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Evaluation of WC-10Ni thermal spraying coating by HVOF on the fatigue and corrosion AISI 4340 steel

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Abstract

Shot peening is a surface process widely used to improve the fatigue strength of materials, through compressive residual stresses induced in their surface layers. Considering mechanical components for high responsible applications, wear and corrosion control is currently accomplished by the use of coated materials.
In the case of chrome plating or hard anodizing, lower fatigue strength in comparison to uncoated parts are associated to high residual tensile stresses and microcracks density. Under constant or variable amplitude loading microcracks will propagate and cross the interface coating substrate without impediment.
The aim of the present study is to analyze the influence of WC-10Ni coating applied by HVOF process on the axial fatigue strength of AISI 4340 steel. The shot peening effect on the fatigue performance of coated AISI 4340 steel was also evaluated. The fractured fatigue specimens were investigated using a scanning electron microscope in order to obtain information about the crack initiation points.

Keywords: Shot peening, Residual stress;4340 Steel; Fatigue, HVOF process

1. Introduction

The determination of fatigue strength is an important parameter to guarantee structural integrity of components subjected to constant and variable amplitude loading [1,2]. In some applications the exposition to aggressive environment enable some corrosion pits that accelerate the fatigue process.

Chrome plating is therefore used to obtain high hardness, resistance to wear and corrosion and also low coefficient of friction [3]. It is well known that chromium plating has adverse health and negative environmental effects [4]. Experimental results have shown that chrome plated specimens have fatigue resistance lower that of base material, attributed to high residual tensile stress and microcracks density contained into the coating [5]. An increase in the fatigue strength of AISI 4340 steel hard chromium electroplated was obtained with the presence of electroless nickel interlayer, which were capable to inhibit or even retain fatigue crack propagation [5,6].

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The shot peening process also proved to be an efficient method to increase the fatigue life of specimens hard chromium electroplated [6].

Thermal spray coating deposited by processes such as detonation gun, High velocity Oxy fuel (HVOF), arc wire among others are used as an important surface protection technique. In particular thermally sprayed HVOF coatings are being tested to replace galvanic chromium deposits. The axial fatigue life of AISI 4340 steel was less affected by WC-17% Co spray coated by HP/HVOF than by hard chromium electroplating [7]. In the same study it was observed that shot peening applied before the WC-10Co – 4Cr deposited by HP/HVOF restored the fatigue strength of AISI 4340 steel. Considering the abrasive wear resistance, specimens coated with WC showed lower wear weight loss than hard chromium electroplated [7]. After salt spray tests, no visual corrosion was observed on specimens WC-10 Co – 4 Cr coated [7]. Still considering HVOF thermal spray coatings, experimental results indicate better erosive wear resistance for WC-12 Co, Cr_3C_2-NiCr and WC-Cr_3C_2-Ni in comparison to bare steel [8]. The influence of process parameters like pressure, spraying distance and substrate temperature during deposition on sliding wear results was observed with respect to the tribological performance of Cr_3C_2 – 25% NiCr reactive plasma sprayed coatings [9]. The study of thickness effect on anti corrosive properties of thermal sprayed Cr_3C_2 – 25NiCr coatings indicate the importance of stress generation during process on behavior against corrosion [10].

The influence of Cr_3C_2 – 25NiCr and WC-10Ni coatings applied by HVOF and hard chromium electroplating on the fatigue strength, abrasive wear and corrosion resistance of AISI 4340 steel, 39HRc-42HRc was evaluated [11]. For the steel WC-10Ni thermal sprayed coated, visual corrosion decreased with increase in coating thickness. It was also observed better corrosion resistance for AISI 4340 steel Cr_3C_2-25NiCr HVOF thermal spray coated in comparison to WC-10Ni.

Both thermal sprayed coatings presented higher abrasive wear resistance with lower wear weight loss than electroplated chromium. A better performance was obtained for specimens WC-10Ni coated. S-N curves showed higher axial fatigue resistance for HVOF coated specimens in comparison to electroplated chromium. On the other hand, thermally sprayed Cr_3C_2 – 25NiCr showed lower fatigue life than base material. Behavior similar to bare AISI 4340 steel was observed for thermal spray coated WC – 10Ni. Analysis of the residual stresses profile for Cr_3C_2-25NiCr and WC-10Ni HVOF thermal spray coated indicate, in both cases, low values for the compressive residual stresses at interface coating/substrate (-50 MPa) which change to tensile at 0,08mm and 0,04mm, respectively.

In reference [7] it is possible to observe higher compressive residual stresses around interface coating substrate for WC-17Co and WC-10Co-4Cr HVOF thermal spray coated. It is well known that shot peening is an effective method to increase the fatigue strength of a mechanical component. An increase in the shot peening intensity resulted in an increase in the maximum compressive residual stress and also the width of the field generated [12]. This tendency was not followed with respect to an increase in the fatigue life of AISI 4340 steel.

The effectiveness of shot peening process to restore the fatigue strength of base metal chromium electroplated is shown [6] for low cycle, high cycle and fatigue limit. The shot peening treatment with steel and ceramic shots resulted in the rotating bending fatigue strength of AISI 4340 steel chromium electroplated up to level of base material without chromium [13].

It was also shown that peening using ceramic shots presented lower scatter in fatigue data than steel shots.

In the present research the shot peening effect on the axial fatigue strength of AISI 4340 steel WC -10Ni HVFO thermal spray coated, is evaluated. In order to study the influence of residual stresses on fatigue life, the stress field was measured by an X-ray tensometry. Scanning electron microscopy was used to investigate the fatigue source appearance.

2. Experimental Procedure

2.1. Materials and mechanical properties

The purpose of this research was to evaluate the effects of shot peening on the axial fatigue strength of high strength steel HVOF thermal spray coated. The coating studied was WC-10Ni, deposited on AISI 4340 steel substrate using a high-velocity oxy-fuel system (HVOF). The chemical composition of the steel was 0,41C-0,73 Mn-0,8Cr-1,74Ni-0,25Mo and 0,25Si, wt%. The mechanical properties of this material quenched from 815ºC to 845ºC followed by tempering in the range 230ºC± 5ºC for 2h are shown in table1.

Table 1. Mechanical properties of AISI 4340

Hardness, HR_C	50-52
Ultimate tensile strength (MPa)	1864
Yield tensile strength (MPa)	1514

2.2. *Axial fatigue of AISI 4340*

The test specimen used for the axial fatigue tests in figure 1 was machined from hot-rolled, quenched and tempered bars, according to ASTM E466.

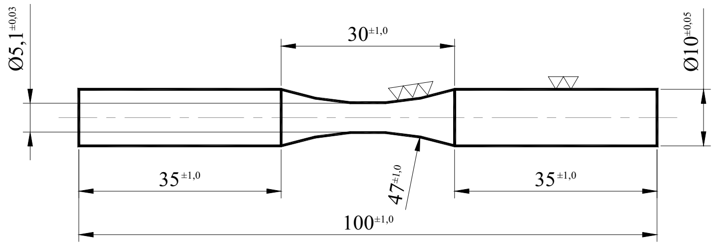

Fig. 1. Axial fatigue testing specimen.

A stress relieves heat treatment at 190ºC for 4 h was applied to reduce residual stresses induced by machining. The specimen surface was prepared for thermal spray coating by grit blasting with aluminum oxide mesh 90 to enhance adhesion.

Fatigue tests were conducted using a sinusoidal load of 10 Hz frequency and load ratio of R=0,1, at room temperature. Experimental tests consider as fatigue strength the complete facture of the specimen or 10^7 load cycles. Four groups of fatigue specimens were prepared to obtain S-N curves for axial fatigue tests. The sample size was 12 for each material condition.

1. Smooth specimens of base material;
2. Smooth specimens of base material shot peened;
3. Smooth specimens of base material with WC-10Ni thermal spray coated by HVOF process, 200µm thick;
4. Smooth specimens of base material shot peened and WC-10Ni thermal spray coated by HVOF process,

For all specimens the S/N curves were determined according to ASTM E 739.

2.3. *HVOF thermal spray processing*

Coatings were deposited using a high velocity oxy-fuel torch, model JP-5000, TAFA 1310 VM Technologies. The spraying parameters used for WC-10Ni are:

Spray Distance: 150mm-300mm
Density: 4,8g/cm^{3,} according to ASTM B 212
Deposition: velocity 900m/s
Deposition rate: 50µm/min

2.4. *Residual stress measurement*

The X-ray diffraction method was used to determine the residual stress field induced by the thermal spray coatings. The absolute values of the residual stresses were measured by “GURTEQ – Non Destructive Testing” with RAYSTRESS® equipment that use X-ray diffraction method”. The accuracy of the stress measurement was $\Delta\sigma = \pm$ 10MPa. In order to obtain the stress distribution by depth, layers of specimens were removed by electrolytic polishing with a nonacid solution.

2.5. Shot peening

S-N curves were obtained for base metal and shot peened AISI 4340 steel. The shot peening parameters used were:

Intensity: 0,006-0,010 A
S230 steel shot
Out put flux: 3kg
Velocity: 250 mm/min
Distance: 200mm
Rotation: 30 rpm
120% covering

The process was performed before blasting with aluminum oxide, according to standard SAE-AMS-S-13165.

3. Results and discussion

The coating hardness was determined with a microhardness testing system using a Vickers diamond indenter on the top surface of polished cross sections and represented in figure 2 for WC-10Ni coating. To perform the indentation, a load of 100g was used and maintained for 15s.

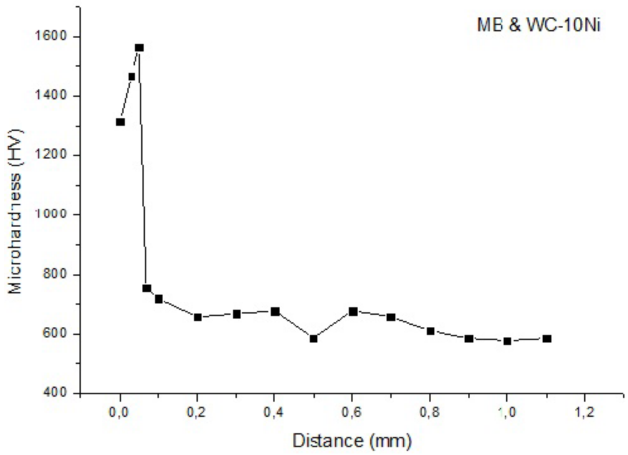

Fig. 2. Vickers microhardness. 100g. WC-10Ni

Figure 2 shows lower values near to the coating surface, increasing until a maximum close to the interface, decreasing again at interface coating substrate. It may be observed that the thickness of the coating was kept c.a.150 µm. The work hardening effects, which resulted from the fact that the thermal spray coated specimens were blasted to enhance adhesion, may be related to the increase in hardness near the interface coating-substrate [15]. Figure 3 shows the WC-10Ni coated 4340 steel cross-section.

Fig. 3. Cross section. WC-10Ni. 100x.

The coating homogeneity is indicated, it can be observed also that roughness increase at interface coating/substrate, associated to aluminum oxide blasting and microstructure not affected by deposition process. As already mentioned, the average coating thickness was 150 µm and porosity c.a. 1-2%.

Table 2 indicates residual internal stresses for AISI 4340 steel base material and after shot peening.

Table 2. Residual internal stress

Material \ Depth (mm)	0.00	0.10	0.20
AISI 4340 steel	+150	+75	0
Shot peened AISI 4340 steel	-330	-630	-170

Tensile residual stresses were obtained for AISI 4340 steel base material at surface and 0,10 mm from the surface. High compressive residual stresses are observing on the specimen surface for shot peened AISI 4340 steel. The residual stress profile shows compressive stress at 0,10 mm from surface and tendency to decrease in value with increase in the depth.

These results agree with those obtained by [12] in which the influence of four shot peening condition on the rotating bending fatigue tests were studied. For the same peening condition, the compressive residual stress field behaves very similar with respect to the depth and width to that obtained in the present research, despite the fact that in the mentioned work [12] higher compressive residual stress was obtained at surface.

The residual stresses for base material WC-10Ni thermal spray coated and base material shot peened and WC-10Ni thermal spray coated by HVOF process. 200 µm thick are indicated in table 3.

As indicated in tables 2 and 3, the HVOF thermal spray process reduced the tensile residual stresses on the specimen surface (0,00 mm depth), from 150 MPa to 30 MPa. Compressive residual stresses are formed from mechanical deformation during particle impact. The tensile shrinkage stresses of the coating are associated to the fast cooling and solidification as particles strike the surface. According to experimental data from table 3, the through thickness residual stresses for shot peened AISI 4340 steel WC-10Ni thermal spray coated, changed from compressive to tensile inside coating, with maximum compressive stresses at 0,02 mm depth. From table 3 it is also possible to observe that the shot peening process changed residual stresses from tensile to compressive until c. a. 0,10 mm depth.

Comparison between tables 2 and 3 with respect to shot peened AISI 4340 steel and shot peened AISI 4340 steel WC-10Ni thermal spray coated, showed for the former that residual stresses were compressive from surface to 0,20 mm depth, while for the latter despite higher compressive value on surface, residual stresses were tensile from 0,13 mm to 0,20 mm depth.

Table 3. Residual stresses. WC-10Ni

		MPa	MPa
N	Depth (mm)	AISI 4340 WC-10Ni	Shot peened AISI 340 WC-10Ni
1	0,00	30	-400
2	0,02	-	-580
3	0,04	-	-500
4	0,07	-	-270
5	0,10	50	-130
6	0,13	-	+150
7	0,16	-	+170
8	0,20	0	+150

Furthermore, the highest compressive residual stress (630 MPa) was obtained for shot peened AISI 4340 steel at 0,10 mm from surface. The axial fatigue S-N curves and data for base and shot peened and coating and shot peened and coated materials, are represented in figure 4 and table 4, respectively.

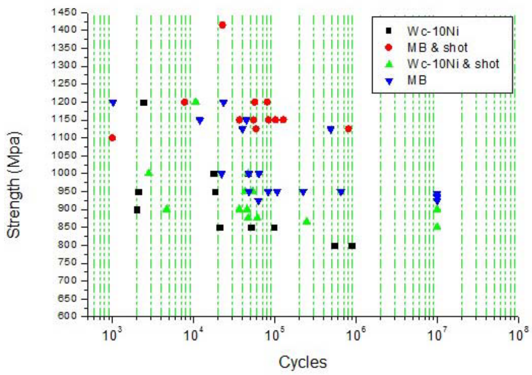

Fig. 4. S-N curves for axial fatigue tests.

As indicated in figure 4, the shot peening process was effective to increase the base metal fatigue strength. Compressive residual stresses at surface and inside substrate played an important role to avoid or delay fatigue crack nucleation and propagation.

Experimental data in table 4 shows that for AISI 4340 steel, axial fatigue strength was studied between maximum stress equal to 1200 MPa and fatigue limit, which corresponds to 935 MPa. It is also important to note an increase in the ratio between standard deviation and the average number of cycles to failure, with the decrease in the maximum applied stress. For the shot peened specimens, table 4 indicates that axial fatigue strength was obtained between maximum stress equal to 1415 MPa and the fatigue limit 1100 MPa.

The same tendency for the ratio between the standard deviation and the average number of cycles to failure observed for base metal, was obtained for the shot peened AISI 4340 steel; whereas lower values indicate less scatter in experimental data. From table 4 it is perfectly clean that the shot peening process increased the fatigue strength of AISI 4340 steel. The ratio between average number of cycles to failure for shot peened and base metal was 3,07; 3,25 and 26,60 for maximum applied stresses equal to 1200 MPa, 1150 MPa and 1125MPa, respectively.

Table 4. Base material axial fatigue data

	AISI 4340				Shot peened AISI 4340				
Stress (MPa)	N (cycles)	N_1 (cycles)	S.D	SD/N_1	N (cycles)	N_2 (cycles)	S.D.	SD/N_1	N2/N1
1415	-	-	-	-	22718	22718	-	-	-
1200	23337	23337	-	-	77790 56907 80545	71747	12925	0,180	3,07
1150	44673 11959	28316	23132	0,816	127507 102393 55184 83615	92175	30519	0,331	3,25
1125	39939 21175	30557	13268	0,434	812825	812825	-	-	26,60
1100	-	-	-	-	107 107	-	-	-	-
1000	64043 22226 47826	44698	21083	0,471					
950	107243 653456 122543 82703 227823	238753	238353	0,998					
945	298715 107 107	298715	-	-					
935	107 107 107	-	-						

The fatigue limit increased 17,6%, from 935MPa to 1100MPa.
Figures 5 and 6 represent the fracture surfaces for the base metal and shot peened base metal, respectively.

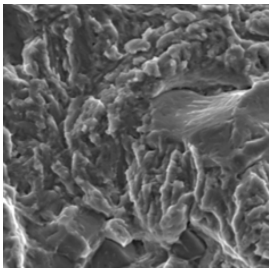

Fig. 5. Fracture surface. Base metal

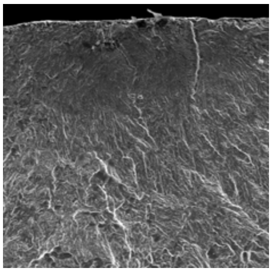

Fig. 6. Fracture surface. Shot peened base metal.

The substrate strength to crack penetration due to the shot peening process is clearly shown in figure 6.

The axial fatigue S-N curves and data for AISI 4340 steel WC-10Ni thermal spray coated and shot peened AISI 4340 steel WC-10Ni thermal spray coated are also represented in figure 4 and table 5, respectively.

Table 5. WC-10Ni thermal spray coated axial fatigue data.

	WC-10Ni coated AISI 4340				Shot peened and WC-10Ni coated AISI 4340				
Stress (MPa)	N (cycles)	N_3 (cycles)	S.D	SD/N_3	N (cycles)	N_4 (cycles)	S.D	SD/N_4	N_4/N_3
1200	2394	2394	-	-	10601	10601	-	-	4,43
1000	17467 36740	27103	13628	0,502	28229 46797	37513	13129	0,349	1,38
950	18346 20780	19563	1721	0,087	42955 53436 86528	60973	22743	0,373	3,12
900	19780 43011 45817	36202	14291	0,394	36603 45876 46870 78325	51918	18201	0,350	1,43
875	-	-	-	-	47062 61368	54215	10115	0,186	-
865	-	-	-	-	247336 91894 106142 63665	127259	81974	0,644	-
850	97625 50746 53137	67169	26402	0,393	10^7 10^7	-	-	-	-
800	541001 878441	709721	238606	0,336	-	-	-	-	-
750	10^7 10^7	-	-	-	-	-	-	-	-

The reduction in the axial fatigue strength of AISI 4340 steel WC-10Ni thermal spray coated by HVOF, in comparison to base metal is related to the presence of oxide inclusions and pores into the coating. Figure 7 shows the fracture surface of AISI 4340 steel WC-10Ni thermal spray coated in which fatigue cracks nucleation and propagation at interface coating/substrate is observed.

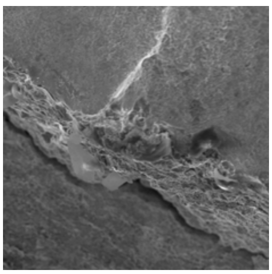

Fig. 7. Fracture surface WC-10Ni.

Despite the fact that tensile residual stresses at surface and inside substrate are lower for the WC-10 Ni thermal spray coated specimens in comparison to base metal, earlier fatigue crack nucleation due to the interface coating/substrate conditions are responsible for the decrease in fatigue strength of coated specimens. Therefore the influence of interface coating/substrate and residual stresses on the fatigue crack propagation process needs to be considered.

4. Conclusions

The work-hardening effects may be related to the increase in hardness near to the interface WC-10Ni coating/ AISI 4340 steel substrate.

Tensile residual stresses were obtained for AISI 4340 steel at surface and 0,10 mm depth. High compressive residual stresses are observed on the specimen surface for shot peened AISI 4340 steel. At 0.10mm surface measurements resulted in – 630 MPa.

The HVOF thermal spray process reduced the tensile residual stresses on base metal specimen surface. The through thickness residual stresses for shot peened AISI 4340 steel WC-10Ni thermal spray coated changed from compressive to tensile inside coating, with maximum compressive stresses at 0,02 mm depth.

The shot peening process was effective to increase the base metal axial fatigue strength. The fatigue limit increase 17,6%, from 935 MPa to 1100 MPa.

The decrease in the axial fatigue strength of AISI 4340 steel WC-10Ni thermal spray coated by HVOF, in comparison to base metal is related to the presence of oxide inclusions and pores into the coating. The fatigue limit decreased 19,8%, from 935 MPa to 750 MPa

The shot peening process increased the axial fatigue strength of AISI 4340 steel WC-10Ni thermal spray coated specimens. The fatigue limit increased 13,3% from 750 MPa to 850 MPa.

Fracture surface analysis indicated that the compressive residual stress field delayed or arrested the fatigue process.

Author Artwork

Herman Jacobus Cornelis Voorwald is Professor of DMT/FEG/UNESP -Univ Estadual Paulista, Guaratinguetá, Brazil and is leader of Fatigue and Aeronautical Materials Research Group.

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