Structure and Mechanical Properties of Mg-Zn-Mn Alloys Doped with Y Elements

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Abstract. Quaternary alloys with nominal components Mg-2Zn-0.3Mn-xY wt.% (x=0, 1, 2) were prepared by melting method. The structure and mechanical properties of as-cast, as-extruded and T6 heat-treated alloys were studied. The results show that the phases of as-cast alloys are mainly a-Mg matrix, with a small amount of MgZn₂ and Mg₃Y₂Zn₃ second phases. The addition of Y could refine the grains. After hot extrusion and T6 heat treatment, the grains were refined, and more second phases precipitated in the alloys. In the samples with same composition, the yield strength and tensile strength of the alloys increased with the order of as-cast, extrusion and T6 heat treatment, and the elongation decreased. For samples with different yttrium content, the higher the yttrium content, the higher the tensile strength and yield strength.

Introduction

Because pure magnesium has low strength and poor corrosion resistance, it cannot be directly used in structural materials. Aluminum, zinc, manganese and Zr are usually added to pure magnesium to form alloy materials with higher mechanical characteristics, which are widely used in transportation, electrical equipment, electronic components [1, 2]. In recent years, the addition and application of Yttrium (Y), Nd, Ce and other rare earth elements in magnesium alloys have received extensive attention. Related research results show that proper addition of rare earth elements can further improve the mechanical properties, corrosion resistance and thermal conductivity of the alloys [3-5]. Mg-Zn-Mn is a series of magnesium alloys which have been studied more recently. The main advantage of Mg-Zn-Mn series alloys is that they have good casting properties and their mechanical and physicochemical properties can be adjusted through deformation and heat treatment processes [5, 6]. At present, the content of Zn in Mg-Zn-Mn series alloys is generally about 2%, and the content of Mn is not more than 0.5%. However, the mechanical properties of Mg-Zn-Mn alloys cannot fully meet the application requirements at present. The main reason may be due to the low addition of rare earth element Y, which is generally less than 0.8% in weight.

For alloy materials, their structure and mechanical properties are intrinsically related. The structural characteristics mainly include the crystal structure of the material, the distribution of alloy phases and so on, while the factors affecting the alloy structure mainly include the addition of alloying elements and their processing technology. For magnesium alloys, the main processing technologies include casting, extrusion deformation and aging treatment [7, 8].

In this paper, the addition of rare earth Y in Mg-Zn-Mn alloy was increased to more than 0.8% (weight percentage). After as-cast magnesium alloy was prepared by melting process, hot extrusion and T6 heat treatment were carried out. The structure and mechanical properties of the materials in
different treatment states are studied, so as to further explore the influence mechanism of Y element addition on mechanical properties of Mg-Zn-Mn series alloys.

Experimental Procedures

The raw materials were commercial high-purity Mg (>99.98 wt.%), Zn (>99.95 wt.%), and two kinds of master alloys (Mg-30.25 wt.% Y and Mg-5.2 wt.% Mn). The nominal alloy composition was designed as Mg-2Zn-0.3Mn-xY wt.% (weight percentage content, x=0, 1, 2). Φ120 mm×400 mm as-cast Mg alloy ingots were firstly prepared via a melting process using a medium-frequency induction-heating furnace protected by Ar gas. The samples are marked as 1#, 2# and 3# based on the nominal Y content. The composition of the as-cast alloys was measured via an Aglient-5100 ICP-OES. Table 1 shows the ICP-OES measurement results. It can be seen that, for 2# alloy, its Y content is slightly lower than that of nominal component. For 3# alloy, the Y content is very close to the nominal component.

Table 1. Composition of Mg-Zn-Mn-Y alloys.

| Nominal components | Measured composition |
|--------------------|----------------------|
|                    | Zn  | Mn  | Y   | Mg  |
| 1#                 | 2.37| 0.36| 0   | Bal.|
| 2#                 | 2.20| 0.30| 0.83| Bal.|
| 3#                 | 2.19| 0.33| 2.00| Bal.|

Next, some of the as-cast alloy ingots were extruded into boards at 673 K, with an extrusion ratio of 9:1 and a billet speed of 2 mm/s under a controlled constant force with a 630 T horizontal extrusion machine. Thus the as-extruded alloy samples were obtained. Then some of the as-extruded samples were further conducted with T6 heat treatment process, which was 1.5 hrs at 673 K + 24 hrs at 448 K. T6 heat treatment belongs to a kind of aging treatment, by which some second phases would precipitate from the solid solution bases.

The structure characterization included investigating the crystal structure of the alloy samples and phases using an X-ray diffraction meter, observing the morphology characteristics of the samples via an optical microscopy (OM), a scanning electron microscope (SEM) equipped with an Energy dispersive X-ray spectrometer (EDS), respectively.

Results and Discussion

Fig. 1 shows the XRD spectra of as-cast, as-extruded and T6 treated alloys. It can be found that the diffraction peak of Mg matrix is dominant, indicating that the as-cast structure of the alloy is mainly α-Mg matrix with a small amount of second phase. Compared with Mg-Zn-Mn alloy, after adding rare earth Y, Mg3Y2Zn3 ternary phases appeared besides MgZn2 phases. Among them, the diffraction peaks of Mg3Y2Zn3 phase in 3# samples are stronger than those in 1# and 2# samples. This indicates that the amount of Mg3Y2Zn3 phase increases with the increase of Y content, that is, the volume fraction of Mg3Y2Zn3 phase in the alloy increases.

Compared with the as-cast alloys, the distribution and strength of the diffraction peaks of MgZn2 and Mg3Y2Zn3 second phases in the as-extruded alloys changed, and new MgZn2 and Mg3Y2Zn3 second phases precipitated during extrusion. Moreover, for alloys containing more Y, the diffraction peaks of Mg3Y2Zn3 ternary phase increase and the peak strength increases, which indicates that more Mg3Y2Zn3 ternary phase precipitates.

After T6 heat treatment, the intensity of the second phase diffraction peaks of MgZn2 and Mg3Y2Zn3 is further strengthened and the number of diffraction peaks is increased, which indicates that new MgZn2 and Mg3Y2Zn3 second phases precipitated, and the volume fraction of MgZn2 and
Mg$_3$Y$_2$Zn$_3$ in the alloy increased. Especially in the 3# alloy, the amount of precipitation of the two second phases is the largest.

Fig. 2 shows the metallographic structure of the as-extruded and T6 heat treated alloys. As can be seen from Fig. 2, the grain size rule of as-extruded (a, b, c) and T6 (d, e, f) treated alloys is $a > b > c$ and $d > e > f$. The results show that the grain size of Mg-Zn-Mn-Y quaternary alloy is obviously smaller than that of Mg-Zn-Mn alloy. With the increase of rare earth Y, the grain refinement becomes more obvious. In addition, compared with the as-cast samples, new second phases precipitated in the as-extruded alloys. Then more second phases precipitated in the T6 heat-treated alloys.

Figure 1. XRD pattern of Mg-Zn-Mn-Y alloy samples (a) as-cast, (b) as-extruded, (c) T6 heat-treated.
In order to verify the existence of the second phase in the alloys, the SEM microstructure of 2# alloy were observed. Fig. 3 shows the SEM photograph of the microstructure of 2# as-cast and T6 heat treated alloys. It can be seen from Fig. 3 that the grain size of as-extruded alloy is about 50 μm. After T6 heat treatment, more second phase precipitated. In addition, the distribution of the second phases can be seen in Fig. 3. Besides the distribution at the grain boundary, the second phases also exhibit dispersion distribution in the grain interior. These second phases include the large particles and small particles. The precipitation phase of large particles is shown by arrows A and B in Fig. 3. The precipitates in the form of small particles are extremely small nano-sized particles in the grain and at the grain boundary. Further EDS analysis of the large second phases indicated by arrows A and B in Fig. 3 showed that the large second phases were Mg$_3$Y$_2$Zn$_3$ ternary phase.

Fig. 4 shows the engineering stress-strain curve of the alloys. Firstly, the yield strength and tensile strength of as-cast samples are poor. With the increase of Y content in samples, the yield strength and tensile strength also increase. This is the result of increasing solid solution strengthening effect with increasing Y content [6]. In addition, the increase of Y element is beneficial to refine the grain size of the alloy, so fine-grain strengthening is also one of the strengthening factors. Secondly, compared with the as-cast samples, the yield strength and tensile strength of the as-extruded samples increased significantly. Because there are many second phases in the extruded samples, these second phases
distribute in the grain and play a role of dispersion strengthening. In addition, the grain size will be refined during extrusion, so the fine-grain strengthening also contributes to the enhancement of the strength of the alloy. Then, compared with the extruded samples, the strength of T6 heat treated samples is still significantly increased. Because there are more secondary phases precipitated in the grain of the alloy during T6 treatment, the dispersion strengthening effect is more obvious. It can be seen that the tensile strength of 3 # samples treated with T6 reaches 365 MPa. It is noteworthy that the elongation of as-extruded and T6 heat treated samples decreased, which is due to the fact that the second phases precipitated in the samples are brittle.

Summary

(1) The phases of as-cast Mg-Zn-Mn-Y alloy were mainly α-Mg matrix and a small amount of MgZn₂ and Mg₃Y₂Zn₃ second phases. Under extrusion and T6 heat treatment, the precipitation of the second phases in the samples increased. With the addition of rare earth Y, the grain size of the alloys was significantly refined.

(2) The mechanical properties of the alloys were studied. Compared with as-cast alloys, the yield strength and tensile strength of the as-extruded and T6 heat-treated alloys increased to a great extent, but the elongation decreased. T6 heat-treated alloys presented the highest the yield strength and tensile strength. The strengthening mechanism depends on fine-grain strengthening and dispersion strengthening. In the same sample state, the yield strength and tensile strength of the alloy increased with the increase of rare earth Y content, which indicates that the addition of Y can improve the mechanical properties of the alloy well.

![Figure 4. Stress-strain curves of as-cast, as extruded and T6 heat-treated alloy.](image)

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