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WC/C coating protection effects on 7075-T6 fatigue strength in an aggressive environment

Sergio Baragetti[a,b]*, Riccardo Gerosa[c], Francesco Villa[a]

[a] *Department of Engineering, University of Bergamo, Viale Marconi 5, Dalmine 24044, Italy*
[b] *GITT - Centre on Innovation Management and Technology Transfer, University of Bergamo, Via Salvecchio 19, Bergamo 24129, Italy*
[c] *Politecnico di Milano, Polo territoriale di Lecco, Via Gaetano Previati 1/c, 23900 Lecco, Italy*

Abstract

Thin hard coatings are typically employed to improve surface material characteristics such as hardness, wear and contact fatigue resistance, and friction behavior. Their effect on the component fatigue strength may vary, depending on the substrate surface finishing and to the microstructural modification of the base material due to the Physical Vapor Deposition (PVD) process thermal loads, particularly critical for a 7075-T6 low ageing temperature (121 °C) alloy. The present work investigates the effects of a low temperature (180 °C) Tungsten Carbide/Carbon (WC/C) PVD coating, in terms of corrosion protection under fatigue loads. The effects of an aggressive environment over uncoated and coated 7075-T6 hourglass specimens were analyzed, by rotating bending (R = -1) step loading fatigue tests at $2 \cdot 10^5$ cycles. A chemically aggressive external condition has been investigated, considering a methanol environment. Results show a certain protective capability of the WC/C coating, which is however offset by the fatigue strength drop found for coated samples at $2 \cdot 10^5$ cycles.

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1. Introduction

PVD coatings are at the present day employed to improve the surface characteristics, such as increased hardness and wear resistance [1], of industrial manufacturing tools for several production applications [2], as well as of engine components [3,4]. PVD treatments are attractive also for their contribution in terms of corrosion resistance,

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* Corresponding author. Tel.: +39-035-205-2382; fax: +39-35-205-2221.
E-mail address: sergio.baragetti@unibg.it

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including protection of aeronautic engines [5], and to guarantee chemical resistance of fuel cells components [6] and protect implanted biomedical or prosthetic devices from the aggressive body environment [7]. Their adoption over high performance components of engines and machines subjected to dynamic loads is sustained by their favorable or neutral behavior in terms of fatigue performances, especially for an infinite fatigue life over an hard steel substrate [8,9]. A certain positive contribution in terms of fatigue strength has been recognized also over aluminum substrates, such as 2011-T6 [10].

In the present work, the effects of corrosion fatigue over WC/C coated and uncoated 7075-T6 specimens are evaluated by means of $2{\cdot}10^5$ cycles rotating bending fatigue tests ($R= - 1$), immersed in an aggressive environment, in order to quantify the effectiveness of WC/C thin hard coatings in terms of corrosion protection on aluminum light alloys subjected to fatigue loads. Methanol was used as a corrosive media due to its proven aggressiveness in terms of static Stress Corrosion Cracking (SCC) and corrosion fatigue on light alloys [11,12]. Water-methanol mixtures are adopted to improve the performances of aeronautic turbines [13], and methanol is used for new generation fuel cells [6]. Methanol has been also adopted as a reference corrosive fluid in the testing of pressure vessels for the Apollo space program [14].

2. Experimental setup

Hourglass rotating bending fatigue specimens were prepared from 7075-T6 bars following ISO standards [15]. The raw material, obtained from commercial bars presenting the composition reported in Tab. 1, was characterized by means of tensile and hardness tests, performed at the metallurgy laboratories of Politecnico di Milano – Polo Territoriale di Lecco, and resulting in a yield strength $R_{p0.2}$ = 597 MPa and an ultimate strength R_m = 650 MPa (INSTRON 4507). The hardness was 190 ± 2 HV (Wolpert durometer).

Table 1. Chemical composition of the tested 7075-T6 aluminum alloy

Si [%]	Fe [%]	Cu [%]	Mn [%]	Mg [%]	Zn [%]	Cr [%]	Ti [%]	Al [%]
0,25	0,32	1,75	0,2	2,55	5,6	0,22	0,12	88,99

The specimens test area was accurately polished with abrasive paper up to 1200 grit, with final polishing on the longitudinal specimen direction. The test surface was then diamond polished, obtaining an average roughness R_a = 0.035 ± 0.008 μm (Taylor Hobson Form Talysurf profilometer). Some specimens were not diamond polished, in order to evaluate the properties of the surface finishing on the protective capabilities and fatigue contribution of the WC/C coating, presenting an average value of R_a = 0.289 ± 0.070 μm.

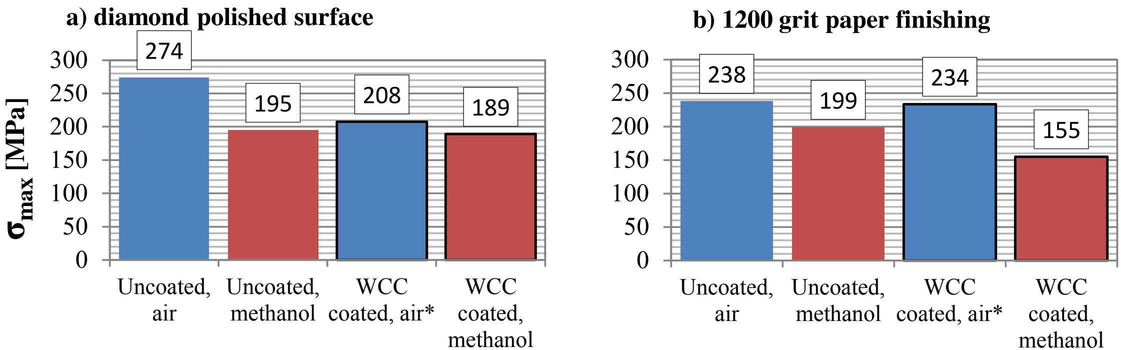
The specimens were then sent to Lafer SpA (Piacenza, Italy) for industrial WC/C coating. The average coating thickness was 2.5 μm, with a maximum deposition temperature of 180 °C. Vickers hardness was measured on the specimens uncoated heads after the deposition process, in order to evaluate the effect of the treatment on the substrate properties, resulting in a value of 181 ± 2 HV, thus showing a modest reduction of the surface hardness. The WC/C process was chosen particularly because of its low temperature, if compared to other PVD treatments, in order to produce minimum material modifications in the substrate, which has an ageing temperature in the T6 temper of 121°C.

The polished and coated specimens were tested at the Structural Mechanics Laboratories of the University of Bergamo, by using an ITALSIGMA four point rotating bending fatigue testing machine (R = -1), equipped with a digitalized force control, which made possible to perform arbitrary step loading tests with a precise setting on the number of cycles and especially on the applied stress interval. The step loading technique, particularly indicated for tests with a strong dependence from the specimen preparation [16], was adopted to find the limiting maximum bending stress at $2{\cdot}10^5$ cycles. The load was set up from 100 MPa and increased by 9 MPa at every step for each unfailed run. The final limiting stress was calculated by linear interpolation, weighted on the number of completed cycles, between the maximum stressess of the failed block and of the previous completed block [16].

Environmental testing was conducted by preparing a waterproof, flexible casing realized by using heat-shrink tubing and hydraulic mastic. The tubing was transparent, allowing to control that the aggressive media was effectively in contact with the test surface: in fact inertial forces from the rotating machine tended to separate the aggressive fluid from the specimen gage area, and a visual control of the experiment was needed to ensure proper testing. In order to obtain reference values directly linked to the employed samples, extended testing in air has been conducted using coated and uncoated specimens.

3. Results and Discussion

Tested specimens have shown a limiting stress σ_{max}, reported in Fig. 1, as obtained from the step loading procedure. For some configurations, a confirmation run at σ_{max} was made in laboratory air, in order to verify the correct number of cycles for the interpolated stress levels, as shown in Tab. 2.



*Averaged on two tests

Fig. 1. Step loading limiting stress results for different environments, coated and ucoated specimens: (a) diamond polished surface finishing; (b)1200 grit abrasive paper finishing.

Table 2. Confirmation run for some step-loading tests in laboratory air

Sample	Substrate Finishing	R_a [µm]	σ_{max} [MPa]	N_{conf}
Uncoated, air	diamond 3 µm	< 0.1	274	123’276
Uncoated, air	1200 grit paper	0.035 ± 0.008	238	449’232
WC/C coated, air	1200 grit paper	0.289 ± 0.070	210	300’636

The limiting stresses obtained by step loading testing indicate a detrimental contribution of the WC/C coating at 200’000 cycles, especially if considering the polished specimens. The effects of thermal loads during the WC/C deposition process could account partially for this reduction, since a certain detrimental effect (-6%) has been found over uncoated 7075-T6 specimens subjected to the same heating of the WC/C coated specimens [17], due to the low ageing temperature of the T6 temper (121 °C). Higher temperature PVD coatings, such as TiN (450 °C) showed indeed a dramatic reduction of fatigue limits in the whole S-N range on a 7075-T6 substrate [18].

However, other contributions must be taken into account, since these results reproduce a trend which has been found in several literature references [9,19,20] for different coated steel substrates. In these studies, a detrimental or neutral contribution of the PVD coatings to fatigue strength is clearly recognized when approaching high stress levels, for low number of cycles regions of the S-N curve – approximately between 10^4 and 10^5 – while a positive fatigue behavior is recovered for higher number of cycles.

If considering the specimens prepared with the 1200 grit abrasive paper, the WC/C coating shows a weak fatigue strength modification between the uncoated and the coated specimens. This fact suggests that the poor coating adhesion could prevent the propagation of possible defects from the coating to the substrate.

For which regards the effects of the aggressive environment with respect to laboratory air, a dramatic fatigue drop is observed both in the diamond polished (-29%) and in the 1200 finishing (-16%) uncoated specimens. If comparing the effect of methanol over diamond polished, WC/C coated specimens, a -11% limited drop of the maximum stress is found, hence suggesting a certain protective capability of the coating. This reduced protection is however absent in the coated specimens prepared with 1200 grit paper: a fatigue strength fall of -34% is found in this case, probably justified by the insufficient adhesion of the coating and the higher surface roughness. For which concerns the fracture mechanism, both coated and uncoated methanol-tested specimens exhibited a highly three dimensional failure surface, showing an evident damage caused by the aggressive methanol environment.

4. Conclusions

In the present work, the effects of WC/C coated and uncoated 7075-T6 specimens in terms of corrosion protection in an aggressive methanol environment have been investigated, by means of step-loading rotating bending ($R = -1$) testing. Two different surface finishing treatments were adopted in order to evaluate the influence of the coating adhesion, in terms of fatigue performances and corrosion fatigue protection.

The results show a dramatic drop of fatigue strength at $2 \cdot 10^5$ cycles for the uncoated specimens – i.e. from -29% to -16%, depending on the surface finishing. A marked dip persist also between the WC/C coated specimens with a 1200 grit surface finishing (-34%), while a certain protection can be found on the diamond polished and WC/C coated specimens, with a limited decrease of -11%.

However, if the effects of the coated, diamond polished specimen immersed in methanol are directly compared to the uncoated, diamond polished specimen in air, a significant drop of -31% is found, almost the same value of the reduction experimented by the diamond polished, uncoated specimen in methanol (-29%). The additional loss, caused by the decrease in terms of fatigue strength experienced by the coated specimens in the $2 \cdot 10^5$ number of cycles region, makes the adoption of a WC/C coating for corrosion protection an ineffective choice, at least when high fatigue stresses are present.

To conclude the investigation, further experimental testing is needed to explore the behavior of WC/C coating on 7075-T6 for fatigue strengths at an higher number of cycles. The effect of the low surface adhesion on the reduced fatigue strength drop of the 1200 grit paper treated and coated specimens has to be investigated as well, by examining the interface between the coating and the substrate.

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