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A super-ductile alloy for the die-casting of aluminium automotive body structural components

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Abstract. Super-ductile die-cast aluminium alloys are critical to future light-weighting of automotive body structures. This paper introduces a die-cast aluminium alloy that can satisfy the requirements of these applications. After a review of currently available alloys, the requirement of a die-cast aluminium alloy for automotive body structural parts is proposed and an Al-Mg-Si system is suggested. The effect of the alloying elements, in the composition, has been investigated on the microstructure and mechanical properties, in particular the yield strength, the ultimate tensile strength and elongation.

Introduction

In the manufacture of fuel efficient transport systems, weight reduction through the use of lightweight materials remains a very successful and simple means of improving fuel economy and reducing harmful emissions. Increases in aluminium alloys usage for automotive applications provide significant opportunities for weight reduction and therefore real scope to achieve the environmental goals [1,2]. The automotive industry utilizes a range of aluminium components [3] and High Pressure Die Casting is one of the most popular manufacturing processes with the attractiveness of manufacturing near net shape parts, with little or no machining, to tight dimensional tolerances. Moreover, an increasing trend in replacing steel parts with lighter aluminium ones being used extensively in automotive areas. One of the significant progresses in most recent years has been in the application of aluminium-intensive car body structure [4,5].

In the automotive body structure, both wrought and cast aluminium alloys are essential in space-frame and monocoque design of aluminium-intensive passenger cars. In order to maximize the benefits of aluminium-intensive car body structure, the die castings need to have comparable mechanical properties with the components made by aluminium sheet. However, the mechanical properties of currently available die-cast alloys are not competitive and cannot satisfy the requirement in industry. In particular, the ductility is not sufficient in manufacturing and in application.

The requirement of cast alloys in automotive body structure

Clear requirements for the cast alloys used in automotive body structure can be derived from the extensively used wrought alloys. The basic requirements for the cast alloys suitable for automotive body structure are summarized as follows:

(1) Die-castable at typical wall thickness of 2 to 4mm with low level of porosity,
(2) Excellent ductility with breaking elongation at least 15% under as-cast condition,
(3) A level of 150MPa of yield strength and 300MPa of ultimate tensile strength of die casting under as-cast condition,
(4) Appropriate corrosion resistant,

(5) Potential of paint baking hardening at 180°C for 30 minutes that is commonly used in industry,
(6) Compatible with wrought aluminium alloys used as sheet/extruded parts in automotive body structure. This is particularly important for the possible closed loop recycling of materials in future.

Of these requirements, the properties and cost are two major concerns. The cost control includes the use of die castings that can easily achieve massive production and hence lowering the component cost. Meanwhile the compatibility with wrought alloys can reduce the recycle cost at the end life of vehicles. This can offer a possibility to achieve a closed loop recycling at the end life of body structure, which is beneficial for environments and cost-saving [9].

In recent years, trials have been made to add rare earth elements or scandium to Al-Mg-Si alloys in order to improve the mechanical properties However, the utilization of costly elements is not preferred in industry. Therefore, the development on new Al-Mg-Si die-cast alloy should focus on the composition optimization with less level of the costly elements.

Experimental

For all experiments a 10kg melt was prepared from commercial purity aluminium and magnesium and master alloys. A standard melting procedure was followed with degassing and fluxing taking place before the melt was thoroughly stirred to enable complete dissolution and homogenization. The melt was then held at 700°C for about 20 minutes before taking sample for composition measurement.

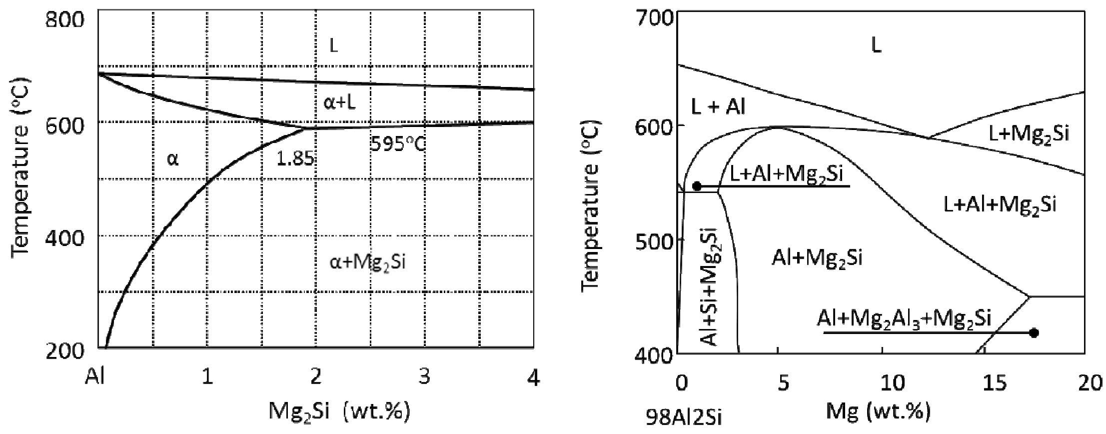
A ϕ40×60mm cylindrical casting made by a steel mold was utilized for composition analysis. The casting was cut across the diameter at 15mm from the bottom and grinded down to 800 grid sand paper. The composition of each alloy was obtained from an optical mass spectroscopy, in which at least five spark analyses were performed and the average was taken as the chemical composition of alloy.

After composition analysis and skimming, casting, consisting of four ASTM tensile standard samples were produced on a 2800kN HPDC machine. The pouring temperature was measured at 650^{o}C and the die temperature was controlled at 210°C in all shots. The tensile tests were conducted following ASTM standard B557, using an Instron 5500 Universal Electromechanical Testing Systems.

The microstructure of each alloy was examined using a Zeiss optical microscope with quantitative metallography, and a Zeiss SUPRA 35VP scanning electron microscope (SEM), equipped with energy dispersive spectroscopy (EDS). Quantitative metallography was conducted using an AxioVision 4.3 Quantimet digital image analysis system.

Results

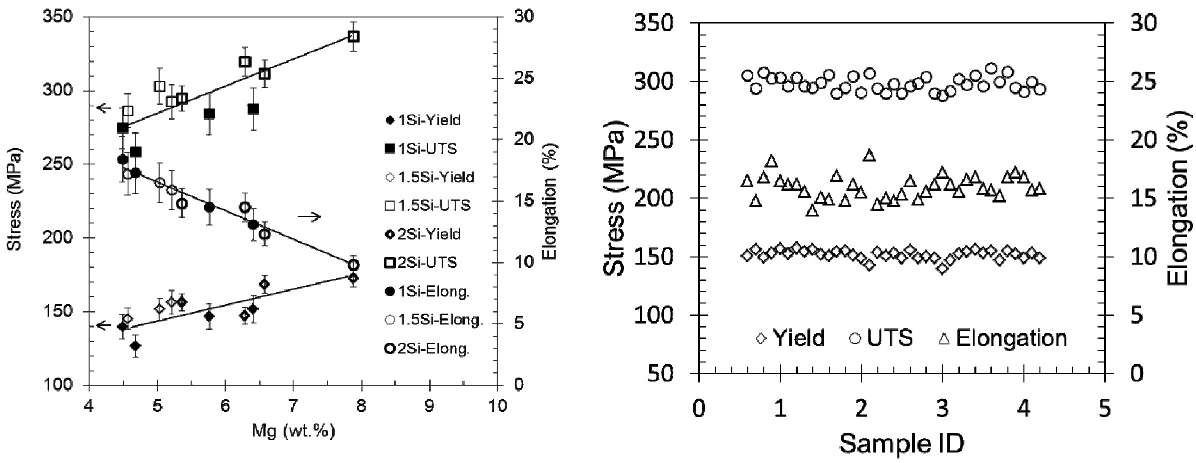
Effect of alloying elements. In order to select the adequate content of Mg and Si, Figure 1 shows phase diagrams of Al-Mg_2Si pseudo-binary phase diagram at Al-rich side and Al-Mg-Si ternary alloy on the cross section of 98Al2Si [6,7]. As the Mg2Si phase has a maximum solubility in Al at 1.85wt-% in equilibrium state, the Si content in the alloy should be chosen near this point where Si can either dissolve into the primary phase or form new phase during eutectic solidification, rather than to form a new primary phase. This is essential to achieve better ductility for the alloy. Similarly in Figure 1b, although Mg content can be varied in a relatively large range to create the α-Al phase without Mg_2Si primary phase, the Mg content should be near 5wt-% in Al-Mg-Si based alloy to maximise the solubility and to enhance the solution strengthening in as-cast state. This also can promote the ductility of cast materials as less eutectic phase in the microstructure.



(a) (b)

Figure 1. The equilibrium phase diagrams (a)Al-Mg2Si binary alloys [12], (b) Al-Mg-Si ternary alloys [13],

Figure 2 shows the effect of Mg and Si on the yield strength, the tensile strength and the elongation of die-cast aluminium alloys, in which other elements include 0.6wt-%Mn, 0.2wt-%Ti and 0.1wt-%Fe. The results confirm that both Mg and Si resulted in a significant increase of the yield strength and the ultimate tensile strength and a significant decrease of the elongation of the die-cast alloys. The results indicate that Mg can promote the mechanical properties of the die-cast alloys more significantly than Si can in as-cast state. This can be attributed to the mechanism of strengthening, in which Mg has a higher level in the alloy and therefore more strengthening in solid solution.



(a) (b)

Figure 2.(a) Effect of magnesium and silicon on the yield strength, the ultimate tensile strength and the total elongation of Al-Mg-Si die-cast alloy (b) The yield strength, the ultimate tensile strength and the total elongation of Al-5Mg-1.5Si-Mn die-cast alloy at optimized composition.

Based on the experimental results, the optimized composition of super ductile Al-Mg-Si alloy has been selected at 5wt-%Mg, 1.5wt-%Si, 0.6wt-%Mn and 0.2wt-%Ti. The mechanical properties of the alloy at the optimized composition are shown in Figure 2 (b). The results from the extensively tested samples confirm that the yield strength was at a level of 150MPa, the ultimate tensile strength at a level of 300MPa, and the elongation at a level of 15%.

The microstructure of the die-cast alloy. The microstructures of as-cast Al-Mg-Si alloy are shown in Fig. 3 consists of primary dendrites or fragmented primary dendrites, globular primary phase and eutectics. The primary dendrites (Fig. 3a) were formed in the shot sleeve of the die caster and had variable sizes from few ten micrometers to several hundred micrometers. Some of the dendrites could be fragmented partially or completely when the mixture melt passed through the ingate of casting, where high speed and high shear were created within the melt. The fragmented dendrites exhibited the relatively large globular morphology (Fig. 3b&c). In the cast microstructure, the fine and relatively spheroidal particles were formed in the die cavity. The mean particle size was at a level of 7.5 micrometers and the shape factor was 0.71 (Fig. 3c).

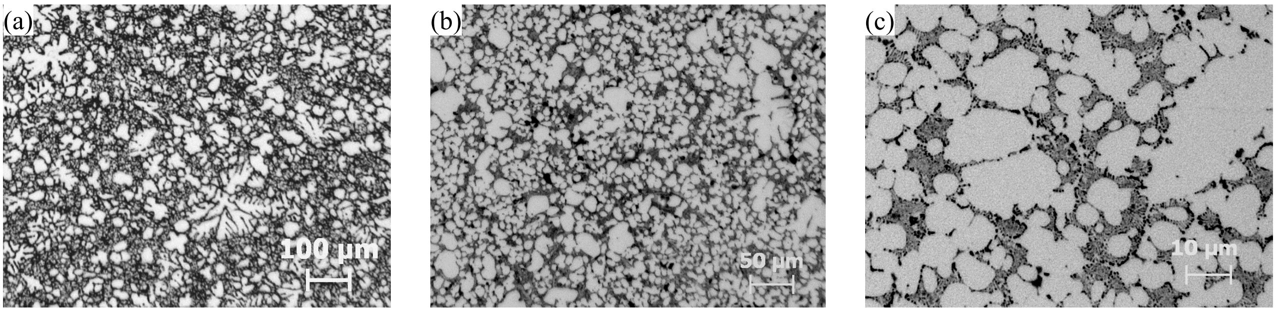
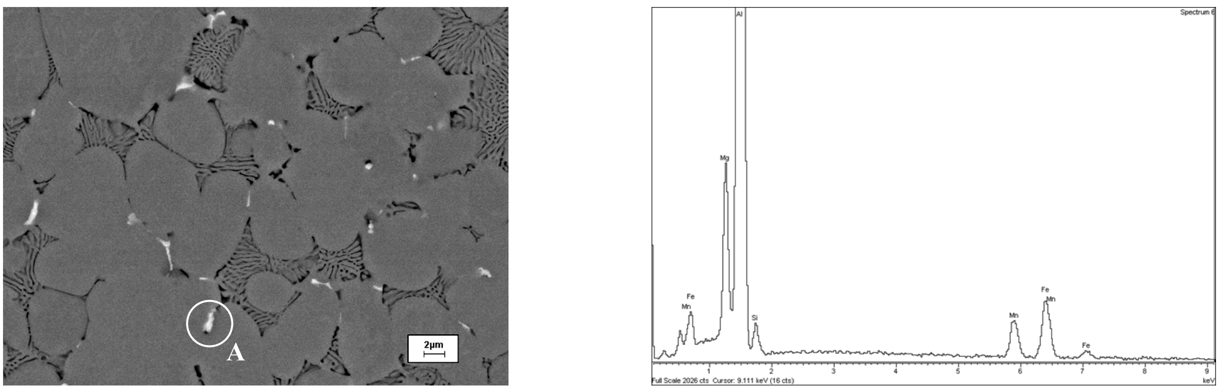


Figure 3. Microstructures of die-cast Al-5Mg-1Si, (a) distribution of primary phase with dendrites or fragmented dendrites morphology, (b) primary phase with fragmented dendrites morphology, (c) primary phase with globular morphology.

The eutectics are formed in the eutectic solidification inside the die cavity. The detail of the eutectic phase is shown in Fig. 4. The lamellar microstructure lay between the primary particles. The EDS analysis has confirmed the eutectic phase consisted of α-Al phase (grey) and Mg_2Si phase (black). The size of the eutectic cells was at a level of 10 micrometers, in which the lamellar Mg_2Si phase was less than 0.2 micrometers in thickness. Mg_2Si phases in varied amounts depended on the bulk level of Mg and Si in the alloy for lower Si content. The Mg_2Si phase was the dominant phase in the as-cast state throughout the range of tested compositions. The proportion of the Mg_2Si phase was relatively low in the alloy. In principle, the Mg_2Si phase should be limited within eutectics in order to provide better ductility for the alloy with adequate strengthening effect.

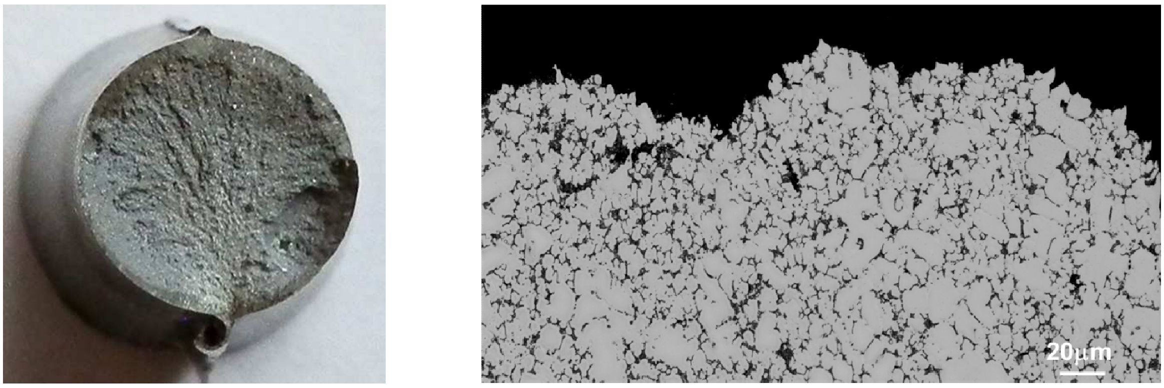


(a) (b)

Figure 4. (a) Backscattered SEM micrograph showing the distribution of intermetallics along grain boundaries in Al-5Mg-1.5Si die-cast alloy, and (b) EDS diagram showing the elements in particle A.

In Fig. 4, the minor phase of tiny intermetallic particles can be found in the matrix (white). The intermetallic compounds located at the boundary between two primary particles or between the eutectic cell and the primary particles. The EDS analysis shown in Fig 10b confirmed that the intermetallic compounds consisted of AlMnFeSi with a compact morphology. The intermetallics is most likely the α-AlMnFeSi phase, rather than β-AlFeSi.

Fracture of die-cast alloy. Fig. 5 shows the overall fracture and the microstructure along a fractured section of die-cast sample. It was clear that the sample was uniformly elongated and no apparent neck near the fractured surface. The microstructure confirms that the fracture occurred along the grain boundaries. The primary grains exhibited uniform deformation towards the fractured surface and no fracture was found across the primary grains. There were few relatively large pores and several tiny pores below the fractured subsurface, which showed irregular shapes. This implies that the subsurface pores were resulted from the stress under loading. The cross sectional micrograph indicates that the fracture was likely resulted from the grain-boundary separation. However, the grain boundary separation is one of brittle fractures, by which the ductility is usually low.



(a) (b)

Figure 5. Optical micrographs showing (a) the overall fracture surface, (b) the microstructure on a section perpendicular to the fractured surface of Al-5Mg-1.5Si die-cast alloy.

To find out more detail, the fractographs of die-cast sample fractured at an elongation of 18.4% with ultimate tensile strength of 302.5MPa were shown in Fig. 6. The sample showed that several air-trapped porosities that were characterized by the smooth surface and round shape were found on the fractured surface. The enlarged fractograph confirmed that the fracture exhibited a combination of a large proportion of intergranular fracture with a small proportion of dimpled rupture. From Figure 6b, decohesion was apparent around the primary dendrites and between the Mg_2Si phase and Al phase in the eutectic cell. Therefore, the alloy exhibited a combination of brittle and ductile fracture.

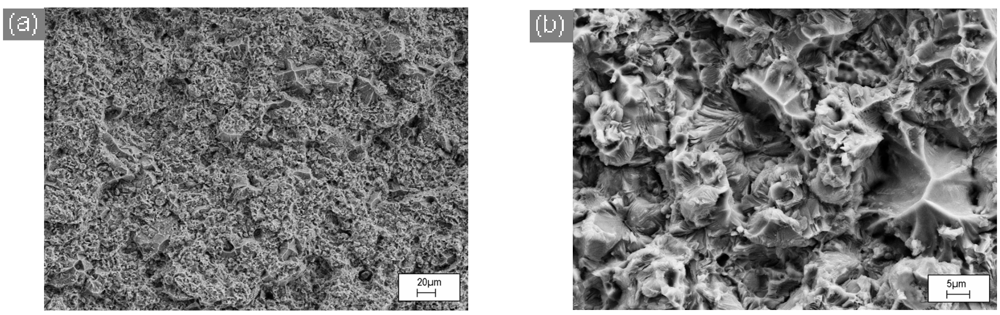


Figure 6. SEM image on the fractured surface of Al-5Mg-1.5Si die-cast alloy, (a) the overall fracture, (b) the detailed image.

Microstructure-properties relationship. The Al-Mg-Si alloy developed in this work has shown improved mechanical properties, particularly in improving the ductility of the alloys, so that the elongation of the die-cast samples is consistently higher than that in literature and designation of the similar alloys. This is attributed to adequate microstructure. The microstructure in die-cast sample is relatively simple, the primary α-Al phase, the intermetallics and the eutectic phase. The primary α-Al phase with fragmented morphology formed in the shot sleeve and the globular morphology formed in the die cavity is fine and uniform distribution. The overall superiority in the elongation is also largely due to the effective role on the morphologies and sizes of the intermetallic compounds so that long-needle shaped β-AlFeSi is eliminated with high content of Mn. Because of the tight control of other impurities in the alloy, the other intermetallics formed during solidification are significantly diminished. The eutectic phase is purely the lamellar of Al+Mg2Si, which is the enforcement for the yield strength and ultimate tensile strength.

Conclusions

An optimized composition has been found that provides a good combination of strength and ductility. This composition comprises of 5-5.5wt-%Mg, 1.5-2.0wt-Si%, 0.5-0.7wt-%Mn, 0.15-0.2wt-%Ti. The other impurity elements should be limited in the alloy; especially Fe which should be controlled to less than 0.25wt-%. The typical mechanical properties of the die-cast alloy at the optimized composition are 150MPa of yield strength, 300MPa of ultimate tensile strength, and 15% of elongation under as-cast condition.

The microstructure of the die-cast aluminium alloy at the optimized composition consists of the primary α-Al phase, the α-AlFeMnSi phase and the eutectic phase. The α-Al phase can either be dendrites or fragmented dendrites solidified in the shot sleeve or the globular morphology formed in the die cavity. The α-AlFeMnSi phase is in the form of a compact morphology with a size of less than 5 micrometres. The eutectic cells are at size of 10 micrometres with a lamellar morphology of the Al phase and Mg_2Si phase.

The cast sample elongates uniformly under tensile load and shows no apparent neck near the fractured surface. The fracture usually occurs along the grain boundaries and the primary grains exhibit uniform deformation towards the fracture. The details of the fractographs confirm the fracture exhibits a combination of a large proportion of intergranular fracture with a small proportion of dimpled rupture, showing the combination of brittle and ductile fracture.

Acknowledgements

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