Additive manufacturing of bimetallic structures

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Received: 19 February 2020 / Accepted: 15 May 2020 / Published online: 1 June 2020

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Abstract

Metals of 12Cr2Si and 9Cr1Mo are investigated with femtosecond fiber laser additive manufacturing. A smooth phase transition is found at the interface of the two graded composition metals, indicating a strong bonding. In contrast, the comparison group of SS316L and SA508 shows an abrupt transition.

Keywords Fiber laser · Femtosecond laser · 3D printing · Additive manufacturing · Bimetallic structure

1 Introduction

Additive manufacturing of bimetals is important to many industries such as energy, automobile, aerospace, chemical and petrochemical industries, power generation, and oil and gas industries. As an example, advanced high temperature nuclear reactor systems may utilize liquid coolants to optimize heat transfer, neutronics, safety, and compactness of the nuclear supply system [1–3]. The structural components of the primary system in contact with the reactor coolant must be adequately compatible with the materials of the reactor components. Bimetallic structure plays an important role here, by using one metal as a cladding with high temperature strength and Lead–Bismuth eutectic (LBE) corrosion resistance to be joined/bonded with another base metal. High-Cr martensitic steel is considered as one of the best candidate materials [2].

Laser additive manufacturing (AM), e.g., powder bed fusion (PBF) system, uses material powders to build three dimensional parts with complicated structures [4–8]. It has been proved to be an efficient, robust, and cost-effective way for the next generation manufacturing. Though many breakthroughs have been achieved, it is still a big challenge for processing dissimilar metals, due to many impact parameters such as their differences in solubility,

intermetallic compounds, weldability, thermal expansion coefficient, melting points, thermal conductivity.

In this paper, we utilized femtosecond fiber laser PBF system to study bimetallic AM process. 12Cr2Si (cladding) and 9Cr1Mo (base) steels are additively fabricated with excellent interface bonding and phase transition. To our knowledge, this is the first publication demonstrating bimetallic AM using a femtosecond laser system, a step further towards making functionally graded bimetallic structures with LBE corrosion resistance.

2 Materials and methods

Figure 1 (Left) shows the bimetallic structures for investigating bimetallic AM process. We choose 12Cr2Si steel as cladding and 9Cr1Mo as base for the study group. SS316L and SA508 serves as the comparison group. A 200 W femtosecond fiber laser PBF AM system (PolarOnyx, CA) is used to fabricate the dissimilar material samples. The powder delivery system is modified to accommodate both powders. A series of experiments are performed to optimize the AM process to make high density cladding and base. The AM parameters are fine tuned to obtain excellent interface bonding, as dissimilar materials tend

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Fig. 1 Bimetallic structures and material selection and an AM sample

to cause defects and/or peel off at the interface. Samples of $50 \times 50 \times 10$ mm were made for testing.

3 Results and discussion

Figure 1 (Right) shows an example made with 12Cr2Si/9Cr1Mo. Bimetallic samples (12Cr2Si/9Cr1Mo) were tested with SEM and EDS to verify their microstructures and compositions. As shown in Figs. 2 and 3, both cladding (12Cr2Si) and base (9Cr1Mo) structures show > 99% density and match with their corresponding compositions.

Electron backscatter diffraction (EBSD) analysis of two bimetallic samples were carried out on the cross section around the interface. The scan size is $200 \mu\text{m} \times 200 \mu\text{m}$. The scanned region appears to be compressed along the vertical direction due to the 70° tilted working condition of EBSD. For the sample of (12Cr2Si/9Cr1Mo), only body centered cubic (BCC) structure (alpha phase) is detected.

The base side has smaller grain size ($\sim 5 \mu\text{m}$) and the cladding side has larger grains ($\sim 100 \mu\text{m}$). A pole figure in Fig. 4 shows the distribution of a specific pole (grain orientation) in space. The color indicates the intensity of the pole in that direction. A very smooth phase transition is observed at the interface of the cladding (12Cr2Si) and the base (9Cr1Mo) in the region of about $100 \mu\text{m}$.

As a comparison, SS316L/SA508 bimetallic structure was also examined (Fig. 5). Both BCC and face centered cubic (FCC) structure (gamma phase) are detected. The BCC phase is found in the weave patterned side with small grains of size less than or equal to $1 \mu\text{m}$. The FCC phase is found in the back side where grain size is about $100 \mu\text{m}$. The difference in the bonding interface between 12Cr2Si/9Cr1Mo and SS316L/SA508 is mainly from Cr composition, where SA508 does not have any Cr. Since Cr has a tendency to promote grain growth in stainless steels [9, 10], this causes a sharp division between the two metals of SS316L/SA508.

Fig. 2 EDS test of the cladding section of a bimetallic sample 12Cr2Si/9Cr1Mo. The composition of 12Cr2Si steel are Cr 13.17 wt%, Si 2.19 wt%, Mn 0.55 wt%, C 3.34 wt%, Fe balanced

Fig. 3 EDS test of the base section of a bimetallic sample 12Cr2Si/9Cr1Mo. The composition of 9Cr1Mo steel are Cr 9.13 wt%, Mo 0.89 wt%, Si 0.56 wt%, Mn 0.74 wt%, C 3.10 wt%, Fe balanced

Fig. 4 EBSD test of phase structure around interface for a bimetallic sample 12Cr2Si/9Cr1Mo

Fig. 5 EBSD test of phase structure around interface for a bimetallic sample SS316L/SA508

To understand the corrosion resistance of selected materials, LBE test has been performed at 550 °C for 336 h (14 days) [3]. Figures 6, 7, 8, 9 gives the energy dispersive X-ray spectroscopy (EDS) experimental results for all four materials. Unlike SS316L, no zone of an excessive Pb/Bi attacking has been found in the cladding of 12Cr2Si steel as shown in Fig. 7. For the 9Cr1Mo steel, similarly to the 12Cr2Si

steel, it is formed a passive oxide scale up to 5 μm thick over the entire surface (Fig. 9), which consists mainly of iron and chromium oxides. No excessive Pb/Bi is observed in 9Cr1Mo steel region either. These indicate that both 12Cr2Si and 9Cr1Mo steels are good candidates against LBE corrosion, which agrees with other researchers [2].

Fig. 6 EDS line scans of the cladding material (SS316L) at the solid-liquid interface, after 336 h of exposure to LBE at 550 °C

Fig. 7 EDS line scans of the cladding material (12Cr-2Si) at the solid–liquid interface, after 336 h of exposure to LBE at 550 °C

Fig. 8 EDS line scans of the base material (SA508) at the solid–liquid interface, after 336 h of exposure to LBE at 550 °C

Fig. 9 EDS line scans of the base material (9Cr-1Mo) at the solid–liquid interface, after 336 h of exposure to LBE at 550 °C

4 Conclusion

Dissimilar metal structures were fabricated via a high-power fs fiber laser additive manufacturing. It shows that smooth phase transition, which is usually associated with excellent strength between dissimilar metals, is achieved with the AM process for graded compositions. Experimental results show that bimetallic structure between 12Cr2Si steel and 9Cr1Mo steel is better than that between SS316L and SA508 with abrupt transition in composition and LBE corrosion resistance. This provides a foundation to extend laser AM to a variety of industries.

Acknowledgements This paper is supported by Department of Energy (DOE) Small Business Innovation Program (SBIR) DE-SC0018602. Special thanks to Drs. Sue Lesica and Tansel Seleklir for their guidance and support.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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