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Preliminary study of the characteristics of a high Mg containing Al-Mg-Si alloy

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Abstract. An Al-20Mg-4Si high Mg containing alloy has been produced and its characteristics investigated. The as-cast alloy revealed primary Mg_2Si particles evenly distributed throughout an α-Al matrix with a β-Al_3Mg_2 fully divorced eutectic phase observed in interdendritic regions. The Mg_2Si particles displayed octahedral, truncated octahedral, and hopper morphologies. Additions of Sb, Ti and Zr had a refining influence reducing the size of the Mg_2Si from 52 ± 4 μm to 25 ± 0.1 μm, 35 ± 1 μm and 34 ± 1 μm respectively. HPDC tensile test samples could be produced with a 0.6 wt.% Mn addition which prevented die soldering. Solution heating for 1 hr was found to dissolve the majority of the Al_3Mg_2 eutectic phase with no evidence of any effect on the primary Mg_2Si. Preliminary results indicate that the heat treatment has a beneficial effect on the elongation and the UTS.

1. Introduction

Industry is continually demanding materials with superior mechanical properties and lower densities for engineering applications. In Al-Mg alloys, with increasing Mg content, the alloy density is reduced and the strength is increased, but this is attained at the expense of ductility, which decreases due to the formation of a brittle β-Al_3Mg_2 phase. This has resulted in limited research conducted on the high Mg containing Al-rich alloy system (~>12wt.%). As a consequence, in high Mg containing Al alloys much of the past research has focused on Al-15wt.%Mg_2Si particulate metal matrix composites (PMMCs) in which the Mg in the melt reacts with Si to form primary Mg_2Si particulates. The formation of both primary and secondary Mg_2Si phases in Al alloys can have major benefits on the mechanical properties. With a high melting temperature (1085 °C), low density (1.99×10^3 kgm^{-3}), high hardness (4.5×10^9 Nm^{-2}), low coefficient of thermal expansion (7.5×10^{-6} K^{-1}), and a high elastic modulus (120 GPa), Mg_2Si particles have become an attractive material for aerospace, automotive, and other advanced applications [1-3]. Furthermore, the presence of Mg in Al Alloys can impart heat treatable properties and, in combination with Si, can enhance corrosion resistance in extreme hostile environments e.g. marine applications [2].

Altering the size, distribution, and morphology of the Mg_2Si or changing the phases formed are the principal methods whereby the mechanical properties can be improved. Coarse primary Mg_2Si particles often lead to poor tensile properties [1,3-6]. As a consequence there have been many studies conducted on the effect of added elements on the refining [1,4-8] or modifying [5,7-9,12,13] of the primary and secondary Mg_2Si phases. Na, Sb, Ca, P, Sr, and rare earth elements such as La and Ce, have all been reported [5-13] to have beneficial effects. This has thus proved to be an attractive method in improving the mechanical properties. Other techniques, such as heat-treatment, have also

been documented as being beneficial in modifying the microstructure and improving the mechanical properties [14,15].

Little research has been conducted on the high Mg containing Al alloys, hence the main purpose of this paper is therefore to explore their characteristics with an aim to understand and improve the ductility.

2. Experimental methods

Commercial purity Al (99.97%), Mg ingot (99.98%), and Al-50%Si master alloy were used as starting materials to prepare a base Al-20Mg-4Si (wt. %) master alloy (all further compositions stated hereafter in wt. %). Two kilograms of the produced master alloy was melted in a resistance furnace with a steel liner at a temperature of 760°C, under a N_2 and SF_6 protective atmosphere. 20 ppm Be was added to the Al melt 10 minutes prior to the addition of Mg, thereby preventing the Mg from oxidizing and evaporating. To investigate the effect of alloying elements, 0.1% Ti, 0.4% Sb, 0.2% Zr, 0.6% Mn were added separately using Al-10Ti, Al-10Sb, Al-20Mn, and Al-10Zr master alloys and to two kilograms of the Al-20Mg-4Si at a temperature of 760°C for 0.5 hr. The Al-20Mg-4Si was subjected to a heat treatment (HT), processed at 430°C for one, four, and eight hours in an air circulated furnace, immediately followed by a water quench. Microstructure analysis was performed on melts cast under TP1 conditions hence creating repeatable and comparable results. The subjected measured cooling rates experienced during casting were ~4 ± 1°Cs^{-1}. All TP1 specimens for microstructural characterization were cast in accordance with the ASTM standard, sectioned 38 mm from the base, and examined under brightfield optical microscopy after polishing and etching with 10% NaOH for 30 seconds. Microstructural parameters, such as the number and size of the primary Mg_2Si particles, were determined using image analysis software provided by Carl Zeiss. Schiel simulations of the alloy, using Thermo-Calc software with the TTAL5 database, indicated the phases formed, formation temperatures and mole fraction of solid.

3. Results and discussion

3.1. Al-20-Mg-4Si cast microstructure

The Al-20Mg-4Si as-cast microstructure consisted of a predominant α-Al matrix with a fully divorced β-Al_3Mg_2 phase located at interdendritic regions, as seen in figure 1(a). The formation and distribution of the β-Al_3Mg_2 phase was in accordance with that observed in other studies [2]. Within this matrix, large primary Mg_2Si particles, 52 ± 4 μm in size were evenly distributed throughout, displaying well-defined classical octrahedral, truncated octahedral and hopper morphologies. These morphologies and their underlying growth mechanisms have been investigated in further detail by Li et al. [1]. Within the interdendritic regions a small proportion of eutectic Mg_2Si could also be observed.

3.2. Thermo-Calc simulations

Scheil simulations of the Al-20Mg-4Si alloy using the TTAL5 database (shown in figure 2) revealed the phase formation with increasing solid fraction. Primary Mg_2Si was found to form first in the melt at ~650°C. At ~570°C, fcc Al formed followed by the β-Al_3Mg_2 phase at ~ 450°C. The phases given by the simulation were in accordance with that observed in the microstructure.

3.3. Effect of element addition

The effect of Ti, Sb, and Zr alloying elements on the original as-cast microstructure was investigated (see figure 1(b), (c) and (d)). Despite the applied constant cooling rate, each element was found to have a grain refining influence on the primary Mg_2Si phase. This particle refinement observed, could be attributed either to the formation of a greater number of potent nucleation sites, or to a restriction in their growth i.e. a reduction in their growth velocity. Quantification of the size of reduction indicated that of these elements, for the given addition levels, Sb had the strongest effect. The average particle

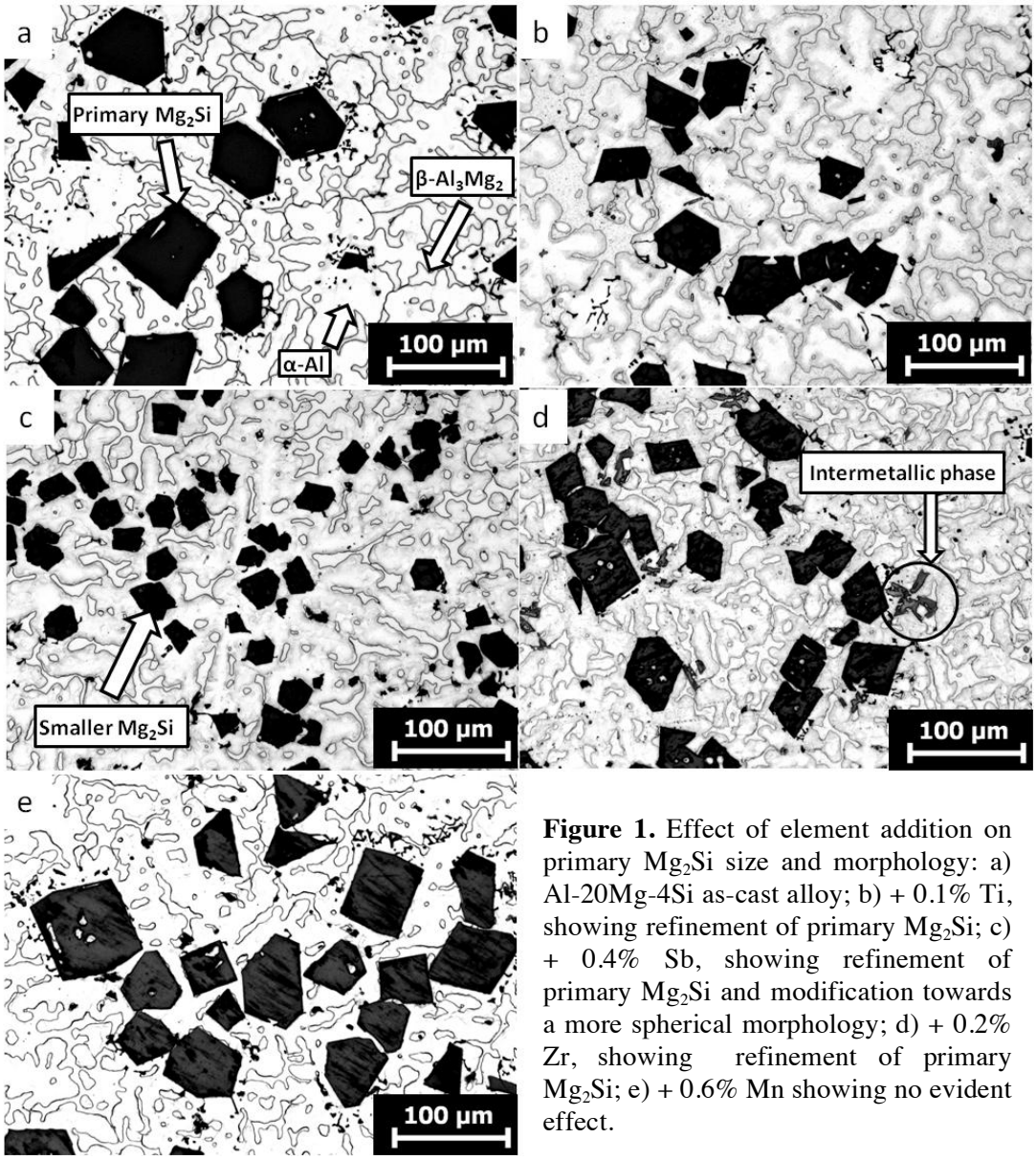

Figure 1. Effect of element addition on primary Mg_2Si size and morphology: a) Al-20Mg-4Si as-cast alloy; b) + 0.1% Ti, showing refinement of primary Mg_2Si; c) + 0.4% Sb, showing refinement of primary Mg_2Si and modification towards a more spherical morphology; d) + 0.2% Zr, showing refinement of primary Mg_2Si; e) + 0.6% Mn showing no evident effect.

size calculated for the primary Mg_2Si was reduced from 52 ± 4 µm for the sample with no addition to; 35 ± 1 µm for an addition of 0.1% Ti; 25 ± 0.1 µm for 0.4% Sb; and 34 ± 0.8 µm for 0.2% Zr. The addition levels were based on the maximum effect of the element as documented in the literature [4,5,6]. Ti and Zr were found to have little effect on the morphology, whereas the primary Mg_2Si exhibited a more spherical structure in the Sb containing alloy.

3.4. Effect of element addition

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The number of particles for a standard region of interest, in the Sb containing alloy, was approximately double that for the Ti and Zr. This indicates that Sb has an effect on both the refinement (by increasing the number of nucleation sites), and modification of the primary Mg_2Si phase (from impurities substituting into the lattice and altering the growth directions).

Since Pacz [16] first discovered the modifying effect of Na on Si eutectic in the 1920's, the effect of elements on the refinement and growth of Si, and its compounds has been widely investigated. P is known to have a refining effect on primary Si, whilst Na, Sr, Ca, have a modifying effect on eutectic Si. More recently mischmetal and rare earth elements have been studied. It has been suggested [5] that for the Sb containing system the refinement of primary Mg_2Si is due to the formation of Mg_3Sb_2 as this phase was observed inside the particles. The Mg_3Sb_2 can act as an effective nucleation site for primary Mg_2Si phases, which results in the refinement of primary Mg_2Si [5-7] as the volume fraction of the Mg_2Si phase remains constant. The misfit has been identified as an important parameter in the potency of the nucleation site. For the Mg_3Sb_2 substrate and Mg_2Si nucleant this misfit is lowest (5.1%) when the orientation relationship between the Mg_2Si and Mg_3Sb_2 phase is (0001) // Mg_3Sb_2 (0001) Mg_2Si [5].

The individually added elements appeared to have no other influence on the microstucture except for Zr which was found, to form additional intermetallic phases located at the interdendritic grain boundarys, as circled in figure 1(e). The 0.6%Mn had no evident effect on the microstructure observed.

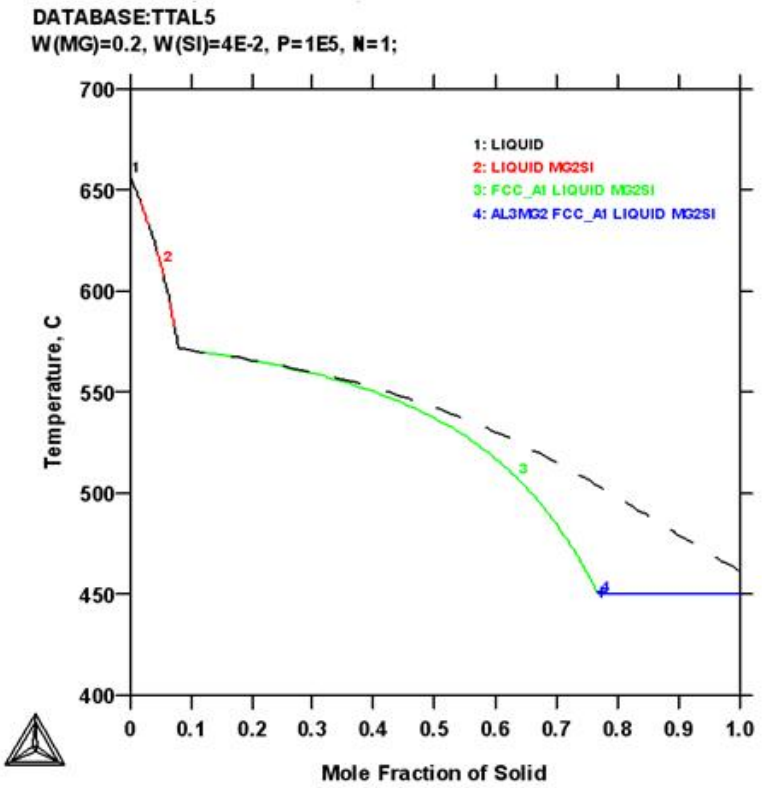

Figure 2. Thermo-Calc Schiel simulation depicting the Al-20Mg-4Si solidification process. The graph shows primary Mg_2Si forming at ~660 ˚C, fcc Al at ~570 ˚C and Al_3Mg_2 at 450 ˚C.

3.5. Effect of heat treatment

Solution heat treatment of the Al-20Mg-4Si alloy at 430°C for one, four and eight hours had a major effect on the observed microstructure (see figure 3). With only an hour treatment time, the majority of the eutectic β-Al_3Mg_2 phase had dissolved, resulting in the coarsening of the α-Al grains. With increasing time the β-Al_3Mg_2 phase continued to decrease with little remaining after a duration of eight hours. There was no evidence to suggest that the treatment had any effect on the size and morphology of the primary and eutectic Mg_2Si which were engulfed within the α-Al grains.

3.6. Tensile test

A preliminary study examined the effect of solution heat treatment on the mechanical properties of the Al-20Mg-4Si-0.6Mn alloy. The Mn addition was necessary to prevent die soldering during casting. Results revealed that a four hour HT had little effect on the yield strength which increased from 237 ± 7 MPa to 245 ± 3 MPa (see figure 4), however, UTS increased from 239 ± 4 MPa to 306 ± 1 MPa (figure 4) and the elongation increased from 0.7 ± 0.1% to 1.9 ± 0.2% (figure 4). This finding is of interest as HT HPDC samples often yield poor results due to the elevated treatment temperatures causing pores in the casting to expand, forming cracks and blisters that reduce the magnitude of the properties that can be attained. This indicates that the heat treatment and the dissolution of the β-Al_3Mg_2 phase have a beneficial effect on the final mechanical properties, especially the ductility. A more comprehensive investigation of the properties is planned for future work.

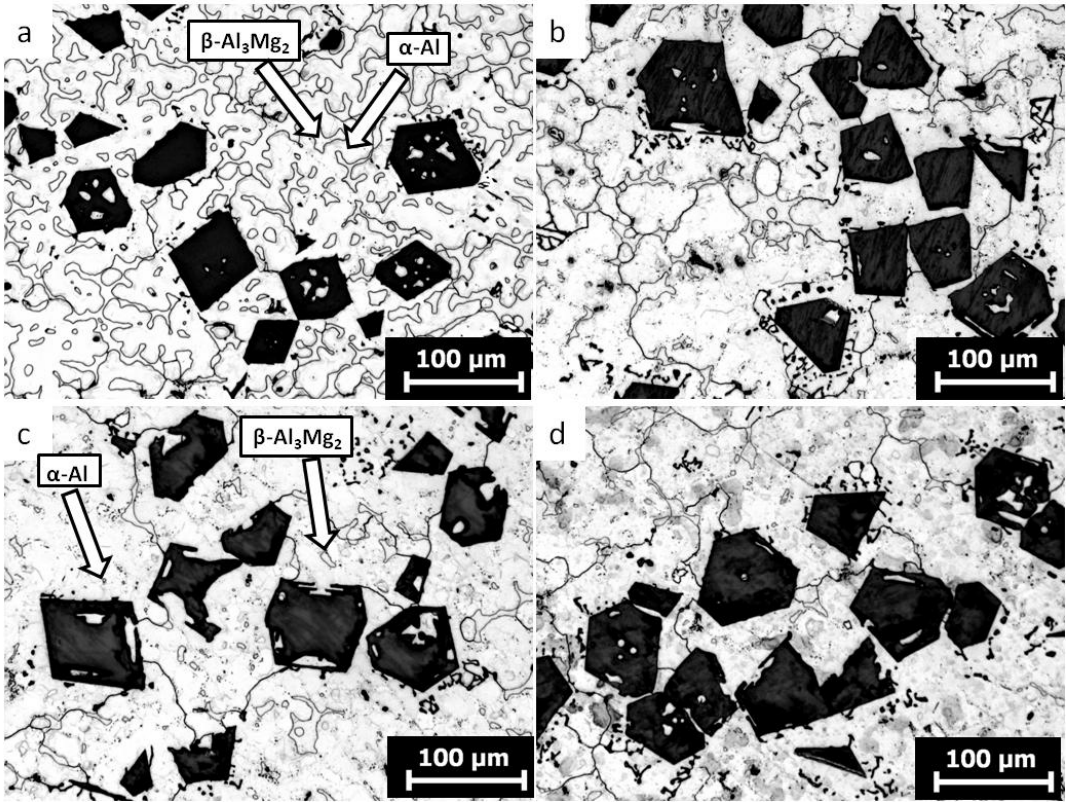

Figure 3. The effect of solution heat treatment on the dissolution of the eutectic β-Al_3Mg_2 phase in the Al-20Mg-4Si alloy: a) non-heat treated sample showing a large fraction of β-Al_3Mg_2: b) heat treated for an hour at 430°C: c) heat treated for four hours at 430°C and quenched; d) heat treated at 430°C for eight hours and quenched, now showing little of the β-Al_3Mg_2 phase remaining.

4. Summary

In this preliminary investigation the characteristics of an Al-20Mg-4Si alloy have been studied. The primary Mg_2Si phase formed, was evenly distributed throughout an α-Al, β-Al_3Mg_2 matrix. The primary Mg_2Si exhibited octahedral, truncated octrahedral and hopper morphologies. It was refined with Sb, Zr, and Ti additions. Of these additions, Sb was found to be the most effective at the addition levels examined, reducing the size from 52 ± 4 to 25 ± 0.1 μm. The Sb also appeared to modify the morphology of the primary Mg_2Si towards a more spherical structure.

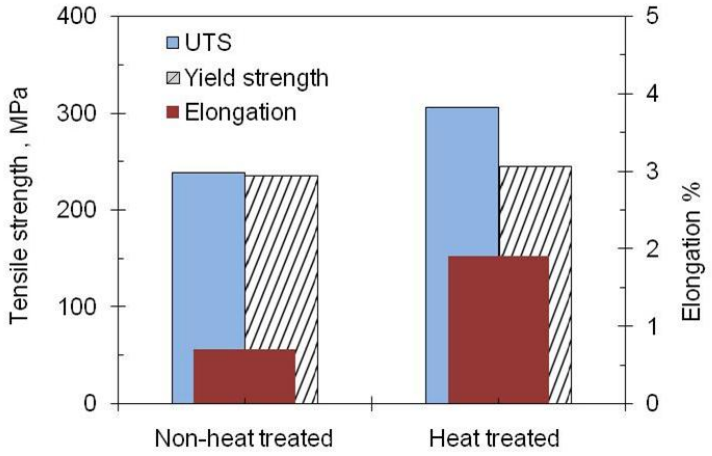

Figure 4. Effect of solution heat treatment at 430°C for an hour on HPDC Al-20Mg-4Si-0.6Mn tensile samples showing a constant yield strength but an increase in both elongation from 0.7 ± 0.1% to 1.9 ± 0.2%, and UTS from 239 ± 4 MPa to 306 ± 1 MPa.

Solution heat treatment of the Al-20Mg-4Si alloy was found to dissolve the β-Al_3Mg_2 eutectic and coarsen the primary α-Al, but had no evident effect on the primary Mg_2Si phase. The treatment was found to improve the elongation and UTS of HPDC Al-20Mg-4Si-0.6Mn tensile samples, with an increase of ~1.2 ± 0.2% and ~ 67 ± 0.7 MPa attained, respectively.

References

[1] Li C, Liu X and Zhang G, 2008 *Mat. Sci. Eng. A* **497** 432
[2] KBM Afflips, 1996 *Aluminium Magnesium Al-Mg: Aluminium based high concentration master alloys*, AlMg.366.E.01
[3] Zhang J, Fan Z, Wang Y.Q and Zhou B.L 2000 *Mat. Sci. Eng.* **16** 913
[4] Dang J., Huang Y and Chen J 2009, *J. Trans. Nonferrous Met. Soc. China* **19** 540
[5] Ren B, Liu Z, Zhao R, Zhang T, Liu Z, Wang M and Wen Y 2010, *J. Trans. Nonferrous Met. Soc. China* **20** 1367
[6] Yan H, Hu Y and Wu X 2010 *Trans. Nonferrous Met. Soc. China* **20** 411
[7] Sun Y and Ahlatci H 2011 *Mater. Desn.* **32** 2983
[8] Li C, Liu X and Wu Y 2008 *J. Alloy Compd.* **465** 145
[9] Guo E, Ma B, Wang L 2008 *Mater. Process Tech.* **206** 161
[10] Liao H, Sun Y and Sun G 2003 *Mat. Sci. Eng.* A **358** 164
[11] Emamy M, Khorshidi R and Honarbakhsh Raouf A 2011 *Mat. Sci. Eng.* A **528** 4337
[12] Wang L, Guo E and Ma B 2008 *J. Rare Earth* **26** 105
[13] Zhao Y, Qin Q, Zhou W and Liang Y 2005 *J. Alloy Compd.* **389** L1
[14] Mori K, Maki S and Ishiguro M 2006 *Int. J. Mach. Tool Manu.* **46** 1966
[15] Mr´owka-Nowotnik G and Sieniawski J 2005 *J. Mater. Process Tech.* **162–163** 367
[16] Pacz A 1921 U.S Patent No. 1387900