Optics and Laser Technology 103 (2018) 8–16

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

Effect of laser remelting on microstructure and properties of WC reinforced Fe-based amorphous composite coatings by laser cladding

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ARTICLE INFO

Article history:
Received 6 November 2017
Received in revised form 5 December 2017
Accepted 5 January 2018

Keywords:
Amorphous composite
Laser cladding
Microstructure
Laser remelting
Corrosion

ABSTRACT

The WC reinforced Fe-based amorphous composite coatings were prepared by laser cladding with rectangular spot. The effect of laser remelting on the microstructure and properties of composite coatings was investigated. The results showed that laser remelting can reduce the cracks and porosities of the cladding coating and improve its surface quality. Large amounts of crystalline phases were precipitated at the top of the cladding and remelting coatings. However, the microstructure at the top of the remelting coating was finer compared to that at the top of the cladding coating. With increasing distance from the surface of substrate, the amorphous phase appeared within the remelting coating and large amounts of carbides rich in Fe and Mo, $Fe_{23}B_6$, γ-Fe and $Cr_{9.1}Si_{0.9}$ phases were also precipitated in the remelting coating. As a result, the corrosion resistance of the remelting coating was higher than that of the cladding coating. The microhardness of the remelting coating was approximately 1.13 times higher than that of the cladding coating.

1. Introduction

Amorphous alloys, also known as metallic glasses, are metastable products obtained by rapid cooling [1]. Since Kramer et al. [2] and Brenner et al. [3] prepared amorphous Sb film and Ni-P amorphous film by vapor deposition and electrodeposition, respectively, many researchers have begun to produce metallic glasses by different methods. For instance, Duwez et al. [4] prepared $Au_{70}Si_{30}$ amorphous alloy by liquid spray quenching in 1960. Chen et al. [5] used rapid continuous casting roller to prepare lots of amorphous ribbons which were formally named as “metallic glass”. In addition, mechanical alloying [6–8], melt spinning [9] and casting methods [10,11] were also widely used to prepare metallic glasses. However, there were few reports that amorphous alloys have be used as structural materials due to limits of the glass forming ability (GFA) and inherent brittleness. In order to solve this problem, Miura et al. [12] prepared a series of FeNiP(Si)B amorphous coatings by flame spraying in 1984. Subsequently, amorphous coatings were produced widely by surface modification techniques, such as plasma spraying [13,14], HVOF [15,16] and laser cladding [17–19]. These amorphous coatings exhibit many excellent properties, such as high hardness, high tensile strength, good wear and corrosion resistance and excellent magnetic properties [20–22].

Compared to the traditional thermal spraying techniques, laser cladding is characterized by high power density (10^4–10^6 W/cm^2), rapid cooling rate (10^4–10^6 K/s), and can produce dense coatings with low dilution and metallurgical bonding to substrate [23]. Therefore, it has become a prospective technique to prepare amorphous coatings with high properties. For example, Yoshioka et al. [24] prepared amorphous Ni-Cr-P-B coating on the surface of low carbon steel by laser cladding, the result showed that when the chemical composition including Cr in 14–17 at.%, P in 15–18 at.%, B in 2–5 at.%, B and P in 19–20 at.% was designed, a amorphous coating can be obtained successfully. Wu et al. [25] prepared Fe-based amorphous coating with a thickness of 1.2 mm by laser cladding, and found that the amorphous coating exhibited high microhardness and corrosion resistance. Li et al. [26] prepared Ni-Fe-B-Si-Nb amorphous coatings by laser cladding and found that amorphous phase did not form when the laser power was 1 kW. However, when the laser power was less than 1 kW (0.7–0.9 kW), amorphous phase appeared and resulted in an improvement in microhardness of coating.

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https://doi.org/10.1016/j.optlastec.2018.01.024
0030-3992/

In order to further improve the performance of amorphous coatings, the particle reinforced amorphous composite coatings prepared by plasma spraying, HVOF or laser cladding have received significant attention. For instance, Xu et al. [27] prepared stainless steel reinforced Fe-based amorphous composite coating by HVOF. The results indicated that the pitting of composite coating in 3.5% NaCl solution was attributed to the formation of oxide (Fe_3O_4) at the interfaces. Yoon et al. [28] prepared B_4C reinforced Fe-based amorphous composite coatings by plasma spraying, and found that the microhardness and wear resistance of the composite coatings were improved significantly. Yue et al. [29] prepared SiC reinforced Zr-based amorphous composite coatings by laser cladding. The results showed that SiC addition could enhance the microhardness and wear resistance, but the corrosion resistance of amorphous composite coatings was reduced. In addition, laser remelting was considered as an effective method to improve the surface quality and properties of cladding coating. It has been extensively adopted to prepare the amorphous coatings with dense structure and excellent properties [30–33]. However, to the authors' knowledge, the research of combining laser cladding with laser remelting to prepare WC reinforced amorphous composite coatings is rarely reported. In this paper, the combination of laser cladding and laser remelting is used to prepare WC reinforced Fe-based amorphous composite coatings, and the emphasis is to comparatively investigate the microstructure and corrosion resistance of composite coatings.

2. Experimental procedures

2.1. Materials

In this experiment, 45 steel (0.45 wt.% C) with dimensions of 60 × 40 × 10 mm^3 was used as the substrate and its chemical composition was listed in Table 1. The mixture of Fe-based amorphous powder with a size of 15–50 μm and WC particles with a size of 15–25 μm at a mass ratio of 9:1 was used as the cladding material. The chemical composition of the Fe-based amorphous powder was listed in Table 2 and its X-ray diffraction (XRD) pattern was shown in Fig. 1.

2.2. Laser cladding and laser remelting

Before laser cladding, the cladding material was pre-placed on the substrate to form a powder bed with a thickness of ~1.2 mm and a width of ~14 mm. The experiment of laser cladding and laser remelting was carried out using a 8 kW semiconductor laser with a wavelength of 980 nm. The processing parameters of laser cladding and laser remelting were listed in Table 3.

2.3. Microstructure and properties

The geometrical profiles of the composite coatings were analyzed by optical microscopy (OM). Phase constituents were analyzed by D/MAX-2500 X-ray diffraction (XRD, target: Cu, 40 kV, 40 mA). Microstructure was characterized by ZEISS Sigma 300 field emission scanning electron microscopy (SEM) equipped with energy dispersive spectrometer (EDS).

Electrochemical measurements were carried out in 3.5 NaCl solution with an electrochemical workstation (CHI 660C, Shanghai, China). The device with a conventional three-electrode cell, which was composed of a working electrode (WE) made from the coating specimen with an exposed area of 0.58 cm^2, a platinum counter electrode (CE), and a saturated calomel reference electrode (SCE) as reference electrode connected to a Luggin capillary bridge. The potentiodynamic polarization curves were recorded at a sweeping rate of 20 mV min^{-1}, starting from the moment when the open circuit potential (OCP) reached its steady state after immersing the specimen in the electrolyte for about 1 h. Meanwhile, electrochemical impedance spectroscopy (EIS) was performed at OCP potentiostatically at a frequency range from 10^{-2}–10^5 Hz. The equivalent circuits and corresponding Nyquist as well as Bode plots were fitted by impedance spectrum data using Zsimpwin software. All potentials mentioned in this work were measured with respect to saturated calomel electrode (SCE). Microhardness was measured by HV-1000 microhardness tester with a load of 0.98 N and a dwelling time of 15 s.

3. Results and discussion

3.1. Macro-profile of coatings

Fig. 2 shows the geometrical morphology of WC reinforced Fe-based amorphous composite coatings before and after laser remelting. The cracks, pores and wavy appearance caused by convection in the molten pool can be seen on the surface of the cladding coating (Fig. 2a). Moreover, some spherical non-melted particles are observed on the surface and both sides of the cladding coating. Obviously, the surface quality of the cladding coating is not well. After laser remelting, the surface of the cladding coating becomes smooth and no cracks and pores are observed (Fig. 2b). Moreover, the width is reduced by 10.03% but the height is increased by 8.25% compared to the cladding coating with a width of 13.36 mm and a height of 0.97 mm (Fig. 2c). This is because the cladding coating is remelted to a liquid melt that is more prone to shrink due to minimization surface energy. Compared to laser cladding, the increasing of laser scanning speed during laser remelting can reduce the temperature of the melt and therefore increase its viscosity and surface tension, leading to an increase in cladding height. In addition, the non-melted particles on the surface and both sides of the cladding coating are also beneficial to an increase in cladding height after laser remelting.

3.2. Microstructure of coatings

Fig. 3 shows the XRD patterns at the top of the cladding and remelting coatings. The phase constituents of the cladding coating are composed of $M_{23}C_6$ (M = Fe, Cr) with a cubic structure, Fe_2B with a tetragonal structure and Fe_3Mo with a rhombohedral structure. Some scattering peaks appear at $2\theta = 44°$ and 95°, indicating the presence of amorphous phase. After laser remelting, there are still $M_{23}C_6$ carbides in the coating, but Fe_2B and Fe_3Mo phases are melted to form the orthogonal FeB and cubic $Fe_{9.7}Mo_{0.3}$ phases. Meanwhile, large amounts of γ-Fe(Cr) and $Cr_{9.1}Si_{0.9}$ are formed and no evidently scattering peaks are observed at the top of the remelting coating, showing that some crystalline phases are remelted to form new phases after rapid solidification.

Fig. 4 shows the XRD patterns at the center of the cladding and remelting coatings. Obviously, compared to those at the top of the cladding and remelting coatings, the relative intensities of crystalline peaks are decreased and the wider diffraction peaks appear at $2\theta = 44°$, 75°, 90° and 115° before and after laser remelting, indicating that the more amorphous phase appears at the center of the cladding and remelting coatings. Generally, the cooling rate decreased with increasing distance from the bottom of molten pool during laser cladding [23]. Therefore, the cooling rate at the center of the molten pool is readily to reach the critical cooling rate for the formation of amorphous phase so that the crystalline nucleation and growth are able to be suppressed, compared to that at the top of the molten pool. As a result, the diffraction peaks of amorphous phase at the center of the coatings are wider than those at