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Synergistic effect of ultrasonic cavitation erosion and corrosion of WC–CoCr and FeCrSiBMn coatings prepared by HVOF spraying

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ABSTRACT

The high-velocity oxygen-fuel (HVOF) spraying process was used to fabricate conventional WC–10Co–4Cr coatings and FeCrSiBMn amorphous/nanocrystalline coatings. The synergistic effect of cavitation erosion and corrosion of both coatings was investigated. The results showed that the WC–10Co–4Cr coating had better cavitation erosion–corrosion resistance than the FeCrSiBMn coating in 3.5 wt.% NaCl solution. After eroded for 30 h, the volume loss rate of the WC–10Co–4Cr coating was about 2/5 that of the FeCrSiBMn coating. In the total cumulative volume loss rate under cavitation erosion–corrosion condition, the pure cavitation erosion played a key role for both coatings, and the total contribution of pure corrosion and erosion-induced corrosion of the WC–10Co–4Cr coating was larger than that of the FeCrSiBMn coating. Mechanical effect was the main factor for cavitation erosion–corrosion behavior of both coatings.

1. Introduction

Cavitation erosion–corrosion is a common mode of material degradation in hydrodynamic systems, which causes reductions in operational efficiency of flow-handling components operated in seawater environment. It is well known that cavitation erosion–corrosion is related to two main effects of mechanical damage and electrochemical corrosion. The synergies or interactions of both effects play important roles in contributing to stress concentration, plastic deformation, crack initiation, crack growth and material deterioration [1–5]. To solve this problem, great attentions have been paid to the selection of appropriate surface treatment techniques, such as cathodic arc plasma ion plating, laser surface melting, laser surface alloying, plasma enhanced magnetron sputtering, electroless plating, atmospheric pressure plasma spraying, and high-velocity oxygen-fuel (HVOF) spraying [6–13]. Among these techniques, HVOF spraying has attracted much attention in recent years due to its advantages of high flame velocity, low flame temperature and dwell time, with which a dense coating with superior bond strength, high hardness, less decarburization, low porosity and oxide content could be prepared [14,15].

WC-based cermet coatings and Fe-based amorphous/nanocrystalline coatings prepared by HVOF spraying have been widely adopted by hydraulic machinery and coastal installations to enhance the cavitation erosion and corrosion resistance of their mechanical components. Many attempts have been made to investigate the cavitation erosion and corrosion resistance of HVOF sprayed WC-based cermet coatings and Fe-based amorphous/nanocrystalline coatings. Ding et al. [16] prepared conventional, submicron and multimodal WC–12Co cermet coatings by HVOF spraying and the multimodal coating exhibited the best cavitation erosion resistance among three coatings due to its dense nanostructure, high microhardness and strong cohesive strength. Similar results were also reported in other studies [17,18]. Cavitation erosion resistance for HVOF sprayed FeCrSiBMn amorphous/nanocrystalline coating in distilled water can be 7 times higher than that of ZG06Cr13Ni5Mo martensite stainless steel [19]. Zheng et al. [20] demonstrated that heat treatment on HVOF sprayed Fe-based amorphous coatings could lead significant change of their cavitation erosion resistance. Some publications pointed out that HVOF sprayed WC-based cermet coatings seem to be an alternative to hard chromium coating [21–23]. Our former study also showed that HVOF sprayed FeCrSiBMn amorphous/nanocrystalline coating has superior corrosion resistance to the hard chromium coating in

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3.5 wt.% NaCl solution [24]. Wang et al. [25] reported that HVOF sprayed FeCrMoMnWBCSi amorphous coatings with a wide passive region exhibit much higher ability to withstand pitting corrosion than that of the 304 stainless steel. Furthermore, the structural changes and the spray parameters in HVOF spray process affected significantly the corrosion resistance of WC-based cermet coatings and Fe-based amorphous/nanocrystalline coatings [26–29]. In earlier studies, we demonstrated that cavitation erosion mainly accelerates the cathodic reaction process of HVOF sprayed near-nanostructured WC–10Co–4Cr coating [30]. However, no any detailed description of the synergistic effect of cavitation erosion and corrosion of HVOF sprayed WC-based cermet and Fe-based amorphous/nanocrystalline coating was given. Therefore, in the present research we focus on the cavitation erosion–corrosion behavior, especially the contributions of pure mechanical erosion, pure electrochemical corrosion, and the synergism between cavitation erosion and corrosion to the overall cavitation erosion–corrosion of HVOF sprayed coatings in 3.5 wt.% NaCl solution.

Previously, the present authors investigated the effect of spray parameters on the microstructure and corrosion behavior of HVOF sprayed conventional WC–10Co–4Cr coatings, and obtained the optimal spray parameter [29]. WC–10Co–4Cr coatings and FeCrSiBMn amorphous/nanocrystalline coatings were both synthesized successfully by HVOF spraying process and their microstructures, corrosion and cavitation erosion behavior were reported [19,24,31,32]. This work is an extension of the reported research. The aim of this study was to assess the relative importance of cavitation erosion, corrosion and the synergism between them in the overall cavitation erosion–corrosion damage of HVOF sprayed conventional WC–10Co–4Cr coatings and FeCrSiBMn amorphous/nanocrystalline coatings in 3.5 wt.% NaCl solution.

2. Experimental procedure

Commercially available WC–CoCr and FeCrSiBMn powders with the particle size of 15–45 μm were used in the present study and their nominal compositions were 4 wt.% Cr-10 wt.% Co-5.3 wt.% C-80.7 wt.% W and 44.7 wt.% Cr-1.98 wt.% Si-2.97 wt.% B-0.08 wt.% Mn-50.27 wt.% Fe, respectively. These powders were deposited on the 1Cr18Ni9Ti stainless steel substrate by using commercial HVOF thermal spray system (Praxair Tafa-JP8000, USA). Details of HVOF spraying process parameters were given in Table 1. The substrate samples were cooled with compressed air jets during and after spraying. Prior to coating deposition, the substrate samples were pre-cleaned in acetone, dried in hot air, and then grit blasted with 30 mesh Al_2O_3 to provide a fresh and rough surface for better adhesion.

The cavitation erosion–corrosion experiments were carried out using a magnetostrictive-driven cavitation facility with electrochemical test system, according to the ASTM G32-10 standard [33]. A detail description of the cavitation erosion–corrosion test apparatus and its screw specimen's dimension was shown in Fig. 1. Prior to the cavitation erosion–corrosion tests, the specimens were ground and polished to mirror finish with an average surface roughness Ra = 0.02 μm, cleaned with acetone in an ultrasonic bath, and dried in hot air. Then, the specimen used to transfer the energy of ultrasonic cavitation was attached to the free end of the horn. The specimens used to assess the relative importance of cavitation erosion, corrosion and the synergism between them in the overall cavitation erosion–corrosion damage were placed co-axially with the horn and were held quiescent at a distance of 0.5 mm from the horn tip.

Table 1
Process parameters employed for HVOF spraying process.

Spray parameters	Coating	
	WC–10Co–4Cr	FeCrSiBMn
Oxygen flow rate (L min^{-1})	897	869
Kerosene flow rate (L min^{-1})	0.38	0.47
Carrier gas flow rate (L min^{-1})	10.86	10.86
Spray distance (mm)	300	330
Powder feed rate (g min^{-1})	50	55
Spray gun speed (mm s^{-1})	280	280

In the testing process, distilled water and 3.5 wt.% NaCl solution were used as the test liquid, respectively. The horn was immersed at a depth of 15 mm in the test liquid held in a 1000 mL beaker and the system kept in a resonant condition by controlling the output power of the ultrasonic generator. The vibratory frequency and double vibratory amplitude were 19 ± 1 kHz and 60 ± 5 μm, respectively. The beaker was surrounded by the flowing cooling water to keep the test liquid inside it at 25–30 °C. The specimen was degreased, rinsed, dried and weighed periodically by an analytical balance with an accuracy of 0.1 mg to determine mass loss. Mass loss was converted to volume loss after the density of the tested specimen was considered. The densities adopted for the WC–10Co–4Cr coating and the FeCrSiBMn coating were 12500 kg m^{-3} [34] and 7850 kg m^{-3} [35], respectively. The eroded surfaces of the coatings were observed by scanning electron microscope (SEM, Hitachi S-3400N, Japan).

EG & G Princeton Applied Research Potentiostat/Galvanostat Model 263 A & 5210 lock-in-amplifier with software M398 was applied to collect electrochemical data under static and cavitating conditions. A three-electrode electrochemical cell composed of a specimen as working electrode, a saturated calomel electrode (SCE) as reference electrode and a platinum wire as counter electrode was used. After cavitation for 15 min, potentiodynamic polarization curves were swept from −250 mV relative to corrosion potential at a fixed rate of 1 mV s^{-1}. The corrosion current density (i_{corr}) and corrosion potential (E_{corr}) were obtained as the intersection point of linear fits to the anodic and cathodic polarization curves, according to the Tafel extrapolation technique. Each test was repeated at least thrice to make sure a good repeatability of the experiment result.

3. Results and discussion

3.1. Cumulative volume loss rates of the coatings

Fig. 2 shows the relationship between cumulative volume loss rate and cavitation erosion time for the WC–10Co–4Cr coating and the FeCrSiBMn coating in distilled water and 3.5 wt.% NaCl solution. Initially, the volume loss rate of the coatings increased rapidly until reaching a peak value. Then a gradual decrease was followed to a steady-state value. After eroded for 30 h, the volume loss rates of the WC–10Co–4Cr coating in distilled water and 3.5 wt.% NaCl solution were 0.00744 and 0.00984 mm^3 h^{-1} respectively, whereas the volume loss rates of the FeCrSiBMn coating in distilled water and 3.5 wt.% NaCl solution were 0.0217 and 0.0243 mm^3 h^{-1} respectively. This indicated that corrosion would accelerate the cavitation erosion damage of the coatings. Moreover, the WC–10Co–4Cr coating exhibited a superior cavitation erosion–corrosion resistance compared to the FeCrSiBMn coating. Firstly, this could be explained that there were more inclusions at the interface between the FeCrSiBMn coating and the substrate (Fig. 1(a) in [24]) than that in the WC–10Co–4Cr coating (Fig. 2(c) in [32]). Secondly, the porosities of both coatings were less than 1%, whereas the hardness of the WC–10Co–4Cr coating (1423 $Hv_{0.1}$) was much higher than that of the FeCrSiBMn coating (1082 $Hv_{0.1}$) since the hardness had a great influence on the cavi-