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Improving the tensile strength of Mg–7Sn–1Al–1Zn alloy through artificial cooling during extrusion

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ABSTRACT

An Mg–7Sn–1Al–1Zn alloy known to have excellent extrudability and superior strength was subjected to artificial cooling during indirect extrusion by directly spraying water onto the extruded rod at the die exit. The results obtained revealed that this artificial cooling dramatically reduces the temperature of the deformation zone during extrusion, thereby creating a finer grain size, an intensified texture and a greater amount of precipitates when compared to extrusion without artificial cooling. The yield and tensile strength of the extruded alloy is also significantly improved, which is attributed to the effects of grain refinement in combination with an enhanced texture and precipitate hardening.

1. Introduction

The automotive industry's demand for wrought magnesium (Mg) alloys has been increasing in recent years due to their mechanical superiority over comparable cast alloys, not to mention their extremely low density relative to other metallic materials. In the case of extruded Mg alloys, however, supply and application has so far been greatly limited by the low maximum extrusion speed of commercial high-strength Mg alloys such as AZ80 and ZK60 [1]; a slower manufacturing speed invariably means a higher final product cost. This has led to an increased interest in Mg–Sn based alloys due to their ability to be extruded without developing surface cracks at speeds equivalent to those used for aluminum alloys [2], which is attributed to the formation of a thermally stable Mg_2Sn phase in place of low-melting temperature $Mg_{17}Al_{12}$ or $MgZn_2$ phases [2–4]. Of all the Mg–Sn based alloys, those with a high Sn content have been the subject of particular focus by virtue of the very attractive combination of high strength and superior extrudability that they offer. Indeed, Elsayed et al. [5] have already developed an Mg–9.8Sn–3.0Al–0.5Zn (wt%) (TAZ1031) alloy exhibiting a symmetrical tension-compression yield strength and high ultimate tensile strength (UTS) of 358 MPa in an as-extruded state, while Sasaki et al. [4] have created an Mg–9.8Sn–1.2Zn–1.0Al (wt%) alloy with a high tensile yield strength (TYS) of 308 MPa through extrusion at a low temperature of 250 °C with a low ram speed of 0.1 mm/s. Meanwhile, Park et al. [6] have also demonstrated an extruded Mg–7.95Sn–0.95Al–0.95Zn (wt%) (TAZ811) alloy exhibiting superior tensile and compressive strengths compared to extruded AZ31 alloy. In our previous study [7], an extraordinarily high-strength TAZ811 alloy (TYS of 390 MPa, UTS of 405 MPa) was fabricated by extruding a billet subjected to cold forging prior to extrusion. It has also been recently reported that Mg–7Sn–1Al–1Zn (wt%) (TAZ711) alloy has comparable tensile strength to commercial high-strength AZ80 alloy extruded under the same conditions [2], in addition to an excellent extrudability that is demonstrable by a maximum extrusion speed of more than 12 m/min [2,8].

It is well known that the microstructure and mechanical properties of extruded Mg alloys are strongly dependent on extrusion parameters such as billet size, die geometry, reduction ratio, initial temperature, and ram speed [8–14]. For instance, with an increase in extrusion speed, the tensile strength of the extruded alloy is gradually reduced by an increase in the final grain size. Similarly, although Mg–Sn based alloys can be rapidly extruded without cracking, such high-speed extrusion invariably induces some degree of deformation heating that reduces the strength of the extruded alloy through grain growth [8,14]. Cheng et al. [14] have also shown a decrease in the tensile strength of extruded TAZ811 alloy (from 244 to 199 MPa in TYS and from 312 to 286 MPa in UTS) with increasing extrusion exit speeds (from 2 to 10 m/min). The additional heating caused by abrupt plastic deformation and friction during high-speed extrusion should therefore be reduced in order to limit grain growth and ensure high strength in the extruded alloy. In this regard, one method that has proven effective in suppressing excessive temperature rise at high extrusion speeds is the application of artificial cooling,

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with Kim et al. [15] using this to achieve an increase in the tensile strength of indirectly extruded AZ31 alloy. However, there has as yet been no investigation into the effect of artificial cooling on Mg–Sn based alloys developed specifically for high speed extrusion. Moreover, although it is well known that the fine precipitates generated during extrusion play an important role in determining the strength of the final product, the influence of artificial cooling on dynamic precipitation has been overlooked by previous studies concerned only with AZ31 alloy that contains no second phases. The main objective of the present study is therefore to determine the microstructural variation that induced by artificial cooling in terms of grain size, texture and precipitate in TAZ711 that is known to have a superior strength and excellent extrudability. The effect of this variation on the tensile properties of the extruded alloy is also explored and discussed herein.

2. Experimental procedure

Cast billets of TAZ711 alloy were prepared by first melting in an electric resistance furnace at 800 °C under an inert atmosphere containing a mixture of CO_2 and SF_6, and then pouring into a steel mold pre-heated to 210 °C. The chemical composition of the resulting billet was found through inductively couple plasma spectrometry to be 6.81Sn–1.10Al–1.07Zn (wt%). These billets were homogenized at 500 °C for 24 h to fully dissolve any macro-segregation of the solute elements and intermetallic compounds formed during solidification, and then water-quenched to obtain a supersaturated solid-solution containing no Mg_2Sn phase. Using a previously described process [16], two billets (⌀50 mm × 150 mm) pre-heated to 350 °C were indirectly extruded at a temperature of 350 °C using a ram speed of 1 mm/s and an extrusion ratio of 20, with artificial cooling being applied to only one of these. A schematic diagram of the indirect extrusion process and associated artificial cooling system is shown in Fig. 1a. In this, cold water was fed at a rate of 3 ℓ/min through two inlets located on the surface of the stem, being then transferred through holes inside the stem and die to spray directly onto the extruded rod at the die exit. The variation in die temperature during extrusion was measured using a thermocouple installed inside the die (Fig. 1a).

The microstructural and textural characteristics of the extruded samples were analyzed by optical microscopy (OM), electron backscatter diffraction (EBSD), field emission scanning electron microscopy (FE-SEM), and X-ray diffraction (XRD). The area fraction of recrystallized grains and secondary phases in each of the extruded samples was obtained by averaging the values taken from five low-magnification OM and SEM images, respectively. The tensile properties of the extruded samples were measured at room temperature using an Instron 4206 universal testing machine with a strain rate of $1.0 \times 10^{-3}\ s^{-1}$. Dog-bone shaped (gage section: ⌀6 mm × 25 mm) specimens were used for tensile testing, the axes of which corresponded to the extrusion direction (ED). The tensile test for each sample was repeated three times to ensure repeatability and confirm the consistency of the results, but for the sake of simplicity, a representative curve for each test was used. It should also be noted that the 6 mm gage diameter of the tensile specimens represents the center of the extruded bars (⌀11.3 mm), and thus their tensile properties are more closely related to the microstructure within this region than that of the sub-surface region. This means that the microstructural characteristics of the extruded bars were analyzed with a particular focus on their center region.

3. Results and discussion

Fig. 1b shows the measured variation in the extrusion load and die temperature during extrusion, the latter being considered a more accurate reflection of the actual temperature applied to the alloy during extrusion. In the case of extrusion without cooling, although the initial extrusion temperature is 350 °C, the die temperature gradually rises to ~378 °C during the initial stage of extrusion due to the heat generated by plastic deformation and friction. This reduces the hot working flow stress, and subsequently leads to a decrease in the extrusion load. However, as the extrusion process stabilizes, the die temperature decreases slightly to ~370 °C; a temperature that is maintained to nearly the end of extrusion. Conversely, when artificial cooling is applied during extrusion, the die temperature is rapidly reduced to ~260 °C immediately after the extruded bar exits the die, this being despite the corresponding increase in extrusion load due to the greater flow stress of the billet. Furthermore, this reduced temperature remains essentially unchanged throughout whole extrusion process, which indicates that artificial cooling applied directly to the extruded bar significantly reduces its actual temperature during extrusion from ~370 to ~260 °C (by ~110 °C). This, in turn, should result in a significant grain refinement through the suppression of grain growth.

As confirmed in our previous study [17], homogenized TAZ711 alloy consists of equiaxed grains with an average size of ~340 um and a very small amount of Al_3Fe or Al_8Mn_5 inclusions; however, any coarse Mg_2Sn phases formed during solidification are fully dissolved by homogenization treatment. Fig. 2 shows the microstructure and texture within the center region of the artificially cooled (AC) and naturally cooled (NC) samples of extruded TAZ711

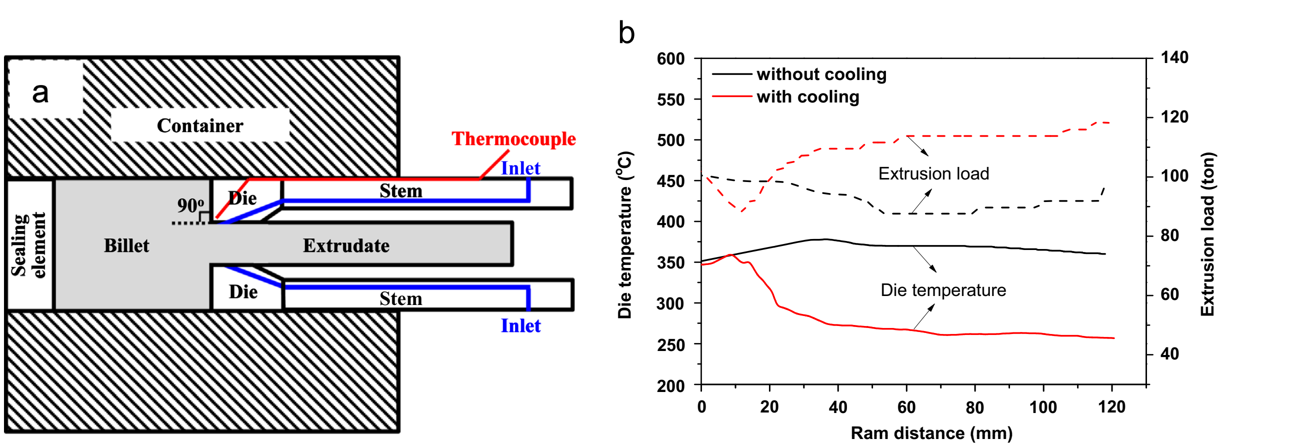

Fig. 1. (a) Schematic diagram of the indirect extrusion process and artificial cooling system used in this study. (b) Variation in die temperature and extrusion load during extrusion.