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Development of a high strength Al–Mg_2Si–Mg–Zn based alloy for high pressure die casting

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ABSTRACT

A high strength Al–Mg_2Si–Mg–Zn based alloy has been developed for the application in high pressure die casting to provide improved mechanical properties. The effect of various alloying elements on the microstructure and mechanical properties including yield strength, ultimate tensile strength and elongation of the alloy was investigated under the as-cast and heat-treated conditions. The typical composition of the high strength alloy has been optimised to be Al–8.0 wt%Mg_2Si–6.0 wt%Mg–3.5 wt%Zn–0.6 wt%Mn (Al–11.0 wt%Mg–2.9 wt%Si–3.5 wt%Zn–0.6 wt%Mn) with unavoidable trace impurities. The mechanical properties of the alloy were enhanced by a quick solution treatment followed by ageing treatment. The improved tensile properties were at a level of yield strength over 300 MPa, the ultimate tensile strength over 420 MPa and the elongation over 3% assessed using international standard tensile samples made by high pressure die casting. The microstructure of the die-cast alloy consisted of the primary α-Al phase, Al–Mg_2Si eutectics, AlMgZn intermetallics and α-AlFeMnSi intermetallics under the as-cast condition. The AlMgZn intermetallic compound was dissolved into the Al-matrix during solution treatment and subsequently precipitated during ageing treatment for providing the effective improvement of the mechanical properties.

1. Introduction

High pressure die casting (HPDC) is a well-developed manufacturing process and has been extensively used to cast aluminium alloys. In comparison with other casting methods, the advantages of HPDC process include [1,2]: (a) high productivity; (b) good dimensional accuracy and surface finish; (c) capable of providing high volume and economical production; (d) capable of making intricate shapes and thin wall castings; and (e) fine grain microstructure and good mechanical properties. However, the turbulent flow during die filling is an inherent problem in conventional HPDC process. This is fundamental for the formation of the internal defects [3,4], in particular porosities in die castings. Therefore it has limited the application of die castings as structural components [5,6].

In the past two decades, the application of lightweighting materials in transportation has been the driving force to develop structural components using HPDC process [7]. The successful development of vacuum assisted HPDC has provided the capability of producing thin-wall castings with much reduced porosities [8]. Therefore, heat treatment is applicable to enhance the mechanical properties of die castings. However, the existing aluminium alloys for HPDC process are mainly based on Al–Si, Al–Si–Cu, and Al–Mg–Si systems [9,10]. Most of these alloys are not particularly suitable for the property enhancement by heat treatment, in particular not suitable for solution heat treatment. Although a quick solution treatment has been used for solution treatment of Al–Si–Cu alloys made by HPDC process [11], the currently available aluminium alloys is not satisfied with the increasing demands of manufacturing structural components by HPDC process. Therefore, the development of high strength aluminium alloys becomes significant to promote the application of aluminium alloys in transport and other fields where an improved strength and lightweight are essential.

The as-cast mechanical properties of the currently available aluminium alloys for HPDC process are listed in Table 1 [12,13], which shows that the hypoeutectic Al–Si based alloys provide yield strengths less than 200 MPa with elongations over 3% and that the hypereutectic Al–Si based alloys provide yield strength at a level of 250 MPa with elongations less than 1% under the as-cast condition. The recent study [11] has found that the heat treatment of cast Al–Si–Cu based alloys can significantly improve their strengths and the slight variation of alloy composition can significantly affect the mechanical properties of the alloy after heat

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Table 1
Typical mechanical property of currently registered aluminium alloys for HPDC process.

Alloy	Alloy system	Temper	UTS (MPa)	Yield strength (MPa)	Elongation (%)
360	Al–Si–Mg	As-cast	305	170	3
A360.0	Al–Si–Mg	As-cast	315	165	4
380	Al–Si–Cu	As-cast	315	160	3
A380.0	Al–Si–Cu	As-cast	325	160	4
383	Al–Si–Cu	As-cast	310	150	4
384	Al–Si–Cu	As-cast	330	165	3
390	Al–Si–Cu–Mg	As-cast	280	240	<1
B390.0	Al–Si–Cu–Mg	As-cast	315	250	<1
392	Al–Si–Cu–Mg	As-cast	290	270	<1
413	Al–Si	As-cast	295	145	3
A413.0	Al–Si	As-cast	290	130	4
C443.0	Al–Si	As-cast	230	95	9
518	Al–Mg	As-cast	310	193	5

treatment. However, studies of microstructure and mechanical properties of other commonly used aluminium alloying systems under as-cast and heat treatment conditions are limited. The present study attempts to investigate Al–Mg_2Si (Al–Mg–Si) system because of its attractive advantages [14,15], including the low cost of raw materials, low density of Mg_2Si and improved mechanical properties. Currently, due to the limitation of alloy composition, Al–Mg_2Si based alloys are normally cast using permanent mould or sand casting processes. The majority of the existing research on Al–Mg_2Si alloys are based on hyper-eutectic compositions [14,15]. The development of high strength aluminium alloys based on hypoeutectic Al–Mg_2Si system not only reduces the weight of existing aluminium castings by reducing the wall thickness, but also provides a heat treatable alloy with a lower solution temperature and shorter solutioning and ageing time.

In the present paper, we describe the effect of extra Mg, Mn and Zn in the Al–Mg_2Si system on the mechanical properties and microstructure of the cast alloys. The effect of solution and ageing heat treatment on the mechanical properties and microstructure was also studied. The composition was optimised for the alloy to provide yield strength over 300 MPa, UTS over 420 MPa and elongation over 3%. The discussion focuses on phase formation and microstructural characteristics with different alloying elements, and the correlation between microstructure and mechanical properties of the die-cast alloy.

2. Experimental

Pure aluminium, pure magnesium and pure zinc, Al–50 wt%Si and Al–20 wt%Mn master alloy ingots were used as the starting materials. Each of them was supplied at a specified composition with commercial purity. During experimental preparation, each element was weighed to a specified ratio with additional amounts for burning loss during melting. A melt of 10 kg was prepared each time in a clay–graphite crucible using an electric resistance furnace. During melting, the temperature of the furnace was controlled to be 730 ± 10 °C. The ingots containing Al, Si and Mn elements were loaded into the crucible and melted first. Mg ingots and Zn ingots that had been preheated to 200 °C were then carefully added into the completely melted alloy. After an hour of homogenisation, the melt was subjected to degassing, during which N_2 was input into the melt by a commercial rotatory degasser at 500 rpm for 3 min and the top surface of the melt was covered by commercial granular flux during degassing. The melt was subsequently homogenised in the furnace for about 30 min before taking samples for composition measurement.

A mushroom casting with a bottom flat of $\varnothing 60\times 10$ mm^2 was made by a steel mould for composition analysis. The casting was cut off 3 mm from the bottom and ground down to 800 grid SiC paper. The composition for onsite casting was obtained from an optical mass spectroscope (OMS), in which at least five spark analyses were tested and the average value was taken as the chemical composition of the alloy. After casting, some of the samples were further analysed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and the results were taken as final composition of each alloy.

After OMS composition analysis and skimming, the melt was manually dosed and subsequently released into the shot sleeve of a 4500 kN HPDC machine for making standard tensile samples. The pouring temperature was usually at 650 °C measured by a K-type thermocouple. A specially designed die was used to cast six ASTM standard samples with three $\varnothing$6.35 mm round samples and three flat samples for each shot (only round samples were used to assess the alloy's tensile property). The main dimensions of the die casting with overflow and biscuit are schematically shown in Fig. 1. During casting, a water-based die releasing lubricant was used on the die block, which was pre-heated by the circulation of mineral oil at 250 °C in all shots. All casting samples were left on floor for at least 24 h before testing their mechanical properties.

The round as-cast tensile samples were heat treated in an electric resistance furnace that was preheated to a given temperature and maintained the temperature consistently for at least one hour before putting the die-cast samples into the chamber of the furnace. The temperature inside the chamber was monitored by a separate thermocouple with a variation of ± 2 °C during the heat treatment. The samples were water quenched immediately after solutioning treatment, but just taken out from the furnace for air cooling after ageing treatment.

The tensile tests were conducted following ASTM standard B557, using an Instron 5500 Universal Electromechanical Testing System equipped with Bluehill control software and a ± 50 kN load cell. All tensile tests were performed at an ambient temperature ($\sim$20 °C). The gauge length of the extensometer was 25 mm

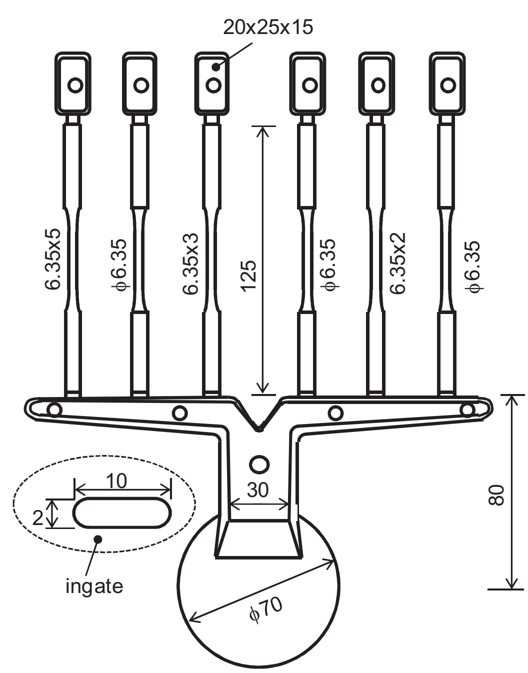

Fig. 1. Diagram of die casting for the standard tensile testing samples of cast aluminium alloy according to the specification defined in ASTM B557-06. The overflow and biscuit are designed in association with the cold chamber die casting machine. The dimensions are in mm.