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A new high-strength extruded Mg-8Al-4Sn-2Zn alloy

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ABSTRACT

The microstructure and mechanical properties of a newly developed high-strength Mg-8Al-4Sn-2Zn alloy (ATZ842) were investigated and compared with those of a commercial high-strength Mg-8Al-0.5Zn alloy (AZ80). The presence of undissolved second phases and the small grain size of homogenized ATZ842 were found to promote dynamic recrystallization (DRX) during extrusion through particle-stimulated nucleation (PSN) and an increase in nucleation sites for DRX, respectively. The extruded ATZ842 was subsequently found to exhibit greatly superior mechanical properties to AZ80 extruded under the same conditions, with a tensile yield strength of 371 MPa, an ultimate tensile strength of 415 MPa, an elongation of 9.1%, and a low tension-compression yield asymmetry of 1.02 all being recorded. These excellent mechanical properties are attributed to the combined effects of grain refinement, an increase in the recrystallized fraction, enhanced dispersion and precipitate strengthening, and improved solid-solution strengthening.

1. Introduction

Increasing interest in reducing the weight of components used in the transportation industry has seen magnesium (Mg) alloys receive significant attention in recent years due to their extremely low density and high specific strength. This is especially true of wrought Mg alloys, which offer superior mechanical properties to cast alloys; however, commercial high-strength wrought Mg alloys such as AZ80 and ZK60 still cannot match the strength of wrought aluminum (Al) alloys such as 2024 and 7075 [1]. There is therefore clearly a need to further improve the mechanical properties of Mg alloys through the development of new alloy systems if they are to provide a commercially viable alternative to Al alloy and steel.

Extruded Mg-Gd-Y alloys have been reported to exhibit a very high strength combined with moderate ductility: Mg-12Gd-3Y-0.6Zr (wt.%) achieving an ultimate tensile strength (UTS) of 446 MPa and a tensile elongation (EL) of 10.2% [2], and Mg-10Gd-5.66Y-1.62Zn-0.65Zr (wt.%) having a 542 MPa UTS and 8.0% EL [3]. However, such performance requires the addition of large amounts of rare-earth elements (RE) ($>$ 10 wt.%), with the associated increase in cost presenting a major obstacle to their commercial application. With this in mind, this study looks at the possibility of achieving high performance with a RE-free Mg alloy in order to better meet both industrial demands and environmental concerns. For this, a RE-free Mg-8Al-4Sn-2Zn alloy (ATZ842) was subjected to direct extrusion, and the resulting microstructure and mechanical properties were investigated and compared with those of a commercial high-strength AZ80 alloy.

2. Experimental procedure

Cast billets of commercial AZ80 and the newly developed ATZ842 were prepared in accordance with a previously described procedure [4]; their chemical composition was subsequently confirmed by inductively coupled plasma spectrometry (Thermo Xseries II) as Mg-7.45Al-0.38Zn-0.15Mn and Mg-7.59Al-3.96Sn-1.94Zn-0.15Mn (wt.%), respectively. Based on equilibrium phase diagrams calculated using PANDAT software, the billets were homogenized for 24 h at either 400 °C (for AZ80) or 390 °C (for ATZ842), then water-quenched. Prior to extrusion, dies with an angle of 90° and the billets (Ø50 mm × 100 mm) themselves were pre-heated at 250 °C for 1 h in a resistance furnace. Direct extrusion of the billets was then performed at a temperature of 250 °C using a ram speed of 0.1 mm/s and an extrusion ratio of 20.

The microstructural characteristics of the two alloys before and after extrusion were analyzed by optical microscopy (OM), field emission scanning electron microscopy (FE-SEM), and transmission electron microscopy (TEM). The sample preparation methods used for each of these analyses have been reported elsewhere [5].

The longitudinal tensile and compressive properties of the as-extruded alloys were measured at room temperature (RT) using an Instron 4206 with an initial strain rate of 1.0×10^{-3} s^{-1}. Dogbone-shaped (gage section: Ø6 mm × 25 mm) specimens were used for

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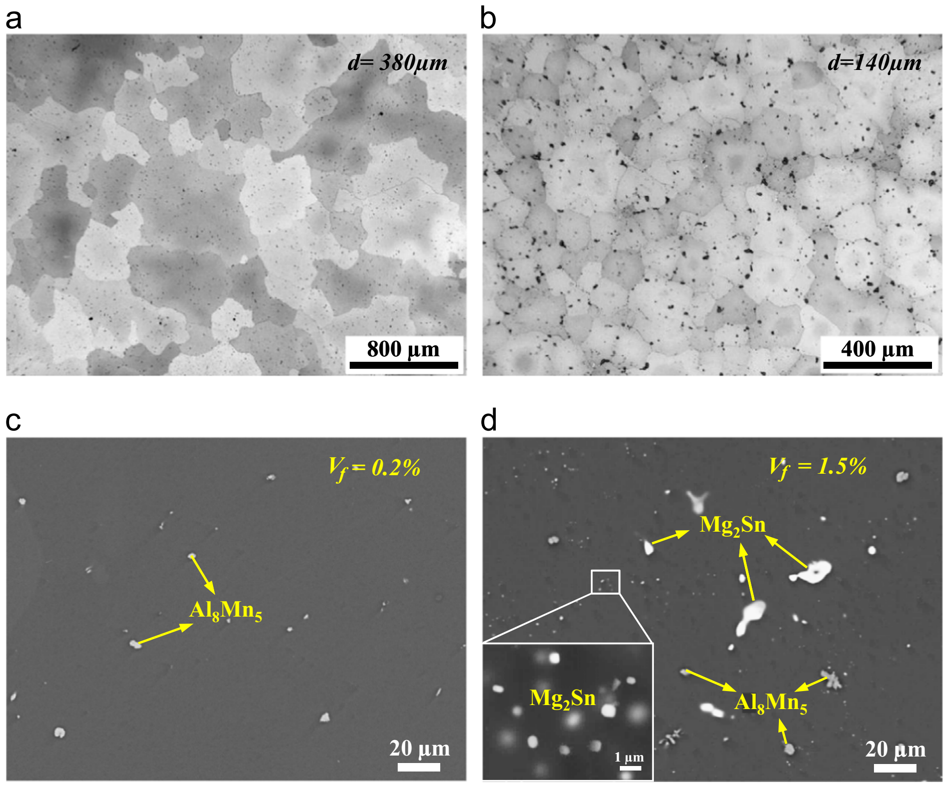

Fig. 1. (a, b) Optical and (c, d) SEM micrographs of homogenized (a, c) AZ80 and (b, d) ATZ842. *d* and V_f represent respectively the average grain size and total volume fraction of the second phases.

tensile testing, while cylindrical specimens (8 mm in diameter × 12 mm in height) were used for compressive tests.

3. Results and discussion

From the microstructures of the homogenized AZ80 (Fig. 1a) and ATZ842 (Fig. 1b), it is clear that in addition to having a greater number of undissolved second phase particles, the average size of the equiaxed a-Mg grains (~140 μm) in ATZ842 is significantly smaller than the grains in AZ80 (~380 μm). Notably, however, it is very similar to that of ZK60 (131 μm) prepared by the same casting procedure, but containing Zr as a grain refining element [5]. As shown in Fig. 1c, the AZ80 contains only a small quantity of undissolved particles (~0.2% by volume), which in a previous study were confirmed by TEM analysis to be Al_8Mn_5 phases [6]. These Al_8Mn_5 phases are also evident in the ATZ842, but it also contains abundant of quite large (3–20 μm) and relatively small (0.5–0.8 μm) Mg_2Sn particles, as shown in Fig. 1d and its inset, respectively. Moreover, the total volume fraction of second phases is increased to ~1.5 %.

Microstructural observation of the extruded alloys also revealed that the AZ80 exhibits a partially DRXed microstructure, with coarse unDRXed grains representing a volume fraction of ~36% (Fig. 2a), whereas the ATZ842 has an almost fully DRXed microstructure with some large particles (Fig. 2b). The partial DRX seen in the AZ80 is most likely due to the relatively low extrusion temperature (250 °C) and slow ram speed (0.1 mm/s) used, which are known to reduce the DRX fraction. It is well known that large particles (> 1 μm diameter) can act as nucleation sites for DRX during hot deformation in what is known as particle-simulated nucleation (PSN) [7,8], and although the larger Mg_2Sn particles (3–20 μm) are partially broken during extrusion, their size remains in excess of 1 μm (Fig. 2b). It is therefore believed that these particles act as heterogeneous sites for nucleation of recrystallization by generating local inhomogeneity in the strain energy during hot extrusion, thus resulting in an increase in the DRX fraction of the extruded alloy. Furthermore, given that DRX proceeds more rapidly with finer grain sizes due to the higher density of grain boundary nucleation sites [9], the small initial grain size of the ATZ842 is also likely to contribute to observed increase in DRX fraction.

In the SEM micrographs of the DRXed regions of the extruded alloys (Fig. 2c and d), ultra-fine DRXed grains and numerous precipitates can be observed in both; however, the ATZ842 has smaller DRXed grains (~0.8 μm) than the AZ80 (~1 μm), as well as a greater number and overall volume fraction of fine precipitates. Subsequent TEM analysis of the extruded ATZ842 (Fig. 3) revealed a large amount of fine rod-like and spherical Mg_2Sn precipitates (100–200 nm), along with fine $Mg_{17}Al_{12}$ precipitates (200–400 nm), all of which are formed by dynamic precipitation from a supersaturated solid solution during hot extrusion. Furthermore, the undissolved 0.5–0.8 μm Mg_2Sn particles identified in the homogenized state (Fig. 1d) are still present after extrusion (A in Fig. 3a). These numerous particles are therefore considered to greatly improve precipitation and dispersion strengthening by hindering the movement of mobile dislocations during plastic deformation, which would imply that these strengthening mechanisms are much effective in ATZ842 than AZ80. Moreover, given reports that the addition of Zn is more effective than Al in increasing the critical resolved shear stress of the basal slip system of Mg solid solutions at RT [10], the higher Zn content of ATZ842 relative to AZ80 is likely to result in enhanced solid-solution strengthening.

The tensile and compressive stress-strain curves for the extruded AZ80 and ATZ842 are shown in Fig. 4a and b, respectively, and the properties obtained from these are given in Table 1. These results demonstrate that the ATZ842 has excellent tensile and compressive strengths, with its tensile yield strength (TYS) of 371 MPa, UTS of 415 MPa, and compressive yield strength (CYS) of