Crack Growth in Mil Annealed Ti-6Al-4V Structural Components

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Abstract There is an increasing use of titanium in primary aircraft structures with bulkheads in the F-22, Super Hornet, and the Joint Strike Fighter being made of titanium. Until recently it was thought that cracking in titanium and high strength aerospace steels was relatively well understood. However, this paper analyses a series of NASA, and Boeing studies into cracking in Ti-6AL-4V to reveal a weak R ratio effect with little closure in Region II. We also see that, in each case, the data conforms to the Generalised Frost-Dugdale crack growth law. This study also implies that the mechanisms driving cracking in high strength aerospace steels and Mil Annealed Ti-6Al-4V are similar.

1. INTRODUCTION

Until recently it had been thought that fatigue crack growth in high strength aerospace steels and titanium was well understood. However, as concluded by Skorupa [1], in his review of fatigue crack growth under variable amplitude loading, viz:

"Experimental results also suggest that the underlying causes of load interaction phenomena are not necessarily similar for different groups of metals, e.g. steels and Al and Ti alloys."

In this context it should be noted that Forth, James, Johnston, and Newman [2] have reported that crack growth data obtained for 4340 steel using CT specimens was essentially R ratio independent. This study led Forth, James, Johnston, and Newman to state: "there is little closure in high strength steels" and "This data also does not follow the crack closure argument." This finding has been substantiated by the recent paper by Jones and Forth [3] who revealed that cracking in a D6ac steel was also essentially R ratio independent and that it conformed to the Generalised Frost-Dugdale law, see Jones, Molent, and Pitt [4].

In recent years there has been an increasing use of titanium in primary structural members due to its high strength, light weight, and good fatigue and fracture toughness properties. Indeed, the bulkheads in the F-22, the Super Hornet, the Swiss F/A-18, and the Joint Strike Fighter are made of titanium. In the F-22, titanium accounts for ~ 36%, by weight, of all structural materials used in the aircraft. The question thus arises: Does Mil Annealed Ti-6Al-4V show a similar (near) R ratio independence to that seen for high strength aerospace steels ?

To answer that question this paper examines NASA and Boeing studies into cracking in Mil Annealed Ti-6Al-4V to reveal that the R ratio effect on crack growth is quite small. We also see that as for cracking in D6ac steel [3], 7050-T7451 aluminium alloy [4], and rail steels [5] cracking conforms to the Generalised Frost-Dugdale law [4], i.e. Equ. (1):

$$da/dN = C^{*} a^{(1-\gamma/2)} (\Delta\kappa)^{\gamma} - (da/dN)_{0} \qquad (1)$$

where $\Delta\kappa$, is the crack driving force, C^{*}, and γ are constants and the term $(da/dN)_0$ reflects both the fatigue threshold and the nature of the notch (defect/discontinuity) from which cracking initiates. (The relationship between this law and the fractal concepts of Carpenteri [6] and Spagnoli [7] is outlined in [4].) We also show that when Equation (1) is rewritten in the form:

$$da/dN = \underline{C}^{*} a^{(1-\gamma/2)} (\Delta K/(\sigma_y (1-R)^{p}))^{\gamma} /(1-K_{max}/K_c) - (da/dN)_{0} \qquad (2)$$

where $\underline{C}^{*}$, and p are material constants and σ_y is the yield stress then the equations governing crack growth in D6ac steel and Mil Annealed Ti-6Al-4V essentially coincide. Indeed, the crack growth rate (da/dN) versus $(\Delta K^{(1-p)} K_{max}{}^{p}/\sigma_y)^{\gamma} a^{(1-\gamma/2)}$ relationship for Mil Annealed Ti-6Al-4V and D6ac steel appears to be very similar. The implication is that the physical processes (mechanisms) driving cracking in high strength aerospace steels and Mil Annealed Ti-6Al-4V are similar. Given the extensive use of titanium in the F-22, the Super Hornet, and the Joint Strike Fighter this finding merit further investigations.

2 CRACKING IN Ti-6Al-4V

It is commonly believed that, like many aircraft quality aluminium alloys, crack growth in Mil Annealed Ti-6Al-4V shows a marked R ratio effect with a significant increase in the R ratio resulting in a significant increase the crack growth rate. One common way to account for R ratio effects is via the Walker crack growth law [8], which we will write in the form:

$$da/dN = \underset{\cdot}{C} (\Delta K^{(1-p)} K_{max}{}^{p} /\sigma_y)^{m} = \underset{\cdot}{C} (\Delta K/ (\sigma_y (1-R)^{p}))^{m} \qquad (3)$$

where C, p and m are experimentally determined constants and $R = K_{min}/K_{max}$. For D6ac steel Jones and Forth [3] gave the values of p and m as 0.05 and 2.6 respectively. In this paper we will show that for Mil Annealed Ti-6Al-4V the K_{max}

dependency, and hence the R ratio dependency, is also very small with a value of $p = 0.08$ and $m = 2.5$.

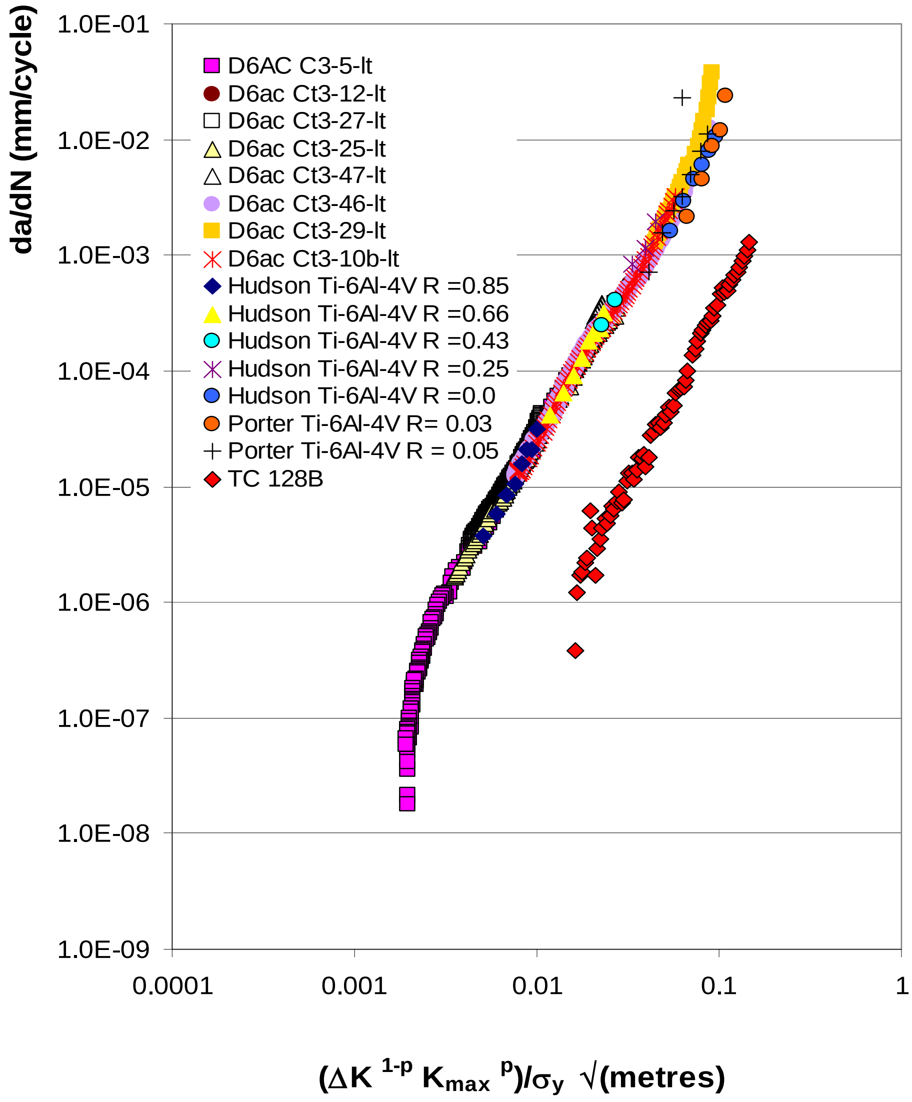

Figure 1 Crack growth in Mil annealed Ti-6Al-4V and D6ac steel

To this end we will first examine Hudson’s early work on cracking in Mil Annealed Ti-6Al-4V [9] M(T) panels. This study analysed 203.2 mm wide, 610 mm long, and 1.27 mm thick centre cracked panels, with an initial (total) crack length of 3.81mm, tested under constant amplitude loading with a mean stress of 172.35 MPa and R ratio’s of 0.25, 0.45, 0.66, and 0.85, which correspond to $\Delta\sigma$’s (= σ_{max} - σ_{min}) of 206.8, 137.9, 68.9, and 27.6 MPa respectively.

Table 1 Test matrix, LI = Load increasing test, K_{max}= constant K_{max} test

		Test frequency Hz
Ct3-5-tl	Constant K_{max}=15	18
Ct3-10b-lt	Constant R=0.3 LI	20
Ct3-12-lt	Constant R=0.9 LI	20
Ct3-25-lt	Constant R=0.7 LI	20
Ct3-27-lt	Constant R=0.9 LI	22
Ct3-29-lt	Constant R=0.3 LI	10
Ct3-46-lt	R=0.1 LI	20
Ct3-47-lt	R=0.8 LI	10

Let us next examine the crack versus cycles data presented by Porter [10] for 4.064 mm thick, 304.8 × 914.4mm Ti-6Al-4V panels containing a centrally located crack. In this instance two sets of constant amplitude tests were performed. One test had σ_{max} = 172.35 MPa, and σ_{min} = 8.62 MPa, i.e. R = 0.05, whilst the other had σ_{max} = 258.5 MPa, and σ_{min} = 8.62 MPa, i.e. R = 0.033. The associated da/dN versus $\Delta K^{(1-p)} K_{max}{}^{p} /(\sigma_y (1-R)^{0.08})$ relationships for both of these tests programs, i.e Hudson's and Porter's, is shown in Figure 1. Here we see that with p ~ 0.08, and σ_y = 900 MPa, see Table 2, the data sets effectively collapse onto a single curve. As such this low value of p reveals that crack growth in Ti-6Al-4V appears to be relatively independent of the R ratio.

Figure 1 also contains the results presented by Jones and Forth [3] for D6ac steel using ASTM compact tension (CT) test geometry, for more details see [3]. Details on the range of R ratio's used in these specimen tests is given in Table 1. For comparison Figure 1 also presents the crack growth behaviour for the rail car steel TC-128B [11]. For D6ac we used p = 0.05 and m = 2.6, see [3], and σ_y = 1500 MPa, see Table 2. The values of p, m and σ_y used for TC 128B are given in Table 2. This figure shows that, as for 4340 and D6ac steel [2, 3], Mil Annealed Ti-6Al-4V has little R ratio dependency in Region II and that when plotted in this fashion the behaviour of D6ac and Mil Annealed Ti-6Al-4V is very similar.

Table 2 Constants

	m* (= γ)	p	σ_y (MPa)
D6ac	2.6	0.05	1500
Ti-6Al-4V	2.5	0.08	900
TC 128B	3	0.2	400

* In this work the value of γ used in Equ. (4) coincides with the value of m used in Equ. (3).

Jones and Forth [3] have shown that crack growth in D6ac steel conforms to the generalized Frost-Dugdale law. Figure 2 shows that this is also the case for Mil Annealed Ti-6Al-4V, and that in this case da/dN can be expressed as:

$$\begin{aligned} da/dN &= 0.6 \text{ x } a^{(1-\gamma/2)} \ (\Delta\kappa/\sigma_y)^{\gamma} - 5.0 \text{ x } 10^{-7} \\ &= 0.6 \text{ x } (\Delta\kappa/\sigma_y)^{2.5}/\, a^{0.25} - 5.0 \text{ x } 10^{-7} \qquad (4) \end{aligned}$$

with $\gamma = 2.5$, and where as per Walker [6] we have defined the crack driving force as per Equ. (5):

$$\Delta\kappa = K_{max}{}^{(1-p)}\, \Delta K^{\,p} \qquad (5)$$

where from Figure 1 we used the value of $p = 0.08$. Interestingly this value of γ compares well with that of $\gamma = 2.6$ obtained by Zhuang et al [12] for Mil Annealed Ti-6Al-4V tested under spectrum loading. (Note that Jones and Forth [3] have shown that for D6ac steel $p = 0.05$ and $\gamma = 2.625$.) Figure 2 shows that this simple linear relationship between da/dN and $(K_{max}{}^{0.08}\ \Delta K^{\,0.92})/\ a^{0.25}$ holds over almost four orders of magnitude, viz: $3 \text{ x } 10^{-6}$ mm/cycle < da/dN < $2 \text{ x } 10^{-2}$ mm/cycle. As noted earlier this low value of p shows that the increment in the crack length per cycle (da/dN) has little R ratio dependency. For the sake of completeness Figure 2 also presents the results for TC 128B steel.

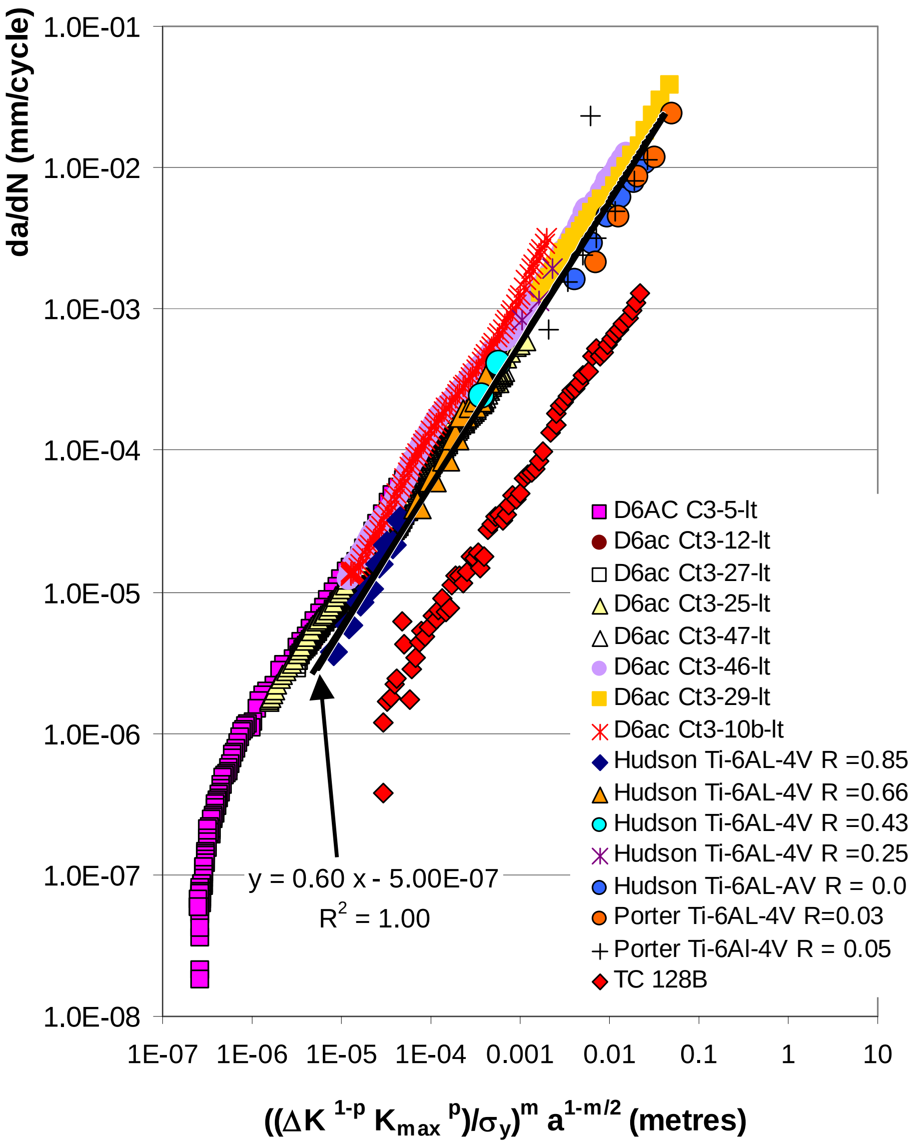

Figure 2 Comparison of the Generalised Frost-Dugdale representation of crack growth in Mil annealed Ti-6Al-4V, D6ac steel and TC 128B steel

3. CONCLUSION

In this paper we have shown that Mil Annealed Ti-6Al-4V appears to exhibit little R ratio dependency, and consequently little closure, in the Paris region. We have also shown that crack growth in Mil Annealed Ti-6Al-4V appears to conform to the Generalised Frost-Dugdale law. Indeed, the crack growth rate (da/dN) versus $(\Delta K^{(1-p)} K_{max}{}^{p}/\sigma_y)^{\gamma} a^{(1-\gamma/2)}$ relationship for Mil Annealed Ti-6Al-4V and D6ac steel appears to be very similar. Given that both D6ac steel and Mil Annealed Ti-6Al-4V also show little R ratio dependency then the implication is that the mechanisms driving cracking in these two quite different materials are similar.

Given the extensive use of titanium in the F-22, the Super Hornet, and the Joint Strike Fighter these findings merit further investigations.

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