Mechanical property changes in HVOF sprayed nanostructured WC-17wt.%Ni(80/20)Cr coating with varying substrate roughness

Tarek A Ben Mahmud¹, Gobinda C Saha¹,² and Tahir I Khan¹,³
¹Department of Mechanical and Manufacturing Engineering, University of Calgary, Alberta, Canada
²Westpower Equipment Ltd., 4451-54th Avenue S.E., Calgary, Alberta, Canada
³Qatar Petroleum Chair, Department of Mechanical & Industrial Engineering, University of Qatar, Doha, Qatar

E-mail: tarekbinmahod@yahoo.com

Abstract. Thermally sprayed coatings developed by use of high velocity oxy-fuel (HVOF) process are known for their superior wear characteristics. In many industrial applications, new parts as well as repaired and refurbished parts coated with WC-Co microstructured coatings have shown enhanced erosion-corrosion and abrasive resistant properties when compared with other surface modification technologies such as chrome replacement, fusion welding, and cladding. This research has been further directed towards the development of HVOF technique to deposit dense nanostructured ceramic-metallic composites. The mechanism of plastic deformation, which determines the strength and ductility of materials, in nanostructured materials are different, thereby leading to novel mechanical properties. Various parameters can influence these properties, but the substrate surface preparation by grit blasting before thermal spraying is one critical parameter. The grit blasting process generates a surface roughness, which ensures mechanical anchoring between the coating and the substrate surface. In this work, the sliding wear behavior and microhardness of WC-17wt.%Ni(80/20)Cr cermet coatings deposited onto carbon steel substrates are examined as a function of three different surface roughness values under different loads. The results show that as-prepared surface with different blasting profiles have a direct influence on the surface roughness and wear performance of the coatings. The sliding wear resistance of the coatings increased as the substrate surface roughness increased. The wear depth decreased with increasing surface roughness.

1. Introduction
The oil sands industry in northern Alberta, Canada faces an ongoing challenge from abrasive wear occurring on surfaces of machinery and components that are involved in the heavy oil recovery process. Due to its highly aggressive nature the produced water in this environment causes unpredictable equipment failure leading to complete plant shutdown and reduced production efficiency. Machine lifetime depends on a combination of several factors, particularly on the degree of wear resistance of the components of the machinery.
Traditionally, several techniques have been used to increase the wear resistance by hardening the substrate surface, including heat treatment, hard facing by fusion welding of wear resistant alloys, powder cladding or surface electrodeposition. Up until recently, tungsten carbide (WC) wear protection systems used to resist wear in oil sands applications included bulk sintered and surface engineered products fabricated using processes such as fusion welding, brazing and thermal spraying. Since 1980’s WC based thermal sprayed coatings have played an increasing role in protecting metal surfaces from high wear and corrosion environments. These included coatings of military and civil aircraft parts and components (landing gears, propellers and hydraulic actuators etc.) as part of their regular manufacturing and maintenance operations[1]. Atmospheric plasma spraying (APS), detonation spray coating (DSC), and high velocity oxy-fuel (HVOF) are the most commonly used techniques for deposition of WC-Co coatings. The HVOF process provides advantages over other techniques such as higher velocity and lower temperature of in-flight particles, producing coatings with minimal porosity, excellent adherence to the substrate, larger fraction of retained WC and correspondingly improved wear properties [2,3]. In HVOF, feedstock particles are heated and propelled at very high velocities (>1 Mach) resulting from the internal combustion of oxygen and fuel (propylene, kerosene, methane, hydrogen etc.) and from the spray gun special design. The HVOF gas velocity can exceed 2,100 m/sec, pushing the particles with velocities between 400 and 800 m/sec, thereby producing coatings with very high density, low oxidation content, high bond strength, high microhardness and durability, and low residual stress. In the process it does not overheat the powder particle [4]. A successful coating application to its engineering usage is strongly linked to the quality of the adhesion between the coating and the substrate or the previously deposited layers. In HVOF, the adhesion / cohesion is of the mechanical type; surface pits and grooves of a rough surface are filled with the spreading semi-molten material due to the impact pressure. Subsequent solidification leads to mechanical interlocking [5]. The coating must remain bonded to the substrate and this is affected by the prepared substrate surface roughness, which ultimately influences the characteristics like wear resistance, residual stress formation and adhesion strength in the coating [6]. Besides, feedstock powder composition and particle structure exhibit different coating efficiencies during spraying resulting in different coating microstructures. In recent studies it has been shown that the wear resistance of WC-17Co cermet coating increases by reducing the size of the carbide grain size [7]. A thin Co layer on the surface of WC-Co feedstock particle by chemical vapor deposition (CVD) had prevented significant decarburization of WC during HVOF process, thereby improving the sliding wear resistance of the coatings [8]. In this research, a novel ‘duplex NiCr alloy coated’ WC-17wt.%Ni(80/20)Cr nanostructured cermet powder has been HVOF sprayed to obtain coatings for high wear oil sands applications. The NiCr alloy binder was chosen to increase the corrosion resistance of the coatings. The tribological behavior of these coatings as a function of substrate roughness was investigated by studying changes in wear resistance using a pin-on-plate sliding abrasive tester (as per ASTM G133 standard) and relating this to changes in microhardness of the coatings.

2. Materials and experimental work

2.1. Feedstock powder

In this work, a ‘duplex NiCr-coated’ nanocrystalline WC grain structured WC-17wt.%Ni(80/20)Cr cermet powder was used. The objective of using this powder particle was to maintain a minimum binder mean free path between the WC grains to achieve a harder coating formation. Furthermore, the powder particles consist of WC grains and 6 wt.% NiCr alloy matrix in the core and a CVD produced external coating consisting of 11 wt.% binder (NiCr). This external coating was designed to reduce the decarburization of WC during the spraying process and reduce the formation of brittle phases in the sprayed coatings. The external NiCr coating was also expected to increase the metallurgical bond between the “splat” which result in the coating on the substrate surface. Figure 1 compares the relationship between the binder mean free path and the hardness of nanostructured and conventional
microstructured WC-Co coatings [9]. The chemical composition and size distribution of the powder used in this work are presented in Table 1.

Table 1. Powder composition analysis

| Powder          | Element, wt.% | Nominal range, μm |
|-----------------|---------------|------------------|
| WC-17Ni(80/20)Cr| Balance | 1.28 | 20.46 | 3.34 | -22 +10 |

2.2. Substrate materials

One of the most common steels employed in the oil sands industry is carbon steel AISI 1018, used as the substrate surface in this work. It has been received in the annealed condition with a composition in wt.%: 0.18-C, 0.16-Si and 0.65-Mn. The geometry of this material is cylindrical rod (Ø8 × h12 mm). One cylindrical face was used as the surface for wear tests. Fifteen samples were grouped into three groups, each group having five samples and were named by grit blasting material mesh size numbers 16, 24, and 36, respectively. The samples were degreased with acetone and then submerged in ultrasonic tank using isopropyl alcohol for 15 minutes before surface blasting. Three different blasting grits composed of 97% Al₂O₃ and 3% TiO₂ were used to roughen the substrate surface that was to be coated. The airflow pressure was set at 0.70 MPa, the standoff distance between torch and substrate was set at 100 mm, and the blowing pressure angle was kept 90°. The surface roughness was measured by a Mitutoyo roughness tester (model: SJ-201P). The values of the as-prepared surface roughness with respect to blasting grit sizes are given in Table 2.

Table 2. Relationship between surface blasting grit size and generated surface roughness.

| US mesh size # | Grit size, μm | Roughness (Rₐ), μm |
|----------------|---------------|------------------|
| 16             | 1,190         | 17               |
| 24             | 707           | 12               |
| 36             | 500           | 9                |

2.3. HVOF spraying

The HVOF spraying process of the engineered nanostructured WC-17wt.%Ni(80/20)Cr powder was carried out at Westpower Equipment Ltd. (Calgary, AB) and the spraying conditions are specified in Table 3. A Sulzer Metco DJ 2700 hybrid diamond jet gun was used. The gun traverse speed was 2,000 mm/minute, and the spray distance was maintained at 254 mm. Approximately 10 μm per pass was
deposited to obtain a final coating thickness of 230 µm. By using a coating thickness gauge 3000FX model (Electromatic Equipment Co., NY) the coating thickness was recorded. The substrate surface was preheated before the spray process to maintain the thermal conductivity close between deposited powder particles and the substrate surface, thereby reducing the generation of residual stresses. The preheating process also guarantees mechanical anchorage at micro-welding sites [10].

2.4. Sliding wear test

Sliding wear tests on the coat surfaces were performed using a custom-designed two-body abrasion wear tester apparatus according to ASTM G133-05 standard. All tests were made at room temperature without lubrication. A multichannel 16-bit 100 kHz data acquisition device USB-1608FS model (microDAQ, OH) was used to gain data and execute a real time analysis of the wear process. The test was conducted under different loads for each grit group number. The sliding speed, stroke length, and run time were 0.029 m/sec, 10 mm and 30 minutes, respectively. Table 4 shows sample organization and test parameters used in the study. Uncoated samples were tested as reference material. Comparison of sliding wear depth in uncoated steel substrates and nanostructured coated materials as a function of applied loads (20, 40, 60 N) is presented. All uncoated and coated samples were cleaned with ethanol and dry compressed air to measure the mass losses before and after sliding wear test. The weight loss measurements were completed by using an electronic analytical balance with a precision of 0.1 mg (model SCIENTECH-ZSA-210) and were recorded before and after the sliding wear tests.

Table 3. The sliding wear test parameters

| Uncoated | Coated |
|----------|--------|
| Grit No. | 16 24 36 |
| Load (N) | 20, 30, 40, 50, 60 20, 30, 40, 50, 60 20, 30, 40, 50, 60 |

2.5. Coating characterization

After the sliding wear test, the samples were cut longitudinally by slow speed diamond cutting saw model METTECH-Mark V-seres-600. The surfaces of all samples were prepared by surface preparation techniques using standard metallographic procedure. The final polish was completed at 1 µm diamond paste. The hardness of the coating was performed using Vickers microhardness tester model Micromet-II, Buehler on all coated and uncoated samples on their cross-sections under a load of 300 g. Ten indentations were taken to get an average of hardness value. Coatings’ microstructures were characterized by scanning electron microscopy (SEM) model FEI XL30 (Phillips). Coatings’ microstructures after the wear tests under 20 N and 60 N loads are presented.

3. Results and discussion

3.1. Characterization of wear depth vs. sliding distance

Figure 2 shows the effect of sliding distance on the worn surface by measuring wear depth of coated and uncoated materials under 40 N loading. All materials have shown similar trends in wear depth plots against the sliding distance. As expected, the maximum wear depth penetration was occurring in the uncoated AISI 1018 material. After the initial wear period (the ‘break-in’ wear) all samples have reached a more stable and constant wear rate and this can be explained by a transition mechanism from a severe to milder mode of wear. The coatings showed distinct spike in abrasive wear approximately in the first 10 m sliding distance. Furthermore, surfaces blasted with grit number 16 (Ra 17 µm) exhibits the lowest wear depth penetration (about 47 µm). It can be seen that as the prepared surface roughness decreases the wear depth increases. This can be attributed to the strong mechanical bonding between the substrate surface asperities and the coating molten particles generated by the surface blasting prior to deposition of the coating. Figure 3 shows a similar trend in wear depth characteristics obtained from uncoated and nanostructured WC-17wt.%Ni(80/20)Cr coatings under a higher load of 60 N.
3.2. Characterization of the mass loss

Figure 4 shows the abrasive wear mass loss as a function of surface roughness under applied load of 60 N. It is seen that the blasting grit #16 prepared surface experienced less mass loss than compared with the surfaces prepared with blasting grit sizes #24 and #36. This is referring to a good bonding between the coating and substrate surface asperities.

Figure 2. Comparison of sliding wear depth for different surface roughness of coated nanostructured and uncoated carbon steel substrate under 40 N load.

Figure 3. Comparison of sliding wear depth for different surface roughness of coated nanostructured and uncoated carbon steel substrate under 60 N load.

Figure 4. Abrasive wear mass loss as a function of different surface roughness under applied load 60N.
3.3. Characterization of coating and wear rate

The results obtained are used to compute the wear rate in terms of distance given by the following equation (1) [11]:

\[
\text{Wear rate} = \frac{\Delta m}{S_d} \left[ \frac{g}{m} \right] \quad \text{(1)}
\]

Where \(\Delta m\) is the difference in mass before and after the sliding wear in grams and \(S_d\) is the sliding distance expressed in m. Figure 5 shows the wear rate as a function of applied load for coated and uncoated test samples that were prepared with different grit prepared surface roughness. It is seen that the nanostructured coated sample with grit 16 exhibited the best wear resistance than that of the other two nanostructured coated samples prepared with grits 24 and 36, respectively. Further, the low wear rates in all three coated surfaces correspond to the low load (20 N). As the applied load increases the wear rate increases. This phenomenon can be referred to the fact that as the wear run progressed with higher loads at a constant speed there were progressively more debris formation from the worn material (WC-Ni-Cr) leaving them trapped between the coated surface and the abrasive tool. Hence, the wear mechanism shifted from being two-body abrasive wear to three-body abrasive wear process, resulting in an increase in wear rate.

To understand the wear characterization of coated samples, the worn surfaces were observed using the SEM. From the sliding wear test, two groups of coated samples (lowest load 20 N and highest load 60 N) were selected and examined, as shown in figures 6 and 7, respectively. The backscattered SEM micrographs (figure 6) after 30 minutes of tests under the applied load (20 N) all three coated samples (grits 16, 24, 36) retained their bonding with corresponding substrates. In figure 7, however, the protective coatings obtained on prepared surfaces blasted with grits 24 and 36 were visibly pulled out during the tests under the load of 60 N. This can be attributed to the removal of softer binder phase (NiCr alloy) followed by hard WC reinforcement pull out, while this was not the case for worn out sample that was coated on surface prepared by blasting grit 16.

Figure 5. Comparison amongst sliding wear rates on the nanostructured coated and uncoated surfaces prepared by blasting grits (#16, #24, #36) under different loads.

Figure 6. SEM micrographs comparing cross-sectional view of worn surfaces under 20 N load of nanostructured WC-17wt.%Ni(80/20)Cr coatings. The pre-spray surfaces were prepared by grits (16, 24, 36).
3.4 Vickers microhardness

Vickers microhardness tests were conducted on the worn surfaces of the coated and uncoated samples to examine the work hardening mechanisms taking place in the coated samples prepared by blasting grits 16, 24, and 36. It is observed that the microhardness remained unchanged and the highest hardness was recorded as 1243 HV0.3.

4. Conclusion

In this research it was shown that the novel ‘duplex NiCr coated’ nanostructured WC-17wt.%Ni(80/20)Cr powder could be HVOF sprayed to obtain coatings with superior wear resistant properties. Furthermore:

- The sliding abrasive wear resistance, mass loss and after-wear Vickers microhardness of the nanostructured WC-17wt.%Ni(80/20)Cr coated surfaces were investigated and correlated with the pre-spray substrate surface preparation using three different blasting material profiles (grits 16, 24, and 36). The results showed that the coarse grained surface blasting material (grit #16) contributed to a lower wear rate (high wear resistance), and the highest wear rate took place on coating substrate that was prepared using #36 blasting grit. This could be attributed to the strong mechanical bonding between the substrate surface and the coating semi-molten particles derived during the former prepared surface for sprayed coatings.
- The SEM micrographs showed that the abrasive wear at a load of 60 N for surfaces blasted to produce a fine roughness (grits 24 and 36) was attributed to plastic deformation followed by removal of metallic phase, i.e. NiCr alloy. This resulted in the loss of the WC particles by “pull out”.

Figure 7. SEM micrographs comparing cross-sectional view of worn surfaces under 60 N load of nanostructured WC-17wt.%Ni(80/20)Cr coatings. The pre-sprayed surfaces were prepared by grits (16, 24, 36).

Figure 8. Vickers microhardness in the nanostructured coated and uncoated surfaces prepared by blasting grits (#16, #24, #36) after sliding wear test under 60 N load.
The Vickers microhardness measurements from the worn coated samples showed no significant difference in work hardening mechanisms between the three surface grits. However, this aspect of the study requires further investigation.

5. Acknowledgment
Authors acknowledge the financial support provided by the University of Al-Zawia in Libya and Westpower Equipment Ltd. in Alberta, Canada for the continuation of this research study.

6. References
[1] Legg K O Overview of Alternative Technologies for Chromium and Cadmium Surface Modification Technology 2001: Proceedings of the Fifteenth International Conference on Surface Modification Technologies (ASM International) pp 235–44
[2] M.R. Dorfman, B.A. Kushner, J. Nerz and A J R 1989 No Title Proc. 12th Int. Thermal Spray Conf. ed E I. A. Buclow (The Welding Institute, London,) p 108
[3] B.R. Marple R S L Therm. Spray Technol Journal of Thermal Spray Technology 14 67–76
[4] Thorpe, R. Kopech, and H. Gagne N 2000 HVOF thermal spray technology , Advanced Materials & Processes 157 27–9
[5] Fauchais P, Fukamoto M, Vardelle a. and Vardelle M 2004 Knowledge Concerning Splat Formation: An Invited Review Journal of Thermal Spray Technology 13 337–60
[6] Staia M H, Ramos E, Carrasquero A, Roman A, Lesage J and Chicot D 2000 Effect of substrate roughness induced by grit blasting upon adhesion of WC-17 % Co thermal sprayed coatings
[7] Saha G C and Khan T I 2011 Comparative Abrasive Wear Study of HVOF Coatings Obtained by Spraying WC-17Co Microcrystalline and Duplex Near-Nanocrystalline Cermet Powders Journal of Engineering Materials and Technology 133 041002
[8] Mateen A, Saha G C, Khan T I and Khalid F A. 2011 Tribological behaviour of HVOF sprayed near-nanostructured and microstructured WC-17wt.%Co coatings Surface and Coatings Technology 206 1077–84
[9] Jia K, Fischer T E and Gallois B 1998 Microstructure, hardness and toughness of nanostructured and conventional WC-Co composites Nanostructured Materials 10 875–91
[10] Paredes R S C, Amico S C and d’Oliveira a. S C M 2006 The effect of roughness and pre-heating of the substrate on the morphology of aluminium coatings deposited by thermal spraying Surface and Coatings Technology 200 3049–55
[11] Raymond G B 2004 Mechanical wear fundamental and testing (Marcel Dekker, Inc)