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Research on the microstructure, fatigue and corrosion behavior of permanent mold and die cast aluminum alloy

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ABSTRACT

Permanent mold (PM) and high pressure die cast (HPDC) AlMg5Si2Mn are employed to investigate the microstructure, fatigue strength and corrosion resistance. Results indicated that the mechanical properties (R_m, $R_{0.2}$ and δ) of HPDC specimens (314 MPa, 189 MPa and 7.3%) are significantly better than those of PM specimens (160 MPa, 111 MPa and 2.5%) due to the finer grain size and less cast defects. Fatigue cracks of PM samples dominantly initiated from shrinkage pores and obscure fatigue striations are observed in crack growth region. Corrosion and pitting potentials of PM and HPDC AlMg5Si2Mn alloy are around −1250 mV, −760 mV and −1220 mV, −690 mV respectively. Numerous pits are observed around the grain boundaries because the corrosion potential of Mg_2Si is more anodic than that of α-Al matrix. In addition, the superior corrosion resistance of HPDC samples can be attributed to the fine grain size and the high boundary density which improved the formation of oxide layer on the surface and prevented further corrosion.

1. Introduction

Al–Mg alloys (e.g. 5083, 5052 and 5456) have been widely applied in automotive, food and marine industries due to the good corrosion resistance, eco-friendliness and mechanical properties [1]. High pressure die casting (HPDC) is a near-net shape technology characterized by the good flexibility, high speed and pressure, thus it is perfectly suitable for the mass production of the components required complicated structure, thin walls and good surface quality [2]. Obviously, it is a promising project that combined the excellent mechanical properties of Al–Mg alloys and the high productivity of die cast technology.

Therefore, silicon (2%) and manganese (0.8%) are added into AlMg5 alloy and the iron content is reduced to 0.15% to improve the toughness, formability and die-sticking tendency of the alloy [3]. Beside the iron content, some other impurity elements (e.g. Cu, Zn and Ti) are strictly controlled in a low level ($\leqslant$0.05%). The good elongation ($\delta \approx 15\%$) of HPDC AlMg5Si2Mn is extreme attractive to automotive manufacturers, thus, AlMg5Si2Mn has been applied to produce high-duty structural components (e.g. rear sub-frame and shock tower [3]). Furthermore, it has been reported that AlMg5Si2Mn alloy deserves some marine applications [4], thus the corrosion behavior of AlMg5Si2Mn castings is worthwhile to be studied in details. Nevertheless, previous investigations concentrated on the microstructures formation [5], mechanical properties [6,7] and fatigue behavior [8,9] of HPDC AlMg5Si2Mn, moreover, the research on the corrosion behavior of PM and HPDC AlMg5Si2Mn alloys is still lacking which limit their further application.

On the other hand, effects of the microstructural features (e.g. grain size, defects, intermetallic distribution and residual stress) on the corrosion behavior of various metals have been extensively studied [10–13]. Particularly, corrosion rates of the alloys with different grain sizes are compared and the experimental results are often contradictory [14,15]. For instance, Ralston et al. [16] revealed that corrosion rate of equal channel angular pressing pure Al decreased with decreased grain size, however, the opposite tendency of corrosion resistance of friction stir processing AA6063-T6 alloy were reported by Mahmoud [10]. Moreover, Ambat et al. [11] compared the corrosion behavior of ingot casting and die-casting AZ91D and found that the die-cast samples with finer grain size possess better corrosion resistance and passivation. Those contradictory conclusions are often related to the modified stress distribution and second phase precipitation induced by the different processing routes, therefore, the consensus in the exclusive effect of grain size on the corrosion resistance is difficult to reach. In addition, grain size also influenced the stress corrosion cracking and inter-granular corrosion behavior [12,13]. Above discussions shed light on the complicated effect of microstructures on the corrosion behavior, hence, corrosion resistance of the components produced by different processes should be evaluated by systematical experiments while not by some kinds of general conclusions.

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For the purpose of conducting rational alloy design, understanding the corrosion behavior and broadening the application of AlMg5Si2Mn alloy, a systematical research on immersion corrosion, electrochemical corrosion, inter-granular corrosion and fatigue behavior is conducted in current work. Permanent mold (PM) and HPDC AlMg5Si2Mn are employed to interpret the effect of microstructure features on the corrosion and fatigue behavior.

2. Experimental procedures

The outline dimensions of permanent mold and die cast samples are 120 mm × 80 mm × 25 mm and 200 mm × 60 mm × 4 mm respectively. The mold and die were preheated to 200 °C and the pouring temperature of the liquid alloy was 700 °C. The chemical composition of AlMg5Si2Mn is listed in Table 1. Tensile specimens and fatigue specimens were sectioned from the initial castings. Dimensions of the cross section area of tensile specimens and bone like fatigue specimens are 10 mm × 4 mm and 6 mm × 4 mm respectively. Gauge length of the tensile specimens is 50 mm. According to ASTM:E466-07, fatigue tests were conducted under the ratio of 0, frequency of 40 Hz and the stress amplitudes ranged from 40 MPa to 150 MPa.

For the electrochemical corrosion tests, machined samples (10 mm × 10 mm) were mounted on copper rod using epoxy resin for electrical connection. Open surfaces of all samples were polished with up to 3000-grit emery paper and then cleaned with deionized water followed by rinsing with methanol and dried. The potentiodynamic polarization measurement was carried out at room temperature using an electrochemical workstation and the electrochemical cell consists of three electrodes: a working electrode, a reference electrode (platinum electrode) and a counter electrode (a carbon rod). The electrode potential was scanned at a scan rate of 1 mV/s and the corrosion current values were recorded for both anodic and cathodic polarization in the unit of mA/cm^2 by dividing the current values of each sample by their initial total surface area.

According to ASTM:G110-92 and ASTM:G67-13, in order to evaluate the susceptibility to inter-granular corrosion of PM and HPDC AlMg5Si2Mn, the depth of the corroded area in NaCl + HCl solution and the mass loss of samples in HNO_3 solution are measured after 24 h immersion. The dimensions of the corroded samples are 4 mm × 10 mm × 50 mm and the ratio of corrosive solution to exposed area is above $0.2\ mL/mm^2$. The uniform immersion corrosion tests were conducted in 3.5% NaCl solution according to ASTM:G31-12a and the exposure times are 7d, 14d, 21d and 28d which were determined according to optimization experiments. The corrosion products were completely removed by $Cr_2O_3 + H_3PO_4$ and HNO_3 solution subsequently and all corrosion tests were conducted at 35 ± 1 °C.

Microstructure and the corroded area of PM/HPDC AlMg5Si2Mn were observed by optical microscope (OM) and SEM to observe the microstructure constitutions and research the corrosion mechanisms.

3. Results and discussion

3.1. Microstructure and tensile properties

Microstructure of HPDC AlMg5Si2Mn is shown in Fig. 1a–d and the details of the microstructure are labelled by arrows and circles. Fig. 1a shows that the light grey and dark region, which are primary α-Al and [Al + Mg_2Si] eutectic regions respectively, consist of the microstructure of HPDC AlMg5Si2Mn. Fig. 1b interpret the α-Al matrix with different grain size. The region labelled A represents the crystals formed in the shot sleeve before shooting process and the average grain size of A grains is around 45 μm. Region B represents the fine size grains formed inside the die cavity and the average grain size is 9.4 μm. Generally, the area of region A is closely related to the duration of the liquid alloy in the shot sleeve because the great undercooling of the shot sleeve promoted the early solidification of the liquid alloy and A grains are often called externally solidified crystals (ESCs). Larger volume fraction ratio of region B and A, which is determined by the dwelling time of the alloy in the shot sleeve and the temperature of melt, is beneficial to the mechanical properties of die casting due to the finer microstructure and better integrity. In addition, [Al + Mg_2Si] eutectic region is pointed by arrow in Fig. 1d and the Mg_2Si dendrites can be clearly observed. The size of eutectic regions is at a level of 10 μm and the thickness of Mg_2Si dendrites less than 0.2 μm which is in good agreement with the conclusion of Ji et al. [6].

On the other hand, microstructure of PM AlMg5Si2Mn is more complicated than that of HPDC AlMg5Si2Mn. Light grey regions in Fig. 1e represent the α-Al matrix with the average size of 210 μm and the bone-like structures along the grain boundaries are [Al + Mg_2Si] eutectic region at the level of 100 μm. Dark regions labelled C and D in Fig. 1f and g represent the script-like α-$Al_{15}(Fe,Mn)_3Si_2$ and platelet β-Al_5FeSi which were commonly observed in aluminum alloys containing high iron content and deteriorated the mechanical properties and integrity of the alloy [7,17]. In addition, the volume fraction of [Al + Mg_2Si] eutectic region of PM and HPDC specimens are 23% and 30% which were calculated from more than ten OM images by image processing software.

Tensile properties of PM and HPDC AlMg5Si2Mn specimens are compared in Fig. 2. It is clear that strength and elongation of HPDC specimens are much more superior to those of PM specimens which is closely related to the microstructure and the formation of cast defects. As is discussed above, size of α-Al grains and eutectic regions of HPDC specimens is much finer than those of PM specimens which may be dominantly responsible for the improved the mechanical properties of HPDC specimens. Grain boundary density and the slip systems with favorable directions are increased by the fine grain size of HPDC samples which represent the good plastic deformation capacity. Therefore, the improved mechanical properties of HPDC specimens can be ascribed to the intensified dislocation-blocking effect of grain boundaries and the interaction of grain boundary and dislocations induced by the high boundary density. However, with respect to the PM specimens, the large size Fe-rich intermetallic with sharp angle boundaries, where the severe stress concentration and micro-cracks formed [18], inevitably deteriorated the integrity and mechanical properties. Furthermore, numerous shrinkage pores, which were caused by the severe shrinkage tendency induced by the high magnesium content, may also contribute to the integrity and mechanical properties degradation.

In order to clarify the mechanical property discrepancy of PM and HPDC specimens, fracture surfaces of them are observed and shown in Fig. 3. Fig. 3a shows numerous cleavage facets and some fine size air pores located in the fracture surface. Similar cleavage steps are also observed in PM specimens (as shown in Fig. 3b), moreover, large size (at the level of 200 μm) shrinkage pores (pointed by the arrow) are observed which is also responsible for the terrible mechanical properties of the PM specimens. In addition, the detrimental effect of Fe-rich particles on the fracture behavior is observed in Fig. 3c and d. It can be observed that small gaps existed between the α-$Al_{15}(Fe,Mn)_3Si_2$ particles and the α-Al matrix which is a good indication of the de-cohesion behavior of them. Moreover, the α-$Al_{15}(Fe,Mn)_3Si_2$ particles split by

Table 1
The nominal and actual chemical composition of AlMg5Si2Mn.

Elements	Mg	Si	Mn	Fe	Cu	Zn	Ti	Al
Mass%	4.5	2.2	0.78	0.1	0.0068	0.0029	0.097	Bal