Improved age-hardening behavior of Mg–Sn–Mn alloy by addition of Ag and Zn

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ABSTRACT

The effect of 0.5 at% Ag and its combination with 0.4 at% Zn on the precipitation hardening behavior of Mg–1.5Sn–0.5Mn (at%) alloy have been investigated using hardness measurements and transmission electron microscopy (TEM). The results show that sole addition of Ag can remarkably improve the peak hardness from 58HV to 77HV after ageing at 200 °C, which is attributed to the increased number density, the size and so the volume fraction of the Mg_2Sn lath precipitates. A combination addition of Ag and Zn further improves the peak-hardness to 83HV and the time to peak hardness has been reduced from 120 h to 100 h. The joint addition of Ag and Zn both increases the number density and refines the Mg_2Sn precipitates. Zn also promotes the Mg_2Sn precipitates lying on the non-basal plane of matrix, as well as the blocky $Mg_{54}Ag_{17}$ phase which has an orientation relationship with α-Mg matrix as $(0\,0\,1)_{\varepsilon'}//(0\,0\,0\,1)_\alpha$, $[2\,0\,0]_{\varepsilon'}//[-1\,-1\,2\,0]_\alpha$, $[0\,-2\,0]_{\varepsilon'}//[1\,-1\,0\,0]_\alpha$. In the peak-aged Ag modified alloys, Ag atoms are segregated in the Mg_2Sn precipitates. Nucleation, growth and coarsening of the Mg_2Sn precipitates simultaneously occur as the ageing proceeds. The growth of Mg_2Sn precipitates exhibits a significant anisotropic behavior. Addition of Ag can promote the precipitation process during the under-age period and retarding the growth of Mg_2Sn during the overage period, leading to a more thermal stable microstructure of the Ag and Ag + Zn modified alloys, from which only a small hardness decrease after 700 h ageing is detected.

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1. Introduction

Owing to their low density and high damping capacity, Mg alloys have a great potential for applications in the aerospace, automobile and electronics industries [1,2]. The most widely used Mg alloys are based on a Mg–Al system, especially AZ91. Alloys in this system usually have excellent castability and reasonable mechanical properties for commercial use. However, they exhibit poor creep properties due to the relatively low melting point of the dominant $Mg_{17}Al_{12}$ precipitates and the low eutectic temperature [3]. Compared to the Mg–Al system, Mg–Sn system is more attractive in terms of the creep resistance, which is resulted from the presence of thermal-resistant Mg_2Sn intermetallics with high melting point of 770 °C, about 300 °C higher than that of the $Mg_{17}Al_{12}$ [3,4]. However, previous investigations indicated that the age-hardening behavior of binary Mg–Sn alloy is not satisfactory. Vander Planken [5] has reported a peak hardness of 62HV after 100 h ageing at 200 °C in Mg–1.65Sn (at%) alloy. Subsequent investigations using transmission electron microscopy (TEM) have demonstrated that this low peak hardness is attributed to coarse Mg_2Sn plates distributed sparsely on the basal plane of matrix [6–9].

According to the Orowan equation [10,11], which relates the critical resolved shear stress to the precipitate distribution, an effective way to improve the precipitation-hardening effect is to refine the precipitates distribution or to increase the volume fraction of precipitates. Since the volume fraction of the precipitates is limited by the solubility of Sn in α-Mg, previous studies to improve the peak hardness of the aged Mg–Sn alloys mainly focused on refining the precipitates. Micro-alloying is one of the most effective methods to refine the precipitates. Some micro-alloying elements such as Na [6], Li combined with In [6] and Zn [7,12,13] have been added to the Mg–Sn systems to improve its age-hardening behavior and their effects are remarkable. An addition of 0.13 at% Na to the Mg–1.3 at% Sn alloy can increase the peak-hardness from 47HV to 63.2HV, and an addition of 0.5 at% Zn to Mg–2.2 at% Sn lead to an increase of the peak-hardness from 62HV to 78.7HV [13].

Since the dislocation slip in Mg alloys mainly occur on the basal planes at ambient temperature [10], another way for strengthening the age-hardenable Mg alloys is to promote the formation the precipitates on the non-basal plane of α-Mg matrix, which is more effective in blocking the basal dislocation slip. The addition of Zn can increase the number of precipitates lying on non-basal planes [13]. A proper addition of Mn in Mg–Sn alloy can promote the β-Mn rod precipitates along the *c*-axis of Mg lattice [14]. However, due to the solubility limit of Mn in α-Mg matrix, the distribution of Mn is sparse.
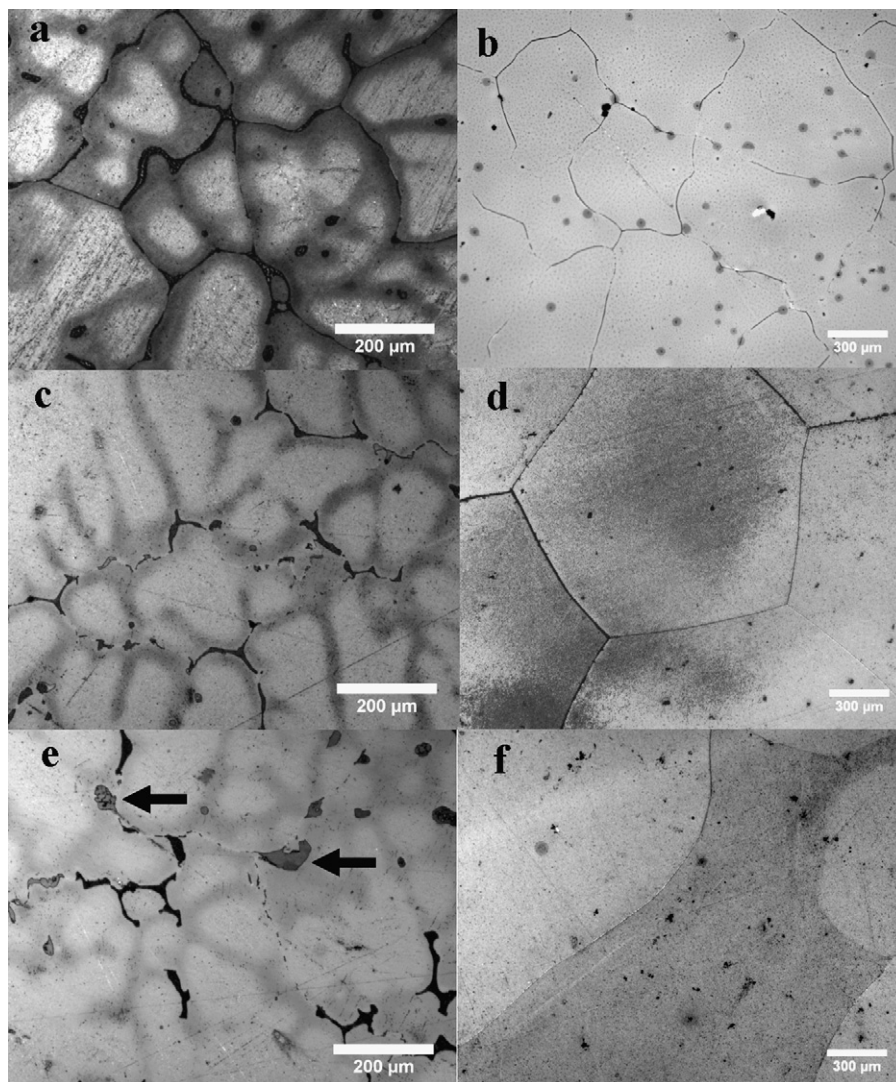
Fig. 1. Optical micrographs showing the microstructure of the as-cast and solution-treated samples of the Mg–1.5Sn–0.5Mn (a and b), Mg–1.5Sn–0.5Mn–0.5Ag (c and d), Mg–1.5Sn–0.5Mn–0.5Ag–0.4Zn (e and f) alloy.

In general, the peak-hardness of the modified Mg–Sn alloys are still lower much than that of Mg–Al alloys [15], Mg–Zn alloys [16] or Mg–RE alloys [17,18] after ageing at 200 °C. Ag is an effective element in enhancing the age-hardening response of some Mg alloys. A minor addition of Ag to Mg–Zn [16,19–21] and Mg–RE [17,18] alloys has remarkably enhanced the age-hardening response, indicating that Ag addition can strongly affect the precipitates process of different Mg alloys. However, the effect of Ag on the precipitation-hardening behavior of Mg–Sn alloys has not been reported.

The aim of the present study is to improve the age-hardening response of the Mg–Sn–Mn alloys by addition of Ag. A combination of a small amount of Zn with Ag (Ag + Zn) was also added to further improve its ageing response. The peak hardness of the Mg–1.5Sn–0.5Mn–0.5Ag–0.4Zn (at%) alloy can reach as high as 83HV after aged at 200 °C, which is comparable to that of AZ91. In addition, after 700 h ageing, the hardness still maintains 75HV, indicating a much better thermal resistance than that of the previously reported Mg–Sn alloys. The effect of Ag and Zn on the precipitation microstructure in these alloys has been also studied.

2. Experimental procedure

Alloys with nominal compositions of Mg–1.5Sn–0.5Mn (the base alloy), Mg–1.5Sn–0.5Mn–0.5Ag (the Ag-modified alloy), and Mg–1.5Sn–0.5Mn–0.5Ag–0.4Zn (the Ag + Zn modified alloy) in at% (Mg–7Sn–1Mn, Mg–7Sn–1Mn–2Ag and Mg–7Sn–1Mn–2Ag–1Zn in wt%) were prepared from pure (99.99%) Mg, Ag, Zn, and Mg–3Mn (wt%) master alloy by induction melting in a mild steel crucible in argon atmosphere and casting into a steel mould. Hereafter, all alloy compositions are described in at%. The ingots were solution-treated at 350 °C for 24 h and then 500 °C for 48 h in an Ar-filled pyrex tube, followed by quenching in water. An artificial ageing treatment was performed in a drying oven at 200 °C for various ageing time. The age-hardening responses were measured with a Vickers hardness tester under a load of 200 g. 7 hardness values were obtained for each sample of different ageing time. The maximum and minimum values were discarded and the average of the remaining 5 values was used as the measurement data for the samples. The error bars indicate the standard errors of the measurements. Samples for optical microscopy (OM) observations were prepared by mechanically grinding and polishing. They were