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Fatigue behavior of foreign object damaged 7075 heat treated aluminum alloy coated with PVD WC/C

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Abstract

The effect of a physically vapor deposited (PVD) WC/C coating on the fatigue behavior of as produced and foreign object damaged (FOD) solution heat treated and aged 7075 aluminum alloy was studied. Coated and uncoated samples were tested under rotating bending to determine the fatigue strengths between 10^4 and 10^6 cycles in both damaged and smooth condition. FOD was produced with single shots of small hard steel spheres impacting at 100 m/s in the minimum cross section. SEM was used to characterize the features of the fracture surfaces.

Keywords: FOD; Fatigue; Thin hard coatings; PVD; Residual stresses

1. Introduction

Thin hard coatings deposited by PVD (Physical Vapor Deposition) are used to improve the wear and corrosion resistance of engineering materials [1–3]. It has also been demonstrated that some coatings prove rather effective against fatigue [4–6]. Aluminum alloys are known as key materials for a number of applications. However, very often the fatigue and the tribological properties of these materials are not so good as those of construction steels. Despite the potentials of coated aluminum alloys with improved mechanical strength, research studies focused on the tribological properties can mainly be found in the literature [7,8]. PVD WC/C coatings usually show good adhesion and exhibit remarkable anti-friction properties [9,10]. They are suitable for automotive applications or the machining tools and dies industry [11–13] and the relatively low deposition temperature allows the deposition on a broad range of materials. The tribological and mechanical characterization of WC/C coatings has already been addressed [14–16], but the effects on the fatigue resistance of the base material have not been studied enough. Good results for WC/C-coated 2011-T6 samples tested under fatigue are given in [17].

Another important issue for engineering materials for the aircraft industry is foreign object damage (FOD) [18–22]. In fact, damage caused by impacts with small particles or debris may significantly lower the fatigue resistance

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of critical components. In this respect, the effect of FOD on the fatigue behavior of Ti-6Al-4V has been extensively investigated [20–22]. By contrast, studies on FO-damaged aluminum alloys have not been carried out yet.

Aluminum alloy 7075 is widely used for automotive and aerospace applications which benefit from its high strength-to-mass ratio to have more power with lower emission of CO_2. In this work, the fatigue behavior of 7075-T6 was studied with rotating bending tests. Both single and combined effects of WC/C and FOD caused by single impact with a small hard steel sphere on the fatigue behavior of the base material were investigated. The coating process performed on the considered material was carried out at about 180°C for 6 hours. This temperature can affect both the mechanical and the corrosion properties of the samples in the T6 temper. Hence, tensile and intergranular corrosion tests were performed for comparing the treated and untreated materials. Finally, coated and then damaged and damaged first and then coated samples were tested to compare their performances.

Nomenclature

N	number of cycles to failure at which the fatigue limit is calculated, 10^n (n = 4, 5, 6)
N_f	number of cycles to failure in the final loading block
$\sigma_{f,n}$	nominal bending stress at minimum cross section of the loading block when failure occurs (MPa)
$\sigma_{p,n}$	nominal bending stress at minimum cross section of the loading block prior to that of failure (MPa)
$\sigma^{S}_{F,n}$	interpolated fatigue limit at 10^n cycles of the smooth uncoated samples (MPa)
$\sigma^{SC}_{F,n}$	interpolated fatigue limit at 10^n cycles of the smooth coated samples (MPa)
$\sigma^{D}_{F,n}$	interpolated fatigue limit at 10^n cycles of the damaged uncoated samples (MPa)
$\sigma^{DC}_{F,n}$	interpolated fatigue limit at 10^n cycles of the damaged first, then coated samples (MPa)
$\sigma^{CD}_{F,n}$	interpolated fatigue limit at 10^n cycles of the coated first, then damaged samples (MPa)
$K_{F,S\text{-}D}$	fatigue stress concentration factor between smooth and damaged uncoated samples = $\sigma^{S}_{F}/\sigma^{D}_{F}$
$K_{F,SC\text{-}CD}$	fatigue stress concentration factor between smooth and damaged coated samples = $\sigma^{SC}_{F}/\sigma^{CD}_{F}$

2. Experimental techniques

This study was carried out on 7075-T6 aluminum alloy with the following chemical composition (wt.%): 6.00 Zn, 3.00 Mg, 2.00 Cu, 0.25 Cr, 0.17 Fe, 0.11 Si, 0.04 Mn, 0.03 Ti and Al bal. Tensile and fatigue samples were machined from a 12 mm diameter bar according to B557 and E606 ASTM standards respectively (Fig. 1).

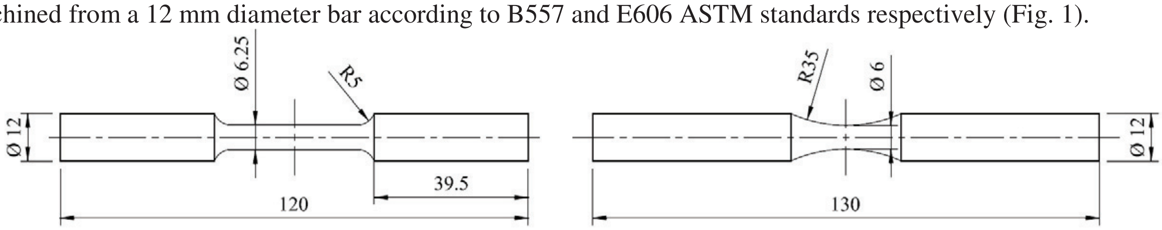

Fig. 1. Sketch of the samples used for the tensile (on the right) and the fatigue (left) tests. Dimensions expressed in mm.

Tensile tests were carried out according to ASTM A 370 standard on both coated and coated samples using an Instron 4507 testing machine. Moreover, micro-hardness tests were carried out on coated and uncoated samples to evaluate the effect of the impact on the base material properties. The gage length of the fatigue samples was carefully prepared to have a mirror-like surface finish. The WC/C coating was deposited at LAFER Spa (Piacenza, Italy) by magnetron sputtering (MS)-PVD under proprietary process conditions. The nominal deposition temperature was 180°C. Some coating parameters provided by LAFER Spa are: thickness in the range 1-3 µm, Vickers hardness of 1600±100 $HV_{0.025}$, friction factor of 0.15 and Young's modulus between 120 and 150 GPa.

Five series of fatigue samples were tested: smooth uncoated (S), smooth coated (SC), uncoated damaged by FOD (D), damaged and then coated (DC) and coated and then damaged (CD). Spherical hard steel shots with diameter of 2 mm were used to produce FOD on D, DC and CD series. A custom-made test bench [23] was used to throw single shots towards the middle of the sample gage length perpendicularly to the longitudinal axis at a speed of 100 m/s. The dimple diameters and depths were measured on some damaged samples by optical image analysis and by profilometer (Taylor Hobson Form Talysurf Intra 50) respectively. With reference to the sample axis, both longitudinal and transversal measuring directions were followed with the profilometer.

Rotating bending (R = −1) tests were carried out by using a computer-controlled machine (Italsigma X2TM412, Forlì, Italy) at 50 Hz in laboratory air at room temperature. The fatigue limits for constant lives of 10^4, 10^5 and 10^6 cycles were calculated for each series of samples by implementing a step-loading technique [21–23]. According to this procedure, the limiting stress $\sigma_{F,n}$ at $N = 10^n$ cycles is determined by interpolating between the stress levels of the last two loading blocks according to the formula:

$$\sigma_{F,n} = \sigma_{p,n} + \frac{N_f}{10^n}\left(\sigma_{f,n} - \sigma_{p,n}\right)$$

The stress values were assumed as the nominal ones over the minimum undamaged sample cross section.

Coaxing, that consists in the fatigue strength increase when a component is cycled below the fatigue limit, may affect the reliability of the step-loading method. However, this phenomenon is typical of ferrous metals [24,25]. In general, the closer to the fatigue limit the initial stress level is, the less influence it has of coaxing results. Accordingly, a second sample was often tested for each testing condition for confirmation. The characterization was finally completed with some SEM observations.

3. Results and discussion

The results of the tensile tests carried out on both uncoated and coated materials are summarized in Table 1. The average diameters and depths measured on the damaged samples were included in the ranges 1000- 1100 µm and 130-165 µm respectively. Figs. 2a and 2b show the top view of the dimples produced by the impacts in an uncoated and a coated sample respectively.

Tab1. Tensile properties before and after the deposition treatment.

Material	σ_y [MPa]	UTS [MPa]
Uncoated	585	656
Coated	544	614

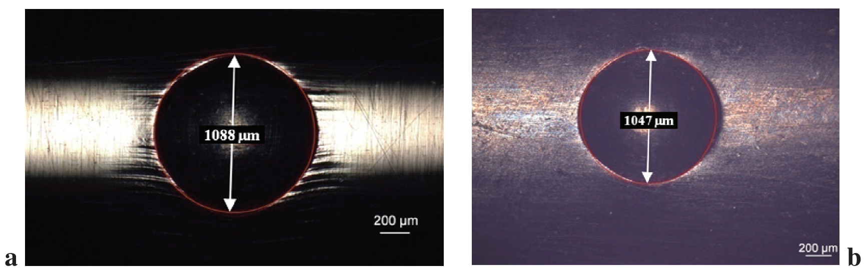

Fig. 2. Optical microscope observations of the damaged areas of (a) an uncoated (D) and (b) a coated (CD) sample.

The effect of the impact (both before and after the coating process) was studied by micro-hardness tests (HV0.01) on damaged samples as illustrated in Figure 3(a) and (b).

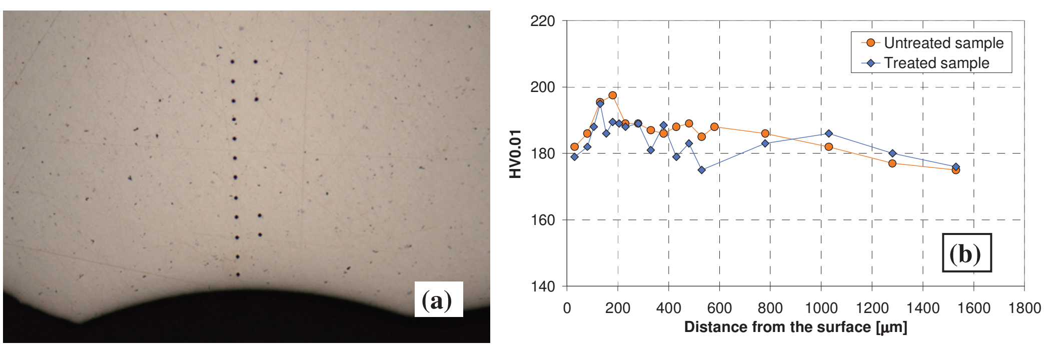

Fig. 3. Micro-hardness indentations and micro-hardness profiles on a treated (coated) and untreated (uncoated) damaged sample.

In Figure 3(b) the micro-hardness profiles are reported. For both the samples (coated and uncoated) the impact caused a strain hardening of the material that resulted in a micro-hardness peak at about 150μm from the surface.

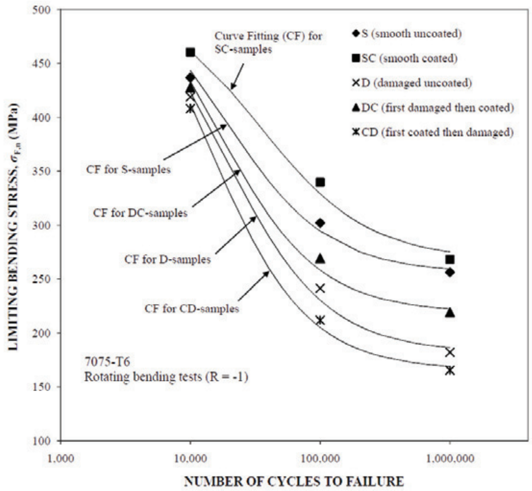

Fig. 5. Limiting bending stress vs. Number of cycle to failure diagram for the five series of samples tested.

Fig. 5 shows the fatigue limits data plotted vs. the number of cycles to failure. The coating was somewhat beneficial to the fatigue resistance of both smooth and damaged 7075-T6. By contrast, damaged WC/C was rather detrimental. In Table 2 the values of the fatigue limits at 10^4, 10^5 and 10^6 load cycles for all the series of samples are reported. A mean improvement of 8% was found in the coated samples with respect to the uncoated ones, whereas the damaged smooth samples fatigue resistance decreased by about 18% (corresponding to a mean fatigue stress concentration factor of 1.23). The coating proved effective in recovering the fatigue resistance of the FOD material: compared with the uncoated damaged condition, a mean fatigue limit improvement of 11% was found. FOD after deposition resulted in the worst fatigue behavior: compared with the coated smooth condition, a mean fatigue resistance fall of -29% (corresponding to a mean fatigue stress concentration factor of 1.45) was found; moreover a mean decrease of about 8% with respect to the uncoated damaged samples resulted. This suggested an additional fatigue stress concentration effect, probably due to multiple severe micro-notches caused by the fractured coating [26].

Tab 2. Calculated limiting bending stress (MPa) at 10^4, 10^5 and 10^6 cycles and main differences between some of the tested conditions.

N	$\sigma^{S}_{F,n}$	$\sigma^{SC}_{F,n}$	$\sigma^{D}_{F,n}$	$\sigma^{DC}_{F,n}$	$\sigma^{CD}_{F,n}$	$K_{F,S\text{-}D}$	$K_{F,SC\text{-}CD}$	Δ(SC-S)%	Δ(D-S)%	Δ(DC-D)%	Δ(CD-SC)%	Δ(CD-D)%
10^4	437	460	419	427	408	1.04	1.13	+5	-4	+2	-11	-3
10^5	302	340	241	269	212	1.25	1.60	+13	-20	+12	-38	-12
10^6	256	268	182	219	166	1.41	1.61	+5	-29	+20	-38	-9
					Average values	1.23	1.45	+8	-18	+11	-29	-8

SEM observations confirmed and justified the previous results and hypothesis. In Figure 6(a), in fact, some radial cracks are shown for a damaged and coated sample at the boundary of the imprint: these defects can lower the fatigue limits especially at high stresses. In Figure 6(b) the effect of the impact on a coated sample is shown: many cracks and fractures can be observed on the damaged surface; their influence on the fatigue resistance is of course negative as demonstrated by the fatigue tests results.

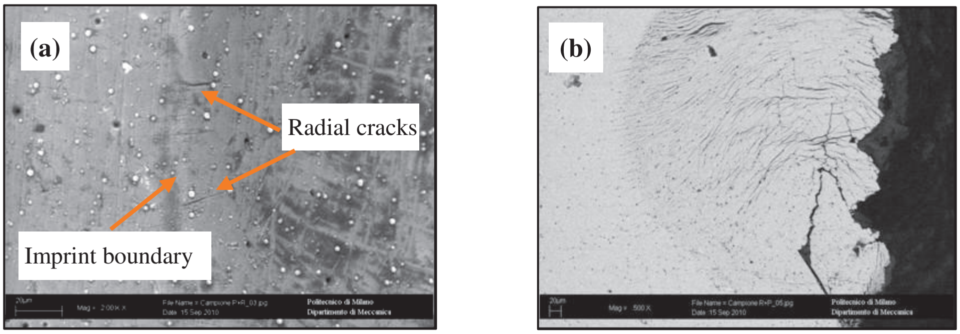

Fig. 6: SEM observation of a damaged and then coated sample (a) and of a coated and then damaged sample (b).

Finally, in order to evaluate the effect of the coating process on the corrosion properties of the material, some intergranular corrosion tests were performed according to AMS 2772D. The evaluation of the corrosive attack was carried out observing the corroded profiles as described in Figure 7 according to the procedure described in [27].

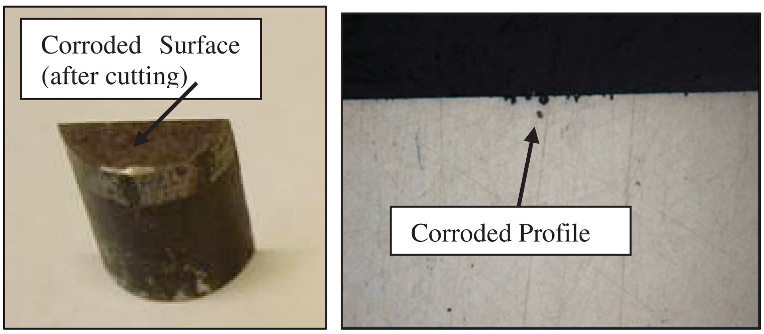

Fig. 7: Corroded surface and profile (after cutting)

The analysis results were reported in Table 3. No notably differences were found between the coated and uncoated materials as described by the corrosion indexes.

Tab.3: corrosion indexes for the coated and uncoated sample – R* is related to the shape of the defect, whereas Rc contains informations about both the defect morphology and the measured corroded length.

Material	R*	Rc
Uncoated	1.46	13.1
Coated	1.76	15.3

4. Conclusions

Rotating bending tests were carried out on PVD WC/C-coated and FO-damaged 7075-T6 samples. Moreover tensile and intergranular corrosion tests were performed on treated and untreated samples. Based on the obtained results, the following points are remarked:

- the WC/C coating improved the fatigue behavior of both smooth and especially damaged 7075-T6 specimens;
- damaged WC/C coated samples showed the worst fatigue behavior, probably due to multiple severe micro-notches caused by the fractured coating;
- SEM observations proved very important for a better understanding of the rotating bending fatigue results, especially the ones performed on coated and damaged or damaged and then coated specimens;
- the effect of the deposition treatment on the T6 temper was studied by tensile and intergranular corrosion tests: for the coated samples a slight decrease of the yield stress and the UTS was found (respectively about 7% and

6%), whereas no notably differences were detected about the corrosion resistance.

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