Selective Laser Melting Of Aluminium Metal Matrix Composites

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SELECTIVE LASER MELTING OF ALUMINIUM METAL MATRIX COMPOSITES

XAIOPENG LI, LACHLAN ASTFALACK, PATRICK DREW, YOR SCHLIWA, TIMOTHY B SERCOMBE

School of Mechanical and Chemical Engineering, The University of Western Australia
Perth, WA, 6009, Australia

ABSTRACT

Aluminium metal matrix composites (AMMCs) are important engineering materials with high specific strength and excellent stiffness. AMMCs have found applications in many industries including aerospace, aircraft and automotive. In conventional processing of AMMCs e.g. casting, the homogenous dispersion of the reinforcements is challenging. As an emerging additive manufacturing (AM) technique, selective laser melting (SLM) provides a promising alternative to fabricate AMMCs with homogenous dispersion of the reinforcements. However, due to the complex physical and chemical processes within SLM, the fabrication of AMMCs can be affected by many SLM-related and reinforcement-related parameters. In this work, SLM of Al12Si with two different reinforcements (SiC and TiN) was compared. The influence of SLM parameters and type of reinforcement on the relative density, microstructure, the interface between the matrix and the reinforcement as well as the mechanical properties of the fabricated components was investigated. This study provides necessary information for successful fabrication of AMMCs with desired mechanical properties.

KEYWORDS: Selective Laser Melting; aluminium; metal matrix composites

INTRODUCTION

Aluminium is one of the most abundant metals in the earth's crust (Frank et al. 2000). After enjoying a rapid development in the past few decades, Al and its alloy have become one of the most important commercial materials (Frank, Haupin et al. 2000). Due to their high specific strength, good corrosion resistance and relatively low cost, Al and its alloy have found a wide range of structural applications in many industries such as automotive, aircraft, aerospace and building industries (Ramnath et al. 2014). With the rapid development of these industries, Al alloys with enhanced properties, for example a combination of high specific strength and excellent wear property, are under high demand. This becomes more imperative as the world environment and energy problems worsen in recent years. To accommodate this fast-growing demand, the development of Aluminium Metal Matrix Composites (AMMCs) with improved and tailorable properties becomes a main focus of the research field (Rohatgi 1993, Surappa 2003). Traditionally, the fabrication of AMMCs is achieved via two primary processing routes, solid state processing and liquid state processing (Srivatsan et al. 1991, Surappa 2003). Due to the vital role of reinforcement in determining the properties of AMMCs the introduction of the reinforcement into the matrix to achieve a homogeneous dispersion throughout the composite becomes the main concern with the fabrication of AMMCs. Although great efforts have been made, the dispersion of the reinforcements homogeneously into the matrix is still challenging (Surappa 2003). Apart from this, the further development of AMMCs is also restrained by several other hurdles. For example,

liquid state processes create composite material with a high density and a near net shape which requires further machining. These are based around casting processes which are plagued by several distinct difficulties including wettability and interfacial chemical reactions (Prokof'eva et al. 1978, Huda et al. 1995). Solid state processes aim to overcome the limitations associated with liquid state processing techniques in controlling the reinforcement distribution (Srivatsan, Ibrahim et al. 1991). However, the as-fabricated components usually lack sufficient density and need to undergo secondary processing to densify the material (Prokof'eva, Taratorina et al. 1978, Louvis et al. 2011).

Selective Laser Melting (SLM) provides a potential alternative to address the abovementioned hurdles in traditional fabrication of AMMCs (Gu et al. 2012). In this work, selective laser melting is used to fabricate Al12Si AMMCs with two different reinforcements: SiC and TiN. The influence of SLM processing parameters such as scan speed, scan spacing and laser focus on the fabricated AMMCs is systematically investigated. The post-heat treatment effects on the mechanical properties and microstructure of the AMMCs are also studied and a brief discussion is given. This study provides necessary insights into the fabrication of AMMCs using SLM.

EXPERIMENTAL

Selective laser melting was conducted on a ReaLizer SLM-100 machine (ReaLizer GmbH, Germany) which is equipped with a fibre laser, which has a laser wavelength of 1.06 µm and maximum power of 200 W at the part bed. The Al12Si powder (LPW Technology, UK) and the reinforcement powders SiC (400 grit, Kemet, Australia), and TiN (-325 mesh, Micron Metals, US) were used in this study. Each reinforcement powder was added into the Al12Si powder to creat 10 vol% and the powder was mixed for 30 min to ensure a homogeneous distribution. A range of different scan speeds, scan spacing and laser focuses were used. The substrate temperature was set to 200°C and an inert, high purity argon gas atmosphere was used during processing to minimise oxidation. Pre-heating of the powder and post-heat treatment of the fabricated components was performed in air at 100°C and 500 ºC, respectively for up to 1 hour. The post heat treatment was followed by water quenching. The density of the fabricated AMMCs was measured using the Archimedes method. The microstructure of the fabricated AMMCs specimens at different processing conditions was characterised using an Olympus reflected light microscope and a FEI Verios 460 scanning electron microscope (SEM, acceleration voltage 5 kV, working distance 6 mm). Tensile tests were carried out on machined specimens (gauge length ~4×6×15 mm^3), using an Instron 5982 machine at a constant strain rate of 1 mm/min. Strain was measured with a 10 mm gauge length extensometer. A Mitutoyo AVK-C2 hardness tester was used for the measurement of hardness of each sample. The sample was indented using the Vickers pyramid indenter. A total of 10 indents were made to each sample.

RESULTS AND DISCUSSION

Al12Si reinforced with SiC

The influence of scan speed and scan spacing on the relative density of the fabricated AMMCs reinforced with SiC is shown in Figure 1(a). It can be seen that there is a defined plateau at lower scan speed from 375 to 600 mm/s where the relative density remains constant for both scan spacings 0.10 and 0.15 mm. After this, the relative density decreases with increasing scan speed from 600 to 1500 mm/s. The decrease is more rapid using 0.15 mm scan spacing when compared

to 0.10 mm scan spacing. This was probably a result of insufficient laser energy to melt the powder at higher scan speeds and higher scan spacing. It is important to note that by varying the scan speed, the maximum relative density is below 94% for both scan spacings which means at lower scan speed the formation of porosity was probably caused by another mechanism rather than the unmelted powder within the fabricated components. In order to make a comparison between the influence of scan speed and scan spacing, a calculated relative densities as a function of the energy density is shown in Figure 1(b). It is clear that the maximum density for a scan spacing of 0.10 mm is achieved at a slightly lower energy density than for 0.15 mm. Energy density directly correlates with the build time, provided that the laser power is constant. A low energy density implies a faster build time, making the production of a high relative density part more desirable at a lower energy density. This suggests that although similar densities may be accomplished using both scan spacings, it is more economical to complete the builds with a scan spacing of 0.10 mm.

The AMMCs components fabricated at scan speeds of 500 and 1250 mm/s at both scan spacings 0.10 and 0.15 mm were analysed using optical microscopy. The microstructure is shown in Figure 2. Different microstructures with different phase formation can be observed due to the variation in laser energy in these four AMMCs components. Interestingly, the amount of SiC decreases noticeably in the components fabricated at higher laser energy. In the meantime at the higher laser energy densities, needle-like phase (Al_4C_3) tend to form, which is detrimental to the strength and toughness of the fabricated AMMCs components (Mercelis and Kruth 2006). Since SiC has a much higher laser absorptivity than Al, it is proposed that there is selective absorption of laser energy into the SiC particles causing regions of extremely high temperature. This then could result in rapid localised reaction rates allowing the SiC to react significantly despite the short interaction time. This reaction and break-down of SiC was probably the underlying reason for the low relative density at high laser energies (low scan speed and small scan spacing). The detailed discussion can be found in our previous work (Li et al. 2015).
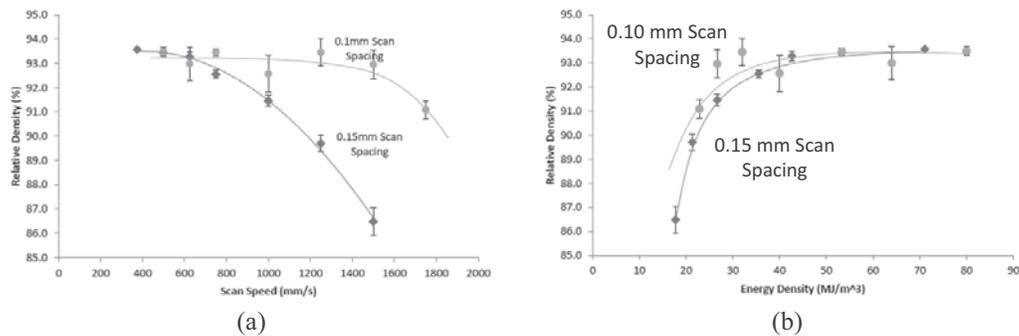

(a)	(b)

Figure 1 The effects of (a) scan speed and (b) energy density on the relative density of samples with scan spacing 0.10 and 0.15 mm.
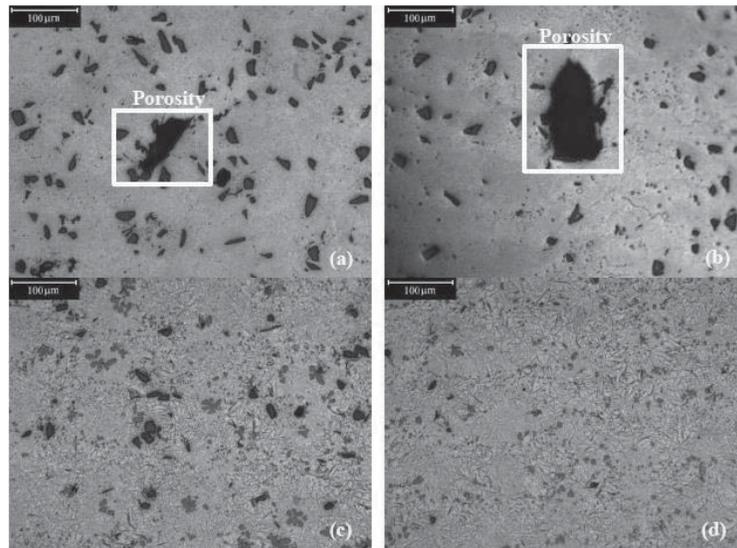
Figure 2. Common examples of the microstructures formed across samples analysed. The build parameters of the four samples are a) 1250 mm/s scan speed and 0.15 mm scan spacing, b) 1250 mm/s scan speed and 0.10 mm scan spacing, c) 500 mm/s scan speed and 0.15 mm scan spacing and d) 500 mm/s scan speed and 0.10 mm scan spacing. At high energies – (c) and (d), there is little SiC left.

Al12Si reinforced with TiN

For additions of TiN, the relative density of the fabricated AMMCs also first increases with increasing scan speed from 500 to 750 mm/s and then decreases rapidly with further increasing scan speed from 1000 to 2000 mm/s, as shown in Figure 3(a). The highest relative density is about 95% at a scan speed of 750 mm/s. According to the optical image of the fabricated AMMCs as shown in Figure 3(b) where no reaction or breakdown of the TiN can be observed, it is likely that the porosity is mainly caused by the incomplete melting and trapped gas.

In order to increase the relative density of the fabricated components, different scan spacing and lens focus positions were trialled, as well as pre-heating the powder. Varying the scan spacing was not effective in increasing the density of the parts. Although pre-heating (drying) the powder seems to increase the relative density the effect is was significant. However, by varying the laser focus, the relative density was increased significantly, (Figure 4(a)). For a lens position of +2 mm, the density plateaus at 97-98% over a relatively wide scan speed range. For a lens position of +4 mm there is peak density at 375 mm/s with densities falling either side. The microscopy analysis showed the expected microstructure containing significantly less porosity (Figure 4(b)).

The mechanical properties of the AMMCs fabricated with the abovementioned optimised parameters are shown in Table 1 and compared to that of the matrix. Although the yield strength was increased, the ductility dropped significantly and indeed cracking of sample was a considerable issue with larger parts when high density conditions were used. The Young's Modulus of the reinforced bars 89.5 GPa which is significantly higher than the unreinforced

matrix (77 GPa). As expected, the hardness of the fabricated samples is also significantly higher in the reinforced materials.
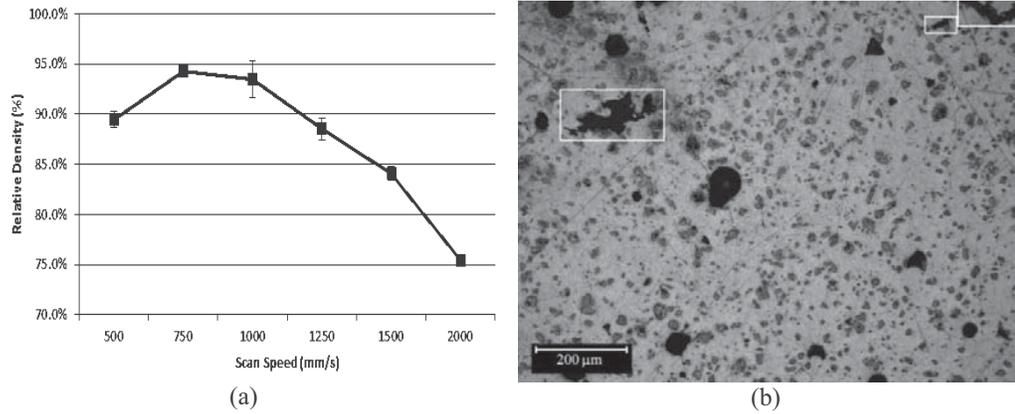

(a)   (b)

Figure 3(a) The influence of scan speed on the relative density of the fabricated Al12Si-10v%TiN and (b) the microstructure at 750mm/s.

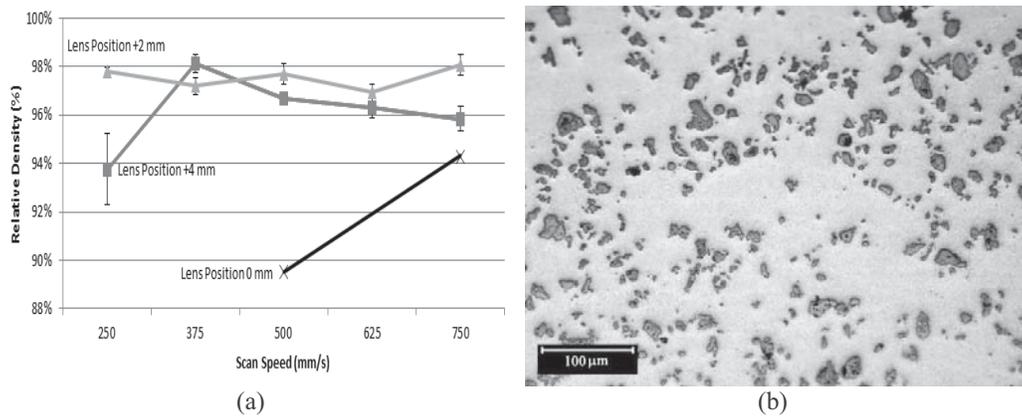(a)   (b)

Figure 4 (a) The effect of lens focus on the relative density of the fabricated Al12Si-10v%TiN nad (b) the with a lens position of +4 mm and at a scan speed of 375 mm/s and scan spacing 0.12 mm

Table 1 Tensile properties of the AMMCs fabricated using optimum parameters

Material	Density (%)	Yield Strength $\sigma_{0.2}$ (MPa)	Ultimate Tensile Strength σ_{UTS} (MPa)	Elongation δ (%)	HV
Al12Si+10%TiN	94.3	254±15	347±18	1.38±0.4	156±15
Al12Si	97.5	223±11	355±8	4.22±0.6	115±7

CONCLUSION

In summary, Al12Si AMMCs with SiC and TiN reinforcements have been fabricated via selective laser melting (SLM). The influence of SLM processing parameters such as scan speed, scan spacing, laser focus as well as powder pre-heating and post-heat treatment on the fabricated AMMCs components has been investigated and briefly discussed. The SiC tends to break down during the build process, and the effect is greater at higher energy densities. Compared with SiC, TiN does not break down during SLM and produces parts with high density and with good dispersion of the reinforcement. However, although the presence increases the yield strength, hardness and Young's Modulus of the matrix, it does decrease the ductility

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