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Microstructure and mechanical properties of as-cast and as-hot-rolled novel Mg-xSn-2.5Zn-2Al alloys (x = 2, 4 wt%)

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ABSTRACT

Two novel Mg-Sn based wrought alloys are developed with good mechanical properties, which are Mg-2Sn-2.5Zn-2Al (TZA222) alloy and Mg-4Sn-2.5Zn-2Al (TZA422) alloy. The as-cast alloys with high elongations to failure over 10% and low tensile strengths just over 70 MPa are suitable for hot deformation processing. After hot rolling at 350 °C of 60% total reduction, the strengths of the alloys are significantly improved, meanwhile, their elongations to failure still remain at high level. The as-hot-rolled TZA422 alloy has better mechanical properties, of which the yield strength, ultimate tensile strength and elongation to failure are 196.9 MPa, 285.5 MPa and 20.7%, respectively. It has nano-sized Mg_2Sn particles dispersed within fine grains with an average size of 10 µm, while the main second phase is coarse $Mg_5Zn_2Al_2$ in the as-cast TZA422 alloy. Both the as-hot-rolled TZA422 and TZA222 alloys have good combinations of strength and ductility, which are comparable to other as-hot-rolled Mg alloys with high performances.

1. Introduction

Mg-Sn based alloys are candidates for low-cost wrought Mg alloys [1]. The solid solubility of Sn in Mg reaches up to 14.5% (as default in wt%), which leaves much space for adjustment of microstructures and mechanical properties of wrought Mg-Sn based alloys. Unlike various Mg-Al based alloys suitable for roll processing, such as AZ31 [2] and AZ61 [3], Mg-Sn based alloys suitable for roll processing are still in an early stage of development. As shown in Table 1, previous studies on wrought Mg-Sn-Zn-Al alloys, the majority of which were dedicated to extruded ones, revealed that Zn and Al addition in Mg-Sn binary alloys resulted in considerable strengthening effects [4–12]. Ultimate tensile strengths of as-cast Mg-3Sn-(0.5–2)Zn-1Al alloys can be significantly improved through hot extrusion, while their elongations to failure can also be mildly improved (Table 1). More often than not, annealing will be performed on wrought Mg alloys in order to obtain an equi-axed grain structure due to recrystallization with a better combination of strength and ductility. This is also applicable for as-hot-rolled Mg-7Sn-5Zn-2Al alloy, the elongation to failure of which is improved from 8% to 21% through annealing (Table 1).

According to alloy composition and processing history, several second phases can present in Mg-Sn-Zn-Al alloys, which play an important role in controlling grain growth during hot deformation or in precipitation strengthening effect. The most frequently appeared second phase is Mg_2Sn with a face-centered cubic structure (FCC, a = 0.676 nm), which exhibits twelve reproducible orientation relationships (ORs) with respect to the Mg matrix [13]. Four of the ORs, designated as OR9 to OR12 in Ref. [13], correspond to pyramidal Mg_2Sn laths inclined with large angles with respect to the Mg basal plane, which are believed to have a higher room temperature strengthening effect than those lying on the Mg basal plane according to dislocation theory [14]. In homogenized Mg-8Sn-1Zn-1Al alloy and extruded Mg-8Sn-2Zn-2Al alloy, Mg_2Sn was the only detected second phase since Zn and Al were solid-soluted in the Mg matrix [11,15]. In T6-treated Mg-5.4Sn-4.2Zn-2Al alloy, blocky β'_2 Mg-Zn precipitates were identified [8]. In wrought Mg-7Sn-5Zn-2Al alloy, nano-sized I-phase with a icosahedral structure and a composition near $Mg_{44}Zn_{41}Al_{15}$ appeared as fine precipitates after rolling, which strengthened the alloy remarkably [10].

This paper aims at investigating novel wrought Mg-Sn-Zn-Al alloys, which can obtain good mechanical properties after hot rolling.

2. Experimental procedure

The nominal and chemical analyzed compositions (in wt%) of two studied alloys are listed in Table 2. Following the principle of American Society for Testing and Materials (ASTM), the alloys were designated as TZA222 and TZA422 alloys. Pure metals of Mg, Sn, Zn and Al (all with purity > 99.9%) were bought from General Research Institute for Nonferrous Metals, Beijing, China. They were melted in a Al_2O_3

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Table 1
Room temperature tensile yield strength ($R_{p0.2}$), ultimate tensile strength (R_m), and elongation to failure (A) of reported Mg-Sn-Zn-Al alloys. T6 refers to solution heat treated and artificial aged, while T4 refers to solution heat treated.

Alloy (wt%)	Status	$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)	Ref
Mg – 2.2Sn – 0.5Zn – 1Al	As-extruded	308	354	12	[4]
Mg – 3Sn-(0.5–2)Zn – 1Al	As-cast	–	140–169	9.2–10.3	[5]
	As-extruded	167–185	267–290	10.3–12.2	
Mg – 5Sn – 1Zn – 1Al	As-cast	90	166	9.3	[6]
Mg – 5Sn – 1Zn-(1–5)Al	As-extruded	227–254	310–353	11–15	[7]
Mg – 5.4Sn – 4.2Zn – 2Al	As-extruded	184	311	11	[8]
	T6	229	303	6	
Mg – 5.4Sn – 5.9Zn – 2Al	As-extruded	243	351	21	[8]
	Single aged	255	350	20	
	Double aged	346	385	15	
Mg – 5.6Sn – 4.4Zn – 2.1Al	Single aged	–	–	–	[9]
Mg – 7Sn – 5Zn – 2Al	As-rolled	318	373	8	[10]
	As-annealed	202	321	21	
Mg – 8Sn – 2Zn – 2Al	As-extruded	186	231	17.6	[11]
	Extruded + T4	245	320	26.5	
Mg – 10Sn – 1Zn – 1Al	Cast + T6	–	–	–	[12]

Table 2
Chemical compositions (in wt%) of the experimental alloys.

Nominal	Chemical analyzed			
	Sn	Zn	Al	Mg
Mg – 2Sn – 2.5Zn – 2Al (TZA222)	1.92	2.56	1.86	Bal.
Mg – 4Sn – 2.5Zn – 2Al (TZA422)	3.82	2.40	1.90	Bal.

crucible under argon gas protection. The melt was kept at 800 °C for 3 min before poured into a cylindrical graphite mould and cooled down to room temperature.

As-cast plates of 20 mm in thickness were cut from the ingots for hot rolling. They were first homogenized at 380 °C for 9 h, followed by cold water quenching. Before hot rolling, they were preheated at 350 °C for 2 h. The hot rolling was performed on a four-high mill with two working rolls of Φ170 × 350 mm. The rolling speed was set to be 18 m/min. The thickness of the as-cast plates was reduced from 20 mm down to 8 mm with reduction of about 2.0 mm per pass. The reduction per pass increased from 10% to 20%, and the total reduction reached 60%. Between every two passes, the rolled plates were annealed at 350 °C for 15 min. After the last pass, the rolled plates were cooled naturally in air. Little edge cracking was detected for the final plates, indicating the present rolling procedure was appropriate for their manufacturing. After hot rolling, tensile samples with a gauge length of 25 mm were machined out of the as-hot-rolled plates along the rolling direction.

For microstructure observation, metallographic specimens were ground using sandpapers from 1000 grit up to 3000 grit, polished with ethanol to obtain a mirror-like surface, and then etched for 20 ~ 40 s at room temperature, using a solution of 5 ml acetic acid, 6 g picric acid, 10 ml H_2O, and 100 ml ethanol. The microstructures were examined using Olympus BX53 M optical microscopy and Zeiss Auriga scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS). Olympus M3 software was used to estimate area fraction of second phase and grain size (in equivalent diameter). The phases in the alloys were analyzed using SmartLab X-ray diffractometer with Cu K_α radiation with 2θ from 20° to 80° at a scanning rate of 0.1°/s. Specimens for transmission electron microscope (TEM) study were ground to be 30 µm in thickness and then punched to be discs of 3 mm in diameter. Such a disc was put in a Model 691. CS ion milling machine to make electron transparent thin area. TEM observation was conducted on a Tecnai G2 F30 S-TWIN equipment.

Table 3
Tensile mechanical properties of TZA222 and TZA422 alloys. $R_{p0.2}$, R_m and A refer to yield strength, ultimate tensile strength, and elongation to failure, respectively.

Alloy	Status	$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)
TZA222	As-cast	71.0 ± 3.8	226.2 ± 3.0	21.2 ± 0.1
TZA222	As-hot-rolled	178.8 ± 7.4	273.8 ± 1.9	20.2 ± 0.3
TZA422	As-cast	71.9 ± 2.1	215.9 ± 8.7	15.0 ± 3.7
TZA422	As-hot-rolled	196.9 ± 6.1	285.5 ± 2.0	20.7 ± 0.6

3. Results

Mechanical properties of the as-cast and the as-hot-rolled alloys are listed in Table 3. The yield strength, ultimate tensile strength and elongation to failure of the as-cast TZA222 alloy are 71.0 MPa, 226.2 MPa, and 21.2%, respectively. While those of the as-cast TZA422 alloy are 71.9 MPa, 215.9 MPa, and 15.0%, respectively. Addition of 2% Sn to TZA222 alloy reduces its elongation to failure in the as-cast state. After the 60% hot rolling, the yield strength, ultimate tensile strength and elongation to failure of the as-hot-rolled TZA222 alloy are 178.8 MPa, 273.8 MPa, 20.2%, respectively. While those of the as-hot-rolled TZA422 alloy are 196.9 MPa, 285.5 MPa, and 20.7%, respectively. Therefore, the hot rolling process greatly improves the strengths of both the alloys. Moreover, the ductility of TZA422 alloy is also enhanced through the hot-rolling. Comparatively, the as-hot-rolled TZA422 alloy has a better combination of strength and ductility, which can also be seen clearly from Fig. 1. The hot rolling process results in a larger improvement on the mechanical properties of the as-cast TZA422 alloy (Fig. 1).

Optical images in Fig. 2 show microstructures of the as-cast and the as-rolled TZA222 and TZA422 alloys. Both the as-cast alloys have equi-axed Mg grains with second phase mainly distributed at grain boundaries (Fig. 2a and b). The area fractions of the second phase in the as-cast TZA222 and TZA422 alloys are measured to be 11.4% and 23.2%, respectively. The latter one is about two times of the former one. The grain sizes of the as-cast TZA222 and TZA422 alloys are 94 ± 31 µm and 69 ± 10 µm, respectively. This suggests that the enhanced grain refinement can be due to the increasing Sn concentration and thereby increasing grain growth restriction factor [16]. The hot rolling process results in recrystallization in both the alloys, since they exhibit equi-axed grains (Fig. 2c and d). Therefore, annealing after hot rolling is not needed, unlike hot-rolled Mg-7Sn-5Zn-2Al alloy (Table 1). After the hot rolling, the grain sizes of TZA222 and TZA422 alloys are reduced significantly to 12 ± 4 µm and 10 ± 3 µm, respectively. The coarse second phase in the as-cast alloys is disappeared. In the as-hot-rolled TZA422 alloy, tiny particles disperse in the grains, which are