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Effect of Cr_3C_2 content on 316L stainless steel fabricated by laser melting deposition

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ABSTRACT

316L stainless steels with different Cr_3C_2 contents were fabricated by laser melting deposition (LMD) to investigate the effect of Cr_3C_2 content on microstructure, microhardness and wear resistance. The microstructure, chemical composition, phase constituents and microhardness were determined by using SEM, EDS, XRD and microhardness tester, respectively. The wear mechanisms were investigated using a ball-on-disc machine under dry condition. As the Cr_3C_2 content of deposited sample increased from 5 to 25 wt%, the morphology of carbides transited from a network to a blocky shape. The laser melting deposited samples mainly consisted of γ-Fe, $Cr_{23}C_6$ and $(Cr,Fe)_7C_3$, while in the sample added with 25 wt % Cr_3C_2, the Cr_3C_2 phase was presented as the minor phase. The microhardness of samples increased obviously from 390 ± 23 HV to 488 ± 23 HV with the addition of Cr_3C_2, which was 2 times that of LMD 316L stainless steel sample (243 ± 20 HV). The wear resistance of three sample was significantly improved with the addition of Cr_3C_2 and the sample with 15 wt% Cr_3C_2 exhibited the highest wear resistance, which could be attributed to the fact that the in situ synthesized eutectic carbides network led to the fine γ-Fe which has a good combination of strength and toughness.

1. Introduction

Laser melting deposition (LMD) is an additive manufacturing (AM) technology that has grown rapidly, which has a wide application potential because it can product geometrically complex objects that cannot be produced by conventional methods and reduces the discard of materials. A wide range of metal alloys like titanium alloys, stainless steels, nickel-based superalloys, cobalt-based alloys are materials used for laser additive manufacturing [1–4]. The 316L stainless steel component, well-known for its superior ductility and excellent corrosion resistance, fabricated by LMD technology have been increasingly developed [5,6].

Kamath et al. [7] showed that it was possible to produce stainless steel parts with a density of more than 99% from SS 316L via control of laser power and scanning speed. The same as Fatemi et al. [8] studied the increasing frequency, current and decreasing scan speed led to fabrication of parts with higher density by direct metal laser sintering. Ma et al. [9] studied the influence of process parameters on the microstructure of 316L stainless steel fabricated by direct laser deposition, the results showed that a precision cuboid metal sample with a uniform surface can be obtained at a small laser scanning spot and a higher laser scanning velocity. Ziętala et al. [10] studied the microstructure and its influence on the microhardness and tensile strength of the 316L stainless steel fabricated using laser engineered net shaping (LENS). The result showed that the microhardness was a little higher than commercially available annealed 316L steel, and the values of YS and UTS for LENS manufactured SS316L were significantly higher than those of conventionally fabricated material. In addition, the microhardness of 316L stainless steel fabricated by LENS (237–307 HV) was higher than that of selective laser melting (213–220 HV) [11]. The 316L stainless steel fabricated by selective laser melting has been investigated by researchers [12,13]. Zhu et al. [14] indicated that the pores and refined grains in the selective laser melting processed 316L stainless steel affected the friction and wear differently. 316L stainless steel fabricated by electron beam melting is currently under development [15,16]. Due to the different solidification characteristics, mechanical properties of 316L stainless steel fabricated by different additive manufacturing technologies are

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different.

However, the low property of 316L stainless steel to resist wear resistance limits their application. Therefore, the improvement of wear performance has been investigated by researchers [17]. The TiB_2 and TiC as reinforcing particles to improve the hardness and wear resistance of 316L stainless steel, respectively [18,19]. The wear resistance of metal matrix composites with Cr_3C_2 as reinforcing particles on the surface of steels was investigated by many researchers [19–23]. It was found that Cr_3C_2 particles dissolved easily due to the extremely high temperature by means of laser cladding and laser surface alloying. The dissolved Cr_3C_2 particles could increase the content of chromium and carbon in the liquid matrix alloy. As a consequence, the compound M_7C_3 (M = Fe, Cr) could be formed during rapid solidification when the Cr/C equivalence ratio reached a certain value [24]. The $(Cr, Fe)_7C_3$ is well known for its excellent combination of high hardness and excellent wear resistance [25–28]. Chang et al. [29] investigated the Fe-Cr-C claddings with various carbon content and observed that the content and morphology of $(Cr, Fe)_7C_3$ carbide changed with the increasing carbon content, and the relationship between wear resistance and hardness was non-linear. While, laser melting deposition 316L stainless steel reinforced by $(Cr, Fe)_7C_3$ was not investigated. In this paper, $(Cr, Fe)_7C_3$ can be formed during rapid solidification by laser melting deposition 316L stainless steel and Cr_3C_2 powders. The morphology of carbides changed with the increasing Cr_3C_2 content, and the microhardness and wear resistance changed with the carbides changed. In addition, a changeable property can be adjusted by varying alloy compositions as the various component phases (ferrite, austenite, etc.) of Fe-based alloys maybe form. The current study aims at (a) fabricating composite material sample of 316L stainless steel and Cr_3C_2; (b) exploring phase and microstructure evolutions with the changed Cr_3C_2 proportion; (c) optimizing the Cr_3C_2 content with the best properties. Therefore, the microstructure, microhardness and wear resistance of the 316L stainless steel with additional different Cr_3C_2 proportion fabricated by laser melting deposition were analyzed and discussed.

2. Experimental procedure

The LMD specimens were fabricated using a Ytterbium Laser System equipped with a YLS-6000 fiber laser, a powder feeder with a coaxial deposition head, a computer numerical control multi-axis motion system and an argon purged processing chamber with an oxygen content less than 18 ppm was used during the LMD process. The substrate material used in the present work was 316L stainless steel in the form of plate having a dimension of 400 mm × 300 mm × 20 mm. Before the experiment, the substrate was ground with 600 SiC paper to remove surface oxides or contaminants. The 316L stainless steel (sample 1) alloy powder was supplied in the form of gas atomised particles with a particle size range of 100–270 mesh. The mixed alloy powders of 95% 316L+5% Cr_3C_2 (wt.%), 85% 316L + 15% Cr_3C_2 (wt.%) and 75% 316L + 25% Cr_3C_2 (wt.%) were sample 2, sample 3 and sample 4 used in the experiments. The chemical composition of the 316L alloy powders is listed in Table 1. Before LMD, the alloy powders were dried in a vacuum furnace at 80 °C for 8 h, and in order to reduce variability between built parts and enable the process to be more controllable, the alloy powders are thoroughly mixed with the aid of a ball milling equipment in an argon atmosphere for 4 h [30]. Within a range of optimization runs, the optimized process parameters were obtained as shown in Table 2, and the as-built sample was deposited for 20 layers for microstructural examinations, as shown in Fig. 1.

Table 1
Chemical composition of 316L stainless steel alloy powders (wt.%).

Elements	C	Cr	Si	Ni	Mn	Mo	Fe
Powder	≤0.03	17.89	0.61	13.1	≤0.49	2.49	Bal.

The deposited samples having a dimension of 30 mm × 20 mm × 12 mm, post-build analysis and test samples were sectioned by a wire electric discharge machining. All samples were polished with 100–2000 grit SiC grinding paper and mechanically polished by diamond polishing. The cross-sections of the deposited samples were prepared and etched with 30 mL HCl +10 mL HNO_3. The microstructure morphology and chemical compositions of the samples were investigated using a scanning electron microscope (SEM, S-3400 N) equipped with an energy-dispersive spectrometer (EDS). The phase constituents were identified by an X-ray diffraction (XRD, D/max2500Pc) at a scanning speed of 4° min^{-1}, ranging from 20° to 100° with Cu Kα radiation. Vickers microhardness measurements were performed using a HVS-1000 Vickers microhardness tester at a load of 2 N and a dwell time of 10 s. The vickers microhardness of four samples was measured in three sets of data at each region and repeated three times for each sample on three samples. The average value and standard deviation were obtained. The as-built samples were produced for friction and wear tests. The tests were carried out on a ball-on-disc machine (MMQ-02G, China) under dry condition at room temperature in air. The surfaces of samples were polished with 100–2000 grit SiC grinding paper and mechanically polished by diamond polishing. All the samples were ultrasonically cleaned in acetone and dried under the blowing air before and after testing to avoid the impact of the impurity on the surface. The Si_3N_4 ball with the diameter of 5 mm was selected as wear material in the test, with a stroke length of 7 mm, a load of 5 N, and the duration time of each test was 60 min with a sliding velocity of 120 mm/min. To evaluate the damage in the friction and wear tests, the typical profiles across the wear tracks and wear volume loss was evaluated by using surface profilometer (Micro XAM-3D). The microstructure morphologies and composition of the worn surface were examined by SEM and EDS.

3. Result and discussion

3.1. Microstructure and constituent phase

Fig. 2 shows the microstructure morphology of LMD stainless steel with addition of different Cr_3C_2 proportion and the typical dendrite (DR) and interdendrite (ID) structures can be observed. As seen from Fig. 2(a), the microstructure of sample 1 was homogeneous and dense without apparent pores, cracks or any other defects. The solidification in the alloying region began in columned form and then continued in dendritic form. Rapid solidification of the molten pool leading to the grain sizes were smaller than the grain of conventional castings. The grain growth was orientated and dendrites of stainless steel sample were bulky compared with

Table 2
Processing parameters of laser melting deposition.

Parameter	Values
Laser power (W)	1800–2000
Scanning velocity (mm/s)	7
Powder feeding rate (r/min)	0.8
Shielding gas flux (L/h)	400–550
Spot diameter (mm)	4
Scanning interval (mm)	2.3