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Al-Mg_2Si-Mg alloys: Microstructure and mechanical properties from high pressure die casting to additive manufacturing

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Abstract

The requirements of light-weighting structures in automotive industry and other transport applications drive the improvement of mechanical properties of aluminium alloys in different manufacturing processes. The present study uses a comparison approach to investigate the microstructure and mechanical properties of an Al-Mg_2Si-Mg alloy processed by HPDC and SLM 3D printing. The microstructure characterisation and mechanical properties under as-cast condition and under as-SLMed condition are introduced. The improvement of mechanical properties are discussed in association with strengthening mechanism.

Key words: aluminium alloys; microstructure; mechanical properties; high pressure die casting; selective laser melting; additive manufacturing

Introduction

Aluminium alloys as lightweight materials are increasingly attractive in automotive industry and other transport manufacturing since its contribution in weight reduction and fuel economy for reducing CO_2 emissions [1,2]. In particular, the commercial application of large castings made by high pressure die casting (HPDC) in car body structure is significant for aluminium alloys for improved mechanical performance using recycled materials [3,4]. On the other hand, selective laser melting (SLM) as an additive manufacturing method has been attracting significant attention in manufacturing net shape components with industrial scale production because of its promising capability of fabricating complex geometries directly from computer-aided design (CAD) models [5,6]. In addition to the improvement of design flexibility and cost reduction, SLM has been found to also deliver equivalent or even better mechanical properties compared to cast and/or wrought counterparts in Ti alloys, Ni-based superalloys and stainless steel, etc. Therefore, it is interesting to compare the microstructure and mechanical properties of aluminium alloys processed by HPDC and SLM.

Mg_2Si is an important strengthening phase in the Al-Mg-Si based alloys and the hypereutectic Al-Mg_2Si system has been well-documented as in situ Al matrix composite [7,8]. However, the presence of large, primary Mg_2Si particles in the microstructure could lead to poor mechanical properties in the as-cast state. In addition, the Al-Mg_2Si system is not easy to die cast due to severe die soldering problems [9,10]. In order to improve the mechanical properties of Al-Mg_2Si alloys, Mg is added to improve both casting and ductility because of its relatively high solid solubility in aluminium. Hence, it is desirable to understand similarity and difference in the Al-Mg_2Si-Mg alloys processed by HPDC and SLM.

In the present paper, we aim to study the microstructure and mechanical properties of Al-5Mg_2Si-2Mg alloy processed by HPDC and SLM. In HPDC, the as-cast microstructure and mechanical properties are described while in SLM, the characterization of powders, microstructure, phase formation and tensile properties are investigated. The discussion focuses on the relationship between the microstructure and mechanical properties in association with the strengthening mechanisms.

Experimental

Commercial Al-5Mg_2Si-2Mg with 0.6Mn-0.2Ti alloy were remelted and degassed for HPDC. In order to reduce oxidation at the melt surface 15 ppm Be was added to the melt. The final composition for casting is 5.08Mg_2Si, 2.1Mg, 0.58Mn, 0.15Fe and 0.17Ti (wt.%). ISO standard round tensile specimens with a gauge length of 50mm for mechanical property measurement were produced using a 4500 kN cold chamber high pressure die casting (HPDC) machine, for which all process parameters had been optimized. The tensile tests were conducted following ASTM standard B557, using an Instron 5500 Universal Electromechanical Testing System equipped with Bluehill software. All tensile tests were performed at ambient temperature. The gauge length of the extensometer was 25 mm and the ramp rate for extension was 1 mm/min.

For 3D printing, Al-5Mg_2Si-2Mg alloy powders were manufactured by gas atomization from commercial ingots. The chemical composition of raw pre-alloyed powder was calibrated by inductively coupled plasma atomic emission spectrometry (ICP-AES), which is 5.05Mg_2Si, 2.03Mg, 0.42Mn, 0.11Fe and 0.10Ti (wt.%). The alloy powder was carefully sieved into a size distribution range of 7-50 μm and the mean size was 25.9 μm. A FS271M SLM system was utilized to fabricate alloy samples. The SLM machine was equipped with a 500 W Gaussian beam fibre laser with a focal laser beam diameter of 90 μm. The SLM operation was performed in an inert argon atmosphere to avoid oxidation of the alloy. The samples were built layer-by-layer on an aluminium alloy plate of AA6061, which was grit-blasted with alumina prior to installation. The laser scanning strategy was used 67° rotating scanning layer-by-layer. The dog-bone-shaped tensile samples with a gauge length of 25 mm and cross-section 4×2 mm^2 and the cubic samples with the dimension of 10×10×10 mm were printed using processing parameters including hatch spacing (h) at 0.1 mm, layer thickness (t) at 0.05 mm, laser power (P) at 270, 310, 350, 390, and 430 W, scan speed (v) at 500, 800, 1000, 1200, and 1400 mm/s. The as-printed samples were then machined before tensile test using a uniaxial MTS material testing system at room temperature (≈20 °C) with an engineering strain rate of 1×10^{-3} s^{-1}.

The microstructure of each alloy was examined using a Zeiss optical microscope with quantitative metallography, and a Zeiss SUPRA 35VP scanning electron microscope (SEM).

Results and Discussion

(1) High Pressure Die Casting

The Calphad approach was used to predict the phase formation of the pseudo-binary Al-Mg_2Si-Mg system. Figure 1 shows the calculated phase diagram for the pseudo-binary Al-Mg_2Si system, in which the pseudo-binary Al-Mg_2Si system behaves effectively like a normal binary eutectic system with a eutectic point at 13.9 wt.% Mg_2Si, apart from a very narrow three-phase region (L+α-Al+Mg_2Si) between 591 °C and 578 °C. With the addition of Mg the eutectic point moves towards lower Mg_2Si concentration. This means that, with increasing Mg content, the volume fraction of primary α-Al decreases and the volume fraction of Al-Mg_2Si eutectic increases. This suggests that addition of Mg in Al-Mg_2Si alloys can promote the formation of primary Mg_2Si.

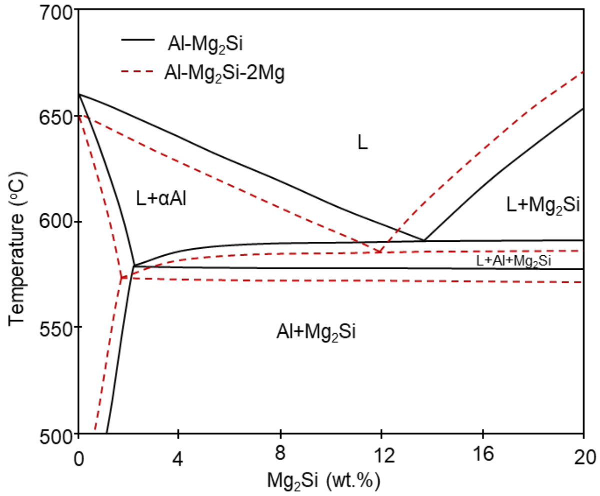

Figure 1. Equilibrium phase diagram of pseudo-binary Al-Mg_2Si and Al-Mg_2Si-Mg system.

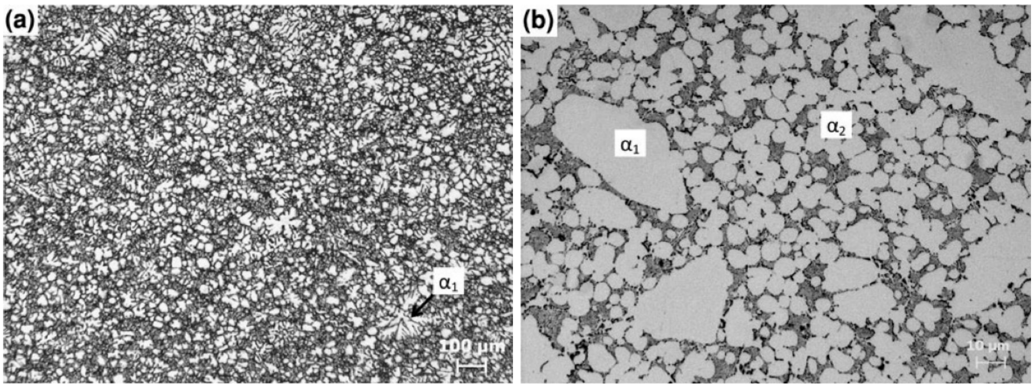

Figure 2. Microstructures of diecast Al-5Mg_2Si-2Mg with 0.6Mn-0.2Ti alloy, (a) low magnification image showing the distribution of the primary α_1-Al phase, and (b) high magnification image showing details of the morphology of the primary α_2-Al phase solidified within the die cavity.

Figure 2 shows the microstructures of the diecast Al-5Mg_2Si-2Mg alloy. Two types of primary α-Al phase are seen in the matrix. Fig 2(a) shows the morphology of dendrites or fragmented dendrites with a larger size (denoted as α_1), while Fig 2(b) shows fine globules (denoted as α_2). During die casting, the solidification commences when the melt is poured into the shot sleeve. Because the cooling rate inside the shot sleeve is similar to that in gravity die casting, a cooling rate ranging from 20 to 80 K/s should be achieved [11], with the solidification initiating from the nucleation of the α-Al crystals that subsequently grow dendritically from contact with the shot sleeve. The primary α-Al dendrites are fragmented when the melt is injected into the die cavity through the ingate at a high speed, resulting in the formation of fragmented dendrites in the microstructure. The size distribution of the primary α-Al phase solidified in the shot sleeve, in which the grain size is between 15 and 100 μm with a mean of 43 μm. The distribution of the primary α-Al phase shows a very close match to a Gaussian distribution, suggesting that the solidification in the die-casting process is relatively consistent for the different amounts of primary α-Al phase. After the melt is injected into the die cavity, the remnant liquid in the mixture that contains α_1 phase starts to solidify immediately. α_2 phase shows a similar globular morphology, which suggests that spherical or globular growth occurs during the solidification inside the die cavity. The size distribution of α_2 is between 3 and 12 μm and the average is 7.5 μm. As the solidification inside the die cavity occurs under a high cooling rate, which is typically ranging from 400 to 500 K/s [11], the high cooling rate increases the nucleation rate, and thus stable globular growth could occur for α_2.

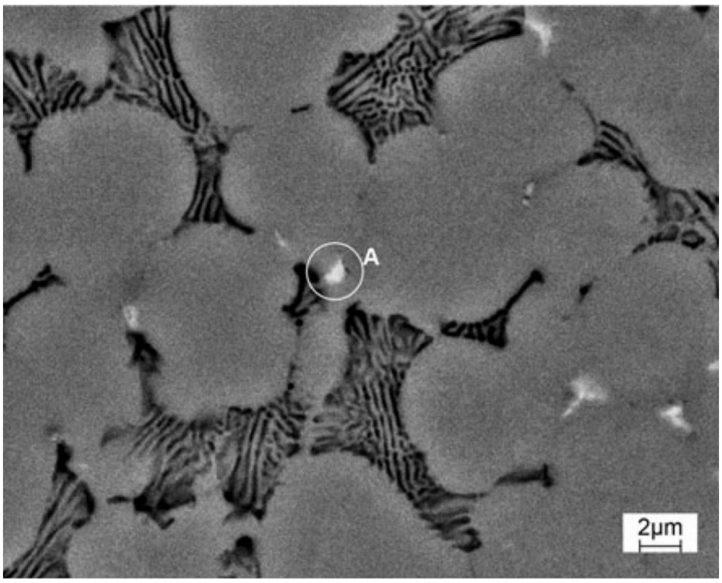

Figure 3. Backscattered SEM micrograph showing the eutectic and intermetallics of diecast Al-5Mg_2Si-2Mg with 0.6Mn-0.2Ti alloy.

The morphology of the eutectic phase is shown in Figure 3. The eutectic microstructure is featured by the lamellar a-Al phase (0.41 µm thick) and Mg_2Si phase with eutectic cells about 10µm in size. The fine lamellae morphology of Mg_2Si phase with frequent branching of the flakes suggests that the solidification follows a conventional path under a high cooling rate. In the alloy, Mn is 0.58 wt.%, and Fe is 0.15 wt.%, resulting in the formation of intermetallics. The intermetallics exhibit a compact morphology with the size being smaller than 2 µm and are located on the boundary between the primary α-Al grains or between the eutectic cells and the primary α-Al grains. EDS analysis reveals that the compact intermetallic compounds consist of Al, Mn, Fe, and Si with the composition being quantified as (at.%) 1.62Si, 3.94Fe, and 2.3Mn, suggesting it is most likely the α-AlFeMnSi phase.

HPDC trials using standard tensile test bars shows that the Al-5Mg_2Si-2Mg with 0.6Mn-0.2Ti alloy provide a yield strength of 138±5MPa, UTS of 302±12 MPa and elongation of 16±6% under as-cast condition.

(2) Selective Laser Melting

Figure 4 shows the EBSD images of as-cast SLM microstructures in the horizontal direction and building directions, which are parallel and perpendicular to the base plate, respectively. Individual grains on the matrix are associated with the different colours. The microstructure on the cross-section parallel to the base plate consist mostly of equiaxed grains with an average size of 20 µm and with some very fine of 1 µm in some areas. Along the vertical direction on the cross-section perpendicular to the base plate, the morphology of columnar grains is clear and their size can be up to hundreds of microns long and up to 1-20 µm wide. Moreover, it is noted that some regions in the conjunction areas of the columnar grains contain fine equiaxed grains. No significant crystallographic textures were noted in the as-fabricated microstructure.

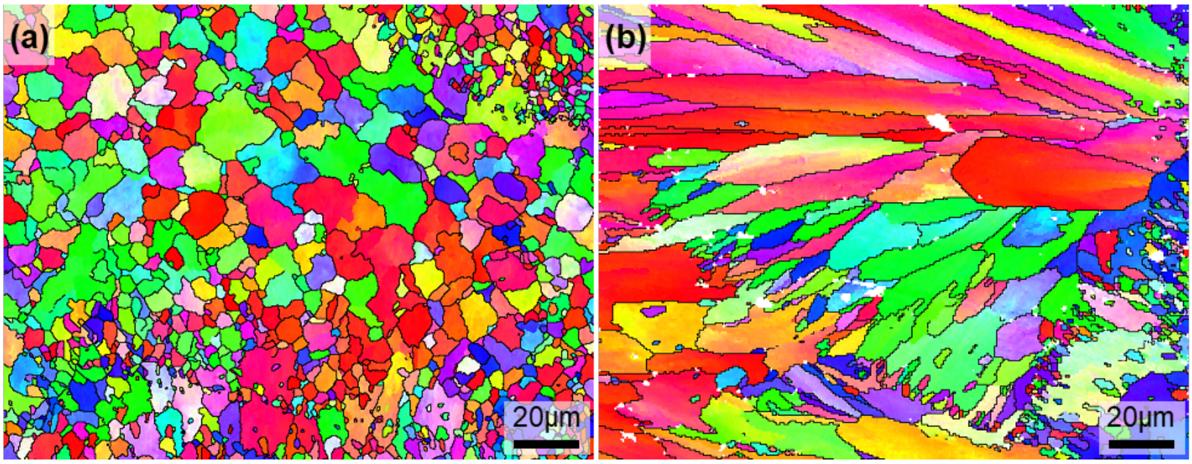

Figure 4. EBSD images of as-SLM Al-5Mg_2Si-2Mg alloy along (a) the horizontal direction (in cross section parallel to base plate), (b) the building direction (in cross section perpendicular to base plate), and (c) corresponding IPF map.

Figure 5 shows the detailed microstructure along the horizontal direction and along the building direction. The typical microstructure appears to be controlled primarily by the melt pool (MP). It is seen a MP coarse zone observable in the matrix in both directions. In the horizontal direction, the equiaxed grains contain a homogenously distributing cell-like sub-structure typically on the scale of about 500 nm, with boundaries of Mg_2Si rich-regions. The typical feature in the horizontal direction is that grains comprise whole section, the only variation from this was the tiny fine grains in the edge of MP zone. However, in the building direction, three zones are clearly observed in the microstructure. A heat affected zone (HAZ) is seen as a transition between MP coarse and MP fine zones. Two differences are found in the microstructures: (1) the equiaxed grain is much large in the building direction (Figure 5e) is much coarser than that in the horizontal direction (Figure 5b); (2) the columnar grains along the vertical direction contained a homogenously distributing nano scale fibre-like structure, as indicated in Figure 5f. These suggest that the effect of base plate heating is obvious. Clearly, no dendritic microstructures are observed in the as-SLM fabricated Al-5Mg_2Si-Mg alloy, but the coarsened equiaxed grains were observed. The typical lamellar eutectic structures are also not observed, but the fibre-like structure should be the eutectic structure under as-SLM fabricated condition. Measurements of the volume fraction of Mg_2Si eutectic have been carried out on the secondary electron images obtained in SEM. These measurements confirmed that there is about 30.63±0.05 vol.% in the MP fine zone and 24.26±0.03 vol.% in the MP coarse zone of Mg_2Si in cells, sub cells and grain boundaries in the as-fabricated samples. Another feature in the microstructure is that the refined microstructure is actually not uniform, it is conjectured the local heterogeneity is the results of multistage solidification in the melt pools. Both HAADF-STEM images and the elemental mapping of cell-like sub-structure confirmed that the Mg and Si is distributed along the Al grain boundaries, confirming the Al-Mg_2Si eutectics are formed in a divorced manner and showed no traditional lamellae structure in the eutectic cells. It is also noted that Mn and Fe are precipitated together with Mg_2Si. The morphological features show likely as α-AlFeMnSi phase. The detailed elemental mapping of Fe-rich phase confirm that the Fe-rich phase is composed of Al, Fe, Mn, and Si. Therefore, although the exact composition is not directly measurable in the fine structure, the morphological features and component elements indicate the Fe-rich intermetallics is most likely to be the same one found in die casting process.

The as-produced SLM Al-5Mg_2Si-2Mg alloy offers excellent mechanical properties, ultimate tensile strength (UTS) of 452±11 MPa, yield strength of 295±14 MPa and elongation of

9.3±2.5%. The tested samples exhibited a good consistency in the yield strength, UTS and elongation.

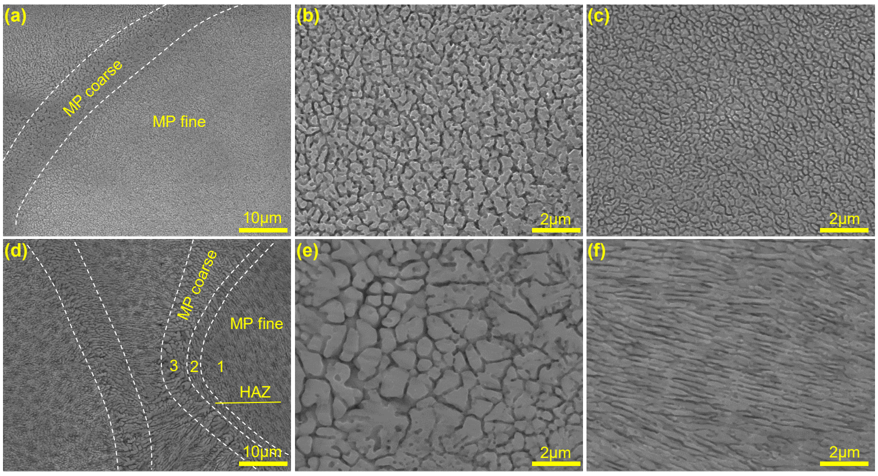

Figure 5. SEM images showing (a) the overall microstructure, (b) the detailed microstructure in zone 3, and (c) the detailed microstructure in zone 1 along the horizontal direction; (d) the overall microstructure, (e) the detailed microstructure in zone 3, and (f) the detailed microstructure in zone 1 along the building direction in the SLM fabricated Al-5Mg2Si-2Mg alloy. 1- MP fine zone, 2- HAZ (heat affected zone), 3- MP coarse zone.

Al-5Mg_2Si-2Mg alloy fabricated by SLM exhibits better yield strength than that by HPDC. This is closely linked with the strengthening mechanisms, which usually include solid solution hardening, grain size strengthening, secondary phase strengthening and strain strengthening mechanism. It is known that rapid cooling during solidification can lead to a significant increase in the solid solubility of certain elements and it is likely the amount of Mg_2Si in solution was increased. According to the equilibrium phase diagram in Figure 1, the effect of solid solution strengthening comes from the solute Mg and Mg_2Si in Al matrix. During the SLM forming process, the rapid cooling in the molten pool hinders the formation of Mg_2Si particles, resulting in further supersaturation of Mg_2Si in the Al matrix. This would enhance the solid-solution strengthening of Al-5Mg_2Si-2Mg alloy processed by SLM. Also, the strengthening by grain refinement is significant as the results of the combination of heterogeneous nucleation and growth restriction of SLM process. This benefits from the formation of fine equiaxed grains can offer high strength according to Hall-Patch mechanism. Moreover, the in-situ eutectic Mg_2Si particles are located at the grain boundaries. Large amounts of nanoscale Mg_2Si particles segregated at grain boundaries of Al matrix can impede the boundary sliding under stress. Also, nanoscale Mg_2Si particles possibly offer the effect of precipitates in the alloy, although no systematic evidence of this was observed. It is suspected that the fine Mg_2Si particles may also promote the dislocation bowing because of the coherency between Mg_2Si and Al matrix, which could offer the strengthening likely to be so-called Orowan mechanism. Obviously, the synergic effect of different mechanisms from the unique microstructures in the SLM fabricated alloy provide the improvement of strengthen.

Summary

(1) In high pressure die casting of Al-5Mg_2Si-2Mg alloy, the microstructure is featured by (a) two types of primary α-Al phase: 15 to 100 μm and an average of 43 μm dendrites and fragmented dendrites formed in the shot sleeve, and an average of 7.5 μm fine globular grains, (b) the lamellar Al-Mg_2Si eutectic with a size of 10 μm, and (c) the Fe-rich intermetallic smaller than 2 μm.

(2) The standard tensile test bars made by high pressure die casting shows that the Al-5Mg_2Si-2Mg with 0.6Mn-0.2Ti alloy provides a yield strength of 138±5MPa, UTS of 302±12 MPa and elongation of 15±4% under as-cast condition.
(3) The Al-5Mg_2Si-2Mg alloy can be successfully processed by SLM additive manufacturing. The SLM samples are featured by significantly refined microstructure in the compact primary α-Al, the divorced Mg_2Si eutectic distributed at α-Al grain boundaries, and some of α-AlFeMnSi phase in association with eutectic Mg_2Si phase. The microstructure on the cross-section parallel to the base plate and along the building direction consists mostly of equiaxed grains at an average size of 20 μm in the melt pool (MP) coarse zone and with very fine of 1 μm in the local area MP fine zone. Along the vertical direction on the cross-section perpendicular to the base plate, the morphology of columnar grains are clear and the size can be up to hundreds of microns in length and up to 1-20 μm wide.
(4) The SLM samples are free of hot cracking with limited other defects and can offer excellent mechanical properties, in which the ultimate tensile strength is 452±11 MPa, the yield strength is 295±14 MPa and the elongation is 9.3±2.5%. Clearly, these mechanical properties are greater than that obtained by high pressure die casting.

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