Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

On the corrosion-induced mechanical degradation for different artificial aging conditions of 2024 aluminum alloy

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A R T I C L E I N F O

Article history:
Received 9 December 2008
Received in revised form 30 April 2009
Accepted 13 May 2009

Keywords:
2024 aluminum alloy
Corrosion
Tensile test
Fracture toughness
Hydrogen embrittlement
Trapping states

A B S T R A C T

In the present work, the effect of different artificial aging conditions of the Al 2024-T3 on the mechanical properties degradation due to corrosion exposure is studied. Different artificial aging conditions had been applied to tensile and fracture toughness specimens, which were subsequently exposed to exfoliation corrosion environment. Microstructure analysis showed that for the reference (T3) and peak-aged (PA) specimens the corrosion-induced surface pits were followed by formation of a microcrack network, while only large surface pits were noticed for the over-aged (OA) specimens. The tensile test results showed that the higher the (OA) condition, the lower degradation due to corrosion exposure the alloy has. Fracture toughness K_{cr} calculated on the basis of nominal thickness of the specimens confirms that the decrease due to corrosion is lower for the (OA) specimens. The K_{cr} values calculated on the basis of effective thickness of the specimens showed that the degree of decrease due to corrosion damage is negligible for the (OA) specimens. This phenomenon has been explained and discussed based on the resulting microstructure for the various aging conditions of the alloy.

1. Introduction

Two decades ago the aluminum alloys possessed almost 65% of the materials used in the aircraft. Nowadays, the total aluminum alloys possess more than 40%, still making them the most usable material in the aircraft industry. The widely used aluminum alloy is the damage-tolerant Al 2024-T3 alloy used in the skin and the wings of the aircraft. The main problems of the design and inspection engineers are the fatigue, corrosion and impact damage that the fuselage and wing skins are subjected to.

A very difficult aspect is the «aging» aircraft, which is by default an in service aircraft that has passed the design goal of usually 25 years. An aging aircraft requires more frequent intervals of inspection and maintenance or replacement of its critical structural components. For the case of aluminum alloy 2024-T3, an essential degradation of the mechanical properties is occurred due to the synergy of cumulative fatigue damage, the corrosion damage, and of course, the natural aging of the precipitate-hardened aluminum alloy (Fig. 1).

The tensile mechanical properties are of great importance to the aircraft industry. The damage tolerance requirements necessitate 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. The effect of natural and artificial aging on the Al 2024-T3 is well known, e.g. [1]. The alloy strengthens due to the precipitation of the S'' phase (Al_2CuMg) that leads to peak-aging (PA) condition and subsequent with increasing aging to the over-aging (OA) condition. It is evident though, that the tensile mechanical properties of the material, on the long term, are a function of the natural aging exposure. Bearing in mind that a typical thermal cycle of an aircraft (takeoff, cruising and landing) can be of the order of $-50\,^{\circ}C$ up to $+50\,^{\circ}C$ at countries with a hot climate, the effect of natural aging is much underestimated since the alloy can reach its (PA) condition in much earlier time.

Corrosion damage of the material is also very essential to the structural integrity of the aircraft. Since the material of a component is subjected to corrosion, it is expected that its critical mechanical properties might vary with increasing service time and thus, must be taken into account for the structural integrity calculation of the component. The effect of corrosion damage on the reference alloy has been studied in various works. The exposure of the alloy 2024-T3 on various accelerated, laboratory environments such as exfoliation corrosion or salt spray corrosion, e.g. [2–4], resulted in the formation of large pits and micro-cracks on the sub-surface of

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0921-5093/$ – see front matter
doi:10.1016/j.msea.2009.05.023

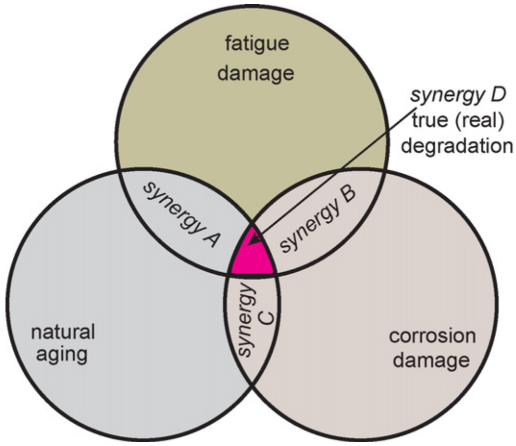

Fig. 1. Mechanical properties degradation mechanisms in precipitated wrought aluminum alloys used in the aircraft and possible synergies amongst them.

the specimens, that lead to exfoliation of the alloy with increasing exposure time. This has a deleterious impact on the residual mechanical properties, especially in the tensile ductility. Petroyiannis et al. [5] noticed that after the exposure of only 2 h, the ductility of the 2024-T3 decreased by 60%. Kamoutsi et al. [3] attributed this decrease to the hydrogen embrittlement mechanism. Alexopoulos and Papanikos [4] performed fracture toughness mechanical tests on the same alloy and for various exposure times to corrosive environment. It has been shown that the total reduction of almost 30% of the fracture toughness after 96 h exposure to exfoliation corrosion solution was attributed primary to the reduction of the alloy's effective thickness (22%) and secondary to the hydrogen embrittlement (8%) mechanism. In addition, when calculated the true fracture toughness values (based on the true thickness of the material after the corrosion exposure) they were saturated after only 24 h of exposure.

In the open literature, all types of accelerated corrosion exposure tests had been applied to the reference sheet alloy 2024 at the T3 condition. As the design life of a typical aircraft is about 25 years, the mechanical properties of the 2024-T3 should vary during this period, due to the natural aging of the alloy. Hence, a more realistic point of view is that the alloy should be exposed to the corrosive environment when first being natural (or artificially) aged to assess its true degradation due to the synergy of aging and corrosion. This is expressed as the case of synergy C in Fig. 1. To the author's knowledge, this is the first time that an assessment of different artificial aging conditions to the corrosion-induced degradation on mechanical properties is attempted. In the literature [6] it is generally reported that the 2xxx wrought aluminum alloys in the T3 condition have low corrosion resistance when compared to the ⟨⟨precipitated⟩⟩ T6 and T8 conditions of the alloy.

In the present work, the effect of artificial aging of the Al 2024-T3 on the mechanical properties degradation due to corrosion exposure is studied. Tensile and fracture toughness specimens will be submitted to artificial aging conditions that correspond to (UA), (PA) and (OA) conditions and then will be subsequently exposed to exfoliation corrosion environment. The microstructure analysis will characterize the corrosion-induced surface pits for the different aged specimens. The tensile and fracture toughness mechanical results will show the effect of the aging condition on the corrosion resistance of the alloy.

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 weight percentage 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 were machined from the material sheet according to ASTM E8 and to ASTM E561, respectively. All specimens were cut such as to test the longitudinal (*L*) direction of the material.

Artificial aging of the specimens was made at 210 °C aging temperature. It was selected such as to be close to the upper bound of the temperature range of the artificial aging of the commercial sheet 2024-T3 [1]. This high aging temperature enables to bring the alloy in to the (OA) condition at a very short period of time (Table 1).

Half of the available specimens were tested in tension and in R-curve testing according to the ASTM E8 and E561, to assess the effect of artificial aging on the respective properties. The other tensile and fracture toughness specimens were exposed for 24 h to the laboratory exfoliation corrosion environment (hereafter called EXCO solution) according to specification ASTM G34. The corrosive solution consisted of the following chemicals diluted in 1 l distilled water; sodium chloride (4.0 M NaCl), potassium nitrate (0.5 M KNO_3) and nitric acid (0.1 M HNO_3). More details can be seen in [4] and in the respective specification. Fig. 2 shows a photograph of the compact-tension specimens with different artificial aging condition and subsequent 24 h exposure to the EXCO environment. The common 24 h exposure time was selected according to the literature [3,4] as the hydrogen embrittlement is saturated. After the exposure, the corroded specimens were subjected to mechanical testing. Tensile tests were carried out according to the ASTM E8 specification, while fracture toughness tests were carried out according to ASTM E561 specification. After the corrosion exposure, a physical fatigue pre-crack had been formed to the C(T) specimens. More details regarding the specimens, corrosion exposure procedure and

Table 1
Mechanical properties of aluminum alloy 2024-T3 (a) after artificial aging at 210 °C and (b) artificial aging and subsequent 24 h exposure to exfoliation corrosion solution.

Aluminum alloy 2024-T3 treatment	Mechanical properties					
	R_p0.2% (MPa)	R_m (MPa)	R_f (%)	W (MJ/m^3)	E (GPa)	K_{cr} (MPa m$^{1/2}$)
(a)						
Reference	391	494	18.57	86.79	69.763	86
2 h artificial aging	476	512	7.79	39.53	69.641	84
4 h artificial aging	454	500	8.94	44.36	68.912	64
6 h artificial aging	443	493	9.19	45.03	68.873	65
8 h artificial aging	436	487	9.43	45.84	68.358	66
(b)						
Reference + 24 h EXCO	369	449	11.95	51.76	61.151	69
2 h artificial aging + 24 h EXCO	458	489	5.51	27.64	62.586	66
4 h artificial aging + 24 h EXCO	434	477	6.44	31.16	63.171	53
6 h artificial aging + 24 h EXCO	423	473	6.99	33.49	62.903	59
8 h artificial aging + 24 h EXCO	418	469	7.62	36.89	61.673	61