Tribological Studies of Conventional Microcrystalline and Engineered Near-Nanocrystalline WC-17Co HVOF Coatings

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ABSTRACT

Tungsten carbide based cermet composite coatings possess the unique surface protection properties enabling their increasing use in the oil sands industry to combat severe sliding and high stress abrasion wear and other types of slurry abrasion and erosion. Thermal spraying such as the use of high velocity oxy-fuel (HVOF) technique has increased the wear life of coatings based on WC-Co system when compared with high velocity air plasma (HVAP) technique. The ability to deposit HVOF coatings with a nanocrystalline structure provides even higher wear resistance and fracture toughness over those achieved using conventional microcrystalline coatings of the same composition. In this research, conventional microcrystalline and engineered near-nanocrystalline WC grains were used to obtain two powder feedstocks of WC-17Co composition. The chemical analysis of the powders by XRD and EDS showed that the novel near-nanocrystalline powder had an engineered particle formation with 'duplex' cobalt layer surrounding WC core, comparing a typical spray-dried microcrystalline WC-17Co particle. Characterization of the coatings by XRD and SEM suggested that in case of near-nanocrystalline WC-17Co coating an extensive decarburization of WC during the spraying of the powder may had been prevented due to the use of the duplex Co coated WC-17Co powder, a novelty in this research. Tribological properties of the coatings were tested by atomic force microscopy, Vickers microhardness, fracture toughness, and two-body pin-on-plate (ASTM G133-05) abrasive wear tests. The near-nanocrystalline WC-17Co coating had shown significantly better performance than the conventional microcrystalline WC-17Co coating.

Keywords: Cermets; Near-nanocrystalline WC-17Co powder; HVOF thermal spraying; Two-body abrasive wear; Fracture toughness

1 INTRODUCTION

Tungsten carbide cobalt coating has been extensively used for wear resistant applications. Tungsten carbide having a Vickers hardness of about 2242 adds to the hardness of the composite while cobalt acts as a softer binder and hence adds to the toughness of the composite. High velocity oxy-fuel (HVOF) process has advantages of low dwell time, lower process temperature and high impingent velocity and, therefore, results in a higher adhesion and higher phase retention during coating [1]. Even then there are chances of decarburization of WC and formation of lower carbides such as W_2C, $(W, Co)_6C$ etc. W_2C has a higher brittleness and therefore degrades the quality of the coating. To minimize this degradation of WC, a 'duplex' Co coated cermet powder was used in this study. Nanocrystalline materials have the advantage of increased hardness and toughness simultaneously which otherwise are exclusive properties [2]. Recent work by Khan *et al*. [3] showed that near-nanocrystalline WC-Co coatings are more resistant to abrasive wear than microcrystalline coatings and that HVOF sprayed micro- and near-nanocrystalline coatings have superior abrasive wear resistance compared to heat treated and untreated steels [4]. Other researchers have found that during HVOF spraying the nanocrystalline WC decarburizes to a higher extent than the microcrystalline WC [5]. Correspondingly, a higher wear rate was reported during sliding in nanocrystalline coatings than in microcrystalline coatings. On the other hand, Stewart *et al*. and others reported that the abrasive wear resistance of nanocrystalline WC-Co coatings was 1.4 to 3.1 times better than that of the coatings obtained by spraying microcrystalline powders [6,7].

In this study, a novel duplex Co coated near-nanocrystalline WC-17Co powder was used for HVOF coating and the hardness, fracture toughness and two-body abrasive wear tests were conducted and compared with those of the conventional microcrystalline WC-17Co cermet powder sprayed coating. The extent of WC decarburization was also investigated and correlated with the wear behavior of the coatings.

2 EXPERIMENTAL PROCEDURE

Two different cermet powders were used as feedstock in the investigation: engineered near-nanocrystalline WC-17Co (provided by MesoCoat Inc., Euclid, OH) and microcrystalline WC-17Co. These were near-nanocrystalline WC-17Co (provided by Sulzer Metco, Westbury, NY). The chemical analysis of the coating powders was carried out using a Noran 8-channel energy dispersive spectrometer (Table 1). Spray deposition of the micro- and near-nanocrystalline powders was carried out at Hyperion Technologies Inc. in Calgary, Canada, under equivalent conditions using a Sulzer Metco (Westbury, NY) Diamond Jet Hybrid DJ2700 HVOF torch. Methane was used as a fuel gas utilizing a DJ2700 aircap. The deposition

parameters are shown in Table 2. The ratio between methane-to-oxygen in the fuel mixture was maintained at 0.68 to create an optimum crystalline phase structure within the final coatings. A traverse speed of the torch across the substrate of approximately 0.2 m/s was used and approximately 5 µm thickness/pass was deposited. Coatings of 210 µm thick were produced for microscopic examination and coatings of 450 µm thick were deposited for two-body abrasive wear test analysis. The coating thickness measurement was performed according to ASTM E376-06 using a thickness gauge 3000FX model.

Table 1: Coating powder characteristics

Characteristics	Coating powder	
	Micro WC-17Co	Near-nano WC-17Co
Element, wt.%	Balance W, 17-Co, 5-C, 1-Others	Balance W, 18.5-Co, 5.6-C, 1.11-O
Manufacturing route	Agglomerated /sintered	Clad/conversion
Shape	Mostly spherical	Mostly spherical

Table 2: Deposition parameters used in the HVOF spraying

Deposition parameter	Parametric value
Shroud gas (air), slpm*	1742
Oxygen, slpm	1346
Methane, slpm	918
Carrier gas (nitrogen), slpm	60
Powder feed rate, g/min	38
Spray angle, degrees	90

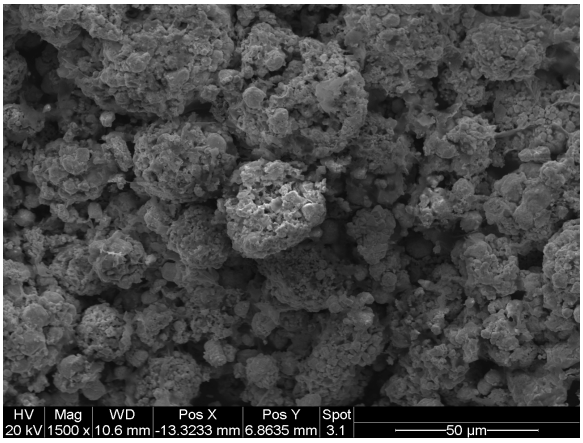
*Standard litre per minute

A hardened AISI 1118 steel 'wear plate' with a microstructure and properties of that of a water-quenched and tempered C-Mn steel was received from an oilfield in Fort McMurray in Alberta, Canada and used to produce samples of cross-section 9 x 7 x 5 mm. The steel had a chemical composition in wt.% of 0.18-C and 1.4-Mn.

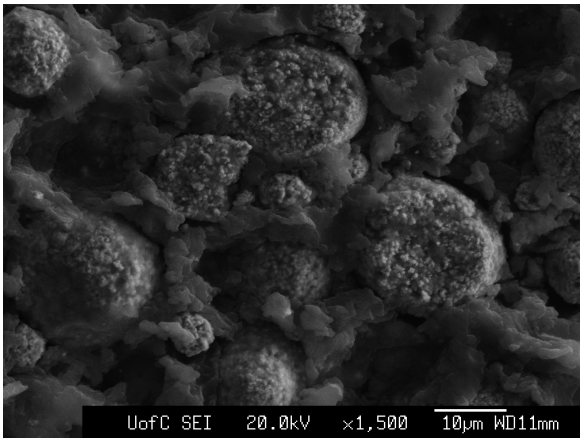
The wear tests of the coated and uncoated samples were carried out under 10, 20, 40 and 60 N loads. The wear rates were studied, as per ASTM G133-05 standard, for varying sliding distance. The microhardness values of the coatings and uncoated steel were determined using a microhardness tester (Micromet II, Buehler) using 300 g load. Atomic force microscopy (AFM, Park system XE100) and scanning electron microscopy (JEOL,JSM-8200) were carried out for microstructural characterization. XRD analysis using Rigaku Multiflex (Rigaku, Japan, model Rigaku multiflex ZD3609N), using a CuKα radiation source with a step size of 0.02°, a step time of 5 s and a 2θ scan window from 10° to 90° was used. XRD study was conducted in order to determine the phase changes that took place during the process of coatings. The fracture toughness for micro- and near-nanocrystalline coatings were calculated using Rockwell hardness tester equipped with a diamond cone and an applied load of 150 Kg.

3 RESULTS AND DISCUSSION

The SEM micrographs in Figures. 1(a) and (b) show differences between the dispersed WC grain sizes in the microcrystalline and near-nanocrystalline WC-17Co as-received powders, respectively. The near-nanocrystalline powder used in this study had a mean WC grain size of 427 nm with a standard deviation of 120 nm. The conventional microcrystalline powder particle size was in the range 15-35 µm with a WC grain size of 3-5 µm.



(a)



(b)

Figure 1: SEM micrographs showing cross-sections through: (a) microcrystalline and (b) near-nanocrystalline particles.

XRD analysis taken from the sprayed coatings showed a significant difference in phase composition compared to the powders before HVOF spraying, see Figure 2. The presence of W_2C and W phases is clearly seen in both types of coatings, whilst peaks of metallic Co is present in near-nanocrystalline coating. The proportion of WC transformed to W_2C and W phases was higher for the microcrystalline coating compared with the near-nanocrystalline coating. Furthermore, peaks of W_3C and mixed carbides such as η-Co_3W_3C were also observed for the microcrystalline coating.

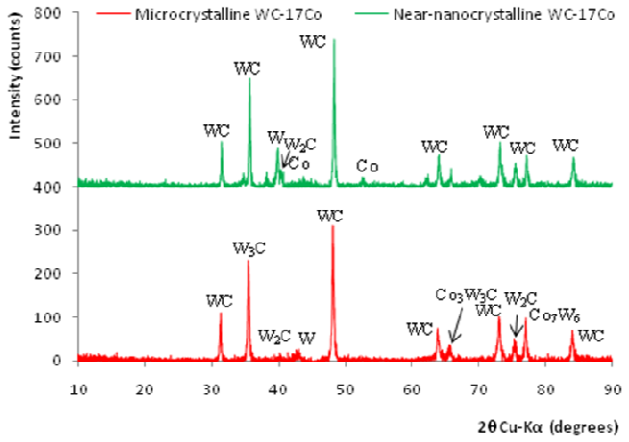
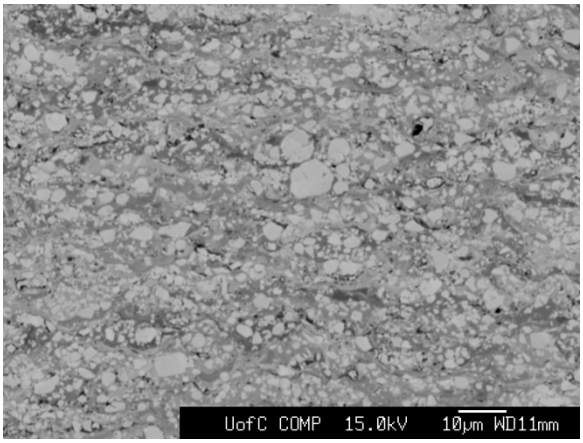
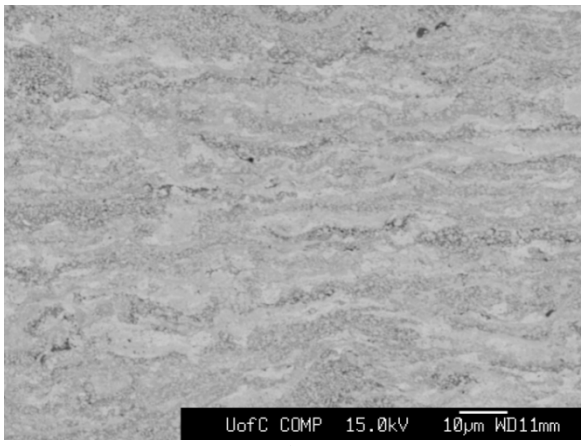


Figure 2: XRD analysis of the sprayed powders.

The microstructures of the coatings were examined using the SEM, and the micrographs of the microcrystalline and near-nanocrystalline as-sprayed coatings are shown in Figures 3(a) and (b), respectively. The near-nanocrystalline coating appeared to be denser and free of micro-voids or porosity compared to the microcrystalline coating.



(a)



(b)

Figure 3: SEM micrographs showing the sprayed: (a) microcrystalline and (b) near-nanocrystalline coatings.

The AFM surface profile measurements taken from the sprayed coatings showed that the near-nanocrystalline WC-17Co coating resulted in a lower surface roughness value compared to the microcrystalline coating (see Table 3). The porosity measurements for the coatings are given in Table 3. It is seen that the near-nanocrystalline coating resulted in a lower porosity than that of the conventional coating.

Table 3: A comparison of characteristics for the microcrystalline and near-nanocrystalline coatings

Characteristic	Coating	
	Micro WC-17Co	Near-nano WC-17Co
Surface roughness, Ra, µm	3.98 ± 0.46	4.17 ± 0.75
Porosity, %	> 1	2.29 ± 0.16
Vickers microhardness, VHN	1440	1237
Fracture toughness, MPa.m$^{1/2}$	25.12 ± 0.8	19.04 ± 1.1

The microhardness and fracture toughness values for the coatings are shown in Table 3. The change in microhardness as a function of depth through the steel substrate and the coated surface is shown in Fig. 4. An almost uniform hardness value of 348 VHN was obtained for the hardened steel. The hardness values were significantly higher for coatings giving a value of 1237 VHN for the microcrystalline coating and a value of 1440 VHN for the near-nanocrystalline coating. Both coatings were sprayed same conditions and a hardness increase of more than 16% for the near-nanocrystalline over the microcrystalline coatings was achieved.

The Anstis *et al* [8] formula was developed by researchers to determine the indentation fracture toughness of coatings. The measurement of the cracks and substituting values into the formula gives a quantitative value for fracture toughness:

$$K_{1C} = 0.016[E/H]^{1/2}Pc^{-3/2} \quad (1)$$

Where K_c is the fracture toughness [MPa*m$^{1/2}$], E is the elastic modulus [GPa], H is the hardness [GPa], P is the indentation load [N], c is the crack length measured from the indentation center [µm]. In Table 3, the fracture toughness calculated for the microcrystalline WC-17Co coating based on crack model (Equation 1) gave a value of 19.04 MPa*m$^{1/2}$ and was in consistent with earlier published data [9]. More importantly, the duplex near-nanocrystalline WC-17Co coating gave a toughness value of 25.12 MPa*m$^{1/2}$. This represented a 31% increase in fracture toughness for the near-nanocrystalline coatings compared to the microcrystalline coating.

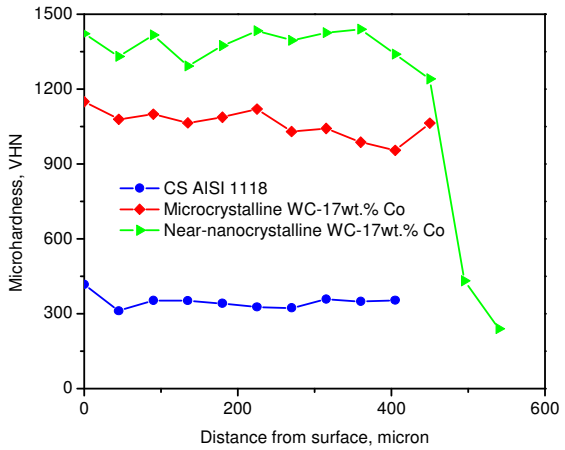


Figure 5: Microhardness depth profiles of hardened steel and micro- and near-nanocrystalline coating surfaces.

The sliding wear rate of the hardened steel and coated surfaces was compared using a range of applied loads using a sliding speed of 1.68 m/min, as shown in Fig. 6. It is evident from the wear test graphs that the best wear resistance was recorded for the near-nanocrystalline coating followed by the microcrystalline coating. The worst wear resistance was shown by the uncoated CS AISI 1118 steel. Comparing the steady state wear rates for the coated and uncoated materials, a value of 5.40 mm^3/m was obtained for the hardened steel, and a lower value of 3.34 mm^3/m was recorded for the microcrystalline WC-17wt.%Co coating. The wear rate of the near-nanocrystalline coating was extremely low with a value of 0.32 mm^3/m, which was approximately 10 times more wear resistant than the conventional microcrystalline coating.

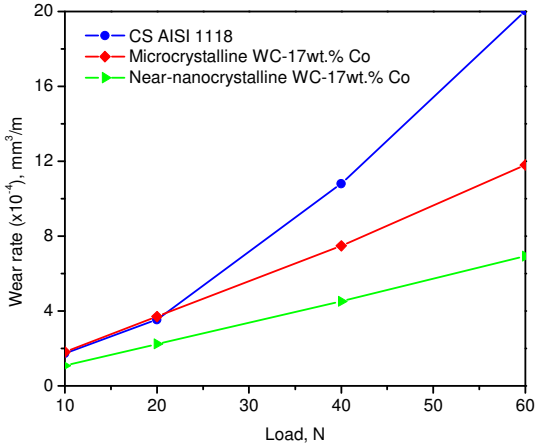


Figure 6: Wear rate as a function of load for hardened steel and microcrystalline and near-nanocrystalline coatings.

4 CONCLUSIONS

Wear is not a material property. It is the response of a material towards a particular system [10]. Therefore, one material may have different response to different environments. Wear mechanism and mode also depend upon the structure of the system where it takes place. In this research, two-body abrasive wear behavior of microcrystalline and engineered near-nanocrystalline WC-17Co coatings was studied. It was observed that the wear rate changed with changing the sliding distance and load. The abrasive wear mechanism was studied and the wear rate was correlated with properties such as coating microhardness, WC grain structure, distribution of Co content in the coating composition, fracture toughness, surface roughness as well as coating phase formation/retention during the HVOF thermal spraying. Sliding velocity, temperature, wear medium and wear environment were kept constant during the tests.

The wear rate changed with different sliding distances. It was recorded by optical microscopy that the grain structure of the coatings changed during sliding, thereby creating an atmosphere in which strain hardening was taking place. Significant strain hardening was also observed when microhardness tests were conducted near the grooves in the near-nanocrystalline coating. SEM images of the grooves revealed that the wear surface was fractured in the case of microcrystalline coating, while the near-nanocrystalline coating surface was plastically deformed.

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