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Microstructure and tribological properties of iron-based metallic glass coatings prepared by atmospheric plasma spraying

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ABSTRACT

Iron-based metallic glass coatings (denoted as FeWCrNiMoBSiC) were prepared on 1Cr18Ni9Ti stainless steel cylinders by atmospheric plasma spraying at different parameters. The morphology, microstructure, and crystalline structure of as-prepared Fe-based metallic glass coatings were analyzed by scanning electron microscopy, transmission electron microscopy, and X-ray diffraction. A Pycnometer and a Vickers hardness tester were adopted to measure the porosity and microhardness of iron-based metallic glass coatings. Moreover, differential scanning calorimetry analysis was conducted to investigate the crystallization behavior of various iron-based metallic glass coatings, and a ball-on-disk tribometer was performed to evaluate the tribological properties of the coatings coupled with silicon nitride ceramic balls under unlubricated conditions. It has been found that the microhardness of iron-based metallic glass coatings increases with increasing plasma arc power, which is related to the degree of melting of feedstock powders and the compactness of as-prepared coatings. Besides, the phase compositions of as-sprayed coatings consist of amorphous structure and limited crystalline structure, and the contents of the amorphous structure and crystalline structure vary with plasma arc power. Moreover, iron-based metallic glass coatings deposited at different plasma arc powers show similar steady-state friction coefficients (0.8–0.9), but their wear rate varies with varying plasma arc power. Particularly, iron-based metallic glass coating with next to the highest hardness exhibits the best anti-wear ability, which is the outcome of the compromise between the hardness and brittle fracture as well as abrasive wear of the coatings during sliding process.

1. Introduction

Amorphous alloy, a kind of materials without characteristics of long-range ordered crystal, possesses many excellent properties such as high hardness, superior corrosion resistance, and good tribological properties thanks to no dislocation and grain boundary in them [1–7]. To date, several methods including melt spinning [8], high-pressure die casting [9], water quenching [10] and suction casting [11] are available for preparing amorphous metals. However, these methods are only suitable for fabricating amorphous alloys with a thickness of centimeter scale, which largely restricts their wide application. This drawback, fortunately, could be eliminated by making use of thermal spraying method, since thermal spraying has a rapid quenching rate of molten particles (around 105–107 K s^{-1}) and is suitable for preparing amorphous coatings on the surfaces of numerous components with different shapes [12,13].

Among various amorphous metals, Fe-based bulk metallic glasses (BMGs) are perhaps the most important antiwear materials, due to the combination of rather low material cost, ultrahigh hardness and strength, and outstanding corrosion-resistance [14–19]. In the field of tribology, Fe-based BMGs are of particular significance, since they can be introduced onto the surface of various mechanical components so as to reduce friction and wear and alleviate deteriorations caused by progressive and undesirable loss or degradation of surface materials. To name a few, Kishitake and co-workers claimed that plasma-sprayed amorphous Fe–10Cr–13P–7C alloy coatings exhibit high hardness and excellent corrosion resistance [20]. Cherigui et al. reported that Fe_3Si and FeNb

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Table 1
Atmospheric plasma spraying parameters for depositing iron-based metallic glass coatings on stainless steel cylinders.

Coatings	Plasma spray parameters								
	Current (A)	Voltage (V)	Power (kW)	Argon flow rate (L/min)	Hydrogen flow rate (L/min)	Powder feed rate (g/min)	Spray distance (mm)	Gun speed (mm/s)	Injector angle (°)
Coating 1	500	50	25	60	11	40	100	800	90
Coating 2	500	60	30	60	16	40	100	800	90
Coating 3	500	70	35	60	22	40	100	800	90
Coating 4	500	80	40	60	30	40	100	800	90

metallic glass coatings deposited by high velocity oxy-fuel spraying (HVOF) and atmospheric plasma spraying (APS) exhibit good magnetic properties [21,22]. Chokethawai and co-workers prepared highly amorphous HVOF coatings from partial amorphous FeCrMoWBCSi powders; and they found that the content of amorphous phases in as-sprayed coating is as much as 50% (mass fraction, the same hereafter), much higher than the amorphous phase content in sprayed powders (18%) [23]. More importantly, the above-mentioned iron-based metallic glass coatings deposited by thermal spraying technology can be well used to ameliorate wear resistance of substrate materials [24,25]. In addition, APS is an effective and widely recognized technique for preparing metallic glass coatings with high quality [26], together with it is more convenient and economical than other thermal spray technologies (such as HVOF, low pressure plasma spraying (LPPS) [27] and vacuum plasma spraying (VPS)), and thus investigating the properties of Fe-based metallic glass coatings prepared by APS has important scientific significance and engineering value.

Bearing those perspectives in mind, APS technique was employed in the present research to prepare Fe-based metallic glass coatings on cast 1Cr18Ni9Ti stainless steel substrate with the amorphous powder of FeWCrNiMoBSiC as the feedstock powder; owing to the spraying parameters strongly affect the structure, phase composition and other properties of APS-spraying coatings [28–30], the influence of spraying parameters on the microstructure and amorphous content as well as tribological properties of as-sprayed Fe-based metallic glass coatings was also investigated. This paper reports the relationship among the spraying parameters and the microstructure, phase composition and tribological properties of as-prepared Fe-based metallic glass coatings. Meanwhile, the structure of as-sprayed coating is compared with iron-based metallic glass coating that was deposited by LPPS in our previous researches [12].

2. Experimental procedure

2.1. Feedstock powders

Commercially available Fe-based amorphous powders (FeWCrNiMoBSiC) provided by Beijing Sangyao Technology development Co., Ltd. (China) with a size of about 5∼50 μm were prepared by alloy water atomization. The composition of the feedstock powders is Fe–10W–4Cr–3Ni–2Mo–4B–4Si–1C by mass ratio.

2.2. Preparation of coatings

An atmospheric plasma spraying system equipped with a PQ-1S plasma torch (Beijing Institute of Aeronautical Manufacturing Technology; Beijing, China) manipulated with an IRB 2400/16 robot (ABB, Switzerland) was employed to spray the feedstock powders onto 1Cr18Ni9Ti stainless steel cylinders (dimensions: 24 mm in diameter and 8 mm in height) to form iron-based metallic glass coatings with a thickness of about 180–220 μm (measured with a digital micrometer at a resolution of 1 μm). Ultra pure argon (purity, 99.9999%) was used as the primary gas, and highly pure hydrogen (purity, 99.999%) was adopted as the secondary gas. The plasma arc powers were adjusted properly so as to obtain desired FeWCrNiMoBSiC metallic glass coatings under different spraying parameters. The details about the sets of spraying parameters are presented in Table 1. For convenience, coatings prepared under different plasma spraying conditions are denoted as coating 1, coating 2, coating 3 and coating 4, respectively. During the plasma spraying process, no accelerated cooling of the coating and steel substrate was conducted, which helps to eliminate the effect of accelerated cooling on formation of amorphous phase from molten feedstock powders.

2.3. Characterization of feedstock powders and coatings

The morphology of feedstock powders and as-sprayed iron-based metallic glass coatings was analyzed with a JSM-5600LV scanning electron microscope (SEM; JEOL, Japan), with which secondary and backscattered electron images were recorded at a voltage of 20 kV.

The porosity of the iron-based coatings was measured based on that the true volume of one material with some pores is smaller than its geometric volume, and the ratio of the difference between them to the geometric volume is the porosity of this material. Therefore, the porosity of the iron-based coatings could be calculated as $P = (1 - V_c^T/V_c) \times 100\% = (1 - V_{s,c}^T - V_s/V_{s,c} - V_s) \times 100\%$, where V_s was the geometric volume of stainless steel substrate, $V_{s,c}$ was the geometric volume of the substrate coated with the iron-based coating, V_c was the geometric volume of the iron-based coating and equal to $(V_{s,c} - V_s)$; $V_{s,c}^T$ was the true volume of the substrate coated with the iron-based coating, and V_c^T was the true volume of the iron-based coating and equal to $(V_{s,c}^T - V_s)$. V_s and $V_{s,c}$ in this paper was $12^2\pi \times 8\ mm^3$ and $12^2\pi \times 8.2\ mm^3$, respectively. The $V_{s,c}^T$ was determined with Micromeritics AccuPyc 1330 Pycnometer (Micrometerics Instrument Corporation, Norcross, GA, USA) in high purity helium (99.999%). The Micromeritics AccuPyc 1330 Pycnometer is a fast, non destructive, fully automatic true volume analyzer that provides high-precision volume. This pycnometer is a device that determines the porosity of samples by actually measuring their true volume very precisely. The AccuPyc works by measuring the amount of displaced gas (helium). The pressures observed upon filling the sample chamber and then discharging it into a second empty chamber allow computation of the sample solid phase volume. Gas molecules rapidly fill the tiniest pores of the sample; only the truly solid phase of the sample displaces the gas [31–33].

A JEM2010 transmission electron microscope (TEM; JEOL, Japan) was used to analyze the microstructure of as-sprayed iron-based metallic glass coatings. The phase composition of the starting powders and as-sprayed coatings was analyzed with a D/Max-2400 X-ray diffractometer (XRD, Rigaku, Japan; Cu-Kα radiation, potential 40 kV, current 100 mA), with which the diffraction data were collected at a step size of 0.02° in the range of $10° \leq 2\theta \leq 90°$.