Abstract. Ceramic coatings applied by several deposition processes on metallic parts for mechanical applications, exhibiting good combinations of hardness, wear, heat resistance and chemical stability, increased the slurry erosion resistance when compared to uncoated metal parts. Using a slurry erosion jet tester, erosion tests were performed on plasma spray coated SAE 1010 and brass substrates, with zirconia-8wt% yttria coatings. The erosion rate was determined by the mass variation under impact angles of 30 and 90°. Furthermore, the hardness gradient created by plastic deformation of the metal substrates was evaluated by micro hardness measurements from the metal-ceramic interface to the interior of the substrates. The quantitative results of the erosion rates and the microstructural characterization by optical and scanning electronic microscopy showed a better performance of the ceramic coated brass substrate when compared to SAE 1010 steel substrates. This result is due to enhanced plastic deformation found in the steel substrate indicated by increased micro hardness, near the coating interface.

Keywords: ceramic coatings, thermal plasma spray, slurry erosion
1. Introduction

The impact of a liquid flow containing solid particles produces a removal of superficial material by repeated impact of particles through a wear process called erosion. The erosive wear process is responsible for 8% of the whole wear processes, causing the decrease of lifetime for many mechanical components, like bomb shovels, valves, transport tubes, among others.1,2,4

Initial studies of the solid particles erosion indicated a complex phenomenon, involving chemical and mechanical parameters relative to the material, being the most important parameters deriving from the erosive flow (composed by the fluid and the erosive particles) and the eroded sample. Parameters related to the erosive flow included speed, density and chemical reactivity1; parameters related to the particles included shape and size, speed and the angle of impact; and the parameters related to the sample included microstructure, fracture toughness and hardness.

There is a growing interest by industries for materials that can resist efficiently to slurry erosion. In this way, ceramic materials are attractive options due to a combination of properties, such as high hardness, high fusion temperature, chemical stability and high level of chemical inertia2,4,7,8. Progresses in understanding, as much the behavior as the erosion mechanisms of the ceramic materials have been done recently, however the behavior and mechanisms related to slurry erosion continue to be badly explained. In relation to the most
important parameters in the erosive wear, a linear increase of the removed volume in relation to the time of erosion\textsuperscript{1,4}, an increase of wear rate in relation with the impact angle of erosive flow\textsuperscript{1,8}, and an increase in the wear rate in relation with the particles size and concentration in the liquid flow have been observed. However, the main parameter controlling the material removal of a ceramic material is its microstructure. It is usually accepted that the superficial material is removed by the intersection of cracks produced by the impact of erosive particles, associated with wear mechanisms by plastic deformation and brittle fracture.

Recently the new technologies of ceramic material superficial deposition on metallic substrates have been receiving the attention in the application of mechanical components subject to erosive wear\textsuperscript{2,4}. However, the methods of superficial deposition present problems relative to the weak adhesion of the deposited layers on the substrates, due to the great differences in their thermal expansion coefficients\textsuperscript{2,7}. The lamellar microstructures produced by the thermal plasma spray of ceramic materials are highly defective, presenting a weak interlamellar bonding, often with empties among the lamellae, unmelted materials and cracks\textsuperscript{7,8}. The influence of the microstructure and morphology of the coating on the erosion behavior has been recognized\textsuperscript{3,7}, while the hardness has not been demonstrated to have any correlation\textsuperscript{7}. The volume of material removed by erosion has been demonstrated to be linear with the time of impact\textsuperscript{2,4,7} and the mechanism of erosive wear is released by fracture in the edge of lamellae when there is weak bonding among them or by the fracture and plastic deformation of lamellae when the cohesion among them is enhanced\textsuperscript{7}.

The objective of this work is to analyze the influence of the substrate on the erosive wear of zirconia-yttria ceramic coatings deposited by thermal plasma spray by evaluation of the
2. Materials and Methods

For deposition of the ceramic coating by thermal plasma spray on the steel and brass substrates, a commercial powder (METCO 204 NS) composed of 92% ZrO₂ and 8% Y₂O₃, with a grain size ranging between 106 and 140 mesh, a density of 5.4 g/cm³ and a fusion point of 2480 °C, has been used. The chemical composition and the mechanical properties of the SAE 1010 steel and brass substrates are listed in table 1.

The surfaces of the steel and brass substrates were roughened prior the deposition of the ceramic coating by grinding with 100, 220 and 320 abrasive paper and subsequent blasting with alumina particles, in order to increase the adhesion of the coating on the substrates. The deposition of the ceramic coating on the substrates was accomplished by a plasma spray process, METCO 3MB-II plasma gun, using the following deposition parameters: tension of 450 V, current of 65 A and a distance of approximately 100 mm.

The slurry erosion tests were conducted using a jet impact tester device at room temperature (22 °C) under impact angles of 30° and 90°, with a jet velocity of 2 m/s and an amount of solid particles of 20 g. The solid particles used in this study were sand, with particles size ranging between 149 and 297 µm and a density of 2.59 g/cm³. The wear rate of erosion was determined by the volume change of the particles before and after the tests; only the ceramic
coating was subject to the erosive wear.

Optical micrographs and microhardness measurements on cross sections of the coatings were conducted with a Neophot 30 optical microscope, while micrographs of the surfaces prior and after erosion testing, as well as the observation of erosion craters in the cross sections were made in a scanning electron microscope, JEOL model JXA 840A.

3. Results and discussion

3.1 Adhesion of the ceramic coatings on the metal substrates

The superficial roughness is an important factor to assure a good adhesion between the ceramic coating deposited by thermal plasma spray and the metal substrate. An increased superficial roughness will provide a higher effective contact area, thus improving the adhesion of the coating on the substrate, because the bonding between coating and substrate is primarily mechanic in nature. The superficial roughness values for SAE 1010 and brass substrates are listed in table 2.

It is supposed that the higher superficial roughness of the brass substrate surface, compared to the steel substrate, is related with its higher ductility and its lower yield strength, see table 1.

Figures 1(a) and (b) show cross sections of the coated steel and brass substrates. A fairly large amount of porosity can be seen in both micrographs, but while for the steel substrate, fig. 1(a),
it is concentrated in the ceramic – metal interface, in the case of the brass substrate, Fig. 1(b), porosity is higher in the coating while the interface is almost pore free. This suggests a better adhesion of the ceramic coating on the brass substrate, probably related to the higher roughness of the brass substrate surface.

3.2 Erosive wear test

Table 3 and figure 2 show the volumetric erosion rates of the ZrO$_2$ – 8% Y$_2$O$_3$ coating on the steel and brass substrates under impact angles of 30 and 90$^\circ$ of the erosive flow. As can be seen, the erosion rates increase with increasing impact angle, independently of the substrate used, in agreement with other works$^{10,11}$. The higher erosion rates using steel as substrate in relation to the brass substrate may be explained by a higher porosity of the coating, as well as the weaker adhesion, see Fig. 1.

3.3 Microhardness

The microhardness in the substrates are listed in Table 4 and graphically represented in Fig. 3. The measurement were conducted starting at the ceramic – metal interface and proceeding perpendicular into substrates at even distances of aprox. 40 $\mu$m and applied force of 0.25 N. In the steel substrate a gradual decrease of the hardness with increasing distance from the
ceramic–metal interface can be noted. We believe that the higher hardness of the steel substrate close to the interface is the result of a hardening effect by deformation caused by the particle impact of the erosive flow. In the case of the brass substrate, no variation of the microhardness has been observed, indicating there has not been plastic deformation of the brass substrate by the particle impact.

3.4 Eroded surface of coatings

Figures 4 and 5 show eroded surface of the ceramic coating deposited on steel and brass substrates for an angle of impact of 90°.

The eroded surface of the ZrO₂–8wt-% Y₂O₃ coating on the SAE 1010 steel substrate (Fig.4a) for an impact angle of 90° presents characteristic lamellae, typical for thermal plasma spray deposited coatings; in some places presenting a plastically deformed shape, apparent cracks over the surface and a significant amount of lamellar fragments between adjacent lamellae. A detailed view of the area (Fig.4b) shows lamellar fragments of several sizes and the curvature of a plastically deformed lamella, caused by the impacts of the erosive particles. Under the same erosion conditions but using a brass substrate (Fig.5a), the coating is composed of smaller sized lamellae when compared to the case of the steel substrate, presenting cracks over the lamellar surface and randomly distributed voids on whole eroded surface. An area of this eroded surface (Fig.5b), shows plastically deformed lamellae.

The largest slurry erosion of the Zr-Y ceramic coating deposited on steel substrate for an
angle of impact of $90^\circ$, is related to the subsuperficial hardening of the steel substrate, according to an increase of the microhardness near the substrate/coating interface (Fig. 3). The high hardness of the steel substrate near the interface contributed with a smaller absorption of energy caused by the impact of the incident particles, and therefore, a larger portion of the impact energy is concentrated in the lamellae producing plastic deformation and fracture (Fig. 4a and b), favored by the voids caused by imperfections of the thermal plasma spray deposition process and by the low adhesion of the coating on the steel substrate (Fig. 1a and b).

4. Conclusions

From the obtained results it can be concluded that the erosive wear of the Zr-Y ceramic coatings presents a larger wear when deposited on a steel substrate. This fact is related to the subsuperficial hardening of the steel substrate that provides a larger energy of impact over the lamellae of the ceramic material, the formation of voids and the weak interfacial adhesion induced by the thermal plasma spray process, producing a mechanism of severe wear by plastic deformation and cracking of the lamellae.

5. Acknowledgements

The author (Marcelo Bondioli) wish to thanks CAPES, for financial support.
6. References


Table 1 – Chemical composition and mechanical properties of the SAE 1010 steel and brass substrates.

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical composition in weight</th>
<th>Mechanical properties</th>
</tr>
</thead>
</table>
| SAE 1010 Steel | 0.08% C, 0.01% Si, 0.40% Mn, 0.018% P, 0.016% S, 0.02% Ni, 0.01% Mo, 0.01% Cu and 0.004% Al | Yield Strength: 216 MPa  
Tensile Strength: 324 MPa  
Ductility, % of elongation (in 50mm): 28 |
| Brass      | 55% Zn and 45% Cu              | Yield Strength: 77 MPa  
Tensile Strength: 310 MPa  
Ductility, % of elongation (in 50mm): 68 |

Table 2 – Superficial roughness measure in brass and SAE 1010 substrate, after alumina grid
blasting.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Roughness in µm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ra</td>
</tr>
<tr>
<td>SAE 1010 steel</td>
<td>4,72</td>
</tr>
<tr>
<td>Brass</td>
<td>5,36</td>
</tr>
</tbody>
</table>

Table 3 – Mean volumetric erosion rate, in relation of the substrate type and impact angle of erosive flow.

<table>
<thead>
<tr>
<th>Substrates</th>
<th>Mean volumetric erosion rate [mm³/Kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30°</td>
</tr>
<tr>
<td>SAE 1010 Steel</td>
<td>238,4</td>
</tr>
<tr>
<td>Brass</td>
<td>178</td>
</tr>
</tbody>
</table>

Table 4 - Results of microhardness tests (HV) measured in SAE 1010 steel substrate and brass substrate, with confidence level of 95%

<table>
<thead>
<tr>
<th>Position (µm)</th>
<th>SAE 1010 Steel</th>
<th>Brass</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>102,44 ± 5,06</td>
<td>51,07 ± 2,67</td>
</tr>
<tr>
<td>Time</td>
<td>Steel Substrate</td>
<td>Brass Substrate</td>
</tr>
<tr>
<td>------</td>
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<td>-----------------</td>
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<tr>
<td>80</td>
<td>96.46 ± 8.20</td>
<td>53.82 ± 4.90</td>
</tr>
<tr>
<td>120</td>
<td>97.02 ± 7.80</td>
<td>51.57 ± 6.43</td>
</tr>
<tr>
<td>160</td>
<td>81.02 ± 10.88</td>
<td>49.09 ± 7.47</td>
</tr>
<tr>
<td>200</td>
<td>85.57 ± 15.42</td>
<td>52.84 ± 1.59</td>
</tr>
<tr>
<td>240</td>
<td>76.80 ± 7.35</td>
<td>53.28 ± 1.67</td>
</tr>
<tr>
<td>280</td>
<td>70.09 ± 5.20</td>
<td>53.83 ± 5.77</td>
</tr>
<tr>
<td>320</td>
<td>77.52 ± 5.88</td>
<td>54.21 ± 1.72</td>
</tr>
<tr>
<td>360</td>
<td>75.21 ± 4.91</td>
<td>54.76 ± 4.47</td>
</tr>
<tr>
<td>400</td>
<td>79.92 ± 0.33</td>
<td>54.02 ± 2.19</td>
</tr>
</tbody>
</table>

Figure 1. Optical micrographs of the ceramic coating – substrate interface. (a) Steel substrate, (b) Brass substrate.
Figure 2. Mean volumetric erosion rates of the ZrO$_2$ – 8 wt-% Y$_2$O$_3$ coating on steel and brass substrates versus impact angle.

Figure 3. Results of microhardness tests (Hv) made in cross sections of erosion craters, in (a)
SAE 1010 steel substrate and (b) brass substrate, with confidence level of 95%.

Figure 4. Eroded surfaces of the ceramic coatings deposited on the steel substrate (a). Detailed view (b). Impact angle of 90°.

Figure 5. Eroded surfaces of the ceramic coatings deposited on the brass substrate (a). Detailed view (b). Impact angle of 90°.