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COMPARISON BETWEEN TWO SURFACE PREPARATIONS OF WC-10CO-4CR AND THEIR EFFECT ON EROSION WEAR RESISTANCE

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Abstract. *Tungsten carbide WC-10Co-4Cr is used in many hydro power generation components such as Francis, Pelton and Kaplan runners to improve surface properties and increase erosion wear resistance. The HVOF process is well known for coating manufacturing and, in addition to many benefits, is associated with failures that can happen during the process, such as cracks and coating detachment. In case of failures during application, the removal of all coating and reapplication is stablished as a good practice, because no coating shop can guarantee the coating quality in a repair. Considering these points, this work aims to understand the limitations of coating repair that uses two different kinds of surface preparation. The first one was the surface sandblasting with aluminum oxide and the second one was electrochemical partial removal of coating. Both preparations were followed by coating deposition and comparison in a slurry erosion test rig. Results indicate that surface roughness increase seems to be one of the key factors for repair improvement.*

Keywords: *coating, erosion, HVOF, tungsten carbide, thermal spraying*

1. INTRODUCTION

According to (Winkler, 2014), there is a current increase of hydro power plants with problems of hydro abrasive erosion. Erosion wear problems results in efficiency losses and increase in the need of maintenance, which impact directly in the revenue of hydro power plants.

The level of erosion wear in hydro power components is influenced by many variables, such as design of the power plant, design of the hydraulic components and sediment content on water.

The design of hydraulic components can be influenced from the shape of the parts up to the selection of materials. In the last case, manufacturers of hydro power components, and even the literature (Thapa et al., 2012), focus attention on WC-10Co-4Cr coatings.

The literature regarding WC-10Co-4Cr reports many improvements of wear resistance with the change of coating process (Bolleli et al., 2015) and even process parameters (Gui et al., 2012) (Murugan et al., 2014), but there is little information regarding problems during the process, such as cracks and detachments, which may be similar to those found in thin films (Hutchingson and Suo, 1992).

For the treatment of cracks and detachments in coatings, the best practice is total removal and reapplication until no problem can be found, because no coating shop can guarantee the quality in a repair. Additionally, the observation of erosion wear in Francis, Kaplan and Pelton runners that can be found in (Winkler, 2014), (Thapa et al., 2012) and (Liang, 2015) indicate that wear is not uniform in such runners. Thus, one may consider making quick repairs for emergency maintenances, until more time is available for a major repair.

The goal of this work is to understand the limitations of a coating repair by testing repaired coatings during erosion wear and to analyze the feasibility of localized repairs.

2. LITERATURE REVIEW

2.1 Erosion wear models

According to (Kosel, 1992): “solid particle erosion is the loss of material that results from repeated impact of small, solid particles”.

The variables that influence the solid particle erosion wear rate depend on the type of material that is being eroded. Such dependence is separated by (Hutchings, 1992) in ductile materials (Eq. 1) and brittle materials (Eq. 2).

$$Mass\_of\_material\_removed = K.\rho.\frac{m.U^{2}}{2.H} \tag{1}$$

$$\frac{E}{\rho} \propto r^{0.7}.U^{3.2}.\frac{\sigma^{0.6}}{K_{c}^{1.3}.H^{0.25}} \tag{2}$$

In Equations 1 and 2, K is a dimensionless factor, ρ is the density of the eroded material, m is the mass of the erosive particle, U is the speed of the erosive particle, E/ρ is the volume eroded per unit of mass of erodent particles, r is the radius of the erosive particle, σ is the density of erosive particles, Kc is the fracture toughness of the eroded material and H is the hardness of the eroded material.

Basically, Equations 1 and 2 can have their dependencies separated in three parts: operation dependency, erosive particle properties and characteristics, and eroded material properties. The operation dependency has a considerable influence in the erosion rate and it is represented by the particle speed. This speed can be related to the speed of water flow in the case of hydro power components, which is influenced by the design of the machine. The erosive particle is characterized by mass, density, size and indirectly by the dimensionless factor. All these variables are influenced by the river conditions in a hydro power plant. The eroded material is represented by hardness and fracture toughness and it is directly related to the machine design.

2.2 Erosion wear in WC-10Co-4Cr coatings

The WC-10Co-4Cr coating is a composite material that has a reinforcement of WC (brittle material) wrapped by a binder of Co and Cr (ductile material). From the erosion wear point of view, (Verdon et al., 1997) and (Gant and Gee, 2015) have shown that the coating may have different behaviors depending on the erosion conditions. The main modes of material removal are:

- Ploughing and micro-cutting on the binder region;
- Delamination due to cracks around the binder;
- And binder corrosion.

The authors (Verdon et al., 1997) studied WC-12Co coatings applied with hydrogen (type 1) and propane (type 2) in a slurry erosion test. Type 1 coating did not change the dominant mechanism (ploughing and micro cuttings) for the studied parameters. Nevertheless, type 2 coating changed wear mechanism from ploughing and micro-cutting to delamination after 140 m/s of flow speed.

2.3 Adhesion of coatings and roughness

The main superficial interaction between the substrate and a thermal sprayed coating is physical (70-80% of the contact area), the remaining is given by chemical and metallurgical interactions (diffusion and chemical reaction between splat/splat and splat/substrate, chemical adsorption) (Lima and Trevisan, 2007).

As the main interaction that results in attachment of the coating to the substrate is physical, one must consider two points: formation of surface topography and splat of particles.

The splat is influenced by the process parameters of the coating gun and substrate initial temperature. The topography is influenced by the sandblasting of the surface.

According to (Lima and Trevisan, 2007), the ideal roughness for coating deposition is between 2.5 and 13 μm and adhesion increases with roughness. For a coating of WC-Co with powder particles of +15/-53 μm using propane for application, (Wang et. al, 2005) concluded that for a roughness higher than 5.8 μm Ra the adhesion was higher than 70 MPa. In case the roughness is lower than 1.7 μm Ra the adhesion reduced to 25-40 MPa.

2.4 Erosion wear in Pelton runners

According to (Duan and Karelin, 2012), the Pelton runner works with flow velocities of 100 m/s from the water jets and accelerations that are normal to the bucket on the order of 50000 m/s^2. The direct impact of a high speed jet in the separation areas called splitter and cutout area, in conjunction with sediments in water, provides high wear in such areas.

The wear inside a Pelton bucket is not uniform and it is not only due to the direct impact in the separation areas. (Thapa, 2004) studied the wear in some runners and concluded that sediments are separated in size due the high accelerations inside the Pelton bucket. Thus, there is an impact of smaller sediments near the outlet edge and impact of bigger particles near the inlet edge (splitter and cutout areas). As a consequence, the wear inside the Pelton bucket it is not uniform and also depends in the size distribution of the particles.

3. EXPERIMENTAL PROCEDURE

3.1 Test samples

The test samples were manufactured with a substrate of ASTM A743 CA6NM and a coating of WC-10Co-4Cr of powder size +10/-38 μm applied by HVOF process with hydrogen using a DJ 2600 hardware. The test samples were divided into three groups:

- A (control group): one coating application only.
- B (electrochemical partial removal): after an initial coating application, a thickness of 150 μm was removed with abrasive, then an additional electrochemical removal was conducted with a commercial nickel stripper, until roughness reached a minimum value of 5.8 μm. Finally, another layer of coating was deposited to complete a thickness 250-300 μm.
- C (sandblasting): same removal with abrasive performed in B, then sandblasting with aluminium oxide. Finally, another layer of coating was deposited to complete a thickness 250-300 μm. The arithmetic average of the roughness profile (Ra) was measured after each step of test sample manufacturing.

3.2 Sediments for testing

The sediments were analyzed by X-Ray diffraction in a range of 2-80º 2θ and a width pass of 0.02º 2θ and a time of 4 s per pass. Results are presented in Table 1.

Table 1 – Sediments analysis

Phase	Mohs hardness	<125 μm	500-1000 μm
Quartz	7	34.5 +/- 0.8	35.8 +/- 0.5
K-Feldspar	6	4.8 +/- 0.7	3.5 +/- 0.5
Plagioclase	6	20.5 +/- 1.0	29.5 +/- 0.7
Mica	2-3	17.2 +/- 1.6	13.8 +/- 1.0
Chlorite	ca. 2.5	7.8 +/- 1.0	6.8 +/- 0.6
Hornblende	5.5-6	6.6 +/- 0.7	4.2 +/- 0.4
Calcite	3	1.5 +/- 0.2	2.2 +/- 0.3
Epidote/Clinozoisite	6-7	7.4 +/- 0.7	3.9 +/- 0.4
Magnetite	5.5		0.3 +/- 0.1

3.3 Slurry erosion test rig

The slurry erosion test was performed according to the schematics in Figure 1. Basically, sediment feed rate and water pressure are regulated to be constant. The amount of wear is calculated as a function of the amount of sediments.

In order to have the required water flow, a water volume was measured for each pressure and a correlation between pressure and water flow was stablished.

To calculate the amount of wear for each test sample, their weight was measured with a high precision scale Kern ALJ 220-4 prior and after the erosion tests.

After the tests, the top of the specimens was characterized using optical microscopy. Sectioning of the specimens was conducted and cross sections were characterized using SEM and EDS mapping.

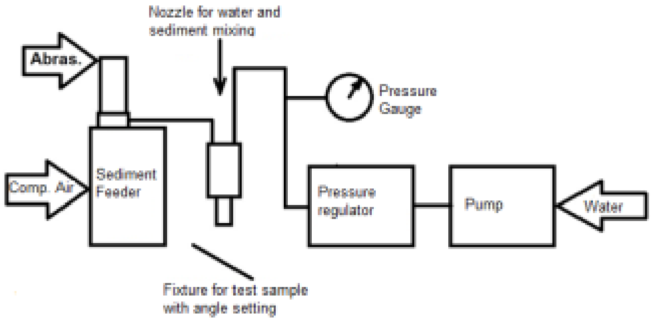

Figure 1 – Slurry erosion test rig schematic

4. RESULTS

As sprayed coatings showed a roughness 5.3-6.5 μm Ra. Grinding of groups B and C reduced the roughness to 1.1-2.1 μm Ra. Partial electrochemical removal increased the roughness of group B to 6-6.4 μm. Nevertheless, blasting of group C did not affect roughness significantly (1.8-2.1 μm Ra).

Table 2 presents the results of erosion wear observed with samples from groups A, B and C. Higher mass losses were observed for samples in group C. Results from groups A and B are similar, being higher for group B.

During the erosion test, detachment of coating in group C (figure 2a/b) was observed, which correlates well with the higher mass losses of the samples in this group. Microscope evaluation of a sample from group B indicated a small line that can have been originated by poor interlayer adhesion (figure 3a/b).

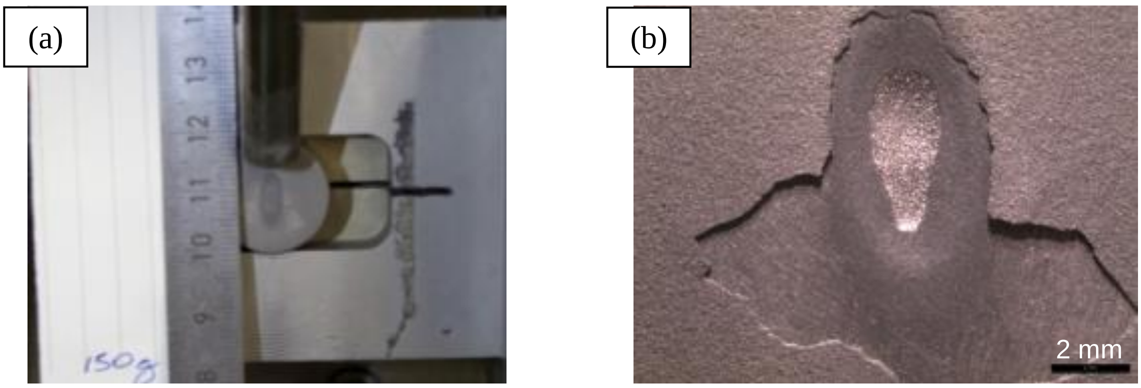

Figure 2: Group C. (a) After 150 g of sediments. (b) After 300 g of sediments.

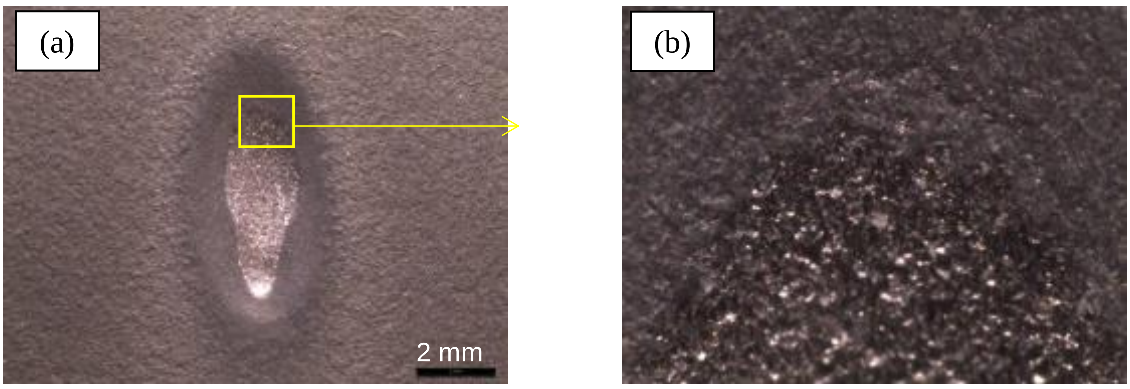

Figure 3: Group B. (a) After 300 g of sediments. (b) Zoom of yellow area.

Table 2 – Average erosion in mg after 300 g of sediments

	Group A	*Group B*	*Group C*
Average	38.0	46.4	123.5
Std Deviation	1.2	2.7	27.4

After the erosion test, one of the test samples from group B was taken for cross sectioning and evaluation in the scanning electron microscope (SEM). Figures 4a and b show the analyzed area, where it was possible to observe a line of separation that is coincident with the surface preparation with electrochemical removal. Such line indicates either inclusion of material or separation between surfaces.

In the left side of Figure 4b there is a delamination (or detachment) and a line in the remaining coating that has thickness consistent with that of the coating after electrochemical removal. In the right side of Figure 4b, coating thickness is on the order of 295 µm.

Comparing the erosion in mg from group A to group B, B has 22.1% ((46.4-38)/38) more mass loss. Supposing that when the thickness measured from the interface (or line between coating layers) is 59 µm, the detachment of coating would be 59/295 = 20% from its mass. This numbers are not exact but they are in the same order, thus, the coating detachment of 59 µm could be the explanation of erosion wear differences between groups A and B.

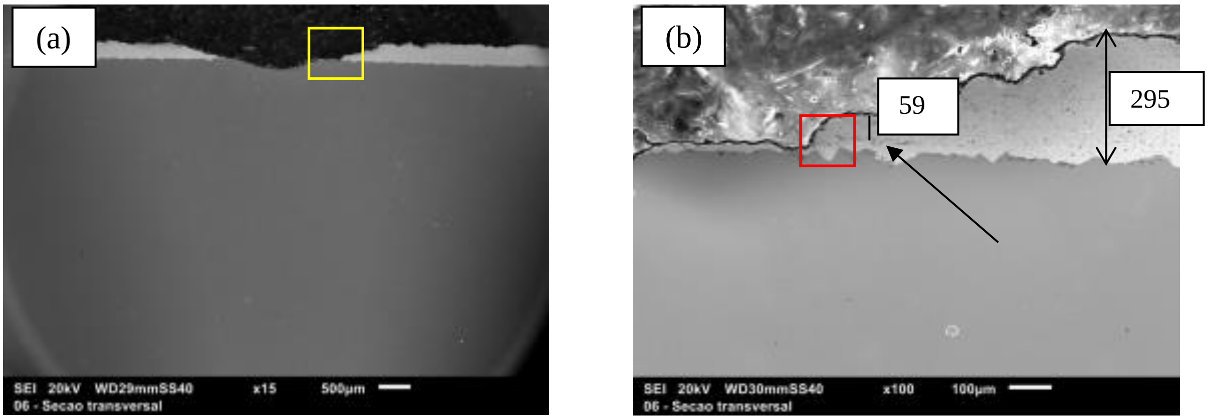

Figure 4: Group B. (a) MEV micrograph of group B section. (b) Zoom of yellow area from figure 4a

Energy dispersive x-ray spectroscopy (EDS) mapping was conducted in the area highlighted in Figure 4b. As shown in Figure 5, the EDS mapping for oxygen (in green) shows a concentration in the interface area, which could have been originated during or after the electrochemical removal.

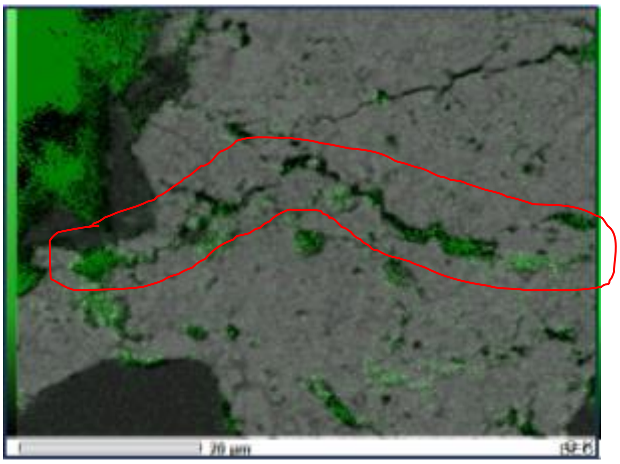

Figure 5: Group B – EDS mapping for O in the red area from figure 4b.

The probable cause of the difference of results between groups A and B was the contamination of the surface by formation of oxides during/after the electrochemical removal. In general, oxides have a lower mechanical strength then the non-oxidized material. With the decrease of thickness in the coating, the oxides could be mechanically affected and due their lower resistance, cracks appeared in the interface with consequent detachments of coatings in group B.

5. CONCLUSION

In this work, coatings of WC-10Co-4Cr, deposited on substrates with different preparation, were tested in erosion tests. The difference between groups A and C are due to early detachment of the coatings C during test, possibly due to low substrate roughness prior to the deposition.

The roughness resulting from the preparation of group A and group B test samples was equal or higher than 5.8 μm (Wang et. Al, 2005). Therefore, based on roughness, the adhesion for group B was expected to be the same as group A. Nevertheless, it seems that group B had early detachment, which can be explained by possible contamination of the interface during the processing.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE