FATIGUE BEHAVIOR, ABRASIVE WEAR AND CORROSION RESISTANCE OF AISI 4340 STEEL COATED WITH HARD CHROME ELECTROPLATING AND WC-10Co-4Cr AND CrC-25NiCr HVOF THERMAL SPRAY COATINGS

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Abstract. *The objective of this research is to compare the influence of the WC-10Co-4Cr and CrC-25NiCr coatings 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, abrasive wear and corrosion resistance. S-N curves were obtained in axial fatigue tests for the base material, chromium plated, WC-10Co-4Cr and CrC-25NiCr 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 and CrC-25NiCr coatings showing the better performance. Regarding corrosion and abrasive wear tests, a good corrosion and abrasive wear resistance was obtained for the WC-10Co-4Cr and CrC-25NiCr coatings. Scanning electron microscopy (SEM) was used to observe crack origin sites and the existence (or not) of a uniform coverage of nearly all substrates.*

Keywords: *HVOF coatings, chromium electroplating, fatigue strength, abrasive wear, corrosion resistance.*

1. INTRODUCTION

Chromium plating is the most used electroplated coating to obtain high level of hardness, resistance to wear and corrosion and low coefficient of friction, for applications in the aerospace, automotive and petrochemical fields (Bodger, Mcgrann and Somerville, 1997; Leeg, 1996). However, the plating baths contain hexavalent chromium, which has adverse health and environmental effects. As a result, wastes generated from plating operations must be disposed of as hazardous waste and plating operations must abide by emissions standards and permissible exposure limits for workers as established by government regulatory agencies (Broszeit, Friedrich and Berg, 1999; Natishan at al., 2000). It too was observed that the hard chromium electroplating reduces the fatigue strength of a component (Hotta at al., 1995). Due to this fact, design of components hard chromium plated, which are subjected to dynamic loads, may consider this negative influence to guarantee safety during operation. Shot peening is a well-known process to increase fatigue life of structures subjected to constant and variable amplitude loading. The compressive residual stress obtained by surface plastic deformation is responsible for the increase in fatigue strength in shot peened mechanical components (Wang at al., 1998). However, 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). 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). 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 at al., 1998). Aircraft landing gear manufacturers are considering tungsten carbide (WC) thermal spray coatings applied by the High Velocity Oxy-Fuel (HVOF) process as an alternative to hard chrome plating. Comparison of experimental data showed better corrosion resistance for several HVOF coatings with respect to chrome plating. In the case of fatigue and friction tests, the results were acceptable indicating interesting perspectives on the use of tungsten carbide and chromium carbide coatings to replace chrome plating. (Bodger, Mcgrann and Somerville, 1997; Nascimento at al., 2001). Analysis of the wear performance of tungsten carbide coated samples in the presence of air, aqueous and aqueous abrasive media indicate better results in terms of volume loss and change in surface roughness than for the mild steel substrate (Coulson, Leheup and Marsh, 1995).

The objective of this research is to compare the influence of the tungsten carbide-10%cobalt-4%chrome (WC-10Co-4Cr) and chromium carbide-25%nickel/chromium (CrC-25NiCr) coatings applied by high velocity oxy fuel (HVOF) thermal spray process and hard-chromium electroplating on the fatigue strength, abrasive wear 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, base material with shot peening and WC-10Co-4Cr coated and base material and CrC-25NiCr 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 and base material and CrC-25NiCr coated in 150 μm thick and 200 μm thick.

2. EXPERIMENTAL PROCEDURES

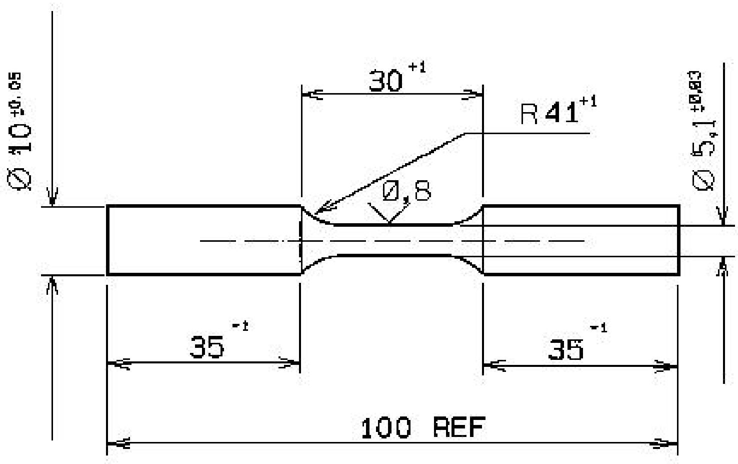

Figure 1. Axial fatigue test specimens

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).

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.

For axial fatigue tests, a sinusoidal load of frequency 30 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. Five 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 conventional 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.
- 12 samples of base metal with CrC-25NiCr spray coating by JP-5000 HP/HVOF spray process of TAFA, 210 μm thick

The 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.

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 10 mm thickness, and 76 mm width and 254 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;
- CrC-25NiCr spray coating by JP-5000 HP/HVOF spray process of TAFA, 150 μm thick;
- CrC-25NiCr 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.

The performance of the coating was also evaluated with respect to abrasive wear. For abrasive wear tests, samples were prepared from annealed AISI 4340 steel with 4 mm thickness and 100 mm square, according to FED-STD-141C. The samples were divided in three groups: one coated with 100 μm thickness of conventional hard chromium electroplating and two groups coated with 100 μm thickness of WC-10Co-4Cr and CrC-25NiCr spray coatings by JP-5000 HP/HVOF spray process of TAFA. The wear tests were conducted in Taber Abraser, at room temperature, using 10 N load and CS-17 abrading wheel for hard chromium electroplating and for WC-10Co-4Cr and CrC-25NiCr spray coatings. The results were analyzed by wear index (mg/1,000 cycles) and total wear (mg/10,000 cycles) data.

The thermal spray coatings applied by HVOF system, used WC powder with 10% Co and 4% and CrC powder with 25% Ni-Cr, resulting in thickness equal to 170 μm and 210 μm, respectively. The equipment used was JP-5000 HP/HVOF spray system with the parameters supplied by the manufacturer.

The conventional 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 °C - 55 °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 °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.

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. Analyses 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

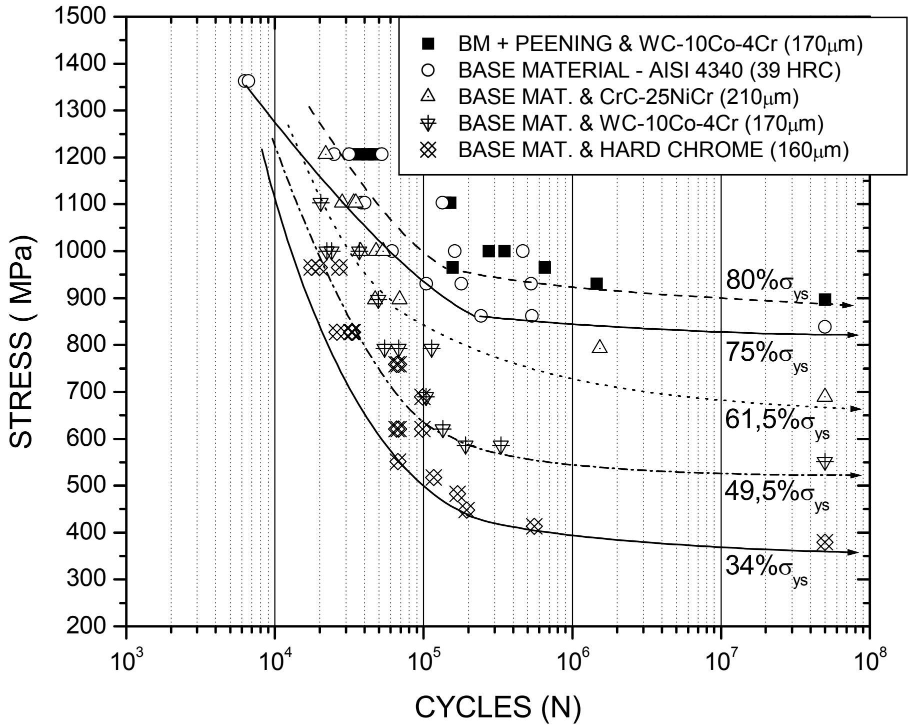

Figure 2. S-N curves for axial fatigue tests.

S-N curves for axial fatigue tests for the base material, base material electroplated with hard chromium, base material coated with WC-10Co-4Cr, base metal shot peened coated with WC-10Co-4Cr and base metal with CrC-25NiCr 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. 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 presents 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) that represents a fracture surface from an 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. (3), 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).

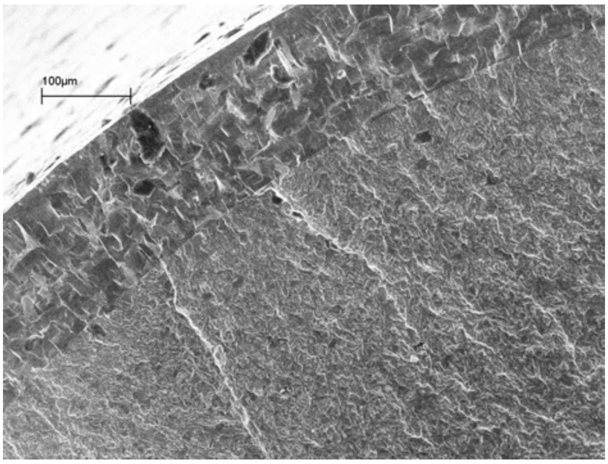

Figure 3. Fracture surface from specimen hard chromium electroplated. 400X.

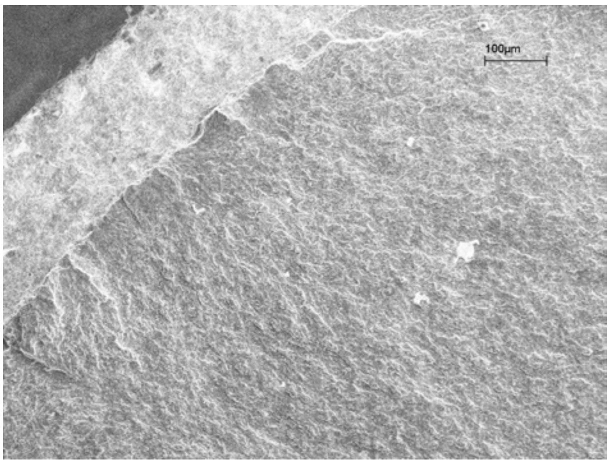

Figure 4. Fracture surface from specimen coated with WC-10Co-4Cr. 200X

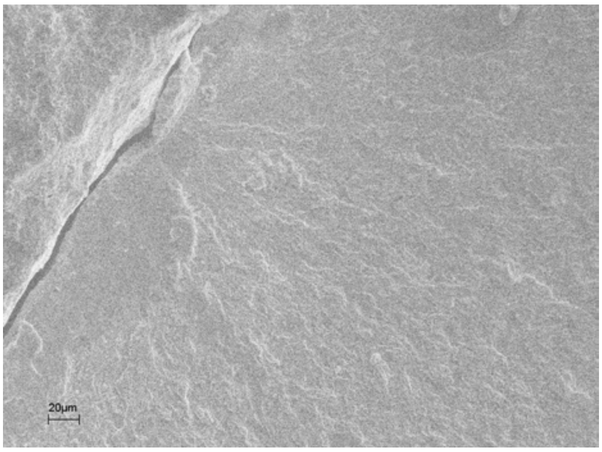

Figure 5. Fracture surface from specimen coated with CrC-25NiCr. 700X

It is also possible to observe that the specimens coated with WC-10Co-4Cr and CrC-25NiCr 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 and CrC-25NiCr 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.

However, there was a reduction in the fatigue strength of AISI 4340 coated with WC-10Co-4Cr and CrC-25NiCr, 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 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 (4) and Fig. (5) shows a fracture surface from an axial fatigue specimen coated with WC-10Co-4Cr and CrC-25NiCr and tested at 71% and 80% of the yield stress, respectively. It is possible to observe cracks starting only at the interface coating-substrate.

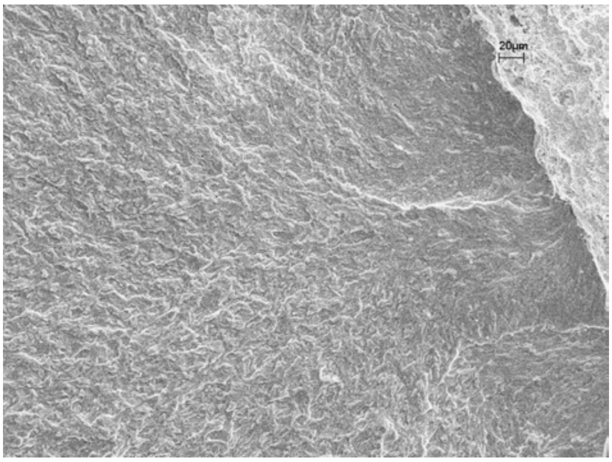

Figure 6. Fracture surface from specimen shot peened and coated with WC-10Co-4Cr. 400X.

Analysis of Fig. (6), that represents a fracture surface from a axial fatigue specimen shot peened and coated with WC-10Co-4Cr 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 three 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 three cases, the deposition process did not affect the microstructure.

3.2. Salt Spray Test

Figure 7. Salt spray test results, 100 μm thick after 750 hours.

Figure 8. Salt spray test results, 150 μm thick after 750 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, WC-10Co-4Cr coating by HVOF process, 200 μm thick, CrC-25NiCr coating by HVOF process, 150 μm thick, and CrC-25NiCr coating by HVOF process, 200 μm thick, are indicate in Fig. (7), (8), (9), (10) and (11), respectively. No visual corrosion was observed on samples with WC-10Co-4Cr, 100 μm thick; 150 μm thick and 200 μm thick, and CrC-25NiCr, 150 μm thick and 200 μm thick, after 750 hours testing. This results showed to be in agreement with the article of Bodger et al, (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 and CrC-25NiCr coatings 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.

Figure 9. Salt spray test results, 200 μm thick after 750 hours.

Figure 10. Salt spray test results, 150 μm thick after 750 hours.

Figure 11. Salt spray test results, 200 μm thick after 750 hours.

3.2. Abrasive Wear Test

The abrasive wear resistance of hard chromium plating, WC-10Co-4Cr and CrC-25NiCr spray coatings was evaluated, and the results in terms of wear weight loss are represented in Fig. (12). One sees the better performance of samples coated with WC-10Co-4Cr and CrC-25NiCr, with lower wear weight loss than the hard chromium electroplated specimens. This behavior may be attributed to the higher hardness and oxide content into the carbide coatings. For hard chromium electroplating, the wear weight loss is also associated to the microcracks density; the higher the crack density the higher the amount of previously detached solid particles, which are suppressed in the microcracks and decrease the wear strength.

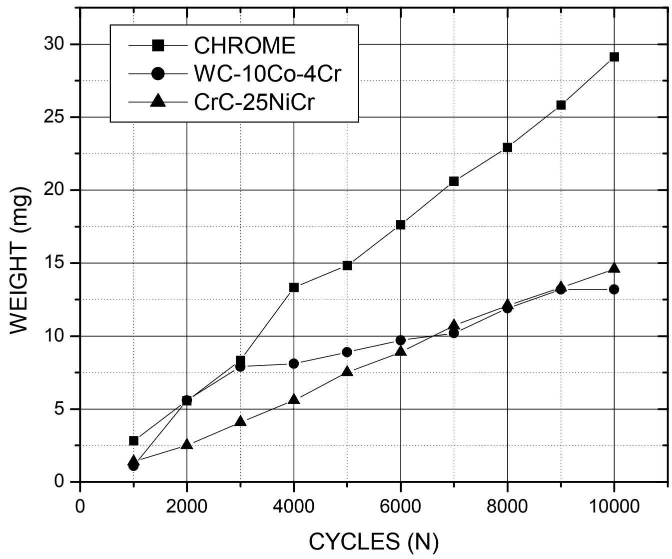

Figure 11. Abrasive wear weight loss versus number of cycles.

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 and CrC-25NiCr 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 and with CrC-25NiCr in thickness of 150 μm and 200 μm, showed that no corrosion was observed.

With respect to abrasive wear resistance, the performance of samples coated with WC-10Co-4Cr and CrC-25NiCr, with lower wear weight loss than the hard chromium electroplated specimens, was observed.

5. ACKNOWLEDGEMENTS

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