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On the microstructure and wear resistance of Fe-based composite coatings processed by plasma cladding with B_4C injection

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Abstract

Fe-based composite coatings were fabricated on Q235 steel substrate by plasma cladding. B_4C particles were injected at the center and edge of the melting pool as strengthening phase. Scanning electron microscopy and pin-on-disc tribometer were applied to study the microstructure and wear resistance of the coatings. The results showed that the central injected B_4C particles dissolved during plasma cladding and cementite generated. Edge injected B_4C particles remained and performed metallurgical bonding with the metal matrix. With Fe-based coating containing edge injected B_4C particles, wear resistance increased largely and the wear rate became 1/8 of the Q235 substrate. Afterwards, Fe-based coatings with edge injected B_4C particles were prepared on real pieces of 50 picks and 12 chutes, which were taken into field probations. Average service lives of the coated picks and chutes increased 3.4 times and 5.6 times, respectively, compared with the conventional 16Mn and 42CrMo pick and chute components.

Keywords: A. Injection molding; B. Surfaces; C. Wear resistance; D. Carbides

1. Introduction

Abrasive wear is the predominant failure form of the components used in mining industry [1]. The severe abrasion always bothers the machinery manufacturer and the maintenance workshop, so that people are eager to find some methods to relieve this problem. While it is quite impractical and costly to completely manufacture large components with wear-resistant materials. Prefabricating a wear-resistant coating layer onto conventional materials becomes one reasonable way.

Plasma cladding, which possesses unique advantages, is one of the most popular surface treatment techniques for surface repairing and enhancement. Compared with the spraying and chemical treatment, plasma cladding may obtain a strong metallurgical bonding between the coating and substrate and deposit a very thick coating [2,3]. Meanwhile, plasma cladding defeats the laser cladding in industrial application because of lower cost and higher efficiency [4]. Therefore, plasma cladding technique becomes one attractive research field that is used to produce several kinds of metal matrix coatings [5–7]. The most important characteristic of plasma cladding is that the raw materials are added in powder form, allowing hard ceramic particles to mix into the coating. These composite coatings can largely improve the properties and offer the substrate high resistance to wear and corrosion [8,9] because of the interaction between the matrix and precipitated particles [10–12]. Among the plenty kinds of ceramic particles, B_4C occupies the third hardest substance in nature (only softer than diamond and cubic boron nitride [13,14]). Paiseworthily, uncomplicated productive process and low cost of B_4C powder make it especially suitable for posing as the strengthening particles in metal matrix coatings [15].

In a recent research project, Fe-based coatings containing B_4C particles were desired to deposit onto pick and chute

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components used in mining industry. Fe-based coating was chosen instead of other metals (e.g. Ni and Co) due to its lower cost and higher bonding with the steel components [16,17]. Plasma cladding technique was employed for fabricating the coatings on conventional carbon steel Q235. Considering the extremely high temperature of the plasma beam (higher than the melting point of B_4C), B_4C powder was separately injected into the melting pool for avoiding dissolution referred to literatures [18,19]. In the lab scale experiments, the microstructure and wear resistance of the coatings obtained from two different B_4C injection areas, i.e. the center and the edge of the melting pool, were studied through scanning electron microscopy (SEM) and pin-on-disc tribometer. Finally, full scale Fe-based coatings with B_4C injection were generated on real pieces of picks and chutes for evaluating their service lives.

2. Experimental setup

Commercial low carbon steel Q235 was manufactured into 200 mm × 100 mm × 15 mm rectangular plates and used as the substrate. All of the steel substrates were grinded and cleaned in acetone before plasma cladding. Fe90 Self-fluxing alloy powder in size range of 46–160 μm was used as the plasma cladding material. Chemical compositions of Q235 steel and Fe90 self-fluxing alloy powder are presented in Table 1. The injection powder was B_4C in size range of 50–180 μm. Morphologies of Fe90 and B_4C powders are shown in Fig. 1. Most of the Fe90 powders are spherical while B_4C powders are cubic. Plasma cladding was conducted using the IGA-500 plasma cladding equipment manufactured by *Henan Igood Wear-Resisting Technology Co., Ltd.* and a separate injection powder feed nozzle. Schematic of the cladding equipment is shown in Fig. 2. Before standard experimental tests, a large number of pre-tests have been conducted for optimizing the plasma cladding parameters and B_4C contents around the properties of the cladded coatings, i.e. surface finishment, thickness of the coating and crack tendency. The optimal content of B_4C is confirmed as 18 wt% and the plasma cladding parameters are listed in Table 2. Plasma cladding was performed with two injection areas, i.e. center of the melting pool and edge of the melting pool (2–4 mm from the center) with above parameters.

Samples for cross-section observation, microstructure observation and wear tests were cut from the plasma cladded specimens. Cross-sections and microstructure of the coatings were observed with Philips-quanta-2000 SEM equipped with an energy-dispersive X-ray spectroscopy (EDS). Wear tests were conducted with a ML-100 pin-on-disc tribometer in ambient environment (i.e. temperature 20 ± 2 °C and relative humidity 40 ± 5%). Three kinds of steel were involved into the wear tests as references: Q235 (substrate steel), 16Mn (steel for manufacturing commercial picks) and 42CrMo (steel for manufacturing commercial chutes). Table 1 presents the chemical compositions of 16Mn and 42CrMo steels. Samples for wear tests were manufactured into Φ 5 mm × 10 mm cylinders (roughness of the testing surface R_a = 0.5 μm) and ultrasonically cleaned with acetone before testing. $100^{\#}$ alumina abrasive paper was used as the oppositional material, which were changed into a new one after each test trial. The normal load was 20 N and the linear speed was set to 0.1 m/s. Each test trial lasted for 30 min, giving a sliding distance for 180 m. Note that for the coating samples, the coatings still fully covered the steel substrates after wear tests, indicating that the tests honestly presented the wear performance of the coatings. AB204-N analytical balance with accuracy of 0.1 mg was applied to measure the wear loss after each test trial and wear rate was accordingly determined. Each test condition and reference contained three test trials and the final wear rate was in the form of mean value coupled with standard deviation.

Table 1
Chemical compositions of Q235 substrate and Fe90 alloy powder (wt%).

Materials	C	Si	Mn	Cr	Mo	B	Ni	Cu	Fe
Q235	0.18	0.29	0.50	–	–	–	–	–	Bal.
Fe90	0.16	0.8	0.05	12.5	0.5	1.0	–	–	Bal.
16Mn	0.16	0.4	1.4	0.3	–	–	0.3	0.25	Bal.
42CrMo	0.42	0.27	0.65	1.05	0.2	–	–	–	Bal.

3. Results and discussion

3.1. Microstructure

Microstructure of the cladded coatings with the injection at the edge and center of the melting pool is shown in Fig. 3. Typical microstructure of composite coatings which consists of precipitated phases in metal matrix [20] can be observed on both edge injected and center injected samples. It should be noted that the metal matrix shown in Figs. 3a and b may be the same while the morphologies of the precipitated phases are totally different from each other. Blunt and gray particles in large size (more than 50 μm) distributed homogenously in the cladded coatings with edge injection (Fig. 3a). Differently, large amount of sharp precipitates (size ranges from 20 to 40 μm) in bright white color occupied the cladded coatings with central injection.

With the help of corresponding EDS analysis, the bulk particles shown in Fig. 3a can be confirmed to be B_4C due to the predominant concentration of B and C elements. The B_4C particles were not observed in the samples with central injection. The sharp precipitates shown in Fig. 3b contain large amount of Fe element, demonstrating the generation of new phase during plasma cladding. It is reported that the center of the melting pool may reach 2600 °C during plasma cladding [21], which would melt the B_4C particles and generate new phase during solidification. Normally in such a C-rich and Fe-rich system, a rapid solidification will result in different forms of cementite [10]. M_3C, M_7C_3 and $M_{23}C_6$ (M = Cr and Fe etc. and C = B and C) are the most common forms of cementite in Fe-based materials. Among them, M_3C usually distributes along grain boundary and shows net-shape, which is dissimilar with the ones shown in Fig. 3b. M_7C_3 and $M_{23}C_6$ usually exist in strip-shape or rod-shape and are therefore suspected to be the precipitates in Fig. 3b. The precipitated cementite can