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TRIBOLOGICAL COATINGS FOR AEROSPACE APPLICATIONS AND THE CASE OF WC-CO PLASMA SPRAY COATINGS

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Abstract: Friction and wear requirements in aerospace systems are dictated by life limiting problems. One challenge is the broad range of contact stresses and sliding speeds for various movable devices. Another challenge is the extreme operation conditions; in particular an aircraft suffers periodical humidity changes depending on the altitude, broad temperature range, abrasive wear by electrostatically attracted dust. This paper discuss conventional WC-12% Co tribological coating deposited by atmospheric plasma spraying. Friction and wear characteristics were analysed using sliding friction tests (pin-on-disc apparatus). Four different test loads were used in order to examine the influence of contact stress on tribological behaviour. From the experimental data obtained plots of the variation of coefficient of friction and the wear rate with sliding distance were constructed. The tensile behaviour of the coated material as well as the corrosion resistance of coated and uncoated specimens was also examined. Having high hardness and good adhesion with the substrate the sprayed coating exhibits satisfactory wear resistance.

Keywords: plasma sprayed WC-Co, aerospace tribological coatings, mechanical properties, wear behaviour

1 INTRODUCTION

1.1 Plasma sprayed coatings in aerospace applications

Life-limiting parameters of aerospace systems include friction and wear in various devices along with extreme operating conditions including humidity variations with altitude changes and broad temperature ranges. Mechanical and endurance requirements of aerospace applications dictate new wear-reduction technologies demanding new materials and advanced technologies. Tribological coatings are typically exposed to high surface pressures and sliding velocities, and therefore require sufficiently good adhesion and thermal stability in order to perform well. Low friction materials usually possess friction coefficients below 0.1 in the presence of liquid lubrication, and

from 0.3 down to 0.08 under boundary layer and dry friction conditions. Materials with friction coefficients exceeding 0.3 usually find tribological application as brake pads, etc. The operational parameters of anti-friction materials span a wide range: sliding speeds between 0.001 m/s and 300 m/s, contact pressures from 0.001 MPa to above 1500 MPa, and temperatures from the cryogenic up to and above 1000°C.

Plasma sprayed deposition of abrasive and abradable coatings are commonly used in aerospace applications and research is focused on both their wear characteristics and degradation mechanisms. The development of vacuum deposition methods enabled composite coatings used in high temperature space lubrication coatings such as the NASA PS-200 series coatings produced by plasma spraying which consisted of BaF₂/CaF₂ lubricant, silver lubricant and binder and Cr₃C₂ support [1].

Composite coatings can either be transition-metal dichalcogenides (MoS_2 , WS_2 , NbSe_2) which are applied as powders mixed with various organic and inorganic binders normally deposited by spray and vacuum deposition methods.

Vacuum deposition also provided a variety of advanced hard coatings for wear protection [2,3], which are currently expanding toward aerospace applications due to the endurance requirement. Alternative tribological material for aerospace tribological applications is diamond-like carbon (DLC), which has high hardness, low friction and low wear. The use of two-phase carbide/DLC nanocomposites is reported to create problems due to DLC graphitization in friction contacts and the associated increase of friction coefficient in the high-vacuum environment [4,5].

Conventional double-layer thermally sprayed coating system is currently applied to in service components by some of the major aeroengine manufacturers. A metallic interlayer coating is applied onto the substrate by plasma spraying, and provides a base onto which a further dry film lubricant (DFL) layer is applied.

This paper discusses WC-12% Co coating deposited by atmospheric plasma spraying. Friction and wear characteristics were analysed using sliding friction tests (pin-on-disc apparatus). Four different test loads were used in order to examine the influence of contact stress on tribological behaviour. From the experimental data obtained plots of the variation of coefficient of friction were constructed and possible wear mechanisms were investigated. The tensile behaviour of the coated material as well as the corrosion resistance of coated and uncoated specimens was also examined. Having high hardness and good adhesion with the substrate the sprayed coating exhibits satisfactory wear resistance.

2 EXPERIMENTAL

WC-Co powder (12 wt. % Co) with particle grain sizes of 45-100 μm type (Sulzer-Metco 71NS) was deposited on the surface of structural steel CK60 specimens having a composition of 0.60% wt C, 0.40% wt Si, 0.75% wt Mn, 0.035% wt P and 0.035% wt S. Tensile and corrosion specimens had dimensions 130 x 90 x 2.1 mm^3 , while flat circular test pieces, approximately 38 mm in diameter and 10 mm thick, were cut-off for wear tests. All specimens were grit blasted using coarse alumina. Ultrasonic cleaning in alcohol followed by hot air drying served to remove oil and grit residues. Spraying was performed within a period of 10 min following sandblasting.

Plasma spraying was carried out using a Metco 7MB gun. The spraying conditions are listed in table 1. Powder was heated for two hours in a furnace at 70° C prior to spraying, in order to eliminate moisture and optimize flow characteristics.

WC-Co coating was deposited on both sides of the flat specimens in equal thicknesses as indicated in table 2 in order to enable balanced loading during tensile testing. Circular test pieces were sprayed to an average coating thickness of 450 μm . The microstructure of the coated samples was observed under a metallographic microscope (Leica DMR) with image analysis software (Image Pro). Brentano diffractometer with $\text{CuK}\alpha$ radiation and a graphite monochromator was used for XRD and full spectrum scanning (20°– 100°) was applied.

Table 1. Spraying parameters

| <i>Plasma gases</i> | |
|---------------------------------------|--|
| Pressure (psi) | Primary gas, nitrogen (N_2): 100 Secondary gas, Hydrogen (H_2): 50 |
| Flow (Scfm) | Primary gas, nitrogen (N_2): 75 Secondary gas, Hydrogen (H_2): 15 ± 5 |
| <i>Power</i> | |
| Current (A) | 400 |
| Voltage (V) | 50-55 |
| <i>Powder feed</i> | |
| Meter Wheel speed (rpm) | 25 |
| Flow rate (ft^3/hr) | 50 |
| <i>Spraying conditions</i> | |
| Distance (mm) | 76 |
| Spray rate (kg/h) | 4.99 |
| Efficiency | 70% |
| Deposition rate (kg/hr) | 3.5 kg/hr |

Table 2. Coating thickness

| sample | Thickness per side (μm) |
|--------|--------------------------------------|
| A | 72 |
| B | 432 |
| C | 203 |
| D | 356 |
| E | 152 |

The corrosion behaviour of coated and uncoated specimens was examined in a 0.5 M NaCl solution (pH 1) at 20°C by measuring the potential of the immersed specimen in the solution vs. standard calomel electrode as a function of immersion time. For the evaluation of friction and wear characteristics sliding friction tests were performed (according to ASTM G 99-05 standard) on a state-of-the-art CSEM pin-on-disc apparatus properly modified to accommodate pins made of: (a) titanium carbonitride (TiCN, type IC 3028) and (b) TiCN+TiN+ Al_2O_3 (type IC 9025). Three normal loads were selected, namely 10N, 5N, 3N and 1N. All tests were conducted at 16 mm track radius and with constant linear speed 0.6 m/s. A photograph of the tribometer used is shown in Figure 1.



Figure 1. Photograph of the tribometer used

3 RESULTS AND DISCUSSION

Figure 2 shows the cross-sectional microstructure of the WC-Co coating produced by the atmospheric plasma spray. The coating presents a lamellar microstructural morphology, typical of the spraying process. The typical morphology of the cermet coating reveals a lamellar structure with some cavities. 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 substrate interface was wavy, the hump heights at the interface being occasionally larger than the initial substrate roughness. The coating is characterized by the presence of rather equidimensional pores. In quantitative terms, the porosity of the coating was measured by image analysis and was found to be equal to 3%. The roughness of the coating free surface was rather high ($R_a=8.2 \mu\text{m}$).

The lamellar structure is formed by the flattening of molten particles upon impact on the substrate surface forming a pancake morphology. A parameter which is used to compare droplet spreading is known as the Madjeski parameter [13]

$$\Phi_m = \frac{d}{D} = \left(\frac{2}{D} \right) \left(\frac{A}{\pi} \right)^{1/2} \quad (1)$$

where D is the initial diameter of the molten particle, d is the splat diameter and A is the area covered by the splat. The Madjeski parameter (Φ_m) of the coating was calculated equal to 0.4.

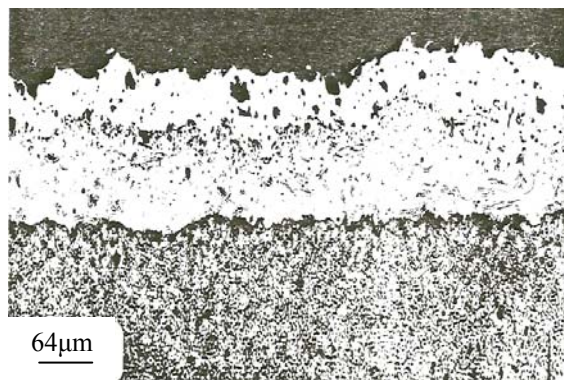
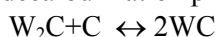
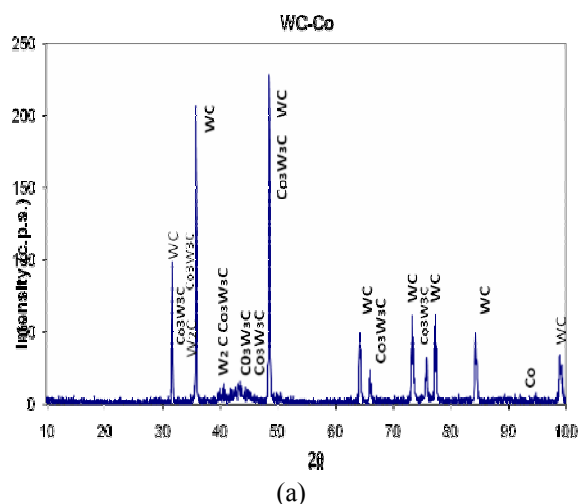


Figure 2. Cross section of the WC-Co coating

Figure 3 shows the XRD diffraction patterns of WC-Co prior and after plasma spraying. The as received WC-Co powder consists of WC and Co phases and also contained some amount of W_3Co_3C . The as-sprayed WC-Co coating includes W_2C peaks, indicating that the WC has been decarburised into W_2C under the present APS conditions. No Co or free C phases were indicated in the XRD spectrum of the coating, probably implying that their presence was in amorphous state, lacking long-range order [17]. The decarburization process is the following:



For the decarburization of WC during the spraying process, a model has been proposed that accounts for the microstructure features observed in the coatings [18]. According to this model decarburization involves melting of cobalt during the spray process, dissolution of WC into the molten cobalt, loss of carbon from the periphery of the particles through oxidation, which thus promotes further WC dissolution locally, and quenching of the particles which results in the formation of an amorphous binder phase, and precipitation of W_2C or W depending on the degree of decarburization.



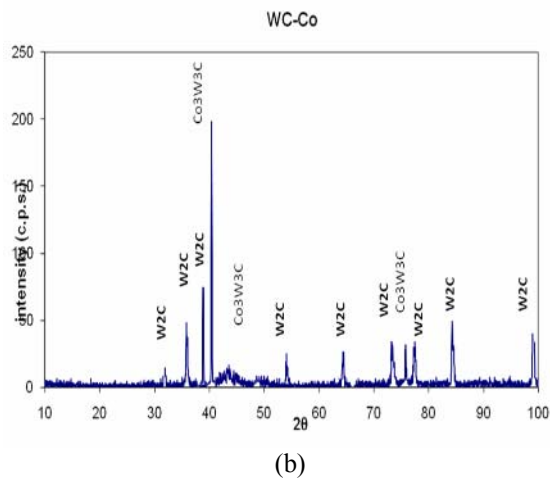


Figure 3. XRD patterns of WC-Co powder prior (a) and after (b) plasma spraying

Figure 4 shows the corrosion potential of the coated and uncoated specimens as a function of immersion time. It can be seen that voltage is moving towards more negative values indicating corrosion of the system. The corrosion rate of the coated steel is lower indicating protection of the WC-Co to the steel substrate. Steel behaviour in chlorine rich environments can be described as follows [19]:

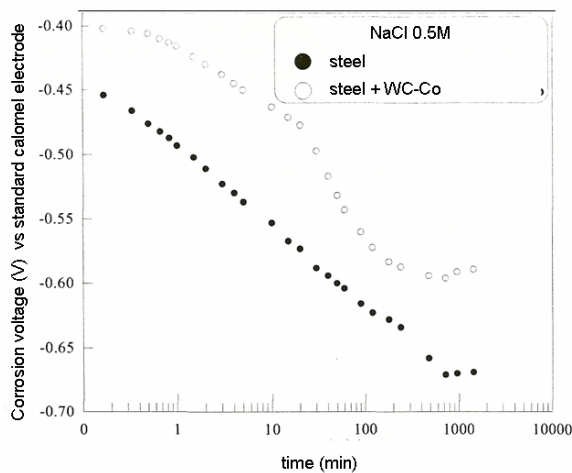
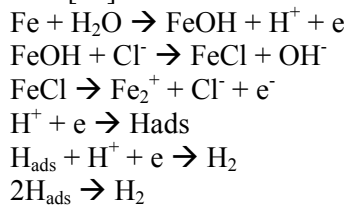


Figure 4. Corrosion voltage as a function of time for coated with WC-Co and uncoated steel

Figure 5 shows the engineering stress – strain curves for the WC-Co coated steel substrate with various coating thickness. During tensile testing the coating started cracking at the end of elastic strains and suffered spalling just after the yield point. The experimental results show that the WC-Co plasma

spray coating weakens the steel substrate in the elastic region.

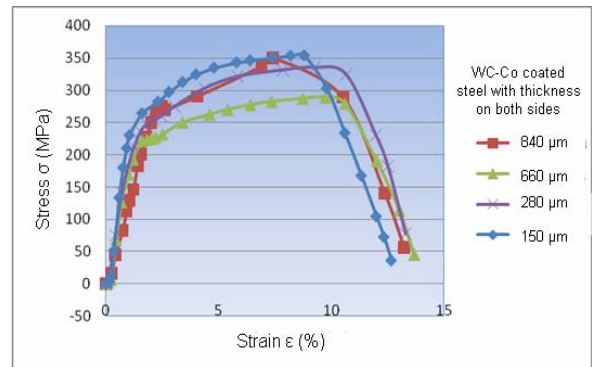


Figure 5. Stress – strain curves of WC-Co coated steel with various thicknesses

Figure 6 shows the dependence of elastic modulus on the coating thickness. It can be noted that the elastic modulus of the coated system decreases drastically with respect to the theoretical calculations as coating thickness increases. This phenomenon may be explained by the fact that the coated component behaves as a laminated composite structure stressed parallel to the lamellas with the coating and the substrate being the constituents, which determine the elastic and elastic-plastic behaviour. Simple rule of mixture approaches should be applicable in order to describe Young's modulus [20]:

$$E_{cs} = V_c * E_c + V_s * E_s \quad (2)$$

E_{cs} is the Young modulus of the coated system, V_c , V_s are the volume fractions of the coating and the substrate and E_c , E_s are the elastic modulus of the coating and the substrate in the composite system. In table 3 the experimental values of E_{cs} are listed and compared with the theoretical values calculated from equation (2) assuming that $E_c = 300$ GPa and $E_s = 207$ GPa [21].

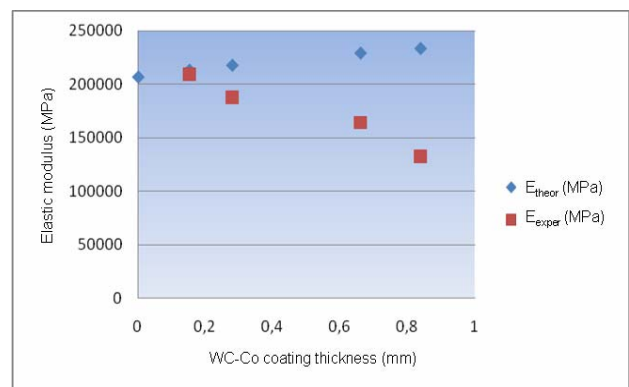


Figure 6. Elastic modulus of the WC-Co coated steel as a function of the coating thickness

It can be observed that there is a tendency agreement between the theoretical and experimental values of the Young modulus. The mean difference of the theoretical and experimental is 21% and it may attributed to the residual stresses, which are developed during cooling and depend upon the different thermal expansion coefficients of the coating ($a_c=4.6 \times 10^{-6} \text{ cm/cm}^\circ\text{C}$) and the substrate ($a_s= 11.3 \times 10^{-6} \text{ cm/cm}^\circ\text{C}$) and can be calculated according to [22]:

$$\sigma_{rc} = E_c \Delta a \Delta T \cdot \frac{1}{1 - \nu_c} \quad (3)$$

where σ_{rc} are the residual stresses, E_c is the elastic modulus of the coating, ν_c is the Poisson's ratio of the coating and ΔT is the temperature gradient during coating formation. Assuming $\nu_c = 0.33$ and $\Delta T= 400^\circ\text{C}$ the mean residual stresses of the WC-Co coating were calculated to be equal to 1200 MPa.

Table 3: Experimental and theoretical values of the elastic modulus

| Total thickness (mm) | Coating thickness (mm) | V_s | V_c | E_{theor} (MPa) | E_{exper} (MPa) |
|----------------------|------------------------|-------|-------|--------------------------|--------------------------|
| 2,2606 | 0,1524 | 0,932 | 0,067 | 213.270 | 209.100 |
| 2,9464 | 0,8382 | 0,715 | 0,284 | 233.457 | 132.400 |
| 2,7686 | 0,6604 | 0,761 | 0,238 | 229.183 | 164.100 |
| 2,3876 | 0,2794 | 0,883 | 0,117 | 217.883 | 187.500 |

The tribological characterization of the WC-Co coatings was intended to include the measurement of friction coefficient and the calculation of wear rate in relation to normal loads applied. Figure 7 shows representative plots for the variation of friction coefficient with sliding distance (or equivalently, time) for WC-Co coatings. Typical patterns, in general, were revealed. A running-in stage was identified in all cases examined; being more profound with the use of IC 3028 pin. During this period the value of the friction coefficient is increasing, probably due to high adhesive micro-contacts between the mating surfaces of the tribocouples [23], leading to a “peak” initial value which, however, cannot be related monotonously with the applied load.

For WC-Co coatings it is difficult to suggest a definite wear mechanism. Microscopic observations on the wear tracks revealed the existence of successive parallel sliding lines indicating an abrasion type wear (microploughing and polishing). However, taking into account the testing conditions, the wear of the counterparts (cutting insert pins) and the similar hardness of tested WC-Co disc and counterpart, a superimposed

mechanism based on adhesion could be suggested [24]. This frictional 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 $< 200 \text{ m}$) becoming thereafter mild, indicating a possible transition of wear mechanism. After testing, a cyclic wear track was clearly shown in WC-Co disc. Regions where parts of the coating are fallen off by delamination, together with grooves, were observed on the worn WC-Co surface, indicating a prominent abrasive wear model.

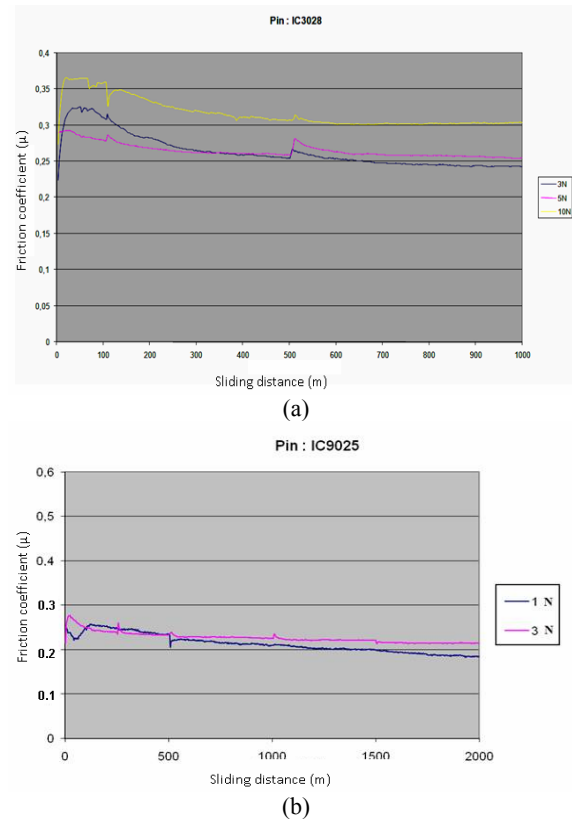


Figure 7. Representative plots for the variation of friction coefficient with sliding distance for WC-Co coatings; (a) IC 3028 and (b) IC 9025 pins

4 CONCLUSION

From the experiments presented in this paper the following conclusions can be drawn regarding the wear and corrosion resistance of WC-Co coatings:

1. WC-12% Co coatings were deposited by atmospheric plasma spray on the surface of mild steel specimens in various thicknesses. The morphology of the coating revealed porosity (3%), wavy surface topography ($R_a=8.2 \mu\text{m}$) and surface hardness of 1038 HV.

2. XRD analysis of the coating revealed that the coating consists of significant quantities of W_2C attributed to decarburization of WC during spraying.

3. The WC-Co coating protects the steel substrate in chlorine rich environment.

4. The WC-Co coating decreases the mechanical strength of the steel substrate. The elastic modulus of the WC-Co coated steel decreases proportionally with the coating thickness. Differences between theoretical and experimental values of the elastic modulus may be attributed to residual stresses. These residual stresses are developed during cooling and depend upon the different thermal expansion coefficients of the coating and the substrate.

5. During wear tests a running-in stage was identified during which the friction coefficient was increasing, due to high adhesive micro-contacts between the mating surfaces of the tribocouples leading to a “peak” initial value which were not related with the applied load.

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