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INFLUENCE OF HIGH VELOCITY OXY-FUEL (HVOF) DEPOSITION PROCESS ON CAVITATION RESISTANCE OF TUNGSTEN CARBIDE COATINGS

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Abstract. *Cavitation is a phenomenon which occurs due to the implosion of water vapor bubbles on a surface, leading to wear, and consequently mass loss. Cavitation erosion can cause damages to components, which can be protected by coatings to reduce the damage occurrence. Thermally sprayed coatings are very used to mitigate against wear applications, including cavitation. The HVOF spray process is one of the most used process, as it results in coatings with a good density, generating hard and tough coatings. Among the materials used in wear resistance, tungsten carbide coatings are the most used, because it offers the combination of high hardness, toughness and adherence that can provide a good cavitation resistance. In this work, the influence of different HVOF process, specifically the fuel type and torch used, on the microstructure and mechanical and cavitation properties of these coatings was studied. Also, the characterization and measuring of porosity, hardness and toughness was made. It was also noted that coatings deposited by HVOF with kerosene fuel, presented higher cavitation resistance, compared with coatings deposited by HVOF process with gas fuel.*

Keywords: *Cavitation Resistance, Tungsten Carbide, HVOF Deposition, Liquid and Gas Fuel.*

1. INTRODUCTION

One wear process very common in industries and power plants is cavitation, which can be defined as a phenomenon caused by the formation and collapse of bubbles in a fluid. As these bubbles rupture occurs near of the surface, they could introduce several damages to a component surface (Shreir, *et al.*, 1994). Cavitation causes major problems in different equipment used in a fluid medium such as pumps, valves and turbines, leading to material damage, reducing equipment life, efficiency and increasing the repair costs. The cavitation process in solid materials usually occurs in four different stages: incubation, acceleration, stationary and wear decrease. Understanding the wear mechanism at each stage is very important to develop solutions that can delay the cavitation process.

One way to repair the damaged components and delay the wear effects of cavitation is using thermal sprayed coatings. Thermal spray based repair of these components is an affordable and effective way to obtain a life extension and maintenance cost reduction (March and Hubble, 1996). Since 1980's, much work has been done to examine the efficacies of thermal spray coatings in cavitation situations. At that time, traditional spray coatings, for instance plasma arc and flame sprays had weak interlamellar bond and were generally porous, offering limited resistance against cavitation. The advent of high velocity spray processes, especially HVOF, offered new opportunities to develop improved wear and corrosion protection in situations demanding high resistance to wear (Pawlowski, 1995).

Cemented carbide based coatings (WC-Co, WC-CoCr) are widely deposited by HVOF process, providing coatings that result in good values of surface hardness and toughness, and thus wear resistance. Among the materials contemplated, Tungsten Carbide – cobalt (WC-Co) based cermet coatings offer the combination high hardness (through the WC phase), toughness (through the Co matrix) and adherence, leading to duality of properties to meet several wear resistance applications (Ndlovu,2009).

In this work, two different WC-Co alloys, with different Co contents have been selected in order to evaluate the effect of binder content on the mechanical properties, (hardness and fracture toughness), as well as cavitation resistance of the coatings. Additionally, these characteristics were evaluated for different HVOF deposition processes, using liquid or gas fuel, in order to verify the influence of these different deposition processes on mechanical properties and cavitation resistance of these coatings.

2. MATERIALS AND METHODS

For this study, two WC based materials commonly used in industrial applications, WC-12Co and WC-17Co (Global Tungsten Products, Towanda, PA, USA) were selected. These were sprayed on steel substrates (AISI 1008) with dimension of 220 x 25 x 2.24 mm. The compositions of the powder and substrate are showed in Tab. 1.

Table 1. Chemical composition of WC-Co alloys and substrate steel. *

Alloy	W	Co	C	Fe	Mn
WC-12Co	82.1%	12%	5.4%	<0,5%	-
WC-17Co	77.3%	17%	5.2%	<0,5%	-
Substrate Steel	-	-	<=0.1%	99.3 – 99.7%	0.3 – 0.5%

* Chemical compositions were provided by the manufacturer

Two different HVOF processes were used for coating deposition. One process used Kerosene as liquid fuel (LF), and the other one used Hydrogen (H_2) as gas fuel (GF). For the liquid fuel deposition, the spray torch JP5000 (Praxair TAFA, Concord, NH, USA) was used and Diamond Jet (DJ2000, Oerlikon Metco, Westbury) was used for gas fuel deposition. Altogether, four coatings were sprayed, and the parameters for each sample are listed in Tab. 2.

Table 2. Parameters used in the spraying process of the coatings for gaseous and liquid fuel torches.

Sample	Distance (m)	Kerosene Flow (L/h)	Hydrogen Flow ($x10^3$, L/h)	Oxygen Flow ($x10^3$, L/h)	Feed Rate (g/min)
WC-12Co GF	0.230	-------	41.06	13.85	38
WC-12Co LF	0.330	24.61	------	56.64	65
WC-17Co GF	0.230	-------	41.06	13.85	38
WC-17Co LF	0.330	24.61	------	56.64	65

Particle diagnostics were conducted prior to the coating deposition process using AccuraSpray^{TM} sensor (Tecnar Automation, QC, Canada). According to Tecnar (2017), this sensor measures the infrared radiation emitted by the sprayed particles and uses it to calculate the average temperature and velocity of the sprayed material. These measurements of particles provide an estimate of particles melting and their kinetic energy.

In order to perform analysis of the microstructure and the cavitation resistance, samples were sectioned into two parts. One section, with dimensions of 60 mm x 25 mm, was used to perform cavitation tests. The other was used for microstructural characterization, and underwent mounting in Bakelite, followed by polishing with diamond grinding disks between 220 and 1200 mesh (Aka-Piatto, Akasel Roskilde, Denmark), and for polishing, diamond suspensions of 3,0 µm, 0,25 µm and silica colloidal 0,04 µm were used (Buehler, Lake Bluff, IL). The microstructure was analyzed by an optical microscope, model Zeiss Imager A.2M (Zeiss Microscopy, Oberkochen, Germany) and SEM microscope with EDS chemical characterization, Tescan model Vega 3, (Tescan Brno, Czech Republic) and EDS model x-act by Oxford (Oxford Instruments, Abingdon-on-Thames, United Kingdom).

The Vickers hardness test was performed with 300 gf of load according to ASTM E384-15 with a standard indentor Shimadzu HMV-2G, (Shimadzu Corporation, Kyoto, Japan). Twenty indents were performed on each cross-section surface. The fracture toughness test was performed on cross section samples with 1,000 gf of load, using Vickers indenter. Five indentations were made on each coating. The toughness (MPa√m) was calculate following the equation proposed by Evans and Wilshaw (1976), Eq. (1).

$$K_{IC} = 0.079\left(\frac{P}{a^{\frac{3}{2}}}\right)\log\left(\frac{4.5a}{c}\right) \tag{1}$$

Where P is the applied load (mN), a is half the diagonal of the indentation (µm) and c is the crack length measured from the center of the indentation (µm). This equation is valid for the range of $0.6 \leq c/a \leq 4.5$ (Varis *et al.*, 2014) and, thus, all results could be considered valid in this test. This approach to fracture toughness evaluation has been successfully applied in various prior studies involving thermal sprayed WC-Co, such as works from Vackel *et al.*, (2015) and Usmani *et al.* (1997).

The characterization of the coatings phases was performed by X-ray diffraction on SDX 6000 equipment (Shimadzu Corporation, Kyoto, Japan) with Cu Kα wavelength of 1,54nm, working voltage of 40 kV, 20 mA current. The reading was performed with a scan speed of 1°/min and 0.02° step, thereby obtaining a diffraction pattern for each sample.

The samples used for cavitation test were grounded and polished on the coating surface, following the same procedures of the cross-section samples. The cavitation test was performed based on ASTM G32 / 15, and slightly modified to the indirect method of testing. This test involves a sample fixed at a distance of 0.5 mm from the tip of the horn, 19.5 mm of diameter, vibrating at 20 kHz frequency in distilled water at 20 ± 1 °C.

After each interval of time, the mass loss was measured, using a precision scale. The volume loss was calculated dividing the mass loss by the density of each coating. The density of the coatings was also calculated, using the porosity of each coating and the density of the powder, provided by the manufacturer, 13,55 g/cm^3 for WC-12Co and 12,91 g/cm^3 for WC-17Co. The surface subjected to the cavitation test was analyzed with the electron microscope, obtaining images of predetermined areas, characterizing volume loss mechanism of the coatings.

3. RESULTS AND DISCUSSION

3.1 Particles and Torches Analysis

The particle diagnostics results for the four conditions are shown in Fig. 1. The particle temperature (T) & velocity (V) differences between the coatings produced by the two spray torches, are supported by previous studies, showing higher V and lower T for HVOF-LF compared to HVOF-GF, for instance Vackel *et al.* (2015) and Sudaprasert *et al.* (2003). The main reason for this difference is the higher gas velocity achievable by HVOF-LF torches, transferring a greater energy to the particles during flight. This higher particle velocity also decreases the time of the particles flight, thus lowering the amount of thermal energy transfer to the feedstock by the plume.

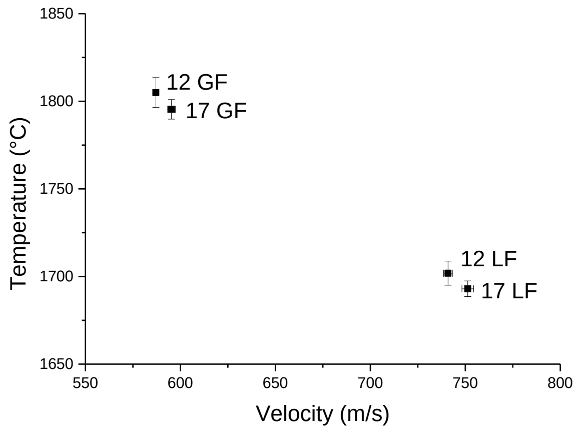

Figure 1. Temperature and velocity for WC-12Co and WC-17Co sprayed by HVOF-GF and HVOF-LF torches.

When comparing the two materials for the same process, the WC-12Co shows slightly higher particle T and lower V compared to the WC-17Co in both the LF and GF conditions. This could be due to the WC-12Co having a larger amount of WC within the individual particles, generating a greater amount of exothermic decarburization per particle, and so raising the measured temperature. Based on the observations made on Figure 1, it can be inferred that the differences between the coatings produced by different torches would be more significant than those brought by the variations in powder compositions.

3.2 Microstructure and Mechanical Properties Analysis

The microstructural analysis can be seen in Fig. 2. It can be noticed that all coatings had a very similar microstructure, with almost the same characteristics. However, some differences still can be noted. The coatings had different levels of porosity and depends on the HVOF process.

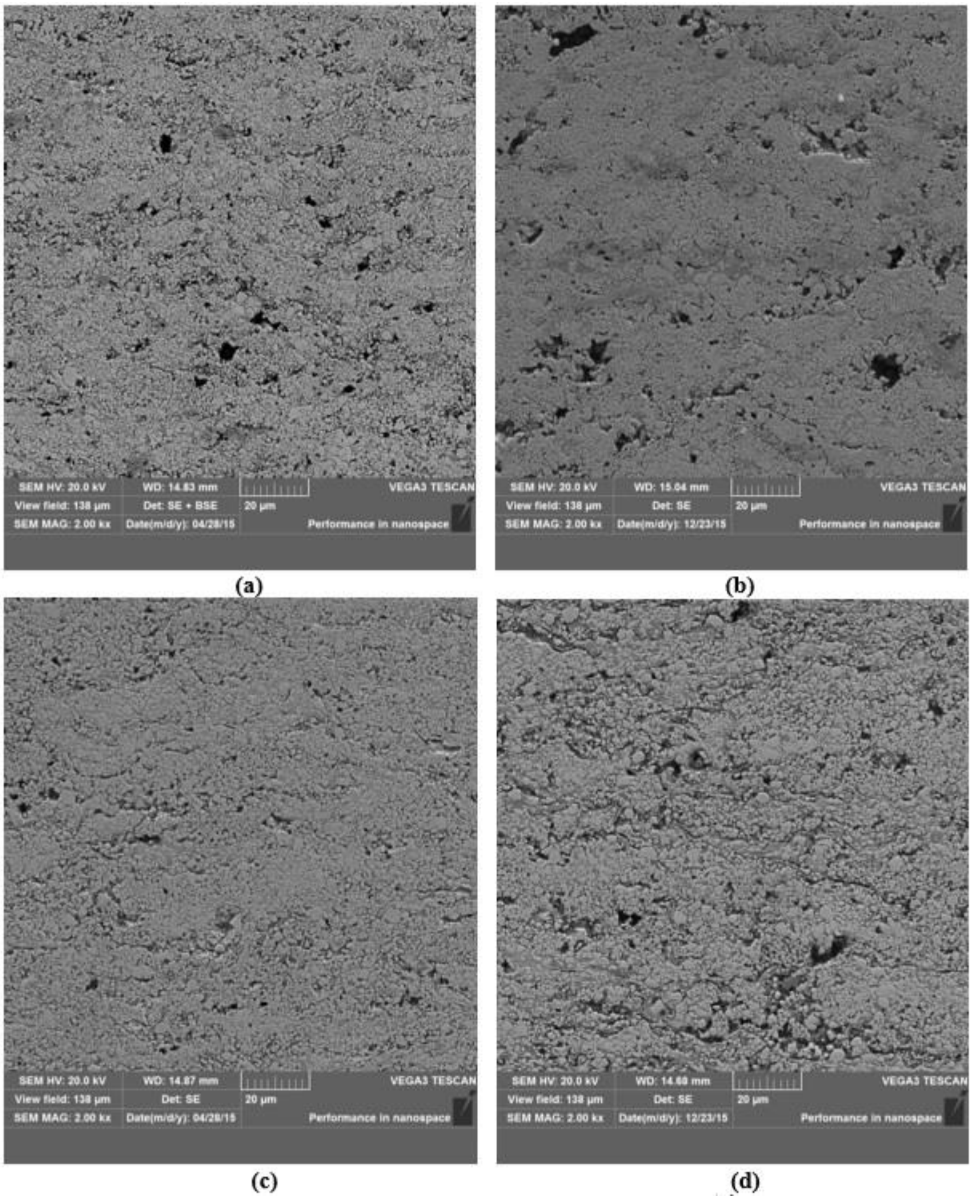

Figure 2. Scanning electron microscopy at 1000x magnification of (a)12 LF (b)12 GF (c)17 LF (d)17 GF sprayed coatings.

The porosity and density of the samples can be seen in Tab. 3. The higher porosity for HVOF-GF samples can be attributed to the lower velocity of this process, with lower compaction (Picas *et al.*, 2009). The difference between the porosity on the microstructures of WC-12Co and WC-17Co were less significant than observed by the different processes.

Table 3. Density and porosity of the coatings for gaseous and liquid fuel torches.

Sample	Porosity (%)	Density (g/cm^3)
12 GF	3.32 ± 0.53	13.10
12 LF	1.30± 0.21	13.37
17 GF	3.15± 0.72	12.50
17 LF	0.47± 0.15	12.85

The XRD analysis is presented in Fig. 3, showing that the formation of WC and W_2C was very similar, regardless of the deposition process and binder content.

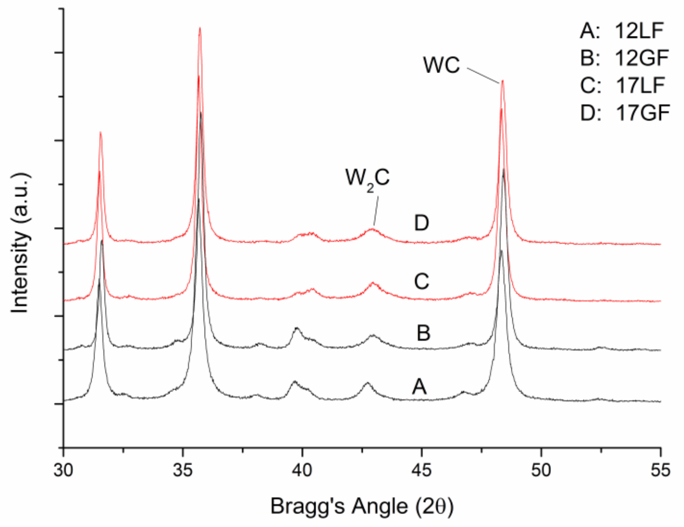

Figure 3. XRD analysis of WC-12Co and WC-17Co coatings sprayed by HVOF-GF and HVOF-LF torches.

The hardness of the coatings was also analyzed, according to Tab. 4. It is possible to realize that the coatings deposited by HVOF-LF presented higher hardness than those obtained by HVOF-GF. This behavior can be attributed to the higher density of the coatings and lower porosity, increasing the hardness of the coatings (Picas *et al.*, 2011). Surprisingly, for each process, the carbide content doesn't show a significant impact on hardness. For instance, if we take variability into account, all the four coatings have very similar hardness results.

Table 4. Vickers hardness and fracture toughness of the coatings for gaseous and liquid fuel torches.

Sample	**Vickers Hardness (HV)**	**Fracture Toughness MPa $\sqrt{m}$**
12 GF	991.56±120.68	4.85±0.17
17 GF	890.20±109.03	5.52±0.89
12 LF	1067.23±85.37	5.69±0.49
17 LF	868.67±117.83	6.68±0.77

Table 4 also shows the fracture toughness comparison among the various coatings. It is evident that the toughness of the coatings was related to the increase of binder content, with higher toughness values of the WC-17Co coatings, if compared to the same deposition process. A higher Co binder content can promote an increase in toughness due to higher energy absorption by the metallic phase than tungsten carbide, as a result of the of the crack tip dulling (Chivavibul *et al.*, 2007). For the conditions tested in this work, the fracture toughness increase in the coatings with better cohesion properties of the lamellae, promoted by the higher particles velocity and, consequently porosity reduction of the HVOF-LF coatings. Similar results were found in literature (Varis *et al.*, 2014). These results can be explained by the effects occurring ahead of crack propagation, that are affected by the microstructure of the material, mainly by the porosity of the coating (Wei, 2010). By the microstructure analysis, the HVOF-LF coatings had a higher density, with a great lamellae cohesion and adherence, leading to an increase in toughness if compared to coatings generated by HVOF-GF process. Furthermore, another effects can be related to the stress over the crack opening, which may be related to residual stress during the deposition.

3.3 Cavitation Analysis

The result of the cavitation volume loss of the deposited coatings is observed in Fig. 4. In the coatings deposited by LF-HVOF less accumulated volume loss was seen, if compared with those by GF-HVOF. The WC-17Co coatings appeared to be more resistant to cavitation erosion phenomena in relation to WC-12Co coatings.

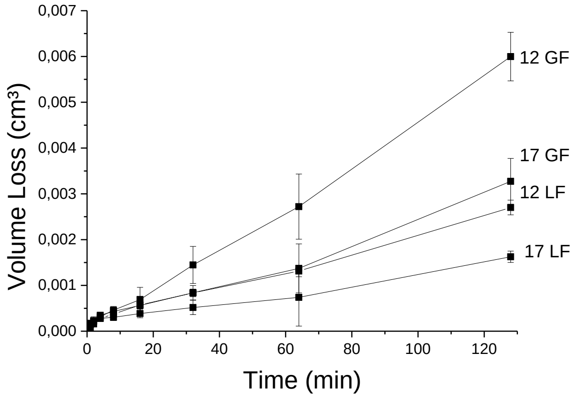

Figure 4. Accumulated volume loss during the cavitation test for sprayed coatings.

Figure 4 shows greater volume loss rate in the earlier stages of the test, through 16 minutes. After 16 minutes of testing, the coatings showed a more linear volume loss until the end of the test. In Fig. 5 the erosion rate response of the various coatings during the ultrasonic cavitation test is showed. The coatings had higher cavitation erosion rate at the start of the test, and then it was reduced significantly before stabilizing, within approximately 16 minutes of test. After these interval of test, a constant volume loss rate can be noticed for all coatings.

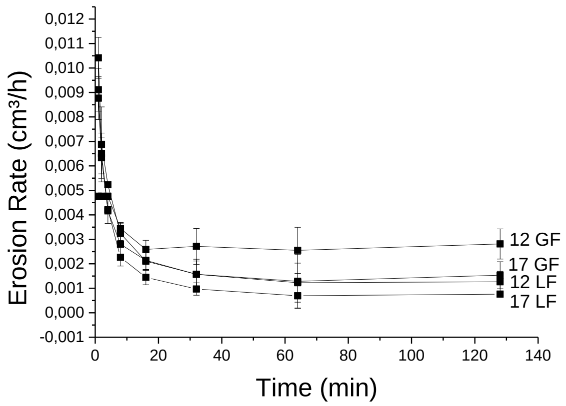

Figure 5. Erosion rate during the cavitation test for sprayed coatings.

This behavior can be explained by the skipping of incubation stage for these samples. As these coatings do not behave as bulk materials, the first stage is acceleration, with a high erosion rate at the beginning, followed by a stationary stage. The wear damage produced by the implosion of bubbles during cavitation can be evaluated in terms of fatigue damage, and by the crack growth rate (Hattori and Nakao, 2001; Bedkowski *et al*., 1999; Patella *et al.*, 2013). The aspects that influenced the crack growth in this material include Co binder content and porosity, which have also been found to affect the cavitation resistance of the material. The correlation between the volume loss, Vickers hardness and toughness of the sprayed coatings is showed in Fig. 6.

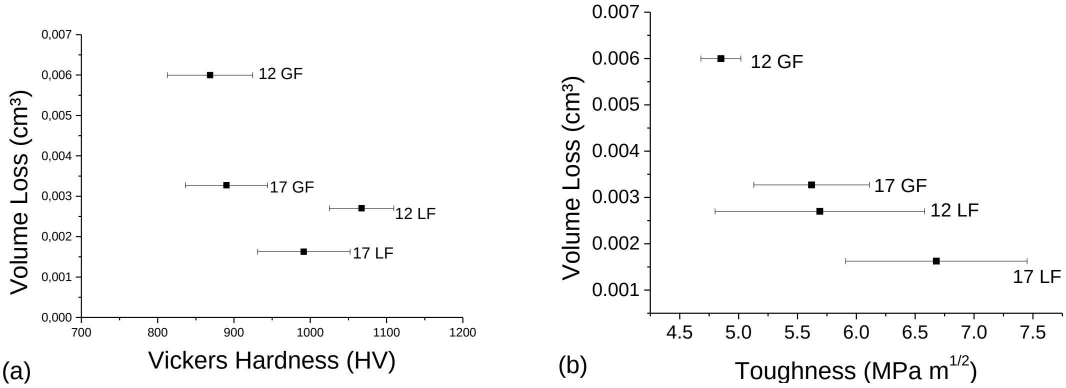

Figure 6. Correlation between volume loss and (a) Vickers hardness and (b) fracture toughness for sprayed coatings.

The binder content increase promoted an increase in toughness of WC-Co coatings sprayed in this work. This feature allows greater absorption of energy, once Co is a ductile binder that can promote a blunting effect at the crack tip. Similar results were found in literature (Lima *et al.*, 2004; Lin *et al.*, 2014). The porosity reduction of the HVOF-LF coatings can also affect the cavitation resistance of the coatings, because the crack formation, and consequently mass loss, can start in pores of the coatings, as reported in the literature (Patella *et al.*, 2013). Another aspect is the higher particles velocity of the HVOF-LF process, which can promote an increase in splats adhesion (Kumar *et al.*, 2016).

According to Hattori and Nakao, (2001) the maximum mass loss rate in cavitation erosion tests can be evaluated in terms of the hardness and fatigue crack growth rate. However, in the present work, cavitation resistance does not show a direct relationship with the hardness of the material, but with the fracture toughness. Fracture toughness can measure the capability of energy absorption during crack growing.

4. CONCLUSIONS

It is possible to conclude that the torch type used for the deposition of coatings by the HVOF technique has a strong influence on the mechanical properties and cavitation resistance of the coating. The different torches with different fuels deposit coatings with significant differences in the velocity and temperature of the sprayed particles, with liquid fuel having higher velocity and lower temperature than gas fuel. In general, the liquid fuel sprayed coatings showed higher cavitation resistance as well as higher hardness and fracture toughness than those obtained by gas fuel. Also, a clear relation has been established between fracture toughness and cavitation resistance, and it can be related to residual stresses formation during deposition, which is focus of future works.

5. ACKNOWLEDGEMENTS

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