THE CORROSION-INDUCED FRACTURE TOUGHNESS DEGRADATION OF ARTIFICIALLY AGED 2024 ALUMINUM ALLOY SPECIMENS

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ABSTRACT

In this paper, the effect of accelerated corrosion exposure on the fracture toughness of the aluminium alloy 2024 is studied. Various exposure times had been applied to the reference condition T3 of the alloy as well as in other conditions, e.g. the peak-aged (PA) and the over-aged (OA) conditions of the sheet alloy. Tensile and fracture toughness specimens of the reference as well as for other aging conditions were corroded in accelerated corrosive environment and subsequently mechanically tested. SEM was applied to characterize the fracture surfaces of the tensile specimens. For the small exposure times of the reference specimens, an essential degradation in ductility and fracture toughness was noticed and was attributed to the hydrogen embrittlement mechanism. For higher exposure times of the reference specimens, an additional decrease was noticed and was attributed to stress concentration on the corrosion-induced surface notches. Fracture toughness tests on 24 h pre-corroded reference alloy (T3 condition) showed an almost 20% decrease. By aging the alloy and subsequently applying the same 24 h corrosion exposure, the degree of decrease due to corrosion damage is almost negligible for the (OA) specimens.

Keywords: 2024; aging; corrosion; fracture toughness; hydrogen embrittlement

INTRODUCTION

The most widely used aluminum alloy in the aeronautics is the damage-tolerant Al 2024-T3 alloy. 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 replacement - maintenance 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 aluminium alloy [1].

The effect of natural and artificial aging on the Al 2024-T3 is well known in the literature. 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 [2].

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, e.g. [3, 4]. The exposure of the alloy 2024-T3 on various accelerated, laboratory environments such as exfoliation corrosion or salt spray corrosion, resulted in the formation of large pits and micro-cracks on the sub-surface of the specimens, that lead to exfoliation of the alloy with increasing exposure time. This has a deleterious impact on the residual mechanical properties and especially in the tensile ductility. Only after 2 h exposure, the ductility of the 2024-T3 decreased by 60%. This was attributed to the hydrogen embrittlement mechanism [5]. Performed fracture toughness tests and for various exposure times to corrosive environment, showed that the total reduction of almost 30% of the fracture toughness after 96 h exposure was attributed primary to the reduction of the alloy's effective thickness (22%) and secondary to the hydrogen embrittlement (8%) mechanism [6].

In this paper, the effect of different artificial aging conditions of the Al 2024-T3 on the fracture toughness degradation is studied. Different artificial aging conditions had been applied to tensile and fracture toughness specimens, which were subsequently exposed to exfoliation corrosion environment. The aging conditions were the reference (T3), the peak-aged (PA) as well as the over-aged (OA). It is shown that the fracture toughness degradation is artificial aging condition dependant; the degree of decrease due to corrosion damage is negligible for the (OA) specimens.

EXPERIMENTAL PROCEDURE

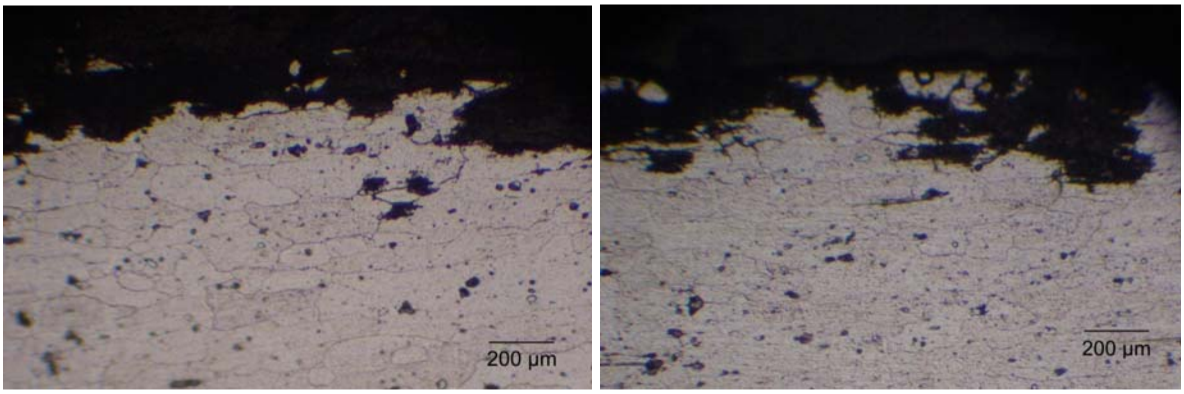
The material used was a wrought aluminum alloy 2024-T3 which was received in sheet form with nominal thickness of 3.2 mm. The chemical composition of the alloy was 0.50% Si, 0.50% Fe, 4.35% Cu, 0.64% Mn, 1.50% Mg, 0.10% Cr, 0.25% Zn, 0.15% Ti and Al rem. Tensile and fracture toughness specimens were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

Tensile and fracture toughness specimens were exposed for various exposure times up to 96 h to the accelerated laboratory exfoliation corrosion environment according to specification ASTM G34 (hereafter corrosive solution will be called EXCO solution). In addition, other specimens were subjected to artificial aging at 210^{o}C aging temperature. This temperature 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. It enables to bring the alloy in to the (OA) condition at a very short period of time. The aged specimens were subsequently exposed for 24 h to the laboratory exfoliation corrosion environment. The common 24 h exposure time was selected according to [5, 6], as the hydrogen embrittlement effect is saturated to the 2024-T3 alloy. After the exposure, some of the corroded specimens were used for metallographic investigations and the rest were subjected to mechanical testing. Tensile and fracture toughness tests were carried out according to the ASTM E8 and E561 specifications, respectively. More details regarding the specimens, corrosion exposure procedure and mechanical testing can be found in [1, 6]. Three specimens were tested in each different case to get reliable average data. After the mechanical testing, the fractured areas of the tensile specimens were examined with Scanning Electron Microscope (SEM).

RESULTS AND DISCUSSION

(a) Microstructure

The resulting microstructure of the alloy 2024-T3 with artificial aging is well known [2] and consists of the formation of the S'' precipitates and subsequent coarsening with continuous aging. The effect of increasing corrosion exposure to the 2024-T3 alloy resulted in the formation of surface pits [5]. The same corrosion exposure duration of different artificial aged specimens had a different effect on the sub-surface microstructure. Figure 1 shows typical microstructures for 2 and 6 hours of artificially aged specimens near the corroded surface, respectively. It was observed that for the low artificially aged specimens (e.g. 2 hrs), the corrosion exposure formed surface pits and a sub-surface micro-cracking network. Though for the high artificially aged specimens the formation of the surface pits was obvious, the micro-cracking network couldn't be noticed for the investigated specimens.



(a) (b)

Fig.1: Typical microstructure of artificially aged specimens (a) 2 hrs AA and (b) 6 hrs AA and subsequent 24 h EXCO corrosion. Photos near the corroded surface of each specimen.

(b) Tensile tests

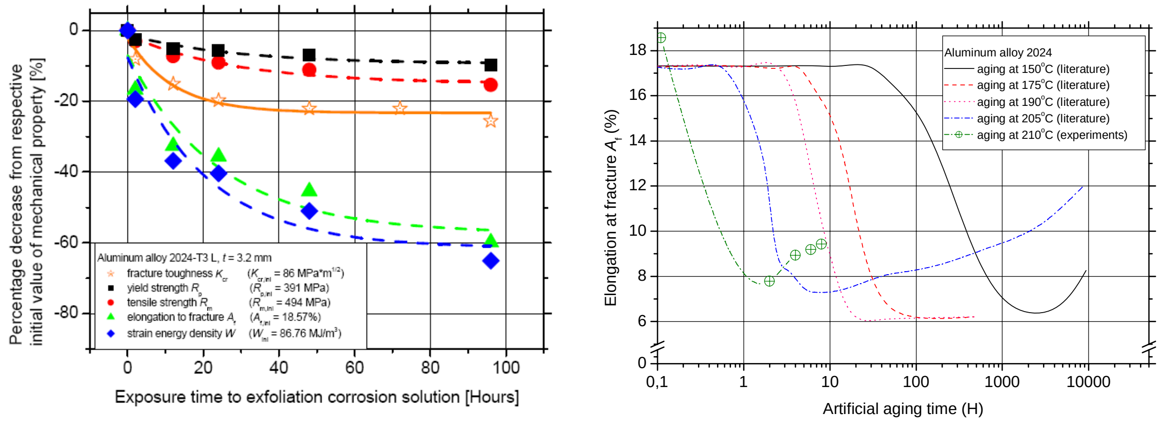
Performed tensile tests on pre-corroded specimens showed that an essential decrease in ductility properties is noticed, even at small exposure times, Figure 2a. A great reduction in elongation to fracture A_f after exposure to EXCO solution was also noticed, only after 2 h of exposure [3] for similar sheet alloy. For the case of the reference T3 alloy, an approximate 20% reduction was noticed after 2 h exposure to the corrosive solution. The decrease in the ductility of the alloy 2024-T3 after exposure to EXCO solution is attributed to both, hydrogen embrittlement and the effect of the corrosion-induced surface cracks.

Kamoutsi et al. [5] showed that for the case of 24 h EXCO exposure of 2024-T3, the machining of the layer with the surface cracks restored all the strength properties of the specimens. Elongation to fracture value after 24 h exposure to EXCO solution was decreased to the 39% of the reference value. After the machining of the corroded layers (elimination of the corrosion-induced surface cracks), A_f value was not fully restored but partially increased up to the value of 66% of the reference value. This means that for the specific case, this difference of (100% - 66% =) 34% of the decrease in A_f is attributed to hydrogen embrittlement; in total of 71% decrease of ductility, 34% is due to hydrogen embrittlement and the rest (27%) is due to the surface cracks effect.

The results of the effect of the different artificial aging conditions on the elongation to fracture property can be seen in Figure 2b. The results are consistent with the literature [2]; with increasing aging condition, peak-aging leads to minimum elongation to fracture value, while over-aging condition further increases the A_f property, Figure 2b.

(c) Fracture toughness tests

Fracture toughness values can also be seen in Figure 2a for the various corrosion exposure times. As fracture toughness is both, strength and ductility dominated, K_{cr} is also decreasing with increasing exposure time and the reduction is in between the strength and the ductility properties. Reduction in K_{cr} is up to almost 30% of its initial value for the case of 96 hours exposure to EXCO solution.



(a) (b)

Fig.2: (a) Percentage reduction of mechanical properties for the various exposure times of aluminum alloy 2024-T3 to the exfoliation corrosion solution and (b) elongation to fracture values for the various artificial aging conditions of aluminum alloy 2024-T3.

The fracture toughness test results for the various artificial aging conditions are presented in Figure 3. The K_{cr} values were calculated based on the nominal thickness t = 3.2 mm of the alloy. A significant decrease is noticed for increasing artificial aging of the alloy. From the reference value of 86 MPa*m$^{1/2}$, values up to 65 MPa*m$^{1/2}$ for the (OA) condition were recorded. It was eminent that the subsequent exposure to the corrosive environment would further decrease this property; for the cases of (UA) condition (0 h and 2 h artificial aging) and the (PA) condition (4 h artificial aging), a large reduction of almost 20% on the K_{cr} due to EXCO exposure is noticed, Figure 3. At the (OA) condition (6 h and 8 h) the K_{cr} values decreased by only 9.2% and 7.6%, respectively, due to the corrosion exposure.

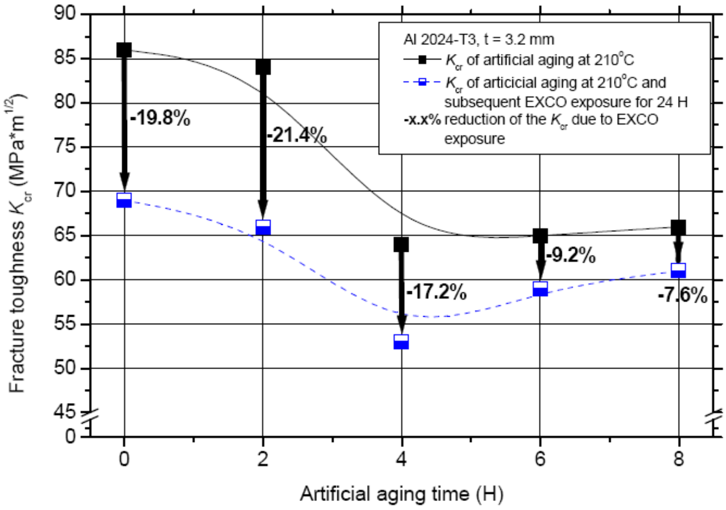
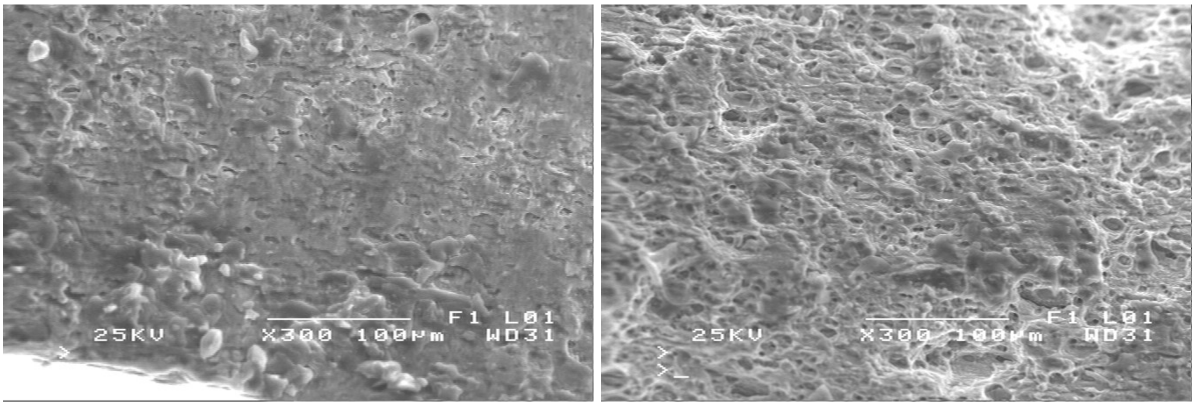


Fig.3: Calculated fracture toughness K_{cr} values based on the nominal thickness of t = 3.2 mm of the 2024-T3 alloy.

(d) Fractographic analysis

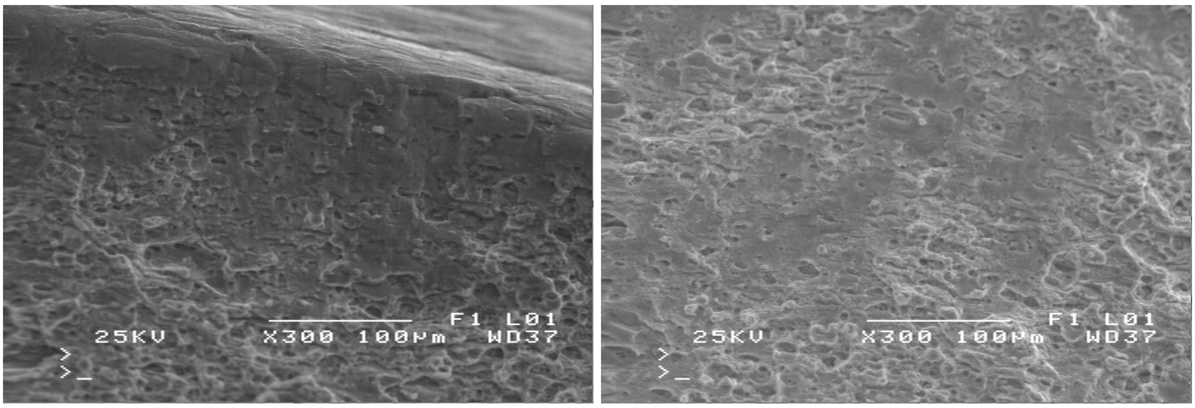
Fracture surfaces of the tensile corroded and uncorroded specimens were examined with SEM. Typical images near the surface of a typical specimen with 2 hours artificial aging can be seen in Figure 4. Figure 4a shows areas of quasi-cleavage fracture (steep surface with lots of dimples) very close to the specimen's surface and areas of ductile fracture (rough surfaces) towards the middle of the cross-section. Figure 4b shows a typical area in between the surface and the middle cross-section; the observed large dimples are evidence of ductile fracture.



(a) (b)

Fig.4: SEM images of tensile specimens fracture area for 2 hrs artificial aging (a) near surface and (b) close to middle cross-section.

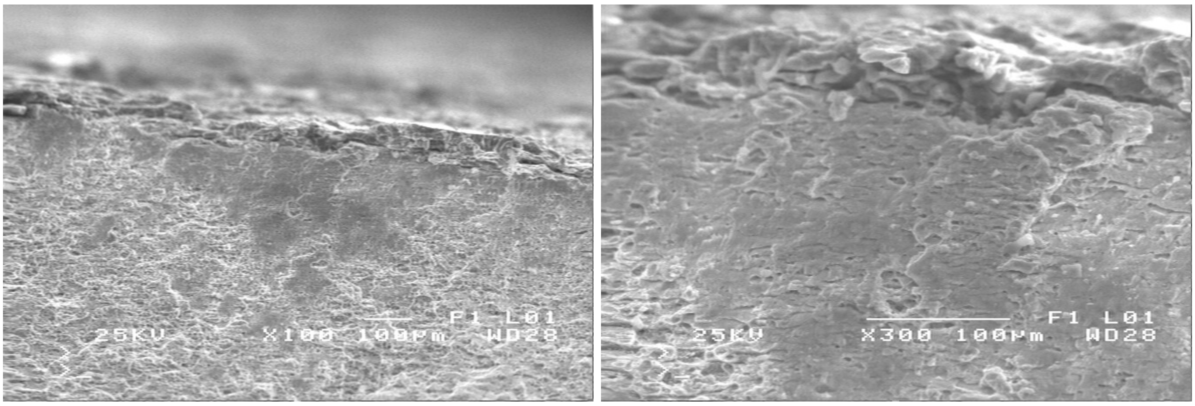
Figure 5 shows typical fracture areas of the tensile specimen for 6 hours artificial aging. As already discussed previously, this aging time corresponds to the (PA) to (OA) transition condition, which means that the alloy hardly presents its maximum strength and low ductility. More quasi-cleavage fracture areas are noticed for this condition; this was evident for the near surface areas as well as for the closer to the middle cross-section of the specimen.



(a) (b)

Fig.5: SEM images of tensile specimens fracture area for 6 hrs artificial aging (a) near surface and (b) close to middle cross-section.

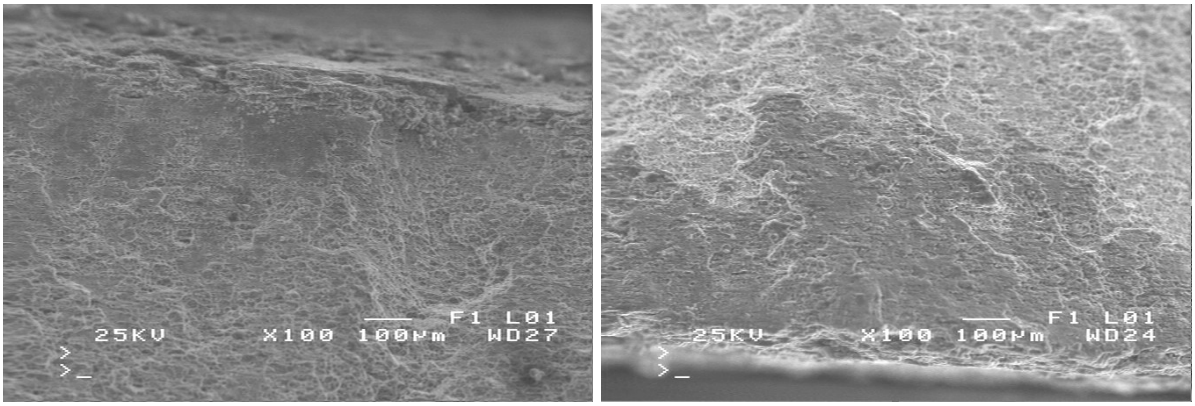
The same corrosion exposure time of 24 hours should yield to the formation of same surface corrosion products on the specimens for all artificial aging times. Figure 6 shows the surface corrosion products in the form of exfoliations as well as the area below the surface that presents a quasi-cleavage fracture with steep roughness. This area shown in magnification in Figure 6b is evidence of the local corrosion-induced hydrogen embrittlement from the surface-diffused hydrogen.



(a) (b)

Fig.6: SEM images of tensile specimens fracture area for 2 hrs artificial aging after 24 hours EXCO exposure (a) area near the corroded surface and (b) higher magnification.

The respective SEM images for the 6 hours artificial aging and the subsequent corrosion exposure of 24 hours can be seen in Figure 7. Figure 7 also shows that the embrittled area below the corroded surface exists for both corroded surfaces of the tensile specimens. The difference in the local fracture mechanism of the specimen is evident; the degree of the hydrogen diffusion on the investigated specimen can be noticed by the area of steep areas in the fracture surface of the specimen below the corroded surfaces. More research is needed to quantify the degree of hydrogen embrittlement on the basis of quantitative image analysis.



(a) (b)

Fig.7: SEM images of tensile specimens fracture area for 6 hrs artificial aging and after 24 hours EXCO exposure (a) area near the upper and (b) near the lower corroded surface.

(d) The effective thickness

As the material is subjected to the corrosive environment, it is eminent that the specimen's cross-section will no longer remain the same and will be a function of the material's exposure time. The "effective thickness" is actually the specimen's true thickness after the corrosion exposure that withstands the applied mechanical load; for the different corrosion exposure times it was calculated based on the respective tensile modulus of elasticity. More details about the calculation of the effective thickness and microscopical measurements to support the results of the effective thickness can be seen in the respective article [6]. To take into account the true thickness of the material, J integral analysis had been preferred instead of the classical stress intensity factor analysis; J integral is much more accurate since it uses the whole elasto-plactic resistance curve of the specimens for the evaluation.

Figure 8a shows the phenomenological (nominal) as well as the true fracture toughness values of the specimens. The true fracture toughness values (calculated based on the effective thickness of the material) seems to be saturated after only 24 h of exposure. By further exposing the alloy to the corrosive environment, its true fracture toughness does not decrease, on the contrary to the nominal fracture toughness. Hence, the total reduction of almost 30% of the fracture toughness after 96 h exposure to exfoliation corrosion solution is attributed primary to the reduction of the alloy's effective thickness (22%) and secondary to the hydrogen embrittlement (8%) mechanism.

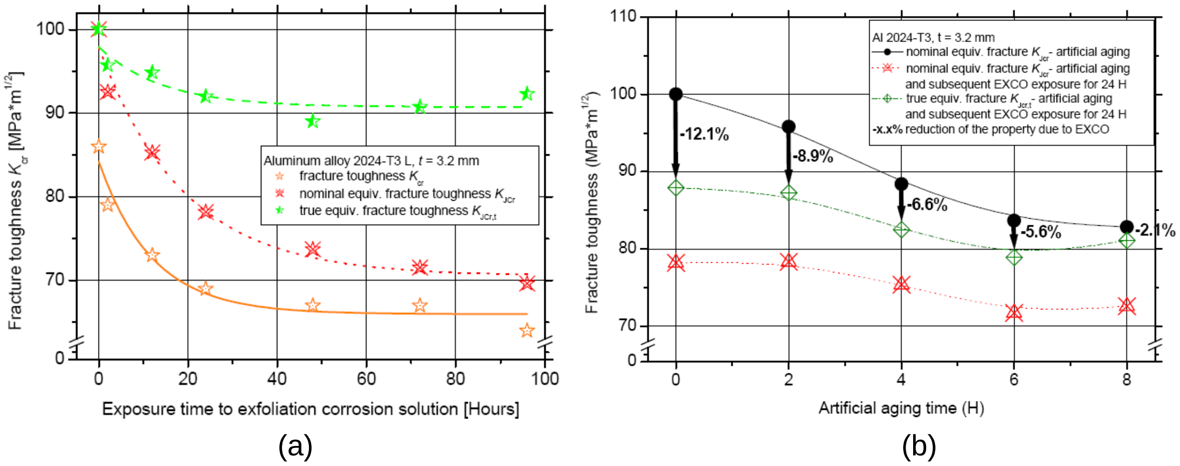


Fig.8: (a) Calculated fracture toughness values for the various exposure times of aluminum alloy 2024-T3 to the exfoliation corrosion solution and (b) fracture toughness results calculated for the nominal and true (or effective) thickness of the specimen.

Likewise, the fracture toughness test results of the different artificial aged specimens had been re-calculated to take into account the effective thickness, Figure 8b. Bearing in mind that the reduction of the specimen's thickness has been already taken into account, the decrease in fracture toughness is attributed either to hydrogen embrittlement or to the stress concentration of the corrosion-induced surface cracks. With increasing aging time, the 24 h EXCO exposure seems to have a lower impact on the fracture toughness degradation. For the increasing aging time, the decrease is of the order of magnitude of 6%, e.g. 4 h and 6 h artificially aged specimens, while for the (OA) alloy of 8 h, the decrease of the fracture toughness is only 2%.

CONCLUSIONS

- A large phenomenological reduction of almost 30% on the K_{cr} due to EXCO exposure is noticed for T3 (reference) condition; the calculations based on the true thickness of the specimens showed that the decrease is of the order of 10%. This decrease is saturated at 24 h exposure and it was attributed to the stress of the corrosion-induced surface cracks or directly to the hydrogen embrittlement degradation mechanism.
- The true decrease of K_{cr} for the reference (UA) specimens up to the (PA) condition is of the same magnitude (10%) for the same 24 h corrosion exposure time; fracture toughness decrease for the (OA) specimens is minimal.

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