composition of Mg-Li alloy, as shown in Fig. 4a-c.

3.2. Microstructure of as-annealed alloys (after extruding at 553 K) cooled by water quenching

Fig. 5 shows the microstructures of the as-extruded Mg-xLi-5Al-2Zn-