Materials and Design 155 (2018) 77–85

Contents lists available at ScienceDirect

Materials and Design

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

Interfacial characteristic and mechanical performance of maraging steel-copper functional bimetal produced by selective laser melting based hybrid manufacture

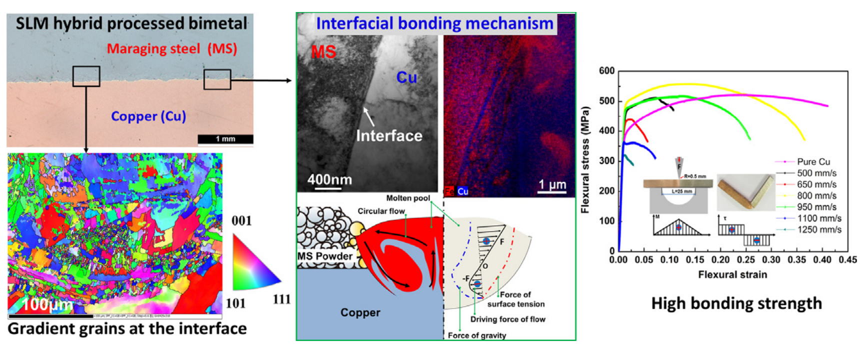
Chaolin Tan [a,b,*], Kesong Zhou [a,b,*], Wenyou Ma [b], Liu Min [b]

[a] School of Materials Science and Engineering, South China University of Technology, Guangzhou 510640, China
[b] National Engineering Laboratory for Modern Materials Surface Engineering Technology, Key Lab of Guangdong for Modern Surface Engineering Technology, Guangdong Institute of New Materials, Guangzhou 510651, China

HIGHLIGHTS

- Combination of SLM additive manufacture and subtractive process was explored to produce steel-copper functional bimetals.
- Good metallurgical bonding with Fe and Cu inter-diffusion was obtained at the interface.
- Gradient sub-micro grains with <111> texture at the interface was detected by EBSD.
- The interfacial bonding mechanism was revealed by FIB+TEM and illustrated in details.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 April 2018
Received in revised form 21 May 2018
Accepted 28 May 2018
Available online 29 May 2018

Keywords:
Selective laser melting
Hybrid manufacture
Interface
Bimetal
Marangoni convection
Gradient structure

ABSTRACT

A combination of selective laser melting (SLM) additive manufacture and subtractive process was explored to produce maraging steel copper bimetal. Relationships among laser parameter, interfacial characteristic and mechanical performance are elucidated. A metallurgical bonded interface with a 30–40 μm inter-diffusion region is formed. Gradient submicro grains with strong ⟨111⟩ orientation exhibit at the interface, which owe to high cooling rate and temperature gradient caused by high thermal conductive copper. A selected region of the interface was extracted by focused ion beam (FIB) for interfacial bonding analysis. The bonding mechanism is revealed and illustrated in detail. Interfacial intense Marangoni flows pull the copper toward the molten pool of maraging steel and the liquid maraging steel penetrates into the melting copper, which contributes to interfacial bonding. The bonding strength of hybrid processed bimetals are evaluated. Fracture in tensile is not present at the interface but on the copper side. The highest flexural strength reaches 557 MPa, which is slightly higher than that of the copper. Effects of parameter on fracture behaviors are also elucidated. This hybrid manufacture increases the productivity and functionality of the direct SLM-produced part, and provides a new approach for producing high-performance functional dissimilar bimetals based on laser additive manufacture.

1. Introduction

Selective laser melting (SLM) is a typical metal additive manufacturing technology, it produces 3D parts in an incremental layer-wise

* Corresponding authors at: School of Materials Science and Engineering, South China University of Technology, Guangzhou 510640, China.
E-mail addresses: kszhou2004@163.com (K. Zhou), tclscut@163.com (C. Tan).

https://doi.org/10.1016/j.matdes.2018.05.064
0264-1275/

manner using laser to melt, sinter and bond powders together on a powder bed [1,2]. SLM has been gradually applied in customized medical [3], tooling inserts [4], refractory metals [5], complex lattice structures [6], and functional components [7], etc., due to high resource efficiency, good production flexibility and mechanical performance. SLM fabrications of titanium alloys [8], aluminum alloys [9], nickel alloys [10] and iron alloys [11] are widely investigated, and the as-achieved properties are comparable or better than traditional wrought condition. Moreover, recent researches about SLM high laser reflective copper alloy [12] and refractory pure tungsten [5] also achieved great progresses.

However, the relatively low productivity of SLM technique cannot be eliminated owing to the layer-wise deposition manner. Most of the SLM systems have a low build rate of 5–20 cm^3/h [13]. For example, SLM maraging steel in EOS M290 machine using the optimum laser parameters and a 40 μm layer thickness can only reach a volumetric deposition rate of 10.8 cm^3/h [11,14]. A combination of additive and subtractive processes can improve productivity and cause synergistic effects on producing functional and high geometrical complexity parts. Besides, multi-material processing can increase the functionality of the direct additive manufacture.

Bimetals are widely applied in various engineering fields due to the greatly increased flexibility in design and production, optimized properties from two metals, and more complex functions [15,16]. Copper-steel bimetal is a typical multi-functional material, which has been widely applied in power generation and transmission industries, heat transfer components, cryogenic sector, and bi-metallic die-casting industry, etc. [17,18]. However, owing to their remarkable different physical and chemical properties, laser joining of copper-steel dissimilar metals encounters the following difficulties: (i) The high laser reflectivity and low absorption (<5%) of copper [19], make the material hard to be deposited on the copper. (ii) The high thermal conductive (401 $W \cdot m^{-1} k^{-1}$) copper dissipates heat rapidly away from the molten pool, leading to difficulties in reaching the melting temperature. (iii) No intermetallic phase exists in the Fe—Cu phase diagram, except a very limited amount of solubility between Cu and Fe [20]. (iv) The significant difference of thermal expansion coefficient and thermal conductivity between copper and steel, will inevitably cause large misfit strain and residual stresses in the joint, leading to solidification cracks [15]. (v) The hydrogen is highly soluble in liquid copper, which normally could form the pores at bonding region [21].

Due to the aforementioned difficulties, a few studies have been carried out recently on the laser additive manufacture of multi-material between copper and steel [18,22,23]. Interfacial diffusion and good bonding between copper and H13 were achieved by SLM these two powders [18]. Similar metallurgical diffusion results were also obtained in multi-material metallic parts between UNS C18400 copper alloy and 316 L stainless steel fabricated by SLM, while massive cracks and pores were obviously observed in the interface and no bonding strength data available [22]. Additionally, fractures occurred in the bonding regions or the heat affected zones (HAZ) in laser direct metal deposition of H13 steel on copper substrate after tensile [23]. These researchers demonstrated the feasibility of laser additive manufacture of multi-materials between copper and steel, but they were unable to reveal the influence of laser parameter, metallurgical bonding mechanism and interfacial microstructure evolution. In this work, we investigated the effect of laser parameter on the interfacial bonding characteristics between T2 copper and maraging steel functional bimetals produced by SLM based hybrid manufacture. Various methods including focused ion beam (FIB), transmission electron microscopy (TEM) and electron backscattered diffraction (EBSD) were applied for in-depth and comprehensive analysis of the interfacial metallurgical bonding mechanism and interfacial microstructure evolution. Tensile and flexural tests were performed to evaluate the bonding strength of the bimetals.

2. Experimental details

2.1. Materials and SLM process

The spherical grade 300 maraging steel (MS) powder (mean diameter of 42 μm) supplied by Electro Optical Systems (EOS) GmbH (Germany) was used for SLM fabrication. Computer numerical control (CNC) machined bulk T2 copper was selected as mating plate. The experiments were carried out in an EOS M290 SLM (powder bed) system. As shown in Fig. 1, the polished and sand blasted copper was fixed on the base plate, and then the gap distance between the copper and the blade coater was adjusted to be 20 ± 5 μm by using micrometer gauge. In order to investigate the laser parameters on the interfacial characteristics, for the first ten layers, we designed the same laser power ($P = 285$ W) for all the samples, while used different scan speeds (v) of 500 mm/s (v_1), 650 mm/s (v_2), 800 mm/s (v_3), 950 mm/s (v_4), 1100 mm/s (v_5) and 1250 mm/s (v_6) respectively in different samples. A layer thickness of 40 μm was selected and the first three layers were melted twice to enhance the interfacial bonding. After ten layers, the laser process was switched to the optimum parameters. As detailedly illustrated in our previous work [11], the optimum process parameters were experimentally optimized, in which the P, v and hatch space (h) were systematically studied in the range of 200–370 W, 500–1800 mm/s and 50–150 μm, respectively. The P, v and h of the optimum parameters are 285 W, 960 mm/s and 110 μm, respectively. The laser scanned in a raster pattern with 67° rotation between the adjacent layers.

2.2. Characterizations

The specimens sectioned along the vertical (build) direction were polished and observed by a Leica Dmirm optical microscope (OM) for interfacial defects analysis. The polished and etched vertical cross-sections were observed by a Zeiss Merlin field emission scanning electron microscope (FE-SEM), fitted with an Oxford energy dispersive spectrometer (EDS). Specimens taken from the interface for EBSD test were mirror polished and then vibration polished. EBSD test was carried out on a Hitachi S-3400 N SEM system at 20 kV through an integrated Oxford/HKL EBSD detector, using a step size of 100 nm. The EBSD data were analyzed using Channel 5 software. A TEM sample (12 × 6 μm) was extracted from the MS-Cu interface by a FEI Scios Dualbeam FIB system. A JEOL 2100F TEM system operating at 200 kV was used for interfacial nanosized structures observation and energy-dispersive X-ray spectroscopy (EDX) analysis. The mechanical properties of interfacial bonding were evaluated by tensile tests and three-point flexural tests using an Instron 5900 universal material testing machine. Specimens for tensile and flexural tests were extracted along building direction with the interface locating in the center of length. The tensile properties were evaluated referring to ASTM E8, the reduced section of the polished tensile specimen was 2.5 mm in thickness, 5 mm in width, and 25 mm in length. The loading speed in tensile tests was 1 mm/min. The flexural tests were carried out based on ASTM E290, the size of flexural specimen was 5 mm × 5 mm × 55 mm after polish, and a loading speed of 0.5 mm/min was used. The ultimate tensile strength (UTS), yield strength (YS) and break elongation (ε_T) of the SLM specimens were estimated by an average value from 3 tensile specimens. An extensometer with primary span distance of 20 mm was used for the strain and ε_T measurements. The ultimate flexural strength (UFS) and flexural strain (ε_F) were also estimated by an average value from 3 times tests.

3. Results and discussion

3.1. Interfacial defects analysis

Fig. 2 shows interfacial defects in the SLM-produced specimens observed by OM and SEM. The distinct copper and MS regions can be