Aluminum Matrix Syntactic Foam Fabricated with Additive Manufacturing

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Keywords

Aluminum, Lightweight, Composite, DED

Abstract

Syntactic foams are lightweight structural composites with hollow reinforcing particles embedded in a soft matrix. These materials have applications in transportation, packaging, and armor due to properties such as relatively high specific stiffness, acoustic dampening, and impact absorption. Aluminum matrices are the most widely studied of metal matrix syntactic foams, but there is little to no research in regards to processing the foams with additive manufacturing. It is theorized that the fast cooling rates and limited kinetic energy input of additive could reduce two issues commonly associated with processing syntactic foams: microsphere flotation in the melt and microsphere fracture during processing. In this study, 4047 aluminum blended with glass particles was deposited on a 4047 Al substrate using an additive process. Characterization of the foams include mechanical testing and microstructural analysis.

Introduction

The aluminum composite built in this study is an aluminum matrix syntactic foam. Metal matrix syntactic foams (MMSF) are lightweight structural composites composed of a metal matrix and rigid, hollow spheres. The hollow spheres embedded in the matrix significantly reduce the weight of the composite, while also offering some. The unique microstructure of the MMSF also offers other benefits such as vibrational dampening and impact absorption. When comparing the MMSF to a metal foam or a particulate composite, there is an improvement to the specific stiffness and specific strength. [1]

Most of the literature surrounding syntactic foams focuses on refining two main processing methods – stir casting and pressure infiltration. [1] Both methods include harsh mechanical forces that can easily fragment the delicate microspheres. Microsphere fragments can cause unwanted densification of the microstructure and possibly create stress concentrations in the matrix which would decrease the mechanical properties of the composite. It is possible that AM could form the material without applying significant mechanical forces to the microspheres. Microsphere buoyancy in the melt can also be countered by laser AM as the fast cooling rates and layer-by-layer nature should lock microspheres into layers instead of allowing them to float to the top of the part. Finally, AM is a near net shape fabrication process, a requirement for syntactic foams.

Aluminum alloys are difficult to laser additive manufacture for several reasons. Aluminum tends to be difficult to impossible to weld due to the high thermal conductivity of the metal (about 41% IACS for 4047 aluminum [2]) and the high surface tension of the liquid aluminum. Aluminum alloys also tend to reflect, rather than absorb, laser energy. Because of this, although aluminum alloys can be made with laser AM [3] [4], alloys tailored to be less reflective and conductive (such as 4047) tend to be more successful. The Missouri S&T LAMP group built 4047 aluminum on their custom-built Directed Energy Deposition (DED) system. This study builds on that work done by Isanaka et al. [4] to laser additive manufacture an aluminum composite on the same DED system.

In this project, a syntactic foam with a 4047 aluminum alloy and hollow borosilicate glass microspheres was fabricated with the Missouri S&T custom-built DED system. This was done by first finding the optimal DED parameters for 4047 aluminum with solid SLS glass particles. Specimens were then optically observed for intact microspheres. This work is a continuation of work presented by the author at the MS&T conference in 2016. [5]

Experimental Procedure

The DED equipment used in this project was custom built by the Missouri S&T LAMP group students. This machine is still in the process of equipment optimization. Figure 1 shows a schematic of the equipment setup. The substrate used in this experiment was a 1”x0.5”x0.125” sheet of 4047 aluminum from Eagle Alloys Corp.

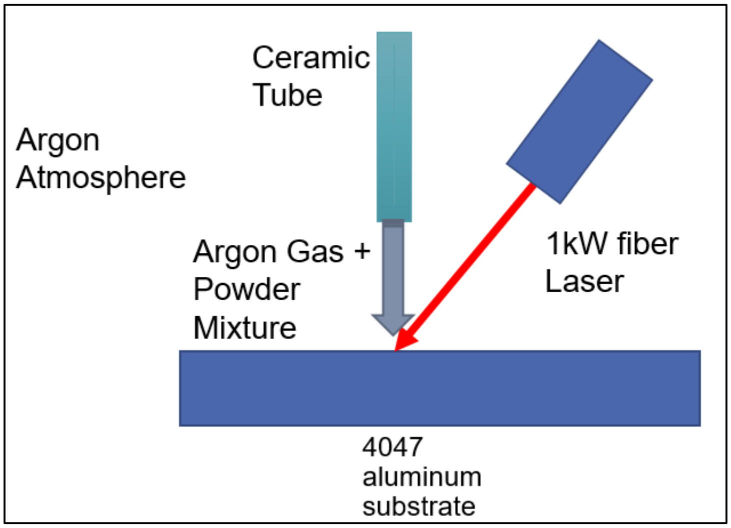

Figure 1: Schematic of the Missouri S&T DED system built by students.

4047 aluminum powder from Valimet Inc. was used in this experiment. The aluminum had a D50 of 70 microns according to the manufacturer. [6] Two types of glass were used. The first was a soda-lime-silicate (SLS) glass that was crushed into a 45 to 75 micron particle size range. This was done by ball milling large glass particles for 24 hours, then sieving to the correct size. The second type of glass was a borosilicate glass from MO-SCI LLC. This material consisted of hollow glass spheres between 1-140 microns in size. The glass was then sieved to the same 45 to 75 micron particles size range as before.

The first composition tested was 4047 aluminum with 30 vol.% SLS glass. This was attempted first in order to understand the laser parameters required to deposit the aluminum composite. The second composition was 4047 aluminum with 15% borosilicate hollow glass spheres. Table 1 shows the final parameters used tuning the machine for each composition. Table 2 shows the compositions of the 4047 aluminum, SLS glass, and borosilicate glass. All three materials melt or soften at temperatures below 1000^{o}C.

Table 1: Laser parameters for the two compositions used in this study.

Composition	Layer Thickness	Number of Layers	Laser Power (KW)	Laser Scan Speed (mm/min)	Powder flow (g/min)
30% SLS Glass	0 0.1	4 6	1 0.4	130 55	0.6 0.6
15% Borosilicate Glass	0 0.1	4 12	1 0.4	130 40	0.6 0.6

Table 2: Compositions of materials used in this study.

4047 Aluminum (wt%) [6]		Typical SLS Glass (wt%) [7]		Borosilicate Microspheres (wt%) [8]	
Al	Balance	SiO_2	70.5	SiO_2	75-90
Si	11.0-13.0	Na_2O	16.3	B_2O_3	5-15
Fe	0.8	K_2O	1.2	Other	1-10
Zn	0.2	MgO	2.9		
Cu	0.3	CaO	5.7		
Mg	0.1	Al_2O_3	2.6		
Mn	0.15	B_2O_3	0.5		
		SO_3	0.2		

Samples were then mounted and polished. Optical microscope images and SEM images were taken. Point EDS data was collected in key areas.

Results and Discussion

The first section of this study was involved with the optimization of DED parameters for a material with 70% aluminum and 30% filler. This was done by depositing a composite comprised of 70% aluminum and 30% (by volume) SLS glass particles. The SLS glass was chosen because it was readily available, inexpensive, and nearly the same density as the aluminum at approximately 2.5 g/cc. The similar densities and particle size between the two materials reduced powder segregation. The SLS glass differed negatively from the borosilicate spheres in several important ways, however. First, the SLS glass was not perfectly spherical as it was made by ball milling. This caused the powder mixture to not flow well, hindering the powder feeding process during deposition. Second, this soft SLS glass was designed to melt at relatively low temperatures and has a wide temperature range under which is stays at a relatively low viscosity. [7] This resulted in the glass powder melting during laser sintering and flowing during processing. Finally, the SLS glass was not hollow.

The laser parameters were tuned to this composition by building single track walls on the surface of the substrate. A balance between the laser power and scan speed was found. A slow scan speed helped to keep a stable melt pool, while a low laser power helped to prevent overheating the melt and the substrate.

Figures 1 and 2 show images of the aluminum and SLS glass composite microstructure. From these images, it is clear that the glass did melt. EDS was also done on this sample in order to confirm the chemistries. The optical image (figure 2) shows that the structure of the aluminum is primarily a eutectic structure with aluminum precipitates. This is the case across all the specimens.

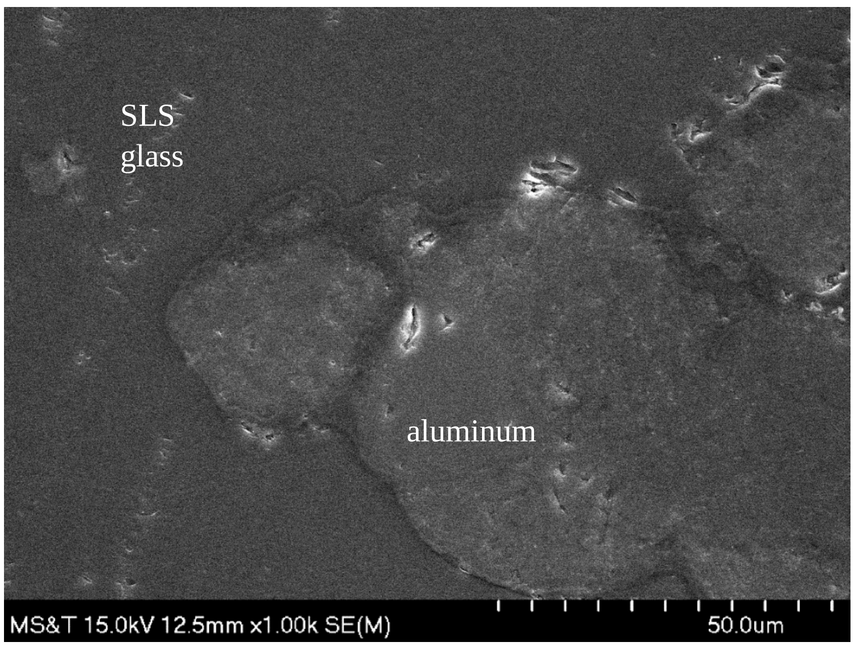

Figure 2: Unetched SEM image of the SLS glass and aluminum specimen. The phases are indicated on the figure.

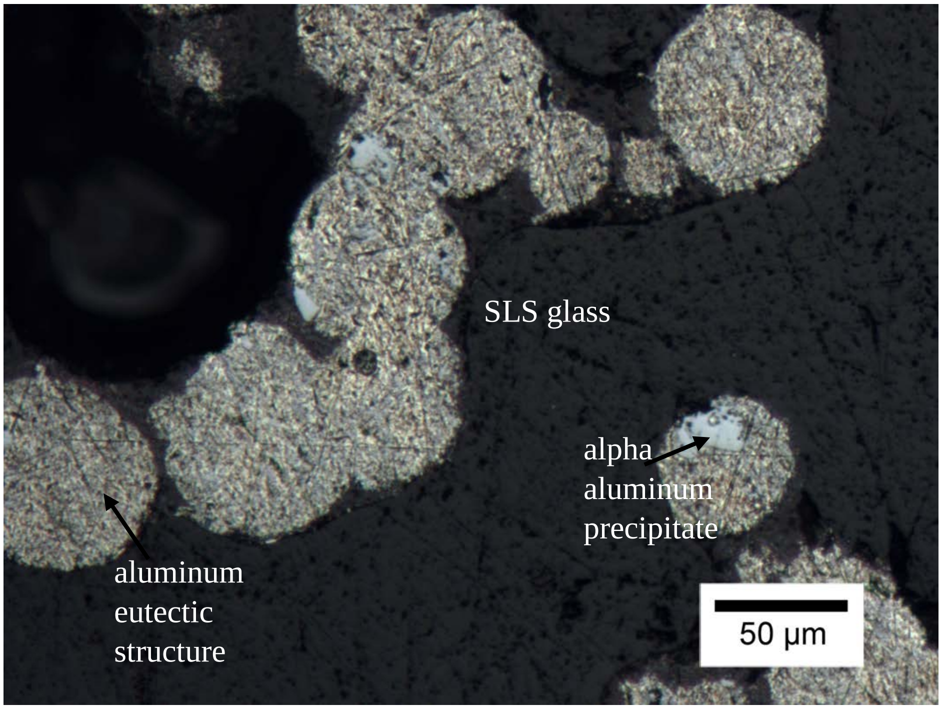

Figure 3: Unetched optical image of the SLS glass and aluminum specimen. The phases are indicated on the figure.

The second section of this study was the deposition of a powder mixture containing hollow borosilicate glass spheres and aluminum. Due to the very low density of the spheres (0.15 g/cc), the powder can easily segregate when agitated. Because of this, only 15 % borosilicate glass microspheres could be mixed into the aluminum without immediate segregation. The parameters had to be further tuned to the change in filler content. This was done in the same manner as before.

Figure 3 shows an optical image of one microsphere within the specimen. There were very few microspheres within the specimens, and most of them were near the outer surfaces of the aluminum deposit. Serial polishing through 1 mm of the specimen, in intervals of approximate 50 microns, revealed less than 10 microspheres per specimen. It is likely that the lightweight microspheres simply do not have the kinetic energy to penetrate the aluminum melt pool, a necessary step of the DED process. It is also possible that some of the microspheres fully melted in the aluminum melt pool. A powder bed process may be a better method for fabricating syntactic foams as the microspheres would not have to inject into the meltpool.

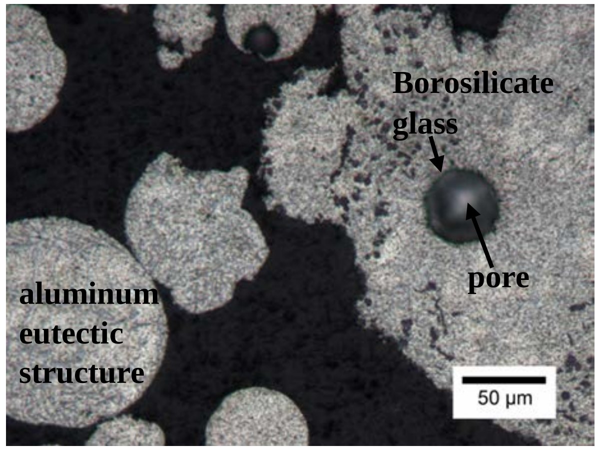

Figure 4: Optical Image of the borosilicate glass and aluminum specimen. Phases on indicated on the figure.

Conclusions and Future Work

The major conclusion to be drawn from this work is that additive manufacturing of an aluminum matrix syntactic foam is possible, but not without great difficulty. A powder bed method may work much better for this composition, to be certain that the microspheres enter the melt pool. Future work for this project includes the utilization of a powder bed, as well as increasing the volume fraction of the microspheres from 15 to 30 volume %.

References

[1] P. K. Rohatgi, N. Gupta, B. F. Schultz and D. D. Luong, "The Synthesis, Compressive Properties, and Applications of Metal Matrix Syntactic Foams," *JOM,* vol. February, 2011.

[2] AlcoTec Wire Coproration, "Alloy 4047 Weld Data Sheet," [Online]. Available: http://www.alcotec.com/us/en/support/upload/a4047tds.pdf. [Accessed August 2017].

[3] G. P. Dinda, A. K. Dasgupta, S. Bhattacharya, H. Natu, B. Dutta and J. Mazumder, "Microstructural Characterization of Laser-Deposited Al 4047 Alloy," *Metallurgical and Materials Transactions A,* vol. 44A, 2013.

[4] S. P. Isanaka, S. Karnati and F. Liou, "Blown powder deposition of 4047 aluminum on 2024 aluminum substrates," *Manufacturing Letters*, vol. 7, pp. 11-14, 2016.

[5] M. Spratt, J. W. Newkirk and K. Chandrashekhara, "Fabrication of Metal Matrix Syntactic Foams with a Laser Additive Manufacturing Process," in *MS&T*, Salt Lake City, Utah, 2016.

[6] Valimet Inc, "Chemical and Physical Characteristics of Valimet Sphereical Aluminum Silicon Powders," [Online]. Available: http://www.valimet.com/documents/2013_pdfs/data_sheets/Silicon%20Data%20Sheet.pdf.

[7] M. Wheeler and C. Roeger, "Scientific Glassblowing Class," Arizona State University, Biology and Chemistry Department.

[8] MO-SCI Specialty Products, LLC, "GL0179 Data Sheet," [Online]. Available: http://www.mo-sci.com/uploads/product-docs/glass-microspheres/GL0179%20Data%20Sheet.pdf.

[9] J. E. Shelby, "Compositions and Properties of Commercial Glasses," in *Introduction to Glass Science*, Cambridge, UK, The Royal Society of Chemistry, 2005, pp. 262-274.