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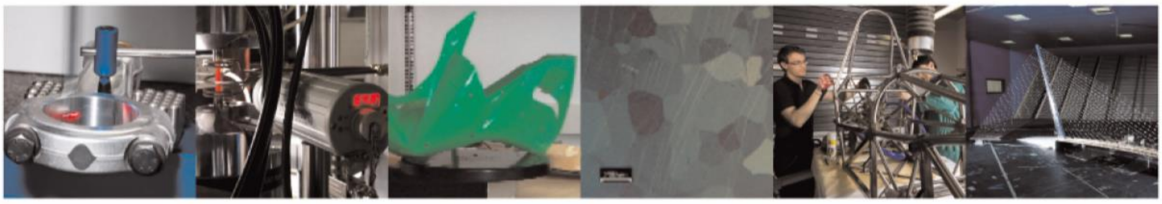

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Multi-material selective laser melting of Fe/Al-12Si components

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Multi-material selective laser melting of Fe/Al-12Si components

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Abstract

In this work, multi-material selective laser melting (SLM) prototype system is demonstrated with the capability of mixing two metallic powders at different compositions on demand. The flexible system can operate for in-situ alloying of different elements as well as producing composite materials. In this preliminary work, Fe/Al-12Si component manufacturing is demonstrated. Initially, pure Fe and Al-12Si powders are studied separately. At a second phase the 55/45 volumetric ratio of Fe/Al-12Si mixture is processed. Finally, deposition of parts composed of Fe, Fe/Al-12Si, and Al-12Si layers is carried out demonstrating the feasibility of the powder-bed based additive manufacturing method for multi-material manufacturing.

Keywords: Additive manufacturing; composite materials; selective laser melting; multiple material additive manufacturing.

1. Introduction

Additive manufacturing methods provide several advantages compared to conventional methods, such as product customization, rapid prototyping, and higher flexibility in terms of achievable geometries. Powder-bed based additive manufacturing processes exhibit further advantages such as the use of finer geometries, internal channels, and lattice structures. On the other hand, directed energy deposition (DED) processes benefit from higher deposition rates, possibility of building over existing components and also the possibility of producing multi-material components. The architecture of the DED systems provide an intrinsic flexibility in terms of using plural powder feeders coupled to the deposition head, which can be used for multi-graded material deposition [1]. Such capacity within powder-bed based additive manufacturing processes can open up to different possibilities for material and product design.

There is an increasing demand for the use of light-weight Al alloys along with steel structures especially in automotive and naval industries. Having low metallurgical compatibility, the assembly of these materials through welding is very difficult. Accordingly, unconventional processes such as the use of explosive cladding, friction stir welding, laser welding and brazing are employed [2–6]. As a process close to additive manufacturing, laser cladding has been employed in a multi-material configuration for producing variants of Fe/Al coatings [7–11]. On the other hand, the use of SLM can be beneficial for producing transition blocks assembling steel components to Al-alloy ones via welding, as well as direct manufacturing of the assembled components. In particular, Figure 1.a reports the concept of using multi-material SLM process for producing transition nodes. In this multi-material node each extremity is made by the same or compatible material of the welded part, while the composition varies between the extremities.

In this work a prototype powder-bed fusion system with multi-material deposition capability is demonstrated. The system is used for carrying out initial selective laser melting tests of multi-material specimens using pure Fe and Al-12Si powders. The final components consist of pure Fe and Al-12Si regions with a transition region in between consisting of composite Fe/Al-12Si with 55/45 volumetric ratio.

2. Materials and methods

2.1. Material

Since the final goal is to demonstrate the feasibility of the multi-material SLM process, pure Fe and near eutectic aluminium alloy were selected as heterologous materials. Pure Fe was preferred to iron-based alloys because the most critical intermetallic generated during the bonding of Fe-based and Al-based alloys is Fe_xAl_y intermetallic. Water atomized pure Fe powder (Metalpolveri, Brescia, Italy) and gas atomized Al-12Si (Oerlikon Metko, Winterthur, Switzerland) powders were used. Average powder grain size was 41 µm and 23 µm for pure Fe and Al-12Si powders respectively.

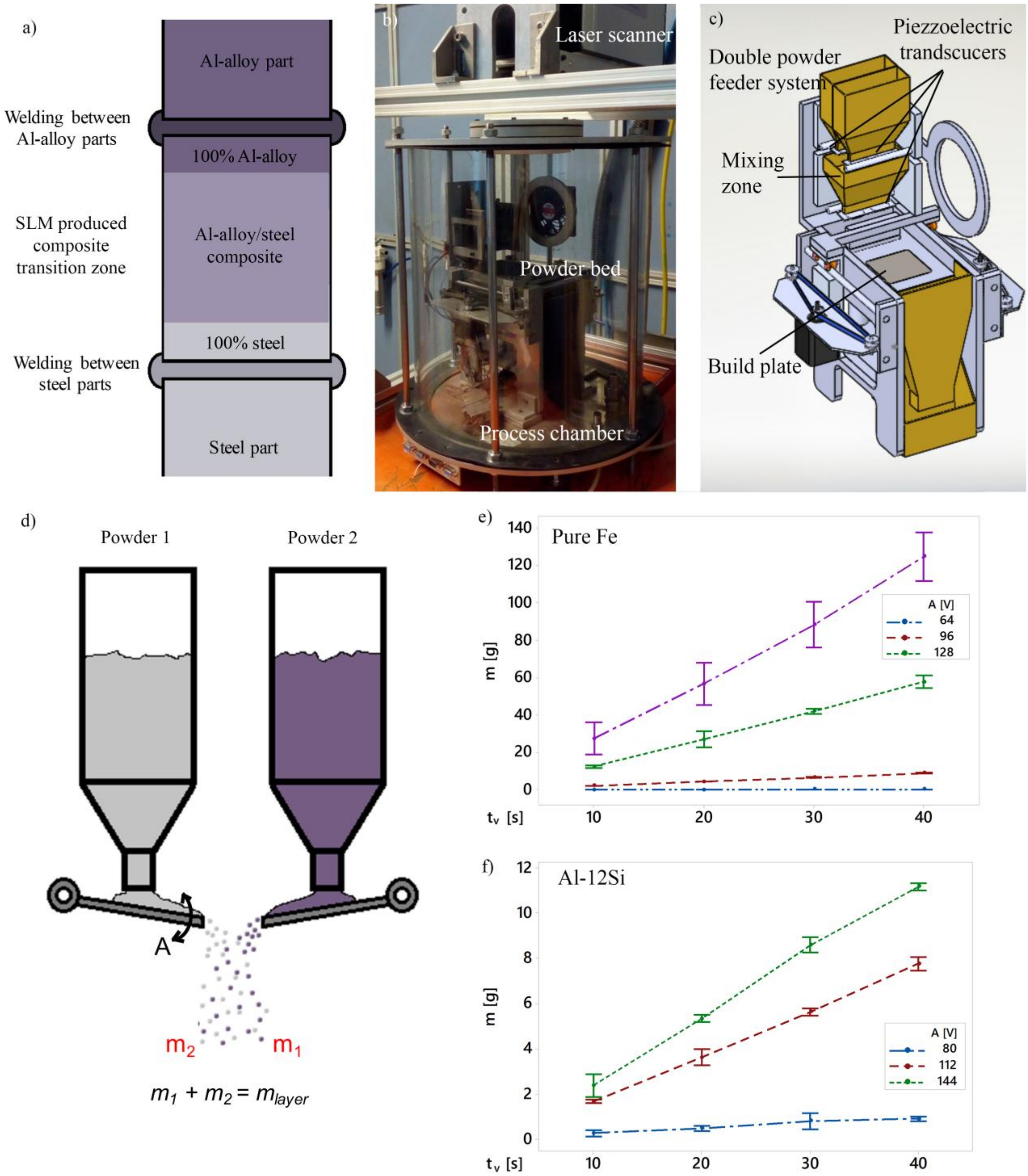

Figure 1. a) Concept of using multi-material transition zone for assembling Al-alloys with steel. b) In-house built prototype SLM system with multi-material processing capability. c) Design of the powder feeder system. d) Working principle of the powder feeder for mixing powders. e) Calibration curves delivered powder mass (*m*) of pure Fe and f) Al-12Si as a function of applied voltage (*A*) and vibration time (t_v). Error bars depict 95% confidence interval for the mean.

2.2. Selective laser melting (SLM) system

A prototype SLM system, namely Powderful, was used throughout the study (Figure 1.b). A multimode fibre laser source with 1 kW maximum power (IPG Photonics YLR-1000, Cambridge, MA, USA) was used with a scanner (El.En. Scan Fiber, Florence, Italy). Scan path trajectory was designed using LogoTag software (Taglio, Piobesi D'alba, Italy). The scanner integrated a 60 mm collimating lens and a 255 mm f-theta lens. In this configuration, the beam diameter at focal plane (d_0) was calculated as 212 µm. The control of the system and monitoring of the machine state was carried out in LabVIEW environment (National Instruments, Austin, TX, USA). Prior to processing, a vacuum was applied down to 50 mbar pressure first and then process gas was flooded. This procedure is repeated 3 times. The system was fitted with a double powder feeder system (Figure 1.c). The system was composed of two upper powder hoppers housing separate materials and a lower mixing hopper. The upper hoppers can be operated singularly for single material processing or can be used simultaneously for mixing the two materials at a desired composition (Figure 1.d). All hoppers were operated with vibrating plates via piezoelectric transducers. The powder feed rate was calibrated as a function of applied voltage (A) to the transducers and vibration time (t_v) for each material (Figure 1.e and 1.f).

The main specifications of the SLM system are reported in Table 1. In the present configuration, process variables were laser power (P), scan speed (v), hatch distance between adjacent scan tracks (h) and layer thickness (t).

Table 1. Main characteristics of the flexible SLM prototype Powderful.

Laser emission wavelength, λ	1070 nm
Max. laser power, P_{max}	1000 W
Delivery fiber diameter, d_f	50 µm
Collimation lens, f_c	60 mm
Focal lens, f_f	255 mm
Nominal beam diameter on focal plane, d_0	212 µm
Depth of field, Δz_{pdc}	6.4 mm
Build platform area (DxWxH)	60x60x20 mm^3

2.3. Experimental plan

Multi-material SLM of Fe/Al system was developed by depositing pure Fe over a mild steel substrate, then depositing a Fe/Al-12Si composite layers, and finally depositing the Al-12Si layers on the top. The SLM parameters for pure Fe and Al-12Si were set separately through preliminary investigations. Parameter combinations producing high density (ρ>99%) specimens were determined by cross-section images and are reported in Table 2. On the other hand, parameters for depositing the Fe/Al-12Si layers with 55/45 volumetric ratio was studied by varying scan speed (v) and laser power (P). Scan lines were applied mono-directionally with fixed hatch distance (h). Finally, multi-material Fe/Al system was produced via SLM consisting of 20 layers of pure Fe, 10 layers of Fe/Al-12Si, and 10 layers of Al-12Si.

Table 2. Parameters used for the production of Fe/Al-12Si multi-material components

Material	Pure Fe	55 v% Fe, 45 v% Al-12Si	Al-12Si
Layer thickness,t (µm)	50	100	100
Hatch distance, h (µm)	110	110	110
Laser power, P (W)	236	142; 236	236
Scan speed, v (mm/s)	120	33; 50; 67	40
Focal position, Δz (mm)	0	0	0

2.4. Characterization

Metallographic cross-sections of SLM parts were prepared by cutting, mounting in resin and polishing. Optical microscopy images were acquired were acquired with 5X objective (Quick Vision ELF from Mitutoyo, Kawasaki, Japan). Vickers microhardness was measured on samples with 0.3 kgf applied load on Al-12Si specimens and 0.5 kgf on the other ones. Over the Fe/Al-12Si micrographs, the proportion of the cracked zones was analysed with image processing software.

3. Results and discussion

Figure 2.a reports the cross-section images of the Fe/Al-12Si layer. The main defect within the deposited material appears as the large cracks rather than porosity due to lack of fusion or excessive melting. Figure 2.b shows the microhardness measurements of the different layers. The Fe/Al-12Si layers show much higher microhardness (450-550 $HV_{0.5}$) compared to the single materials, pure Fe (90-100 $HV_{0.5}$) and Al-12Si (150-160 $HV_{0.3}$) due to the formation of the FeAl intermetallic. The microharndess of the Fe/Al-12Si layer is influenced only by the scan speed as the analysis of variance (ANOVA) confirms. The observed microhardness values are higher than the ones obtained by laser cladding [10] and lower than the ones obtained by SLM of

the prealloyed powder with higher scan speed [12]. The microhardness variation can be mainly attributed to cooling rates induced by different scan speeds.

The micrograph analysis showed that crack proportion is influenced only by laser power as confirmed by ANOVA. Average crack proportion increased from 3.3±0.1 to 5.7±0.2 as the laser power increased from 142 W to 236 W. These cracks are expected to be formed due to the high fragility of the FeAl intermetallic. For further processing the Fe/Al-12Si layers were produced employing P=142 W and v=33 mm/s.

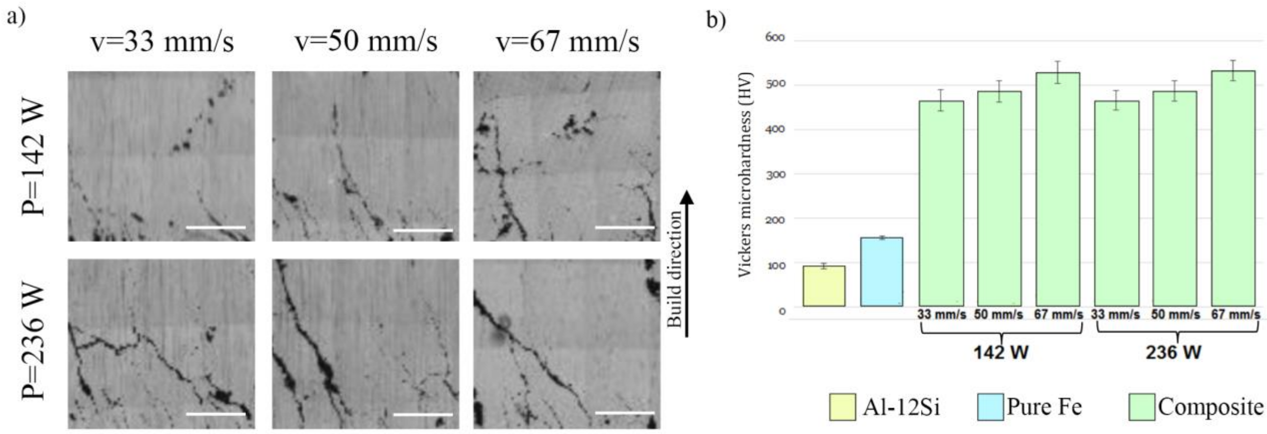

Figure 2. a) Cross-section images of the Fe/Al-12Si layer as a function of process parameters (marker shows 1 mm). b) Comparison of microhardness of Al-12Si, pure Fe and Fe/Al-12Si layers produced by multi-material SLM system (applied load was 0.3 kgf for Al-12Si samples and 0.5 kgf for the others).

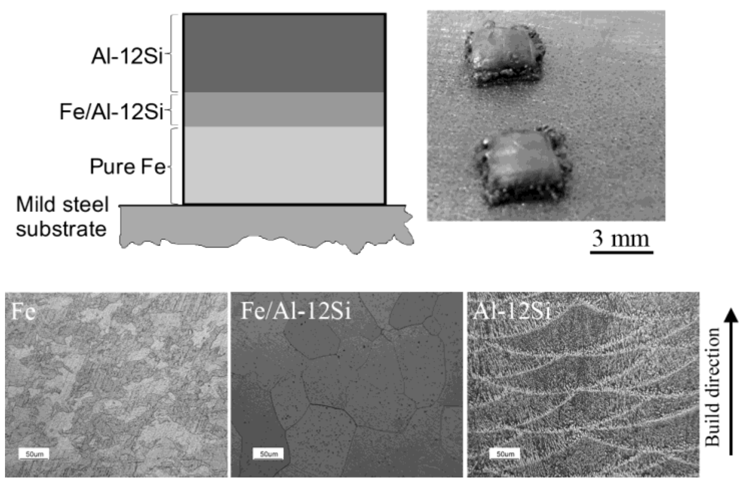

Figure 3. Production of the multi-material specimens by multi-material SLM system and cross-section images of the different layers.

Figure 3 depicts the deposited Fe/Al-12Si multi-material system along with the produced samples. All required layers were produced successfully. However, bonding between consecutive materials was observed to be problematic. Material microstructures are also presented in Figure 3 belonging to the deposits obtained separately. Both pure Fe and Al-12Si are pore-free and exhibit fine microstructure due to the fast cooling cycles. On the other hand, the Fe/Al-12Si layer shows large grains with grain size between 50 and 75 µm. The formation of finer grains were observed during the SLM of prealloyed Fe/Al powder, where smaller laser beam diameter, lower power and higher scan speeds were employed [12]. The observation implies that the in-situ formation of Fe/Al intermetallic is possible and the laser process parameters can be used to material microstructure.

The results confirm the feasibility of the approach. At this point, an important aspect of the multi-material SLM, the re-use of the powder feedstock, should be also assessed. Recycling of the powder feedstock is an important economical factor, and may induce changes in part quality due to degradation already in the case of SLM with single material [13,14]. In the case of multi-material SLM powder separation is required in addition to the commonly employed sieving methods for powder recycle. Additive manufacturing industry can refer to electronics and pharmaceutical industries for methods applied in a similar manner for powder recycling and separation [15,16]. For the given material composition, magnetic powder separation method can be useful [17]. Density and shape based separation techniques can be potentially adapted to the fine metallic powders. The use of powder mixtures requires further precautions to be taken in powder handling and stocking, since their combination can constitute safety issues. In particular, thermite (Al/Fe_2O_3) can form during the processing of the given material combination, which is highly reactive [18].

4. Conclusions

In this work a multi-material SLM platform is proposed and its initial use for producing Fe/Al-12Si multi-material structures is demonstrated. The main outcomes of the work are summarized as follows:

- The paper presents a new concept of SLM machine enabling controlled and gradually construction of layers with different chemical composition.
- SLM process can be used for multi-material additive production, where material variations between layers is required.

- SLM process of Fe/Al-12Si layers showed large cracks due to the low compatibility and miscibility of these two materials. The obtained Fe/Al-12Si layers showed high hardness, which is a characteristic of the Fe/Al intermetallic. The hardness depended on the scan speed.
- Material transformation from pure Fe to Fe/Al-12Si and finally to Al-12Si could be achieved during the SLM process. Adhesion between consecutive layers was scarce, which requires further investigations for improved processing strategies.
- The multi-material SLM can be used for material switch between layers, as well as in-situ alloying and eventually multi-graded components. Final applications are hybrid or transitional junction elements, such as the nodes in a heterologous frame space.

The present work confirms the feasibility of the approach. Future works will address the processing strategies for improving the part quality and a comprehensive analysis over the component metallurgy.

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List of figures

List of tables