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ABSTRACT

Experimental evaluation of high temperature, Fatigue Crack Growth Rate (FCGR) data for Ti-6Al-4V, a titanium alloy, is presented. The FCGR data were measured at room temperature, 175, 230, 290 and 345°C using the Direct Current Potential Difference (DCPD) technique. Compact Tension (CT) specimens were used in the program and crack growth rates (da/dN) vs. Mode I stress intensity factor ranges (ΔK) were plotted as a function of temperature. A temperature rise from 175 to 345°C did not cause a substantial increase in crack growth rates within the Stage II region where a linear relationship describes the behavior. Fonnation of secondary cracks, observed at higher temperatures, may have slowed the crack propagation as observed in the fractography.

Keywords: Fatigue Crack Growth Rate (FCGR), Low Cycle Fatigue, Ti-6Al-4V, DCPD, CT specimen, High Temperature

LIST OF ABBREVIATIONS

FCGR	Fatigue crack growth rate
DCPD	Direct current potential drop
CT	Compact Tension
DTLP	Damage tolerant life prediction
LCF	Low cycle fatigue
STOA	Solution treated and over aged
ANOVA	Analysis of variance
F	F-distribution
f	Density function
Critical f	Critical value of F-distribution at 95% confidence level

1 INTRODUCTION

A number of studies are reported in the literature on the fatigue crack growth behavior and mechanics of crack growth in titanium alloys /1-20/. These studies are applicable to measuring fatigue crack growth rates, mechanics of FCGR and developing a fracture mechanics based damage tolerant design of engine disks. Damage tolerant life prediction (DTLP) techniques for the design of airframe structures have been in practice since the early 1970's. DTLP procedures are now receiving increased attention for establishing turbine engine disc design life limits in new engines and for extending the usable service life of disks whose life limits have been established conventionally /18,19/. The concepts have been considered for several new generation engines such as the F100-PW-220, F110-GE-100 and F109-GA-10 engines. They have also been applied to existing engines such as the PW F100 and GE TF34 in the US, and the GE J85-CAN40/15 in Canada for extending the usable service lives of discs /18/. In order to implement this procedure, FCGR and low cycle fatigue (LCF) data of disc materials at the appropriate operating temperature and stress are essentially required. Therefore, the objective of this paper is to report some elevated temperature FCGR properties of Ti-6Al-4V alloy, which is used in compressors that typically operate at up to about 290°C.

2 EXPERIMENTAL

The specimens used were machined from two forged Ti-6Al-4V compressor disks that were solution treated and aged (STOA). Compact Tension specimens were machined while the notch was made using electron discharge machining process. The dimensions of the specimens conformed to ASTM E-647 specifications /20/. A total of 4 specimens were tested at each temperature range. Constantan thermocouple wires (0.032 inch and 0.02 inch diameters) were used for the current supply and voltage leads respectively. The wires were resistance welded to the specimens. Fiberglass insulating sheaths were used to insulate the current and voltage leads. Specimen preparation and test parameters (R ratio, K gradient, pre-cracking, and post-test correction) are explained in detail in /1/.

Experimental measurement of FCGR data for Ti-6Al-4V alloy forgings has been done by many researchers /2-6/ and with the use of DCPD method /7-16/. However, high temperature FCGR data at a wide range of temperatures is not available in the literature except for a few efforts made by military operators. In this paper, FCGR data generated at room temperature, 175, 230, 290 and 345°C using the DCPD technique is presented. Compact tension (CT) specimens were used in this experimental program.

2.1 Hardware/Software Features

The hardware and data acquisition features, integrated with a personal computer, consisted of a waveform synthesizer (Qua Tech WSB10B), a Metrabyte DASH16 interface and a converter. Once programmed with the parameters of the desired waveform, no additional support was required to continuously synthesize the desired signal. The acquisition rates and number of conversions is coordinated with the programming parameters of the WSB10B interface. The FCGR software* was developed using the code "BASIC". It consists of the test setup and control section, analysis and a graphics section. The package was integrated with the controllers of the servo-hydraulic test machine and a PC for direct control of test parameters.

3 FCGR RESULTS AND DISCUSSION

A total of 16 CT specimens were used in this testing program. The specimens were machined from two Ti-6Al-4V compressor disk forgings, referred to as Disk I and Disk II, using an EDM process. Allied-Signal Engines, Phoenix, AZ, supplied the compressor disk forgings. Two specimens from each disk were used at each temperature.

The FCGR (da/dN vs. ΔK) plots are shown in Figures 1-4, for temperatures 175, 230, 290 and 345°C. The da/dN vs ΔK plots at all temperatures indicate a steady increase in FCGR with increasing temperature. The average ΔK at the beginning of each experiment was about 9 MPa$\sqrt{m}$ and the average ΔK at the point of specimen failure was about 65-70 MPa$\sqrt{m}$. The FCGR vs. Mode I ΔK of long crack growth data converged at about 10-12 MPa$\sqrt{m}$. The initial portion of each curve, Figures 1-4, reveals FCGR characteristic of Stage I propagation at values close to the threshold value for long crack propagation. This area is referred to as Stage I, and transitioned to Stage II between Mode I ΔK range of 8 to 12 MPa$\sqrt{m}$ depending on test temperature. In Stage II the FCGR data can be fitted with a linear or Paris equation. With an increase in temperature the transition to Stage II occurred at a lower ΔK range.

Stage II, where a steady crack growth rate occurs, was fitted with a straight line and parameters such as intercept (C) and slope (m) determined for all the tests.

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*Fracture Technology Associates in Bethlehem, Pennsylvania manufactured the FCGR measurement system.

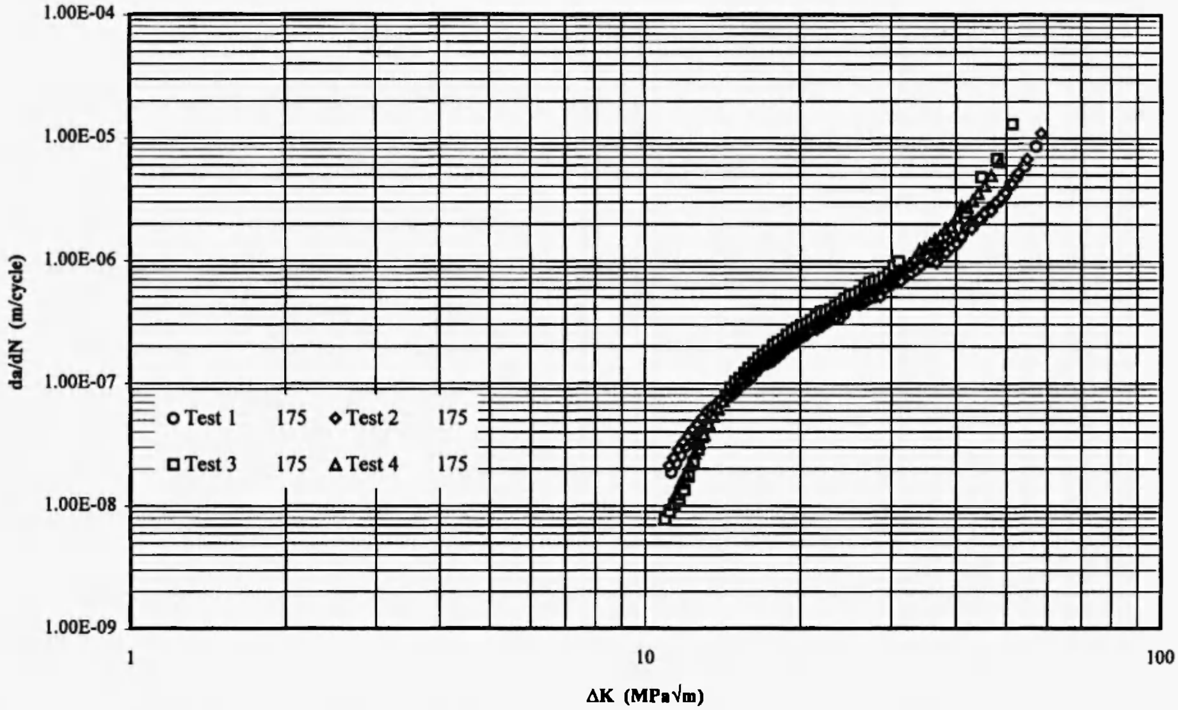

Fig. 1: Fatigue crack growth behavior of Ti-6Al-4V alloy at 175°C (Tests 1-2 Disk I, and 3-4 Disk II, respectively).

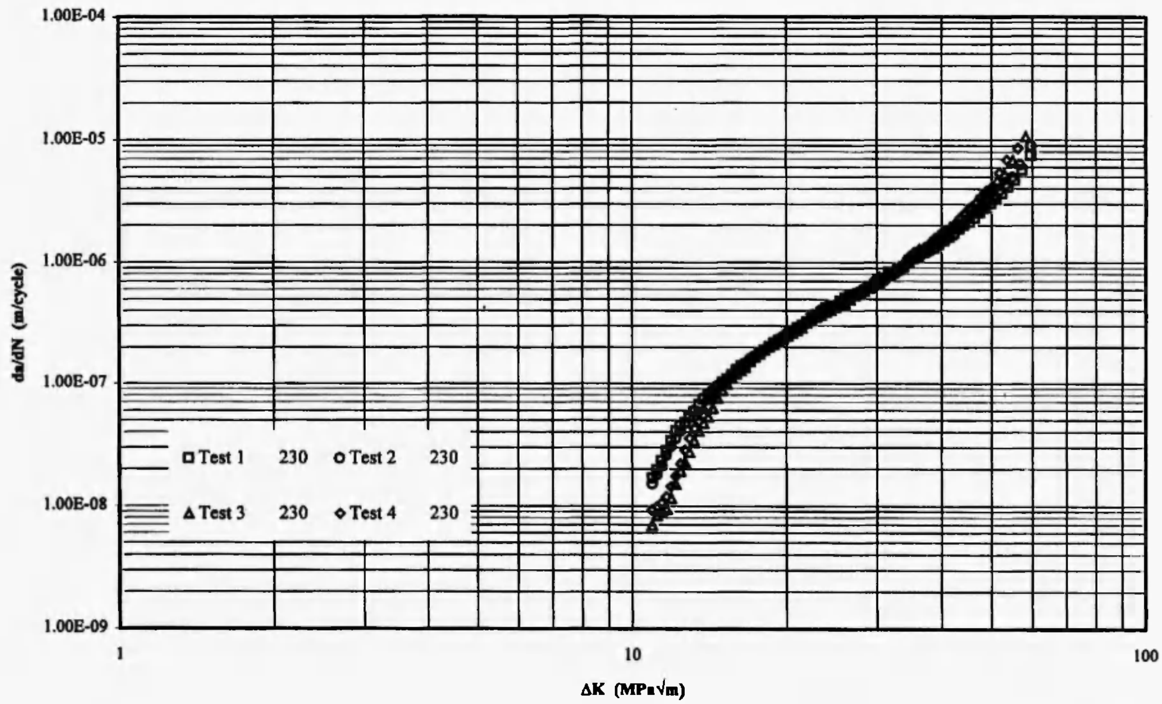

Fig. 2: Fatigue crack growth behavior of Ti-6Al-4V alloy at 230°C (Tests 1-2 Disk I, and 3-4 Disk II, respectively).

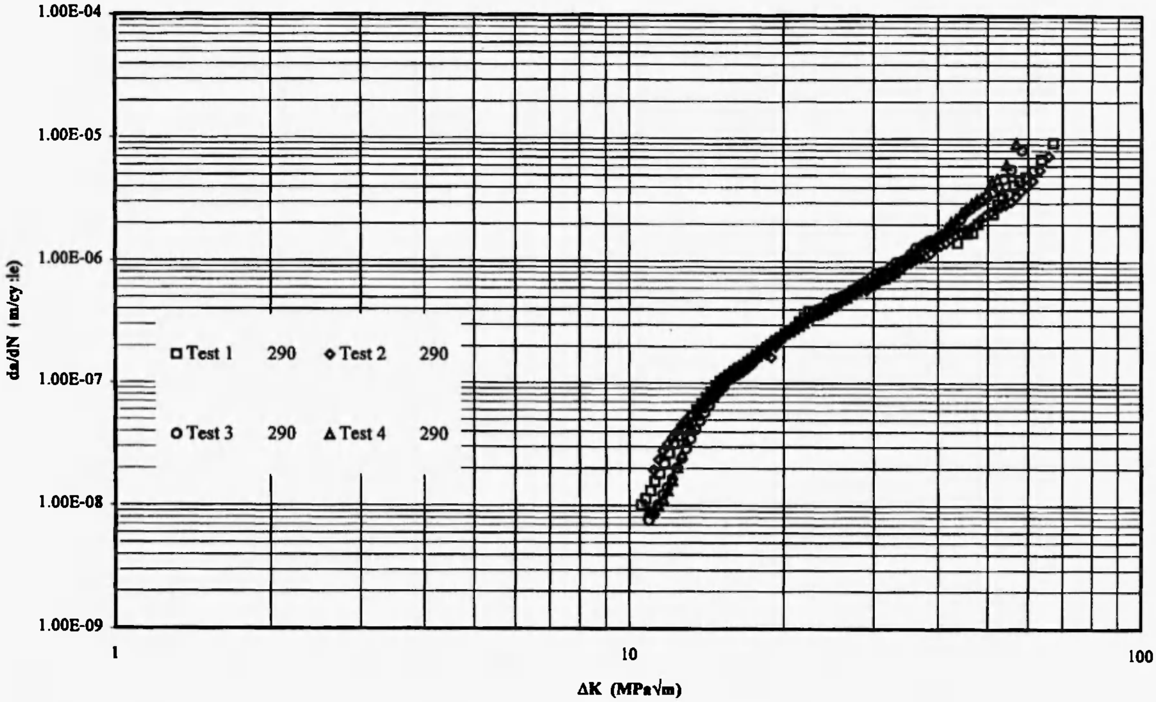

Fig. 3: Fatigue crack growth behavior of Ti-6Al-4V alloy at 290°C (Tests 1-2 Disk I, and 3-4 Disk II, respectively).

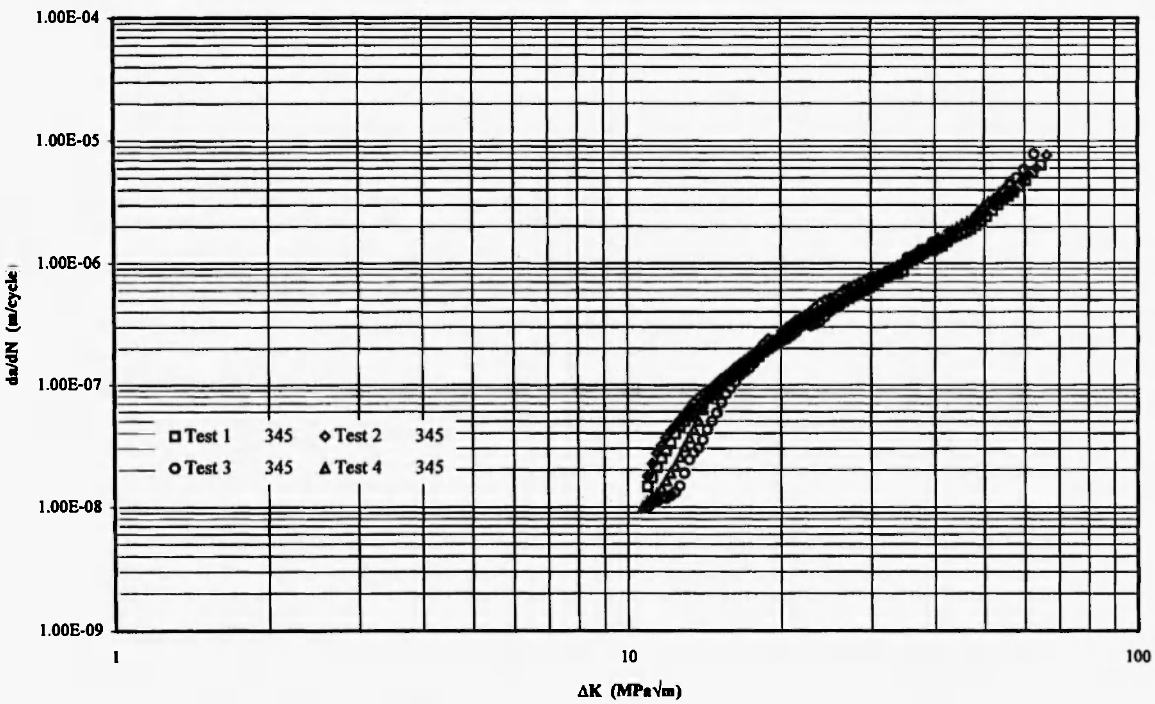

Fig. 4: Fatigue crack growth behavior of Ti-6Al-4V alloy at 345°C (Tests 1-2 Disk I, and 3-4 Disk II, respectively).

The parameters (C and m) are summarized in Table 1 showing a small variation or scatter between similar tests.

A two-factor analysis of variance (ANOVA) was performed with values of C and m as the test parameters at each temperature and the results are presented in Tables 2-3, respectively for both the disks from where the specimens were machined. This was done to ascertain that a) there is no significant difference in the FCGR response at different temperatures, b) there is no significant difference in the mean FCGR response for specimens from the two disks, and c) there is no interaction between the metallurgy of two disks at the temperatures. The ANOVA software assumes a F-distribution of the random variable with fixed degree of freedom and its density function (f) is calculated. Critical values of frequency distribution (crack growth rates in this case) at a confidence level of 95% shows that the FCGR response is not affected significantly by temperature. However, the statistical analysis indicates that the data from the two disks are different, and also that there is no significant interaction between the metallurgy of specimens from the two disks at different temperatures.

Even though a difference is indicated between the two groups of specimens in the analysis, the difference is not considered significant for the purposes of fatigue life prediction. Table 4 shows the average values of 'C' and 'm' for specimens from the two disks. A variation in results from the two disks is likely to be caused by differences in microstructure.

The values of 'C' and 'm' obtained from tests at 175°C to 345°C indicate a slight decrease in FCGR with increase in temperature. This observation has also been reported by /17/, where tests at elevated temperatures on Ti-6Al-4V indicated a decrease in FCGR, at higher temperatures due to the growth of secondary cracks and branching mechanisms at higher temperatures. However, to the contrary, a slight increase in fatigue crack growth rates in the mid rate regime has been reported by /6/. This was speculated to be due to a decrease in the Young's modulus of Ti-6Al-4V at higher temperatures. Secondary crack formation is shown in Figures 5-6 for two temperatures (230°C (disk II) and 290°C (disk I)) along with fatigue striations documented for two disks. Secondary cracking was a representative feature for both the disks at and over 230°C. The da/dN values reported by /10/ and /17/ for room temperature tests on Ti-6Al-4V specimens using the DCPD method have been compared with results obtained in this work in Table 5. The variation in the data is due to different test parameters such as frequency, load waveform, temperature, and materials parameters such as microstructure and specimen dimensions used in the testing and methodologies used in the reduction of data. Tests conducted at high temperatures revealed a slight decrease in FCGR for Ti-6Al-4V (STOA) alloy. This, however, is expected since 175-345°C is the typical range in which it is used in compressor disks and other high temperature applications.

4 CONCLUSIONS

The FCGR data for Ti-6Al-4V in the temperature range of 175 – 345°C is presented in this paper. Stage II fatigue crack growth rates were not substantially influenced by temperature in the range of 175-345°C. A slight decrease in FCGR with increasing temperature may be attributed to the growth of secondary cracks or branching mechanisms. The DCPD method was implemented as a crack growth measurement technique from this research and was an important objective of this program. The DCPD was found to be a reliable method for experimental evaluation of FCGR measurement in Ti-6Al-4V. Fatigue crack growth data obtained in this program were consistent and tests were repeatable.

5. ACKNOWLEDGMENT

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Table 1
Crack growth rate parameters (C and m) for various tests.

	Specimen 1	Specimen 2	Specimen 1	Specimen 2
Temperature °C	**C**	**C**	**m**	**m**
Disk I 175	5.920E-11	6.058E-11	3.043	2.917
230	1.033E-10	9.040E-11	2.863	2.908
290	9.091E-11	8.256E-11	2.925	2.947
345	9.464E-11	1.039E-10	2.918	2.926
Disk II 175	2.320E-11	3.046E-11	3.419	3.317
230	3.352E-11	4.540E-11	3.281	3.209
290	3.982E-11	5.342E-11	3.250	3.156
345	2.894E-11	6.474E-11	3.305	3.026

Table 2
ANOVA table using 'm' as test parameter for Disk I and Disk II

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	'f'	Critical 'f'
Temperature	0.041	3	0.014	1.85	4.07
Disk Type	0.394	1	0.394	52.23	5.32
Interaction	0.016	3	0.005	0.706	4.07
Error	0.06	8	0.0075		

Table 3
ANOVA table using 'C' as test parameter for Disk I and Disk II

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	'f'	Critical 'f'
Temperature	4.44E-19	3	1.48E-19	2.3	4.07
Disk Type	3.8E-18	1	3.8E-18	58.8	5.32
Interaction	5.9E-20	3	1.96E-20	0.304	4.07
Error	5.16E-19	8	6.45E-20		

Note f= density function, Critical 'f'= critical values of frequency distribution.

Table 4
Average values of 'C' and 'm' for Ti-6Al-4V as a function of temperature

Temperature (°C)	C	m
175	1.799E -11	3.619
230	3.681 E -11	3.349
290	5.444 E -11	3.177
345	6.248 E -11	3.109

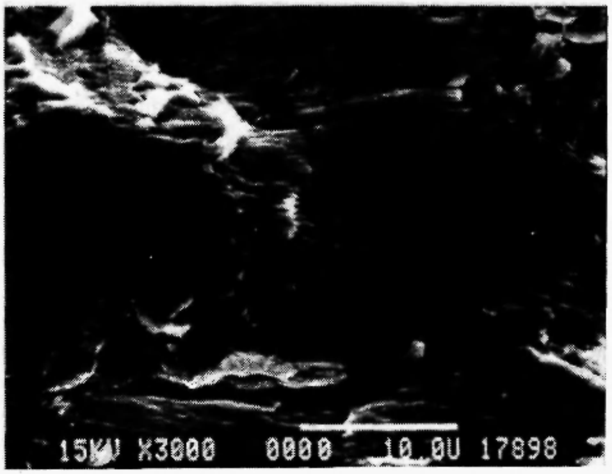

Fig. 5: Fracture surface showing fatigue striations and secondary cracks, (Disk II, 230°C)

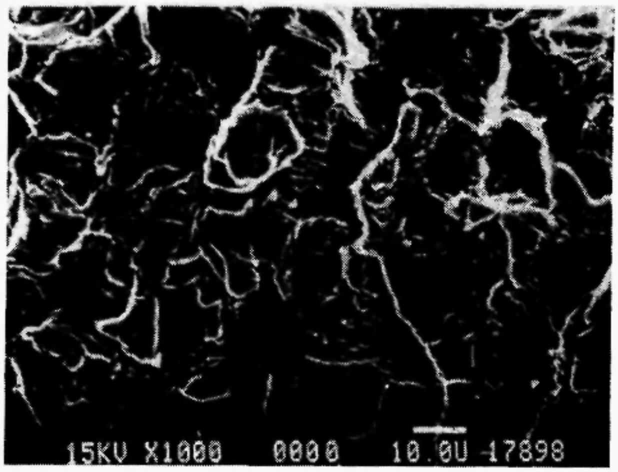

Fig. 6: Fracture surface showing fatigue striations and secondary cracks, (Disk I, 290°C)

Table 5
Comparison of da/dN data at room temperature with references /6/ and /10/

ΔK (MPa√m)	da/dN (m/cycle) (Present Work)	da/dN (m/cycle) Reported by /6/	da/dN (m/cycle) Reported by /10/
10	2.336 E-08	8.001 E-08	5.499 E-09
29	2.133 E-06	8.001 E-06	5.499 E-06

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