MECHANICAL AND WEAR BEHAVIOUR OF TITANIA PLASMA-SPRAYED COATINGS

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ABSTRACT

Titania (TiO_2) coatings were deposited onto steel substrates via atmospheric plasma spraying and their microstructure was evaluated by optical microscopy. It was characterized by the typical lamellar structure of thermally sprayed coatings, whilst their overall porosity was quite low. In order to estimate the influence of the oxide coating on the performance of the substrate, three test series were performed on coated substrates of different geometry: uniaxial tensile tests of flat specimens, rotating-beam fatigue tests of cylindrical specimens and pin-on-disc tests of disc-shaped specimens.

KEYWORDS: Atmospheric plasma spraying, Titania coatings, Mechanical behaviour

1. INTRODUCTION

Plasma sprayed titania (TiO_2) coatings are candidate materials for abrasion and wear resistance. They are characterized by sufficient hardness, relatively high density and adhesion to metallic substrates /1, 2/; while they are also evaluating for light bearing applications, such as shaft-bearing sleeves and pump seals to resist wear below 540^{o}C /3/. The wear of TiO_2 coatings against stainless steel was examined in /4/ and was found that coating had a good wear resistance in dry conditions. TiO_2 coatings are typically deposited by Atmospheric Plasma Spraying (APS), however the relatively low melting point (1855^{o}C) of TiO_2 allows their deposition also by High Velocity Oxy-Fuel (HVOF) technique, which is characterized by lower gun temperatures but higher particles' velocity, compared to APS technique /5, 6/. Recent studies demonstrated that nano-structured titania coatings deposited by HVOF exhibit superior structural characteristics, mechanical performance and wear resistance, when compared to titania coatings elaborated by conventional feedstock powders or APS technique /7, 8, 9/. Due to the biocompatibility of TiO_2, a novel application field for titania thermally-sprayed coatings is that of biomedical, mainly as an alternative to hydroxyapatite coatings on prosthetic parts /10, 11/. In the present work, titania coatings were deposited on metallic substrates by APS technique and their effect on the mechanical properties of the non-coated metal was examined under uniaxial tensile and fatigue loading. Their tribological behaviour was evaluated by pin-on-disc tests.

2. EXPERIMENTAL PART

Commercially available TiO_2 powder, with particles' size of -53+10μm, was used as feedstock for APS-deposited coatings onto CK60 structural steel substrate, with a nominal chemical composition (wt.%) of 0.60 C, 0.40 Si, 0.75 Mn, 0.035 P and 0.035 S. In order to accomplish the tests' requirements, prior to deposition CK60 specimens were machined to the three different geometries: 130x90x2.1mm flat specimens for tensile testing, cylindrical specimens according to ASTM E466-96 specification for fatigue testing and 10 mm- thick disc specimens with a diameter of 38 mm for wear tests. The respective substrates' surfaces to be coated were grit blasted using coarse alumina, in order to enhance coatings' adhesion. Prior to praying the titania powder was heated for two hours in a furnace at 70° C to eliminate moisture and optimize flow characteristics. The spraying conditions applied are listed in Table 1.

Table 1: Spraying parameters

Plasma gases	
Pressure (psi)	Primary gas, nitrogen (N_2): 100 Secondary gas, Hydrogen (H_2): 50
Flow (Scfm)	Primary gas, nitrogen (N_2): 80 Secondary gas, Hydrogen (H_2): 15
Power	
Current (A)	500
Voltage (V)	60-70
Powder feed	
Meter Wheel speed (rpm)	25
Flow rate (ft^3/hr)	37
Spraying conditions	
Distance (mm)	75-100
Spray rate (kg/h)	3.2
Efficiency	65%
Deposition rate (kg/hr)	2.06 kg/hr

In the case of flat tensile specimens, TiO_2 coating was deposited on both sides of the flat substrate in equal thickness. In order to estimate the effect of the brittle coating's thickness on the mechanical behaviour alteration of the metal, four series of specimens were prepared for a targeted TiO_2 thickness of 100, 150, 200 and 250 μm. In the case of cylindrical fatigue specimens, a ~200 μm-thick coating was deposited on the whole external surface of the cylinder. Finally, for wear tests a ~450 μm-thick coating was deposited onto the one circular side of the discs.

Rotating-beam fatigue testing was conducted using an RBF-200w rotating beam fatigue machine (Figure 1a). The fatigue tests were conducted at room temperature under a rotating beam and stress ratio R=1 at a frequency of 50 Hz, with maximum tensile stress imposed the 70% of the yield point of the CK60, as previously determined by uniaxial tensile testing. For the evaluation of the tribological behaviour, tests were performed on a pin-on-disc apparatus (Figure 1b), according to ASTM G 99-05 standard, using commercially available TiCN-coated inserts as counterbody. The applied load was varying from 2 up to 10 N, whilst the track radius and the linear speed remained the same for all tests, equal to 16 mm and 0.6 m/s, respectively.

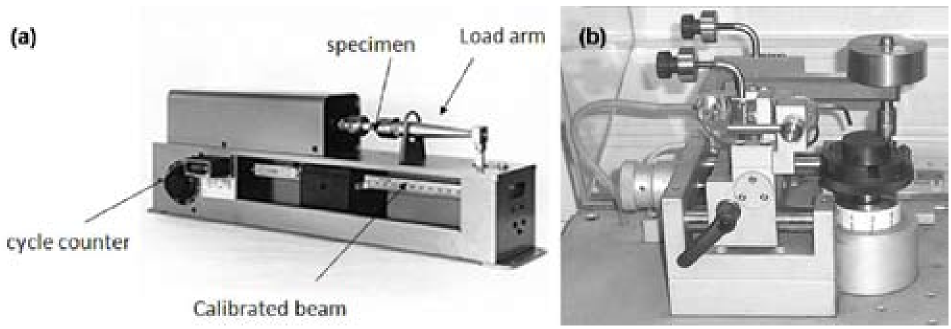

Figure 1: (a) Rotating -beam fatigue testing machine (b) Pin-on-disc tribometer.

3. RESULTS AND DISCUSSION

Figure 2 shows the cross-sectional microstructure of the titania air plasma sprayed coating produced by the atmospheric plasma spray. The microstructure of plasma sprayed coatings is described as a build-up of lenticularly shaped flattened particles with thick mid sections. This results from powder being injected into hot plasma which melts the particles and accelerates them to splat onto the substrate. Molten particles solidify at high cooling rates thus preventing excessive liquid drop flow. The coating is porous and exhibits the lamellar structure of plasma sprayed coatings. The porosity of the coating was 5.5%. Smaller pores are located within individual lamellae while larger pores are mostly found along interlamellar boundaries. The coating also exhibited a few areas of poor adhesive bonding with the steel substrate and random cracks that cannot be directly correlated to the deposition process or the post-deposition sectioning of the specimen to be prepared for microscopic examination.

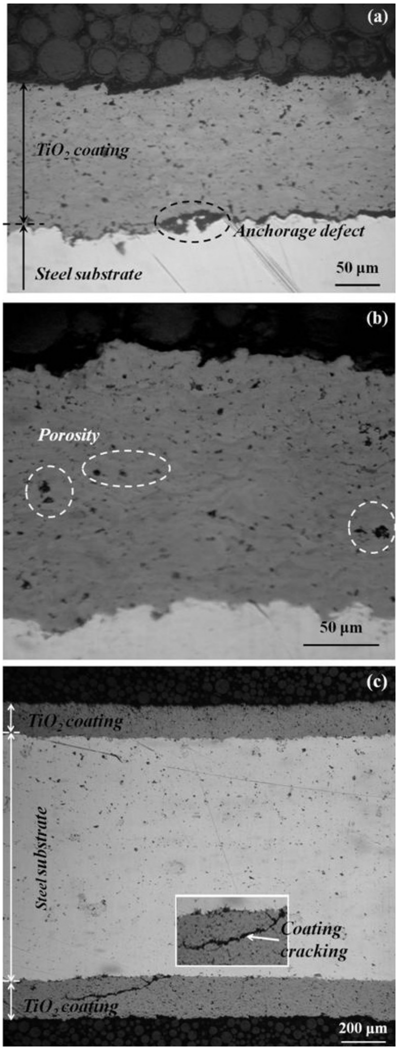

Figure 2: Characteristic optical micrographs of cross-sections of the system examined.

Figure 3 shows the engineering stress – strain curves for the titania coated steel substrate with various coating thickness. The experimental results show that the TiO_2 plasma spray coating weakens the steel substrate. It can also be observed that the tensile strength decreases proportionally but slightly with the coating thickness (Figure 3). During tensile testing the coating stared cracking at the end of elastic strains and suffered spalling just after the yield point.

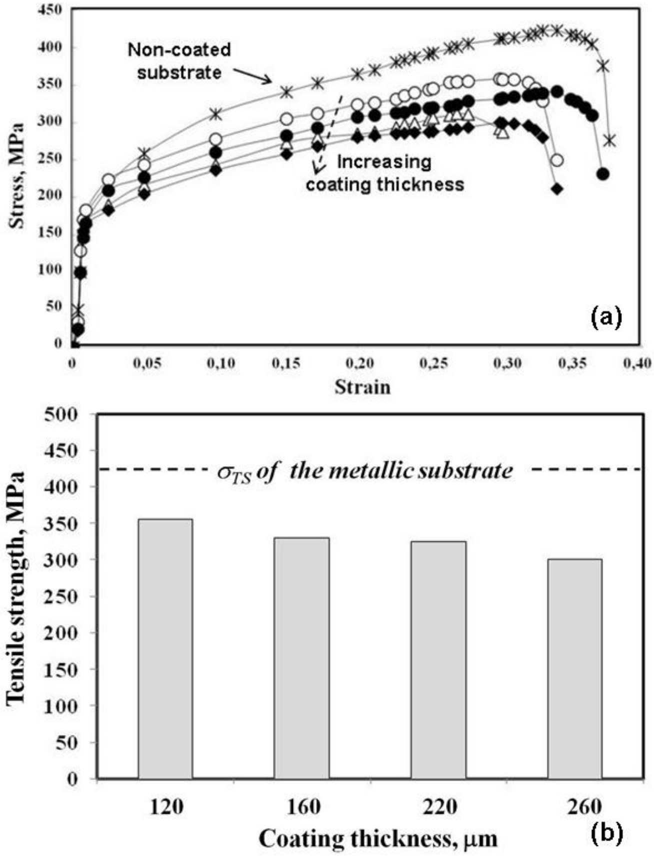

Figure 3: Tensile testing results: (a) Stress–strain curves of titania coated steel with various thicknesses and (b) Tensile strength as a function of the thickness of the coating.

The fatigue life of the metallic substrate was prolonged from ~42.000 up to ~130.000 cycles, as the maximum tensile stress applied was decreasing from 150 to 130 MPa. In the case of TiO_2-coated steel, in all cases the fatigue life was significantly inferior to that of the non-coated substrate; however, the extended scattering of the experimental results did not allow clearly identifying the effect of coating on the systems behaviour under cyclic loading.

A typical fracture surface of the coated system is presented in Figure 4 and it can be seen that cracks initiated within the substrate in a layer close to the surface. In general, in such systems the fracture resistance is strongly related to the adhesion of the coating. In particular, if the TiO_2 coating has a weak adhesion strength it may detach from the substrate leaving behind residual debris which act as crack promoters /12/. It has been reported that in cases of poor coating adherence an external stress or temperature variation causes coating detachment and spallation /13/.

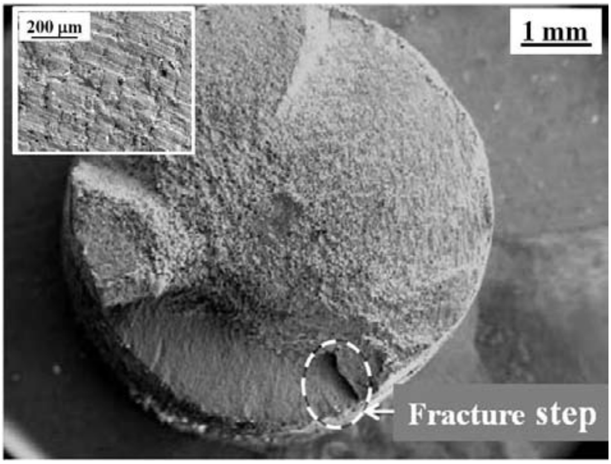

Figure 4: Micrograph of a typical fracture surface of a TiO_2-coated specimen failed under cyclic fatigue regime.

The results on the tribological behavior of the coated systems are presented in Figure 5. The steady-state friction coefficient, as well as the wear volume per sliding lap is plotted against the normal load applied. For low values of applied load (2N) the friction coefficient exhibits a rather low value for dry sliding, in the range of 0.5. Increasing the normal load up to 5N, friction coefficient increases also up to a value of 0.72; whilst further increase up to 10 N results in a slight decrease to a value of 0.6. A similar behavior of APS titania coatings was also reported by other researcher /4/ and it was attributed to differentiation of the micro-tribo-mechanisms activated at low and high loads. In our previous work /14/ concerning the wear micro-mechanisms taking place during sliding of a brittle counterbody on the surface of an also brittle oxide layer, such a behaviour was attributed to the alteration from micro-cutting of coating's protructions to extensive fracture of the coating and to the produced debris intervation.

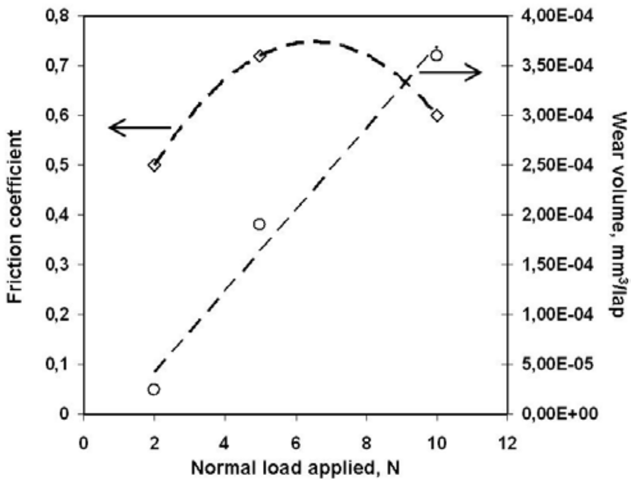

Figure 5: Tribological behaviour of the examined coatings: Steady-state friction coefficient and wear volume as a function of the normal load applied.

The wear volume per sliding lap increases almost linearly with the applied load, exhibiting values in the range of 2.5×10^{-5}-3.6×10^{-4} mm^3/lap for the experimental conditions applied in this work.

Microscopic observations on the wear tracks (Figure 6) revealed the existence of successive parallel sliding lines indicating an abrasion and polishing wear micro-mechanism. This wear behaviour could be attributed to the surface integrity state of the coating (roughness, hardness, microstructure, residual stresses) combined with a three-body (coating-wear debris-counterpart tip) dynamic contact. Moreover, the wear rate was very high at the initial stage (sliding distance < 200 m) becoming thereafter mild, indicating a possible transition of wear mechanism. After testing, a cyclic wear track was clearly shown in TiO_2 disc. Regions where parts of the coating are fallen off by delamination, together with grooves, were observed on the worn TiO_2 surface, indicating a prominent abrasive wear mode. At high load the wear seems to be determined by grinding wear and micromechanical delamination wear.

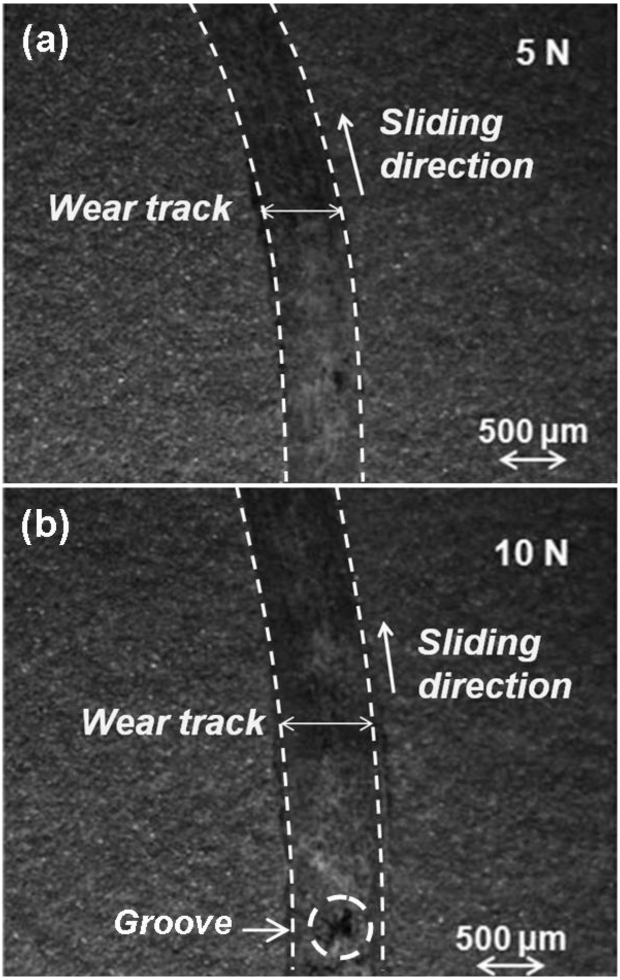

Figure 6: Wear tracks on the surface of the titania coatings under applying (a) 5 and (b) 10 N normal load (stereoscopic micrographs).

4. CONCLUSIONS

The tensile, fatigue and wear properties of TiO_2 air plasma sprayed were investigated. The presence of the coating decreases the tensile strength of the steel substrate. Both the elastic modulus and the tensile strength of the TiO_2 coated steel decreases almost proportionally with the coating thickness. Under cyclic loading regime, the coated systems exhibit inferior fatigue time, whilst fracture is initiated at the vicinity of the coating/ substrate interface. During dry sliding tests, the friction coefficient has a maximum for intermediate values of applied loads, indicating an alteration on the micro-mechanisms taking place. At the same time, wear volume removed per sliding lap increases almost linearly with the load.

Acknowledgments
The authors would like to thank Prof. N. Melanitis of the Hellenic Naval Academy for conducting the fatigue tests.

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