Materials and Design 57 (2014) 632–637

Contents lists available at ScienceDirect

Materials and Design

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

Friction welding of Al–12Si parts produced by selective laser melting

K.G. Prashanth [a,*], R. Damodaram [b], S. Scudino [a], Z. Wang [a], K. Prasad Rao [b], J. Eckert [a,c]

[a] IFW Dresden, Institut für Komplexe Materialien, Postfach 27 01 16, D-01171 Dresden, Germany
[b] Indian Institute of Technology Madras, Chennai 600036, India
[c] TU Dresden, Institut für Werkstoffwissenschaft, D-01062 Dresden, Germany

ARTICLE INFO

Article history:
Received 1 November 2013
Accepted 11 January 2014
Available online 21 January 2014

Keywords:
Selective laser melting
Aluminium alloys
Friction welding
Tensile behavior

ABSTRACT

Al–12Si samples produced by selective laser melting (SLM) are welded using solid-state friction welding. The weld metal shows the presence of texture with excess Si diffusing out from the Al matrix. Microstructural investigations reveal a pronounced change in the shape and size of the Si phase in the weld metal compared to the base material, with the formation of extremely fine particles uniformly distributed in the Al matrix. This variation in the microstructure is expected to have significant changes in the mechanical properties of the welded material. The hardness measurements reveal a drop of hardness in the weld zone with respect to the base metal. Similarly, the room temperature tensile tests show a significant improvement of ductility in the welded SLM samples. However, the yield and the ultimate strength show only a marginal drop in the welded samples compared to the as-prepared SLM specimens. The present work demonstrates that solid-state friction welding not only permits to successfully join materials produced by SLM, but also helps to significantly improve their ductility.

1. Introduction

Selective laser melting (SLM) is a three dimensional additive manufacturing process which produces metal parts with high degree of geometrical freedom from 3D computer models, such as computer-aided design CAD data [1–3]. The SLM part is generated layer by layer through the selective melting of the powder as dictated by the CAD model. Due to the layer by layer processing, SLM allows for the production of objects with intricate shapes and complex geometries that would be extremely difficult or impossible to fabricate through conventional subtractive manufacturing techniques [4]. A major drawback for the wide application of SLM as an industrial processing route is the limited size of the products. This is a direct consequence of the limited dimensions of the available building chambers, which allow for the production of samples with volumes of about 0.02 m^3 [5]. A possible way to overcome this problem would be the use of the welding processes to join the small SLM objects to form parts with no dimensional limitations.

In this work, we have analyzed this possibility by welding Al–12Si parts produced by SLM. The yield strength of the Al–12Si alloy processed by SLM is four times higher than yield strength of a conventionally cast Al–12Si alloy [3]. Such high-strength alloys cannot accommodate the stresses that arise during the fusion welding processes, which may lead to the formation of cracks [6]. To avoid such solidification related problems, solid-state welding can be utilized. This method does not present issues related to solidification cracking, liquation cracking, segregation and formation of brittle eutectics/intermetallics [6,7]. In addition, solid-state welding results in fine-grained microstructures with superior mechanical properties compared to the conventional fusion weld processes and in a narrow heat affected zone and low residual stresses in the weldment [6,8,9].

Among the solid-state joining processes, friction welding (FW) has drawn considerable attention due to economic considerations and high productivity [5,9]. In this process, heat is generated by the conversion of mechanical energy into thermal energy at the interfaces of the parts, rotated under pressure. Friction time and pressure, upset time and pressure, and rotation speed are the main parameters that govern the FW process. Compared with other welding techniques, friction welding displays advantages such as high materials saving; short joining time and possibility of making dissimilar joints [9–15].

The analysis of the effects of welding on the microstructure and mechanical properties of the joined SLM parts is of particular interest for the possible implementation of this type of material into a conventional industrial processing line, such as automated or robot welding for high production applications. Accordingly, in this work structural and microstructural characterizations are performed on the welded parts. The mechanical properties of the welded samples are analyzed through hardness measurements and room temperature tensile tests followed by detailed fracture surface analysis. Factors leading to failure during the tensile tests are discussed and compared with the corresponding welded parts produced by casting.

* Corresponding author. Tel.: +49 351 4659 685; fax: +49 351 4659 452.
E-mail address: k.g.prashanth@ifw-dresden.com (K.G. Prashanth).

0261-3069/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2014.01.026

2. Experimental details and sample preparation

Cylindrical rods of 12 mm diameter and 60 mm length were produced on a Al substrate plate by SLM from spherical gas-atomized powder with nominal composition Al–12Si (wt.%). SLM processing was carried out under high purity argon at room temperature using an SLM 250 HL device (SLM Solutions) equipped with an Yb–YAG laser. The parameters used for preparing the samples are: scanning speed 1455 mm/s for the volume and 1939 mm/s for the contour, power 320 W both for the volume and contour, layer thickness 50 μm, hatch spacing 110 μm and hatch style rotation 73°. Support structures were built between the rods and the substrate plate in order to ensure good mechanical stability of the SLM parts and to guarantee adequate heat dissipation during processing. Cylindrical Al–12Si bulk samples with 12 mm diameter and 60 mm length were prepared by graphite mold casting in order to compare their welding properties with the SLM samples.

FW was carried out using a continuous drive friction-welding machine with 200 kN capacity. The parameters used in the present study are: friction pressure 75 MPa, upset pressure 100 MPa, burn off length 3 mm and spindle speed 1000 rpm. Surface oxidation may affect the joint strength of the weldment [12]; therefore, the surface of the sample faces was machined before welding to produce a smooth oxide-free surface. This also ensures perpendicularity in the samples that guarantees the achievement of sound welds.

Structural analysis was performed by X-ray diffraction (XRD) using a D3290 PANalytical X'pert PRO with Co Kα radiation ($\lambda = 0.17889$ nm) in Bragg–Brentano configuration. The Rietveld method was applied for the profile-fitting structure refinement using the WinPlotR software package [16]. The microstructure was characterized by optical microscopy (OM) using a Zeiss Axioskope 40 and by scanning electron microscopy (SEM) using a Gemini 1530 microscope equipped with an energy-dispersive X-ray spectroscopy (EDX) setup.

The Vickers hardness measurements were performed using a computer controlled Struers Duramin 5 Vickers hardness tester (according to the standard, ASTM: E384-11e1) with a typical diamond indenter in the form of pyramid with square base and an angle of 136° between opposite faces. A load of 0.1 N was applied for 10 s during each measurement. Cylindrical tensile specimens (according to the standard, ASTM: E8/E8M – 13a) with a total length of 52 mm, and length and diameter of the gauge length of 17.5 and 3.5 mm were machined from the welded samples; particular care was taken to ensure that the center of the weldments corresponds to the center of the tensile bars. Tensile tests were carried out at room temperature using an Instron 8562 testing facility under quasistatic loading (strain rate $\sim 1 \times 10^{-4}\ s^{-1}$). The strain during the tensile tests was measured directly on the specimens using a Fiedler laser-extensometer.

3. Results and discussion

3.1. Structural analysis

The production of the Al–12Si samples by SLM has been reported in detail elsewhere [3] and only the contents related with the present manuscript are discussed hereafter. Fig. 1(a) shows a typical image of a friction welded Al–12Si joint with symmetrical and smooth flash at the joint, indicating adequate heat generation, plastic deformation and expulsion of oxide scales and other contaminants during the welding process [17,18].

The XRD patterns of the base metal for the samples prepared by casting and SLM are shown in Fig. 2 along with the patterns of the weld zones. The diffraction peaks of Al and Si are observed in all cases with differences in their peak intensities and widths. The

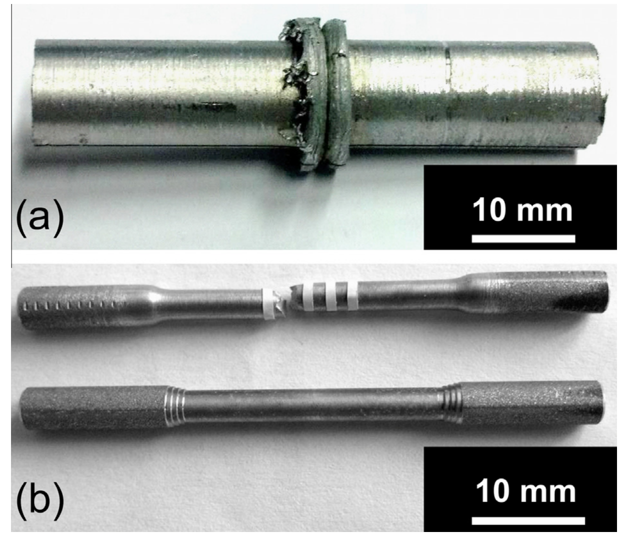

Fig. 1. (a) Typical image of a friction welded Al–12Si joint with symmetrical and smooth flash at the joint. (b) Examples of tensile specimens machined from the welded samples.

SLM-base metal shows a reversed intensity of the Al (111) and (200) peaks with respect to the same material produced by casting, indicating the presence of texture in the SLM sample [3]. The intensity of the Si peaks in the SLM-base metal is rather weak, suggesting a reduced amount of "free" Si in the material. This can be ascribed to the extended solubility of Si in Al resulting from the high cooling rates achieved during the SLM process [3,19]. In addition, the Si peaks are broad, implying a reduced size of the Si phase. The XRD pattern of the SLM-weld zone still shows texture of the Al (111) and (200) peaks; however, this effect is much less pronounced than in the SLM-base metal. The intensity of the Si peaks increases and their width decreases in the SLM-weld zone compared to the SLM-base metal. This suggests that grain growth occurs in the weld zone. The XRD pattern of the cast-weld zone also shows similar texture of the Al (111) and (200) peaks as observed for the SLM-weld zone.

These observations have been corroborated by Rietveld profile fitting analysis [20] carried out on the XRD patterns of the different samples. The lattice parameter of Al increases from 4.0508 Å for

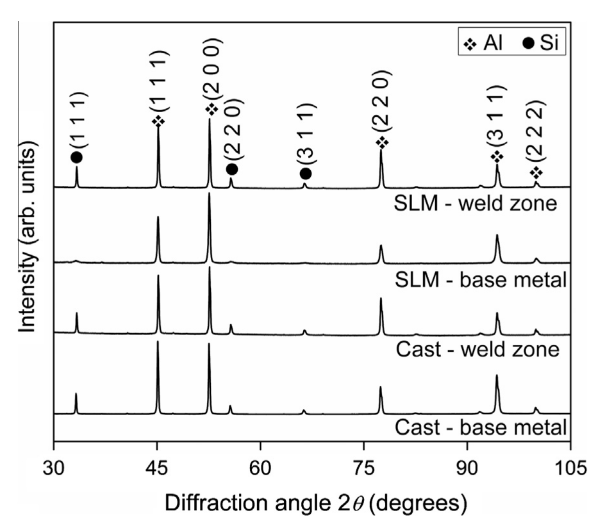

Fig. 2. XRD patterns ($\lambda = 0.17889$ nm) of the base metal and weld zone for the cast and SLM Al–12Si samples.