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Experimental investigation on selective laser melting behaviour and processing windows of *in situ* reacted Al/Fe_2O_3 powder mixture

S. Dadbakhsh [a,*], L. Hao [a], P.G.E. Jerrard [b], D.Z. Zhang [a,c]

[a] *College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK*
[b] *Manufacturing Technology Centre, Ansty Park, Coventry, UK*
[c] *State Key Laboratory on Mechanical Transmission, Chongqing University, China*

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ABSTRACT

This study investigates the material behaviour and processing windows for selective laser melting (SLM), an additive manufacturing (AM) process, to directly fabricate net-shape Al metal matrix composite parts from Al/5wt.%Fe_2O_3, Al/10wt.%Fe_2O_3 and Al/15wt.%Fe_2O_3 powder mixtures. The processing windows of laser powers and scanning speeds are plotted in relation to the resulting surface roughness, density and hardness of SLM specimens. It is found that the *in situ* reaction of Al/Fe_2O_3 powder mixtures significantly influences the SLM processability and manipulates the range of applicable processing parameters for the direct production of particle reinforced Al matrix parts. The *in situ* reaction (affected by the proportion of Fe_2O_3 additive to the powder mixture) releases extra heat and collaborates with laser energy which can modify the visual surface and microstructural appearance or alter material characteristics in SLM processing windows. Higher Fe_2O_3 content leads to an increase in hardness, but a decrease in density of the SLM samples may occur.

1. Introduction

Selective laser melting (SLM) is a laser based additive manufacturing (AM) process in which three-dimensional parts are built layer by layer using laser scanning on a powder bed. The powder is selectively melted and solidified in laser affected regions and the next layer is subsequently built on top of the current layer [1–4]. SLM is a multifaceted process involving several physical phenomena which vary according to material behaviour, caused by melting the powder to a liquid state and subsequent consolidation through rapid cooling [5]. Particular melting and consolidation issues may appear in SLM process: for instance, certain surface tension values of the molten material may cause a ‘balling’ effect where newly molten material does not wet the underlying substrate, forming broken liquid cylinders and roughening the surface after consolidation. Even in the case of full melting, porosity can be found due to phenomena such as trapped gas and shrinkage, resulting in poor mechanical properties of finished parts [6,7]. Various SLM parameters can result in a broad range of non-equilibrium phenomena affecting part fabrication. These include parameters such as laser power and scanning speed; and material properties like surface tension and thermal conductivity [8].

Aluminium alloys are widely used in applications within the aerospace and automotive industries mainly because of their light weight, high specific strength and good thermal conductivity. It should be noted that various mechanical properties of Al alloys can be highly altered by process conditions such as the rate of solidification [9–11]. The SLM process offers great flexibility in enhancing the solidification rate of molten Al alloys. This has motivated recent attempts to investigate the SLM of Al based materials in both metal alloy and metal matrix composite (MMC) forms [12–16]. One of these attempts [14] has demonstrated the feasibility and potential of SLM as a novel production method to manufacture high performance *in situ* formed Al metal matrix composites via an exothermic reaction in the mixture of Al/Fe_2O_3.

Despite recent advances in the SLM of Al alloys, there is still a lack of understanding on the melting and consolidation behaviour of this family of materials, which is necessary to fully exploit the potential of the SLM of Al alloys and composites for industrial applications. To address this issue, this work investigates the processing windows to enable the SLM of mixtures of Al with 5, 10, and 15 wt.% Fe_2O_3. Analysis focuses on the material behaviour and the resulting properties including surface roughness, density and hardness over a wide range of laser powers and scanning speeds. The influence of additional Fe_2O_3 on the processing windows (on the basis of surface roughness, density and hardness) is discussed with a brief overview on microstructural analysis. The microstructural characteristics of these SLM processed materials are comprehensively reported elsewhere [17].

2. Materials and experiments

Pure Al powder (99.7 wt.% purity and a mean particle size of 40 μm) was mixed with Fe_2O_3 powder (sieved below 53 μm) to produce powder mixtures of 5, 10, and 15 wt.% Fe_2O_3. Fig. 1 shows an example of the mixed powders demonstrating a random distribution of the pure Al and

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[*] Corresponding author. Tel.: +44 1392 722080.
E-mail address: s.dadbakhsh@ex.ac.uk (S. Dadbakhsh).

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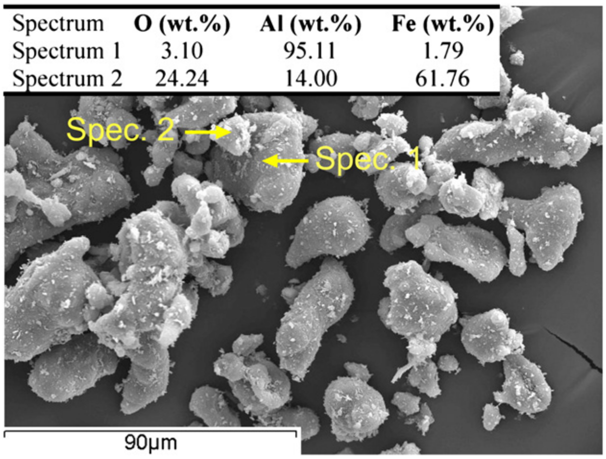

Spectrum	O (wt.%)	Al (wt.%)	Fe (wt.%)
Spectrum 1	3.10	95.11	1.79
Spectrum 2	24.24	14.00	61.76

Fig. 1. SEM micrograph of Al/10wt.%Fe_2O_3 powder mixture (the overall chemical composition was acquired by EDS).

Fe_2O_3 particles (the specs. 1 and 2 demonstrate Al and Fe_2O_3 particles respectively). An SLM machine (Realizer 250, MCP Ltd.) was used to process the powder mixtures. Argon gas was pumped continuously into the build chamber to keep the O_2 level below 0.9% during processing. Multilayer SLM samples with dimensions of 10 mm × 10 mm × 6 mm were fabricated from Al/5-15wt.%Fe_2O_3 using a laser spot diameter of 0.16 mm, scan line spacing of 0.05 mm, and powder layer thicknesses of 0.05 mm. The samples were produced in an array format where laser power (P) and scanning speed (v) were set in the range of 39–91 W and 0.5–0.14 m/s respectively. Double scanning (twice scanning of each layer) was implemented in the x direction for the first layer and in the y direction for the next layer; with this scanning routine continuing for alternating layers.

The surface roughness was measured using a Talyscan-150 (Taylor Hobson Precision Ltd.) with a non-contact laser probe to measure any vertical displacement. The tests measured roughness in 2D mode through a 5 mm line. The 2D roughness parameter of R_a was reported from the average of at least 4 measurements for each sample. R_a is, in fact, the arithmetic average of the 2D roughness profiles, demonstrating the magnitude of surface roughness. The densities of these samples were calculated by determining their dimensions and weight (mass/volume measurements). The hardness was determined using Vickers hardness test (5 kg load was applied for 30s) from the mean average of at least 4 hardness readings in conjunction with an Aleco Hardness Tester.

The samples were cross sectioned, 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. The microstructure was viewed using a Zeiss Axioplan 2 optical microscope. The chemical composition of specimens was evaluated and powders were studied using a Hitachi S-3200N scanning electron microscope (SEM) equipped with an energy dispersive spectrometry (EDS) microprobe system.

3. Results

3.1. Visual inspections

The apparent melting pool can be considered as an important feature for process optimisation and so visual inspections of the melting pool and laser spark were recorded during processing. Fig. 2a and b shows the spark to fabricate parts from Al/5wt.%Fe_2O_3 and Al/15wt.%Fe_2O_3 powder mixture using the same laser power and scanning speed. As seen from Fig. 2a, the energy produced by the laser creates a focused spot-shaped spark to produce Al/5wt.%Fe_2O_3 parts, causing the material to melt within a relatively small volume; in contrast Fig. 2b shows the same parameters used to fabricate parts from Al/15wt.%Fe_2O_3 powder mixture lead to a clearly larger spark and larger melting volume. Moreover, the showering of powders (pushing powders around and vaporising melted material) is more evident in the presence of higher Fe_2O_3 content. This may affect the surface morphology of melted layers and the overall surface finish of SLM parts produced from such powder mixtures. The top surface of parts made from the Al/5wt.%Fe_2O_3 powder mixture is composed of small individual sphere-shaped particles, as seen from Fig. 2c. The top surface of parts made from the Al/15wt.%Fe_2O_3 powder mixture is fused and appears as interconnected formations with small valleys in between (Fig. 2d). It is likely that the extra heat released from the higher thermite mixture (i.e. 15 wt.% Fe_2O_3 in this case) expands the laser melting pool leading to connections between melted spheres. It is interesting to note that Fe_2O_3 powder is dark red, and causes a more reddish colour for Al/15wt.%Fe_2O_3 powder mixture (Fig. 2b) than that of Al/5wt.%Fe_2O_3.

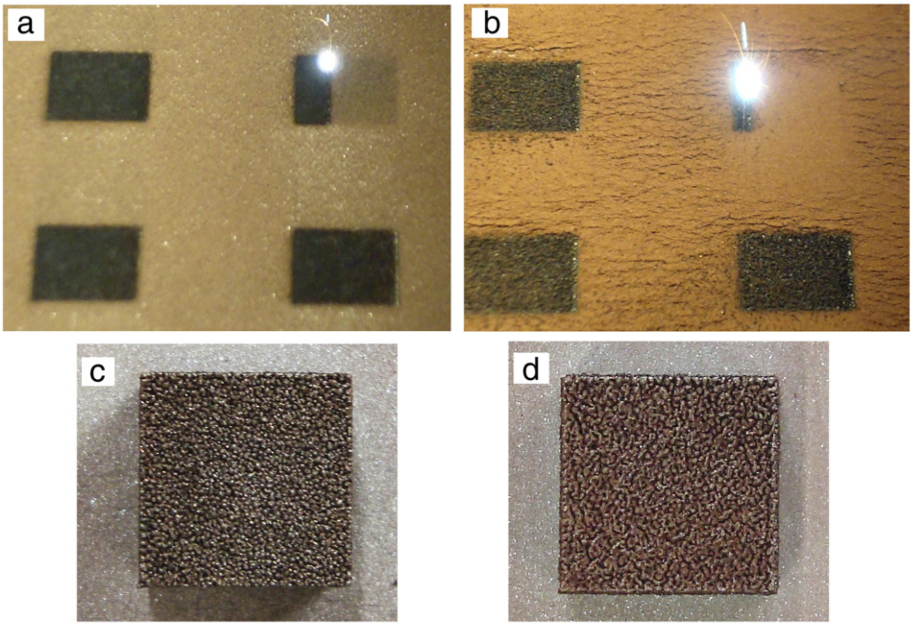

Fig. 2. The visual appearance of parts being fabricated from (a) Al/5wt.%Fe_2O_3 and (b) Al/15wt.%Fe_2O_3 powder mixture using $P = 82$ W and $v = 0.33$ m/s. The surface appearance of final parts manufactured from (c) Al/5wt.%Fe_2O_3 and (d) Al/15wt.%Fe_2O_3 powder mixture.