EVALUATION OF HVOF SPRAYED WC-13Co-4Cr AND HARD CHROMIUM ELECTROPLATED ON STAINLESS STEEL 15-5PH FATIGUE STRENGTH

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ABSTRACT
Fatigue failure is the result of a crack initiation and propagation as a consequence of cyclic loading. In the aeronautical industry, for components like landing gear, fatigue strength is an important parameter to be considered in project, as well as the corrosion and wear resistance. The 15-5 PH stainless steel is an aeronautical material used in applications that require high mechanical strength and corrosion resistance. Nevertheless its application is restricted due to low wear resistance. Therefore a hardening surface treatment is necessary. Nowadays the most applied surface hardening process in the aircraft industry is Chromium Electroplated, which increases the corrosion and wear resistance. Even considering satisfactory results, the use of hard chromium process has been restricted due to environment impact and to the human health. The main objective of this research was to study the influence of WC-13Co-4Cr HVOF thermal spray coated in the axial fatigue strength of 15-5PH stainless steel. Experimental results were compared with chromium electroplated. Compressive residual stress induced by the shot peening process were responsible for the increase in the fatigue life of HVOF coated material

Keywords: Thermal spray coatings, fatigue, 15-5PH steel, shot peening.

INTRODUCTION
The majority of mechanical failures are caused by fatigue due to cyclic loadings and surface degradation. Aeronautical steels, such as 15-5PH stainless steel, are submitted to variable amplitude loading and components are designed according to the required fatigue strength and corrosion resistance due to aggressive environments at which the material is submitted (Voorwald, 2008; Vincent, 2013).

However the 15-5PH stainless steel application is restricted due its low wear resistance, and under certain environmental conditions, corrosion may still occur with this material in aeronautical structures (Ital, 2008; Abad, 2010).

It is noted that surface integrity affects the fatigue strength (Vincent, 2013), therefore, corrosion degradation or any kind of surface damage may decrease the fatigue life. In order to avoid the surface degradation in aeronautical steels hard chromium coating has been used for many years. The hard chromium coating is used to obtain high level of hardness, wear and corrosion resistance (Vincent, 2013). Although this coating provides efficient material surface
protection, its replacement has been considered due to health and environmental damage, related to ion Cr6+, which is considered extremely aggressive (Bonora, 2010).

Thermal spray coatings as HVOF (High Velocity Oxygen Fuel) are being considered to replace chromium electroplated. HVOF coatings are based on thermal spraying and mechanical anchoring of the powders sprayed onto base material. Considering that the powders are in molten or semi-molten states at different sizes, the coating structure becomes non-uniform, with high adherence at the surface (TAHA-al et al., 2009). Better results considering fatigue strength and wear resistance comparing to chromium electroplated were obtained. In addition, the process is considered clean and harmless to the environment and human health (Culha, 2009; Ibrahim, 2007).

Generally, all surface discontinuity and residual stresses influence fatigue strength, and may lead to a premature failure in mechanical components. In the electroplated hard chromium process, high tensile residual stresses and high microcracks density are obtained, thus reducing the fatigue performance (Nascimento, 2001). According to Costa, 2009 and co-authors, results for fatigue strength of AISI 4340 steel HVOF coated was superior than the material chromium electroplated. Studies indicated that HVOF coated specimens have higher wear and corrosion resistance in comparison with hard chrome coatings (Nascimento, 2011).

In general, surface treatments reduce fatigue life due to the tensile residual stress induced by coating process and possible stress concentration points. Shot peening is a surface treatment widely used to introduce compressive residual stress by controlled plastic deformation, that provide corresponding crack closure stress, that will reduce the driving force for crack propagation. This process may prevent fatigue crack initiation and delay fatigue crack propagation (Costa, 2009; Carvalho, 2007; Manfridini, 2014; Vielma, 2014).

The influence of WC-13Co-4Cr coating applied by HVOF and hard chromium electroplated on fatigue strength was evaluated in this research. Scanning electron microscopy was used to analyse the fracture surface of fatigue test specimens and optical metallography was used to verify material microstructure, thickness and adhesion of coatings. Residual stresses were also associated to the fatigue performance.

**EXPERIMENTAL PROCEDURES**

The material used in this work was a martensitic stainless steel 15-5PH that combines high mechanical strength and high corrosion resistance. The 15-5PH steel chemical composition is shown in table 1.

Mechanical properties were obtained by means of precipitation hardening heat treatment according to AMS 5658 (Gurova, 1997), in the condition H1025 at 552 °C, for 4 hours, and quenched in regular air. The mechanical properties obtained are:

- Tensile Strength: 1100 MPa.
- Hardness: 39,0 - 40,0 HRc
Table 1- 15-5PH Chemical Composition

<table>
<thead>
<tr>
<th>ELEMENTS</th>
<th>MINIMUM (%)</th>
<th>MAXIMUM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>-</td>
<td>0,07</td>
</tr>
<tr>
<td>Magnesium</td>
<td>-</td>
<td>1,00</td>
</tr>
<tr>
<td>Silicon</td>
<td>-</td>
<td>1,00</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>-</td>
<td>0,03</td>
</tr>
<tr>
<td>Sulfur</td>
<td>-</td>
<td>0,015</td>
</tr>
<tr>
<td>Chromium</td>
<td>14</td>
<td>15,50</td>
</tr>
<tr>
<td>Nickel</td>
<td>3,50</td>
<td>5,50</td>
</tr>
<tr>
<td>Niobium</td>
<td>-</td>
<td>0,45</td>
</tr>
<tr>
<td>Cooper</td>
<td>2,50</td>
<td>4,50</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>-</td>
<td>0,50</td>
</tr>
</tbody>
</table>

In this paper the process HVOF WC-13Co-4Cr thermal spray coating was deposited on base materials using a high velocity oxygen-fuel torch machine, model TAFA Technologies, JP 5000. The parameters applied for WC-13Co-4Cr coating were:

- Oxygen pressure: 0,93-1,00 MPa
- Fuel: Kerosene
- Fuel pressure: 0,78-0,85 MPa
- Powder pressure: 0,02-0,04 MPa
- Pistol distance: 300 mm
- Temperature: 150 °C

The coated layer thickness obtained by the HVOF process was, in average, 150µm, with surface roughness Ra= 2,5 ± 0,2 µm.

The application of hard chromium electroplating was carried out from a chromic acid solution containing 250g/L, and from sulfur acid solution with 2,5 g/L, under catalytic bath based on sulfate. The current density used was from 31 A/dm² to 46 A/dm², with deposition rate of 20 µm/h, at 55°C.

In order to increase the fatigue strength shot peening process was applied according to MIL-S-13125C, with intensity from 0,008 to 0,021 A, using steel beads type S 230, with 65 HRc hardness. Shot peening surface treatment was applied before coatings deposition, covering the axial fatigue specimen’s central area. At the end of process the surface roughness Ra was approximately 3,0 µm.

The axial fatigue tests for this study applied as parameters a sinusoidal load with 10 Hz for frequency and load ratio of R= -1. Specimens were prepared according to ASTM E 466, and are represented in figure 1. Stress relieves heat treatment at 190 °C for 4h was performed to reduce residual stress induced by machining. HVOF coated specimens were blasted with aluminum oxide mesh 90 to enhance adhesion.

The coating hardness was determined with a microhardness testing system using a Vickers diamond indenter on the top surface of polished cross sections. To perform the indentation a load of 100 g was used and maintained during 15 s.
Experimental test considered as fatigue strength, the complete fracture of specimens or 10^6 load cycles.

Four groups of axial fatigue specimens were prepared to obtain S-N curves:
1. Smooth specimens of base material
2. Smooth specimens of base material WC-13Co-4Cr HVOF thermal spray coated, 150 µm.
3. Smooth specimens of base material, shot peened and WC-13Co-4Cr HVOF thermal spray coated, 150 µm.
4. Smooth specimens of base material, shot peened and hard chromium electroplated 150 µm.

The X-ray diffraction technique was used to determine the residual stress field induced by thermal spray coating. Coated layers were removed by electrolytic polishing with a non-acid solution to obtain the stress distribution as function of depth.

Parameters used in this test were: x-ray voltage source 25 kV and electric current of 1.5 mA (Gurova, 1997)

**RESULTS AND DISCUSSION**

Figures 2 and 3 show microhardness values for thermal spray coating WC-13Co-4Cr and electroplated chromium respectively.

From figure 2, the microhardness of coated layer was, in average, 1600 HV, and coating average thickness around 200µm. The increase in hardness close to the interface for WC-13Co-4Cr may be associated with the fact that thermal spray coated specimens were submitted to a process to enhance adhesion, resulting in work-hardening effects (Voorwald, 2008). Lower coatings microhardness were obtained for AISI 4340 steel Cr3C2-25NiCr and WC-10 Ni HVOF thermal spray coated (Souza, 2008).

Figure 3 shows the microhardness result for specimens coated with chromium electroplated. The coating average thickness is approximately 200 µm and average microhardness 850 HV. According to Culha, 2011, higher microhardness values for thermal sprayed coating gives better results in abrasive wear tests, compared to electroplated chromium results for the same test.
Figure 4 represents coating profile for HVOF process. From figure 4a it is possible to observe coating homogeneity and strong interface coating/substrate. As already mentioned, tungsten carbide thermal spray coated specimens were blasted with aluminum oxide mesh 90 to enhance adhesion. This pretreatment improves the adhesion coating/substrate and increase roughness at the interface as represented is figure 4b. Density of porous and oxide inclusion into the coating, inherent from the thermal spray process, are also indicated. The microstructure was not affected by the HVOF process.
Electroplated hard chromium optical microscopy in figure 5 indicates coating homogeneity and strong interface coating substrate. Microcracks associated to high internal residual stress, coating hardness and corrosion resistance area also shown (Souza, 2008).

S-N curves shown on figure 6, indicates the negative effect of WC-13Co-4Cr and Hard Chromium on fatigue strength, when comparing with base material. WC-13Co-4Cr specimens this tendency is observed from 104 to 106 cycles. For maximum applied stress of 895 MPa, which represents 75% of ultimate tensile strength, the decrease was 75.79 % in fatigue life. The negative effect is more evident on high cycle range, which for maximum applied stress of 775 MPa the decrease of 91.25% was observed. The residual stress profile represented in figure 7 shows -300 MPa compressive stress at interface coating/substrate, increasing to -50 MPa at 0.1 and 0.2 mm from interface for the HVOF thermal spray coated - base material. A reduction in the axial fatigue strength was also observed for AISI 4340 steel WC-CrC-Ni HVOF thermal spray coated in comparison to the uncoated steel (Souza, 2008).
Fracture surface analysis of HVOF coated, in figure 8, indicates crack growth at the interface coating/substrate and further propagation inside substrate. The reduction in the fatigue strength of 15-5 PH stainless steel WC-13Co-4Cr thermally spray coated is associated to pores and stress concentration effects of oxide inclusion at interface coating/substrate. Increase in the fatigue performance of HVOF coated base material is related to the shot peening process (Selvadurai, 2015).
Considering residual strength inherent from shot peening process and HVOF, the maximum compressive stress was measured at 0,1 mm from interface on WC-13Co-4Cr+SP specimens. The influence of the compressive residual stress field on the fatigue crack propagation is clearly observed in figure 9, which represents the fracture surface for 15-5PH stainless steel shot peened and WC-13Cr-4Co thermal spray coated. Crack arrest and delay and growth inside substrate results in propagation at interface coating/substrate increasing fatigue life.

As shown in table 2, the shot peening has positive effect on fatigue life, resulting in tests with lower strengths related to ultimate tensile strength ($\sigma_{\text{max}} = 596$ MPa), an increase of 70 % in fatigue strength. The positive effect on fatigue life occurs as a consequence of shot peening process, and its influence is greater as the maximum stress level decreases. However, the shot
peening demonstrated efficiency in increasing fatigue strength on coated specimens, did not
totally recover the reduction of fatigue life caused by thermal spray coating.

Table 2 - Comparison study between WC-13Co-4Cr

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Fatigue Tests</th>
<th>Stress (MPa)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>775</td>
<td>596</td>
<td></td>
</tr>
<tr>
<td>WC-13Co-4Cr</td>
<td>19,326 Cycles</td>
<td>171,783 Cycles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WC-13Co-4Cr+ SP</td>
<td>56,045 Cycles</td>
<td>584,062 Cycles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase of Fatigue Life (%)</td>
<td>65</td>
<td>70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The decrease in fatigue strength for chromium electroplated 15-5PH stainless steel (figure 6)
is attributed to the high density of microcracks, as shown in figure 10. High tensile residual
stresses in the chromium coatings strengthen interface coating/substrate, and variable
amplitude loadings, are fundamental for fatigue crack nucleation and propagation across
interface inside substrate. According to figure 10, the shot peening acts to retard or even avoid
crack propagation, increasing fatigue life.

Table 3 show the comparison between chromium electroplated and HVOF thermal spray
coating on shot peened 15-5 PH stainless steel fatigue strength. As already mentioned both
coatings decreased the fatigue strength for this material. The results in table 2 show better
performance for the WC-13Co-4Cr HVOF thermal spray coating.  For the maximum stress
applied of 656 MPa the reduction induced by chromium electroplated process was 76 % in
fatigue life related to base material results, and the same comparison with base material the
reduction for thermal spray coat was 28,9 %.

Fig. 10 - Fracture surface of axial fatigue specimen. Hard Chromium. (a) 15x; (b) 200x
Table 3 - Reduction of fatigue life related to base material

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Reduction in Fatigue Life (%)</th>
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<tbody>
<tr>
<td></td>
<td>656 MPa</td>
</tr>
<tr>
<td></td>
<td>596 MPa</td>
</tr>
<tr>
<td>WC-13Co-4Cr+ SP</td>
<td>28.9 %</td>
</tr>
<tr>
<td></td>
<td>42 %</td>
</tr>
<tr>
<td>Hard Chromium+SP</td>
<td>76.4 %</td>
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<td></td>
<td>58 %</td>
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</tbody>
</table>

CONCLUSION

1. Experimental results indicated higher microhardness for WC-13Co-4Cr in comparison to electroplated chromium.

2. Electroplated chromium and WC-13Co-4Cr reduced the 15-5PH stainless steel axial fatigue strength.

3. Compressive residual stresses were obtained for WC-13Co-4Cr HVOF thermally spray coated, at interface coating/substrate.

4. Greater depth and width of compressive residual stress field is associated to shot peening process.

5. The shot peening process increased the axial fatigue strength of 15-5PH stainless steel WC-13Co-4Cr HVOF thermal spray coated.

ACKNOWLEDGMENTS

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