Materials and Design 145 (2018) 1–10

Contents lists available at ScienceDirect

Materials and Design

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

Selective laser melting of stainless steel and alumina composite: Experimental and simulation studies on processing parameters, microstructure and mechanical properties

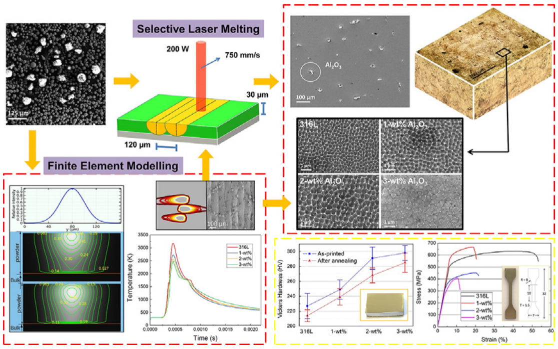
Xinwei Li [1], Habimana Jean Willy [1], Shuai Chang, Wanheng Lu, Tun Seng Herng, Jun Ding *

Department of Materials Science and Engineering, National University of Singapore, 117576, Singapore

HIGHLIGHTS

- Printable alumina/316L composite structures by selective laser melting, product shown improved mechanical properties.
- Usage of agglomerate reinforcement particles produced composite with even dispersion after laser melting.
- Optical properties, and not thermal, resulted in the increased energy requirement for full melting.
- In turn lowers the maximum temperature attainable and hence decreased cooling rate, resulting in coarser cellular dendrites.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 3 January 2018
Received in revised form 1 February 2018
Accepted 17 February 2018
Available online xxxx

Keywords:
Selective laser melting
Stainless steel
Alumina
Finite element modeling
Metal matrix composite
Microlattice

ABSTRACT

Metal matrix composites (MMC) find their uses as high performance materials. The selective laser melting (SLM) of a 316L stainless steel and Al_2O_3 MMC is presented in this paper. Agglomerate Al_2O_3 particles had shown to be an adequate powder choice with uniform dispersions in the resultant prints. Relative density, phase, microstructure and mechanical properties of all 1-, 2-, 3-wt% doped products were carefully analyzed. Finite element modeling model was developed to study the associated multi-physics phenomena with high efficiency for process parameter optimization. It is found that the change in SLM temperature profile with Al_2O_3 addition is mainly due to the change in optical properties rather than thermal. Hence, both simulation and experimentation revealed that higher laser energy input is needed for optimized melting. In addition, cellular dendrites were found to coarsen with increasing Al_2O_3 addition due to the decreased cooling rate. With hard particle strengthening effects, all samples showed improved hardness with 3-wt% up to 298 HV and 1-wt% samples showing much improved yielding and tensile stresses of 579 and 662 MPa from 316L. Corresponding microlattice built this way demonstrated a 30 and 23% increase in specific strength and energy absorption from that of 316L too.

1. Introduction

Much research and development have been focused recently on additive manufacturing (AM), which is a layer-by-layer building process based on a computer-aided design. Selective laser melting (SLM) is a very versatile metal AM process in which high dimensional accuracy

---

* Corresponding author.
E-mail addresses: E0054235@u.nus.edu (X. Li), E0013658@u.nus.edu (H.J. Willy), msecs@nus.edu.sg (S. Chang), mselwa@nus.edu.sg (W. Lu), msehts@nus.edu.sg (T.S. Herng), msedingj@nus.edu.sg (J. Ding).

[1] These authors contributed equally.

https://doi.org/10.1016/j.matdes.2018.02.050

and build quality are obtainable. Such a process holds superior advantages to conventional manufacturing including design flexibility, no additional costs for geometric complexity, one-step completion, time and cost efficiency for initial prototyping or startup [1]. One example of design flexibility and complexity will be that of a microlattice, which is exclusively manufactural only by an AM process. Applications and potentials of microlattices had been reviewed by Rashed et al. [2], fully demonstrating the niches and importance of metal AM.

The excellent ductility and corrosion resistance of 316L stainless steel (SS) prompts it widely studied in both conventional powder metallurgy [3,4] and AM techniques [5]. It however has limited strength; of which it may find more applications if this can be improved. Many works hence focused on the reinforcement of 316L matrices with ceramics to produce a metal matrix composite (MMC) which hosts the excellent mechanical properties of metals and yet the corrosion and wear resistance of ceramics [6,7]. Such reinforced metals find uses in high end applications such as automotive, aerospace and medicine [5]. Conventional routes usually involve casting, molding, pressing – all of which are very much limited in design freedom. However, through SLM, we can shape these high performing MMCs into highly complex geometric designs otherwise not achievable by conventional manufacturing.

Although a good number of works on 316L MMC through conventional manufacturing, very few were done using SLM. An early work on this was reported in 2009 by Hao et al. [8] on incorporating micro-hydroxyapatite particles to enhance the bioactivity of 316L. Physical blending of feedstock powders was adopted and composites were printable. Wei et al. [9] also worked on such a composite by using SLM powders based on the adhesion of nano-hydroxyapatite particles onto 316L powders via ball milling. Nano-particles successfully adhered to 316L, showing no presence of clustering and hence the reasonable flowability of the resultant mixture powder. Their work showed improved mechanical properties and the success of using nano-powders as reinforcements. Another work on bioactive metallic materials was reported by Zheng et al. [10] on 316L with $CaSiO_3$ incorporation. Although the objective is achieved, decreasing tensile properties were however realized with increasing proportions of $CaSiO_3$, highlighting the significance of SLM defects such as pores and cracks when using powder of different morphology. AlMangour et al. did extensive studies on 316L reinforced with TiB_2 [11,12] and TiC [13–18]; of which high microhardnesses of around 400 HV and 600 HV were attained respectively with increased wear resistances and compressive strengths. Influences of powder morphology, balling milling methods, scanning strategies, energy densities were investigated and these factors were reported to heavily influence the microstructural evolution and mechanical properties.

Most of the previously discussed works on MMC with SLM focused on powder mixtures based on the implant or adhesion of fine or nano-scaled reinforcement particles onto the larger 316L powders. They adopted ball milling methods which are complex and resource exhaustive. Main challenges faced for a powder-bed AM process like SLM will be powder mixing techniques whereby good uniformity and flowability are needed. On top of that, SLM process parameter optimization on a new powder system can be seriously resource and time consuming. Hao et al. [8] gave a very comprehensive study on the processing parameters; they started from scratch, fine tuning various parameters with multiplicative steps involved. To neutralize experimental errors and fluctuations, they replicated three samples for repeatability to ensure accuracy. Simulation may deem more effective for such kind of studies; however no previously mentioned authors studied their SLM composite processing with simulation models. In fact, despite a good number of SLM simulation models proposed [19,20], none of them has been effectively used for SLM parameter optimization for a mixture of powders.

To date, no SLM or any laser forming of an alumina (Al_2O_3) and 316L composite has been reported. Al_2O_3 is shown to be a widely popular ceramic as reinforcement [6,7] and previous works on its addition into 316L through conventional manufacturing had shown that such composites are promising [21,22]. In addition, Al_2O_3 is an attractive ceramic due to its inherent hardness (~1400–1800 HV), low density (~3.95 g/cm^3), inert nature and biocompatibility. In this work, we propose to adopt a simple roller mixing method using agglomerate Al_2O_3 particles expected to uniformly disperse in the metal matrix after laser melting as reinforcements for 316L. Through this, we hope to open up on more possibilities for powder preparation and choice apart from fine-scaled powders and ball milling methods. We also developed an effective finite element (FE) simulation method to study the changes to physical properties of printed 316L and powders after the addition of Al_2O_3. Such studies can be used for efficient SLM parameter optimization; physical phenomena such as melt layer and cooling rates can also be observed. Through this work, we propose a new approach in the SLM of composites, which is to use FE simulation as a parallel aid to experimentation.

2. Methods

2.1. Experimentation

Gas atomized 316L SS powders with an average particle size of 35.6 μm were obtained from SLM Solutions (SLM Solutions Group AG, Germany) and puriss grade Al_2O_3 particles of average agglomerate size of 79 μm were obtained from Sigma Aldrich. Powder mixing was done by physical mixing in a roller mixer for about 4 h. Three types of powder mixture were prepared: 1, 2, 3 wt% (weight percent) of Al_2O_3 in 316L (Table 1). Powder morphology of starting powders and distribution of mixtures were investigated with the Zeiss Supra 40 field emission scanning electron microscope (SEM), particle size analyses were done with RETSCH Camsizer XT dynamic imager. Powder flowabilities were investigated with the Copley Scientific Flowability Tester BEP2, where the times taken for powders to flow through a 10 mm diameter funnel were recorded.

SLM machine in use is SLM 280 HL by SLM Solutions. It houses one 1067 nm wavelength fiber laser of up to 400 W laser power with a beam diameter of about 80 μm. Scanning strategy is based on the innate scanning strategy of Materialise Magics software. For parameter optimizations, blocks of 6 × 6 × 1 mm^3 were printed. For all other characterization, larger blocks of 15 × 10 × 5 mm^3 were printed. 1 cm^3 microlattices and non-standard tensile specimen were built accordingly too. Due to the metastable nature of SLM, all batches of samples for comparison were built exactly the same way in the SLM. Detailed working principles of the SLM can be found elsewhere [5].

Metallurgical surfaces were mirror polished for characterizations. To reveal microstructures, samples were immersion etched with Carpenter's 300 series SS etchant (ratio of 122 ml HCl, 6 ml HNO_3, 122 ml ethanol, 8.5 g $FeCl_3$, 2.4 g $CuCl_2$) for 40 min. Microstructures were observed with both the Olympus GX51 metallurgical optical microscope (OM), and the SEM equipped with an energy dispersive x-ray spectroscopy (EDX) system. X-ray diffraction (XRD) structural studies were done with Bruker D8 Advanced Diffractometer. Archimedes principle density measurements were done in accordance to ASTM-B962 standards with a weighing balance accurate to 0.0001 g and readings were reported from 4 samples. Vickers microhardness were presented from 8 readings using a Zwick Roell microindenter in accordance to ASTM-E92 standards with 1 kgf load for 10 s. Heat treatments were done with a custom-built high temperature vacuum

Table 1
Abbreviations of samples to be used in the text.

Sample	Abbreviated names used
316L stainless steel	316L
1 wt% of Al_2O_3 in 316L	1-wt%
2 wt% of Al_2O_3 in 316L	2-wt%
3 wt% of Al_2O_3 in 316L	3-wt%