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Characterising crack growth in commercially pure titanium

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ABSTRACT

One of the challenges in aircraft sustainment is to develop additively manufactured (AM) replacement parts for legacy aircraft. This is particularly important for fixed and rotary wing aircraft that operate in in aggressive environments, i.e. off carriers, in a marine environment, etc. On the other hand the United States Air Force (USAF) have now adopted the concept of using AM to rapidly field limited-life unmanned air platforms. Whilst the temptation is to use AM Ti-6Al-4 V for these purposes, Ti-6Al-4 V powder is both costly and its supply is somewhat restricted. This paper reveals that the yield and ultimate strengths, the strain to failure of commercially pure (CP) Titanium, which is highly corrosion resistant, and it's resistance to crack growth is superior to that of the commonly used aluminium ally AA7050-T7451, which is used in the F/A-18 Hornet, Super Hornet and F-35 (Joint Strike Fighter). Interestingly, when allowance is made for these improved properties then, if the crack growth rate da/dN is expressed as per the Hartman-Schijve crack growth equation, the resultant crack growth curves for Grade 2, 3 and 4 Titanium, and AA7050-T7451 all fall onto (essentially) the same master curve. It is also shown that the effect of different aggressive environments on Grade 3 Titanium is merely to change the fatigue threshold and that, when allowance is made for this, the crack growth curves associated with these different environments also fall onto the same master curve determined for CP Titanium and AA7050-T7451 tested in a laboratory air environment. Consequently, the damage tolerance and durability analyses presented in this paper suggest that CP Titanium may be attractive both for use as replacement parts for many aircraft parts, and for unmanned aerial vehicles (UAV's).

1. Introduction

The memo by the US Department of Defense (DoD), Under Secretary, Acquisition and Sustainment [1] mandated the use of additive manufacturing (AM) within the US Department of Defence (DoD). This memo subsequently led to the development of guidelines for the airworthiness certification of AM parts and repairs [2]. As a result, a great deal of attention has been paid to crack growth in AM Ti-6Al-4 V [3–17]. In this context, it has been shown [16] that the fatigue life of AM Ti-6Al-4 V replacement parts under representative flight load spectra is such that they would be attractive for use as limited life replacement parts on operational aircraft. Indeed, the USAF have now adopted the concept of using AM to rapidly field limited-life unmanned air platforms [18,19]

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Unfortunately, whilst Titanium alloys have long been used in the aerospace industry [20] and would appear to be an attractive option, the cost of Ti-6Al-4 V powder is a limiting factor [21]. The problem is compounded by the fact that many AM processes can only be used to manufacture relatively small parts. As such the challenge is to use cheaper powders, coupled with AM processes that can be used to manufacture larger parts, and yet still have acceptable mechanical properties, i.e. corrosion resistance, yield strength, ultimate strength, elongation to failure, crack growth, etc, and yet yield parts that have an acceptable fatigue life (durability/economic life). As explained in [22–25] there are instances in which cold spray offers several advantages over other AM processes. As such, it has been suggested that AM parts produced by cold spray (CS) may be able to address several of these challenges.

The ability of AM parts fabricated using cold spray process to rapidly build large parts is aptly illustrated by the 5 m tall cold spray fabricated version of the Gilmour Space ERIS-S rocket, which weighs 27 metric tonnes [26], see Fig. 1. This structure was built in less than 28 hrs. An example of the use of this technology to build an unmanned aerial vehicle is given in [27]. An additional advantage of cold spray is that it can fuse dissimilar metals to create composite (layered) metal parts, see Fig. 2.

Since the certification of military aircraft requires a damage tolerance analysis [2,28,29] the present paper focuses on crack growth in CP Titanium, which is known to possess excellent resistance to environmental degradation, and is widely used in the bio-medical field [30–32]. In this context, it will be shown that CP Titanium has a da/dN versus ΔK curve that is superior to that of AA7075-T6, which is used in many legacy aircraft, as well as to the commonly used aluminium ally AA7050-T7451, which is used in the F/A-18 Hornet, Super Hornet and F-35 (Joint Strike Fighter). Interestingly, it is shown that if the crack growth rate da/dN is expressed as per the Hartman-Schijve crack growth equation then when allowance is made for the differences in the fatigue thresholds and fracture toughness's the crack growth curves for CP Grades 2, 3 and 4 Titanium, and AA7050-T7451 all fall onto (essentially) the same master curve. It is also shown that the effect of different environments on crack growth in CP Grade 3 Titanium is merely to change the fatigue threshold, and that when allowance is made for this then the crack growth curves associated with these different environments all fall onto (essentially) the same (Hartman-Schijve) master curve.

An outcome of the analyses presented in this paper is that it would appear that CP Titanium may be attractive for the use as replacement parts for many aircraft, particularly aircraft that are operated in an aggressive environment, and also for limited life UAV's.

2. Characterising crack growth in CP Grades 2, 3, and 4 titanium

Before assessing the economic life/durability of a CP Titanium part it is informative to compare the crack growth behaviour of CP Grades 2, 3 and 4 Titanium. To this end Fig. 3 contains plots of the crack growth rate (da/dN) against the range of the stress intensity factor ΔK for these three grades of CP Titanium tested at several different R ratio's in air. The Grade 2 crack growth curves are from [33]. The Grade 3 crack growth data is for IMI130 tested in a range of environments (dry Argon, 3.5% NaCl, laboratory air) is taken from [34]. The Grade 4 data is from [35]. Fig. 3 also contains the $R = 0.7$ and 0.1 Grade 2 crack growth curves given in [36], which to differentiate from the data presented in [33] is labelled Grade 2–2. CP Titanium can also be welded, hence Fig. 3 also contains the $R = 0.7$ da/dN versus ΔK curve for cracking in a weld that is given in [36]. For comparison, Fig. 3 also presents the R = 0.1 and 0.7 crack growth curves given in [37] for AA7050-T7451. To continue this study Fig. 4 presents the da/dN versus ΔK curves given in [33] for CP Grade 2 Titanium tested in laboratory air at R ratio's of 0.05, 0.1, 0.3 and 0.6. The yield and ultimate stresses for the CP Grade 2, 3 and 4 Titanium's studied in [33–36] are given in Table 1. For comparison the yield and ultimate stresses for the aluminium alloys AA7050-T7451 [38] and AA7010-T7651 [39], and for AM CP Titanium [32,41,42] are also given in Table 1.

Let us next examine how the data shown in Figs. 3 and 4 simplifies if da/dN is expressed in terms of Hartman–Schijve variant of the NASGRO [44,45] equation [46], viz:

Fig. 1. A reduced scale AM version of the Gilmour Space ERIS-S rocket [26].

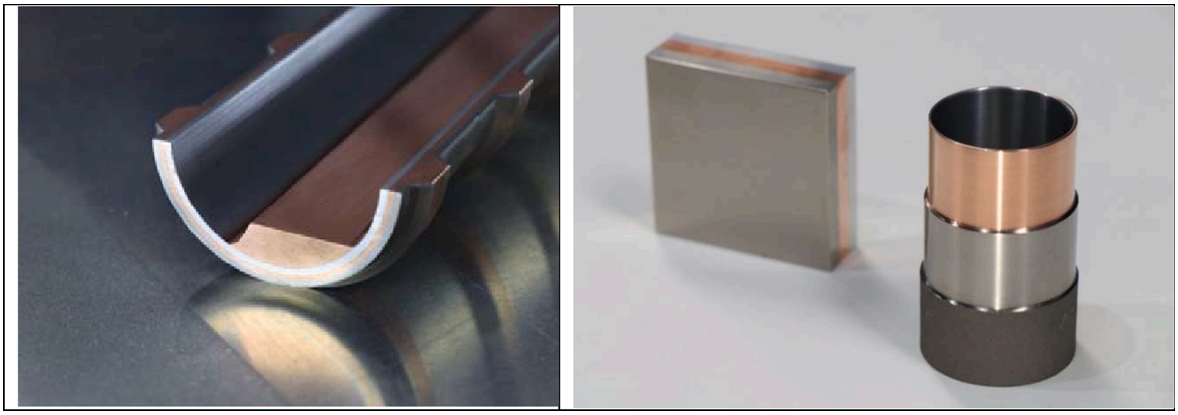

Fig. 2. Examples of multi-layered Ti6Al4V/Coper/Aluminium alloy AM parts produced by Titomic.

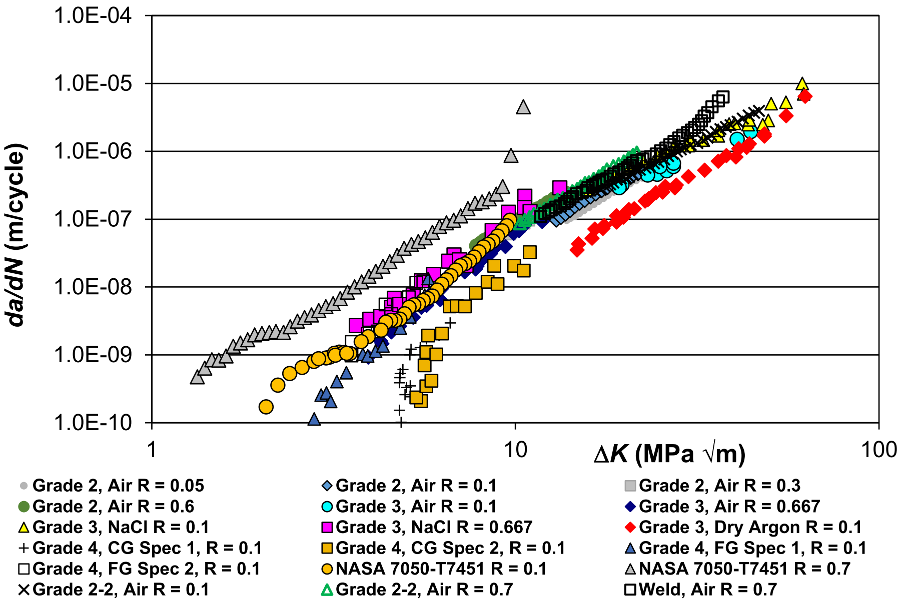

Fig. 3. Comparison of da/dN versus ΔK for CP Grades 2, 3 and 4 Titanium and in the weld of CP Grade 2 Titanium with AA7050-T7451, from [33–37]

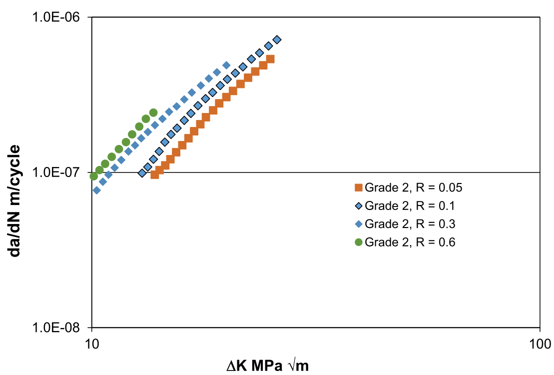

Fig. 4. Comparison of da/dN versus ΔK for CP Grade 2 Titanium tested in laboratory air at different R ratio's, from [33].

Table 1
Yield and ultimate stresses.

Specimen descriptor	σ_y (MPa)	σ_{ult} (MPa)	Failure strain (mm/mm)
CP Grade 2 Titanium [40]	275–410	344	0.2
CP Grade 3 Titanium	377–520	440	0.18
(IMI 130) [40]	480–552	550	0.15
Grade 4 Titanium [40]	540	650	0.10
Annealed Cold Spray CP Grade 2 Titanium*	629	731	0.20
AM (Selective Laser Melt, SLM) CP Titanium [32]	510	580	0.05
AM (Selective Laser Melt, SLM) CP Titanium [41]	385	880	0.48
AM (Laser Engineered Net Surface, LENS) CP Titanium [42]	760	840	0.06
Annealed Cold Spray Ti-6Al-4 V*	465	510	0.11
AA7050-T7451 [38]	435	521	0.11
AA7010-T73651 [39]	456	518	0.15

* Values taken from tests performed by Titomic in accordance to the test standard ASTM E8-00b [43].

$$\mathrm{da}/\mathrm{dN} = D(\Delta\kappa)^p \tag{1}$$

Here a is the crack length/depth, N is the number of cycles, D and p are material constants. The crack driving force $\Delta\kappa$ used in Equation (1) is as suggested by Schwalbe [47], viz:

$$\Delta\kappa = (\Delta K - \Delta K_{\mathrm{thr}})/(1 - K_{\mathrm{max}}/A)^{1/2} \tag{2}$$

where A is the cyclic fracture toughness, K is the stress intensity factor, K_{max} and K_{min} are the maximum and minimum values of stress intensity factor seen in the cycle, $\Delta K = (K_{max} - K_{\mathrm{min}})$ is the range of the stress intensity factor that is seen in the cycle, and ΔK_{thr} is an “effective fatigue threshold”. As explained in [46], the terms ΔK_{thr} and A are best thought of as parameters that are chosen in order to fit the measured *da/dN* versus ΔK data. Application of this formulation to a range of aerospace and non-aerospace materials are given in [16,17,37,46,48–64].

Fig. 5 reveals that when *da/dN* is expressed as a function $\Delta\kappa$ then the crack growth curves associated with CP Grades 2, 3 and 4 Titanium, welded CP Grade Titanium, and AA7050-T7451 essentially collapse onto a single master curve regardless of the R ratio, with $D = 7.0 \times 10^{-10}$ and $p = 2$. The *da/dN* versus $\Delta\kappa$ curve shown in Fig. 5 for AA7050-T7451 is taken from [46]. The values of ΔK_{thr} and A used in Fig. 5 are given in Table 2. It thus appears that, as a first approximation, the differences in the crack growth curves shown in Figs. 3 and 4 for these different grades of CP Titanium and welded CP Grade 2 Titanium, and the effect of different R ratio’s on these crack growth curves can be accounted for by allowing for the differences in the thresholds and the cyclic fracture toughness’s, and that the governing equation can be approximated by:

$$da/dN = 7.0\ 10^{-10}(\Delta\kappa)^{2.0} \tag{3}$$

It is well known that CP Grades 2, 3 and 4 Titanium are particularly resistant to corrosion. As such this makes them attractive for use

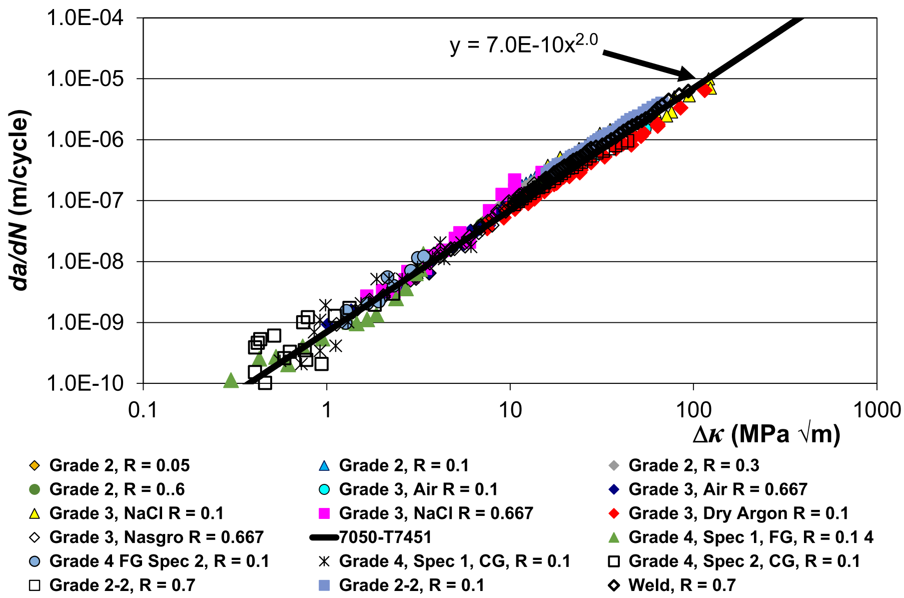

Fig. 5. The da/dN versus Δκ curves for CP Titanium shown in Figs. 3 and 4 and for AA7050-T7451, from [33–37].

Table 2
Values of ΔK_{thr} and A used in Figs. 3-5.

	ΔK_{thr} (MPa$\sqrt{m}$)	A (MPa$\sqrt{m}$)
Grade 2, Lab Air		
R = 0.05	5.2	66
R = 0.1	5.0	66
R = 0.3	2.5	66
R = 0.6	2.0	66
Grade 2–2, Lab Air		
R = 0.1	3	90
R = 0.7	2	90
Grade 3 (IMI 130), Lab Air		
R = 0.1	2.4	90
R = 0.667	3	90
Grade 3 (IMI 130), 3.5% NaCl		
R = 0.1	2.4	90
R = 0.667	2.1	90
Grade 3 (IMI 130), Dry Argon		
R = 0.1	8.0	90
R = 0.667	2.1	90
Grade 4, tested at R = 0.1, Lab Air		
Fine grain (FG) Specimen 1	4.2	99
Fine grain (FG) Specimen 2	4.8	99
Fine grain (CG) Specimen 1	2.5	99
Fine grain (CG) Specimen 1	2.3	99

on carrier aircraft. To address the effect of an aggressive environment on crack growth in CP Titanium Figs. 3 and 5 also contain the crack growth curves for CP Grade 3 Titanium tested in 3.5% NaCl and dry Argon, an inert gas. Here we see that, for each of the R ratio's, despite the different environments yielding different da/dN versus ΔK curves the associated da/dN versus Δκ curves all collapse onto (essentially) the same master curve. (The values of ΔK_{thr} and A used in this representation are also given in Table 2.) As such, it also appears that, as a first approximation, when expressed in this form the effect of the different environments on the crack growth in CP Grade 3 Titanium is also accounted for by allowing for its effect on the thresholds and the cyclic fracture toughness's.

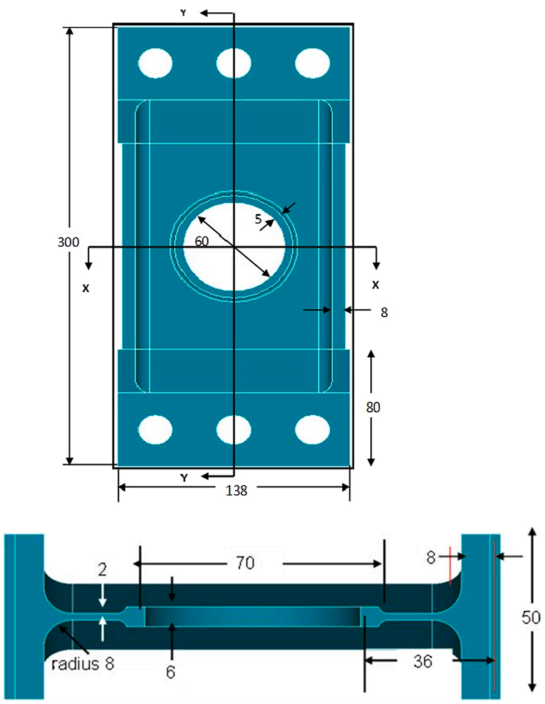

Fig. 6. The Round-Robin test geometry, dimensions in mm.

3. A study into the potential of CP titanium parts for use under an industry standard helicopter flight load spectrum

Irving, Lin and Bristow [65] presented the results of a round-robin study into the damage tolerance of a representative AA7010-73651 helicopter component. The test specimen discussed in [65] was a flanged plate with a central lightning hole, see Fig. 6. It was chosen to represent the geometry of a typical helicopter structural component. This specimen was subjected to a typical rotorcraft flight load spectrum (Asterix) that was derived from strain data measured on a helicopter lift frame. The Asterix spectrum consisted of 371,610 cycles, and represents 190.5 flights, or 140 sorties. It is a high R ratio spectrum that is dominated by cycles at $R = 0.8$, and has a limited number of negative stress ratio excursions, see [65,66].

The ability of the Hartman-Schijve equation, i.e. Equation (1), to compute the measured crack growth history in this specimen was illustrated in [66]. The measured and computed crack growth histories given in [66] are shown in Fig. 7. (The Hartman-Schijve equation has also been shown [48] to be able to compute crack growth in 7050-T7451 specimens tested under a range of helicopter flight load spectra. These spectra were derivatives of a US Army H-60 Black Hawk helicopter flight load spectrum [67].) Having thus established the ability of Equation (1) to accurately compute the measured crack growth history for this particular specimen geometry and flight load spectrum, Equation (3), with the values of A (=66 MPa$\sqrt{m}$) and ΔK_{thr} (=2 MPa$\sqrt{m}$) taken from Table 2 was then used to compute the crack growth history for aspecimen fabricated using CP Grade 2 Titanium. The resultant computed crack growth history is also shown in Fig. 7. This study suggests that a CP Grade 2 Titanium specimen would be significantly more damage tolerant than the 7010-T73651 test specimen. As such noting the yield and ultimate strength values given in Table 1 for CP Titanium, it would appear that CP Titanium may have the potential for fabricating replacement parts for aluminium alloy airframes. This potential will be further examined in the next section.

At this stage it is important to note that as per USAF Structures Bulletin EZ-19–01 [2], the Joint Services Structural Guidelines JSSG2006 [28], and the USAF airworthiness certification requirements as delineated in MIL-STD-1530D [29], a limited life design requires a durability assessment in which the EIDS are as given in JSSG2006. Furthermore, as documented in [68], a limited life design requires the use of the small crack da/dN versus ΔK curve. If this is not done then, as shown in [68], the value of the EIDS can become spectrum dependent. Examples of how to perform durability analyses using a methodology that is consistent with the building block requirement delineated in MIL-STD-1530D [29] can be found in [46–50] for a range of operational flight load spectra, viz: helicopter, combat aircraft, maritime, civil aircraft, etc. Applications of the formulation used in these various papers to compute the growth of small cracks in AM Ti-6Al-4 V are given in [55,56].

4. A study into the potential of Grade 2/3 titanium for use as a replacement Y488 bulkhead for F/A-18 aircraft

Having established a link between cracking in CP Grades 2, 3 and 4 Titanium and AA7050-T7451 let us next consider their potential use for manufacturing a replacement F/A-18 bulkhead. The susceptibility of the AA7050-T7451 F/A-18 Y488 bulkhead to cracking has been established by a series of full scale fatigue tests that were performed as part of the Australian Defence Science and Technology Group's Flaw IdeNtification through the Application of Loads (FINAL) test program [69]. This test program utilised ex-service Canadian Forces (CF) and U.S. Navy (USN) wing attachment centre barrel (CB) sections loaded using an industry standard modified mini-FALSTAFF spectrum, see [69], which is representative of flight loads seen by fighter aircraft. The location of the Y488 bulkhead in the F/A-18 centre barrel is shown in Fig. 8. The crack growth history associated with one such test [70] is shown in Fig. 9.

The USAF approach for certifying both conventionally manufactured and AM replacement parts is outlined in Structures Bulletin EZ-190–01 [2], JSSG2006 [28], and MIL-STD-1530D [29]. When assessing the durability/economic life assessment of a replacement part the approach outlined in [2] follows that outlined in MIL-STD-1530D [29] in that when determining the life it requires an assumed minimum size equivalent initial damage size (EIDS) of at least 0.254 mm (0.01 in.). Given the da/dN versus ΔK crack growth curves shown in Fig. 3, the similarity in the da/dN versus $\Delta\kappa$ crack growth curves for CP Titanium and 7050-T7451 shown in Fig. 5, and that the small crack growth curve needed for a durability analysis can often be (approximately) determined from the da/dN versus $\Delta\kappa$ relationship by setting the fatigue threshold to a small value [8,9,44,46–54], the crack growth history for a CP Grade 4 Titanium "replacement" bulkhead can therefore be estimated by transposing the "test data" curve shown in Fig. 9 to start from an EIDS of 0.254 mm. This estimated curve is also shown in Fig. 9. The life associated with this CP Titanium replacement Y488 bulkhead is thus estimated to be approximately 4,900 flight hrs. Following the approach outlined in [2,29] this would equate to an operational life of approximately 2,450 flight hrs. This corresponds to approximately 12 years of operational service.

5. Crack growth in AM TTi-6Al-4V under a P3c flight load spectrum

To further illustrate the potential for CP Titanium let us next consider crack growth in a CP Titanium specimen subjected to a representative US Navy P3C (Orion) flight load spectrum. This problem chosen for this study was a 80 mm wide by 2.6 mm thick specimen containing a centrally located 6 mm diameter hole with a flight load spectrum corresponding to fatigue critical location FCA-351, which is in the P3C wing skin near the lower front spar [71,72]. This problem was chosen since it had previously been used [16] to evaluate the potential of an AM Ti-6Al-4 V replacement part. The peak stress at this location (i.e. at FCA-351) is approximately 171 MPa [71,72]. As in [16] the hole was assumed to contain two sets of diametrically opposed semi-circular cracks (EIDS) at the intersection of the bore of the hole with the free surface, see Fig. 10. As previously mentioned USAF Structures Bulletin EZ-SB-19–01 [2] and MIL-STD-1530D [67] require that the durability/economic life assessment of an aerospace (replacement) part be based on a fracture mechanics assessment with an EIDS of at least 0.254 mm (0.01 in.), see Fig. 10. To this end the life of the part was computed using Equation (3) with, as per Table 2, $A = 66$ MPa $\sqrt{m}$. To ensure a conservative life the fatigue threshold (ΔK_{thr}) was (again) taken,

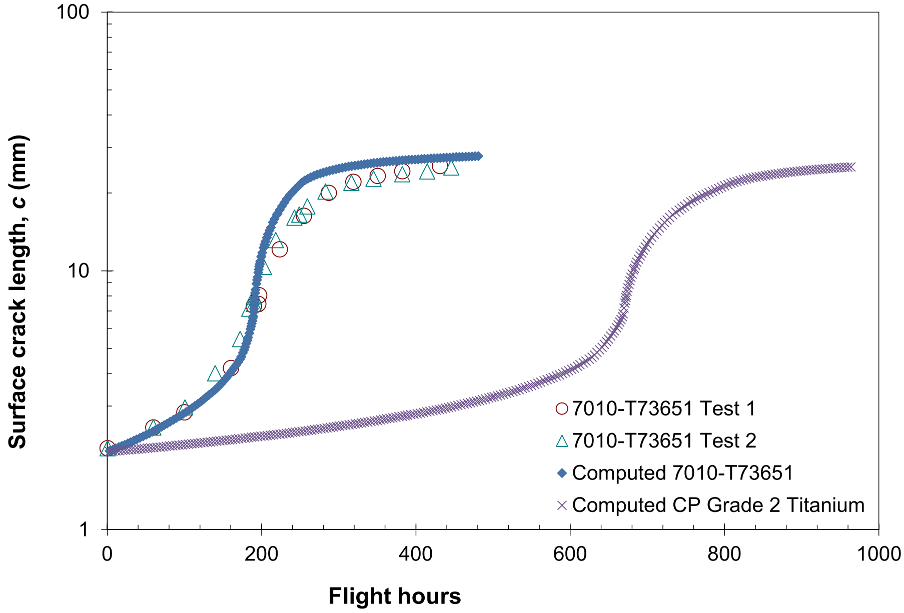

Fig. 7. Measured and computed surface crack length histories for a representative specimen under an Asterix flight load spectrum.

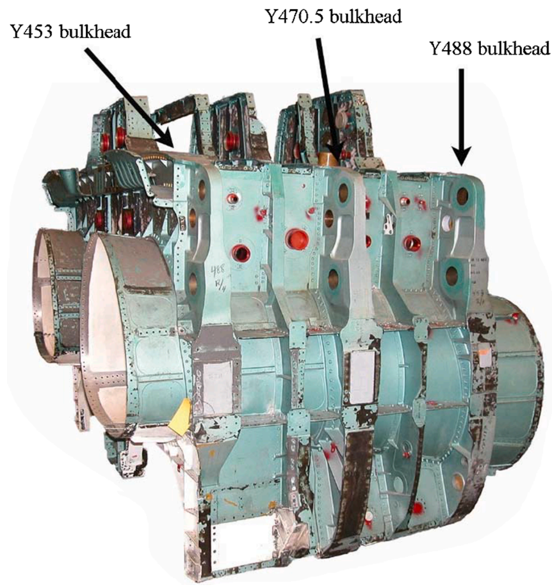

Fig. 8. The F/A-18 centre barrel structure showing the location of the Y488 bulkhead. Picture courtesy of L. Molent, DST Group, Australia.

as per [8,9,44,46–54], to be 0.1 MPa $\sqrt{m}$ rather than using the value of 2 MPa $\sqrt{m}$ given in Table 2. The resultant computed life was approximately 6,200 flight hrs, and the crack growth history is shown in Fig. 11. To be consistent with Structures Bulletin EZ-SB-19–01 [2] and MIL-STD-1530D [67] the operational life is estimated to be the computed life divided by a factor of two, i.e. 3,100 flight hrs. In the case of the P3C the original design life of the aircraft is approximately 15,000 flight hrs [72]. Thus the computed operational life represents a significant fraction of the operational life of the airframe.

6. Conclusions

This paper has revealed that crack growth in CP Grades 2, 3 and 4 Titanium, and AA7050-T7451 all (essentially) fall onto the same da/dN versus $\Delta\kappa$ master curve. It has also been shown that, as a first approximation, the effect of different environments on CP Grade 3 Titanium is merely to change the fatigue threshold. Furthermore, when allowance is made for this then the crack growth curves

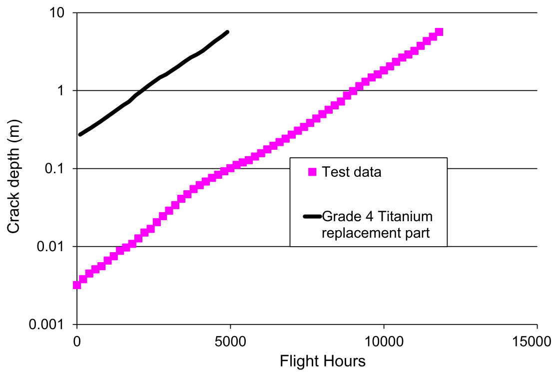

Fig. 9. Crack growth in F/A-18 Y488 bulkhead and a Grade 4 Titanium replacement bulkhead.

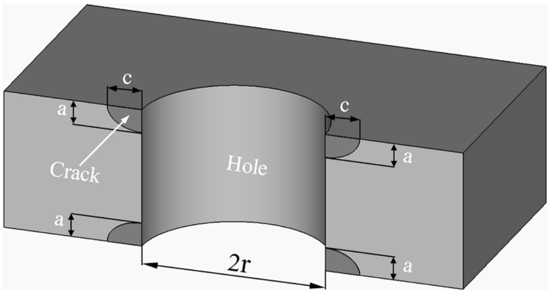

Fig. 10. Schematic diagram of the specimen geometry.

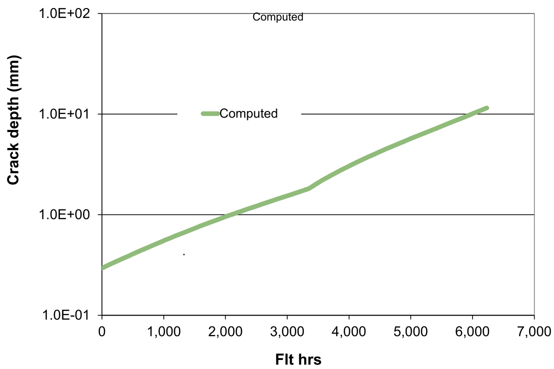

Fig. 11. The resultant crack depth versus flight hours (Flt hrs) history.

associated with these different environments all (essentially) fall onto the (same) master curve determined for CP Grades 2, and 4 Titanium and AA7050-T7451 tested in a laboratory air environment.

The analyses presented in this paper also suggests that CP Titanium has the potential for use as replacement parts for military aircraft, particularly for aircraft that operate in an aggressive environment, and for limited life unmanned aerial vehicles (UAV's).

Author contributions

Conceptualisation and initial draft preparation - R. Jones; Overall oversight/direction and provision of internal Titomic funds- JL., Experimental testing of Ti-6Al-4 V– A. Ang; Specimen manufacture and review of the final manuscript – VP; Overview of the paper and its relationship to aircraft certification – JL.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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