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Experimental and theoretical studies of corrosion-induced mechanical properties degradation of aircraft 2024 aluminum alloy

N.D. Alexopoulos [a,*,1], P. Papanikos [b]

[a] Laboratory of Structural Mechanics, Department of Rural and Surveying Engineering, National Technical University of Athens, Zografou Campus, 9 Iroon Polytechniou St, 15780 Athens, Greece
[b] Department of Product and Systems Design Engineering, University of the Aegean, Ermoupolis, Syros 84100, Greece

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ABSTRACT

In the present work, the influence of the corrosion exposure time on the mechanical properties degradation of the aluminum 2024-T3 alloy is studied. Tensile and fracture toughness mechanical tests had been carried out on pre-corroded specimens, exposed for different times to laboratory accelerated, exfoliation corrosion solution. The test results show that both the tensile mechanical properties as well as the fracture toughness exponentially decreased with increasing exposure time. A mechanical model has been devised to calculate the specimen's remaining effective thickness after different corrosion exposure times. It has been shown that the decrease in the alloy's fracture toughness is mainly associated with the thickness reduction degradation mechanism and a small reduction is attributed to hydrogen embrittlement. The hydrogen embrittlement degradation mechanism is saturated for exposure times up to 24 h. For higher exposure times, the prevailing degradation mechanism of alloy's fracture toughness is the formation of corrosion-induced surface cracks and the resulting reduction of the effective thickness of the test specimen. An FE model has been developed for a fast calculation of the uncorroded alloy's fracture toughness with good results. The model has also been exploited to predict the alloy's fracture toughness degradation for the increasing exposure time to corrosive environment.

1. Introduction

During the last decades much attention has been paid to the damage tolerance evaluation of the aircraft fuselage and skin structure. There is a strong need for the damage tolerant structural materials to define their inspection intervals such as to reduce the maintenance costs and the structural weight of the aircraft. A study has been performed on repairs of the fuselages of 71 Boeing 747 aircraft with an average life of 29,500 flight hours and were briefly discussed in [1]. These repairs were classified according to the type of damage. The distribution over the damage types was 396 repairs of fatigue cracks (57.6%), 202 repairs of corrosion damage (29.4%), and 90 repairs of impact damage (13%).

The possibility that the corrosion damage will interact with other forms of damage, e.g. fatigue cracks, can result in loss of the structural integrity and may lead to fatal consequences, e.g. the Aloha Airlines accident. Though many researchers are working to develop damage functions accounting for both fatigue and corrosion damage [2–4], the developed analytical models did not present satisfactory results [5–7]. Hence, the structural integrity assessment of fatigue and corrosion in aging aircrafts is still relying heavily on test data. To face the corrosion-induced structural degradation issue, available data usually refer to accelerated laboratory tests. The most common accelerated corrosion laboratory test used for the aeronautical aluminum alloys 2xxx and 7xxx is the exfoliation corrosion (EXCO) test. It has been reported that 24 h exposure of the alloy 2024-T4 to the exfoliation corrosion solution corresponds to nearly 6 years of natural exposure of the same structural element regarding its surface exfoliation [8].

For the aluminum alloy 2024-T3, being the most widely used aluminum alloy in the aircraft, various mechanical tests had been carried out to assess the influence of the corrosion damage on the material's structural integrity. Tensile and fatigue mechanical tests had been carried out in pre-corroded material [9–13], resulting to a degradation of the material's mechanical properties. For example, it has been found that even for 2 h exposure to the exfoliation corrosion solution, there exists a dramatic degradation of the ductility properties of the order of magnitude of 35% and 50% in the L and LT

* Corresponding author. Tel.: +30 210 6434384.
E-mail address: nalexop@tee.gr (N.D. Alexopoulos).
1 Present address: Department of Financial and Management Engineering, University of the Aegean, 821 00, Chios, Greece.

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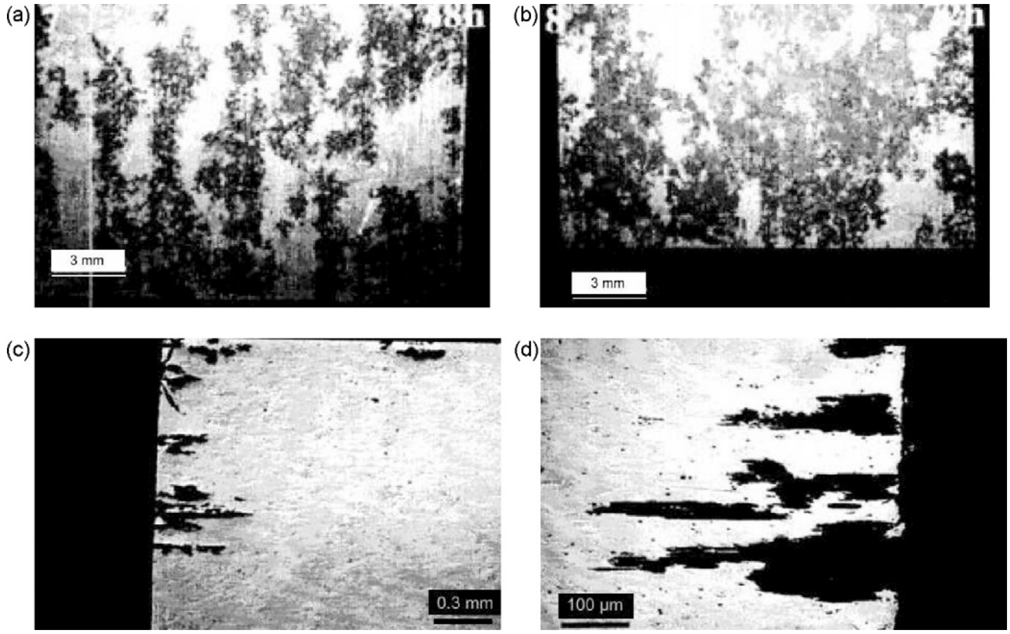

Fig. 1. Macrostructure of 2024-T3 sheets after exposure (a) 48 h and (b) 72 h to exfoliation corrosion solution and resulting surface corrosion-induced cracks at the specimen's cross-section after exposure to the same solution for (c) 48 h and for (d) 72 h.[14]

directions, respectively. By increasing the material's exposure time to the corrosive solution, e.g. 96 h, the degradation of ductility and strength properties reaches 90% and 20%, respectively.

The resulting microstructure of pre-corroded specimens of 2024-T3 alloy exposed for various times to the exfoliation corrosion solution has been also studied [14]. In Fig. 1, typical macro- and microstructures with the surface corrosion products as well as the corrosion depth (or depth of attack) for two different exposure times are presented. In [13,15], the mechanical removal of the surface corrosion layers of a pre-corroded tensile specimen, restored the strength properties but not the ductility properties. In [16], this phenomenon was attributed to an embrittlement mechanism, which was supported by analysis of the fractured surfaces of the tensile specimens. In [14,16,17], the quantitative degradation of the mechanical properties had been correlated with quantitative measurements of the trapped hydrogen in the material's microstructure, thus verifying the hydrogen embrittlement mechanism in 2024 alloy.

For the needs of the aircraft industry, the damage tolerance requirements necessitates the design engineer to take into account the material's yield strength R_p, its fracture toughness K_{cr}, the fatigue S/N curves and the fatigue crack growth curves da/dN of the material of the critical components. Since the material of the component is subjected to corrosion, it is expected that the above mechanical properties of the material should vary with increasing service time and must be taken into account for the structural integrity calculation of the component. The degradation of the tensile mechanical properties as well as the fatigue properties of the Al 2024-T3 has been examined extensively in the open literature, however, there is no thorough investigation regarding the influence of the corrosion on the material's fracture toughness.

In the present work, the influence of the corrosion exposure time on the mechanical properties degradation of the aluminum 2024-T3 alloy is assessed. Tensile and fracture toughness mechanical tests had been carried out on pre-corroded specimens, exposed for different times to laboratory accelerated, exfoliation corrosion solution. A mechanical model has been devised to calculate the specimen's remaining effective thickness after different corrosion exposure times. Investigation has been made to reveal the degradation mechanisms of the alloy's fracture toughness with the increasing exposure time to corrosive environment. An FE model has been developed for a fast calculation of the uncorroded alloy's fracture toughness with good results. The model has also been exploited to assess the alloy's fracture toughness degradation for the increasing exposure time to corrosive environment.

2. Material test data

The material used was a wrought aluminum alloy 2024-T3 which was received in sheet form with nominal thickness of 3.2 mm. The chemical composition of the alloy is 0.50% Si, 0.50% Fe, 4.35% Cu, 0.64% Mn, 1.50% Mg, 0.10% Cr, 0.25% Zn, 0.15% Ti and Al rem. Tensile and fracture toughness specimens

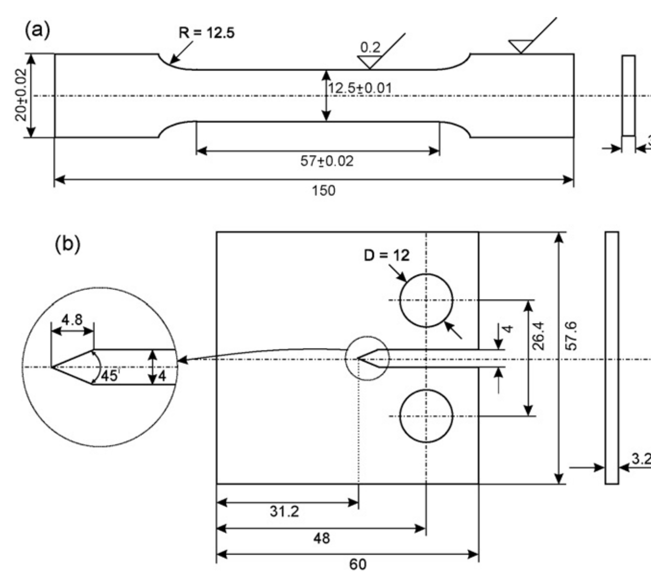

Fig. 2. (a) Tensile and (b) fracture toughness test specimen configurations of the investigated aluminum alloy according to the specifications ASTM E8 and E561, respectively.