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Influence of Sn addition on the microstructure and mechanical properties of extruded Mg–8Al–2Zn alloy

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ABSTRACT

The effect of adding Sn to an extruded Mg–8Al–2Zn (AZ82 alloy) was investigated by analyzing its microstructural characteristics before and after extrusion, and by conducting tensile and compressive tests with 2, 4, and 6 wt% Sn addition. This revealed that although second phases formed during solidification are nearly fully dissolved by homogenization treatment in AZ82 alloy with 2 wt% Sn, numerous Mg_2Sn particles remain in AZ82 alloys with 4 and 6 wt% Sn due to this concentration being over the solubility limit. All of the extruded alloys were found to have a fully recrystallized structure, yet the addition of 6 wt% Sn created a considerable quantity of large, banded Mg_2Sn particles oriented along the extrusion direction. The tensile and compressive yield strength gradually increased with Sn content mainly due to a decrease in the size of recrystallized grains and an increased amount of fine Mg_2Sn precipitates, though this came at the expense of a decrease in elongation. It was also found that the ultimate tensile strength improves with Sn addition of up to 4 wt%, but deteriorates beyond that point due to premature fracture caused by crack initiation at large particles.

1. Introduction

It is well known that minimizing the weight of vehicles is one of the most effective means of improving their fuel efficiency and reducing their carbon dioxide emissions [1]. As magnesium (Mg) is currently the lightest structural metal available, it has received steadily increasing attention within the transportation industry, with wrought Mg alloys being of particular interest due to their superior mechanical properties and greater weight reduction when compared to cast Mg alloys. Among the commercially available wrought Mg alloys, those with a high Al content in combination with Zn (e.g., AZ80 and AZ91) have been widely used and intensively researched due to the distinct advantage they offer in terms of providing high room-temperature strength at a relatively low material cost. However, further improvement in the strength of these alloys is needed to expand their use to a wider range of applications, as their current maximum strength is still less than that of commercial high-strength Al alloys that often represent the major competition to Mg alloys.

There has already been quite an extensive research effort directed toward enhancing the strength of Mg–Al–Zn alloys by means of various methods such as the use of metal matrix composites (MMCs) [2,3], rapid solidification powder metallurgy (RS/PM) [4,5], or severe plastic deformation (SPD) [6–8]. For instance, Ho et al. [3] successfully fabricated an AZ91 composite reinforced with 15.54 wt% copper particulates using a disintegrated melt deposition (DMD) process followed by extrusion, and reported that this leads to a considerable increase in both tensile yield strength (TYS) and ultimate tensile strength (UTS). Zhang et al. [5] have also developed a PM AZ91 alloy with a remarkably high-strength (TYS of 360–478 MPa and UTS of 394–532 MPa) by powder extrusion followed by low temperature aging. In addition, Shi et al. [8] recently demonstrated that an AZ80 alloy subjected to a combination of equal channel angular extrusion (ECAE) and subsequent forging exhibits an excellent TYS of 347 MPa and UTS of 434 MPa. However, although these methods are very effective in improving the strength of wrought Mg alloys, the complexity of the fabricating processes such as DMD and RS/PM inevitably leads to a significant increase in the cost of the final product. Furthermore, SPD processes have also proven to be difficult to apply on a commercial scale due to their inability to be used as part of a continuous process and/or with large-sized material.

Alloying techniques are widely used with Mg alloys to improve their mechanical properties, with recent reports indicating that the addition of Sn can be used to modify the microstructure and enhance the mechanical properties of Mg–Al–Zn alloys. For example, Li et al.

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[9] have shown that Sn addition can effectively suppress the formation of discontinuous $Mg_{17}Al_{12}$ precipitates in AZ91 during aging. It has also been reported by Kim et al. [10] that the addition of 3–5 wt% Sn to a squeeze-cast AZ51 alloy causes the precipitation of Mg_2Sn and $Mg_{17}Al_{12}$ particles along solidification cell boundaries, which in turn results in an increase in strength. More recently, Dong et al. [11] and Turen [12] found that ~0.5 wt% Sn addition can improve the tensile properties of cast AZ64 and AZ91, respectively, through refinement of their microstructure and modification of their intermetallic phases. However, all this research into the effect of Sn on Mg–Al–Zn alloys has so far focused solely on cast alloys, and has therefore largely overlooked the fact that Sn addition could potentially enhance the mechanical properties of the extruded alloy by controlling the dynamic precipitation of Mg_2Sn particles during extrusion. This is supported by the fact that high strength has already been achieved in extruded Mg–Sn based alloys by creating numerous fine Mg_2Sn precipitates such as Mg–7Sn–1Al–1Zn [13], Mg–8Sn–1Al–1Zn [14] and Mg–9.8Sn–1Al–1.2Zn [15]. This study therefore looks at the effect of adding Sn to an extruded Mg–Al–Zn alloy, with a particular focus on the microstructural evolution and mechanical properties associated with different Sn contents.

2. Experimental procedure

2.1. Permanent mold casting and homogenization heat treatment

The nominal composition of the alloy studied was Mg–8Al–2Zn–0.15Mn–*x*Sn, which was based on AZT82*x* (where $x=0$, 2, 4, and 6 wt% Sn). To prepare billets for extrusion, different alloy compositions were melted under an inert atmosphere containing a mixture of CO_2 and SF_6, and were then stabilized at 740 °C. After holding each melt at 740 °C for 20 min, they were poured into a steel mold that had been pre-heated to 200 °C. The composition of each billet was measured using inductively coupled plasma spectrometry (ICP: Thermo Xseries II) and found to be very close to their nominal values, which are given in Table 1.

To determine the appropriate heat treatment temperature for the homogenization of each billet, an equilibrium phase diagram for Mg–7.5Al–2Zn–0.15Mn–*x*Sn ($x=0$–8 wt%) was created using the PANDAT program (Fig. 1). Homogenization was then conducted for 24 h at temperatures of ~20 °C less than the calculated melting temperature of each alloy, as shown in Table 2. Note that unlike AZ82 and AZT822 alloys, which are homogenized in a two-phase region of *a*-Mg and $Al_{11}Mn_4$ phases, the homogenization temperature of the AZT824 and AZT826 alloys with a relatively high Sn content is positioned in a multi-phase region consisting of *a*-Mg, $Al_{11}Mn_4$, Mg_2Sn, and $Mg_{17}Al_{12}$ phases (Fig. 1). This suggests that there should be residual second phases in all of the alloys tested following homogenization heat treatment, but the amount and composition of these should differ depending on the Sn content.

2.2. Indirect extrusion

Indirect extrusion experiments were carried out at an initial billet temperature of 250 °C, a ram speed of 1 mm/s, and an extrusion ratio of 20. The capacity of the indirect extrusion machine used was 500 t, and no lubricant was applied due to an absence of the friction that is encountered in conventional direct extrusion between the billet and the walls of the container. Prior to extrusion, billets with a diameter of 52 mm and a length of 200 mm were pre-heated at 250 °C for 1 h in a resistance furnace alongside dies with an angle of 90°. During extrusion, the die was pressed toward the billet using a hollow ram, with the variation in die temperature resulting from this being measured using a thermocouple installed inside the die. A schematic diagram of this indirect extrusion process can be found elsewhere [16].

2.3. Microstructure observation and mechanical tests

The microstructure of each alloy was observed using an Epiphot 200 optical microscope (OM), a JSM-7001F field emission scanning electron microscope (FE-SEM), and a JEM-2100F field emission transmission electron microscope (FE-TEM). The sample

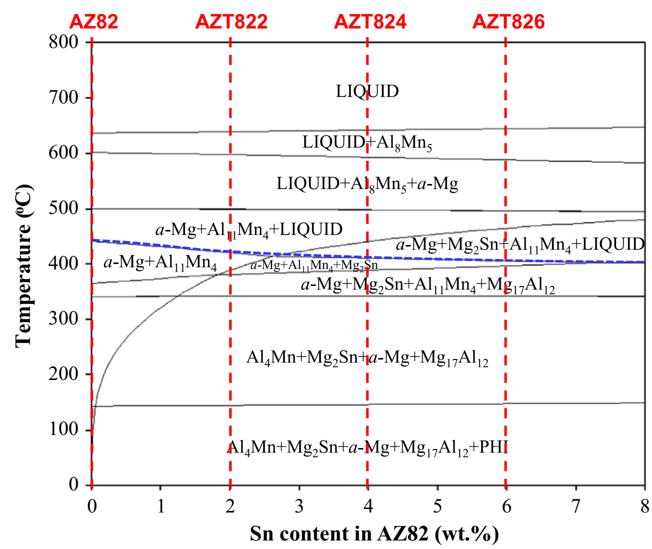

Fig. 1. Equilibrium phase diagram for Mg–7.5Al–2Zn–0.15Mn–*x*Sn ($x=0$–8 wt%), as calculated with PANDAT software.

Table 2
Calculated melting temperatures and homogenization heat treatment conditions of each alloy used in this study.

Alloy	Calculated T_m (°C)	Homogenization condition		
		Temperature (°C)	Time (h)	Phase diagram zone
AZ82	441	420	24	*a*-Mg + $Al_{11}Mn_4$
AZT822	420	390	24	*a*-Mg + $Al_{11}Mn_4$
AZT824	410	390	24	*a*-Mg + Mg_2Sn + $Al_{11}Mn_4$ + $Mg_{17}Al_{12}$
AZT826	406	390	24	*a*-Mg + Mg_2Sn + $Al_{11}Mn_4$ + $Mg_{17}Al_{12}$

Table 1
Chemical composition of the alloys used in this study (wt%).

Alloy	Al	Zn	Sn	Mn	Si	Cu	Ni	Ca	Mg
AZ82	7.45	1.85	< 0.001	0.15	0.010	< 0.001	< 0.001	< 0.001	Bal.
AZT822	7.43	1.88	1.94	0.15	0.009	< 0.001	< 0.001	< 0.001	Bal.
AZT824	7.59	1.94	3.96	0.15	0.009	< 0.001	< 0.001	< 0.001	Bal.
AZT826	7.42	1.88	5.78	0.14	0.009	< 0.001	< 0.001	< 0.001	Bal.