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Procedures for Precision Measurement of Fatigue-Crack-Growth-Rate Using Crack-Opening-Displacement Techniques

G. R. YODER, L. A. COOLEY, AND T. W. CROOKER

*Metals Performance Branch
Material Science and Technology Division*

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18. ABSTRACT (Continue on reverse side if necessary and identify by block number) This paper describes experimental and analytical procedures whereby the conventional commercial fracture mechanics clip-gage can be used for precision measurement of fatigue-crack-growth-rate in compact tension specimens. Potential sources of error in measuring crack length via COD techniques are delineated. Comparisons are made among crack length data obtained via specimen surface observations and crack-opening-displacement (COD) techniques. Comparisons are also made among data analyzed by the secant and 7-point incremental polynomial methods. It is emphasized (Continues)		

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20. Abstract (Continued)

that COD techniques can enhance the accuracy of the secant method of data reduction. Step-loading procedures using COD techniques are described. Proposed amendments to ASTM E647-78T regarding incrementing of crack-length measurements via COD techniques are discussed.

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PROCEDURES FOR PRECISION MEASUREMENT OF FATIGUE-CRACK-GROWTH-RATE USING CRACK-OPENING-DISPLACEMENT TECHNIQUES

INTRODUCTION

We are presently engaged in two types of fatigue-crack-growth-rate (FCGR) testing programs. The first program involves the influence of microstructural parameters on FCGR in high-strength titanium alloys. This program requires a high rate of FCGR data generation because of the large number of relevant microstructural parameters under investigation. The second program involves the influence of environmental parameters on FCGR in a variety of alloys in marine environments. This program often requires crack length measurements to be performed under adverse conditions.

In both programs, we have found crack-length measurement via crack-opening-displacement (COD) techniques to be a highly valuable procedure. In this paper, we will attempt to provide a detailed description of how these procedures are carried out and how our techniques have been verified per ASTM E647-78T (1).

EXPERIMENTAL DETAILS

The data shown in this report were obtained on two high-strength $\alpha + \beta$ titanium alloys, designated Alloys 1 and 2. Alloy 1 is Ti-6Al-4V containing 0.06 weight-percent interstitial oxygen and Alloy 2 is Ti-8Al-1Mo-1V containing 0.11 weight-percent interstitial oxygen. Both alloys were tested in the beta-annealed condition which produces coarse-grained Widmanstätten microstructures. Tensile properties of the two alloys for the transverse (T) orientation are given below in Table 1.

Note: Manuscript submitted September 19, 1979.

Table 1 - Tensile Properties

Alloy	0.2% Yield Strength σ_{ys} (MPa)	Tensile Strength σ_{UTS} (MPa)	Young's Modulus E (GPa)	Reduction in Area (%)	Elongation (%)
1	740	818	115	34	10
2	794	894	128	21	11

FCGR data were obtained from 1-T WOL-type compact tension (CT) specimens with a half-height to width (h/W) ratio of 0.486. In each case, specimen width (W) was 64.8 mm, specimen thickness (B) was 25.4 mm and the crack path was in the TL orientation (2). Details of the specimen geometry and the stress-intensity factor expression are given in reference 3.

FCGR testing was performed on an MTS 810.04 electrohydraulic closed-loop materials testing system. All FCGR tests were conducted in ambient room air under tension-tension cycling with a haversine waveform. A cyclic frequency of 5 Hz and a load ratio of $R = P_{min}/P_{max} = 0.1$ were used.

COD measurements were made on the CT specimens using an MTS 632.02B-01 clip-gage, with a sensitivity of 7.874 mV per millimeter of COD. The clip-gage was fixed to the specimen at the crack mouth via knife edges mounted on the specimen with set screws driven into drilled and tapped holes, as shown in Fig. 1. Care was taken to align the knife-edge surfaces parallel to the surfaces of the notch. Clip-gage signals were read out on the 100 mV range of a Hewlett-Packard 3440A/3443A digital voltmeter. Optical measurements of crack length were made on both faces of the CT specimen using Gaertner traveling optical micrometers at a magnification of approximately 15X. Both the test specimen and the experimental apparatus listed above are widely-used conventional fracture mechanics test equipment. No special apparatus of any kind was used in this investigation.

PROCEDURES FOR CRACK LENGTH MEASUREMENT VIA COD

The basic procedures for obtaining crack length from measurements of COD in CT specimens are well documented (4,5). However, it is our experience that the success of this method for precision measurement of crack length rests upon strict adherence to certain detailed procedures as outlined below.

The first step in this procedure is an accurate COD calibration for the specimen of interest. A schematic of a typical normalized calibration curve of $\frac{EB(COD)}{P}$ vs. crack length-to-width ratio (a/W) is shown in Fig. 2. For the work described in this paper, we relied upon COD calibration expressions formulated in reference 6. It is useful to emphasize here that the term COD in this paper refers exclusively to crack-mouth-opening-displacement, whereas the term compliance refers to relationships involving load-line-displacement.

The second step requires an accurate determination of the normalized parameter $\frac{EB(COD)}{P}$. Load (P) and COD are experimental measurements which are normally read from digital electronic instrumentation. B is readily obtained from ordinary micrometer measurements of specimen thickness. However, we have found that the selection of an appropriate value of Young's modulus (E) can be a significant source of error in this procedure. In our experience, superior results accrue when the value of E is obtained from tensile test data. An acceptable fallback from this requirement is to measure an "apparent" value of E from COD measurements on an uncracked CT specimen. An unacceptable approach, in our view, is the use of a "handbook" value of E for the generic class of the alloy being tested. This is especially unsatisfactory for titanium alloys where E can vary by more than 15 percent due to heat treatment alone. Even "apparent" values of E obtained from uncracked CT specimens should be treated with caution due to the known variance between the compliance characteristics of machined notches and sharp cracks.

Values of COD at maximum load ($P_{\max}$) are obtained experimentally according to the system illustrated in Fig. 3. The typical nonlinear shape of the initial portion of the P-vs.-COD curve raises another admonition regarding the accuracy of this crack length measurement procedure, as documented in ref. 7. Because of this nonlinearity, more than one digital reading of P vs. COD must be taken to obtain the true value of the upper, linear slope of these curves. The practice we have developed is to record P and COD at two points, $P_{\max}$ and $1/2 P_{\max}$. The degree to which this nonlinearity occurs in P-vs.-COD curves varies widely, depending upon specimen thickness and crack length (7). Simplified procedures which attempt to determine crack length from a single COD measurement at $P_{\max}$ are to be avoided in the interest of accuracy.

A final consideration which is of importance on the basis of our experience is the selection of Δa increments between crack length readings. With the use of the clip-gage for crack length measurement, the basis for selecting Δa increments changes from the optically-based criteria outlined in ASTM E647-78T (1). Here the criteria become based upon $\Delta(\text{COD})$ increments (and the accuracy with which these increments can be read out on the electronic instrumentation at hand) - and to some extent, the method of data reduction to be employed. We have found - as will be illustrated in subsequent sections - that $\Delta(\text{COD})$ increments of approximately 0.20 mV (as measured from a digital electronic voltmeter with an accuracy of approximately ± 0.015 mV) provide excellent results. With the 7-point incremental polynomial method of data reduction, we find that $\Delta(\text{COD})$ increments of 0.20 mV (± 0.10 mV) provide results that are in excellent agreement with those obtained from optical measurements of crack length at the specimen surface ($\bar{a}_s$) as per ASTM E647-78T. With the secant method, we have found that the resultant scatter in

da/dN is virtually the same as obtained with the 7-point incremental polynomial method -if the intervals of $\Delta(\text{COD})$ are somewhat more restrictive, viz. 0.20 mV ($\frac{+0.10}{-0.04}$ mV).

In either case, it is important to note that with the COD technique for measurement of crack length, a nominally constant value for $\Delta(\text{COD})$ increments should be used, which may correspond to increments in actual crack growth ($\bar{a}_{\text{COD}}$) that vary as much as an order of magnitude, depending on a/W . This effect, illustrated in Fig. 2, derives from the fact that $\frac{EB(\text{COD})}{P}$ increases exponentially as a function of a/W . For the 1T WOL-type CT specimen ($W = 64.8$ mm), with increments of $\Delta(\text{COD}) \approx 0.20$ mV, $\Delta(\bar{a}_{\text{COD}})$ values can be as large as 2.5 mm at low a/W values and can approach 0.25 mm at high a/W values. In comparison, ASTM E647-78T specifies crack length measurement intervals, $0.25 \text{ mm} \leq \Delta a \leq 1.3 \text{ mm}$. We wish to close this section by reemphasizing the importance of instrumentation accuracy considerations in the successful use of COD for precision crack length measurements.

COMPARISON OF CRACK LENGTH MEASUREMENT TECHNIQUES

With each of three replicate specimens of Alloy 1, which were individually cycled at overlapping ranges of ΔK , measurements of crack length were made by both the optical technique ($\bar{a}_s$) at the specimen surface as per ASTM E647-78T and the COD clip-gage technique ($\bar{a}_{\text{COD}}$) as outlined above. For the 7-point incremental polynomial method of reducing the crack length vs. elapsed cycles (a -vs.- N) data, results from the two measurement techniques can be compared in Figs. 4 and 5 for $\bar{a}_s$ and $\bar{a}_{\text{COD}}$, respectively. The dashed line in Fig. 5 traces the reference curve from Fig. 4 to facilitate comparison. It is readily apparent that both methods of crack length measurements provide virtually identical results. Scatter amongst the data from the three specimens is minimal in both instances.

It is noted that values of surface crack length were corrected for tunneling as measured from final crack front profiles. Tunneling depths varied from 0.89 to 1.35 mm (0.035 to 0.053 in.). The value of $E = 115$ GPa was averaged from two 12.8-mm (0.505-in.) dia. tensile tests. Further, as suggested earlier, approximately constant intervals of $\Delta(\text{COD}) \approx 0.20$ mV (± 0.10 mV) were used in the $\bar{a}_{\text{COD}}$ technique relative to Fig. 5.

COMPARISON OF DATA REDUCTION METHODS

In a single-specimen test of Alloy 2, crack length was measured by the COD clip-gage technique ($\bar{a}_{\text{COD}}$). As with Alloy 1, we measured E from duplicate tensile tests. Figures 6 and 7 afford comparison of the reduction of the $\bar{a}_{\text{COD}}$ -vs.- N data by the 7-point incremental polynomial and secant methods, respectively. For the 7-point incremental polynomial method (Fig. 6), approximately constant increments of $\Delta(\text{COD}) \approx 0.20$ mV (± 0.10 mV) were again used. The dashed line in Fig. 7 traces the reference curve from Fig. 6 to facilitate comparison with the secant method. The correspondence between the two sets of data is excellent. However, note by the separately denoted data symbols that when using the secant method of data reduction, increased scatter in the da/dN - ΔK data becomes apparent when the $\Delta(\text{COD})$ interval becomes less than 0.16 mV.[†] Thus, as indicated earlier, increments of $\Delta(\text{COD})$ should be restricted to 0.20 mV ($\frac{+0.10}{-0.04}$ mV) for optimization of the secant method. If this is done, Fig. 7 suggests that the scatter in da/dN generated by the secant method is virtually the same obtained with the 7-point incremental polynomial method, as displayed in Fig. 6.

[†] NOTE: Increments of $\Delta(\text{COD})$ as small as 0.10 mV were not considered in Fig. 7.

This observation might at first seem surprising since it is well-known that the secant method generates much greater scatter in the reduction of optically measured crack growth data ($\bar{a}_s$ -vs.-N) obtained from the specimen surface (3). The difference observed herein with $\bar{a}_{COD}$ -vs.-N data is attributed to a pair of factors: First, the COD clip-gage measurement inherently averages crack growth variations through the specimen thickness (which is significant since fatigue cracks grow discontinuously at any one point along the crack front, including the surface). Secondly, measurements of crack growth from $\Delta(COD)$ increments of about 0.20 mV in size are made with relatively high precision from digital electronic voltmeter readings with an accuracy of approximately 0.015 mV (as quoted earlier).

PROCEDURES FOR STEP-LOADING

Step-loading offers several advantages for FCGR testing. It offers the opportunity to generate a greater span of da/dN - ΔK data from a single specimen, which can be a great advantage in situations where test materials are limited. It can also substantially reduce the number of elapsed cycles necessary to generate a da/dN - ΔK curve, thus hastening data generation. This aspect can be of particular importance in time-consuming, low-frequency corrosion-fatigue tests. The principal benefit comes from step-loading through the early stages of the test at low a/W and da/dN values where the dK/da gradient is shallow. What follows is a brief description of how we systematically define a step-loading program based upon COD measurements of crack length and the secant method of data reduction.

The first step involves the preliminary interval selection, shown schematically in Fig. 8. A number of data points are chosen with ΔK values spaced equidistant on the logarithmic ΔK scale. With use of the secant data reduction

method, we allow the extent of each interval of constant-load amplitude to be governed by the criterion of a $\Delta(\text{COD})$ increment of 0.20 mV. This criterion consequently determines the extent of each ΔK interval - as well as the amount of load change between intervals. A specific example for a step-loading test on Alloy 2 is shown in Fig. 9. The anticipated effect of a ± 5 percent uncertainty on da/dN is illustrated. The test program, defined in terms of specific loads, is shown in Fig. 10. Note the small increments of maximum load change ($\Delta P_{\text{max}} \approx 3$ to 6 percent) and ΔK incremental change per step. The da/dN - ΔK data resulting from this program are shown in Fig. 11. The reference line shown comes from constant-load-amplitude data shown in Fig. 6. We have made numerous comparisons of this type and find the step-loading procedures outlined above to be perfectly satisfactory. However, these procedures do rely upon the use of the secant method of data reduction, which in our experience is greatly enhanced by clip-gage measurement of crack length.

One area of concern in step-loading is the possibility of nonsteady-state transients in da/dN introduced as a result of the periodic incremental load increases. This concern is the rationale for limiting ΔP_{max} to values of less than 10 percent in all of our tests. To date, we have seen no evidence of transient phenomena as a result of step-loading, including data from tests conducted in seawater where hydrogen embrittlement mechanisms are operative (8).

PROPOSED AMENDMENT TO ASTM E647-78T

Section 8.6.2.1 of ASTM E647-78T specifies that, for the CT specimen, crack length measurement intervals shall be spaced according to:

$$\Delta a \leq 0.02 W \text{ for } 0.25 \leq a/W \leq 0.60$$

$$\Delta a \leq 0.01 W \text{ for } a/W \geq 0.60$$

with the further provision that the minimum Δa shall be 0.25 mm (0.01 in.). Where crack lengths are obtained by optical measurement, these rules appear to be satisfactory. However, as we have attempted to show in this paper, an altogether different set of rules may be applicable where crack lengths are obtained by COD measurement.

Specifically, for the WOL-type CT specimen, present rules specify that the maximum Δa shall not exceed 1.25 mm (0.05 in.). For crack length measurement at low a/W values using COD techniques, this maximum value should be doubled. This is necessary to accommodate the requirements of the COD technique and, on the basis of our experience, results in no significant change in the final $da/dN-\Delta K$ curve.

SUMMARY

In this paper, we have attempted to summarize recent developments and experience in our laboratory relating to FCGR test methods, as follows.

- When proper procedures spelled out in this paper are followed, COD measurement of crack length in FCGR testing is convenient, reliable and accurate.
- Using COD measurement of crack length, which inherently averages crack length variations through the specimen thickness, the 7-point incremental polynomial and secant methods of data reduction produce virtually identical $da/dN-\Delta K$ results.
- Using COD measurement of crack length combined with the secant method of data reduction, step-loading programs which hasten the gathering of $da/dN-\Delta K$ data can be successfully utilized.

Minor amendments should be made to the crack length measurement provisions of ASTM E647-78T to accommodate procedures for COD measurement of crack length.

ACKNOWLEDGEMENTS

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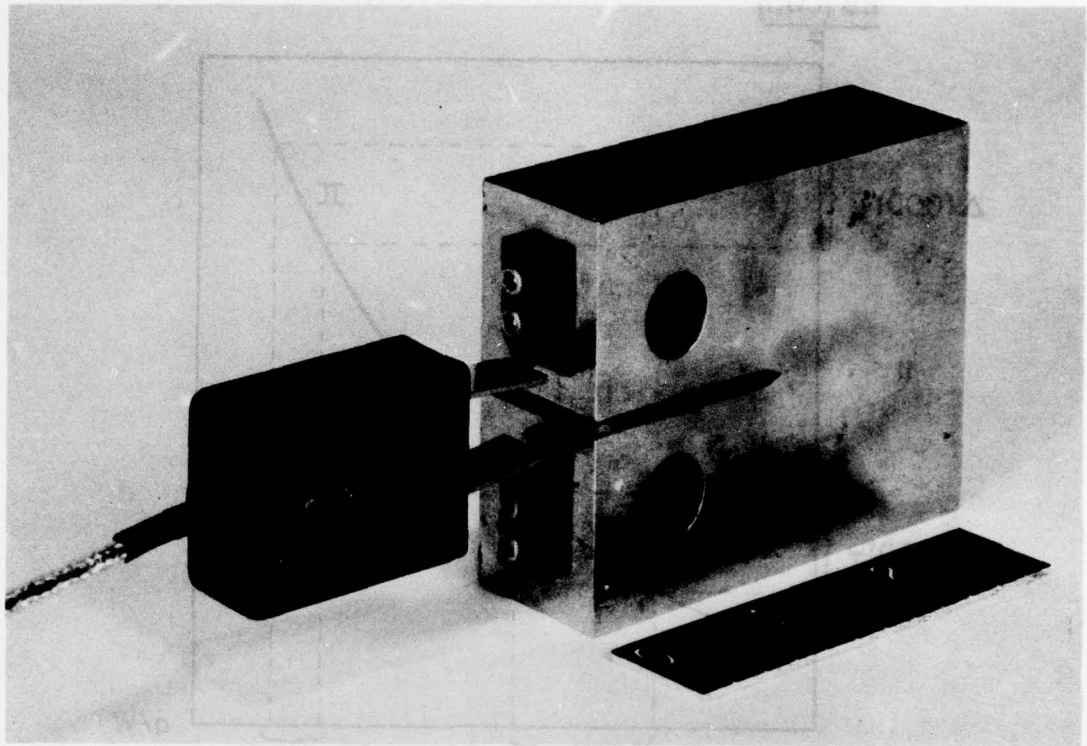


Fig. 1 — WOL-type compact tension (CT) specimen with clip-gage attached

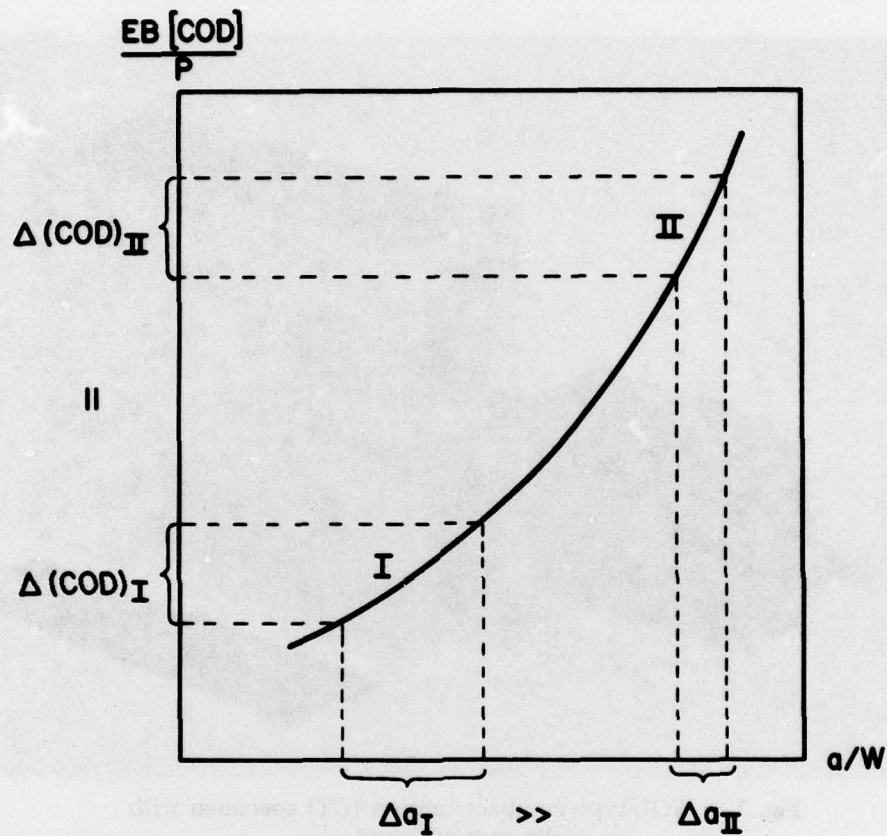
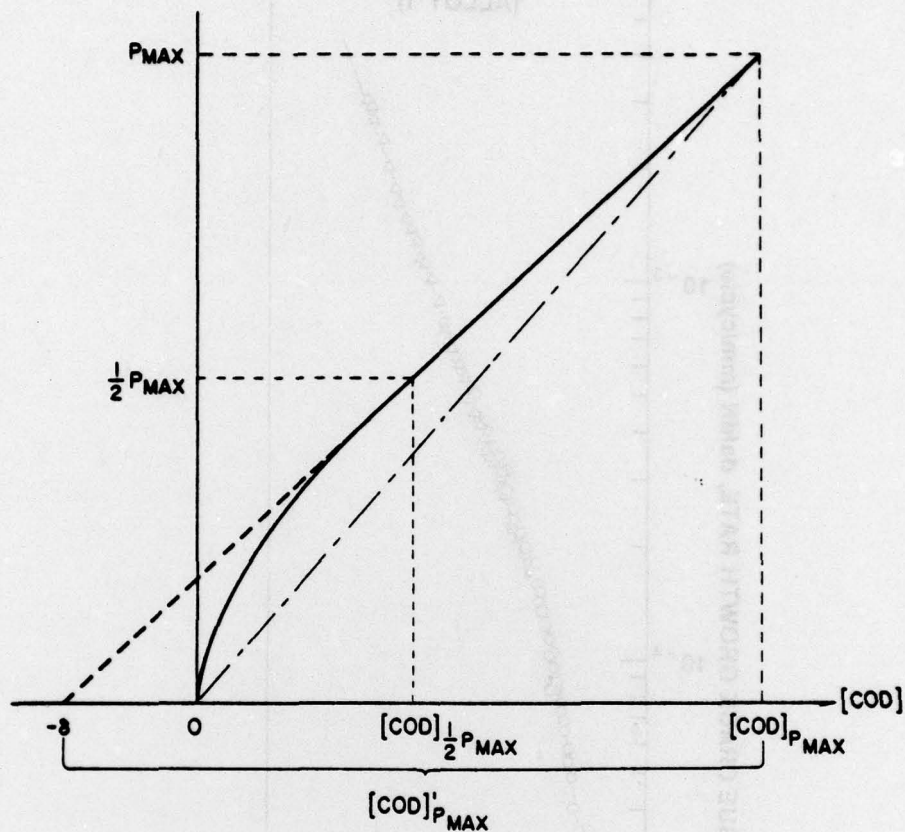


Fig. 2 - Schematic illustration of a normalized crack-opening-displacement (COD) calibration curve, showing the manner in which crack length increments (Δa) selected on the basis of a constant COD increment $\Delta(\text{COD})$ vary as a function of crack depth (a/W)



$$[COD]'_{P_{MAX}} = [COD]_{P_{MAX}} + 181$$

$$= ([COD]_{P_{MAX}} - [COD]_{\frac{1}{2} P_{MAX}}) \times 2$$

Fig. 3 - Schematic illustration of a typical trace of load (P) vs. COD, and the effect of nonlinearity upon the measurement of the COD/P ratio used in crack length measurement

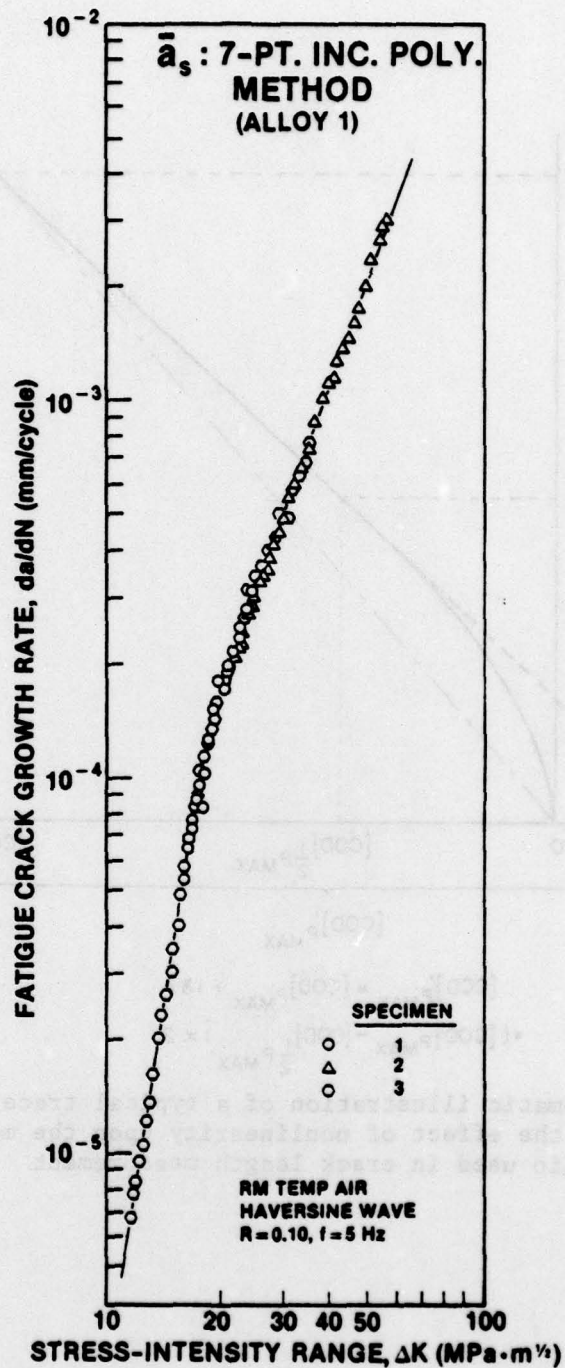


Fig. 4 - da/dN vs. ΔK data for Alloy 1 from three replicate specimens, with crack length measurements via optical technique and data reduction via 7-point incremental polynomial method

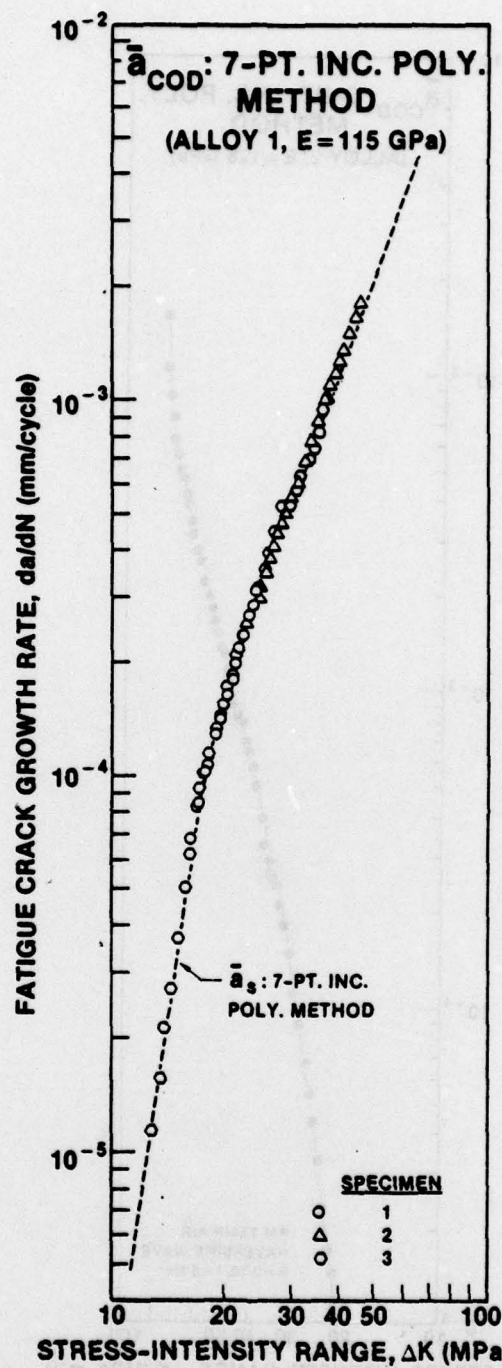


Fig. 5 - da/dN vs. ΔK data for Alloy 1 from three replicate specimens, with crack length measurements via COD technique and data reduction via 7-point incremental polynomial method. The dashed line is the reference curve from Fig. 4.

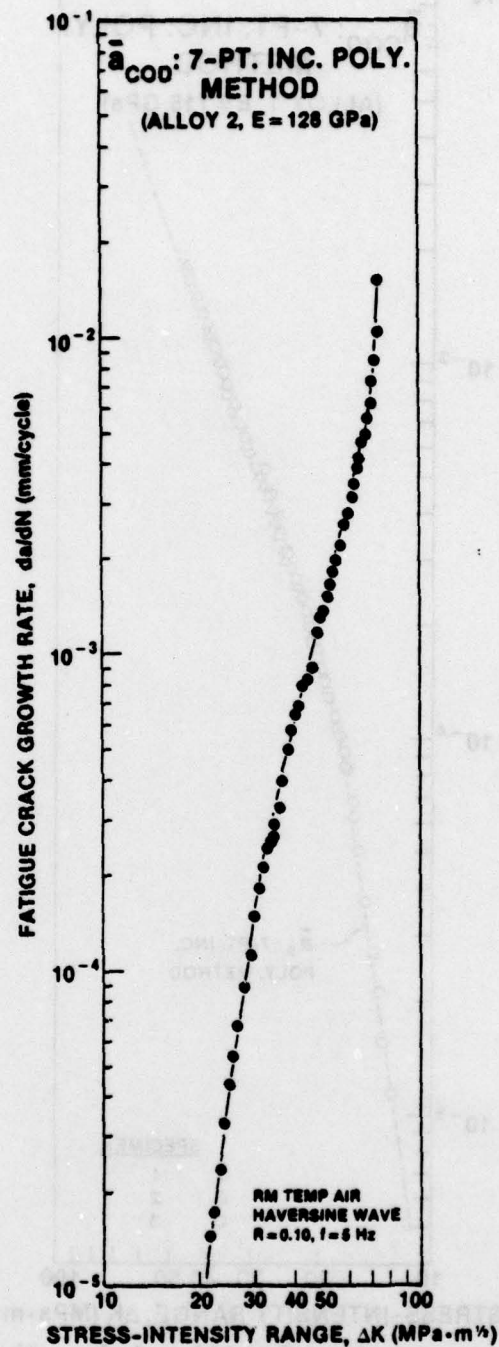


Fig. 6 - da/dN vs. ΔK data for Alloy 2, with data reduction via 7-point incremental polynomial method and crack length measurement via COD technique

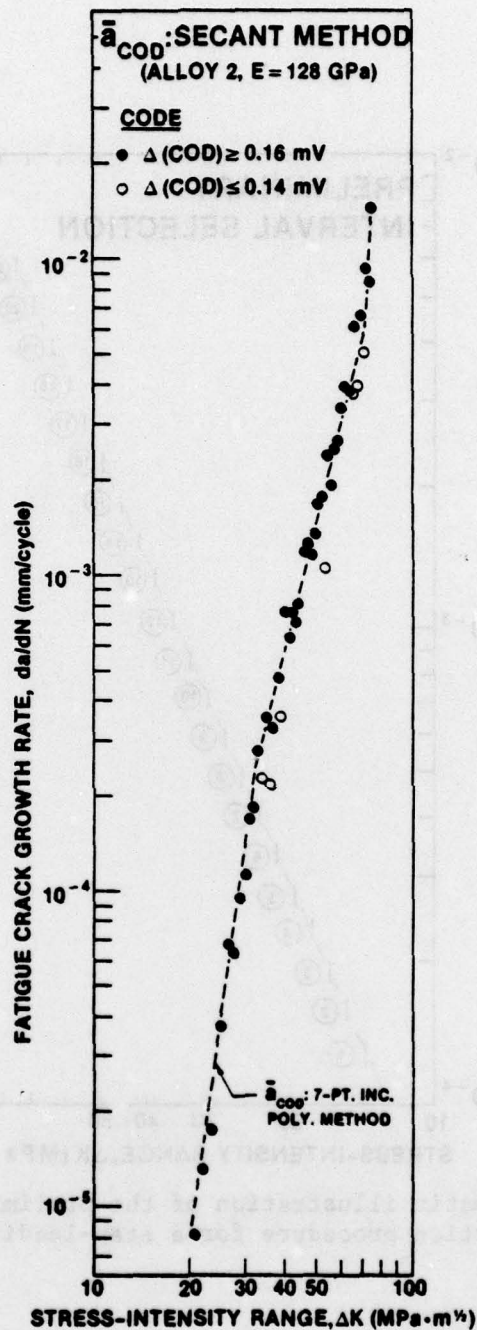


Fig. 7 - da/dN vs. ΔK data for Alloy 2, with data reduction via secant method and crack length measurement via COD technique. The dashed line is the reference curve from Fig. 6. Note the apparent increase in scatter when the $\Delta(COD)$ intervals fall below 0.16 mV.

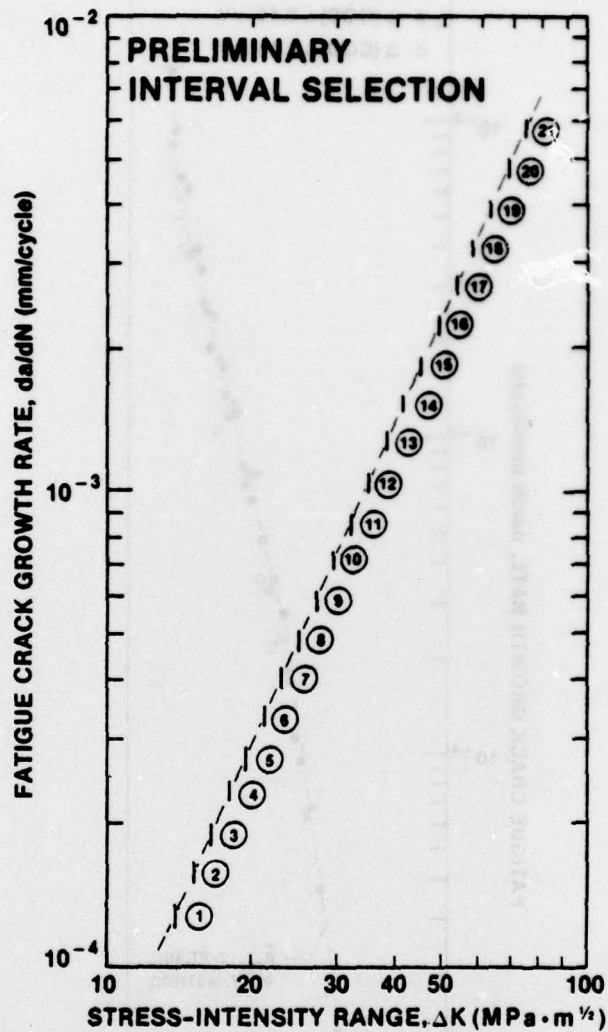


Fig. 8 - Schematic illustration of the preliminary data interval selection procedure for a step-loading program

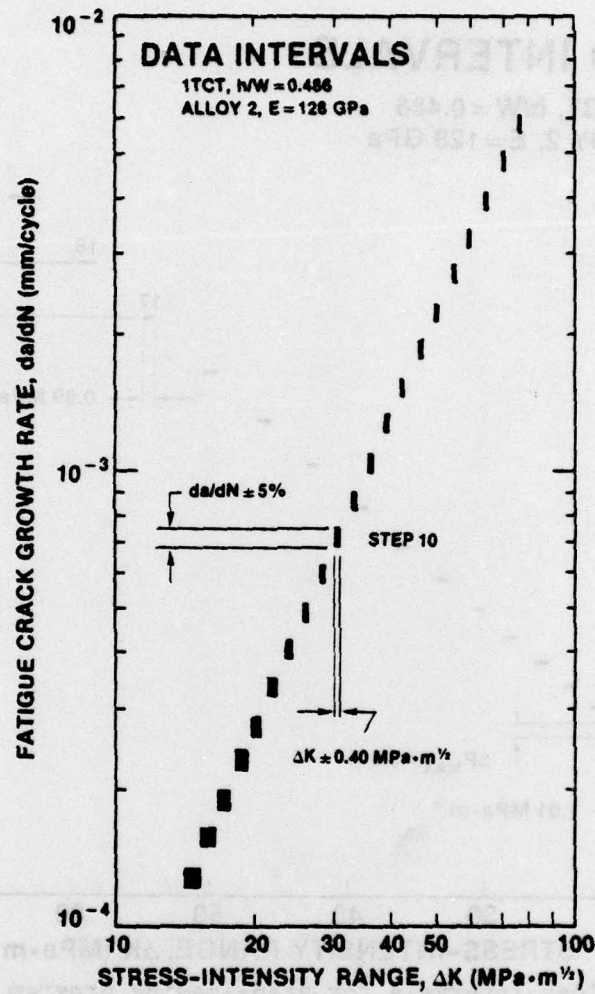


Fig. 9 - Data intervals for step-loading program for Alloy 2, based upon crack length measurement via COD increment technique

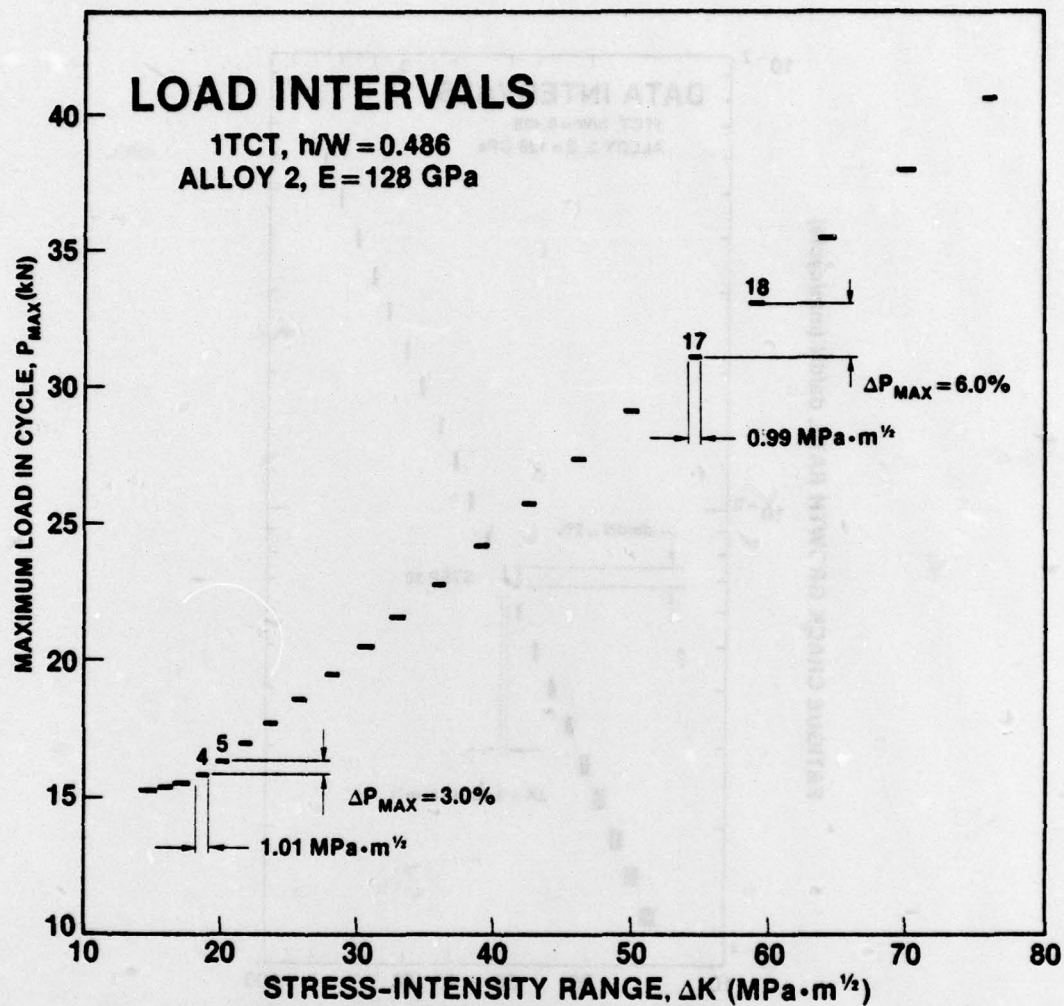


Fig. 10 - Load intervals for step-loading program outlined in Fig. 9. Note that maximum step-loading increments (ΔP_{max}) remain small throughout the test.

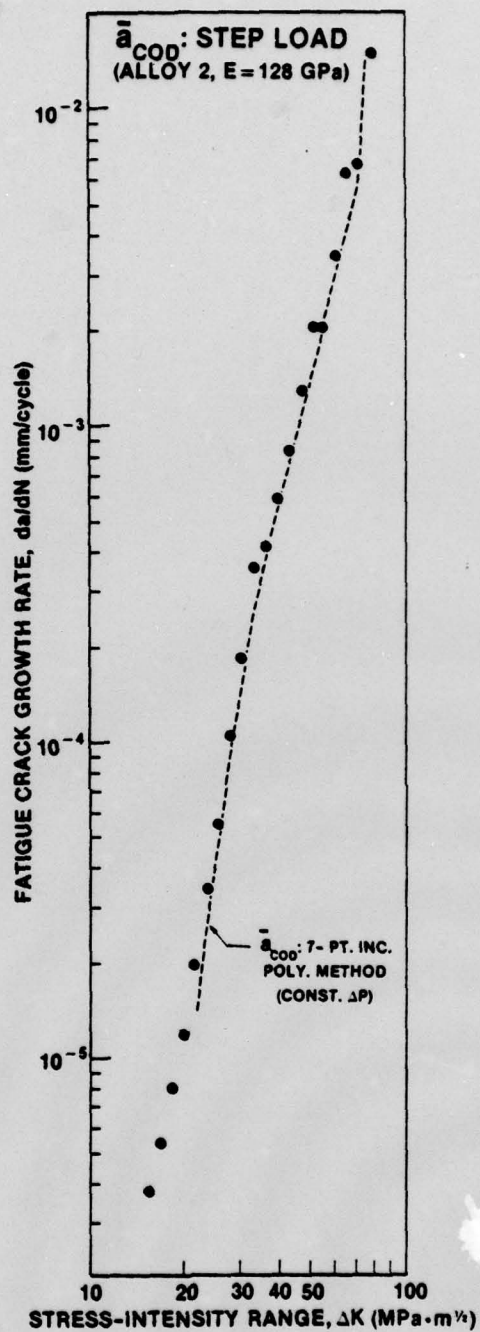


Fig. 11 - da/dN vs. ΔK data for Alloy 2 generated via step-load procedures with secant method of data reduction. The dashed line is the reference curve from Fig. 6.