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Cavitation erosion of several oxy-fuel sprayed coatings tested in deionized water and artificial seawater

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ABSTRACT

Cavitation damage is a concern for stainless steel and other metals in seawater environments, and new coatings are needed to resist such surface damage in that kind of environment. Consequently, a NiCr alloy coating, a WC–17Co/NiCr composite coating, a Fe-based metallic glass coating, a WC–$(W,Cr)_2C$–Ni cermet coating, and a WC–17Co cermet coating were prepared on metal alloy substrates using high velocity oxy-fuel spraying (HVOF). The microstructure and phase composition of as-sprayed coatings and substrates were analyzed using optical microscopy and X-ray diffraction. Vicker's microindentation hardness was measured as well. The cavitation erosion behavior of the five kinds of HVOF-sprayed coatings and three kinds of alloys (316 stainless steel, TC4 titanium alloy and ZL101 aluminum alloy) in both deionized water and artificial seawater was evaluated according to ASTM standard method G 32-10. The corrosion behavior of the alloys and HVOF-sprayed coatings in artificial seawater was evaluated by potentiodynamic polarization tests to reveal the correlation between corrosion and cavitation behavior. Based on the test results, an analysis of the microstructural damage processes, and the cavitation–corrosion synergism of the coatings, the WC–17Co cermet coating was found to be the most promising coating to prevent metallic substrates from cavitation damage in seawater.

1. Introduction

Cavitation is defined as the formation and subsequent collapse within a liquid of cavities or bubbles that contain vapor or mixture of vapor and gas [1], and it usually arises as a result of strong pressure fluctuations produced by motion of the liquid or of the solid boundary. As the pressure suddenly falls below the vapor pressure, the tensile stress imposed on the liquid produces cavities, because of the massive small solid and gaseous cavitation nuclei generally present in a real liquid [2–6]. These cavities or bubbles then collapse violently when they are submitted to a higher pressure. Micro-jets or shock waves with a high speed of up to 500–600 m/s and a high pressure of up to several GPa generated by the implosion of bubbles on a solid surface cause fatigue, fracture and loss of material, resulting in the so-called cavitation erosion phenomenon [7–10]. Generally, cavitation erosion can occur in almost all hydrodynamic systems and turbo machines [11–14], causing change in flow kinematics and drop in machine efficiency as well as noise, thermal effect and serious material damage. Two solutions, fortunately, can be adopted to reduce cavitation damage. One is to realize optimal design of hydrodynamic profiles, and another is to develop novel alloys or coatings possessing improved cavitation–erosion resistance [15,16]. In this respect, various coatings should be of significance, since they are usually more cost-effective than alloys.

Among various methods for preparing a variety of coatings, we are particularly interested in the thermal spraying technique, because it has good adaptability to numerous parts with a variety of shape and size. Moreover, it is imperative to better understand the cavitation erosion mechanism so as to provide guidance to the selection of coatings for preventing cavitation erosion. Unfortunately, the cavitation erosion mechanism of materials, especially coatings, is still not well understood [17]. Therefore, in the present research we focus on the cavitation erosion behavior and mechanism of three kinds of alloys for application to components such as rudder, hydraulic turbines, and steel piles of offshore drilling platforms [18,19] as well as five kinds of coatings in seawater environment, attempting to acquire some first-hand data for promoting exploration and utilization of marine resources. This should be significant, since seawater as an aggressive aqueous solution can cause corrosion and loss of material *via* an electrochemical process,

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and the conjoint action of cavitation erosion and corrosion in seawater may cause severe damage of many alloys and coatings [20–25].

Bearing those perspectives in mind, in this research we prepared NiCr alloy coating, WC–17Co/NiCr composite coating, Fe-based metallic glass coating, WC–$(W,Cr)_2C$–Ni cermet coating, and WC–17Co cermet coating by high velocity oxy-fuel spraying (HVOF). The cavitation erosion behavior of as-prepared coatings in deionized water and artificial seawater was evaluated and compared with that of 316 stainless steel, TC4 titanium alloy and ZL101 aluminum alloy. These three alloys were selected and studied, because they are widely applied to fabricate various devices and parts used in cavitation erosion environment, and their cavitation erosion mechanisms remain unknown at this stage. Particularly, although most Al alloys have low cavitation erosion resistance, many components (like scroll case intensifier pump) made from ZL101 aluminum alloy are indispensable for liquid transportation system, and they inevitably suffer serious cavitation erosion. Therefore, ZL101 aluminum alloy was also investigated. This paper reports the cavitation erosion behavior and mechanism of the tested materials in relation to their hardness, porosity, chemical behavior in artificial seawater as well as microstructure and eroded surface feature. The present research, hopefully, is to provide references for selecting suitable coating materials applicable to seawater environment.

2. Experimental procedure

2.1. Materials and process

Five kinds of coatings were deposited on 316 stainless steel substrate (30 mm × 24 mm × 10 mm) with a Diamond Jet 2700 high velocity oxy-fuel spraying equipment (Sulzer-Metco, USA; manipulated with an IRB 2400/16 robot (ABB, Switzerland)). The optimized spray parameters used in the present study are listed in Table 1. The optimum spray parameters were determined based on comprehensive considerations of the flame temperature, flame atmosphere, substrate temperature, deposition rate, spreading and stack extent of flat particles, and the uniformity of coatings. The composition, manufacturing method and particle size of corresponding feedstock powders are presented in Table 2. Prior to spraying, a GS-943 sand blasting machine (Beijing Changkong Sand Blasting Equipment Company Ltd., China; quartz sand, grit size range: 80–120 μm) was employed to roughen the working surface (30 mm × 24 mm) of the stainless steel substrate so as to enhance the coating–substrate adhesion. The roughened stainless steel substrates were cleaned with acetone in an ultrasonic bath. The thickness of the five as-sprayed coatings, measured with a digital micrometer at a resolution of 1 μm, is about 300 μm. Before cavitation tests were commenced, the stainless steel substrates separately coated with the five kinds of coatings and the blocks of stainless steel, Ti alloy and Al alloy were mechanically ground with a series of emery papers and finely polished with 1 μm diamond paste.

Table 1
Parameters for HVOF spraying.

Parameters	Value
Oxygen flow (m^3/h)	19.8
Natural gas flow (m^3/h)	15.3
Air flow (m^3/h)	17.2
Powder feed rate (g/min)	25
Gun speed (mm/s)	800
Interpass spacing (mm)	3
Spraying distance (cm)	27
Substrate temperature (°C)	< 150

2.2. Cavitation erosion test

Cavitation erosion tests in deionized water and artificial seawater were conducted with a laboratory test apparatus according to the ASTM G 32-10 method, with which vibration-induced pressure fluctuations were adopted to induce cavitation erosion effect [1]. A schematic description of the test apparatus is given in Fig. 1. Analytical grade chemicals and deionized water were used to prepare artificial seawater, and the composition of resultant artificial seawater is listed in Table 3. To-be-tested specimen was immersed in liquid medium at a depth of 12 ± 4 mm and held stationary below an ultrasonic tip horn (diameter 16 mm) at a distance of 0.5 mm. Cavitation erosion tests were conducted at a vibration frequency of 20 kHz, a duration of 6 h and a peak-to-peak amplitude of 50 μm, while water temperature was maintained constant (25 ± 2 °C) with a circulatory system. Mass loss (W_m) was measured with an electronic balance at a resolution of 10^{-4} g, and then it was converted to volume loss (W_v) after the density of the tested specimen was considered. The density values of various specimens, determined with an AccuPyc 1330 Pycnometer (Micromeritics, USA) in high purity helium (99.999%), are presented in Table 4. Relative cavitation erosion resistance (denoted as *RCER*) is defined as the ratio of the total volume erosion of the specimen possessing the best cavitation erosion

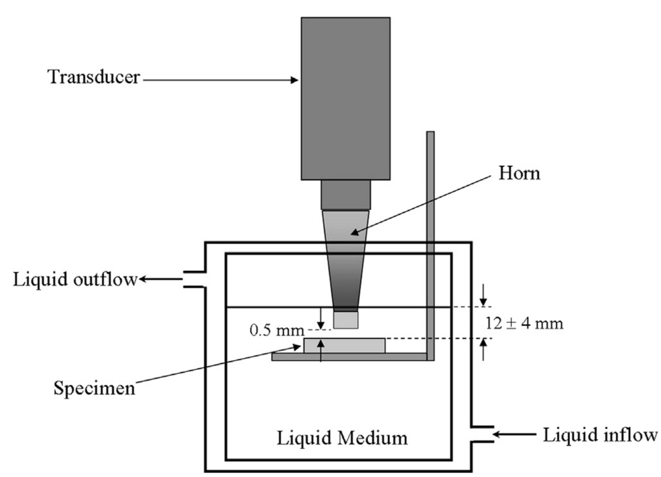

Fig. 1. Schematic illustration of cavitation erosion test rig.

Table 2
Composition, manufacturing method and particle size of feedstock powders.

Powder	Composition (mass fraction, %)	Manufacturing methods	Particle size (μm)
NiCr	$Ni_{80}Cr_{20}$	Alloy gas atomization	15–45
WC–17Co/NiCr	50 (WC–17Co)+50 (NiCr)	Physically blending	15–45
Fe-based metallic glass	Fe–10W–4Cr–3Ni–2Mo–4B–4Si–1C	Alloy water atomization	< 45
WC–$(W,Cr)_2C$–Ni	WC–27CrNi	Agglomerated and sintered	15–45
WC–17Co	WC–17Co	Agglomerated and sintered	15–45