

## **Effect of Porosity on Cavitation Erosion Resistance of HVOF Processed Tungsten Carbide Coatings**

**T. Pramod<sup>1</sup>, R.K. Kumar<sup>2</sup>, S. Seetharamu<sup>3</sup> and M. Kamaraj<sup>4</sup>**

<sup>1, 2, 3</sup> *Materials Technology Division, Central Power Research Institute  
Prof. Sir C.V. Raman Road, Bangalore, India.*

<sup>4</sup> *Department of Metallurgical and Materials Engineering,  
Indian Institute of Technology (Madras), Chennai, India.*

### **Abstract**

The phenomenon of cavitation is widely experienced in both pumps and under-water components of hydro power plants. The mechanism of material damage during cavitation is mainly attributed to implosion of high velocity bubbles on to the surface giving raise to local increase in stresses in excess of 1.4 GPa. In addition, material wastage due to particle induced erosion is observed in hydro plants utilizing silt laden water for power generation. In order to mitigate the severe erosion due to silt and cavitation, the components are presently given a hard coating of 300 to 500 microns using High Velocity Oxy Fuel ( HVOF ) technique.

The present paper highlights the results of cavitation erosion resistance evaluated on two different tungsten carbide coating processed through HVOF. The samples of size 15 x 15 mm were cut and polished using various diamond grits to achieve a polished scratch free surface. The properties of coating such as chemical composition, phase analysis, hardness, porosity, surface roughness were evaluated. The indentation toughness of coatings was evaluated at a test load of 10 kg on the cross section of coatings. The cavitation erosion resistance was carried out on a vibratory type cavitation test rig according to ASTM G32 for duration of 10 hours. The weight loss of coating and surface roughness of cavitated surface was measured at different intervals. The progression of surface damage morphology at different locations of the coating was observed in Scanning Electron Microscope. The effect of porosity, initial surface roughness was studied with respect to the metal

loss during cavitation. The mechanism of metal removal has been identified based on the progress of surface degradation.

**Keywords:** HVOF Technique, Cavitation erosion resistance, Porosity, Surface topography, Surface roughness, SEM.

## 1. Introduction

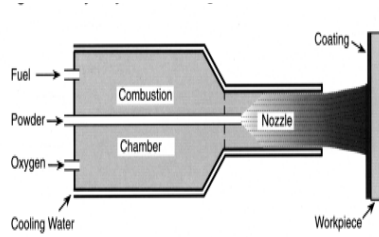
Hydraulic machinery such as turbine, pump are used in the generation of electric power, mining industry etc., are always working in liquid or air-liquid two phase flow condition. Cavitation and silt erosion are the main reason for the energy and material loss in this kind of machine. In order to protect the machine from cavitation and silt erosion, many research institutes are involved in developing a new erosion resistant coating to increase the lifetime of the machines. The erosion resistant hard surface coating of turbine is one of the methods of minimizing effect of erosion.

Cavitation is a phenomenon of formation of vapor bubbles in low pressure regions and their collapse in high pressure regions, increasing the local metal wall stresses in excess of the yield strength of the material [1-3]. Cavitation can present different forms in hydraulic turbines depending on the machine design and the operating condition. The prevalence of cavitation would result in high vibration levels, instabilities and material damage due to erosion. It is difficult to avoid cavitation completely in hydraulic turbines but can be reduced to economic acceptable level. The amount of cavitation damage caused to the turbine material depends on cavitation intensity & the resistance of material. As the cavitation erosion occurs at solid/liquid interface, often related to surface properties rather than bulk properties. Thus most of the hydro components are surface coated to achieve improved erosion life.

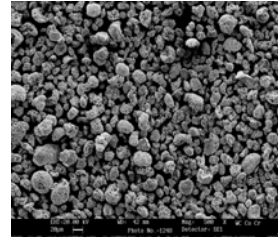
In recent years, HVOF spraying has been considered an asset to the family of thermal spray processes. The application of HVOF based coatings holds promise in hydro plants in the view of its advantages in higher density and bond strength. The service life of presently used hard carbide coatings are affected by hardness, carbide size, porosity, processing conditions & field conditions [4, 6]. Thus the need for optimizing the process variables is considered important from the view point for achieving optimum erosion resistance properties in the coatings.

### 1.1 Principle of HVOF Thermal Spray Process

The HVOF (High Velocity Oxygen Fuel) Thermal Spray Process is designed to produce extremely high spray velocity. This method is basically a high pressure water cooled HVOF combustion chamber and long nozzle. Fuel (kerosene, acetylene, propylene and hydrogen) and oxygen are fed into the chamber, combustion produces a hot high pressure flame which is forced down a nozzle increasing its velocity. Powder is fed axially into the HVOF combustion chamber under high pressure. Fig. 1 shows the schematic of the HVOF Process. The morphology of the feed stock powder used for coating process is shown in Fig. 2.



**Fig. 1:** Schematic of HVOF Process



**Fig. 2:** WC-CoCr spray powders  
-45 +15 $\mu$  size

The heated powder particles leave the nozzle at high velocities in excess of 700 m/s) strikes the substrate surface forms dense coating in successive layers.

## 2. Materials Studied

Two tungsten carbide coatings were made on to 304 grade base stainless steel of steel of size 100x100 x8 mm by HVOF technique. JP 5000 equipment with sulzer metco WOKA 3602 spray powder having average grain size of 1.6 micron was used for spraying. The process parameters followed during the coating process are given in table.1.

Table 1: Process Parameters of HVOF Technique.

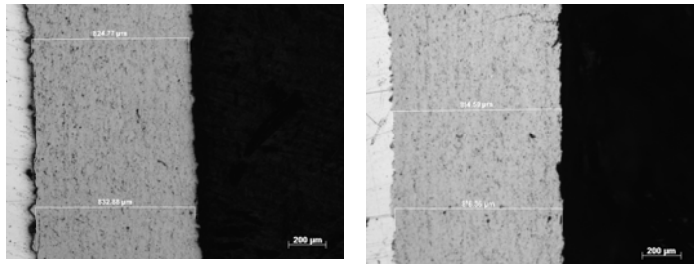
Primary gas flow ( Nitrogen )		50 lpm
Kerosene flow		15lph
Nozzle diameter		10 mm
Oxygen flow		1100 scfh
Transverse speed		175 mm/s
Approx. thickness of coating per pass		6-8 $\mu$ m
Spray distance	HVOF-1	300 mm
	HVOF-2	370 mm
Spray rate	HVOF-1	70 g/min
	HVOF-2	90 g/min

Fig. 3 shows the cross sectional view of both coatings. The coating thickness was observed to be in the range of 800 to 890 micron. The chemical compositions of the coatings were evaluated by Energy Dispersive X-Ray analysis and the hardness value was measured by Vickers scale at a test load of 0.3 kg and the results are given in table.2.

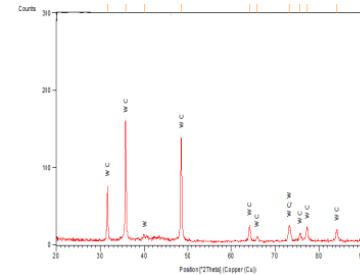
**Table 2:** Chemical composition of HVOF 1 and HVOF 2 (wt %).

Coating Type	C	W	Co	Cr	HV0.3
HVOF-1	5.6	80.2	8.92	3.96	1045
HVOF-2	5.8	79.8	9.61	4.13	1160

The phase analysis of the coating was carried out using XRD and the result has shown predominantly the tungsten carbide peaks with a small peak of metallic tungsten (Fig. 4). Small samples of size  $15 \times 15 \times 8$  mm were cut by EDM process from the plates prepared. The cut samples were polished using different grits of diamond grinding.



**Fig. 3:** Coating cross section with measured thickness  
a) HVOF 1 and b) HVOF

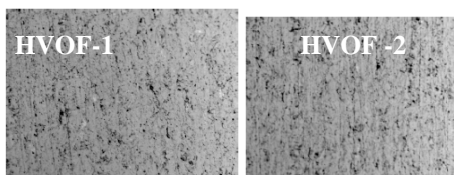


**Fig. 4:** Phase analysis of HVOF coating by XRD

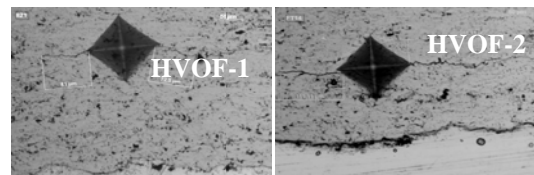
Discs (220 to 1200 grit) followed by cloth polishing using  $9\mu$ ,  $6\mu$  and  $1\mu$  diamond suspension spray.

### 2.1 Porosity of coatings

Thermal spray coatings are susceptible to formation of porosity due to lack of fusion between sprayed particle and expansion of gases generated during the spray process. The determination of area of porosity was carried out on the coating cross section by ASTM E2109 procedure and the optical micrograph of porosity is shown in Fig. 5. The average porosity value was reported based on five locations. The measured average porosity values were observed to be 2.5% and 3.6% for HVOF-1 and HVOF-2 coatings respectively.



**Fig. 5:** Optical micrograph showing porosity on the cross section of the coatings.



**Fig. 6:** Indentation toughness across the cross section.

### 2.2 Toughness measurement on coatings

The indentation toughness of coating was measured in the cross section at 10 kg load using Vickers indentation (Fig. 6). The average toughness value was calculated based on crack length observed using the formula.

$$K_c = 0.0193 * HV * D * (E/H_v)^{2/5} * a^{(-1/2)}$$

Where,  $K_c$  is Fracture Toughness ( $\text{MPa}\sqrt{\text{m}}$ ),  $HV$  is Vickers hardness (GPa),  $D$  is Diagonal ( $\mu\text{m}$ ),  $E$  is Young's Modulus (GPa) and  $a$  is Crack Length ( $\mu\text{m}$ ). The average toughness values of HVOF-1 and HVOF-2 coating based on 10 indentations are 2.3 and 1.78 respectively.

### 3. Experimental Procedures

Cavitation erosion resistance has been measured by means of a vibratory cavitation test rig. The ultrasonic vibratory test comprises of an electronic generator that generates 1500 watt of electrical energy. The detail of the cavitation test rig is shown in Fig. 7. The horn amplifies the small vibration into amplitude of 110 micron (peak to peak). The end of horn is attached with a replaceable titanium tip. The water level above the tip was maintained at 25 mm. During half of each vibration cycle, a low pressure is created at the horn tip surface, producing cavitation bubbles. During the other half of the cycle, bubbles collapse at the specimen surface producing damage and erosion of the specimen. Although the mechanism for generating fluid cavitation in this method differs from that occurring in flowing systems and hydraulic machines, the nature of the material damage mechanism is believed to be basically similar. The method therefore offers a small scale, relatively simple and controllable test that can be used to compare the cavitation erosion resistance of different materials and to study the nature and progress of damage in a given material in detail.



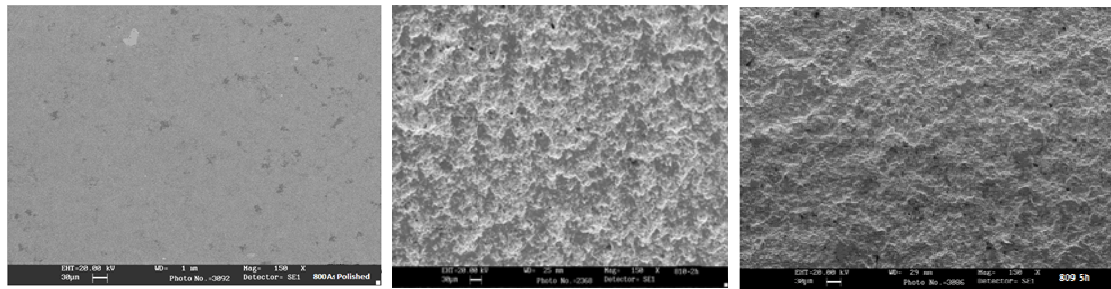
**Fig. 7:** Cavitation test setup.

The cavitation testing was carried out as per ASTM G32. The test specimen was placed at a small distance of 1 mm below the tip of the ultrasonic probe. The cavitation erosion was conducted for a total duration of 9 hrs and weight loss was measured at periodic intervals. The samples were cleaned in acetone, dried, weighed to an accuracy of 0.1mg using an electronic balance, to determine weight loss. The eroded surfaces were studied in SEM for identifying the mechanism of material damage in these coatings.

## 4. Results and Discussion

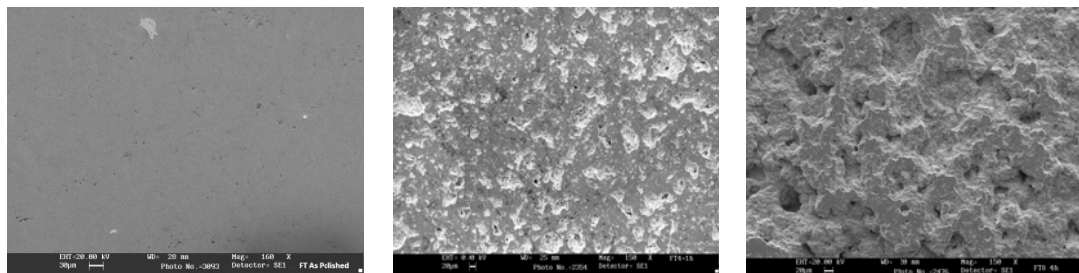
### 4.1 Surface degradation during cavitation

The evolution of surface damages during cavitation is observed through SEM. Fig. 8 and 9 shows the topography of various time varied cavitation tested coatings. The damage is observed to get initiated in the regions of porosity and progresses during continued exposure resulting in large craters in the affected areas. Under the conditions of low cohesive strength of built-up layers in the coating coupled with localized bubble implosion pressures, delamination of the layers becomes the mode of metal removal giving rise to increased rate of metal loss.



**Fig. 8:** Surface topography of cavitated tested HVOF-1 coating after different exposure periods.

a) As polished region b) 2h c) 5h

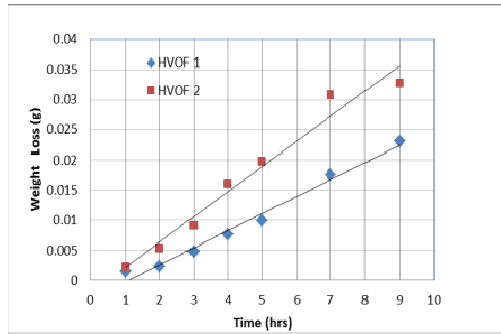


**Fig. 9:** Surface topography of cavitated tested HVOF2 coating after different exposure periods.

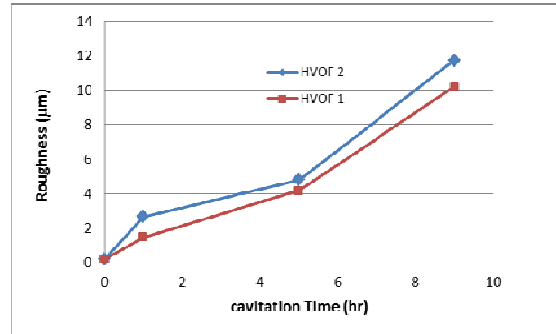
a) As polished region b) 1h c) 4h

### 4.2 Cavitation loss measurements

The variation of weight loss of the samples with cavitation time is shown in Fig. 10 and the roughness value of the cavitated surface is shown in Fig. 11. In general, the weight loss increases linearly with cavitation time for both coatings. The metal loss due to cavitation is observed to be 1.4 to 2.3 times higher in HVOF-2 coatings and the rate of weight loss is nearly two times in HVOF-1. The extensive damage in the surface morphology of HVOF-2 coating in combination with higher porosity level lend support to this finding. The change in roughness assumes a lower value during the initial periods of cavitation upto 5 hrs and increases at a higher rate during the extended periods of cavitation.



**Fig. 10:** Cavitation loss with time



**Fig. 11:** Variation of roughness with time

## 5. Conclusions

The systematic study on the cavitation resistance of HVOF processed tungsten carbide coating studies has been carried out covering the porosity, surface degradation studies and the evolution of surface roughness. The salient findings of the studies are as follows.

1. The process parameters such as powder spray rate and spray distance affects the porosity of the coating.
2. Small variation in hardness does not affect the cavitation erosion resistance.
3. The coating porosity readily affects the rate of metal loss during cavitation and the metal loss in the initial stage of cavitation occurs in porosity regions. While the actual metal loss during initial stages of cavitation is comparable with different porosities, the higher porosity coatings experience accelerated surface damage during extended hours of cavitation. Thus the rate of metal loss is considered the function of final surface porosity of the coating.
4. Coating with combination of higher toughness and low porosity are considered important for achieving improved cavitation resistance.
5. The roughness of the cavitated surface progressively increases with time and follows similar trend with that of metal loss.

## 6. Acknowledgement

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