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Effect of Al alloys on selective laser melting behaviour and microstructure of *in situ* formed particle reinforced composites

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ABSTRACT

This work investigates the effects of various Al alloys (including Al, AlMg1SiCu, and AlSi10Mg), mixed with 15 wt% Fe_2O_3, on the selective laser melting (SLM) facilitated *in situ* reaction and formation of Al metal matrix composite (MMC) components. The results contribute to the development of medium/high strength Al composite parts which can be produced as complex net-shape products via the SLM process. Visual observation and computed tomography (CT) scanning reveal the best SLM consolidation performance and the lowest porosity for AlSi10Mg. SLM facilitated *in situ* reaction and subsequent rapid solidification introduce very fine particles (down to ~50–100 nm), reinforcing the microstructure of all Al (alloy) composites. The particles are Al–Fe intermetallics, Al oxides such as α–Al_2O_3, plus Si crystals (alone or in combination) depending on the alloy composition. Ultrafine/nanoscale dendritic feature appears in the reinforced matrix of AlSi10Mg/15 wt%Fe_2O_3, in contrast with featureless matrix of Al/15 wt%Fe_2O_3. The *in situ* particle reinforced Al (alloy) composites are significantly harder than corresponding conventionally manufactured (e.g. casting) Al alloys without Fe_2O_3, due to superior microstructural characteristics such as featureless or very fine dendritic matrix, ultrafine/nanoscale particles, and also enhanced solid solubility of the SLM products.

1. Introduction

Selective laser melting (SLM) is an additive layer manufacturing process to produce three-dimensional parts with complex geometries, showing great potential to manufacture advanced net-shape components for space, aviation, automotive and other industries. During the SLM process, the laser interacts with a powder bed (commonly from metallic powders); it melts and consolidates the powder, layer by layer on top of each other [1–5]. The solidification of a small molten pool over a wide metallic bed endows the SLM process a high cooling rate and rapid solidification which can be used to modify and achieve unique microstructures to produce superior materials [6,7]. The rapid solidification involves many non-equilibrium phenomena such as microstructural refinement, solid solubility extension, and formation of metastable phases, which can be used in microstructural modifications to improve properties [8,9]. In addition, the powder base nature of SLM offers great opportunities to fabricate complicated composite parts through both *ex situ* and *in situ* approaches [10].

The vast applications of Al alloys have attracted the engineers/researchers to investigate the SLM of various Al powders (though published researches in this field seem to be still little) [11–15]. For example, Brandl et al. [11] have characterised the as-SLM microstructure of AlSi10Mg with cellular dendrites of α–Al and interdendritic Si-particles. Olakanmi et al. [15] have investigated the densification of laser sintered Al–12Si powder, reporting a density in the range of ~1.65–2.15 g/cm^3 and microhardness in the range of ~55–107 HV depending on the used laser parameters. Buchbinder et al. [12] has used a newly designed high laser power machine (1 kW) to successfully manufacture nearly dense AlSi10Mg SLM parts, whilst currently available SLM machines provide laser powers around 100, 200 and 400 W.

The further exploitation of lightweight high performance Al parts has directed these efforts to research on SLM of Al metal matrix composites. For example, a recent research has investigated the capability of SLM process for producing *in situ* reinforcements inside Al matrix [16]. The finding shows that SLM can activate an *in situ* reaction in the mixture of pure Al with Fe_2O_3 powders to produce three-dimensional Al matrix composites reinforced with very fine *in situ* particles. Meanwhile, rapid solidification enables the generation of advantageous *in situ* formed microstructures and provides better mechanical properties.

Two important and widely-used examples of Al alloys are AlMg1SiCu and AlSi10Mg. The former (AlMg1SiCu) contains low percentage of alloying elements such as Mg and Si, which makes its casting behaviour more or less similar to pure Al. In contrast, AlSi10Mg contains high percentage of alloying elements with a near Al–Si eutectic composition, especially utilised for casting purposes [9,17,18].

The SLM of *in situ* formed particle reinforced Al matrix composite represents a promising future, but there is little understanding

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of the effect of different Al alloys on the SLM consolidation behaviour and *in situ* formed microstructure. A comprehensive comparison study is therefore required to illustrate unclear influence of alloy composition on SLM stimulated *in situ* interaction, and to build a better knowledge of the phenomena governing the *in situ* formation of particle reinforced MMCs in presence of rapid solidification. Hence, this work presents a comparative study on the SLM of Al, AlMg1SiCu, AlSi10Mg alloys mixed with 15 wt% Fe_2O_3 powders, investigating the differences between the resultant MMCs in terms of microstructural features, hardness properties, and consolidation conditions.

2. Materials and experiments

Powder mixtures of pure Al (mean particle size ~40 μm - Alpoco, UK), AlMg1SiCu (mean particle size ~40 μm - Alpoco, UK), and AlSi10Mg (mean particle size ~40 μm - EOS GmbH, Germany) with 15 wt% Fe_2O_3 powder (sieved below 53 μm - Inoxia, UK) were prepared. The mixing was carried out by blending and vibrating the mixture at least 30 min using a test sieve shaker. The homogenous mixing appeared in a uniform reddish colour of the powder mixtures. The desegregation was not an issue in blending since tiny pieces of Fe_2O_3 powder tended to adhere to Al powder surface. The chemical compositions of these Al alloys are shown in Table 1, according to the used standards by powder manufacturers.

An SLM machine (Realizer 250, MCP Ltd.) was used to process powder mixtures. Argon gas was pumped into the build chamber to keep the O_2 level below 0.9%. The powder deposition was conducted by rotation of a slotted shaft at the bottom of powder loader container. Multilayer SLM samples were fabricated using spot size of 0.16 mm, scan line spacing of 0.05 mm, layer thickness of 0.075 mm, laser power of 74 W, and scanning speed of 0.20 m/s (parameters were picked on the basis of the previous experiences to reach a good hardness and composite microstructure). Twice scanning was carried out for every layer. The scanning strategy was alternating, as schematically shown in Ref. [1], i.e., *x* direction for the first layer and subsequently *y* direction for the next layer, and so on. All operations were recorded using a common high resolution digital camera with the same setup.

The densities of the samples were calculated by determining their dimensions and weight (mass/volume measurements). A computed tomography (CT) scanning system (X-Tek Benchtop CT 160Xi) was used to reveal the porosity formation in three dimensions and evaluate the relative density. The Vickers hardness (5 kg load was applied for 30 s) was determined using an Aleco Hardness Tester from the average of at least 4 hardness readings. The microhardness (100 g load was applied for 30 s) was measured from the average of at least 5 hardness readings using a Future-Tech Microhardness Tester FM testing machine. The former hardness method (5 kg load) illustrates the overall hardness in presence of porosity, but the latter (100 g) accentuates the hardness of solid microstructure.

Phase identification of product was carried out using a Bruker D8 Advance X-ray diffractometer (XRD). The phases were identified using the machine software, allowing the identification of low percentage of secondary phases (i.e., weak peaks) with a high accuracy. The *x*-*y* cross sections (i.e., in the plane of one layer) of the parts was investigated using an atomic force microscopy (AFM) (Innova Bruker scanning probe microscope), which can provide extremely high magnifications of surface topography.

For microstructural analysis, the sample *x*-*y* cross sections were polished and chemically etched at room temperature, using a solvent composed of 95 ml water, 2.5 ml HNO_3, 1.5 ml HCl and 1.0 ml HF, for ~60–120 s. The microstructure was viewed using a Hitachi S-3200N scanning electron microscope (SEM) equipped with an energy dispersive spectrometry (EDS) microprobe system and also an xT Nova Nanolab 200 high resolution SEM.

3. Results and discussion

3.1. Visual observation of SLM behaviour and physical phenomena

The processing of various Al alloys mixed with 15 wt% Fe_2O_3 to form three-dimensional samples was successfully carried out with

Table 1
Chemical composition (in weight%) of the standard alloys used in this work.

Element	Si	Fe	Cu	Mn	Mg	Other	Al
Al	–	–	–	–	–	–	99.7 purity
AlMg1SiCu	0.40–0.80*	⩽ 0.70	0.15–0.40*	0.15	0.80–1.20	⩽ 0.6	Balance
AlSi10Mg	9.0–11.0	⩽ 0.55	⩽ 0.05	⩽ 0.45	0.2–0.45	⩽ 0.40	Balance

* The content was higher than the standard.

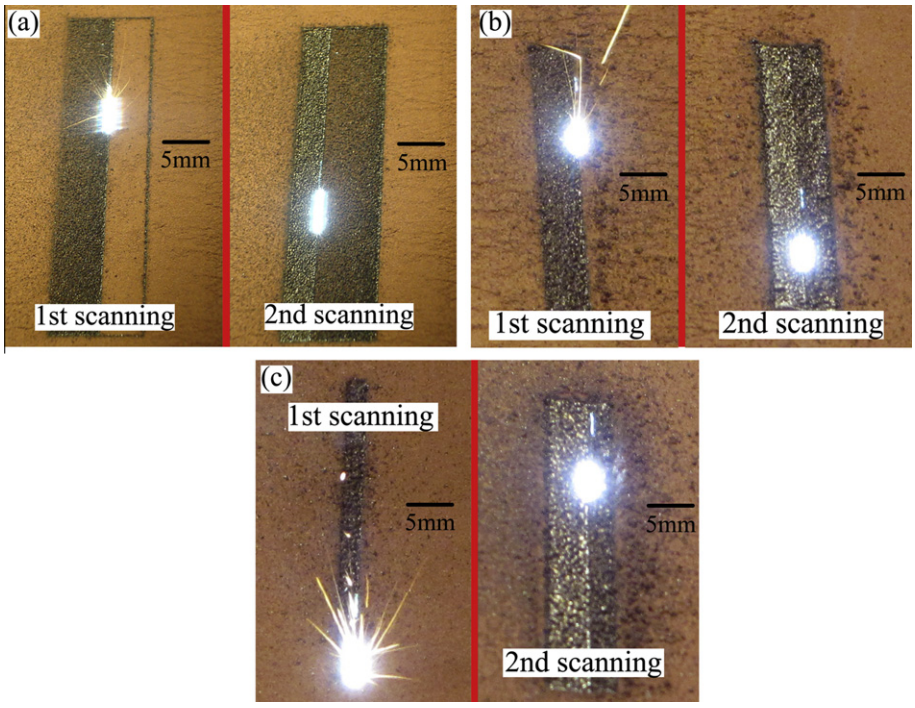

Fig. 1. The visual appearance of SLM process during first and secondary scanning of each layer for (a) Al/15wt%Fe_2O_3, (b) AlMg1SiCu/15wt%Fe_2O_3, and (c) AlSi10Mg/15 wt%Fe_2O_3.