Effect of T6 Treatment on the Microstructure and Properties of Mg-Zn-Ce with Different Zn Contents

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ABSTRACT:The alloy compositions and heat treatment processes of Mg-Zn-Ce were designed and formulated based on phase diagram calculations. Mg-5Zn-0.2Ce and Mg-7Zn-0.3Ce alloys with different Zn contents were prepared through rapid solidification and T6 treatment. The study showed that when the Zn content is less than its maximum solubility in Mg (6.2 wt.%), T6 heat treatment results in a coarse microstructure and the occurrence of secondary recrystallization. When the Zn content is greater than 6.2 wt.%, T6 heat treatment refines the grains and significantly improves the mechanical properties. However, T6 treatments will generally produce a large number of MgZn and $Mg_{12}Ce$ precipitates distributed within the Mg-Zn-Ce alloy microstructure. These precipitates greatly enhance the comprehensive mechanical properties of the alloy.

Keywords: Mg-Zn-Ce, microstructure, properties, T6 treatment, Zn contents

1 Introduction

Mg-Zn alloys possess advantages such as heat resistance and good biocompatibility, presenting a broad application prospect [1]. Although Mg-Zn alloys have high strength, their low ductility makes them prone to fracture under high-stress conditions, limiting their use in certain high-stress applications. Therefore, it is necessary to modify the material through alloying and process optimization. A series of Mg-Zn-based alloys with good overall mechanical properties have been developed, such as Mg-Zn-Al alloys, Mg-Zn-Cu alloys, Mg-Zn-Sn alloys, and Mg-Zn-RE (rare earth) alloys [2-5].

Among RE elements, Ce has abundant reserves, is inexpensive, has good ductility, and possesses a hexagonal crystal structure, which energetically favors co-segregation of Zn and Ce at grain boundaries. Therefore, adding Ce as a microalloying element to Mg-Zn alloys can significantly improve the strength and elongation of the alloys. However, Mg-Zn alloys exhibit significant grain boundary precipitation during aging, which is detrimental to the plasticity and fracture behavior of the alloy. Given that the maximum solubility of Zn in the Mg matrix is 6.2wt.%, it is necessary to explore the effects of appropriate solution-aging treatment processes on the microstructure and properties of Mg alloys with different Zn contents (up to about 6.2wt.% maximum solubility).

This study designed the optimal compositions of Mg-Zn-Ce alloys through phase diagram calculations and obtained Mg-5Zn-0.2Ce and Mg-7Zn-0.3Ce alloy materials using rapid solidification and T6 solution aging treatment processes. By observing the alloy microstructure and analyzing the elemental composition, the microscopic mechanisms of microstructure and property changes under the influence of different Zn contents were investigated. This provides theoretical guidance and experimental methods for the development and application of Mg-Zn-RE alloys.

2 Experimental procedure

The experimental alloy compositions selected based on phase diagram calculations were Mg-5Zn-0.2Ce and Mg-7Zn-0.3Ce. Additionally, to promote the precipitation of Ce-containing phases in the microstructure, Mn was added at a content of 0.04wt.%. After the alloy elements were uniformly mixed through melting, the melt was poured into a 200 ℃ preheated iron mold and rapidly cooled with cooling water to obtain the cast Mg-Zn-Ce alloy. Subsequently, the alloy samples underwent T6 heat treatment, which consisted of solutionizing at 450℃ for 6 hours and aging at 180℃ for 36 hours, resulting in four sets of alloy samples: Mg-5Zn-0.2Ce, Mg-5Zn-0.2Ce+T6, Mg-7Zn-0.3Ce, and Mg-5Zn-0.2Ce+T6, labeled as alloys 1#, 1-1#, 2#, and 2-1#, respectively.

3 Result and discussion

1. Microstructure Analysis

Figure 1 shows the microstructures of Mg-Zn-Ce alloys with different compositions before and after T6 heat treatment. From Figures 1(a) and 1(b), it can be seen that the average grain size of the Mg-5Zn-0.2Ce (1#) alloy is approximately 107 μm, and there is a network-like second phase at the grain boundaries. EDS analysis identified this second phase at the grain boundaries as the stable MgZn phase, with some Ce atoms adsorbed and Mn elements also gathered near the grain boundaries. After T6 treatment, the second phase at the grain boundaries in the 1-1# alloy disappeared, and the microstructure became significantly coarser (highlighted by the red dashed circles in Figure 1(b)), with an average size of about 310 μm. Additionally, remelting occurred at the grain boundaries, forming small-sized subgrains (highlighted by the black dashed circles in Figure 1(b)), with an average size of about 55 μm. T6 heat treatment also caused the precipitation of lamellar precipitates within the grains along a specific orientation (composition not identified), with a measured precipitation angle of approximately 130° (indicated by the white arrows in Figure 1(b), angles of 137.8° and 131.4°). Related studies in the reference [6] suggest that these phases might be LPSO phases. This could be due to Ce, as a rare earth element, forming LPSO phases with a long-period structure in the microstructure after aging treatment. These LPSO phases can impede dislocation motion, suppress basal plane slip, and increase the strength of the magnesium alloy.

From Figures 1(c) and 1(d), the grain size of the Mg-7Zn-0.3Ce (2#) alloy is about 106 μm, and the grain boundaries still feature a network-like MgZn phase, with rod-like $Mg_{12}Ce$ phases nearby. EDS atomic distribution analysis revealed that this phase nucleates on a Mn substrate. After T6 heat treatment, the grain size of the 2-1# alloy is about 110 μm, with minimal grain coarsening. The microstructure still contains lamellar precipitates, but their size is greatly reduced, and the precipitation angle remains around 130° (as indicated by the white arrows in Figure 1(d), angle of 131.3°).SEM and EDS analyses of the microstructures of the T6-treated 2-1# alloys (as shown in Figure 1(d)) indicate that the grain boundaries consist of island-like MgZn phases, and within the grains, there are point-like MgZn phases. Additionally, the rod-like $Mg_{12}Ce$ phase nucleates near the MgZn phase within the microstructure, both at grain boundaries and within the grains.

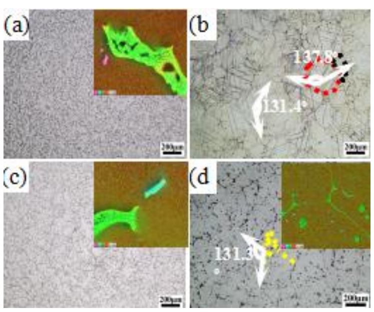

Figure 1. The microstructures of Mg-Zn-Ce alloys with different compositions before and after T6 heat treatment: (a)1#; (b)1-1#; (c)2#;(d)2-1#.

2.Mechanical Properties Analysis

Figure 2 shows the stress-strain curves for Mg-Zn-Ce alloys with different compositions before and after T6 heat treatment, and Table 1 provides the corresponding specific performance values. It can be observed that the strength and elongation of the Mg-5Zn-0.2Ce (1#) alloy deteriorate after heat treatment. This is due to the significant grain coarsening caused by the solution treatment in the T6 process. Additionally, the unstable interface connection between the subgrains at the grain boundaries and the large grains further reduces the overall mechanical properties of the alloy.

In contrast, the strength of the Mg-7Zn-0.3Ce (2#) alloy significantly increases after T6 treatment, reaching 215.95 MPa, while its plasticity slightly decreases to 4.04%. The minimal change in grain size after T6 treatment indicates that the aging treatment in the T6 process has produced an age-hardening effect. The substantial increase in alloy strength is primarily attributed to a significant amount of precipitates in the microstructure. However, the Mg12Ce precipitate phase formed in the microstructure is brittle, and an increased quantity of this phase can reduce the alloy's plasticity. This is the main reason for the reduced elongation observed in the 2-1# alloy.

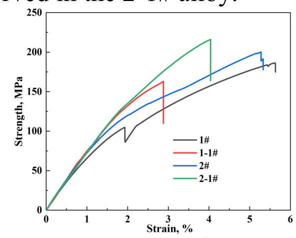

Figure 2. The stress-strain curves for Mg-Zn-Ce alloys with different compositions before and after T6 heat treatment.

Table 1. The strength and strain for Mg-Zn-Ce alloys with different compositions before and after T6 heat treatment

Properties	1#	2#	3#	4#
Strength(MPa)	183.78	162.98	198.60	215.95
Strain(%)	5.43	2.88	5.20	4.04

4 Conclusion

1) T6 solution and aging treatment significantly coarsens the grain size of low-zinc magnesium alloys and deteriorates their overall mechanical properties. For high-zinc magnesium alloys, T6 treatment greatly increases their tensile strength. Therefore, for Mg-Zn alloys, it is necessary to formulate an appropriate heat treatment process based on the Zn content.

2) Due to the higher Zn content and increased Ce content, the strength and elongation of Mg-7Zn-0.3Ce alloy are generally higher than those of Mg-5Zn-0.2Ce alloy before and after T6 treatment. This is because the substantial amount of secondary phases and precipitates in the microstructure has a strengthening effect on the alloy.

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