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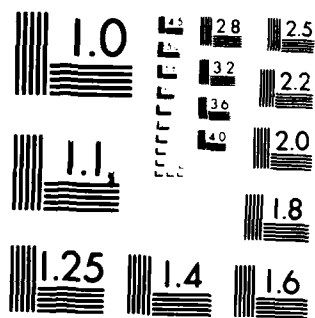
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Materials Report 82-E

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K.I. McRae

July 1982

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APPLICATION OF "FRACTOMAT/KRAK GAGES"
TO CRACK GROWTH MEASUREMENTS IN
STRUCTURAL COMPONENTS

by

K.I. McRae

July 1982

Approved:


Section Head




Chief

RESEARCH AND DEVELOPMENT BRANCH
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Abstract

Accurate crack size measurements are required for fracture mechanics' solution to component life predictions. Usual methods have limitations and the development of a real-time crack measurement technique would be of great value.

The operation and accuracy of the "Fractomat" device for crack growth measurement is assessed during its normal application to standard fracture mechanics specimens. The technique is found to be at least as accurate as surface microscopic examination. The further application of this technique to crack measurement of in-service structural components is also postulated for cases in which the most likely flaw location and orientation are known. The potential application is then demonstrated by examination of crack growth during the laboratory fatigue fracture of a typical aircraft structural component, the forward wing trunnion of the CF-100 aircraft.

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Introduction

The determination of the rate of crack growth in a material subjected to uniform cyclic loading requires an accurate and reproducible means of crack length measurement. The most common method for the external measurement of crack length is visual examination of the advancing crack tip utilizing a travelling vernier microscope with a magnification in the range of 20-50X. Alternative techniques employ the measurement of the specimen compliance or the direct measurement of specimen potential excited by a constant current. The compliance technique is accurate but is highly subject to specimen geometry. The direct potential method is experimentally complex and is subject to variations in specimen resistance due to specimen composition. The direct potential method also has the obvious disadvantage that it may not be applied to non-conductive materials. DREP has previously evaluated a commercial crack detection coating system (B.F. Peters, unpublished manuscript) which consists of encapsulated conductive dye which is applied to and electrically isolated from the specimen surface. This method was found to reliably detect crack initiation but required a difficult and extensive application procedure.

Recently, a similar technique, which may be referred to as an "indirect" potential method, has been developed and is marketed commercially as the FRACTOMAT/KRAK GAGE. This method differs from the direct potential method in that a potential drop is measured in a thin metal foil which has been adhesively bonded to the specimen surface. This crack length measurement technique is, therefore, independent of both the specimen geometry and composition. It has been demonstrated elsewhere¹ that the specimen independence and accuracy of this method makes it an attractive and convenient technique for the measurement of crack length in standard fracture mechanics specimens such as the compact tension specimen (CT). It is also believed that this technique may possibly be applied to the detection of crack growth in less standard geometries typical of many structural components. To validate the use of indirect potential measurement in fracture mechanics specimens, crack growth rate was studied in standard dimension compact tension specimens (1TCT) of 7075-T6 aluminum alloy. The possible application of

this method to the nondestructive detection and measurement of flaw growth in structural components is illustrated by a similar fatigue examination of the forward wing trunnion of the CF-100 aircraft.

THEORY OF OPERATION

Measurement of crack length by the indirect potential method is accomplished by creating a potential drop proportional to crack length in a thin metal (constantan) foil which has been adhesively bonded to and is electrically isolated from the specimen using standard strain gauge attachment procedures². An uncracked foil will produce a voltage, U_0 , when a constant excitation current, I , is supplied. If the foil or KRAK-GAGE is properly bonded to the specimen, slow, controlled crack growth in the specimen will yield a corresponding crack in the metal foil. The geometry of the foil gauge is critical and has been designed so that a voltage U_a is produced which is proportional to the crack length, a . The detected output voltage of the gauge is, therefore, the sum of the two voltages, $U_0 + U_a$.

The FRACTOMAT is the control and read out device for the KRAK-GAGE. It contains a nominal 100 mA constant current source for the excitation of the foil gauge, as shown schematically in Figure 1. The constant current input to the differential amplifier 4 is adjusted such that the initial output of the uncracked gauge is zero, thereby eliminating U_0 . The resulting voltage U_a , is then measured directly. The FRACTOMAT instrument has the capability for the control and direct digital readout of the crack length for two separate foil gauges. The outputs of the individual foil gauges may be displayed separately or averaged to provide a measure of the mean crack length. This instrument also contains limit detectors which may be used for the control of the test instrumentation and a direct analog signal, proportional to crack length, which may be used for plotting and display purposes.

Crack Growth Measurement in 7075-T6 Aluminum

The application of the FRACTOMAT/KRAK GAGE instrumentation to standard fracture mechanics testing may be illustrated by the measurement of crack growth rate in one inch thick 7075-T6 aluminum plate. Compact tension

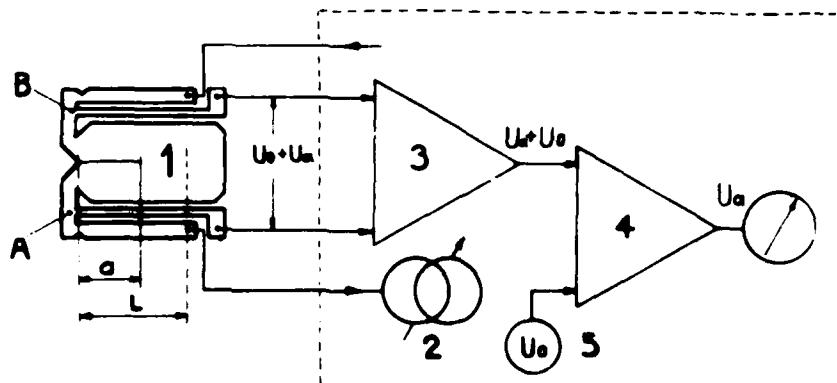


Figure 1. Schematic Diagram of Fractomat/Krak-Gage

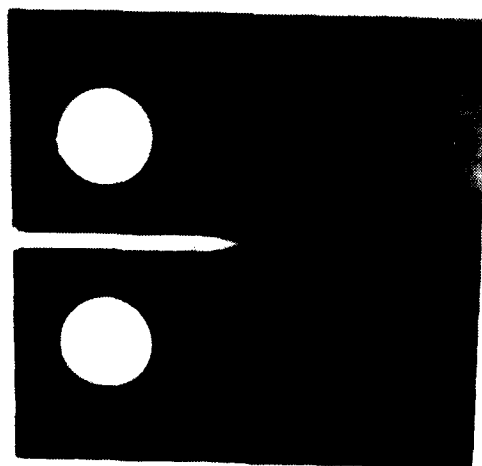


Figure 2. Compact Tension Specimen with Krak-Gage Attached

specimens were manufactured from this plate and 20 mm gage foils were installed on both sides of all specimens. A typical compact tension specimen with gauge foils and connections to the FRACTOMAT attached is seen in Figure 2. These specimens were then fatigued using an MTS servo-hydraulic testing system of 50 Kip capacity operating at frequencies of 1-5 Hz and a stress ratio, $R=0.25$. Loading of the specimens was accomplished using standard pin and clevis grips designed in accordance with ASTM specification E399-78³ (Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials). Total crack length (a) was measured as a function of the number of fatigue cycles (N) using both a vernier microscope and the FRACTOMAT device. A comparison of the two measurement techniques may be made by observation of the two a - N curves presented in Figures 3 and 4. It is evident that the FRACTOMAT is capable of providing a continuous, real-time display of the surface crack length which compares favourably to the microscope measurement technique. Unfortunately, crack length measurement using the vernier microscope has some rather large sources of error, most notably the uncertainty in the actual position of the crack tip and the reading error associated with the vernier. The expected error of the microscopic method is of the order of 0.001 in. which is well within that specified in ASTM E647-78⁴ (Tentative Test Method for Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/cycle). However, the indirect potential method has a theoretically infinite resolution of crack length. The most significant error of this method is most likely the degree to which the crack in the foil follows the associated crack in the specimen. This error and the total error of the FRACTOMAT method are thought to be even smaller than the standard visual measurement technique. The correlation of the results of the two measurement techniques is considered to be adequate justification of the indirect potential method.

A more useful measure of the crack growth rate may be obtained by plotting the incremental crack growth (da/dN) as a function of the alternating stress intensity. This growth rate is found to vary according to the relation:

$$da/dN = c(\Delta K)^n$$

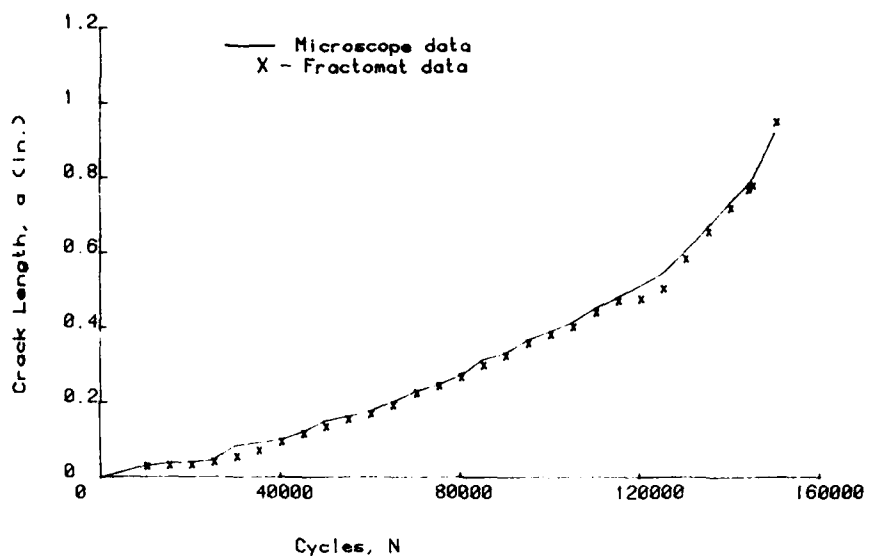


Figure 3. Crack Length vs Cycles -7075-T6 Aluminum Alloy Specimen #4

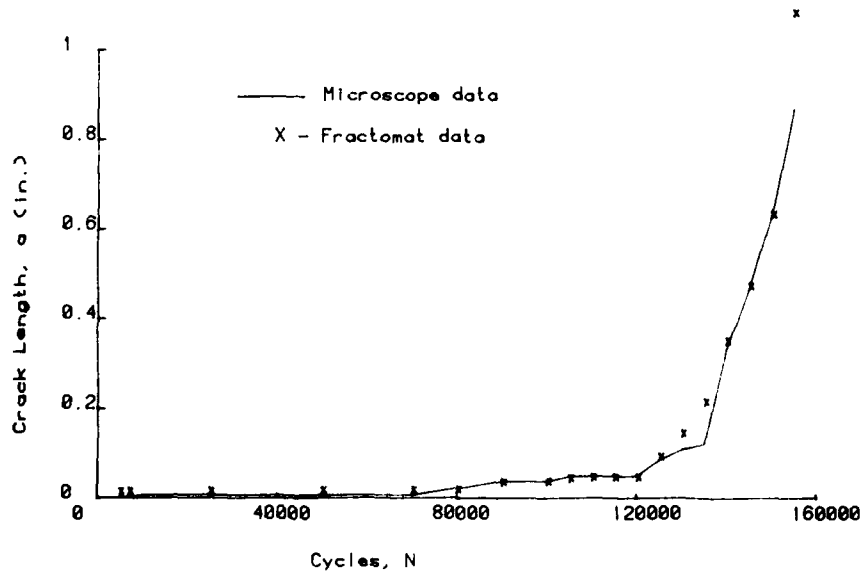


Figure 4. Crack Length vs Cycles -7075-T6 Aluminum Alloy Specimen #6

The stress intensity factor, ΔK , is a measure of the stress field magnitude at the crack tip and may be calculated for the compact tension specimen by the following operation³:

$$\Delta K = (\Delta P/BW^{1/2}) \cdot f(a/W)$$

$$\text{where } f(a/W) = \frac{(2+a/W)(0.886+4.46a/W-13.32(a/W)^2+14.92(a/W)^3-5.6(a/W)^4)}{(1-a/W)^{3/2}}$$

B = specimen thickness (in.)

W = specimen width (in.)

P = alternating load (lb.)

The exponent, n , may be considered to be a material property which is also dependent upon the stress ratio and specimen thickness and is a relative measure of the susceptibility of the material to crack growth. Figure 5 is the log-log plot of da/dN as a function of ΔK . This plot also illustrates the "dog-leg" feature typical of many alloys at low crack growth rates. Least squares fitting of this data produced a value of $n = 3.25$ for the 1 inch thick 7075-T6 Al plate.

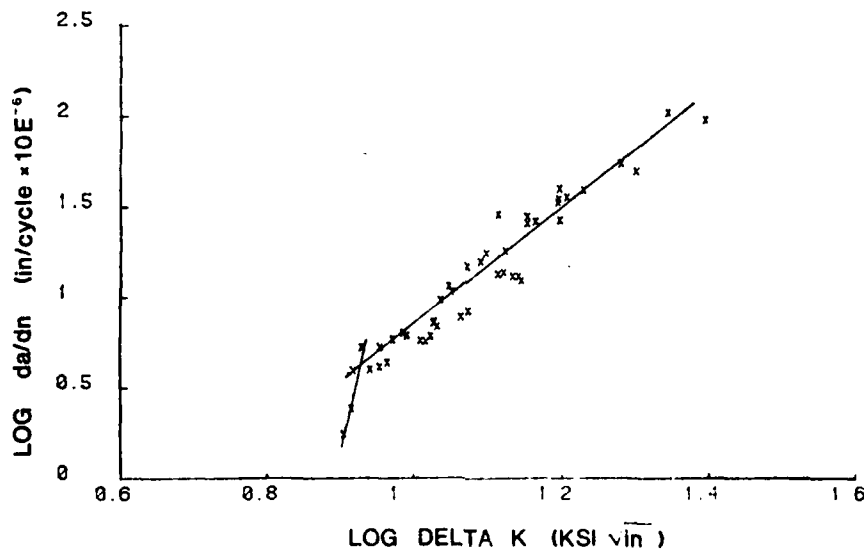


Figure 5. Crack Growth Rate 7075-T6 Aluminum

Application to the CF-100 Forward Wing Trunnion

Since the indirect potential method is truly specimen independent, it may also be applied to many testing situations for which other measurement techniques are not suitable. To illustrate the use of this method as a crack monitoring device capable of applications other than normal fracture mechanics specimens, foil gauges were installed on both sides of a saw-cut starter notch in a forward wing trunnion of the CF-100 aircraft. The trunnion material is an AISI 4340 low-alloy steel which has been heat treated to produce a moderate tensile strength (180 KSI) and a relatively high fracture toughness ($K_{IC} > 100 \text{ KSI}\sqrt{\text{in}}$). The component was installed in the three point bend fixture of the MTS testing system, as seen in Figure 6. The trunnion was then fatigued at a rate of 5 Hz, a stress ratio $R=0.2$ and a mean load of 15 Klb. Crack growth was monitored in the same manner as described previously for the 7075-T6 Al compact tension specimens, i.e. by the indirect potential measurement method and by optical measurement with a vernier microscope. A plot of crack length (a) versus the number of fatigue cycles (Figure 7) shows the close correlation between these two methods. Crack growth rate (da/dN) was also calculated and plotted as a function of the alternating stress intensity (ΔK), as shown in Figure 8. The stress intensity factor, ΔK , is estimated for this specimen using the equation for a standard three-point bend specimen¹, i.e.

$$\Delta K = (PS/BW^{3/2}) \cdot f(a/W)$$

$$\text{where } f(a/W) = \frac{3(a/W)^{1/2} - [1.99 - (a/W)(1-a/W)92.15 - 3.93a/W + 2.7(a/W)^2]}{2(1+2a/W)(1-a/W)^{3/2}}$$

B = specimen thickness (in)

W = specimen width (in)

S = span between load points (in)

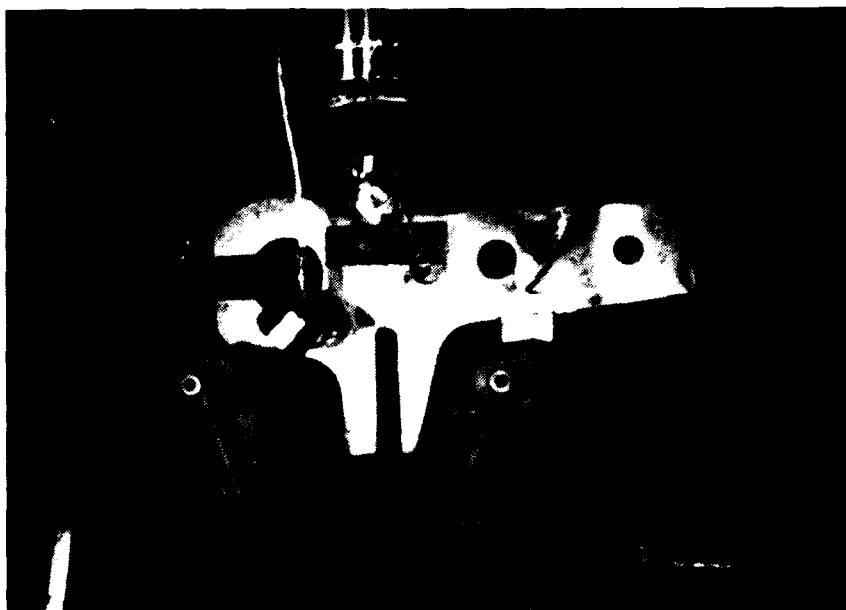


Figure 6. Set-Up for CF-100 Wing Trunnion Fatigue Testing

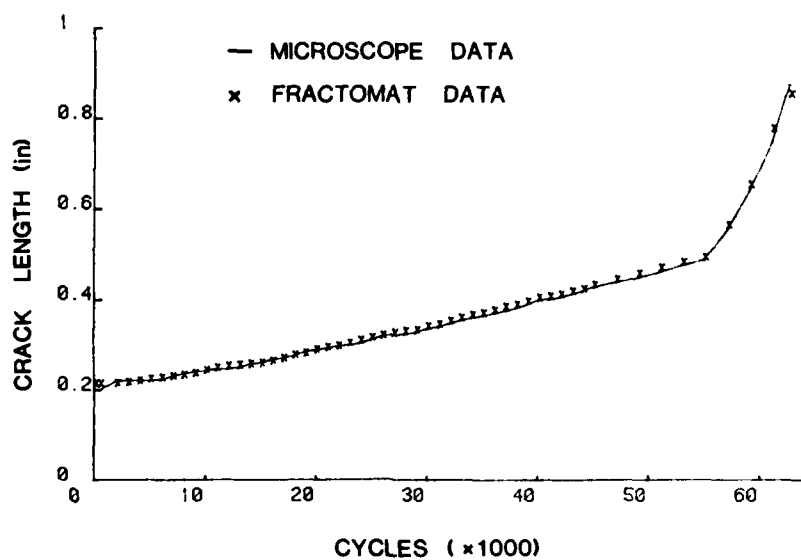


Figure 7. Crack Growth in CF-100 Wing Trunnion

These data are also least squares fitted to the equation

$$da/dN = C(\Delta K)^n$$

to determine values for the coefficients C and n. The calculated value of n is found to be 2.01, which is in reasonable agreement with the literature value of 2.25 for 4340 steel which had been heated to a slightly higher yield strength and lower fracture toughness.⁴

Another valuable feature of this method is that a continuous voltage proportional to crack length is available for plotting or computation purposes. Crack length may then be plotted as a function of a system parameter such as specimen compliance or load-point displacement or as a function of some external parameter. To illustrate this, the output voltages of the two foil gauges were averaged and subsequently applied to the X-axis of an X-Y recorder, while a calibrated voltage proportional to the total acoustic emission event count was also applied to the Y-axis. The resulting plot, Figure 9, provides valuable information regarding the acoustic emission intensity relative to crack length, and, ultimately, to the stress intensity factor.

CONCLUSIONS

The indirect potential method is a relatively simple and direct means of crack length measurement for a variety of specimens. Although specifically designed for fracture mechanics applications, such as the determination of crack growth rate and fracture toughness testing, the method also has definite applications to the detection and measurement of flaw growth in critical structural components. This has been confirmed by the coincidence of crack length measurements made by the indirect potential method and by direct optical measurement during the laboratory fatigue test of a CF-100 wing trunnion. It is postulated that this method may be suitable as an in situ, real-time measure of crack initiation and growth. This technique would be more sensitive and less complicated than alternative techniques such as acoustic emission monitoring, particularly, in cases

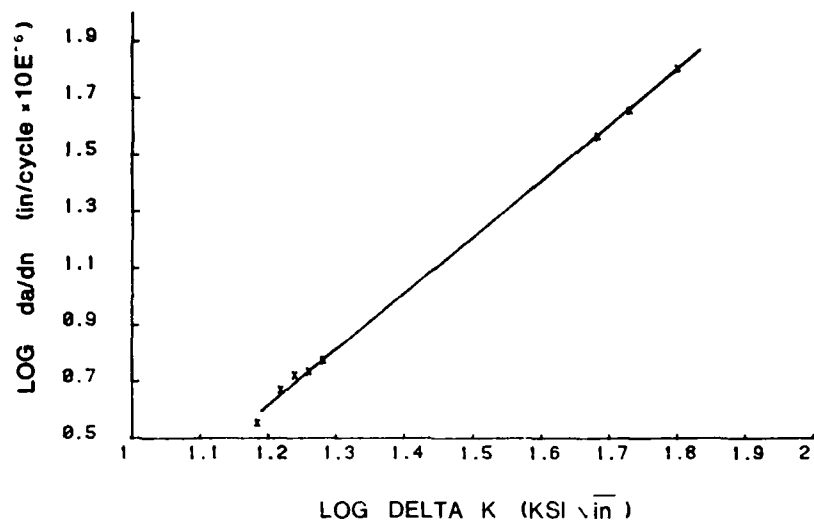


Figure 8. Crack Growth Rate for CF-100 Wing Trunnion

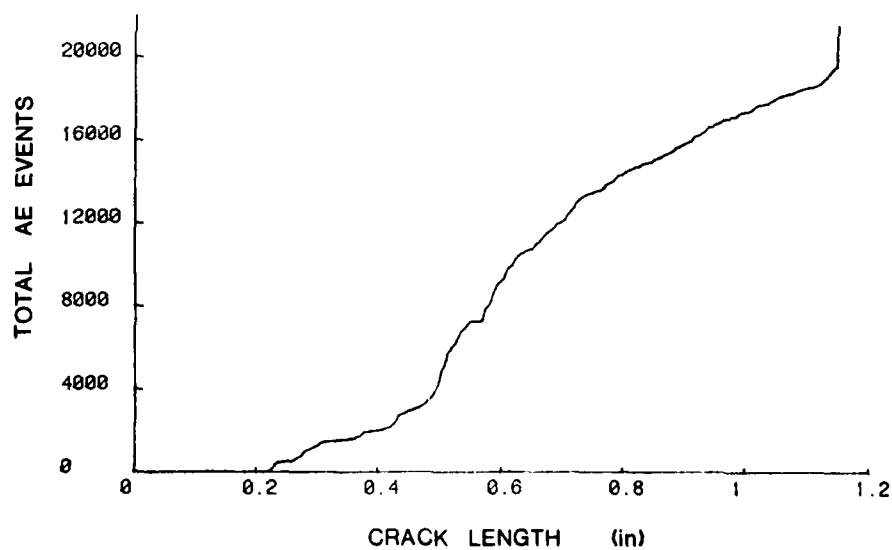


Figure 9. Acoustic Emission Events as a Function of Crack Length

such as this, where the component material is a high strength steel. Possible applications would include any critical structural component with the following features:

- (1) the approximate position and direction of crack growth must be known.
- (2) the component must provide adequate area for the installation of the foil gauge. Many typical problem areas, such as fastener holes, are not therefore suitable for this technique.
- (3) the normal operating environment of the component must not be so severe as to interfere with the operation of the foil gauge. High temperature environments are an obvious instance for which this technique is not applicable.

In the event that the monitored structural component possesses all of these features and also has a readily calculable stress intensity function, such as the CF-100 wing trunnion, the method may also be expended to provide a direct measure of the residual life of that component.

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1. P.C. Paris and B.R. Hayden, "A New System for Fatigue Crack Growth Measurements and Control", ASTM Symposium on Fatigue Crack Growth, Pittsburgh, 1979.
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4. "Tentative Test Method for Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/Cycle", ASTM Specification E647-78, Annual ASTM Standards (10), 1979.
5. "Damage Tolerant Design Handbook - Part 2", MCIC-HB-01, Metals and Ceramics Information Center, Battelle Columbus Laboratories, Columbus, Ohio, 1975.

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Title: Application of "Fractomat/Krak Gages" to
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1. ORIGINATING ACTIVITY Defence Research Establishment Pacific FMO Victoria, BC VOS 1B0		2a. DOCUMENT SECURITY CLASSIFICATION Unclassified	
3. DOCUMENT TITLE Application of "Fractomat/Krak Gages" to Crack Growth Measurements in Structural Components (U)		2b. GROUP	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Materials Report			
5. AUTHOR(S) (Last name, first name, middle initial) McRae, K. I.			
6. DOCUMENT DATE July 1982		7a. TOTAL NO. OF PAGES 11	7b. NO. OF REFS 5
8a. PROJECT OR GRANT NO. 26B		9a. ORIGINATOR'S DOCUMENT NUMBER(S) Materials Report 82-E	
8b. CONTRACT NO. n/a		9b. OTHER DOCUMENT NO.(S) (Any other numbers that may be assigned this document) n/a	
10. DISTRIBUTION STATEMENT Unlimited Distribution			
11. SUPPLEMENTARY NOTES n/a		12. SPONSORING ACTIVITY Materials Engineering Section, Defence Res. Est. Pacific, FMO Victoria, BC	

13. ABSTRACT

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crack growth measurement

foil gauges

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