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# Effects of extrusion and Ag, Zn addition on the age-hardening response and microstructure of a Mg-7Sn alloy

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ABSTRACT

The effects of extrusion and macro-alloying of Ag and Zn on the age-hardening behavior and microstructure of a Mg-7Sn alloy were investigated. The results show that the extrusion process and extrusion combined with 2 wt%Ag or 2 wt%Ag+1 wt%Zn addition can significantly improve the hardness of the unextruded Mg-7Sn alloy from 46 HV to 52 HV, 72.5 HV and 77.5 HV, respectively at the unaged state. The strengthening effect is mainly attributed to the dynamic precipitation and much refined grain size obtained by the extrusion process. Due to the depletion of the alloying elements by dynamic precipitation, the hardness increments resulted from artificial ageing at 160 °C are almost equal (around 10 HV) for the base and macro-alloyed Mg-7Sn extruded alloys. The extruded alloys exhibit a bimodal grain size distribution containing major dynamically recrystallized fine grains and minor severely deformed coarse grains. There are two types of $Mg_2Sn$ precipitates. One is the spherical particles distributed randomly and the other is the laths formed within the matrix. Ag or Ag+Zn addition to the extruded Mg-7Sn alloy can significantly refine the size of $Mg_2Sn$ laths. Blocky ε'-$Mg_{54}Ag_{17}$ phase is also formed along grain boundaries in the extruded Mg-7Sn-2Ag-1Zn alloy.



## 1. Introduction

Nowadays, the development of high-performance magnesium alloys has received considerable attention for reducing the weight of transportation vehicles [1–3]. However, the majority of Mg alloys components available are cast products. Few applications of wrought Mg alloys have been explored because of the lack of formability of hexagonal Mg at ambient temperatures [1]. This leads to significantly restricted applications of Mg alloys. Another drawback of the commercial wrought Mg alloys such as ZK60 or AZ31 is the lower yield strength compared to their counterpart Al alloys [1]. One reason is that these commercial wrought Mg alloys cannot be strengthened by heat treatment such as solution and ageing treatment. Therefore, development of high-strength wrought Mg alloys is strongly desired.

Mg-Sn alloys have received increasing attention in the past decades due to their great potential for developing creep-resistant alloys and wrought alloy products [4–7]. However, the mechanical properties of the binary Mg-Sn alloy are poor [8]. Micro-alloying or macro-alloying is an effective way to improve the age-hardening response of the alloy. Various alloying elements, such as Na, In+Li [5], Zn [9,10], Ca [11], Ag [12] and Cu [13] have been added to Mg-Sn alloys to improve the strength. These alloying elements addition can significantly refine the size and increase the number density of the $Mg_2Sn$ precipitates. As a result, the precipitation-hardening effect is enhanced significantly.

It is well known that grain refinement is an effective way to improve the strength and ductility simultaneously. In order to further improve the properties of Mg alloys, wrought process such as the extrusion, forging and rolling was always employed. The wrought process can not only produce fine grain sizes associated with dynamic recrystallization [14–17], but can also introduce a high density of dislocations, which provide much more heterogeneous nucleation sites for precipitation. As a result, the age-hardening response can be enhanced remarkably [18,19]. These wrought processes have been applied to several age-hardening Mg alloys, and reasonable mechanical properties were obtained [18–22].

In a previous study, one of the present authors has shown that Ag and its combination with Zn are beneficial to both the age-hardening response and the thermal-resistance of Mg-Sn alloys [12]. In order to further improve the mechanical properties of the Ag and Zn modified Mg-Sn alloys, an extrusion process between solid-solution and ageing treatment has been employed in the present study, with the aim of both refining the grain size and enhance the precipitates density in the aged alloy.

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## 2. Experimental procedure

Alloys with nominal compositions of Mg-7Sn, Mg-7Sn-2Ag and Mg-7Sn-2Ag-1Zn (in weight percent) were prepared in an electric furnace under a mixture of $CO_2$ and $SF_6$, and cast into a steel mold. In order to prevent possible melting of the eutectics along grain boundaries, the cast alloys were solution-treated through a multi-step, i.e., firstly hold at 350 °C for 12 h, then 460 °C for 12 h and finally 480 °C for 12 h, followed by quenching into water. Cylindrical samples with a diameter of 40 mm were machined from the homogenized billets for extrusion. Prior to extrusion, the samples were pre-heated at 300 °C for 0.5 h in a resistance furnace. Then the direct extrusion experiments were carried out at an initial billet temperature of 300 °C, an extrusion ratio of 5, and a ram speed of 1 mm/s. Then the extruded samples were artificially aged at 160 °C in a drying oven for a maximum holding time of 1000 h.

The age-hardening response was measured with a Vickers hardness tester under a load of 200 g. Samples for optical microscopy (OM) and scanning electron microscopy (SEM) were etched in a solution of acetic picral (1 ml of acetic acid, 1.2 g of picric acid, 2 ml of water and 20 ml of ethanol). Phase constituents analysis was performed in a Bruker DW-1000 X-ray diffraction (XRD) machine. TEM specimens were prepared by twin-jet electropolishing in a solution containing 3 ml perchloric acid and 297 ml ethanol. Characterizations of the microstructure were performed in a TecnaiG$^2$ F20 TEM and JEOL 2100 TEM. For the sake of comparison, microstructure and mechanical properties of the Mg-7Sn alloy without extrusion were also examined.

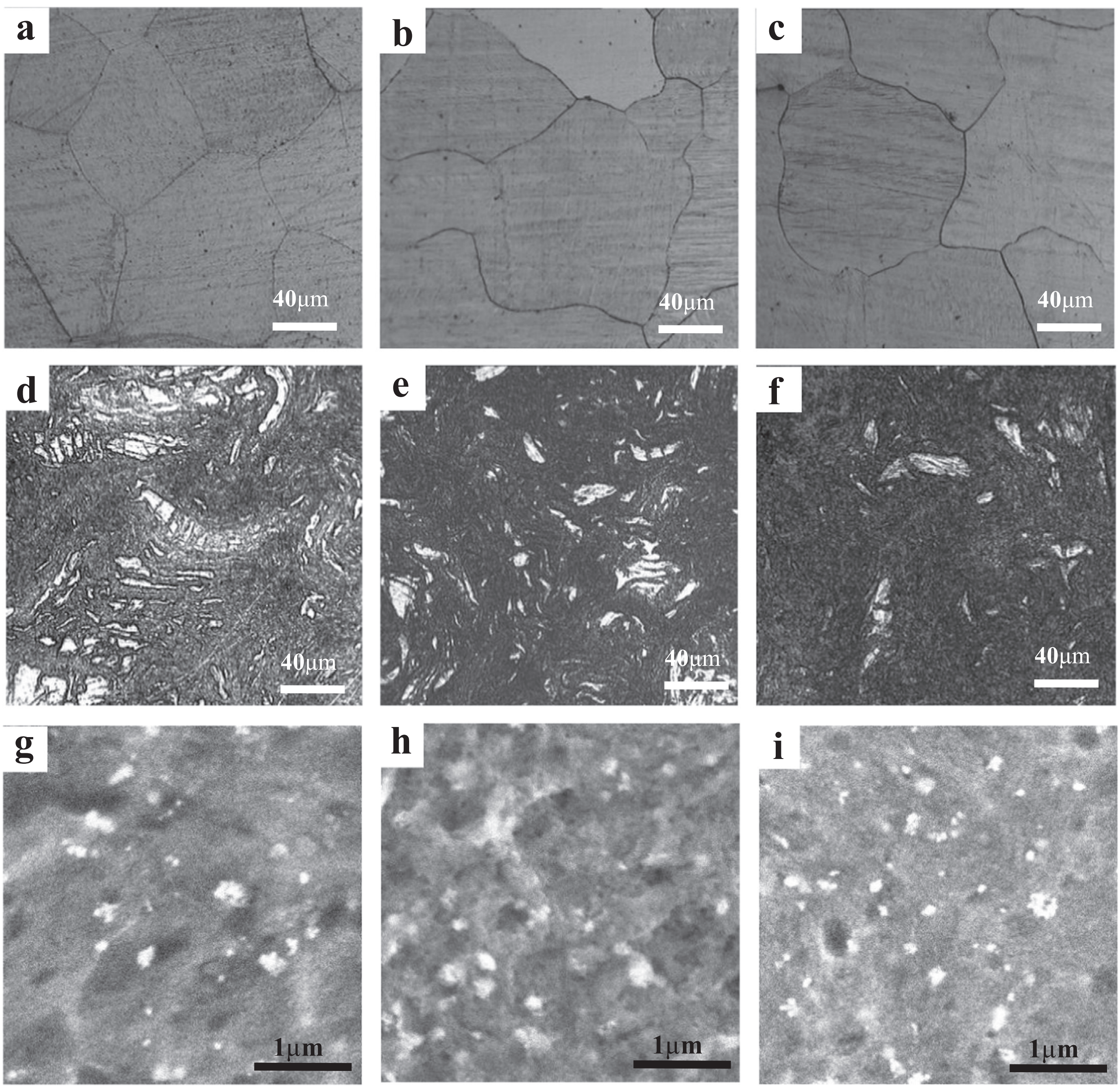


**Fig. 1.** OM micrographs showing the microstructure of (a) solution-treated Mg-7Sn alloy, (b) solution-treated Mg-7Sn-2Ag alloy, (c) solution-treated Mg-7Sn-2Ag-1Zn alloy, (d) as-extruded Mg-7Sn alloy, (e) as-extruded Mg-7Sn-2Ag alloy and (f) as-extruded Mg-7Sn-2Ag-1Zn alloy. SEM micrographs showing the precipitates microstructure of (g) as-extruded Mg-7Sn alloy, (h) as-extruded Mg-7Sn-2Ag alloy and (i) as-extruded Mg-7Sn-2Ag-1Zn alloy resulted by extrusion.