Journal of Manufacturing Processes 36 (2018) 33–43

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Investigation of porosity reduction, microstructure and mechanical properties for joining of selective laser melting fabricated aluminium composite via friction stir welding

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A R T I C L E I N F O

Keywords:
Friction stir welding
Selective laser melting
Aluminium composite

A B S T R A C T

Friction stir welding of selective laser melting printed $AlSi_{10}Mg$ and $AlSi_{10}Mg$ -2% wt. nAl_2O_3 parts were conducted. This study investigated the weldability and mechanical properties of the welds by evaluating their chemical composition, porosity, weld microstructure evolution, micro-hardness and tensile strength. The selective laser melting fabricated parts were successfully welded with results comparable to friction stir welding of the wrought AA6061 sheet, without the presence of weld defects and porosity. After friction stir welding, the agglomerated and sintered nAl_2O_3 particles were fragmented and dispersed in the matrix. Significant grain refinement was achieved in the weld with an average grain size ranging from 2.3 to 3.5 μm due to the dynamic recrystallisation process developing in friction stir welding. Larger grains were observed with the use of a higher tool rotation speed. The precipitation of Si attributed to a reduction in the hardness as well as yield strength of the as-welded material. The addition of nAl_2O_3 contributed to finer grains and higher hardness due to Zener pinner effect.

1. Introduction

Aluminium matrix composites (AMCs) have drawn much research interest owing to their high elastic modulus, wear resistance and stiffness [1,2]. A small concentration of reinforcement particles can provide a significant strengthening effect [3]. However, the joining of AMCs using conventional welding methods was challenging [3] as brittle secondary phases can be formed by the reactions between the reinforcement particles and the matrix [4].

Friction stir welding (FSW) was invented in the UK in 1991 by The Welding Institute (TWI) [5]. Its working principle involves the use of a tool with a threaded pin being forced into the abutting edges between two clamped sheets and transversing along the welding direction. The material in the weld region was softened by the frictional heat between the tool and the workpiece. After softening, it gets driven from the front to the back of the rotating tool during FSW [6]. It also experiences intensely plastic deformation and dynamic recrystallisation which formed fine equiaxed grains [7]. Over recent years, many research works have been conducted on the FSW of aluminium sheets due to its relatively low melting temperature and high reactivity, making it unattractive for conventional fusion welding [6–9]. Studies have shown that FSW is capable of producing sound welds with good mechanical properties due to the microstructure refinement [8].

Recently, selective laser melting (SLM) has received increasing attention due to its ability to fabricate metal and composites components with complex geometry and superior mechanical properties [10–14]. Together with Computer Aided Design (CAD) technique, SLM process can be used to fabricate components with complex shapes efficiently [10]. Typical issues in SLM of aluminium alloy 6061 includes the formation of hot tearing and hot cracking [15]. By adding in silicon particles, these defects can be avoided in the SLM of $AlSi_{10}Mg$ due to the improved fluidity of the melt pool. Since studies on joining of aluminium composites parts fabricated by SLM have been limited, there is a need for conducting a systematic investigation on its weldability. As friction stir welding has been a promising joining method to weld aluminium alloy and its composites without forming significant brittle intermetallic compound [16], this study aims to evaluate the weldability of SLM fabricated aluminium composites via the use of FSW.

2. Experimental details

In the study, gas atomised aluminium powders $AlSi_{10}Mg$ with

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https://doi.org/10.1016/j.jmapro.2018.09.024
Received 14 December 2017; Received in revised form 9 September 2018; Accepted 19 September 2018

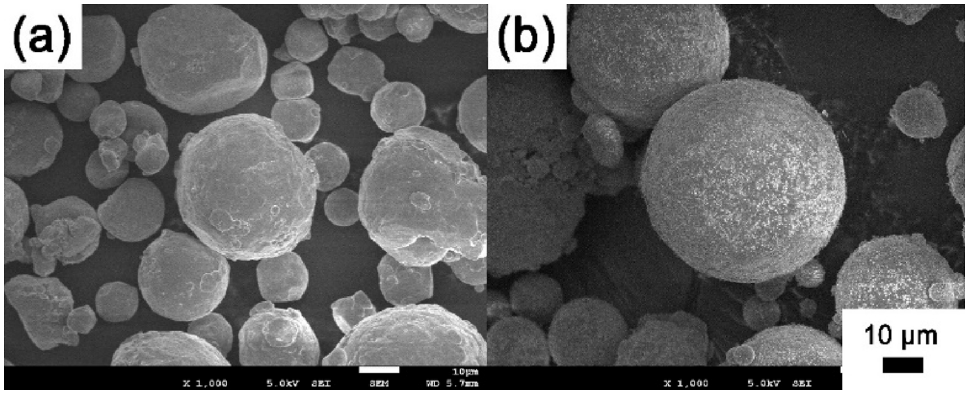

Fig. 1. FESEM image of (a) as-received gas atomised $AlSi_{10}Mg$ powder, (b) blended $AlSi_{10}Mg$ powder with 2% wt. nAl_2O_3.

normally distributed size of 20 μm–63 μm were fabricated by TLS Technik GmbH & Co., Germany (Fig. 1a). The nano-sized alumina (nAl_2O_3) reinforcement powders used were supplied by Sumitomo, Japan. Their nominal diameter is 320 nm. The blended powders were examined under the field emission scanning electron microscope (FESEM) as shown in Fig. 1b. The SLM process was used to fabricate rectangular blocks with the dimension of 90 mm by 60 mm by 10 mm. Process parameters of SLM include laser power of 350 W, scanning speed of 1500 mm/s, hatching distance of 0.2 mm and layer thickness of 50 μm.

A robotic FSW system with a maximum downward loading capacity of 12 kN force was used to butt weld SLM fabricated parts. The surfaces were carefully wire brushed and degreased with acetone before performing a single pass butt welding. The tool shoulder had a diameter, threaded conical probe length and base diameter measuring 15 mm, 6.5 mm and 7 mm respectively. The FSW parameters used in this study were tabulated in Table 1.

Metallurgical samples were cut out from the cross-section of the friction stir welded workpiece. Polishing was carried out with conventional methods for aluminium alloys. Characterisation of the welded samples was performed with the aid of FESEM equipped with energy dispersive X-ray spectroscopy (EDS) and electron backscattered diffraction (EBSD). EBSD mapping and misorientation angle histogram were plotted with a step size between 0.2 μm and 0.5 μm using Channel 5 software from HKL Technology A/S. At least five Vickers hardness indentations were performed in the stir zone of the welded samples using 50 g force loading for 15 s. According to ASTM E08-04 standard, tensile test coupons were prepared from the welded workpiece. The width of the reduced section and gauge length measured 6 mm and 25 mm, respectively. The coupons were tested in the direction perpendicular to the joints with the crosshead speed of 1 mm min^{-1}. At least, three flat rectangular sub-sized dog-bone shaped samples were tested for each set of samples. After the tensile tests, fractography at the fracture sites was analysed using FESEM.

Table 1
Parameters used for FSW.

Process parameters	Rotation speed, RS (rpm)	Transverse speed, TS (mm/s)	Tilt angle, TA (°)	Downward force (kN)
FSW with high heat input	1200	1	4.5	3.5-4.5
FSW with low heat input	600	1	4.5	3.5-4.5

3. Results and discussions

3.1. Chemical composition and porosity analysis

Fig. 2 shows the cross-section and EDS results of the weld prepared with high heat input. The weld was classified into the basin-shaped stir zone, thermomechanical affected zone (TMAZ) and heat affected zone (HAZ) as indicated in Fig. 2a. A wider weld region was observed in the top region of the weld. This was mainly attributed to the higher amount of heat generated from the tool shoulder in comparison to the tool pin. The EDS results show a significant increase in Si content in the weld (Fig. 2). The precipitation of Si particles appeared to take place preferably in the advancing side of the weld region shown in Fig. 2b and c. This was attributed to the higher heat generation on the advancing side of the weld resulting from slightly higher shear and frictional forces between the opposing direction of the tool and workpiece [9].

Micro CT scans were performed at the weld region of the samples (Fig. 3), and the relative porosity was tabulated in Table 2. The relative porosity was defined as the percentage of the volume of pores to the volume of the specified volume (9 mm^3) in the stir zone. In this study, the as-fabricated $AlSi_{10}Mg$ samples had a relative density approximating 97.8%. The as-fabricated SLM $AlSi_{10}Mg$ - 2% wt. nAl_2O_3 was prepared with the same process parameters as that of the $AlSi_{10}Mg$. It was difficult to fabricate dense plates via SLM due to oxide formation, high reflectivity, and thermal conductivity. Buchbinder et al. [17] studied the SLM fabrication of $AlSi_{10}Mg$ and reported their relative density was between 95.3% to 98.0% when using a high laser power. The causes of porosity in the SLM fabricated samples were due to the insufficient heat input to melt the powders. After FSW, porosity was significantly reduced in the weld, agreeing with the FESEM observation from Fig. 4. It is believed that the plastic deformation and dynamic recrystallisation process developing in FSW was able to exclude porosity in the weld. Based on the micro CT scan results, the FSW process eliminated up to 9% porosity in the weld, as shown in Table 2.

3.2. Weld microstructure

Fig. 4 shows the FESEM images of as-fabricated and as-welded samples. The melt pool of SLM fabricated samples is presented in Fig. 4a. Grain boundaries enriched with Si were also observed within the melt pools formed by the laser beam when it melted the $AlSi_{10}Mg$ powders. During SLM, the powders were melted as it absorbed the energy from the laser beam. It then solidified when the laser travelled away from it. The grains then grew along the thermal gradient, as solidification took place from the boundary of the melt pool to the centre [12]. Therefore, fine eutectic Al-Si structures were produced from rapid melting and solidification process during SLM [12].

After FSW, as shown in Fig. 2, a basin-shaped weld was divided into the stir zone, TMAZ and HAZ. The TMAZ was a transition zone between