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EVALUATION OF WC-10Co-4Cr THERMAL SPRAY COATING BY HVOF AND HARD CHROMIUM ELECTROPLATING ON THE FATIGUE LIFE AND CORROSION RESISTANCE OF AISI 4340 HIGH STRENGTH STEEL

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Abstract. *The objective of this research is to compare the influence of the WC-10Co-4Cr coating applied by high velocity oxy fuel (HVOF) process and hard-chromium electroplating on the fatigue strength of AISI 4340 steel with and without shot peening and corrosion resistance. S-N curves were obtained in axial fatigue tests for the base material, chromium plated and WC-10Co-4Cr coated specimens. The results showed that the coatings were damaging to the AISI 4340 steel behavior when submitted to fatigue testing, with the WC-10Co-4Cr thermal spray coatings showing the better performance. Regarding corrosion by salt spray test, a good corrosion resistance was obtained for the WC-10Co-4Cr thermal spray coating. Scanning electron microscopy (SEM) were used to observe crack origin sites and the existence (or not) of a uniform coverage of nearly all substrates.*

Keywords. *WC-10Co-4Cr HVOF thermal spray coating, hard chromium electroplating, fatigue strength, AISI 4340 steel, corrosion resistance.*

1. Introduction

High temperature capability, low density and hydrogen embrittlement resistance are properties required for conventional aircraft and advanced space propulsion systems (Paton, 1991). To improve and design metals and alloys for aerospace applications, investigations are aimed at strengthening mechanisms, phase transformations, plasticity, creep, fatigue, environmental effects and dynamic and static fracture (Rosenstein, 1991). Damages to the material resulting from surface-environment interactions are responsible for several failures of structural components during service. Surface treatments of chrome plating on steel have been extensively used in the aerospace, automotive and petrochemical fields, to control wear and corrosion of many components (Bodger, Mcgrann and Somerville, 1997; Tyler, 1995; Bolles, 1995; Leeg, 1996). Problems concerning chrome plating like health and environmental hazards, increasing costs and a performance not in accordance to the specifications are resulting in a search to identify possible alternatives (Bolles, 1995).

Experimental results have also shown that chrome-plated samples, while producing improved abrasive wear properties, have fatigue strength that are lower than those of uncoated parts (Nascimento et al., 1999; Hotta et al., 1995). Considering the fact that crack initiation is a surface phenomenon controlled by aspects as residual stress level near the surface, compressive residual stresses can increase fatigue life (Hotta et al., 1995, Mcgrann et al., 1998). An important characteristic of chromium electroplating is the high tensile residual internal stresses that originate from the decomposition of chromium hydrides during the electrodeposition process (Jones, 1989; Kuo and. Wu, 1996), and relieved by local micro cracking during electroplating. Results shown in the literature indicate that the high velocity oxy fuel (HVOF) spraying has great potential as a coating process, as a consequence of interesting mechanical behavior offered by this thermal spraying technology (Bolles, 1995; Guilemany and Paco, 1998). In special, the high velocity oxy fuel thermal spraying have been shown to produce more wear resistant coatings than, for example, those obtained by hard chromium electroplating (Nascimento et al., 2001). Comparison between WC-12Co and WC-17Co coatings indicate higher friction coefficients for the latter, as a consequence of the larger amount of metallic matrix present (Guilemany and Paco, 1998). Furthermore, the wear mechanisms were identified as plastic deformation and adhesive wear. The improvement on the abrasive wear behavior of heat treated coatings formed by WC-17%wtCo powders sprayed by HVOF method, was attributed to the residual stress state, coating integrity and microstructure (Stewart, Shipway and McCartney, 1998). The residual stress state in the coating, which arise from parameters of the spraying process or by heat treatments post spraying, is directly related to the performance of the coating. The wear resistance of WC-Co coatings deposited using HVOF process under impact conditions was lower compared to pure contact abrasion and directly associated to the characteristics of the substrate (Kennedy, Helali and Hashmi, 1994). There are several industrial applications in which corrosion resistance plays an important role. This represents a challenge to materials engineers, as corrosion increases maintenance costs. Thermal spraying techniques have been developed too to produce corrosion resistant coatings. The rapid development of the high velocity oxyfuel (HVOF) spraying technique has increased the demand for HVOF sprayed coatings. This technique involves low temperatures and high velocities, thus producing high-density coatings. It has been found that increased porosity lowers corrosion resistance. Hence, the HVOF technique increases the corrosion resistance of a given coating-substrate system, because of the low porosity of the coating. The metal matrix composition of the coating is another factor that plays an important role during corrosion (Guilemany et al., 1998). In studies, the WC-10Co-4Cr were sprayed by the HVOF and characterized. The resultant coatings show differences in porosity, roughness, and composition with varying conditions. However, all the coatings exhibit a very low porosity level (Guilemany et al., 1996). The WC-10Co-4Cr coating was tested in corrosion and the results showed that the coating completed the tests with no corrosion (Bodger, Mcgrann and Somerville, 1997). In relation to fatigue, results obtained revealed interesting perspectives in the use of tungsten carbide coating to replace chrome plating (Bodger, Mcgrann and Somerville, 1997). The fatigue life of a coated component may be reduced due to cracks that start in the coating and propagate through interface coating-substrate into base material (Pejryd et al., 1995). The fatigue strength of thermal spray coated components is highly dependent on the residual stress state in the coating which arise as a result of the high temperatures involved in the process and differences of thermal expansion between coating and substrate materials. Improvement of fatigue life by a factor of ten occurred as a result of compressive residual stress in the coating (Mcgrann et al., 1998). Shot peening has a wide field of applications, particularly in the manufacture of industrial components, as a process used to increase fatigue life of structures. Studies on the applications of shot peening in mechanical components indicate increase in fatigue strength as a result of compressive residual stresses that are obtained by surface plastic deformation (Torres et al., 2000; Nascimento et al., 2001).

The objective of this research is to compare the influence of the tungsten carbide-10%cobalt-4%chrome (WC-10Co-4Cr) coating applied by high velocity oxy fuel (HVOF) thermal spray process and hard-chromium electroplating on the fatigue strength and corrosion resistance of AISI 4340 steel. S-N curves were obtained in axial fatigue tests for the base material, base material and chromium plated, base material and WC-10Co-4Cr coated and base material with shot peening and WC-10Co-4Cr coated specimens. Salt spray tests were performed with base material and WC-10Co-4Cr coated in 100 μm thick, 150 μm thick and 200 μm thick.

2. Experimental procedures

The AISI 4340 steel is widely used in aircraft components where strength and toughness are fundamental design requirements. The chemical analysis of the material used in this research indicates accordance with specifications. The fatigue experimental program was performed on axial fatigue test specimens machined from hot rolled and quenched and tempered bars according to Fig. (1).

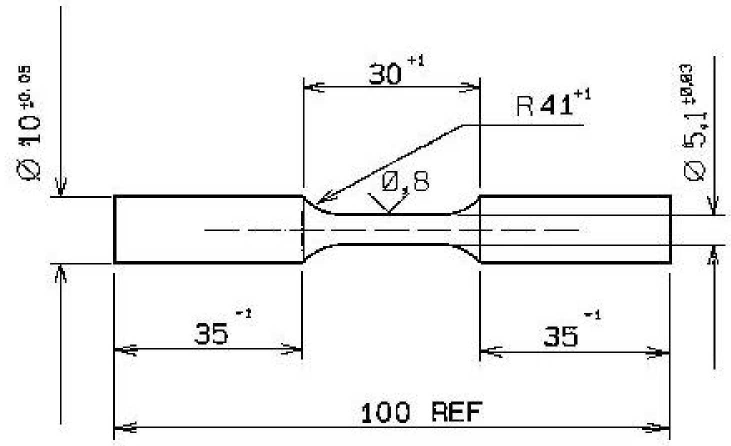

Figure 1. Axial fatigue test specimens

The specimens were polished in the reduced section with 600 grit papers, inspected dimensionally and by magnetic particle inspection. Fatigue tests specimens were quenched from 815 ^{o}C - 845 ^{o}C in oil (20 ^{o}C) and tempered in the range of (520 ± 5) ^{o}C for two hours. Mechanical properties of the material after the heat treatment are: hardness of 39 HRc; yield tensile strength of 1118 MPa, and ultimate tensile strength of 1210 MPa. After final preparation, samples were subjected to a stress relieve heat treatment at 190 ^{o}C for 4 hours to reduce residual stresses induced by machining. Average superficial roughness in the reduced section of the samples was $R_a \approx 2.75$ μm and standard deviation of 0.89 μm.

2.1. Axial fatigue tests

For axial fatigue tests, a sinusoidal load of frequency 50 Hz and load ratio R=0.1 was applied throughout this study. The test considers as fatigue strength the complete fracture of the specimens or 10^7 load cycles. Four groups of fatigue specimens were prepared to obtain S-N curves for axial fatigue tests:

- 12 smooth specimens of base metal;
- 12 samples of base metal with hard chromium electroplating, 160 μm thick;
- 12 samples of base metal with WC-10Co-4Cr spray coating by JP-5000 HP/HVOF spray process of TAFA, 170 μm thick;

- 12 samples of base metal with shot peening with WC-10Co-4Cr spray coating by JP-5000 HP/HVOF spray process of TAFA, 170 μm thick.

The tungsten carbide thermal spray coated specimens were blasted with aluminum oxide mesh 90 to enhance adhesion. The axial fatigue test specimens were prepared according to standard ASTM E 466.

2.2. Salt Spray test

The performance of the coatings was evaluated with respect to chemical corrosion in specific environment. The samples were prepared from normalized AISI 4340 steel with 5 mm thickness, and 75 mm width and 250 or 125 mm length, surface roughness $R_a \approx 0.2$ μm, and in the following conditions:

- WC-10Co-4Cr spray coating by JP-5000 HP/HVOF spray process of TAFA, 100 μm thick;
- WC-10Co-4Cr spray coating by JP-5000 HP/HVOF spray process of TAFA, 150 μm thick;
- WC-10Co-4Cr spray coating by JP-5000 HP/HVOF spray process of TAFA, 200 μm thick;

Experimental tests were conducted in accordance with ASTM B 117, in 5% wt NaCl, pH of 6.5 - 7.2, at 35 ^{o}C. Samples were supported at 20^{o} from the vertical. Tests results were analyzed with respect to superficial appearances.

2.3. Tungsten carbide coating

The tungsten carbide thermal spray coating applied by HVOF system, used WC powder with 10% Co and 4% Cr, resulting in thickness from 100 μm to 200 μm. The high velocity oxygen fuel spray system responsible for sample preparation was the equipment JP-5000 HP/HVOF spray system of TAFA. The parameters were: Spray Distance: 380 mm; Powder: 1350V; Flows: Kerosene: 22,7 l/h, Oxygen: de 52,4 m^3/h, Water: 8 gal/min, Powder: 5,9 kg/h.

2.4. Hard chromium electroplating

The hard chromium electroplating was carried out from a chromic acid solution with 250 g/L of CrO_3 and 2.5 g/L of H_2SO_4, at 50 ^{o}C - 55 ^{o}C, with a current density from 31 A/dm^2 to 46 A/dm^2, and speed of deposition equal to 25 μm/h. A bath with a single catalyst based on sulfate was used. After the coating deposition, the samples were subjected to a hydrogen embrittlement relief treatment at 190 ^{o}C for 8 hours. Average surface roughness of the hard chromium electroplating was $R_a \approx 3.13$ μm in the reduced section and standard deviation of 0.79 μm, in the as-electroplated condition.

2.5. Shot peening

S-N curves were obtained for base metal and shot peening condition of 0.0063 A, carried out on an air-blast machine according to standard MIL-S-13165. Based on scanning electron microscopy, coating morphology, microcracks formed in hard chromium plating and fatigue cracks, were observed. Analysis of fracture surfaces were carried out on rotating bending fatigue specimens by scanning electron microscope, model LEO 435 vpi and Zeiss DSM 950.

3. Results and discussion

3.1. Axial fatigue test

S-N curves for axial fatigue tests for the base material, base material electroplated with hard chromium, base material coated with WC-10Co-4Cr and base metal shot peened coated with WC-10Co-4Cr specimens are presented in Fig. (2). Figure 2 shows that the effect of coating in the axial fatigue test is to decrease the fatigue strength of AISI 4340 steel. The tendency is observed for low number of cycles (10^4), high number of cycles (10^5) and for the fatigue limit, 10^7 cycles.

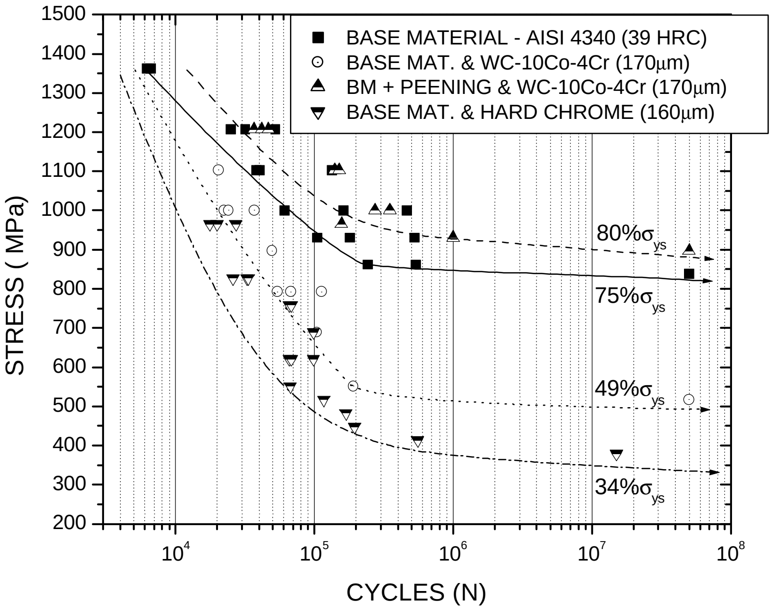

Figure 2. S-N curves for axial fatigue tests.

It is possible to observe a significant reduction in the fatigue strength of AISI 4340 steel associated to chromium electroplating. This may be attributed to microcracks density originated of the electroplating process. Microcracks density quantitative analysis indicated median values 223 microcracks/cm with standard deviation of 57.5 microcracks/cm for the hard chromium electroplating. Microcracks density arises as a relief of the tensile residual internal stresses, which increase when the chromium thickness increases. This means that the hard chromium electroplating is responsible for higher tensile residual internal stresses and/or present the highest crack initiation-propagation front amount. The reduction in the fatigue strength of AISI 4340 steel plated with hard chromium is associated to the high tensile residual internal stresses, microcracks density and strong adhesion coating/substrate interface which allows the crack growth from coating through the interface into the base material. This behaviour is shown in Fig. (3) which represent a fracture surface from a axial fatigue specimen electroplated with hard chromium, 160 μm thick, and tested at 55% of the yield stress. From analyses of Fig. (3) one sees cracks starting at the free coating surface, from inside the chromium plating and at the interface coating-substrate. It is also observed in the fracture surface indicated in Fig. (4), from a axial fatigue specimen electroplated with hard chromium, 160 μm thick, and tested at 55% of the yield stress the coating homogeneity, strong interface substrate/coating and microcracks density distributed along thickness in a radial shape (Nascimento et al., 2001; Souza et al., 2001).

It is also possible to observe that the specimens coated with WC-10Co-4Cr applied by HVOF process show the lower decrease in fatigue strength and the specimens treated with shot peening and coated with WC-10Co-4Cr applied by HVOF process indicate that this decrease in fatigue strength is totally recovered by the shot peening process. The lower decrease in fatigue strength of the specimens coated with WC-10Co-4Cr applied by HVOF process may be attributed to the process itself because is well known that HVOF thermal spray process produces compressive residual internal stresses within the substrate, which are formed from mechanical deformation on surface caused by particle impact of coating in the substrate. These surface deformations counteract the tensile shrinkage stresses of the coating caused by fast cooling and solidification as particles strike the surface. These tensile stresses in the coating also generate compressive stresses within the surface of the substrate. Of previous studies, the residual internal stresses change throughout coating thickness and the through-thickness residual stresses change from about 300 MPa tensile at 0.025 mm depth to about 680 MPa compressive at 0.06 mm from the surface. This means that the crack initiation may occur easily on the coating surface but its propagation throughout thickness may be delayed when the compressive residual stress site is reached.

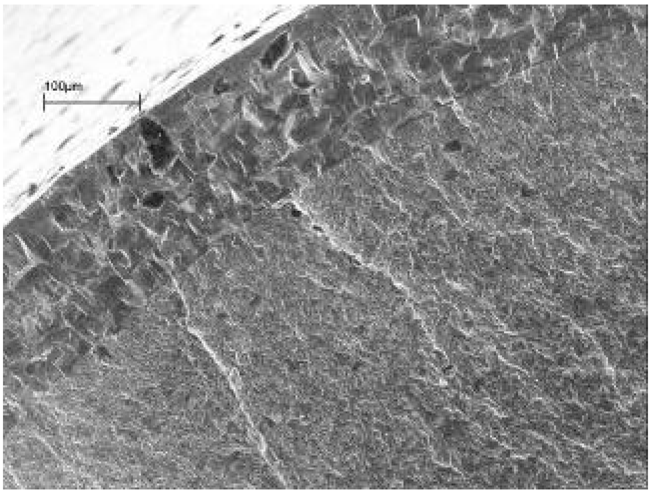

Figure 3. Fracture surface from specimen hard chromium electroplated. 400X.

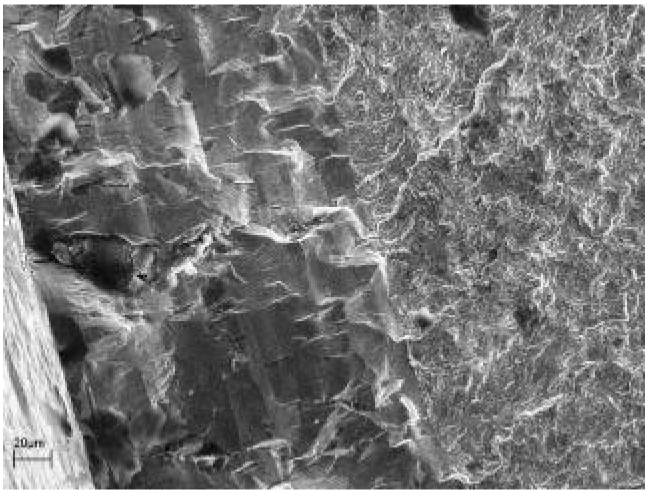

Figure 4. Fracture surface from specimen hard chromium electroplated. 800X

However, there was a reduction in the fatigue strength of AISI 4340 coated with WC-10Co-4Cr, despite of the compressive residual stresses induced by the process. This can be due to the high density of pores and oxide inclusions into the coating that commonly forms during the process. Thermal spray is generally conducted in air, so chemical interactions occur, notably oxidation which can be evident in the coating microstructure as oxide inclusions, mainly in grain boundaries. These inclusions in coatings subsurface are possible cracks nucleation/initiation sites. As mentioned before, the decrease in fatigue strength of the specimens coated with WC-10Co-4Cr applied by HVOF process was totally recovered by the shot peening process. It is well known that fatigue crack initiation occurs at surface, depends on the residual stresses profile near to it and that compressive residual stresses delay fatigue crack propagation (Nascimento et al., 2001; Souza et al., 2001).

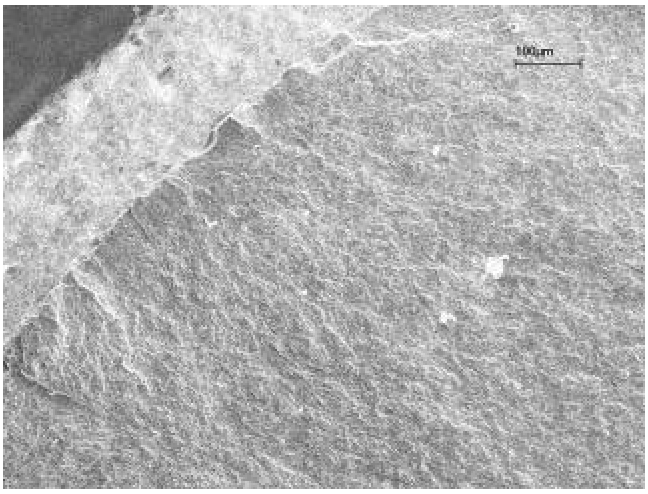

Figure 5. Fracture surface from specimen coated with WC-10Co-4Cr. 200X

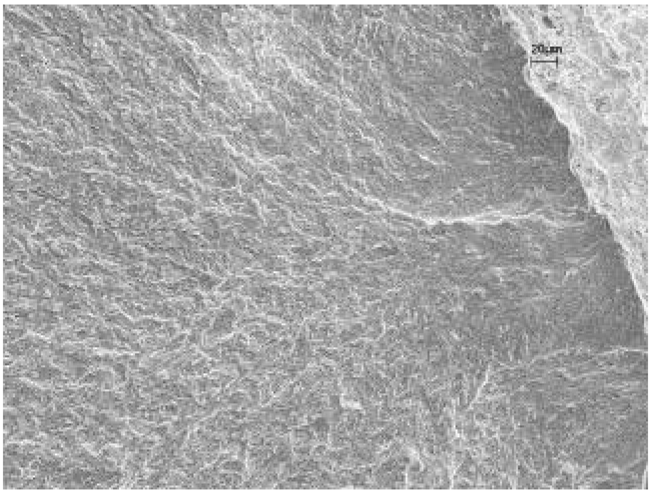

Figure 6. Fracture surface from specimen shot peened and coated with WC-10Co-4Cr. 400X

Figure (5) shows a fracture surface from a axial fatigue specimen coated with WC-10Co-4Cr applied by HVOF process, 170 μm thick, and tested at 71% of the yield stress. It is possible to observe cracks starting only at the interface coating-substrate. Analysis of Fig. (6), that represents a fracture surface from a axial fatigue specimen shot peened and coated with WC-10Co-4Cr applied by HVOF process, 170 μm thick, and tested at 89% of the yield stress, indicate fatigue crack nucleation and propagation inside base metal as a result of the shot peening process and fatigue crack nucleation and propagation from interface coating/substrate, throughout base metal. In the same figure, it is possible to observe that in some cases cracks are arrested at interface coating/substrate due to the compressive residual stresses induced by the shot peening process. This explains the increase in the fatigue strength for WC-10Co-4Cr coated specimens after shot peening, probably as a result of an interaction between the compressive residual stresses induced by the shot peening process and HVOF process, and increased resistance to fatigue crack propagation. In both figures, fatigue source appearance is distributed around specimen surface as a consequence of the influence of the coating on fatigue crack nucleation. It is possible to observe the coating homogeneity, strong interface substrate/coating, increase in roughness at the interface coating/substrate due to aluminum oxide blasting, increasing adhesion. In both cases, the deposition process did not affect the microstructure.

3.2. Salt Spray test

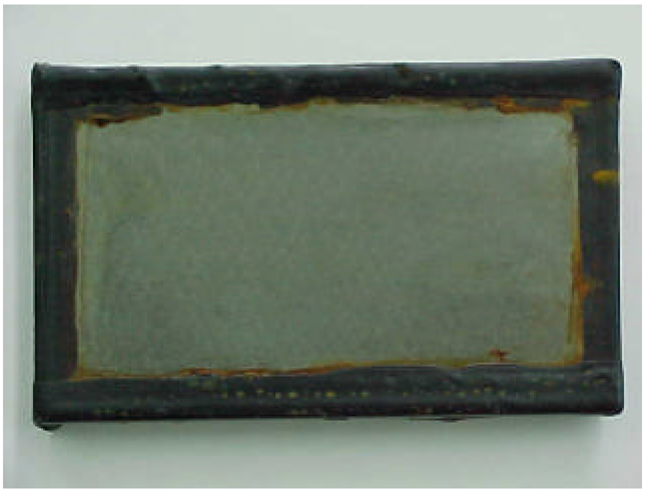

Figure 7. Salt spray test results, 100 µm thick after 504 hours.

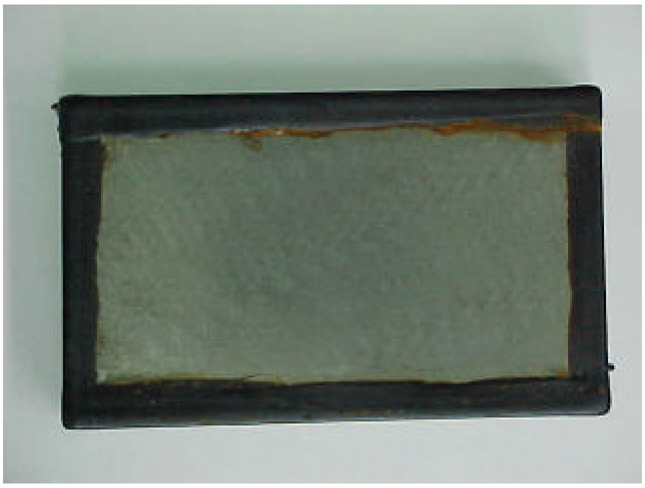

Figure 8. Salt spray test results, 150 µm thick after 504 hours.

Figure 9. Salt spray test results, 200 µm thick after 504 hours.

The results of the corrosion testing, performed in a qualitative way, were obtained by visual inspection of the specimen surface after exposure to salt spray test. The salt spray test results for samples with WC-10Co-4Cr coating by HVOF spray process, 100 μm thick; WC-10Co-4Cr coating by HVOF process, 150 μm thick and WC-10Co-4Cr coating by HVOF process, 200 μm thick are indicate in Fig. (7), (8) and (9), respectively. No visual corrosion was observed on samples with WC-10Co-4Cr coating by HVOF spray process, 100 μm thick; WC-10Co-4Cr coating by HVOF process, 150 μm thick and WC-10Co-4Cr coating by HVOF process, 200 μm thick after 504 hours testing. This results showed to be in agreement with the article of Bodger, Mcgrann and Somerville (1997), and Guilemany et al (1998), that affirms that the HVOF technique increases the corrosion resistance of a given coating-substrate system, because of the low porosity of the coating. The WC-10Co-4Cr coating exhibit a very low porosity level; the metal matrix composition of the coating is another factor that plays an important role during corrosion, and it is known that the chrome has excellent resistance to corrosion.

4. Conclusions

The base material electroplated with hard chromium has a significant reduction in the axial fatigue strength associated to the microcracks density, the high tensile residual internal stresses and strong adhesion coating/substrate interface which allows the crack growth from coating through the interface into the base material.

AISI 4340 steel coated with WC-10Co-4Cr has a lower decrease in the fatigue strength associated to the HVOF thermal spray process that produces compressive residual internal stresses within the substrate.

The base material shot peened and coated with WC-10Co-4Cr recovered totally the decrease in fatigue strength probably due to the superposition the compressive residual internal stresses induced by HVOF thermal spray and shot peening processes.

Corrosion tests, indicated by visual inspection of the specimens coated by HVOF process with WC-10Co-4Cr in thickness of 100 μm, 150 μm and 200 μm showed that no corrosion was observed.

5. Acknowledgements

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