Effect of Al content on the microstructure and mechanical properties of Mg-5wt%Sn-xAl as-cast alloys

Z Q Sun1,2,3, Y J Li1,2,3,4, K Zhang1,2, X G Li1,2, M L Ma1,2, G L Shi1,2 and J W Yuan1,2

1State Key Laboratory of Nonferrous Metals and Processes, GRINM Co., Ltd., Beijing 100088, China
2GRIMAT Engineering Institute Co., Ltd., Beijing 101407, China
3General Research Institute for Nonferrous Metals, Beijing 100088, China

Email: lyj@grinm.com

Abstract: Microstructure and mechanical properties of Mg-5wt.% Sn-xAl as-cast alloys were studied, for the Al content range from 0.5 to 3.0wt.%. It was found that Al element was mainly distributed in Mg17Al12 phase in as-cast alloys, and its increase rose the Mg17Al12 phase share. There were no ternary phases in these alloys. Only two forms of Mg2Sn and Mg17Al12 phases were detected, namely (i) Mg17Al12 phase attached to the end of Mg2Sn phase and (ii) Mg2Sn phase enclosed by Mg17Al12 phases. The grain sizes of the alloys got refined with the growing content of Al element, and 1.5wt% Al content corresponded to the grain size of 33.5um. As for the mechanical properties, the ultimate tensile and yield strengths of the alloys were improved at larger contents of Al. The Mg-5wt.%Sn-3.0wt% alloy had the highest ultimate tensile and yield strengths of 212 and 167MPa, respectively, while Mg-5wt.%Sn-1.5wt%Al alloy had the best elongation of 16.5%.

1. Introduction
Heat-resistant magnesium alloys have a great application in automobile, electronic communication, aerospace, et al. [1-3]. However, the most widely used heat resistant rare earth-magnesium alloys are too expensive to use extensively [4]. Tin has a high solid solubility in magnesium, which is 14.5wt.% at the eutectic temperature of 561.2℃, and the generated Mg2Sn phase has the melting point at 771℃. Mg2Sn is a kind of elevated temperature stable phase which can still hold steady at the temperature of 200℃, so Mg-Sn alloys have the potential to be used as a new kind of heat-resistant magnesium [5-8]. However, the mechanical properties limit the use of the Mg-Sn binary alloy, so the third element is needed [9-10]. The contents of Al can improve the microstructures of the binary alloys, as well as the room-temperature mechanical properties. Therefore, the effect of Al content was studied [11-14].

2. Material and Methods
Pure magnesium (99.9wt.%), pure tin (99.9wt.%) and pure aluminum (99.9wt.%) were melted in semi-continuous casting induction furnace with the protection of RJ-2 fusing agent, which was preheated to 120℃ for 2 h. Ar2 and R-134a with the ratio of 20:1 were used as the protective gas environment. When melting, crucibles were preheated to 300℃ firstly, and then added pure magnesium, heated to 750℃ to melt completely, afterwards, added a percentage of pure tin and pure aluminum, and insulated for 30
Finally, the completely melted melt was taken out, using stainless steel crucible with the size of Φ60 mm×70 mm. Six alloys with different components of Al were designed in this experiment. All samples were cut from the same part of each lathed ingot. The metallographic samples were sanded on 240#, 600#, 1000#, 2000# and 5000# sandpapers, and then mechanically polished to the mirror surface on ymp-2 type metallographic sample polishing machine, subsequently, corroding with a solution of 5% picric acid, and observed it under Carl Zeiss Axiovet 200MAT optical microscope. ZEISS scanning electron microscope was used for the higher multiple microstructure morphology, and microstructure compositions were analyzed by energy spectrometer on this machine. X-ray diffraction (XRD) samples were tested in X’pert PRO MPD type X-ray diffractometer, whose target material is Cu. Hardness test was carried out on HBS-62.5 type load digital display Brinell hardness tester, with the loading time of 25s. And tensile test was carried out on the mts-810 universal testing machine with the rate of 2mm/min. Transmission electron microscope samples were tested in JEOL JEM-2010 type microscope with the working voltage of 200KV.

3. Results and discussion

3.1. Effect of Al addition on microstructure of Mg-5wt%Sn-xAl alloys

The X-ray diffraction results were shown in figure 1. It resulted that there were no ternary phases in these alloys, the phases in the alloys mainly included Mg2Sn phases and Mg17Al12 phases. As the Al contents increased, the peaks of Mg17Al12 phases increased. Metallographic structures of the alloys with different Al contents were shown in figure 2, statistics reflected that when Sn content was 5wt.%, invariably, with the content of Al elements increased, the average grain sizes of the alloys decreased and then increased. As was shown in figure 3, the average grain sizes were respectively 92.2, 80.4, 33.5, 46.6, 47.8, and 68.2 µm.

![Figure 1](image-url)

(a) 0.5wt.%; (b) 1.0wt.%; (c) 1.5wt.%; (d) 2.0wt.%; (e) x=2.5wt.%; (f) 3.0wt.%.

**Figure 1.** X-ray diffraction images of Mg-5Sn-xAl as-cast alloys.

The SEM and EDS experiments were proceeded for further studies of the microstructures in the alloys, which results were shown in Figure 4. Four different contrast phases had been observed. By EDS analysis, it can be found that region a contained α-Mg matrix phases, region b was the solute atomic segregation region in the α-Mg matrix, region c contained unbalanced eutectic Mg2Sn phases, and region d covered an unbalanced eutectic structure composed of Mg17Al12 and matrix phases. At Al content of 3 wt.%, the semi-continuous distribution of region d at the grain boundaries became more apparent.
However, not all Al elements were distributed in the $\text{Mg}_{17}\text{Al}_{12}$ phases, since some of them were segregated in the $\alpha$-Mg matrix.

Figure 2. Metallographic structures of Mg-5Sn-$x$Al as-cast alloys.

(a) 0.5wt%; (b) 1.0wt%; (c) 1.5wt%; (d) 2.0wt%; (e) 2.5wt%; (f) 3.0wt%.

The TEM test of Mg-5Sn-1.5wt% alloy indicated that there were two distributions of $\text{Mg}_{17}\text{Al}_{12}$ phases, one of which was attached to Mg$_2$Sn phases, as was shown in figure 5(A), where region $a$ represents Mg$_2$Sn phases and region $b$ represents Mg$_{17}$Al$_{12}$ phases; and the other was enclosed in Mg$_2$Sn phases, as shown in figure 5(B), where region $c$ and $d$ represented Mg$_2$Sn and Mg$_{17}$Al$_{12}$ phases, respectively. By calibrating the diffraction spots of the Mg-5Sn-1.5wt% alloy of figure 6, Mg$_{17}$Al$_{12}$ phases of face-centered cubic structure were found, and the lattice constant $a$ was 10.56nm. Meanwhile,
the Mg₂Sn phases in the alloy were also face-centered cubic structure, and the lattice constant \( a \) was 6.76nm.

![SEM and EDS images of Mg-5Sn-xAl alloys](image)

(A) 0.5wt%; (B) 1.5wt%; (C) 3.0wt%

**Figure 4.** SEM and EDS images of Mg-5Sn-xAl alloys.

![TEM images and diffraction spots of Mg-5Sn-1.5wt% alloy](image)

a, b, c, d showed different phase compositions of different regions

**Figure 5.** TEM images and diffraction spots of Mg-5Sn-1.5wt% alloy.

3.2. **Effect of Al addition on mechanical properties of Mg-5wt%Sn-xAl alloys**

For mechanical properties, it can be seen in figure 7 that with an increase in Al content, the hardness,
tensile strength, and yield strength of the alloys increased. However, the elongation of the alloy firstly increased and then decreased with the increase of Al content. When Al content was 1.5wt.%, the alloy had the best elongation of 16.5%.

Room-temperature strength properties of Mg-5Sn- xAl alloys were mainly affected by solid solution strengthening of Al atoms, second phase strengthening of Mg17Al12 phases and fine-cristalline strengthening of both. With the Al contents increased, solid solution strengthening and second phase strengthening played the lead role on the improving of strength properties, but fine-cristalline played a lead role on the improving of plastic properties.

![Diffraction spots of the Mg-5Sn-1.5wt% alloy](image)

**Figure 6.** Diffraction spots of the Mg-5Sn-1.5wt% alloy.

![Mechanical properties of Mg-5Sn- x Al alloy](image)

**Figure 7.** Mechanical properties of Mg-5Sn- x Al alloy.

4. Conclusions
1. Addition of Al element can refine the grain size of the Mg-Sn- xAl alloys, when the content of Al element was 1.5wt.%, the alloy had the finest grain size of 33.5μm, as well as the best elongation of 16.5wt.%. 
2. The ultimate tensile strength and yield strength of the alloys improved when the contents of Al aggrandized. Mg-5wt.%Sn-3.0wt% had the best ultimate tensile strength of 212MPa and the best yield strength of 167MPa.

3. As the content of Al increased, the number of Mg17Al12 phases increased, but not all Al elements distributed in the Mg17Al12 phase, quit a lot of Al elements were segregated in the α-Mg matrix.

4. Through TEM analysis, two kinds of distributions of Mg17Al12 phase were found, and both of it interrupted the continuous distribution of Mg2Sn phase, the skeletal morphology of Mg2Sn phase was broken and was partially transformed into a short-rod morphology.

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