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Water-lubricated tribological behavior of WC-Ni coatings deposited by off-angle HVOF spraying

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ABSTRACT

The off-angle thermally sprayed coatings generally present noticeable degradation in coating feature and characteristic, such as density, microhardness and/or toughness. A critical spray angle was previously suggested for different thermal spray techniques, e.g. HVOF of 45°, wire arc spraying of 60°, plasma spraying of 50° or 45°, primarily based on degree of the degradation benchmarked on that of normal angle. In this study, the feasibility of off-angle HVOF spraying of WC-Ni coatings is clarified directly by wear performance under water lubrication, since reported wear test results seem to be controversial. It is found that, the coating porosity is almost tripled with an upper limit within 3% as reducing the spray angle from 90° to 30°, while the maximum variation in the WC phase retention is about 13.6%, and about 11.7% in both microhardness and elastic modulus, and about 26.4% in indentation fracture toughness, respectively. As compared to a reported dry abrasive wear test showing that specific wear rate of HVOF WC-Co coatings at a spray angle of 30° was nearly doubled to that of 90° within 10^{-4}–10^{-5} mm^3/Nm, our water-lubricated wear test shows a comparably low specific wear rate below 10^{-7} mm^3/Nm with about 30% maximum variation for WC-10Ni coatings off-angle sprayed with respect to that of normal spray angle. A notable reduction in friction coefficient is confirmed for off-angle sprayed coatings at 30° and 45°. The improved tribological behavior is mainly attributed to the higher porosity with well-dispersed micro-pores facilitating a better water lubrication, as well as the mostly retained mechanical properties of off-angle coatings due to controlled porosity in a certain range. The off-angle sprayed WC-Ni coatings down to the spray angle of 30° are applicable in tribological applications due to improved fluid lubricating characteristic.

1. Introduction

Off-angle spraying is indispensable for thermal spray technologies in industrial practice to coat components of complicated shape [1–3]. It has been reported that off-angle thermal spray may lead to notable degradation of coatings features and characteristics, for surface features mainly including higher porosity (lower density) and cracking [1,5], and for surface characteristics including lower microhardness [1,4,5], lower fracture toughness [2,5] or less compressive residual stress [4,5], respectively. Among the different thermal spray technologies, high-velocity oxy-fuel (HVOF) spraying has advantage in the off-angle spraying capable of obtaining denser coatings over other techniques such as plasma spraying and wire arc spraying, as a result of the higher velocity of powders accelerated by the HVOF spray flame [1]. Since the plasma spray and wire arc spray processes are associated with low velocity of sprayed powders, the deposited coatings suffered great oxidation due to the high-temperature heating of sprayed powders with longer dwelling time in the flame, and the limited oxidation during HVOF spraying may be a dominant factor to obtain a relatively denser coating preferably for spraying non-oxide ceramic-metallic composite coatings [6–10]. For instance, for deposition of WC based composite coatings, HVOF sprayed WC-12Co coatings may reach a porosity of about 3% [1] whereas the plasma sprayed WC-12Co coatings could reach about 15% [4]. Consequently, a critical spray angle was suggested for the different thermal spray techniques, i.e. HVOF spraying no less than 45° [4], arc spraying no less than 60° [1], plasma spraying no less than 50° [1] or 45° [3], since substantial rise in porosity and/or degradation in coating characteristics occurred below such a spay angle.

Note that, for practical applications, the coating performance should be a direct criterion to assess the applicability of these coatings. However, coating performance is not fully explored in relation to the spray angle even though the degradation in off-angle sprayed coating features and characteristics are thought to be detrimental to the final performance. In this aspect, the porosity, hardness and toughness etc. should be concerned and understood as a sum of surface integrity parameters that have a combined effect on the high performance of components [11]. Up to date, wear resistance has been evaluated for the feasibility of off-angle spraying in few publications. Despite the reduced hardness and compressive residual stress of off-angle sprayed coatings, Strock et

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al. [4]. firstly reported an unexpected wear resistance enhancement for off-angle HVOF sprayed WC-CoCr coatings in comparison with that of normal angle sprayed coatings during dry fretting wear test against NiAl-bronze alloy or AISI 4340 steel wear pair under a load of 1.8 MPa and a frequency of 300 Hz for 8 h or 16 h. The exceptional wear response was attributed to more uniformly distribution of phases across the coating surface at off-angle spraying, and the enhanced wear resistance of off-angle sprayed coatings also caused greater wear of the wear pairs. More recently, Houdkova et al. [5] confirmed poorer wear behavior of off-angle HVOF sprayed hardmetal coatings evaluated by a dry sand/rubber wheel test under low-stress condition with a load of 22 N and a sliding distance of 1.436 m, where significant reduction in wear resistance was observed at less than 45° for WC-17Co coatings and less than 60° for Cr_3C_2-NiCr coatings, with a high wear rate of nearly doubled for WC-Co and over doubled for Cr_3C_2-NiCr as comparing the 30° sprayed coating to that of normal angle. Recalculating the reported data, the specific wear rate could be estimated to within a range of 10^{-4}–10^{-5} mm^3/Nm. The authors recommended a maximum 30° diversion from the normal angle for WC-Co and 15° diversion for Cr_3C_2-NiCr coatings, i.e. the critical spray angle is 60° for WC-Co coatings and 75° for Cr_3C_2-NiCr coatings based on the wear performance evaluation.

Systematic investigation is still necessary to clarify the influence of off-angle spraying scheme on the surface features and characteristics of thermally sprayed coatings and correlate them to the resultant performance under specific working conditions. Subsequently, the criterion based on coating performance could be established to evaluate feasibility of the off-angle spraying for coatings in industrial application. On this motivation, tribological behavior of off-angle HVOF sprayed WC-Ni coatings are explored in this study under water lubrication condition taking into account variations in coating features and characteristics under the off-angle spraying scheme. Water lubrication wear is frequently considered for components using WC-based cemented carbides material either in bulk or coating form, such as wear pairs of mechanical seals using water as coolant and lubricant [12–14]. The WC phase transformation in the coatings is analyzed along with the changes in porosity, hardness and toughness as varying the spray angle from 90° to 30°. A comparable wear resistance of all sprayed coatings is observed at a very low specific wear rate below 10^{-7} mm^3/Nm against high hardness WC-9Ni cemented carbide wear pair. The wear response of off-angle sprayed coatings with lower friction coefficient is discussed in correlation with the changes in the surface integrity parameters as well as the interactions between them since they have a combined effect on the final performance [11].

2. Experimental

The substrates for HVOF spraying experiments were 17-4PH precipitation strengthening martensitic stainless steel rectangle bars with a size of 12 × 12 × 60 mm^3. The substrates were cleaned with acetone, and then the surface to be coated was blasted with alumina grits of 60# mesh. WC-10Ni powders in diameter of + 15–45 μm were used as feedstock material. The feedstock powders were pretreated by heating up to 120 °C kept with 30 min followed cooling to room temperature in an electrically drying oven and then loaded into the powder feeder of HVOF system. An EvoCoat HOVF system equipped with Woka-610-Si HVOF spray gun on which the powders were fed into the HVOF flame with two laterally fixed inlets using N_2 as carrier gas. The HVOF process of off-angle spraying is schematically shown in Fig. 1, where the spray angle α is varied from 30° to 90° in this study. During spray process, the spray gun installed on a 6-axis robot is programmed to move with multiple sets of passes along the length of the steel substrate to deposit a coating of thickness about 200 μm, where each set of passes consists of partial overlapping 4 passes with a pitch of 5 mm between the parallel passes. No forced cooling was conducted during spraying. The surface temperature of samples was monitored with infrared temperature meter and was not higher than 200 °C at the termination of program for each set of passes. Such a surface temperature was controlled by compressed air cooling during an interval time of within 30 s between each set of passes. The typical spray parameters are summarized in Table 1.

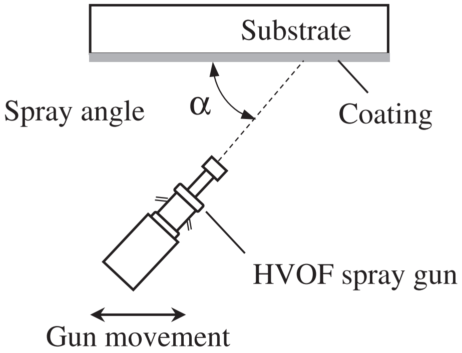

Fig. 1. Spray scheme of HVOF process with varying incident angle.

Characterizations of coated samples mainly include two aspects, i.e. surface features and surface characteristics, as categorized for surface integrity parameters which should be well controlled for components to achieve a high performance [11]. In this study, the surface features including surface roughness, porosity, metallurgical microstructure as well as phase structure were analyzed for coatings obtained under different spray angles, and surface characteristics were measured including microhardness, elastic modulus, and indentation fracture toughness. The cross-sectional morphology of coatings was observed by using a Zeiss SUPRA55 field emission scanning electron microscope. Based on the SEM image analysis, the porosity of coatings was calculated with a set of images at a magnification of 200 according to the conventional method adopted for cemented carbide bulk material as well as coatings [15,16]. Furthermore, the porosity down to a submicron range was also resolved on images at a magnification of 5000–15,000 and compared with the above-mentioned porosity analysis. Microhardness under different loads was also measured comparatively at 100 g and 300 g load with 10 s dwelling time, on the cross section of coatings using a HXD-1000TM Vickers indentation tester and each value was averaged over 10 measurements. The surface roughness of coatings was measured on a Kosaka ET4000AK surface profilometer. The phase structure was analyzed using X-ray diffraction measurement with Cu $K\alpha$ radiation on a SHIMADZU XRD-600 diffractometer. Elastic modulus of the coatings was measured by using a non-contact approach developed in our lab based on advanced ultrasonic technique by which both transverse and longitudinal waves through the coatings are simultaneously recorded in a single water-immersed ultrasonic probe. And then, the measured velocities of transverse and longitudinal waves were used to calculate the Poisson ratio and elastic modulus of coatings, similar to a recent study where the two wave velocities are measured separately via a laser ultrasonic method [17]. In this way, Poisson is derived from the measurement, other than empirically assumed in conventional method [18]. The coating fracture toughness was obtained by Eq. (1)

Table 1
Typical parameters of HVOF spray for WC-10Ni coatings.

Kerosene flow	22.7 l/h
Oxygen flow	811 NLPM
O/F ratio (λ)	1.11
Spray distance	350 mm
Spray speed	300 mm/s
Track pitch	5 mm
Spray angle	30°, 45°, 60°, 90°
Carrier gas N_2 flow	7 NLPM
Powder flow	75 g/min
Shielding gas N_2 flow	2000 l/h

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