

Improving the Wear Behavior of WC-CoCr-based HVOF Coating by Surface Grinding

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WC-CoCr-based high velocity oxy fuel (HVOF) coatings are being used for several components which are prone to severe erosion or abrasion. In this study, the HVOF coating was applied by liquid fuel-based equipment. These coated samples were subjected to surface grinding of various depths (100, 200, and 300 μm). Hardness test after surface grinding showed that the coating hardness increased by 33% after grinding to a depth of 200 μm (1472 Hv). The residual stress after different depths of grinding was measured using x-ray diffraction. It showed that the compressive residual stress of coating increased with grinding. Increase in hardness of the coating (after grinding) is believed to be due to the increase in compressive residual stress. The abrasive wear resistance increased after grinding to a depth of 100 μm thickness and remained constant during successive grinding. In contrast, the erosive wear resistance increased the most when the grinding thickness was 200 μm . It is concluded that the surface grinding of coatings helps in increasing abrasive and erosive wear resistance. The increase in microhardness of the coating is believed to be the reason for high wear resistance. SEM studies of worn out surface show carbide grain pull out due to removal of softer phase, i.e. cobalt and chromium, and is followed by tungsten carbide grain pull out.

Keywords abrasion, erosion, grinding, hardness, HVOF, residual stress

1. Introduction

Thermally sprayed cermet coatings have emerged as a viable solution for a wide range of wear resistance applications to improve the service life of machine components. Tungsten carbide and chromium carbide-based coatings are frequently used for many of the applications in gas turbine, steam turbine, aero engine as well as hydro turbines to improve the resistance to sliding, abrasive and erosive wear (Ref 1-3). The former coating is used up to 500 °C and the latter up to 800 °C. Also, for sliding wear and abrasive wear resistance, the carbide coatings are considered to be a viable alternative to hard chrome plating due to the strict environmental regulations. These cermet coatings are deposited by high velocity processes namely high velocity oxy-fuel (HVOF), detonation gun spray (DS) processes and also by plasma spray process (Ref 4-6). WC and Cr_3C_2 coatings with different metallic binders such as Co, Ni, and Fe have been studied using different amounts of binder contents with Co and Ni being the most commonly used binders. Addition of Cr to the matrix has been found to improve

the wear and corrosion resistance of these cermets (Ref 6). The wear behavior of WC-based coatings with varying amounts of Co content deposited by different thermal spray processes has been studied by a number of researchers (Ref 7-14). It has been reported that the abrasive wear rate for the cermet coatings is controlled by factors such as the morphology of the starting powder, the size and distribution of the carbide particles, hardness of the carbide particles relative to the abrasive, properties of the matrix and its volume fraction and the coating process, which determine the coating characteristics like the phases, density, microhardness, and the residual stresses.

The effect of grinding on coating has been studied to a limited extent (Ref 1). The depth of grinding on coating has, however, not been studied in detail. In the present study, the effect of grinding on WC-CoCr-based HVOF coating has been examined after different depths of grinding. The aim of this study was to compare the abrasive and erosive wear behaviors of ground samples with as-coated samples (without grinding).

2. Experimental

2.1 Materials and Surface Preparation

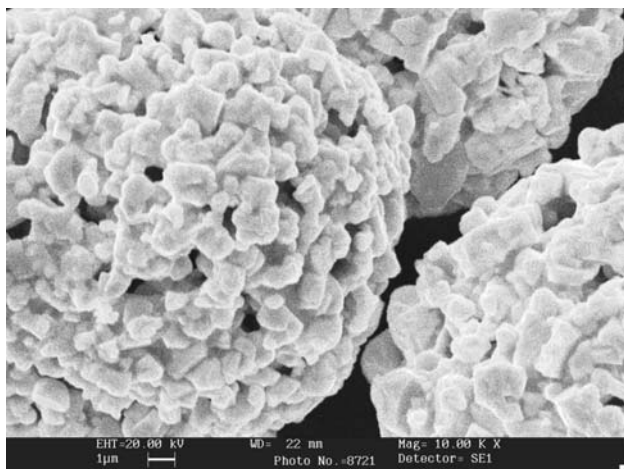
Spherical powders of 11 to 45 μm size from Sulzer Metco, Switzerland (WOKA-3603: WC-9Co-5Cr) were used. The approximate chemical composition of the WOKA-3603 powder is given in Table 1.

For spraying, 100 \times 100 \times 7 mm AISI 410 stainless steel plates were used as substrate. Before coating, plates were grit-blasted using suction-type grit-blasting machine with alumina grit of size 22 to 24 mesh. The SEM micrograph of the spray powder is given in Fig. 1.

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Table 1 Chemical composition of WOKA-3603

Element name	% Weight range
Cobalt	8.5-9.5
Carbon	5.1-5.8
Chromium	4.5-5.5
Nickel	0.8-1.2
Iron	0.3 max
Tungsten	Balance

**Fig. 1** HVOF spray powder

2.2 High Velocity Oxy Fuel (HVOF) Coatings

Metjet-III system from Metallization, UK, was used to deposit the HVOF coating. This system is based on liquid fuel (kerosene of aviation grade) and oxygen gas. The HVOF spray gun was mounted on a 6-axis ABB robot for carrying out the HVOF coating. This coating was carried out inside an acoustic chamber because the HVOF coating process produces very heavy noise. In brief, the HVOF spraying parameters are listed in Table 2. The coating thickness was maintained around 500 μm . To examine the effect of grinding, four sets of samples were made. The details of the samples are given in Table 3. The coated samples were ground using diamond abrasive wheel and the grinding parameters are given in Table 4. Grinding was carried out with water soluble coolant and the final surface roughness for all the samples were maintained around 0.2 μm measured using a perthometer.

2.3 Coating Characterization

The powder and coatings were analyzed using M/s Philips Make XRD equipment (MPD model) with 40 kV voltage, 30 mA current, 1° divergence slit, 1° antiscatter slit and 0.3 mm receiving slit and a scan speed of 0.02° (2 θ) per second.

Surface roughness was measured with a perthometer from M/s Maho, Japan. Cross sections of the HVOF-coated samples and abrasion test samples were observed using scanning electron microscope (SEM).

The Vickers microhardness was measured using the micro-macro hardness tester from M/s Wilson Wolport, Germany (Model Tukon 2100). Indentations were made at a load of 300 g. Hardness measurements were carried out on the cross

Table 2 A typical HVOF coating spray parameter

Spray parameters	Value
Combustion chamber pressure	0.7 MPa
Spray distance	350 mm
Spray angle	90°
Powder feed rate	70 g/min
Fuel flow rate	24.75 L/h
Oxygen flow rate	950 slpm
Carrier gas flow rate	45 slpm
Barrel length	150 mm
Spraying powder	WC-9Co-5Cr, WOKA 3603
Gun movement speed and offset per pass	0.2 m/s, 5.0 mm

Table 3 The details of the sample made for the study

Sample code	Description of the sample
HVOF-0	The sample without grinding
HVOF-100	The sample with 100 μm surface grinding
HVOF-200	The sample with 200 μm surface grinding
HVOF-300	The sample with 300 μm surface grinding

Table 4 Grinding conditions

Parameter	Value
Wheel speed, m/s	30
Table speed, m/s	5
In feed per pass	
Rough grinding, μm	10
Finishing, μm	5

section of the HVOF-coated sample so that the result is not affected by the base metal. For each sample, ten readings were taken and the average value has been reported.

Residual stress measurement was done using x-ray diffraction (XRD) on the equipment from M/s American stress measuring technology (Model XTRESS 3003). Residual stress was also measured in as-coated HVOF samples. XRD was done by peak shift $\sin^2 \psi$ technique using Cr $K\alpha$ radiation (wave length 2.2910 \AA) (Ref 15). The Bragg reflection (for WC) used for the measurement was from (256) plane and diffraction angle at 138.5° (2 θ). The measurements were carried out at a tube voltage of 30 kV, current of 6 mA and collimator diameter 4 mm. The Young's modulus value of 534.4 GPa and Poisson's ratio 0.22 were used for estimating the residual stress for both HVOF as-coated and ground samples.

2.4 Abrasive Wear Study

The coated samples of 70 \times 25 \times 5 mm dimensions were tested as per ASTM standard G-65. The coated sample for abrasion test was polished with diamond paste to attain the required surface finish as per ASTM standard (Ref 15). The sample was mounted firmly in the sample holder and was allowed to press against the rim of the rubber wheel with the desired normal force by applying a known dead weight using a

lever arrangement. Dry silica sand was used as an abrasive which has a particle size from 250 to 400 μm . The dry silica sand was then allowed to fall freely between the wheel and the coated surface while the rubber wheel was rubbing against the coated surface. The abrasive particles used were not recycled. Prior to the test, the coated sample was ultrasonically cleaned with acetone, dried and weighed using a Sartorius electronic weighing balance with an accuracy of 0.01 mg. The coating mass loss was measured at every 5-min interval. The total duration of the test was 30 min as per ASTM standard. The mass loss obtained was normalized with the coating density to obtain the volume wear loss. The test conditions followed are given in Table 5. The coating density values were estimated by

Table 5 Test conditions of abrasive wear study

Parameters	Value
Normal load, N	10
Wheel, rpm	202
Wheel surface speed, m/s	2.4
Abrasive material	Silica
Particle size range, μ	150-300
Feed rate, kg/h	19.2

Table 6 Slurry erosion test condition

Description	Condition
Nozzle diameter	6 mm
Slurry medium/erodent	Quartz sand
Particle size	-425 + 250 μm
Distance between nozzle and sample	35 mm
Erodent concentration	250 g 10 L water
Velocity	16 m/s
Slurry flow	26 L/min
Angle of impingement	90°
Test duration	60 min

the coating weight gain method in which the mass of the coating deposited was normalized with the coating volume. The density of the HVOF coating used for calculation of volume loss is 12.8 g/cm^3 . To compare the abrasive wear data, the same test was also conducted on AISI 410 SS sample which is generally used in hydro turbine components (Ref 3).

2.5 Erosive Wear Study

Slurry erosion tests were carried out using a water jet impingement erosion apparatus which is based on ASTM G-76 standard. It consists of a 10 L water reservoir, in which 250 g of mineral sand of -40 to +80 mesh is added. The slurry passes through a tungsten carbide 6 mm diameter nozzle, providing a jet velocity of 16 m/s. A rectangular sample of size 50 \times 50 \times 6 mm is kept in front of a sand-laden water jet at an angle of 90°. Sand laden water is circulated in a controlled manner by a variable speed pump controlled by a frequency inverter. The flow parameters, such as flow pressure (up stream of the tungsten carbide nozzle), are monitored and the water reservoir is kept under normal atmospheric condition. The pH of the water is also monitored throughout the experiment. The jet velocities are determined by volume flow rate divided by the area of the carbide nozzle. The velocities determined are an indication of potential energy, which can be determined by the pressure gauge mounted ahead of the slurry jet. Typical pressure readings were in the range of 1.2-1.5 kg/cm^2 for jet velocities in the range of 15-20 m/s. These pressure readings were monitored continuously during the complete experiment. Slurry erosion test conditions are given in Table 6.

3. Results and Discussion

3.1 X-ray Diffraction Analyses

The XRD pattern for the coating powder of WOKA 3603 is shown in Fig. 2. In WOKA 3603 powder, different phases of

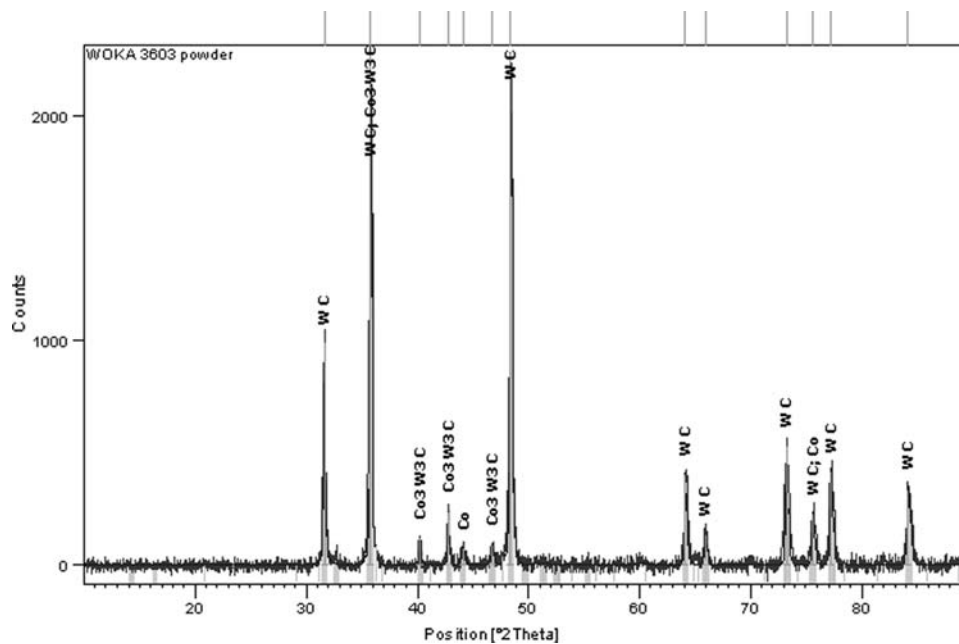


Fig. 2 XRD pattern of coating powder

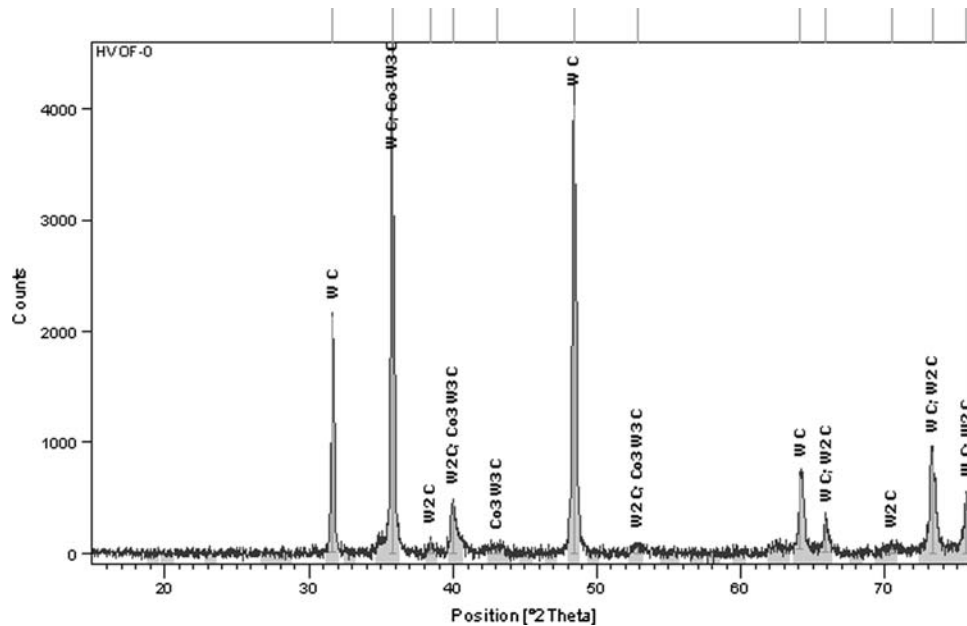


Fig. 3 XRD pattern of HVOF-coated sample (HVOF-0)

WC, Co, and $\text{Co}_3\text{W}_3\text{C}$ were detected. Figure 3 shows the XRD pattern for as-sprayed WC-Co-Cr coating by HVOF process with the powder WOKA-3603. The XRD pattern shows the presence of WC, W_2C , and $\text{Co}_3\text{W}_3\text{C}$ compounds. W_2C (di-tungsten carbide) has formed due to partial decarburization of tungsten carbide (WC). W_2C compound formation during the deposition process also has been reported elsewhere (Ref 8, 15). Cobalt peak is not seen in the coating (HVOF-0), which indicates that it has dissolved into the coating due to high HVOF flame temperature and may be present in the form of an amorphous phase.

3.2 Hardness and Residual Stress Measurement

Microhardness data for the various samples are shown in Table 7. For comparison, the hardness was also measured on an AISI 410 stainless steel plate. The hardness values show that there is a substantial increase in the hardness of HVOF coating after grinding. The increase in hardness was highest when the grinding thickness was 200 μm (Hv 1472). If it is compared with the as-coated sample, 33% increase in hardness can be observed over the as-coated sample hardness (Hv 1106). The hardness after 300 μm grinding decreased to 1348 Hv. The increase in hardness of coating may be due to increase in residual stress after surface grinding (Ref 10).

The residual stress measurement of the WC-CoCr coating was carried out using XRD techniques. Table 8 shows residual stress values. In the as-sprayed condition, the coating was found to have compressive stresses. This is from the high velocity imparted to hard WC particles by HVOF spraying. The WC particles are heavy and not softened by the spray temperature. They essentiallypeen the metal substrate and successive coating layers as they impact. Their mass kinetic energy is transferred as compressive stress.

The residual stress was also measured after grinding different levels of thickness. It was found that grinding in general resulted in higher residual compressive stresses as compared to their as-sprayed counterpart. Given the fact that

Table 7 Average hardness of coatings after and before surface grinding

Material	Microhardness (HV _{0.3})
AISI 410 SS	199
HVOF-0 (as-coated)	1106
HVOF-100	1300
HVOF-200	1472
HVOF-300	1348

Table 8 Effect of surface grinding on residual stress

Sample description	Residual stress, MPa	
	Longitudinal	Transverse
HVOF-0 (as-sprayed)	-26.2	-24.3
HVOF-100	-56.3	-82.7
HVOF-200	-72.6	-126.4
HVOF-300	-64.5	-117.3

coolant was used while grinding, the heat generation at the surface was minimal. The resulting compressive residual stress was possible as a result of mechanical interaction of abrasive grains with the work piece leading to non-uniform plastic deformation which introduced compressive residual stress (Ref 16). This compressive residual stress increased with the increase in grinding thickness up to 200 μm and later decreased.

XRD patterns of WC-CoCr-based powder and their coating, given in Fig. 4 and 5, show the peak broadening of the ground sample compare to as-sprayed sample and powder sample, which confirms the presence of residual stress in the surface ground samples. The powder sample pattern can be treated as zero residual stress sample, whereas the as-sprayed and ground

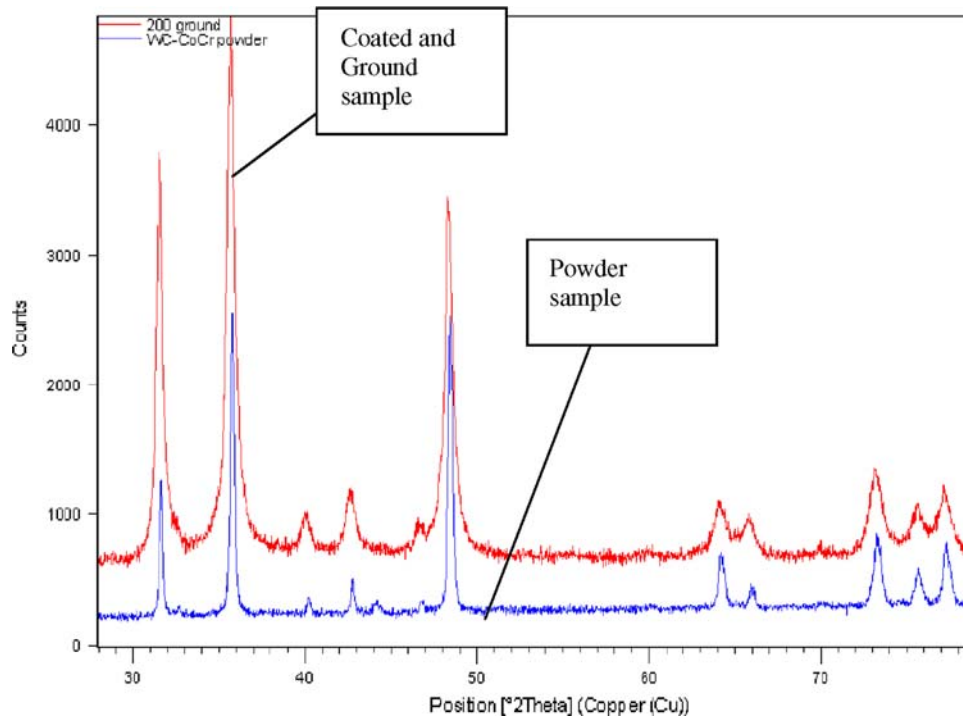


Fig. 4 Comparison of HVOF coating powder and surface ground coated sample

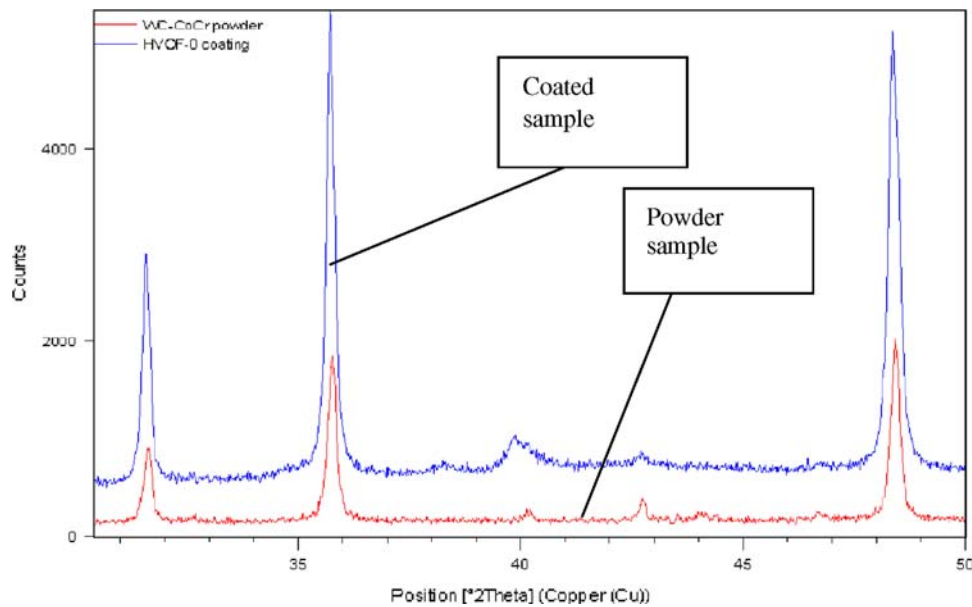


Fig. 5 Comparison of HVOF coating and powder sample

samples showed substantial amount of peak broadening which is due to the presence of residual stress (Ref 17).

3.3 Abrasive Wear Behavior

The abrasive wear rate of the HVOF-coated sample for different samples with different grinding thicknesses is given in Fig. 6. The wear rate of as-coated sample is higher than the ground sample. Volume loss (wear rate) of the as-coated sample is 1.74 mm^3 and that of ground sample is around 0.62 mm^3 .

Therefore, by surface grinding, the coating becomes more wear resistant than the as-coated sample. The increase in wear resistance can be attributed to the increase in microhardness of the coating because the wear rate is directly proportional to the hardness of the material being subjected to wear. The volume loss of the coating was calculated by taking the coating density as 12.8 g/cm^3 .

To understand the wear behavior of coated sample, the abraded surfaces were observed under SEM. The micrographs are shown in Fig. 7. It can be seen that tungsten carbide grains

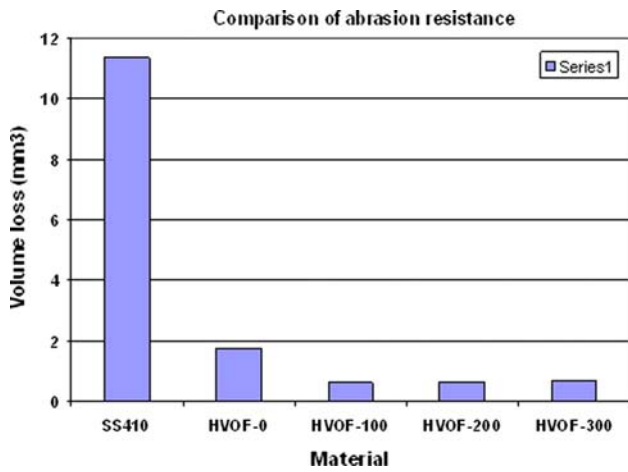


Fig. 6 Comparison of abrasive wear resistance of WC-CoCr-based coating 410 SS

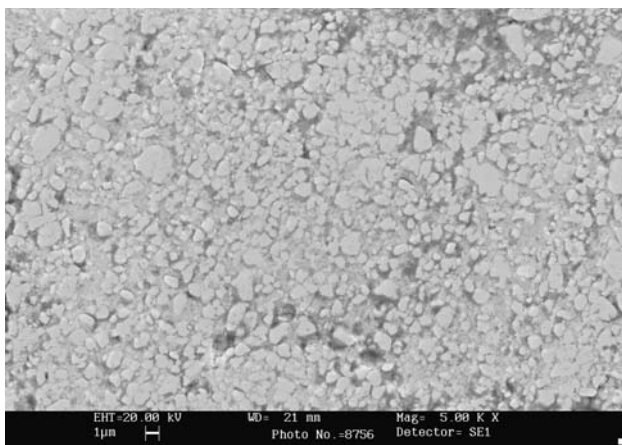


Fig. 7 SEM micrograph of surface after abrasive wear test

bonded with each other by metallic support. In the same figure, it also can be seen that a few grains of tungsten carbide have come out in some regions of the micrograph. In these HVOF-coated samples, the mechanism of wear was by selective removal of the binder caused probably by plastic deformation and fatigue due to the repeated action of the abrasive particles followed by the undermining of the carbide particles resulting in their eventual pullout (Ref 6, 8). Cobalt is softer compared to tungsten carbide and prone to plastic deformation. In the coating matrix, tungsten carbide grains are held in the coating by the metallic phase. The moment the metallic phase is removed from the coating, the carbide grains become free and easily come out. A similar grain removal mechanism has also been reported elsewhere (Ref 7, 8).

3.4 Erosive Wear Behavior

The liquid slurry impingement test result is shown in Fig. 8. The erosion rate goes down with the increase of surface grinding. Erosion rate, i.e. volume loss for HVOF-0 (as-coated sample) sample, was 4.28 mm^3 . The volume loss for HVOF-100, HVOF-200 and HVOF-300 μm coatings was 2.49, 0.71, and 0.79 mm^3 , respectively. This indicates that the coated sample becomes more erosion resistant by surface grinding of

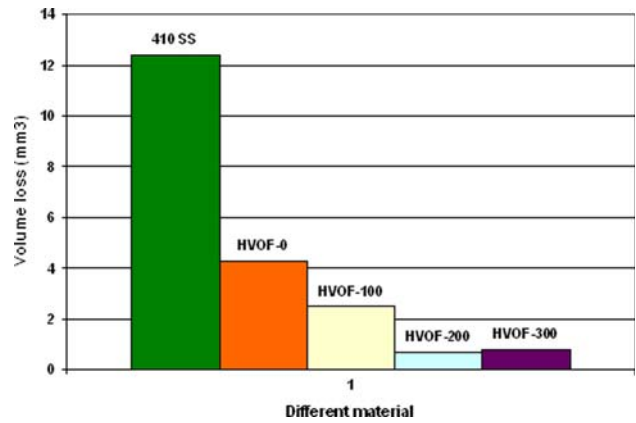


Fig. 8 Erosion resistance performance of different coating samples and base metal

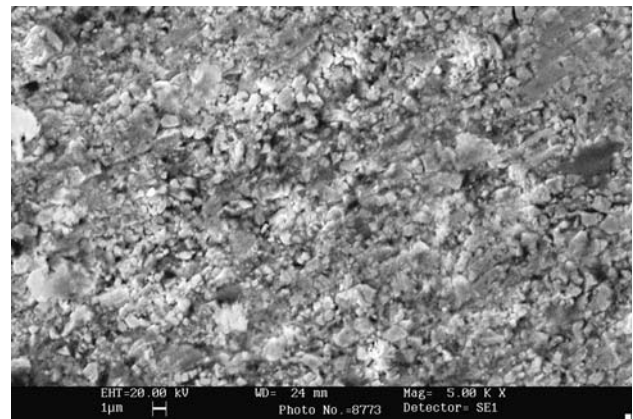


Fig. 9 SEM micrograph of eroded surface of HVOF-coated sample

around $200 \mu\text{m}$ thickness. The increase in erosion resistance of the coating after surface grinding is due to the increase in hardness which also has been seen for the case of abrasive wear behavior. This is because the wear resistance is directly proportional to the surface hardness (Ref 18).

To understand the erosion mechanism, the eroded surface was observed under the SEM. The surface shows removal of tungsten carbide particle due to cracking and followed by carbide pull out which can be seen in the SEM micrograph of Fig. 9. Basically under high pressure of impingement, the brittle grains of tungsten carbide crack. With time these cracked particles become loose and come out. The moment one pit is developed upon the surface, it becomes weakest spot on the surface and the metallic phase eroded away. Similar explanation also has been reported elsewhere (Ref 8, 10).

4. Conclusion

From the above-mentioned tests of different coating and ground samples, the following conclusions can be drawn.

- The surface microhardness of the WC-CoCr-based HVOF coating sample increased by surface grinding. Approximately 33% increase in hardness was observed over the

as-coated samples by surface grinding to a thickness of 200 μm . The reason for high hardness is believed to be the incorporation of residual stress by surface grinding. The presence of residual stress was confirmed by broadening of the XRD pattern and internal stress data measured by residual stress analyzer. This residual stress is compressive in nature that will help the life of a dynamic component like turbine blade, etc.

- Residual stress measurement on the surface of different ground samples shows an increase in residual stress and x-ray peak broadening compared to powder sample.
- The abrasive wear resistance also increased by 64.3% after surface grinding to a depth of 100 μm . The volume loss of as-coated sample was 1.74 mm^3 and that of ground samples was around 0.6 mm^3 . When it is compared with 410 SS sample, the abrasive wear resistance of HVOF-200 increased by 12 times over the conventional 410 SS plate.
- The erosive wear resistance increased by 83.4% after surface grinding. The increase in erosive wear resistance was higher for the coating ground to a depth of 200 μm . When it is compared with 410 SS sample, the erosion resistance is 20 times better than the conventional 410 SS plate.
- SEM examination shows that abrasive wear starts due to plastic deformation and subsequent removal of metallic phase, i.e. cobalt. As a result, proximal tungsten carbide grain gets free and eventually come out. In case of erosive wear, it is observed that the tungsten carbide grains being the brittle phase crack easily due to high impingement of sand loaded water. The cracked particle slowly comes out and exposes the metallic phase to erosion.
- The abrasive and erosive wear resistances of WC-CoCr-based HVOF coating can be improved further by surface grinding to a depth of 200 μm thickness. This improvement is due to the increase in microhardness of the coating by removal of the lower hardness surface layers.

5. Future Study

This study showed that there is a stress gradient across the thickness due to grinding parameters. Further study can be undertaken to understand the level of stress after deposition of one pass to another pass for a particular set of deposition parameters. This also can be done by changing the various HVOF spray process parameters.

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