Development of a High Strength Al–Mg\textsubscript{2}Si-Mg-Zn Based Cast Alloy

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Abstract. This paper explores the possibility of developing an Al-Mg\textsubscript{2}Si-Mg-Zn based sand cast alloy having improved mechanical properties. The effect of Zn and free Mg after combining with Si to form Mg\textsubscript{2}Si on microstructure and mechanical properties was investigated under as-cast condition. Eight different alloys were prepared by varying Mg(4.15 – 12.0 wt.%) and Zn(2.58 – 6.22 wt.%) contents and 0.2 proof strength, tensile strength, elongation at failure and hardness were measured under as-cast condition. The microstructural investigation was conducted by optical microscopy and all alloys were found to contained α-Al, Al-Mg\textsubscript{2}Si eutectic and Mg\textsubscript{2}Si phases. The addition of Mg generally improves the proof strength and decreases the elongation, while the tensile strength shows a peak for alloys having Mg contents between the range 3 – 6 wt.%. Addition of Zn content also has the similar effect in improving strength and hardness and decreasing ductility. Comparing all alloys, alloy 3 having 5.41wt.%Mg, 1.85%Si and 5.45%Zn has the best combination of properties.

1. Introduction
Al–Si foundry alloys are widely used in the automotive industry due attractive foundry properties, good mechanical properties with high strength-to-weight ratio, corrosion resistance and ease of recycling [1]. Enhancement of mechanical properties by proper heat treatment procedure also offers attractive advantage [2]. Among the sand cast varieties of the currently available sand cast aluminium alloys, the heat-treatable Al-7Si-Mg alloys are still a popular choice for automobile and similar application. The enhanced mechanical properties of these alloys are attributed to the precipitation of Mg\textsubscript{2}Si particles in the α-Al matrix.

In the past two decades, various manufacturing industry had started to use Al- Mg\textsubscript{2}Si (Al-Mg-Si) alloys in structure and such other applications. Alloying elements present in Al– Mg\textsubscript{2}Si–Mg–Zn based alloys change properties significantly by alteration of the morphology, structure, size distribution and size of grains and precipitates. For this, greater vehicle fuel efficiency, more weight-savings, and decreased CO\textsubscript{2} emissions in transport have been achieved quickly [2]. Al- Mg\textsubscript{2}Si alloy is such an alloy which gives desirable high strength by Mg\textsubscript{2}Si particles. The past studies [2] on the Al-Mg\textsubscript{2}Si alloy are mainly based on the hyper-eutectic alloys for die casting applications and little information could be found for hypo-eutectic alloys for manufacturing sand cast quality automotive components.

In this paper, the focus is to develop a cast hypo-eutectic Al-Mg\textsubscript{2}Si alloy and compare its properties with those for the popular Al-7Si-Mg alloys. The effect Zn and excess Mg addition on structure and properties will also be investigated. This is because, several investigators found that aluminium alloys containing both zinc and magnesium developed substantially higher strengths than those containing...
any of these alloying elements added singly, and significantly higher strengths were obtained from these alloys [3-7].

2. Experimental
In this work, commercially pure aluminium ingot, pure magnesium ingot, pure zinc ingot, Al–50wt% Si master alloy ingot and Al–80wt% Mn master alloy purchased locally were used raw materials. Eight different alloy compositions were produced from these starting materials. A melt of 5 kg was prepared each time in gas-fired clay bonded graphite crucible. The melt was held for about 15 minutes at about 720°C for homogenisation. After degassing and dressing, the temperature of the melt was raised quickly to 750°C and then poured in Y-block sand mould.

Optical emission spectroscopy was performed to analyse each casting. From the Y-block casting of 200*100*20 mm dimension, tensile specimens following ASTM E8 standards were prepared. Tensile test was conducted at room temperature using Shimadzu universal testing machine to determine 0.2 proof strength, tensile and elongation at failure of the sample. Three specimens were tested for each condition and average values were reported. Brinell hardness of the specimens was measured by using Universal Hardness Testing machine using 5 mm diameter steel ball and 500 kg load. Finally, the optical microstructure of each sample was examined to analyse their structure. Standard metallographic techniques were used to prepare each sample.

3. Results and discussion
Mg₂Si is a compound of Mg and Si elements with atom ratio of Mg:Si = 2:1 and the weight ratio of Mg:Si = 1.73:1. The Mg₂Si crystal occurs during solidification because the maximum solids solubility of Si into Mg is less than 0.03%[5]. Al–Mg₂Si can be regarded as a simple pseudo-binary alloy, Figure 1. This is particularly useful to simplify the thermodynamics of Al–Mg–Si system with a specific ratio in a binary phase diagram. However, the present experiments were carried out using individual element and it is easier to understand using Mg and Si. To balance the need in thermodynamic calculation and experimental confirmation, the corresponding compositions of each alloy is reported in the form of total Mg and Si, Mg₂Si, excess Mg (after forming Mg₂Si) are listed in Table 1.

| Table 1. Chemical composition of the studied eight alloys. |
|---|---|---|---|---|---|---|
| %Mg | %Si | %Zn | %Mn | %Fe | Al |
| Alloy 1 | 4.15 | 1.46 | 6.22 | 0.19 | 0.16 | Balance |
| Alloy 2 | 4.29 | 1.93 | 2.58 | 0.06 | 0.31 | Balance |
| Alloy 3 | 5.41 | 1.85 | 5.45 | 0.02 | 0.25 | Balance |
| Alloy 4 | 5.83 | 2.19 | 4.91 | 0.02 | 0.24 | Balance |
| Alloy 5 | 6.94 | 2.55 | 5.26 | 0.19 | 0.18 | Balance |
| Alloy 6 | 7.40 | 4.19 | 5.01 | 0.02 | 0.16 | Balance |
| Alloy 7 | 11.6 | 6.58 | 3.83 | 0.14 | 0.18 | Balance |
| Alloy 8 | 12.0 | 8.84 | 4.17 | 0.17 | 0.14 | Balance |

3.1 General Properties of Al-Mg₂Si-Mg-Zn Alloys
A summary of mechanical properties of the eight tested alloys is given in Table 2. Compared with the mechanical properties of commonly used sand-cast Al-7Si-0.3Mg (LM25 or A356) alloys in the as-cast conditions (0.2 Proof strength = 90 MPa, Tensile strength = 180 MPa, Elongation = 5 %), all Al-Mg₂Si-Mg-Zn alloys showed improved strength and decreased ductility with Alloy 3 (5wt% Mg₂Si and 2.2% excess Mg) showed the highest value.
Figure 1: The pseudo-binary phase diagram of Al-Mg₂Si system.

Table 2. Mechanical properties of studied eight alloys.

|         | 0.2 Proof Strength (MPa) | Tensile Strength (MPa) | Elongation (in 50 mm) (%) | BHN (500 kg, 5 mm) |
|---------|--------------------------|------------------------|---------------------------|-------------------|
| Alloy 1 | 154                      | 196                    | 2.4                       | 98                |
| Alloy 2 | 150                      | 194                    | 3.0                       | 76                |
| Alloy 3 | 229                      | 237                    | 1.0                       | 108               |
| Alloy 4 | 215                      | 224                    | 2.2                       | 99                |
| Alloy 5 | 215                      | 217                    | 2.1                       | 101               |
| Alloy 6 | 211                      | 215                    | 2.1                       | 55                |
| Alloy 7 | 124                      | 187                    | 1.9                       | 101               |
| Alloy 8 | 121                      | 181                    | 1.7                       | 99                |

Normally, reduced porosity and improved microstructural uniformity in the castings result in the decrement of sources for brittle fracture and improve the mechanical properties. Pores present in the microstructure favour crack initiation and propagation therefore are bad for the mechanical performance of the material [2]. The reduced defects can retard the initialisation of cracks and improve the mechanical properties. More Mg and Si in the alloy create more eutectic Al-Mg₂Si phases, which result in increased strength and decreased ductility. By analysing thermodynamics and the phase diagram, we understand that although Mg content can be varied in large range, it is preferred in a range of 5–8 wt.% in Al-Mg-Si based alloy for getting relatively narrow solidification range [8], and a better mechanical property. In the present work, this is also evident as Alloy 1 to 8, containing Mg₂Si content in the range of 5–11 wt.% produce higher mechanical strength. Alloy 2 is a special case, as it contains lower Zn content.

3.2 Effect of Mg Content on the Mechanical Properties

The pseudo-binary Al–Mg₂Si system (Figure1) normally behave like a normal binary eutectic system with a eutectic point at 13.9 wt% Mg₂Si (Al–8.81 wt%Mg–5.09 wt%Si). With extra Mg in the Al–
Mg$_2$Si system, the eutectic point was shifted towards a lower Mg$_2$Si concentration and the area of coexistence for the three phases (L + α-Al + Mg$_2$Si) was enlarged. This means that, for a given Mg$_2$Si content, an extra Mg addition resulted in a decrease of the volume fraction of the primary α-Al phase and an increase of the volume fraction of Al–Mg$_2$Si eutectic phase.

Figures 2(a) and 2(b) showed the variation of the 0.2 proof strength, tensile strength, elongation and hardness of the as-cast Al-Mg$_2$Si-Mg-Zn alloys with Mg contents. In general, the proof strength and tensile strength were improved with increasing Mg content. Conversely, the elongation was decreased with increasing Mg in the alloys. This may be attributed to the fact that alloys having lower Mg content have a much higher solid fraction of α-Al phase, which maintained their ductility. With increasing Mg content, Al-Mg$_2$Si eutectics were formed, which improved strength and reduced ductility. When the coarse primary Mg$_2$Si phase was formed at a high Mg content (alloy 7), both the ductility and tensile strength were decreased markedly.

**Figure 2(a):** Variations of 0.2 Proof Strength, tensile strength and elongation with Mg content.

**Figure 2(b):** Variations of hardness with Mg content.
The solid fraction of the primary $\alpha$-Al is a key factor which affecting the alloy ductility. The increase in yield strength was associated with decrease in elongation. When considering equilibrium condition, maximum solid solubility of Mg in Al is 17.4wt% and $\text{Mg}_2\text{Si}$ in Al is 1.85wt% [10]. It should be noted that when the $\alpha$-Al/$\text{Mg}_2\text{Si}$ eutectic phase started to form, Mg atoms were rejected from the $\alpha$-Al phase. Therefore, the combination between $\text{Mg}_2\text{Si}$ and extra Mg content helped to maximize the strengths with proper ductility. Same occurrence can also be found in Al-Si eutectic alloys, in which case the primary Si phase can be observed [11-13].

3.3 Effect of Zn Contents on the Mechanical Properties

Figure 3 showed the effect of Zn addition on the mechanical properties of Al-$\text{Mg}_2\text{Si}$-Mg-Zn alloys. The addition of Zn resulted in an increase in proof strength and hardness and a decrease in ductility of the alloys, while the tensile strength remained mostly constant. The low ductility of high-zinc contained alloys was attributed to the coarse grain structure of these alloys [4]. From Figure 3(a) zinc was the 2nd highest (i.e., 5.45%), ductility was the lowest. Although 6.22% Zn (which was highest Zn content among the seven alloys), ductility was higher (2.4%) due to low Mg content (4.15%). When zinc was increased to 2.58, 4.91 and 5.45%, ductility was decreased to 3.0, 2.2 and 1, respectively. The hardness variation was also found to be sensitive to Zn composition as shown in Figure 3(b).

![Figure 3(a): Variations of 0.2 Proof Strength, tensile strength and elongation with Zn content.](image)

![Figure 3(b): Variations of hardness with Zn content](image)
When Zn is added to these alloys, there was no Zn-rich primary phase observed, even in the alloy with 4.3wt.% Zn. This was because Zn has a high solubility in aluminium in both liquid and solid states [14]. Zn addition to alloy 2 (5.45% Zn) was expected to react with the Mg and form the Mg$_2$Zn phase, which improved the mechanical properties under as-cast conditions.

3.4 Effect of Mg on Microstructure
Alloys having a lower Mg content showed predominantly coarse $\alpha$-Al matrix in their structures. Few small Al-Mg$_2$Si eutectics were also seen. According to Feng Yan [5], increasing Mg can increase the Al-Mg$_2$Si eutectics in the Al-Mg$_2$Si alloy at the hypo-eutectic composition. With increasing Mg content, the microstructure consisted of fine primary $\alpha$-Al phase surrounded by Al-Mg$_2$Si eutectic phase. Upon further increase in Mg level, polygon shaped primary Mg$_2$Si phase was appeared in the structure. It is clear from Figures 4(g) and 4(h) that most primary Mg$_2$Si particles exhibited polygon shape when the Mg contents were 11.6%, such as hexagon, rectangle and trapezoid. However, with raising the Mg content to 12%, as shown in Figure 4(h), the shape of primary Mg$_2$Si particles changed to polygon shapes with hole [9]. The Mg$_2$Si particles had an average size of 61.5 μm and were randomly distributed.

![Figure 4: Optical micrographs of (a) alloy 1, (b) alloy 2, (c) alloy 3, (d) alloy 4.](image-url)
Figure 4 (contd..): Optical micrographs of (e) alloy 5, (f) alloy 6, (g) alloy 7, and (h) alloy 8.

ductility. A lower Si content could prevent the formation of the primary Mg$_2$Si phase. With varied Mg and Zn contents, the microstructure of the alloys consisted of α-Al, Al-Mg$_2$Si, Mg$_2$Si phases. By promoting the formation of laminar/fibrous Mg$_2$Si eutectic phase, the strength of the Al-Mg$_2$Si-Mg-Zn based alloy was expected to increase.

5. Reference
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