Study and characterization of high velocity oxy-fuel thermally sprayed wear coatings

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Coatings have been used as an efficient and economic way of adapting industrial equipment components to a specific application. The importance and demand for coating protection has significantly increased in recent years, mainly for wear and corrosion applications. Several techniques and processes are available for coatings deposition. Electroplating (hard chrome) and welding (hard facing) have been traditionally used for wear applications. However, the use of thermal spray has increased in the last years, including traditional applications of those processes. In this work a study and characterization of tungsten carbide based coatings was carried out. The coatings were applied by high velocity oxygen fuel thermal spraying (HVOF) using two different HVOF systems. Microstructure, hardness, as well as wear characteristics of the coatings were evaluated. The results show that the obtained coatings present great characteristics and can be expected to face successfully several wear conditions.

1 Introduction

The use of hard coatings to improve wear resistance of mechanical components has been common for several decades, with several application techniques that include welding, cladding, electroplating (Hard Chrome), PVD (physical vapor deposition), CVD (chemical vapor deposition) and thermal spray. Thermal spraying is one of the techniques with higher development in the last years, coming up as an alternative, economically viable, related to the other commonly used processes [1, 2, 3].

Three basic types of wear are generally considered [1]: abrasive wear, that happens when hard particles slide or are forced against a surface in relation to which they are in movement, provoking displacement or material removal; adhesive wear, when two surfaces in attrition contact suffer local plastic deformation, occurring a local welding among the asperities; and erosive wear that results of the collision of solid particles or drops of liquids carried by a fluid against a surface. Several types of coatings can be used to combat all the three wear types, including situations where the wear is combined with corrosion in ambient or even high temperatures. The analysis for choice of the ideal coating and application process should take into account cost factors as well as medium and long-term efficiency, considering also the limitations and specificities of each process. For example, despite of the high wear resistance of PVD and CVD coatings such coatings are thin and have low impact and big abrasive particles loading resistance. Furthermore, the component to be coated can be too big to be covered in a PVD or CVD camera or to present any other geometric or thermal restrictions to those processes [1]. Among the most commonly thermal spray processes used to apply wear resistant coatings, High Velocity Oxygen Fuel (HVOF) process has been the choice mainly for carbides application [4]. The process is based on a high-pressure internal combustion system similar to a rocket motor in miniature. Fuel and oxygen are mixed to produce a jet of supersonic gas above 2000 m/s and 2800 °C [5]. The used fuels include kerosene, hydrogen, propylene, propane, acetylene, methyl-acetylene propadyene (MAP) and natural gas. The powder material is introduced into the hot flame inside the torch exit pipe. The produced coatings present higher hardness, adhesion, durability and larger possibility of thickness than the coatings produced by other thermal spray processes. An inherent advantage of the HVOF process is its ability to spray semi-melted particles to very high speeds (around 900 m/s) resulting in a quite dense coating with high adhesion and low oxides content. Overheated carbides can be decomposed and form less beneficial phases to the coating. HVOF process is plenty effective when accelerating very much the particles without heating excess. Carbides of several types are especially appropriate for HVOF application since they do not request significant coalition to deposit and to form an effective wear protective surface. Typical compositions are among 8 to 30% of the main alloy content that acts primarily as a binder for carbide particles [5]. One of the most used wear alloys has been WC-Co [6], sometimes tied up to other elements as Ni and Cr in order to offer better combined corrosion and wear resistance [7].

2 Experimental Procedure

For the development of the present work, WC-Co based coatings were produced by using two types of equipments: a conventional high pressure HP-HVOF model JP-5000 (Tafa, Inc., Concord, NH, USA) equipment and a portable HVOF equipment for use "in the field", model TJ-4000 (Tafa, Inc., Concord, NH, USA). The applied material was a spray dried and sintered WC-12%Co spherical powder (-325 mesh, 1342-VF, TAFA, Inc., Concord, NH, USA). The conditions and specific application parameters for each of the equipment are presented in Table 1. The coatings were applied on low carbon steel substrates. All samples were degreased and grit blasted with aluminum oxide (#60) before spraying. The average thickness of the coatings was 0,5 mm (500 μm). The samples with dimensions of 20 x 80 x 4,54 mm (3/16”) and ∅25 x 25 mm (1 inch), were mounted in a carrousel rotating at 80 rpm, staying the spray torch at a fixed distance, with vertical displacement of 0,5 m/min. A compressed air jet addressed to the posterior part of the carrousel was used to cool the samples. Samples temperature was measured during the deposition of the coatings through an optical pyrometer. It was not allowed to the samples to overcome 150 °C by means of the interruption of the application combined to air-cooling.

Table 1. HVOF application parameters

Parameter	JP-5000	TJ-4000
Torch barrel length (mm)	200	80
Spray distance (mm)	380	200
Spraying rate (g/min)	76	61,2
Oxygen flow rate (slpm)	944	472
Kerosene fuel flow rate (slpm)	0,378	0,23
Powder flow rate (slpm)	10,6	6,1
Combustion pressure (psi)	106 ± 5	100 ± 5
Oxygen pressure (psi)	143 ± 10	300
Fuel pressure (psi)	125 ± 10	90 ± 10
Carrier gas pressure (N) (psi)	50	22

The samples were evaluated with relationship to roughness, micro and macro hardness, adhesion and wear resistance. The roughness of sprayed surfaces was evaluated through a Mitutoyo roughness measurer model Surftest 301 (Mitutoyo, Japan). Vickers micro hardness measurements were accomplished with a load of 1000 g, taking the average value of 10 readings for each sample. Vickers macro hardness measurements were accomplished with load of 15 kg, also with average of 10 readings for sample. Wear resistance measurements were accomplished through Three Bodies Abrasion Test in agreement with ASTM-G-65-85 standard [8], procedure B. The used abrasive was quartz round sand, according to specifications of that standard. The test was done with a sand flow rate of 250 g/min, 200 rpm for the rubber wheel. The applied load was 130 N with 2000 total test revolutions. Coating thickness average was 500 μm. Scanning Electronic Microscopy (SEM), of the obtained coatings, as well as of abrasion wear tested surfaces was carried out using a JEOL electronic microscopy Model JXA-840-A. Dispersive Energy Analysis (EDS) complemented these evaluations.

3 Results and discussion

The results of roughness measurements have presented an average value of 5,30 μm for JP-5000 and 5,14 μm for TJ-4000 samples (Ra). Six samples were measured for each system. Calculated standard deviation was 0,343 and 0,417 for JP-5000 and TJ-4000 samples, respectively. Roughness level can be considered low having no significant variation among the samples coated by the two different equipments. According the powder manufacturer the surface roughness of the used powder in the as-sprayed condition should be 3,25 μm in Ra for a thickness of 2 mm. Since the layer thickness in this application is only 0,5 mm, the roughness is accompanying the profile obtained by abrasive grit blasting executed with aluminum oxide. Micro and macro hardness measurements are presented in Table 2. Micro hardness results are, basically, similar for the two studied systems, presenting high values in agreement to the expected results for the applied material. It is important to observe that the measurements were done on polished samples, with load of 1000 g in order to facilitate the reading of the printed diagonals. Generally, when the load is increased in micro hardness tests using diamond pyramidal indentator there are a tendency to reduce the obtained values, which would be larger in the readings with load of 200 or 300 g, for example, that are traditionally used [9, 10].

Table 2. Vickers micro and macro hardness (Kg/mm^2)

	JP-5000		TJ-4000	
	HV_{1000}	HV	HV_{1000}	HV
1	1235	791	867	812
2	1090	812	867	835
3	1090	791	915	812
4	1090	812	1159	770
5	1090	770	968	770
6	1318	791	1159	791
7	1159	750	1235	791
8	1159	750	1090	791
9	1411	791	1235	812
10	1159	791	1235	791
Mean (x)	1180,1	784,9	1073	797,5
SDev (σ)	104,47	20,76	146,51	19,28

Vickers hardness results have also showed quite high and similar values for the two systems, with an average variation of less than 2%. Tensile adhesion tests (TAT) were accomplished in conformity with ASTM-C-633-79 standard [11]. The adhesive used in the tests was a white epoxy Scotch Weld DP-460 (3M, Campinas, SP, Brazil) that has a traction tensile resistance around 35 MPa. Since coatings obtained by HVOF are known to overcome 68 MPa in TAT tests [12, 13], the accomplished test was just considered a verification of spraying and surface preparation quality. All tested samples have broken in the adhesive in the range between 28 to 35 MPa, which invalidates the test according the standard. Optical and scanning electron micro structural analysis has evidenced the similarity among the microstructures accomplished with the two equipments in morphology as well as regarding to density. **Figures 1** and **2** are representative of the coatings executed by the two equipments. It can be observed very low porosity (**Fig. 1)** and quite uniform distribution of WC (clear phase) in the metallic matrix regardless the used equipment (**Fig. 2**). No significant evidence of carbides dissolution can be noted as verified in spectroscopy analysis.

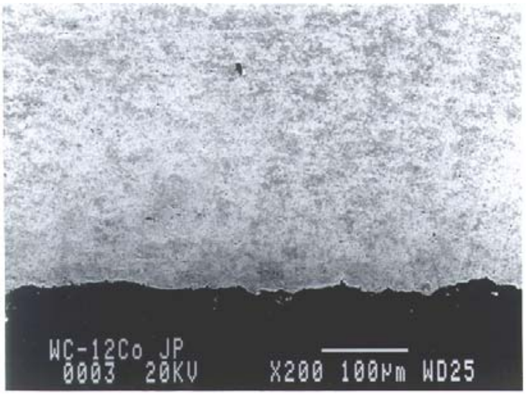
The results of abrasive wear tests accomplished in conformity with ASTM-G-65-85 are presented in Table 3. Mass loss results obtained by direct weighing in precision scale (0,001 g) were normalized for volume loss, according to the following equation [8]:

$$\text{Volume loss (mm}^3) = \frac{\text{Mass loss (g) x 1000}}{\text{Density (g/cm}^3)} \qquad \textbf{(1)}$$

Still according to the standard and considering the wear of the rubber wheel during the tests (2 mm diametrally), an adjustment was accomplished in the calculated value using **Eq. (1)**, showed in **Eq.(2)**:

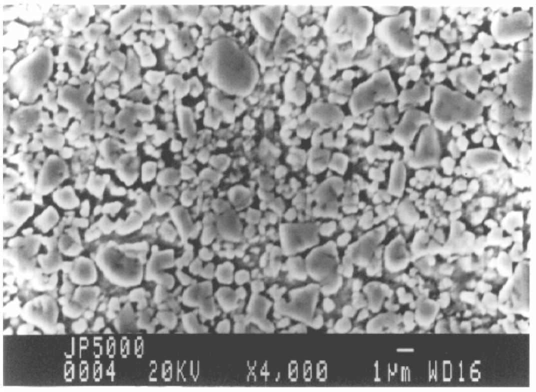
$$\text{Adj Volume loss (mm}^3\text{)} = \text{Volume Loss} \times \frac{228{,}6}{226{,}6} \quad \textbf{(2)}$$

(a) JP-5000

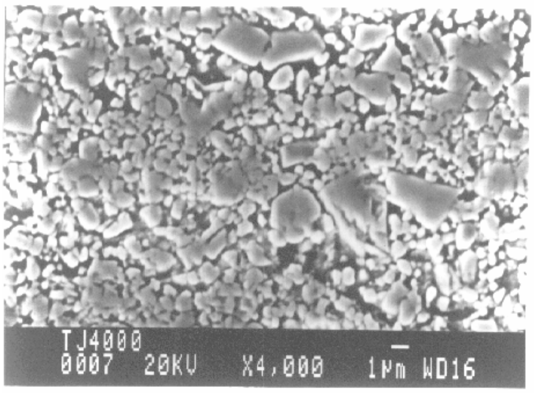


(b) TJ-4000

Figure 1. WC-12%Co coatings microstructure



(a) JP-5000



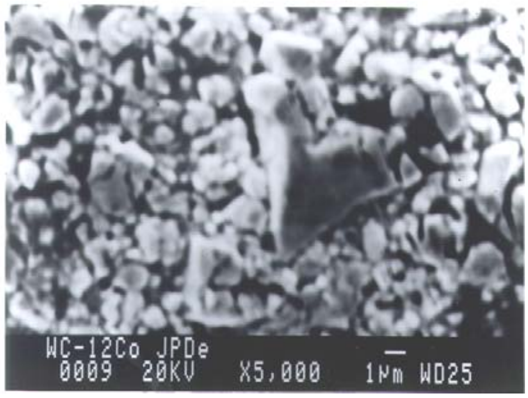
(b) TJ-4000

Fig. 2. WC-12%Co coating microstructures

Table 7. ASTM-G-65 abrasive wear test results

Sample	Mass Loss (g)	Volume Loss (mm^3)	Sample	Mass Loss (g)	Volume Loss (mm^3)
JP-1	0,054	3,83	TJ-1	0,058	4,12
JP-2	0,061	4,33	TJ-2	0,055	3,90
JP-3	0,064	4,54	TJ-3	0,065	4,61
JP-4	0,056	3,97	TJ-4	0,059	4,19
JP-5	0,051	3,62	TJ-5	0,055	3,90
JP-6	0,065	4,61	TJ-6	0,063	4,47
JP-7	0,057	4,04	TJ-7	0,060	4,26
JP-8	0,053	3,76	TJ-8	0,064	4,54
JP-9	0,056	3,97	TJ-9	0,061	4,33
Mean JP	0,057	4,07	Mean TJ	0,060	4,26
SDev (σ)	0,0045	0,326	SDev (σ)	0,0034	0,243

The density value for WC12%Co coating layer was considered 14,2 g/cm^3 based on physical properties values of the same material obtained by powder metallurgy [7]. Observing the values of Table 7, the similarity of the obtained results for the two systems in study can be verified with an average variation of less than 5%. The microstructure and morphology of the evaluated coatings, as well as the obtained roughness and superficial hardness values suggest a similar behavior for the two systems in the wear test evidenced by the results. **Figure 3** shows the microstructure of wear patterns obtained in the three bodies abrasion tests evaluated by SEM. The analysis of the elements was accomplished by spectroscopy of dispersive energy (EDS).



(a) JP-5000

(b) TJ-4000

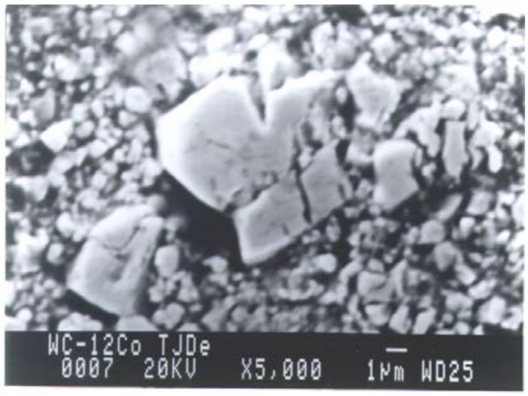


Fig. 3. Wear patterns in abrasive wear tests

It can be noticed in **Fig. 3** that an extensive wear of the metallic matrix has occurred which can be evidenced by the "grooves" between carbide particles and was confirmed by the spectrometry results. More than an abrasive wear of cobalt matrix phase it seems that some detachment of tungsten carbide particles has occurred influencing erosive wear more than abrasive. These removed particles are in the range size of 1 to 10 μm, in agreement with the original particle size of the used powder, shown in **Fig. 4**. It is also important to stand out that the obtained resistance values in the wear tests are quite high (low value of mass loss) which means that a good performance of these coatings in abrasive wear applications can be expected. In similar abrasive wear tests WC-12%Co sprayed by HVOF have presented an average wear rate of only 20% of that for hard chromium [14, 15].

Fig. 4 WC-12%Co original used powder

4 Conclusions

The results obtained in the present study allow the following considerations:

-The application of WC-12%Co coatings by two different HVOF equipments, i.e., JP-5000 and TJ-4000 have presented similar results with relationship to micro and macro hardness, microstructure, surface roughness and abrasive wear.

-Deeper analysis of the microstructure and wear patterns accomplished by SEM and EDS have showed no evidence of carbides dissolution in none of the obtained coatings.

-Even without a specific study of final cost of coatings for each type of equipment, it is important to stand out the possibility of obtaining advantages with the TJ-4000 unity due to its lower oxygen and fuel consumption. Any way, other factors such as deposition rates and energy consumption should be better evaluated for such comparison.

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4 Literature

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