EFFECT OF INDIUM ADDITION ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AS-CAST AND HOT-ROLLED AM60 MAGNESIUM ALLOY

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Abstract

In this study, effect of indium (In) addition on microstructure and mechanical properties of AM60 magnesium alloys was investigated. In additions were made by 0.2, 0.5 and 1 wt.%. Alloys were produced by conventional gravity casting in a steel mould. A homogenization treatment at 350 °C for 24 h was performed after casting processes. Homogenized samples were 1 pass hot-rolled by 40 % thickness reduction at 350 °C. The results showed that the average grain size of as-cast and hot-rolled AM60 alloys decreased with In addition. SEM analysis revealed that In addition led to formation of tiny Mg-In binary second phases at triple junctions. Tensile strength of as-cast AM60 alloy increased with increasing amount of In up to 0.5 wt.% above which it decreased. However, after hot-rolling process, AM60 alloy containing 0.2 wt.% In showed the best tensile properties. These improvements were attributed to the refinement of microstructure and dispersion strengthening by Mg-In intermetallic phases.

Keywords: AM60 magnesium alloys, indium modification, rolling, microstructure, mechanical properties

1. INTRODUCTION

Magnesium alloys are considered as promising materials for applications in automotive and aerospace industries in order to provide higher fuel efficiency since they have primarily very low specific strength, excellent machinability and castability [1]. AM60 alloy is one of the most commercially used cast magnesium alloys due to good combination of strength and ductility [2]. However, there is still need for increasing the strength and ductility of AM60 alloy further [1,2]. Employment of different alloying elements and hot forming processes such as rolling, extrusion etc. are the main methods to improve these properties. Numerous studies revealed that rare earth elements can improve strength of magnesium alloys [3-5]. It was reported that tin addition can improve the strength of AZ91 and AZ82 magnesium alloys due to the formation of thermally stable and dense Mg_2Sn intermetallic compounds [6, 7].

Indium is said to promote non-basal slip activity and decrease c/a ratio [8]. Becerra et al. [9, 10] reported that indium can effectively refine α-Mg grain size and increase c/a ratio beyond 3.3 at.% addition. Jin et al. [11] investigated the effect of indium addition on corrosion resistance of AP65 magnesium alloys and showed that indium addition accelerated overall corrosion. It was suggested that indium might provide low strengthening effect to magnesium alloys since In and Mg have very similar atom sizes although indium has a maximum solid solubility in magnesium as high as 53 wt.% [8]. However, grain refinement and possible formation of Mg-In binary compounds under non-equilibrium cooling conditions may help to improve the mechanical properties of magnesium alloys. In the literature, there is no study that investigated the effect of indium on mechanical properties of magnesium alloys under both as-cast and hot-rolled conditions. Therefore, this study aimed for clarifying the effect of indium addition on microstructure and mechanical properties of as-cast and hot-rolled AM60 magnesium alloy.

2. EXPERIMENTAL PROCEDURE

The Mg-6 wt.% Al-0.3 wt.% Mn alloys with different In additions (0, 0.5, 1 wt.%) were produced by gravity casting. The chemical compositions of the alloys were measured by wave-length dispersion X-ray fluorescence (XRF) and listed in **Table 1**. High purity Mg (99.9%), Al (99.9%), In (99.9%) and Al-Mn master alloy were used to prepare the alloys. The alloys were melted in stainless steel crucible placed in an electric resistance furnace under controlled Ar gas flow. After holding the melt at 750 °C for 45 minutes and stirring for 15 minutes, the melt was poured into a steel mould preheated to 250 °C. A homogenization treatment at 350 °C for 24 h was performed after the casting processes. Homogenized samples were hot-rolled by 40% thickness reduction at 1 pass at 350 °C.

Table 1 Chemical composition of the alloys (wt.%)

Element	**Al**	**Mn**	**In**	**Other**	**Mg**
AM60	5.89	0.15	-	0.015	Bal.
AM60-0.2 In	6.05	0.18	0.22	0.012	Bal.
AM60-0.5 In	6.14	0.20	0.57	0.010	Bal.
AM60-1 In	5.95	0.15	1.11	0.012	Bal.

For microstructure analysis, all the samples were mechanically ground with 240, 400, 600, 800, 1000, 1200 and 2000 grit emery papers followed by polishing with 6 μm and 1 μm diamond paste. The polished samples were etched with 6 gr picric acid, 5 ml glacial acetic acid, 10 ml distilled water and 100 ml ethanol. The microstructure images of the samples were taken by optical microscope and scanning electron microscope. According to EN ISO 6892-1, the tensile specimens with a gauge section of 40 mm x 9 mm x 2 mm were machined from the as-cast and hot-rolled alloys. Tensile tests were performed with a strain rate of 0.00167 1/s at room temperature and each test condition was repeated three times

3. RESULTS AND DISCUSSION

3.1. Microstructure

Figure 1 and **Figure 2** show the optical microstructures of the as-cast and hot-rolled AM60 alloys respectively with 0.2, 0.5 and 1 wt.% indium additions. The as-cast AM60 alloy consisted of primary α-Mg grains and a low amount of β-$Mg_{17}Al_{12}$ intermetallic phase since the maximum solid solubility of Al in α-Mg is about 12 wt.%. However, it was reported that β-$Mg_{17}Al_{12}$ phase can form as a result of non-equilibrium cooling conditions during casting with Al content as low as 2 wt.% [12]. Furthermore, the average α-Mg grain size decreased with increasing indium content up to 0.5 above which it slightly increased. After hot-rolling, almost fully dynamically recrystallized grain structures were obtained in all alloys. However, some unrecrystallized grains were also observed in AM60 alloy. That is to say, indium addition promoted dynamic recrystallization mechanism. The average recrystallized grain sizes were measured as 10.9 μm, 9.0 μm, 9.5 μm and 9.7 μm for hot-rolled AM60, AM60-0.2In, AM60-0.5In and AM60-1In alloys respectively. The formation of Mg-In binary compounds may result in pinning effect to some extent during the hot-rolling process. It should also be noted dynamically recrystallized grain size can be affected by the initial grain size of the alloys.

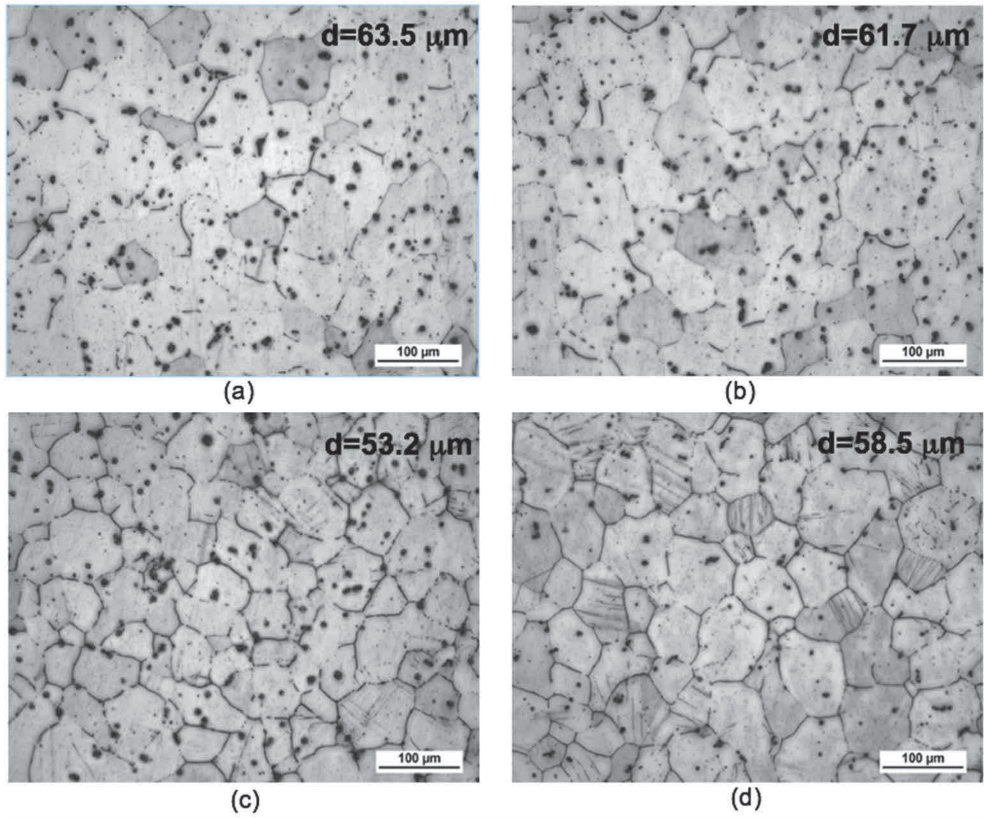

Figure 1 Microstructure images of as-cast a) AM60, b) AM60-0.2In, c) AM60-0.5In, d) AM60-1In

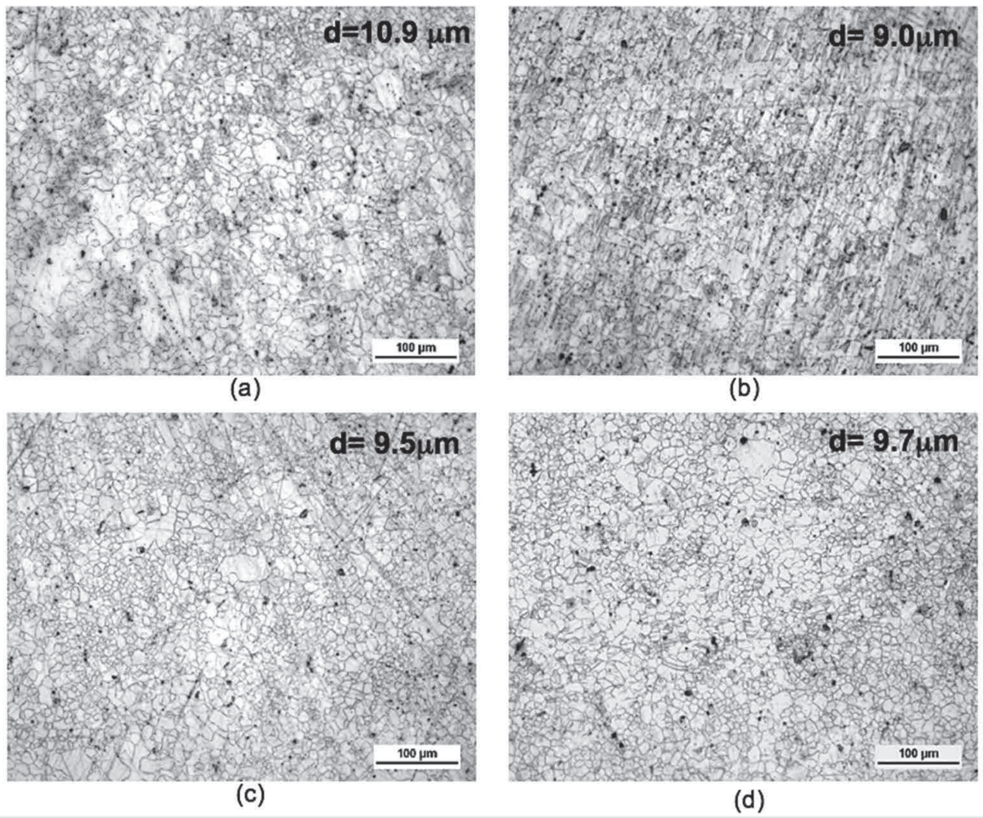

Figure 2 Microstructure images of hot-rolled a) AM60, b) AM60-0.2In, c) AM60-0.5In, and d) AM60-1In

Figure 3 shows SEM microstructures of as-cast AM60 and AM60-1In alloys. Corresponding energy-dispersive spectroscopy (EDS) results of the points in **Figure 3** are given in **Table 2**. It can be seen that, the microstructure of AM60 alloy consisted of primary α-Mg grains and divorced β-$Mg_{17}Al_{12}$ phase. With 1 wt.% In addition, β-$Mg_{17}Al_{12}$ phase appeared to be decreased and a new compound, which can be Mg-In binary compound, with high In concentration was observed. The Mg-In binary compounds were mostly seen as tiny particles located at triple junctions in AM60-1In alloy.

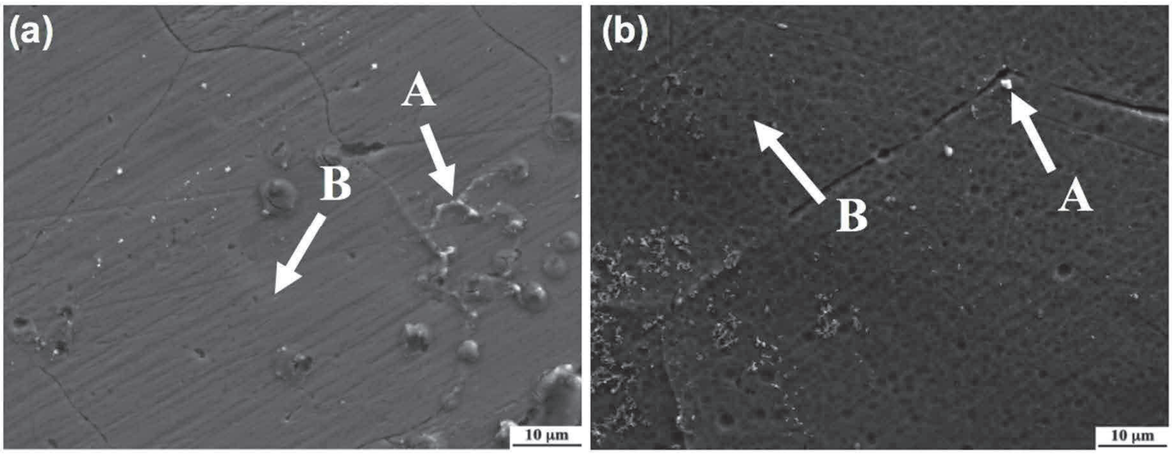

Figure 3 SEM images of as-cast a) AM60 and b) AM60-1In alloys

Table 2 EDS results of the points indicated in **Figure 3**

Alloys	Point	Elements (wt.%)			
		Mg	**Al**	**Mn**	**In**
AM60	A	78.67	21.32	0.01	-
	B	94.37	5.57	0.06	-
AM60-1 In	A	62.22	4.05	0.36	33.37
	B	95.49	3.36	0.29	0.86

3.2. Mechanical Properties

Figure 4 a), b) illustrates tensile test results of as-cast and hot-rolled AM60 alloys with different In additions. AM6-0.5In alloy exhibited the best mechanical properties among the as-cast alloys with 70 MPa yield strength and 215 MPa ultimate tensile strength allied with 7 % elongation. Further In addition led to a sharp decrease in mechanical properties of as-cast alloys. This behaviour was attributed to a possible premature crack propagation caused by Mg-In binary compounds in the AM60-1In alloy whereas grain refinement and solid solution strengthening dominated the improvement in mechanical properties of AM60-0.5In alloy. As presented in **Figure 2**, hot-rolling process gave rise to a much finer microstructure with less dislocation density due to dynamic recrystallization mechanism. Therefore, the mechanical properties of the as-cast alloys remarkably improved after hot-rolling process as shown in **Figure 4 (b)**. It should be noted that In-added hot-rolled alloys showed greater mechanical properties than AM60 alloy. This is mostly because of the different average dynamically recrystallized grain sizes of the alloys and dispersion strengthening caused by Mg-In binary compounds. Further investigations, such as higher additions than 1 wt.% of In and different rolling processing routes and parameters can provide better understanding the relationship between In and the properties of AM60.

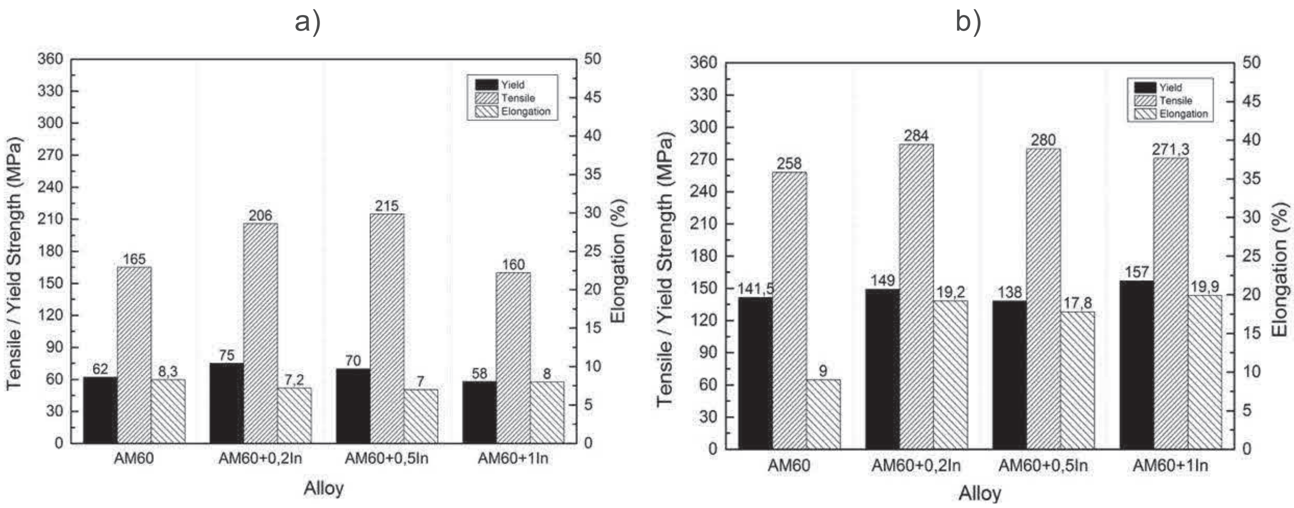

Figure 4 Tensile test results of (a) as-cast and (b) hot-rolled alloys

4. CONCLUSION

The following conclusions can be drawn:

- The microstructure of AM60 alloy consisted of primary α-Mg grains and divorced β-$Mg_{17}Al_{12}$ phase. With 1wt.% In addition, β-$Mg_{17}Al_{12}$ phase appeared to be decreased in volume fraction and a new compound, which thought to be Mg-In binary compound, was observed.
- The average as-cast α-Mg grain size decreased with increasing In content up to 0.5 above which it slightly increased. After hot-rolling, almost fully dynamically recrystallized grain structures were obtained in all alloys. However, some unrecrystallized grains were also observed in AM60 alloy. That is to say, indium addition promoted dynamic recrystallization mechanism.
- AM6-0.5In alloy exhibited the best mechanical properties among the as-cast alloys. The mechanical properties of the as-cast alloys remarkably improved after hot-rolling process. In-added hot-rolled alloys showed greater mechanical properties than AM60 alloy.

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