Fracture Technology Associates

Automated Fatigue Crack Growth Testing – Series 2001
ACR, $K_{residual}$, K_{max} Sensitivity Supplement
Version 3.12.03
March 19, 2012

Contact: Keith Donald
Fracture Technology Associates
2412 Emrick Boulevard
Bethlehem, PA 18020
610-868-3054
www.FractureTech.com

1.0 Introduction to FTA's FCGR software system

See standard manual for details of this section.

2.0 Installation Guide

See standard manual for details of this section.

3.0 Using the FTA – ACR, $K_{residual}$, K_{max} Sensitivity Software Supplement

The supplement provides additional information about testing and analysis requirements unique to the adjusted compliance ratio (ACR) crack closure method, K residual determination using the crack-compliance method, and K_{max} sensitivity used to develop a master curve. Full familiarity with the Automated Fatigue Crack Growth Testing and Analysis Manual is assumed. Background on the methodology is included in Section 7.0 of this supplement. References on ACR are included at the end of Section 7.4. Knowledge and understanding of this background material is essential for the successful application of this software enhancement. As such, the material provided in this supplement is an outline of the additional software features rather than a step by step tutorial of the testing and analysis process.

For easy cross reference to the standard manual, the section numbering system of the standard manual has been maintained, hence numerous gaps in section numbering will be noted in this supplement.

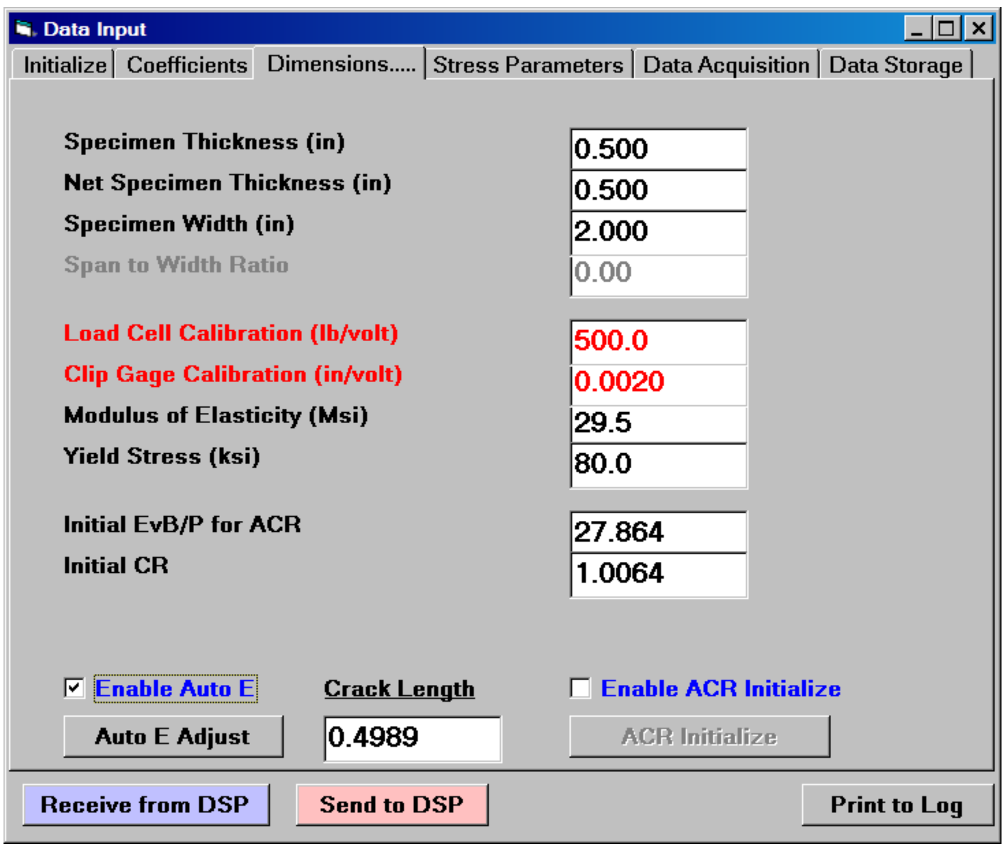
4.0 FTA Testing Software for ACR, $K_{residual}$, K_{max} Sensitivity – Description of Menus and Tabs

The following section offers a complete description of the display forms and input parameters associated with using **ACR, $K_{residual}$ and K_{max} Sensitivity**. Please refer to the Steady State Reference Manual for descriptions common to both standard testing and these advanced concepts.

4.4 Input

4.4.1 Data

4.4.1.3 Dimensions (compliance)



- **Initial EvB/P** (normalized compliance) for the adjusted compliance ratio (ACR) crack closure measurement technique.

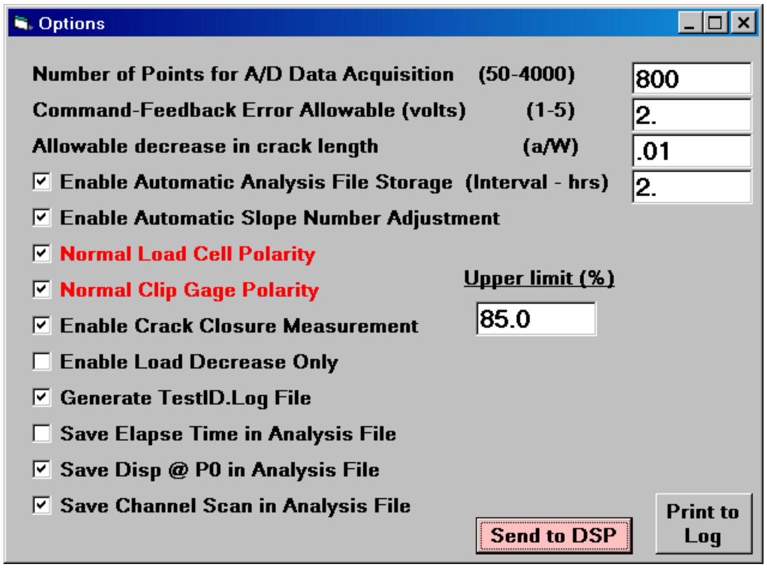
- **Initial CR** (compliance ratio) for the ACR crack closure measurement technique. Default value is 1. Do not enter 0!

Pressing **ACR Initialize** sets the initial conditions for the ACR method. Conditions should be set after cycling at the expected precrack load and frequency has begun, but before crack initiation. The **Enable ACR Initialize** checkbox must be checked to activate the **ACR Initialize** command button.

For tests below R = 0.7, establish the proper Initial EvB/P and CR for the ACR method as follows. Force data storage by clicking **Receive from DSP**, then **Enable Instant Storage** and **Send to DSP**. This updates the crack growth rate, which can be viewed on the **Status** screen. Allow a number of cycles to go by and repeat. When crack length is stable, but before the precrack has initiated, tick **Enable ACR Initialize** (**Dimensions** tab) and **Send to DSP**. Note resulting values **Initial EvB/P** and **Initial CR (Dimensions)**. The value of Initial CR should be close to 1.00.

4.4.2 OPTIONS

4.4.2.1 Options (compliance)



Enable Crack Closure Measurement: enables crack closure measurement. This includes the ASTM 2% opening load method as well as the ACR method. When this option is selected, only the portion of the load-displacement curve above closure (and above the minimum slope level) will be used in the crack length determination. See **Upper Limit %**, below. One column of compliance ratio and five columns of opening load values corresponding to 1%, 2%, 4% 8% and 16% compliance offsets are added to the .in3 file. Note: Compliance Ratio (CR), not Adjusted Compliance Ratio (ACR) data are stored. Post processing must be performed on raw data to get meaningful ACR results.

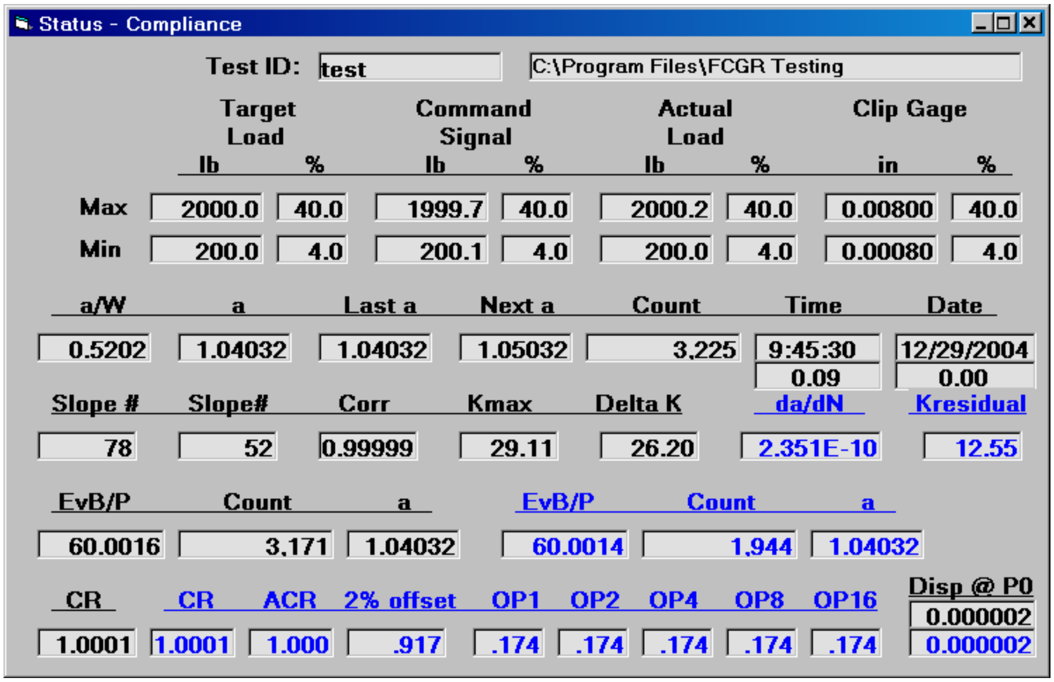
Upper limit %: sets an upper limit for the linear part of the load-displacement curve when **Enable Crack Closure Measurement** is selected. The default value is 85%.

Save Disp @ Zero Load in Analysis File: computes and saves the displacement at zero load in the .in3 file. The calculation uses the slope and mean value of the load-displacement data to extrapolate to a displacement at zero load. Changes in this value in relationship to changes in crack length are used to compute the K due to residual stress using the crack-compliance technique. *This feature requires precise linearity and stability of the load-displacement data in order to provide meaningful results and is deselected by default.*

Save Channel Scan in Analysis File: adds two extra columns in the .in3 file corresponding to the average readings of analog input channel 11 and 12. The ‘Channel Scan’ form must be open in order for this option to work. A gain factor should be chosen to convert the voltage from channel 11 to temperature. This feature may be useful if temperature compensation is desired for compensating $K_{residual}$ data.

4.6 Display

4.6.1 STATUS (COMPLIANCE)



- **CR**: compliance ratio used for ACR closure technique.

- **Kresidual:** Kresidual calculation using the crack-compliance technique.

$$K_{res} = K_{\max} \cdot \frac{d\delta_{res}}{d\delta_{\max}}$$

- **CR**: Compliance ratio normalized by the initial compliance ratio

- **ACR**: Adjusted Compliance Ratio $\Delta K_{ACR} = ACR \bullet \Delta K_{APP}$

- **2% offset**: equivalent factor using ASTM 2% opening load technique

$$\Delta K_{OP} = 2\% offsetfactor \bullet \Delta K_{APP}$$

- **OP1**: ratio of opening load to maximum load based on 1% compliance offset

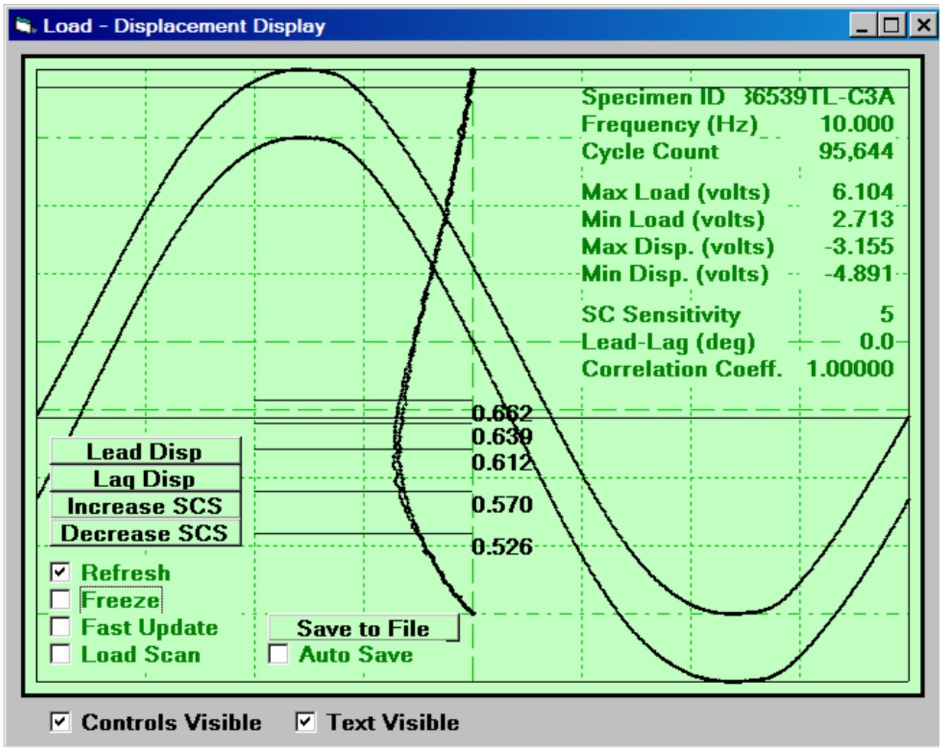
- **OP2**: ratio of opening load to maximum load based on 2% compliance offset

- **OP4**: ratio of opening load to maximum load based on 4% compliance offset

- **OP8**: ratio of opening load to maximum load based on 8% compliance offset

- **OP16**: ratio of opening load to maximum load based on 16% compliance offset

4.6.3 LOAD – DISPLACEMENT DISPLAY



Load (top curve) and displacement (bottom curve) versus time are displayed for one cycle. Each signal is automatically scaled to the same relative amplitude. The voltage of each signal is displayed in the upper right hand corner.

The vertical trace is a signal cancellation signal that has been expanded to exaggerate non-linear effects due to crack closure. The vertical axis is load, with deviation in linearity between load and displacement shown on the horizontal axis. The five offset values due to crack closure are clearly indicated. These correspond to the OP1, OP2, OP4, OP8 and OP16 values in the **Status – Compliance** display. The thin black horizontal lines show the upper and lower limits for slope measurement.

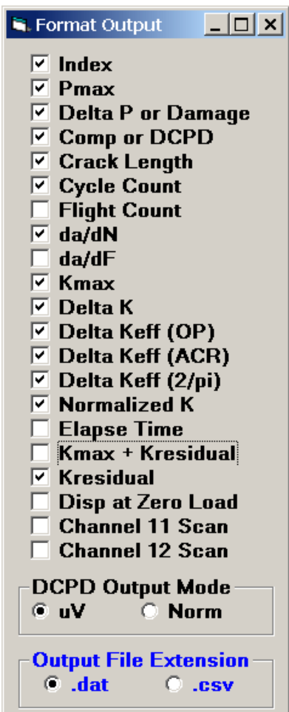
5.0 Using the FTA Analysis Software

See standard manual for details of this section.

6.0 FTA Analysis Software for ACR, $K_{residual}$, K_{max} Sensitivity – Description of Menus and Tabs

6.2 Main Menu: General

6.2.2 FORMAT



The following columns of data are often included in the data output file (.dat) when using the ACR, $K_{residual}$ and K_{max} sensitivity.

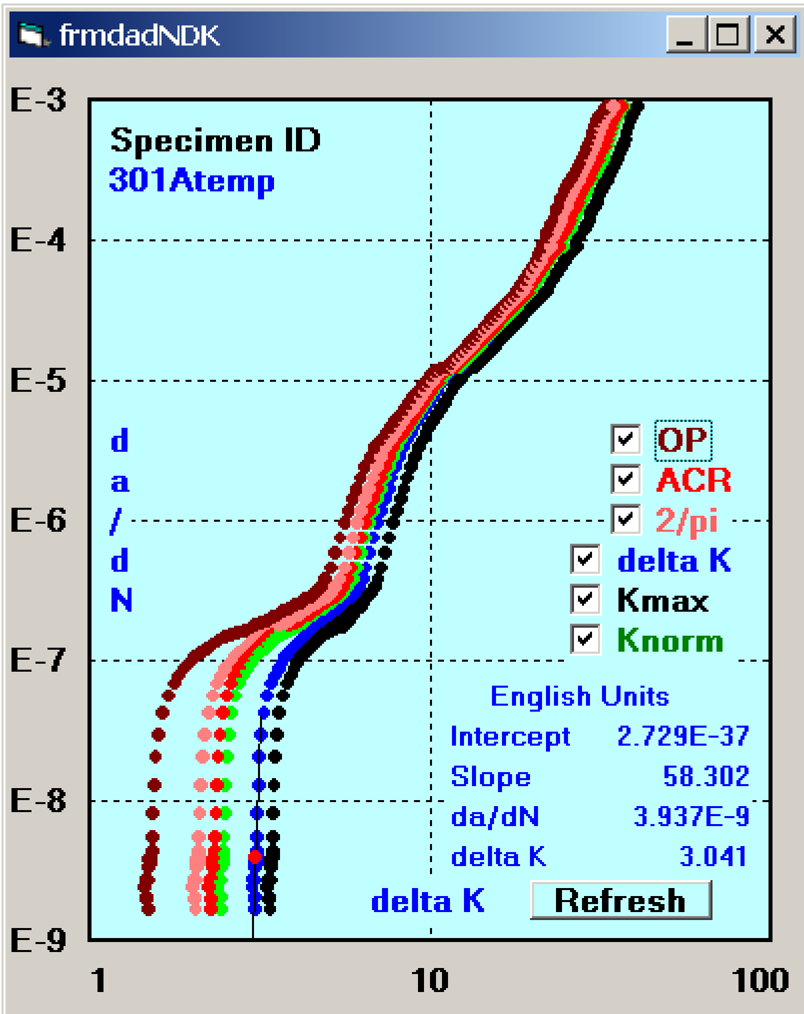
- **Delta Keff (OP)** Estimation of ΔK effective using the ASTM 2% opening load method.
- **Delta Keff (ACR)** Estimation of ΔK effective using the ACR method.
- **Delta Keff (2/pi)** Estimation of ΔK effective using 2/π correction to the opening load.

$$K_{norm} = \Delta K_{ACR}^{\,1-n} \bullet (K_{\max} + K_{residual})^{n}$$

- **Normalized K**
- **Kmax + Kresidual** Sum of K_{max} and $K_{residual}$
- **Kresidual** $K_{res} = K_{\max} \cdot \frac{d\delta_{res}}{d\delta_{\max}}$
- **Displacement at Zero Load** Used for K residual calculation

6.2.3 DISPLAY

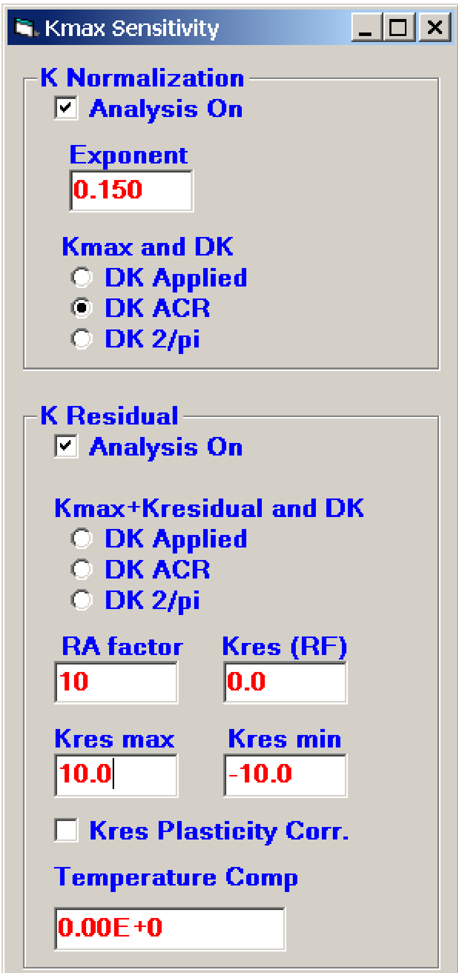
6.2.3.1 da/dN - dK



The crack growth rate data are displayed on log-log scales with the crack growth rate (da/dN) in engineering units per cycle as a function of the cyclic stress intensity. With all check boxes enabled, ΔK, K_{max}, K_{norm}, ΔK_{op}, ΔK_{ACR} and $\Delta K_{2/\pi}$ are displayed.

6.2.4 ANALYSIS UTILITIES

6.2.4.3 Kmax Sensitivity



This utility allows entering parameters associated with $K_{normalization}$ and $K_{residual}$.

Knormalization is activated by enabling the check box **Analysis On**. The options allow selecting either $\Delta K_{applied}$ or two estimates of ΔK based on the ACR method or the $2/\pi$ correction to the opening load method in the equation below.

$$K_{norm} = \Delta K^{1-n} \bullet K_{max}{}^{n}$$

- **Exponent:** The value of n in the above equation. This is referred to the K_{max} sensitivity exponent. Typical values range for 0.1 to 0.25.

K Residual is activated by enabling the check box **Analysis On**. This allows computing a $K_{residual}$. If desired the K normalization can include $K_{residual}$ as follows:

$$K_{norm} = \Delta K^{1-n} \bullet (K_{\max} + K_{residual})^{n}$$

As before, ΔK can be either $\Delta K_{applied}$ or two estimates of ΔK based on the ACR method or the $2/\pi$ correction to the opening load method.

- **RA Factor:** A rolling average (**RA**) factor for the K residual calculation has been added. This number can vary from 1 to 11 and is used to designate the number of points used in the rolling average of $K_{residual}$ according to the following equation:

  Number of points in rolling average = (2 • RAfactor) - 1

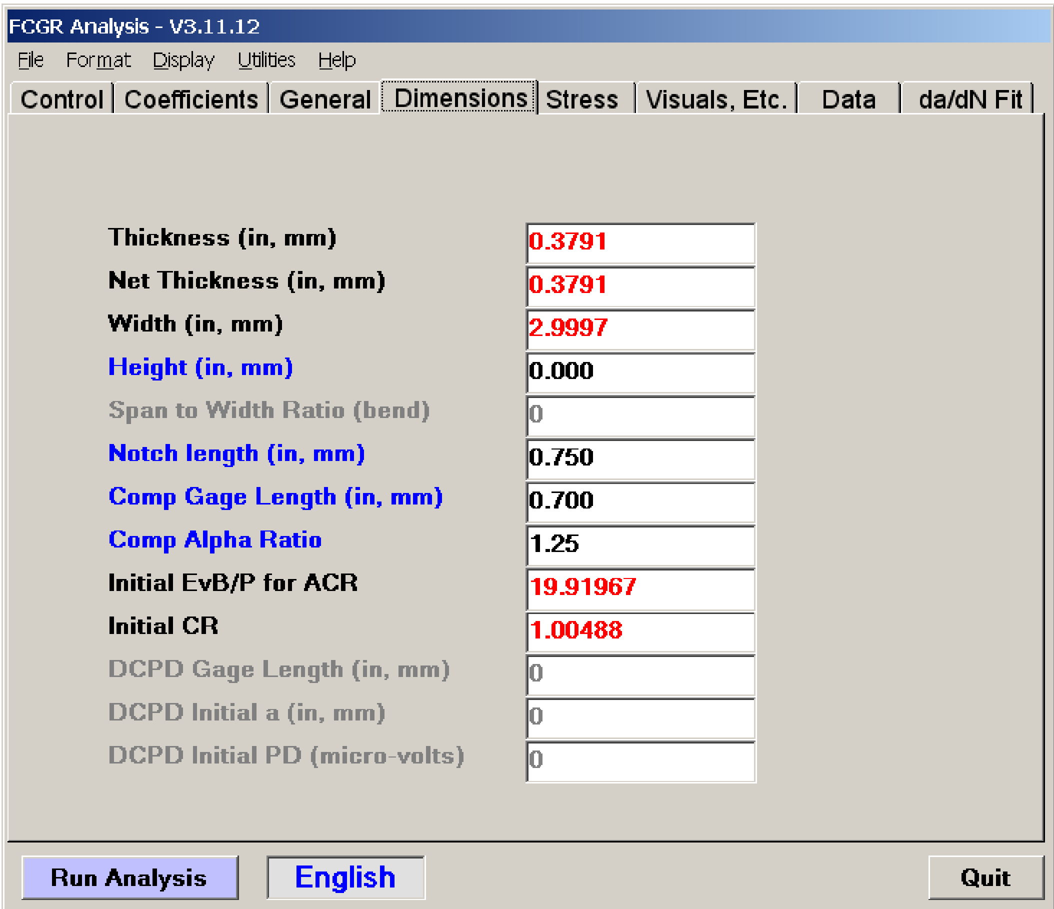
- **Kres (RF):** If an estimate of $K_{residual}$ such as that derived from notch clamping measurements and a restoring force calculation are desired, that calculated value is entered in this text box. Any non-zero value overrides a crack-compliance calculated $K_{residual}$.

- **Kres max and Kres min:** Calculations of $K_{residual}$ are subject to scatter due to noise and unintended or intended shifts in the displacement signal. It is useful to establish upper and lower limits on acceptable values of $K_{residual}$ to filter out unrealistic calculations of $K_{residual}$.

- **Kres Plasticity Corr.:** $K_{residual}$ calculations do not differentiate between displacement shifts from residual stress and crack tip plasticity. This check box enables compensation for crack tip plasticity by subtracting displacement due to plasticity from the overall displacement.

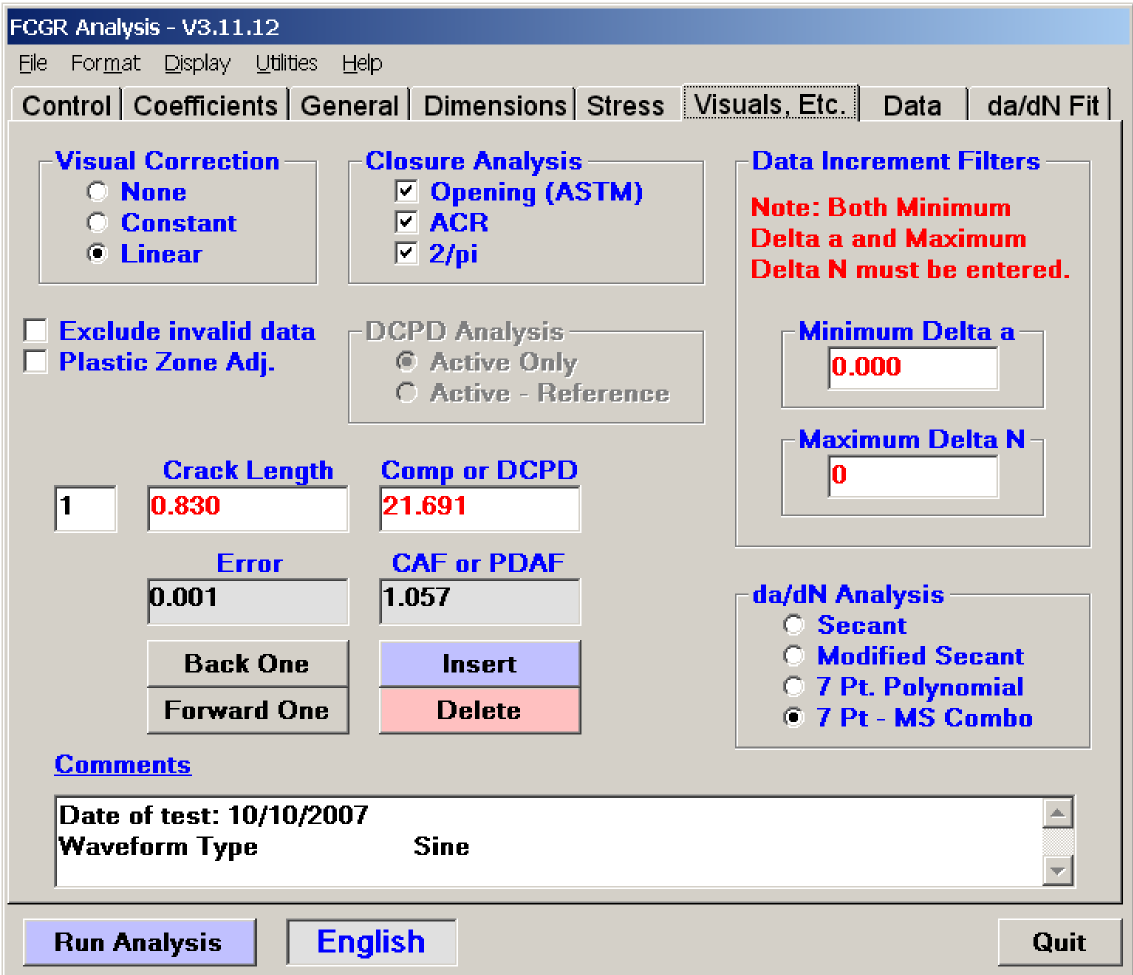
- **Temperature Comp:** If the relationship between temperature and the measured shift in displacement at zero load is known, this parameter is used to make that correction in the $K_{residual}$ calculation. The value is entered in units of length per unit of temperature. Using this compensation requires that during testing, temperature was monitored on analog input channel 11 using the **Channel Scan** feature under **Display**, and that the **Save Channel Scan in Analysis File** check box was enabled in the **Options** menu.

6.5 Main Menu: Dimensions Tab



The initial **EvB/P for ACR** and **Initial CR** affect the ACR closure analysis and should have been determined prior to initiation of a crack during precracking.

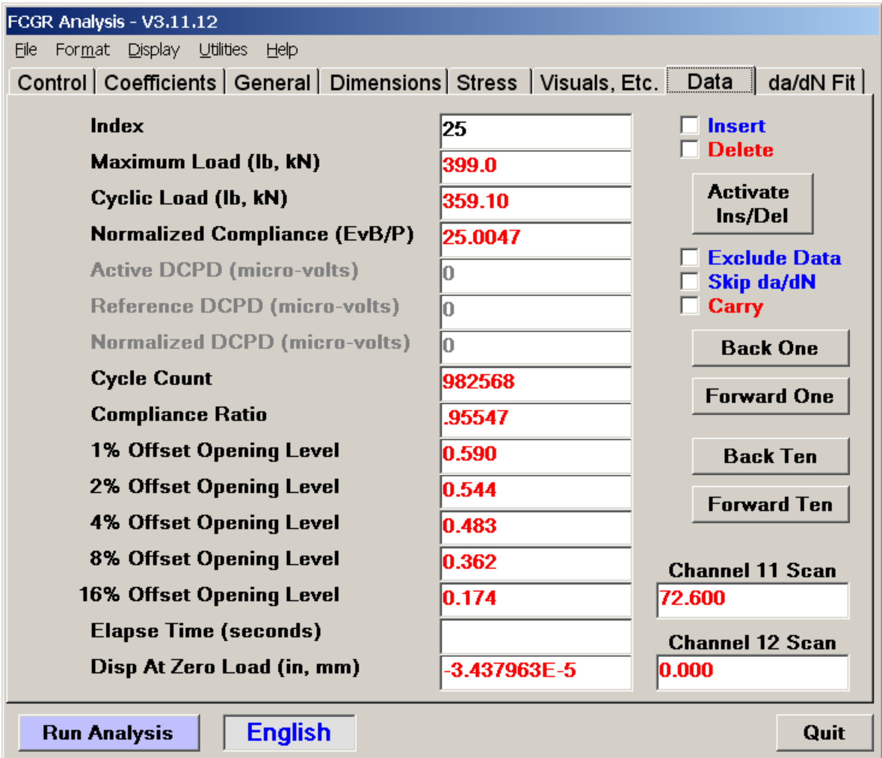
6.8 Main Menu: Visual, Etc. Tab



Closure Analysis is activated by enabling the check box for three closure method as summarized below.

- **Opening (ASTM)** Enable estimation of ΔK effective using the ASTM 2% opening load method.
- **ACR** Enable estimation of ΔK effective using the ACR method.
- **2/pi** Enable estimation of ΔK effective using 2/π correction to the opening load.

6.9 Main Menu: Data Tab



Data fields related to crack closure and K residual are summarized below.

- **Compliance Ratio:** Compliance ratio

- **1% Offset Opening Level:** Ratio of opening load to maximum load based on 1% compliance offset

- **2% Offset Opening Level:** Ratio of opening load to maximum load based on 2% compliance offset

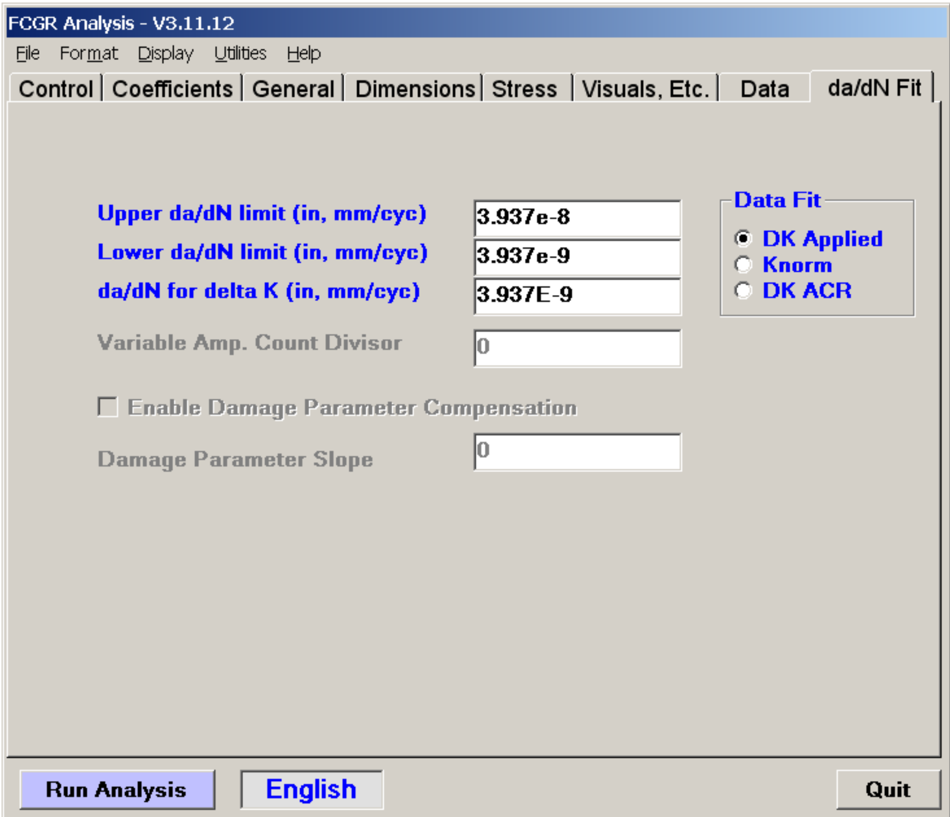
- **4% Offset Opening Level:** Ratio of opening load to maximum load based on 4% compliance offset

- **8% Offset Opening Level:** Ratio of opening load to maximum load based on 8% compliance offset

- **16% Offset Opening Level:** Ratio of opening load to maximum load based on 16% compliance offset

- **Displacement at Zero Load:** Calculated displacement at zero load used for crack-compliance method of determining $K_{residual}$.

6.10 Main Menu: da/dN Fit Tab



Data Fit The da/dN vs. ΔK data can be fit in terms of $\Delta K_{applied}$, ΔK_{ACR}, or K_{norm}.

7.0 Background on ACR, $K_{residual}$, K_{max} Sensitivity

7.1 THE FUNDAMENTALS OF ACR METHOD AND THE MASTER CURVE CONCEPT

7.2 THE FUNDAMENTALS OF CRACK COMPLIANCE METHOD FOR DETERMINING $K_{RESIDUAL}$

7.3 THE FUNDAMENTALS OF CONSTANT K_{MAX} TEST FOR GENERATING THE MASTER CURVE

7.4 ASTM DRAFT STANDARD FOR ACR WITH REFERENCES

7.1 THE FUNDAMENTALS OF ACR METHOD AND THE MASTER CURVE CONCEPT

The Fundamentals of the ACR Method and the Master Curve Concept

By:
Keith Donald
Fracture Technology Associates

Acknowledgements

Mark James, Gary Bray, Bob Bucci
Alcoa Technical Center

Ed Phillips
NASA-Langley Research Center

Paul Paris
Washington Unviersity

Diana Lados
Worcester Polytechnic Institute

Introduction

- The adjusted compliance ratio (ACR) is an experimental method of determining a reduction in ΔK due to crack closure and is designated ΔK_{ACR}. It is particularly useful for remote closure associated with long crack samples such as the C(T).

- ACR is one example of a partial closure model that assumes crack-tip strain below the opening load, even at P_{min}

- It is derived from the compliance ratio (CR) concept that uses near crack-tip strain measurements to estimate ΔK_{eff}.

- ACR allows remote displacement or strain measurements to be used for estimating ΔK_{ACR}.

Significant Events

- 1968 Crack closure discovered (Elber).
- 1985 Offset method of measuring crack closure introduced (FTA).
- 1990 Evidence of cyclic crack tip strain below the opening load. Crack tip strain measurements validate Compliance Ratio concept (FTA).
- 1995 E647 Annex added for opening load measurement.
- 1996 Adjusted Compliance Ratio concept introduced enabling Compliance Ratio concept to be used with remote measurement (FTA).
- 1997 Second ASTM RR opening data re-analyzed using ACR method.
- 1997 ACR combined with K_{max} sensitivity concept for life prediction methodology using "Master Curve" (FTA).
- 1998 $2/\pi$ partial closure model introduced (Paris) .
- 2005 Real-time "Crack-compliance" method of $K_{residual}$ introduced (FTA).
- 2009 E647 draft annex of ACR method, ACR Workshop

Compliance Ratio

Compliance Ratio (CR) requires near crack-tip strain measurements to estimate ΔK_{eff}.

Basic Assumptions:

1 An elastic analysis is assumed.

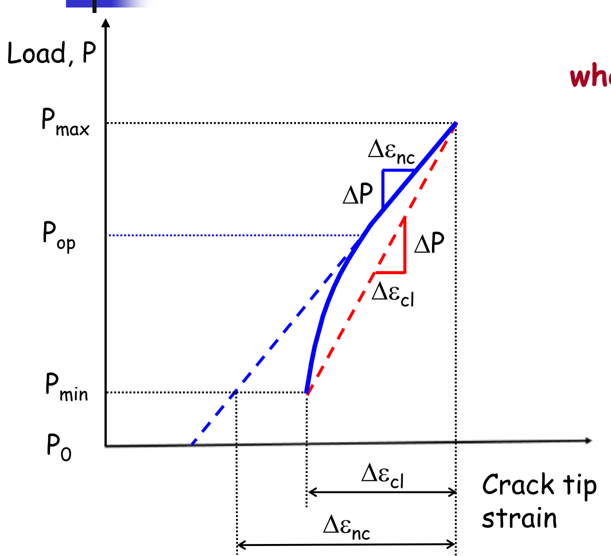
2 Strain gage must be large relative to the size of the crack tip plastic zone (plane strain).

3 Strain gage must be small relative to sample size and crack size.

4 Strain gage must be nearer the crack tip than the bulk of the crack closure shielding mechanism.

This is difficult to achieve: The compliance ratio is extremely sensitive to the measurement location.

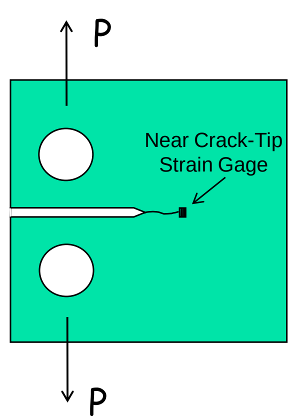
Compliance Ratio



$$\Delta K_{CR} = CR \cdot \Delta K_{app}$$

where

$$CR = \frac{\Delta\varepsilon_{cl}}{\Delta\varepsilon_{nc}}$$



Adjusted Compliance Ratio

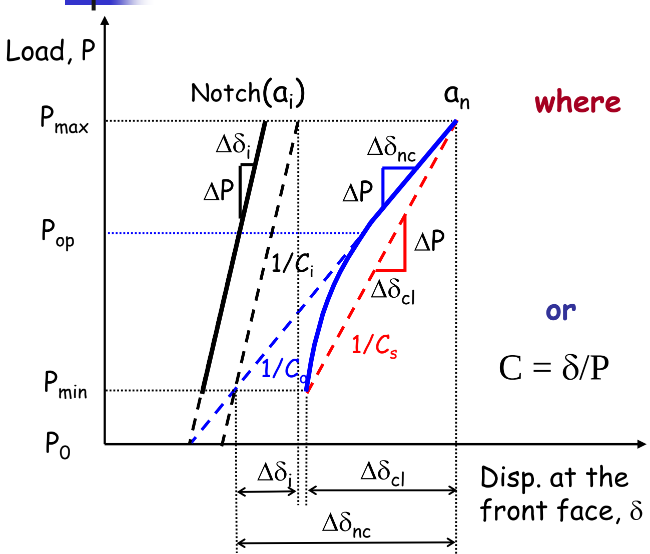
By subtracting the compliance prior to initiation of a crack, ACR allows remote displacement or strain measurements to be used for determining ΔK_{ACR}.

Basic Assumptions:

1 An elastic analysis is assumed.
2 Remote locations include crack mouth opening displacement and back-face strain gages.
3 The remote location must be sufficiently removed from the crack so that the bulk closure mechanism is characterized.
4 Local locations such as strain gages in or near the path of the crack may not be reliable since even the sign of the compliance could change as the crack advances (compact tension sample).

ACR is easy to implement using remote measurements and appears to be insensitive to the measurement location.

Adjusted Compliance Ratio (ACR) (Method 1)



$$\Delta K_{ACR} = ACR \cdot \Delta K_{app}$$

where

$$ACR = \frac{\Delta\delta_{cl} - \Delta\delta_i}{\Delta\delta_{nc} - \Delta\delta_i}$$

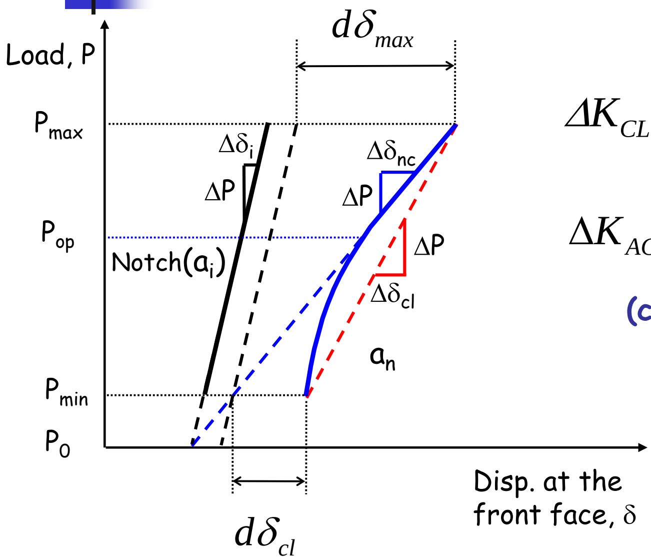
(constant load only)

or

$$C = \delta/P \qquad ACR = \frac{C_s - C_i}{C_o - C_i}$$

(suitable for K-control)

Adjusted Compliance Ratio (ACR) (Method 2)



$$\Delta K_{CL} = \Delta K_{APP} \cdot \frac{d\delta_{cl}}{d\delta_{max}}$$

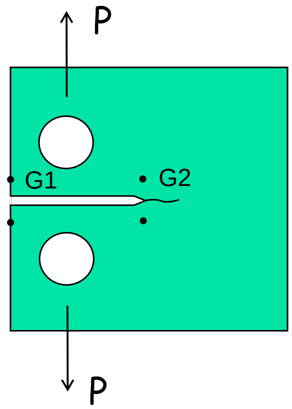
$$\Delta K_{ACR} = \Delta K_{APP} - \Delta K_{CL}$$

(constant load only)

Useful Characteristics of the ACR Method

- Different <u>remote</u> measurement locations give the same value of ACR.
- ACR is easily implemented since it uses the same load-displacement data as the opening load concept.
- The ACR method is most suitable for removing the effects of remote closure. Ideal for load-shedding decreasing-K and long crack to <u>physically</u> small crack correlation.
- ACR combined with K_{max} sensitivity offers a novel approach to material characterization by utilizing a “Master Curve”.

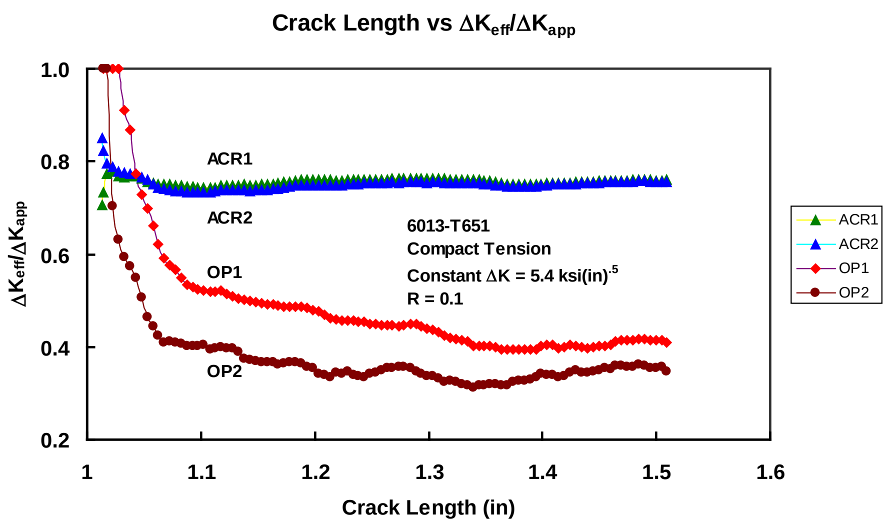
The ACR value is independent of the remote measurement location



Two measurement locations, G1 and G2, have very difference compliances, compliance ratios, and ASTM opening loads.

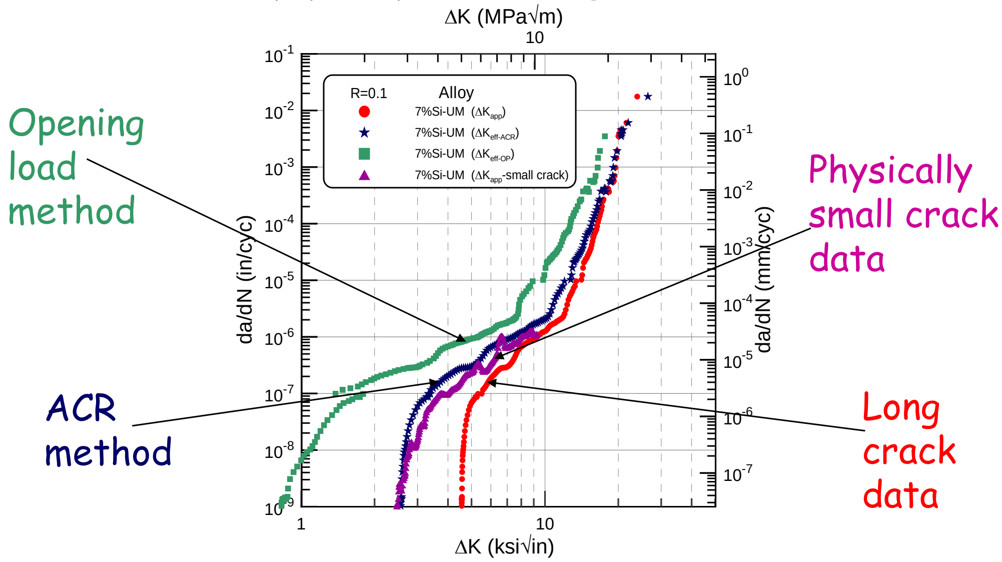
The ACR for these two locations is the same.

Same ACR for G1 and G2 Locations



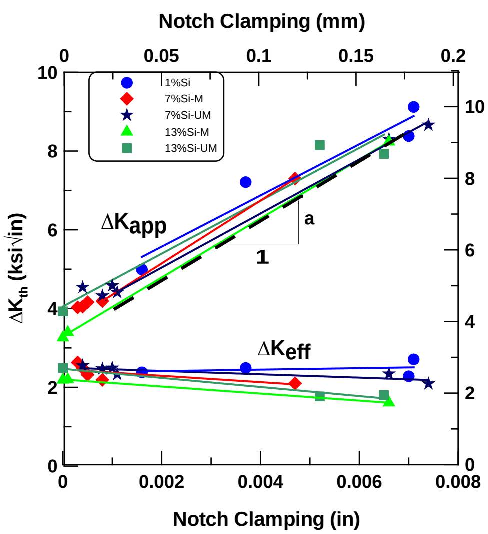
ACR compensates for physically small crack behavior

7%Si … Long crack before and after closure correction vs. physically small crack growth data …



ACR Corrects for Compressive Residual Stress

Restoring force model for clamping effect.



Diana A. Lados

"Fatigue Crack Growth Mechanisms in Al-Si-Mg Alloys"

Ph.D. Dissertation – Chapter 3

Worcester Polytechnic Institute

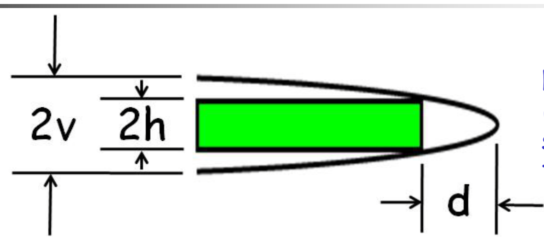
January 2004

Limitations of the ACR Method

ACR is least effective under scenarios where events local to the crack tip drive dominant shielding.
For example:

- Region II increasing K whereby closure maybe be dominated by crack tip plasticity.
- Any other scenario whereby the shielding mechanism is predominately local to the crack tip.

The 2/π Partial Closure Model (Paris)



Note: Analysis is independent of the size of the gap at the crack tip.

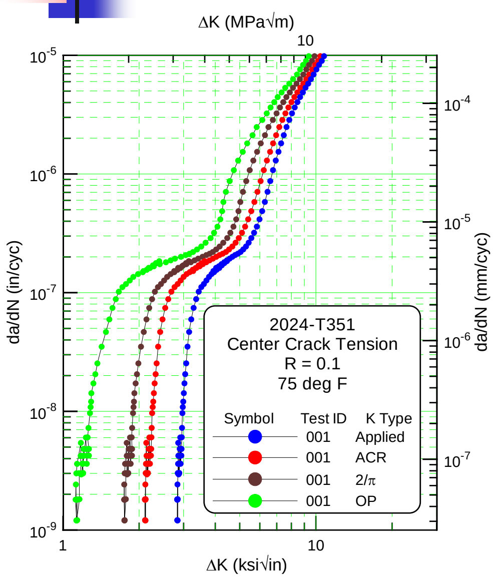
$$K = \frac{E \cdot v}{2}\sqrt{\frac{\pi}{2d}}$$ (remote stress)

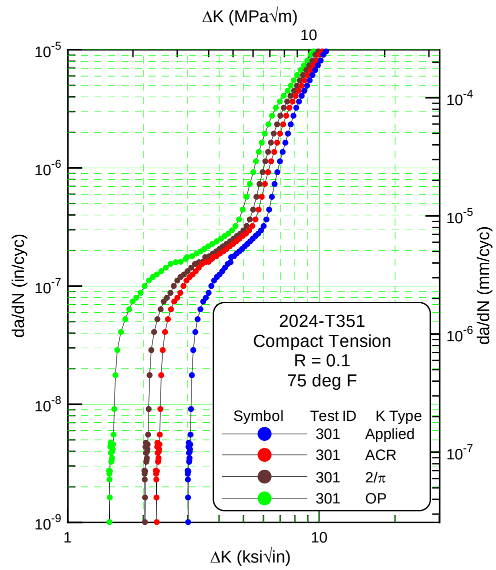
$$K_{wedge} = \frac{E \cdot h}{\sqrt{2\pi d}}$$ (no remote stress, K due to wedge)

@ h=v $$\frac{K_{wedge}}{K} = \frac{2}{\pi}$$

$\therefore K_{op} \bullet (1 - 2/\pi)$ is added to ΔK_{op} for estimation of ΔK_{eff}

Closure Model Comparisons: ΔK_{app}, ΔK_{ACR}, $\Delta K_{2/\pi}$, ΔK_{op}





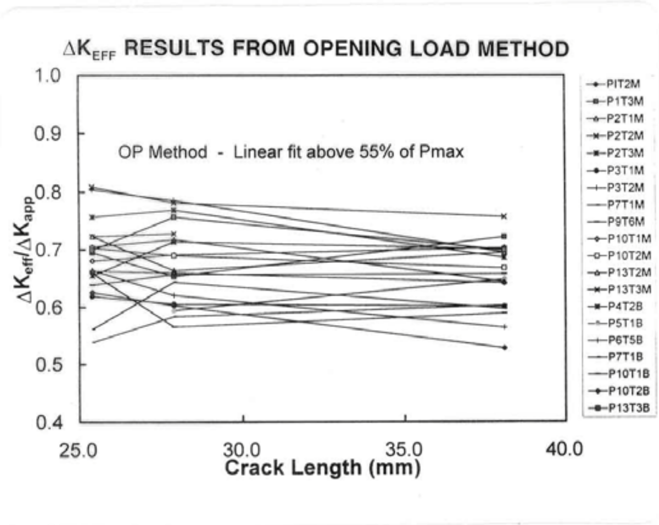
Useful Applications

1 Second ASTM RR opening data were re-analyzed using ACR method. ACR method links variation in growth rates to ΔK_{ACR} whereas the ASTM opening load method does not correlate using ΔK_{eff}.

2 K_{max} sensitivity concept combined with ACR suggests that stress ratio effect is not just related to closure but is also a function of K_{max}.

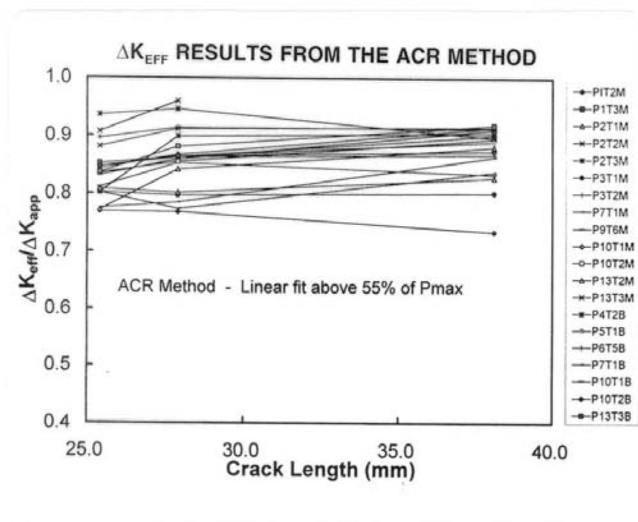
3 Crack size effects were correlated using ACR on 2024-T351 from the ASTM Round Robin Program

Example 1:
OP Analysis of ASTM RR Data



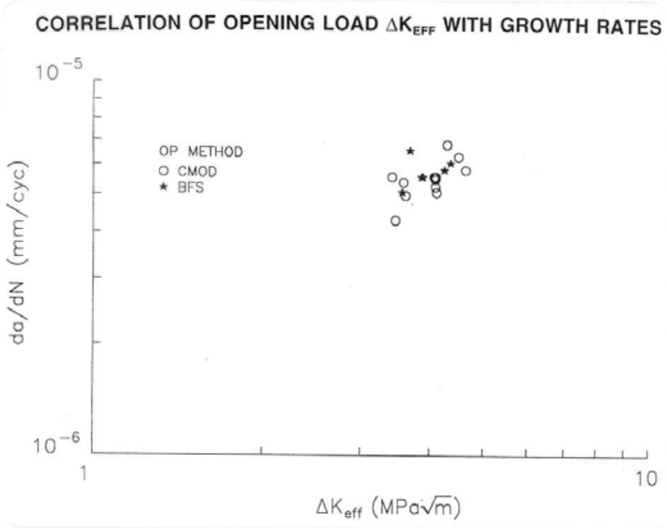
Large variation in estimation of ΔK_{eff} using ASTM opening load method.

Example 1:
ACR Analysis of ASTM RR Data



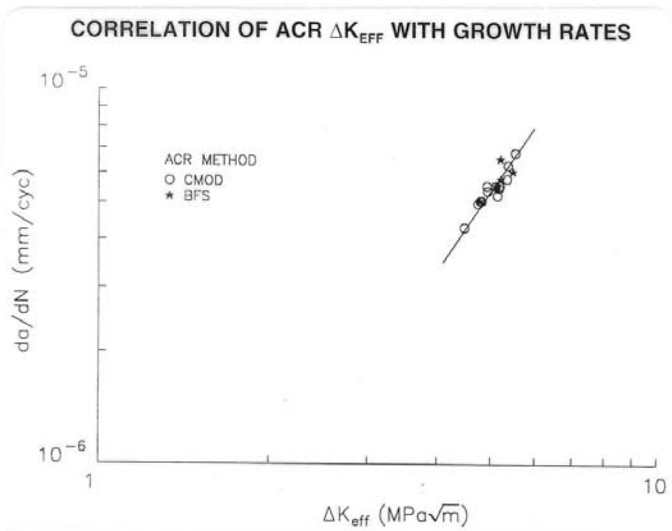
Large variation in estimation of ΔK_{eff} using ACR method.

Example 1:
OP Analysis of ASTM RR Data



Minimal correlation of crack growth rates with ΔK_{eff} using opening load method.

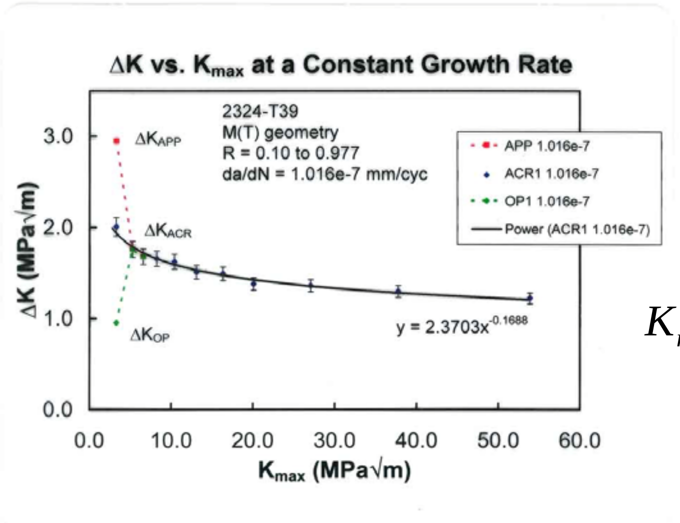
Example 1:
ACR Analysis of ASTM RR Data



Strong correlation of crack growth rates with ΔK_{ACR}.

Crack mouth opening displacement (o) and back face strain gages (★) demonstrate remote measurement location independence.

Example 2: K_{max} Sensitivity Concept



ACR method gives best correlation with high stress ratio (constant K_{max}) data when K_{max} sensitivity is accounted for.

$$K_{norm} = \Delta K^{1-n} \bullet K_{max}{}^{n}$$

n = 0.144

Example 2: "Master Curve" Approach

Small crack:

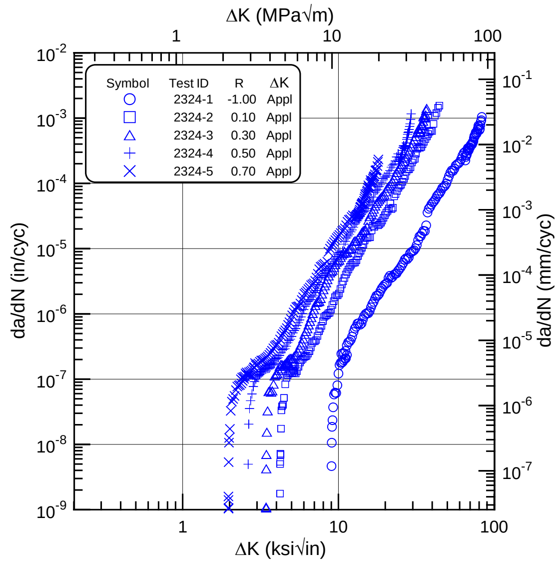
$$K_{norm} = \Delta K^{1-n} \bullet K_{max}{}^{n}$$

Long crack:

$$K_{norm} = \Delta K_{ACR}{}^{1-n} \bullet K_{max}{}^{n}$$

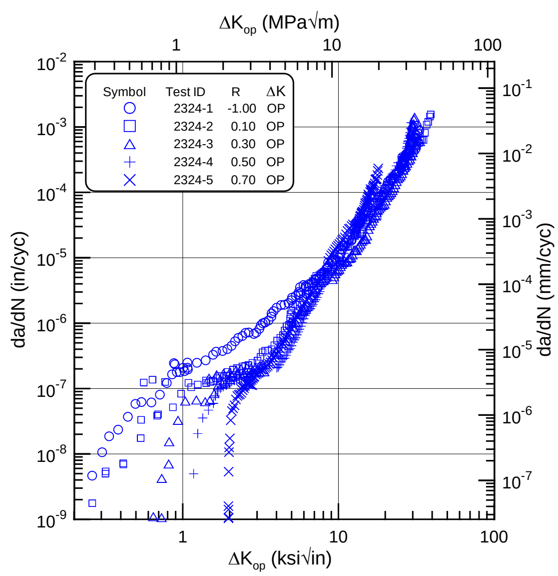
Example 2: $\Delta K_{applied}$

Fatigue Crack Growth Rate vs. Stress Intensity

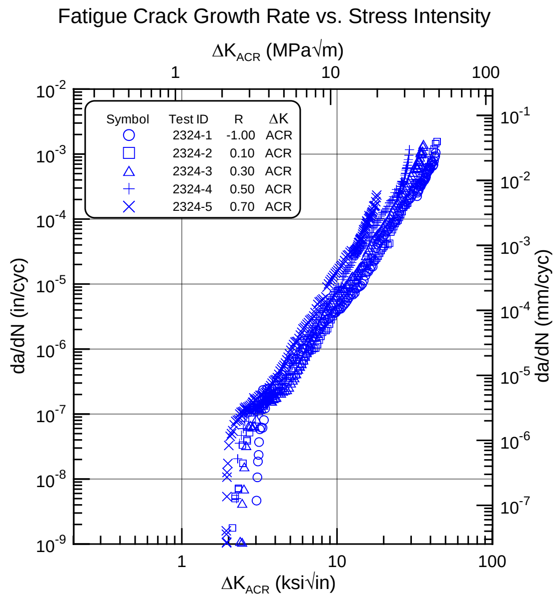


Example 2: ΔK_{op}

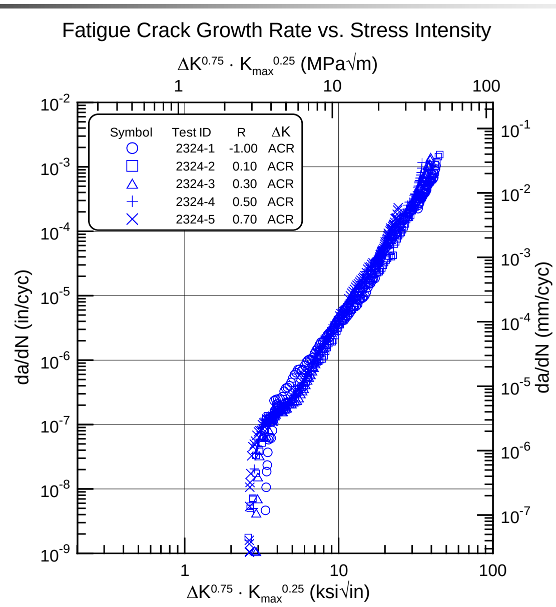
Fatigue Crack Growth Rate vs. Stress Intensity



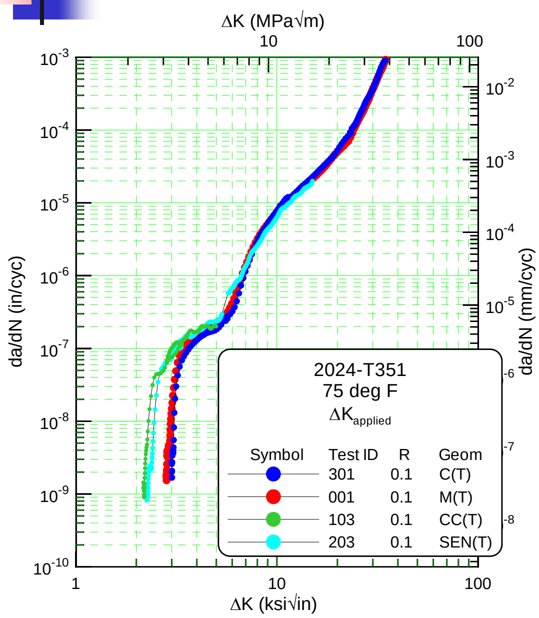
Example 2: ΔK_{ACR}



Example 2: K_{norm} ("Master Curve")



Example 3:
“Low” stress ratio FCGR data

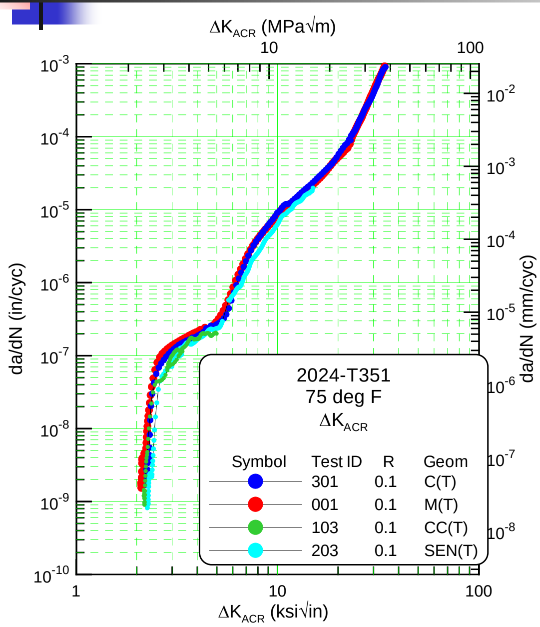


R = 0.1

“Long” crack samples give higher threshold than “physically small/short” crack samples.

This is most likely the result of “remote” closure associated with the “long” crack samples.

Example 3:
“Long” crack data corrected using ACR



R = 0.1

ACR method captures physically small crack behavior by compensating for remote closure.

Summary and Conclusions

- ACR provides additional information about the crack closure process that cannot be obtained from opening load alone.
- ACR is easily implemented since it uses the same load-displacement data as the opening load concept.
- ACR combined with K_{max} sensitivity offers a novel approach to material characterization by utilizing a "Master Curve".

7.2 THE FUNDAMENTALS OF CRACK COMPLIANCE METHOD FOR DETERMINING $K_{RESIDUAL}$

The Fundamentals of the Crack-Compliance Method for Determining $K_{residual}$

By:
Keith Donald
Fracture Technology Associates

Acknowledgements

Mark James, Bob Bucci, Bob Shultz, Rich Brazill
Alcoa Technical Center

Dale Ball, Young Kwon
Lockheed Martin

Trung Nguyen
NAVAIR

Stephen Smith, John Newman
NASA-Langley Research Center

Diana Lados
Worcester Polytechnic Institute

Introduction

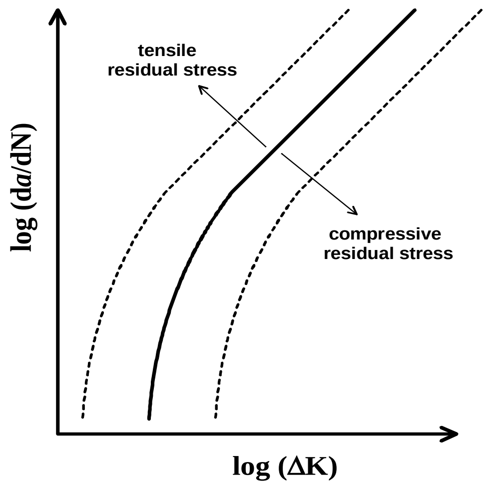
- Variability in fatigue crack growth rates (FCGR) has often been attributed to material variability, test variability, sample geometry, crack size and/or load history effects. However, global residual stress may be a key source of variability.
- Methods to compensate for the effect of residual stress are necessary to obtain an "intrinsic" material fatigue crack growth rate curve.
- The Crack Compliance method offers the ability to determine $K_{residual}$ by measuring the change in displacement at zero load during crack growth rate experiments.
- The practical application of the methodology requires precise signal stability and linearity -- far beyond that necessary for standard fatigue crack growth rate experiments.

Benefits

- Reducing sources of variability in life prediction methodology may reduce excess weight penalties.
- The Crack Compliance technique provides an experimental method for evaluating beneficial applications of residual stress.

  For example: Altering the global residual stress distribution such that fastener holes are located in a compressive residual stress field.

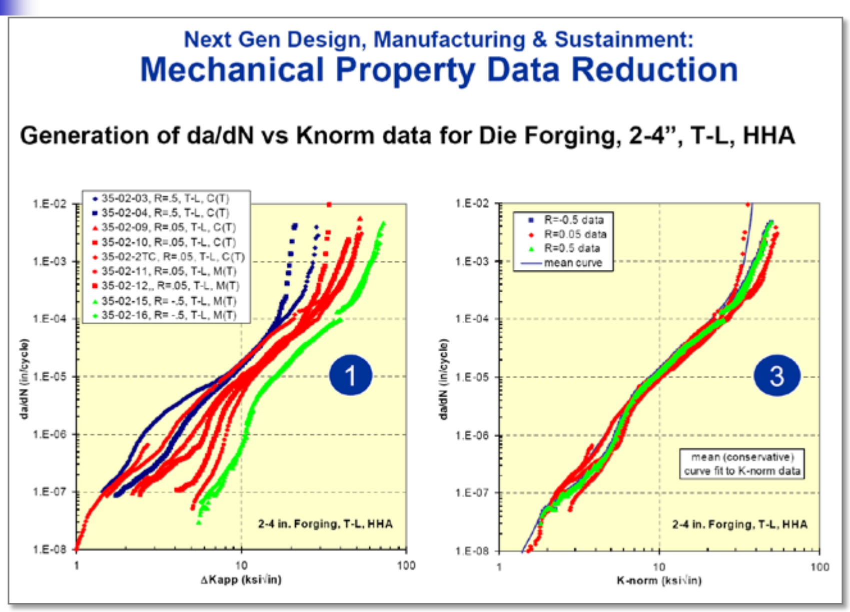
Effect of Residual Stress on Fatigue Crack Growth Rates



Tensile residual stresses gives faster rates. Compressive residual stresses give slower rates.

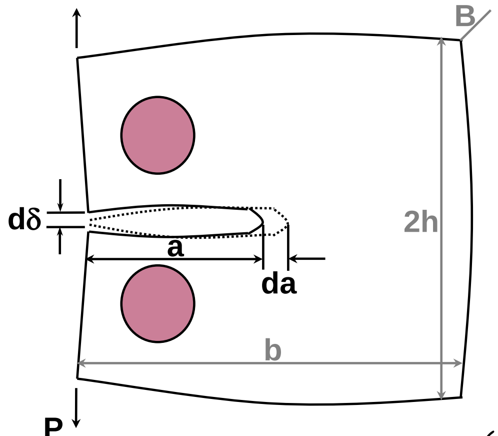
Edge crack and center crack samples often show opposite effects.

da/dN Data with Substantial Residual Stress Correlates using ACR and $K_{residual}$



Ref: Ball, et. al., ASIP 2006

$K_{residual}$ Determination (Cut-Compliance Method)



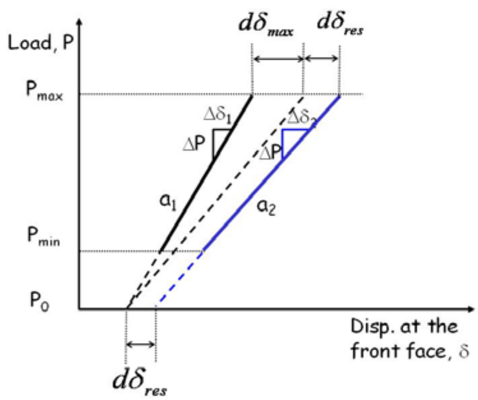
$$K_{res} = \frac{E}{Z(a)} \cdot \frac{d\delta}{da}$$

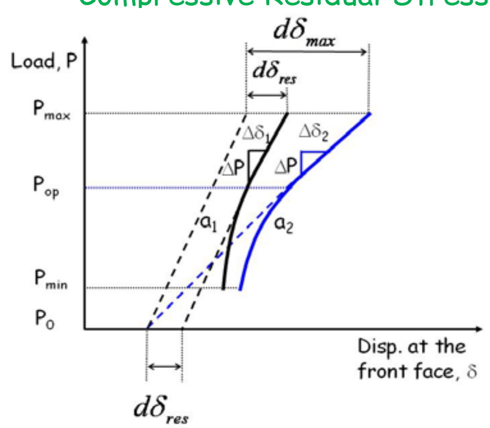
$$Z(a) = \text{influence function} = \frac{2KB}{P}$$

$$Z(a) = \frac{4 \cdot (2b + a) \cdot F_2\left(a/b, h/b \right)}{(b-a)^{3/2}}$$

(for disp. measurements at the front-face)

$K_{residual}$ Determination (Crack-Compliance Method)





$$K_{res} = K_{\max} \cdot \frac{d\delta_{res}}{d\delta_{\max}}$$

The critical measurement is $d\delta_{res}$ (displacement at zero load). This simple formula for $K_{residual}$ applies to any test coupon geometry.

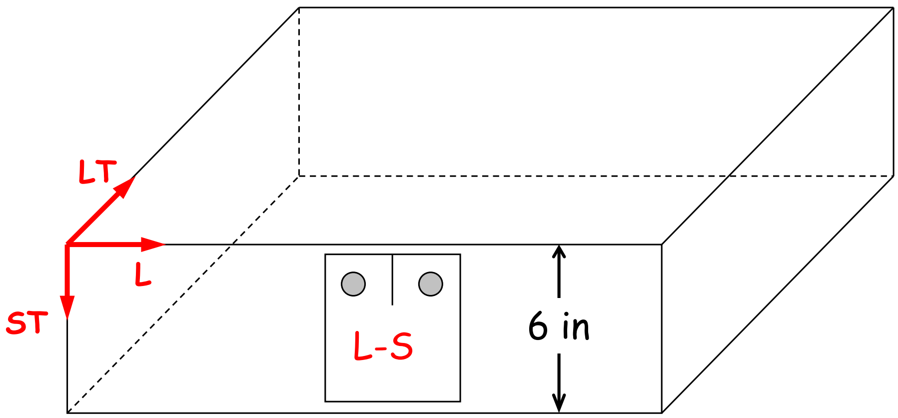
Note: Elastic analysis assumed. Crack tip plasticity must be small or properly compensation for.

Crack-Compliance Verification

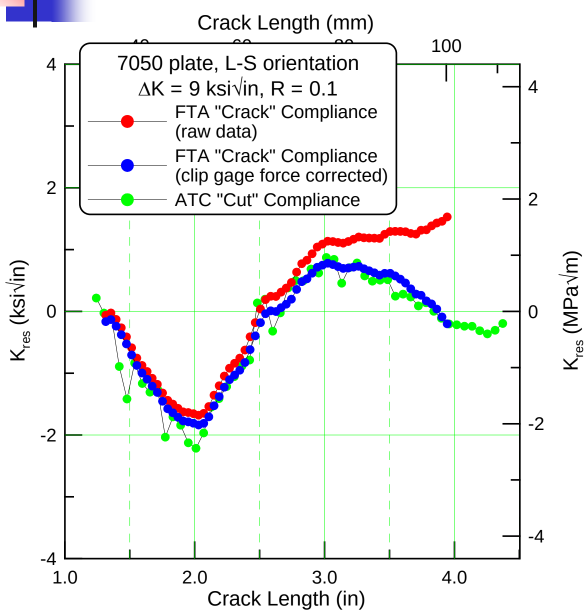
- Material 7050 plate (6 in. thick)
- Sample Type C(T) (W = 4.5 in, B = 0.20 in, L-S orientation)
- Environment Lab Air (75°F, RH = 40%)
- Test Conditions 10 Hz, $Kmax_c$ = 10.0 ksi√in, R = 0.1

Test Specimen Extraction

Specimen orientation selected to maximize residual stress effect

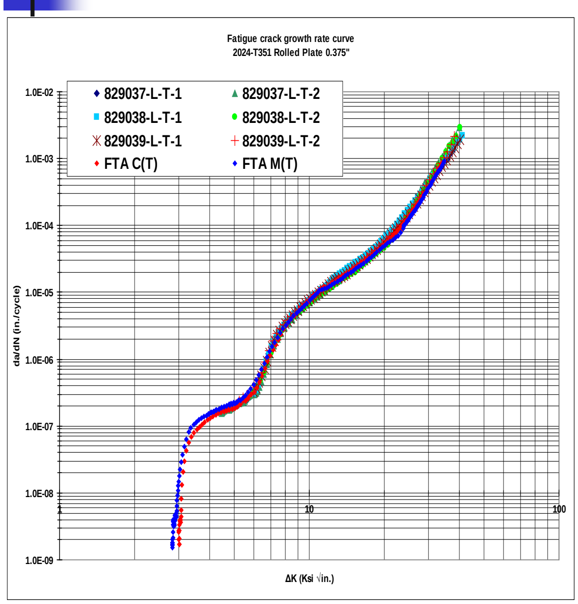


Comparing Crack-Compliance with Cut-Compliance



"Crack" compliance technique requires greater linearity and stability than necessary for standard crack growth rate and crack closure measurement.

Example 1: Variability in 2024-T351 FCGR Data

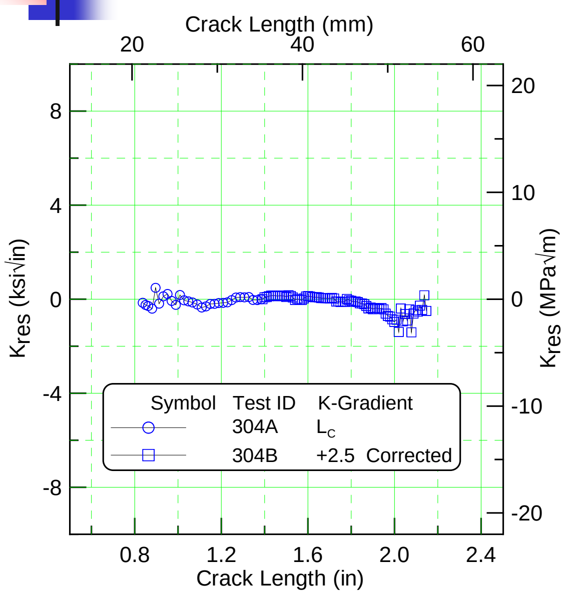


Four M(T) samples and four C(T) samples

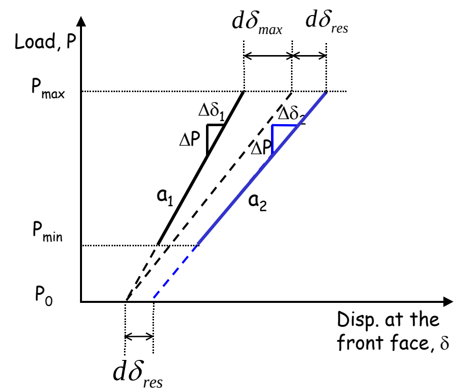
R = 0.1

Two samples from this investigation are in good agreement with six Alcoa samples from RR data base.

Example 1:
No evidence of residual stress



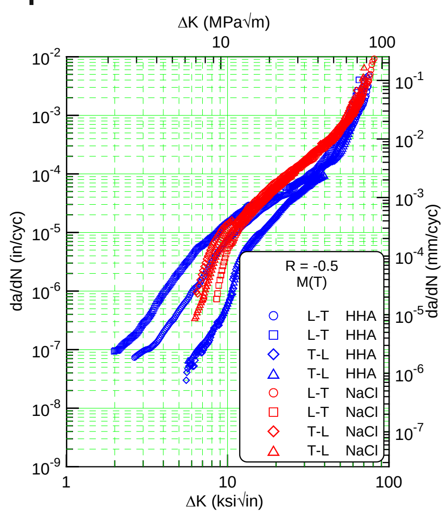
$$K_{res} = K_{max} \cdot \frac{d\delta_{res}}{d\delta_{max}}$$



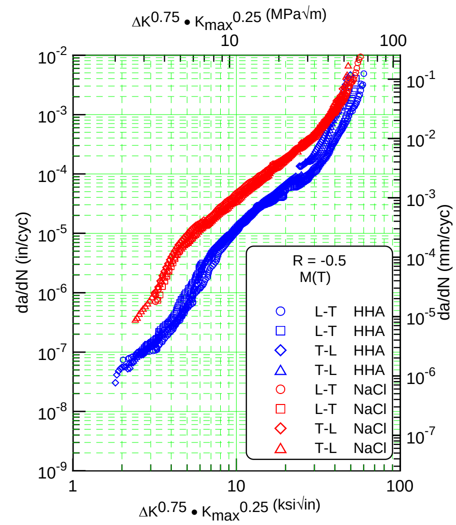
Example 2:
"Master Curve" Approach

$$K_{norm} = \Delta K_{ACR}{}^{1-n} \bullet (K_{\max} + K_{residual})^n$$

Example 2:
HHA vs. 3.5% NaCl



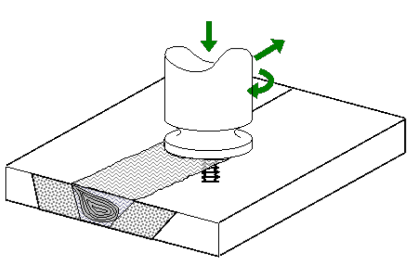
$\Delta K_{applied}$



K_{norm}

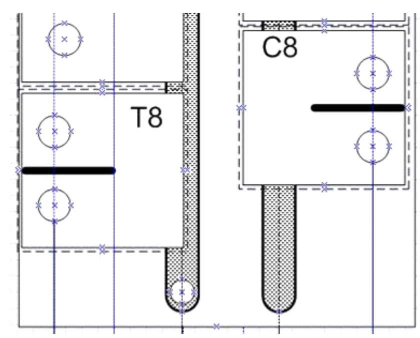
Example 3:
C(T) Friction Stir Weld

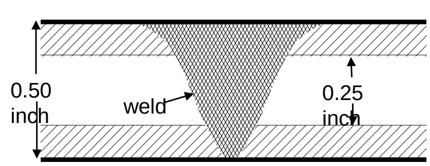
- FSW Material
  - Aluminum alloy 2024-T351 plate
  - Machined down to 1/2 inch thick before friction stir welded
  - Machined 1/8 inch from each side
  - Final thickness = 1/4 inch



FSW Process

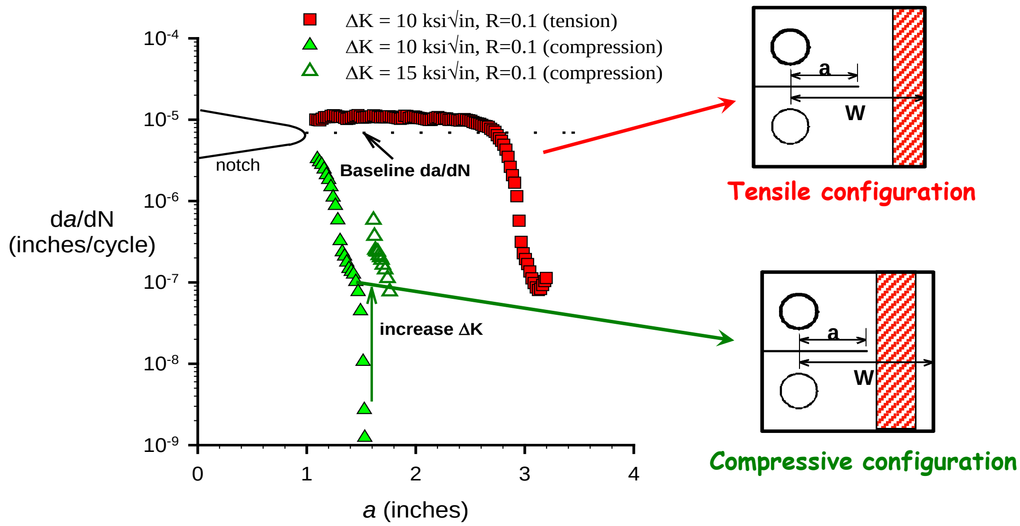
Specimen Configurations



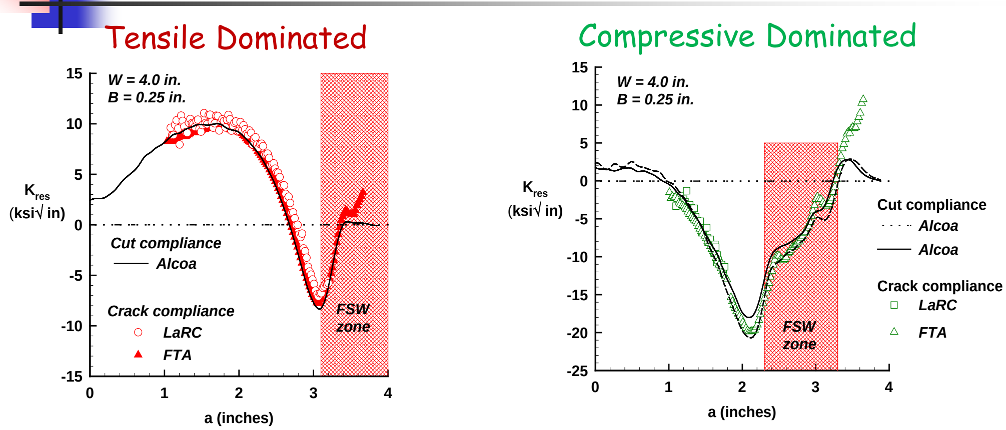


FSW Cross-section

Example 3: Variation in FCGR with Crack Length

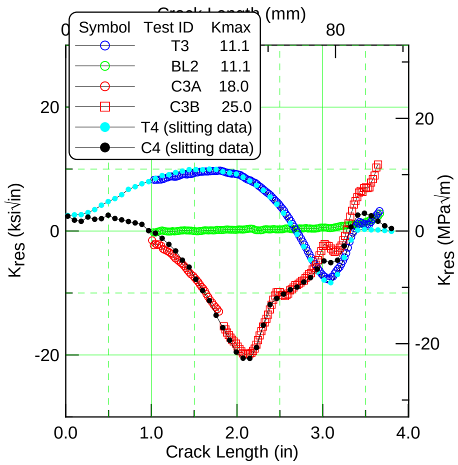


Example 3: $K_{residual}$ Profile

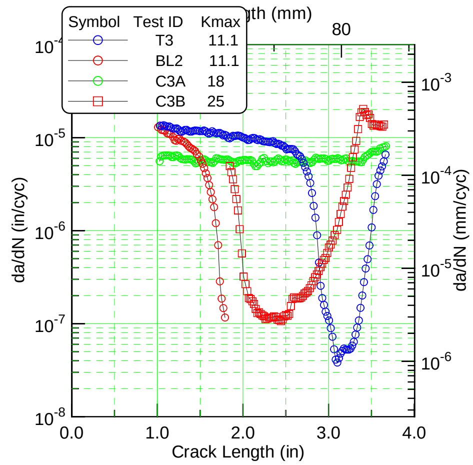


Crack-compliance from two laboratories in good agreement with cut-compliance.

Example 3: K_{res} and da/dN vs. Crack Length



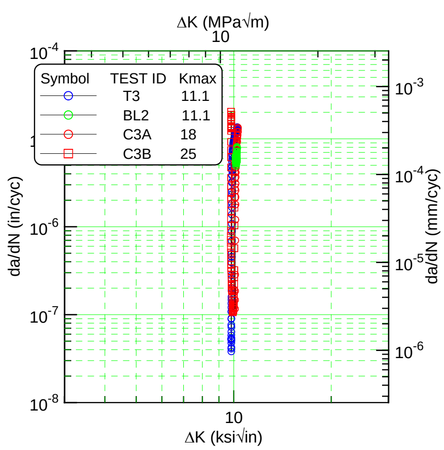
$K_{residual}$



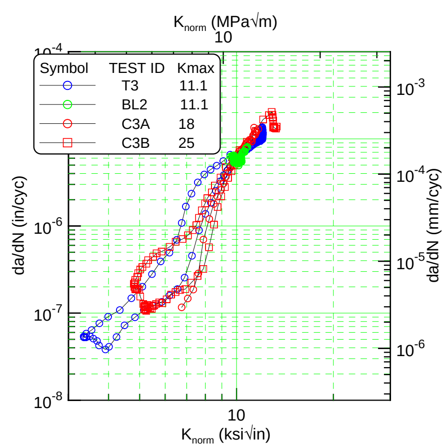
da/dN

Example 3: da/dN vs. ΔK and K_{norm}

$$K_{norm} = \Delta K_{ACR}^{\;1-n} \bullet (K_{\max} + K_{residual})^{n}$$



$\Delta K_{applied}$



K_{norm}

M(T) Sample Considerations

- Robustness of technique is confirmed for C(T) geometry.
- M(T) samples have about 1/5 as much displacement as similar sized C(T) samples for the same stress intensity.
- For crack length, crack growth rates, and crack closure determination, only the slope of the load-displacement curve is necessary.
- For $K_{residual}$ determination, the stability of the displacement at zero load is critical.

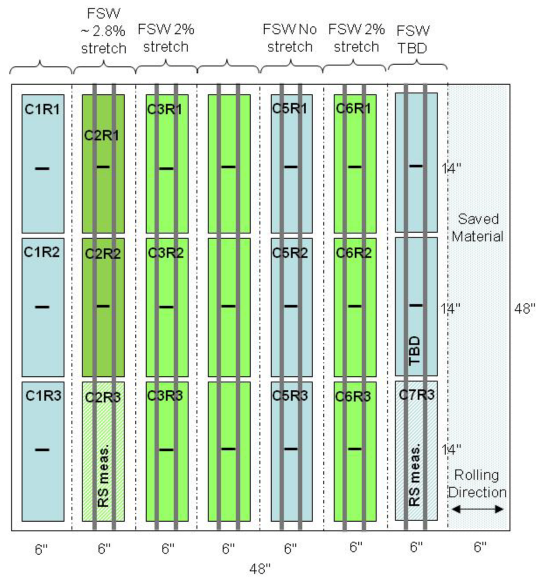
Photograph of M(T) Set-up with Isolation Chamber

Note dual clip gages and thermocouple placed inside chamber near clip gage.

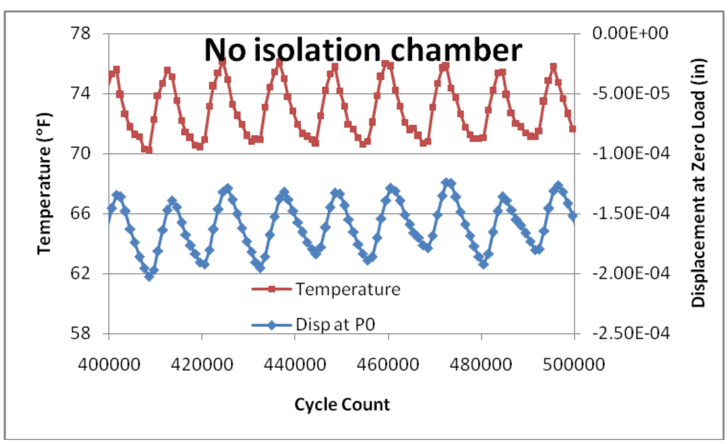
Two clip gages are necessary to increase sensitivity and cancel bending effects.

Overview - Material/Process Conditions & Layout

- As received Material:
  - 2024-T351 Plate
  - 48" x 48" x 0.5"
- Material conditions to be tested
  - Base metal
  - w/ RS introduced by FSW
    - Double weld pass
    - No stretch (crack grows in compression RS field)
    - 2% applied stretch (crack grows in tension RS field)
    - Original 4% stretch target resulted in grip failure at ~2.8% stretch
- M(T) specimen
  - 14" long x 4" wide; final machined to 0.25" thk
  - T-L orientation
  - Tensile tests from broken halves



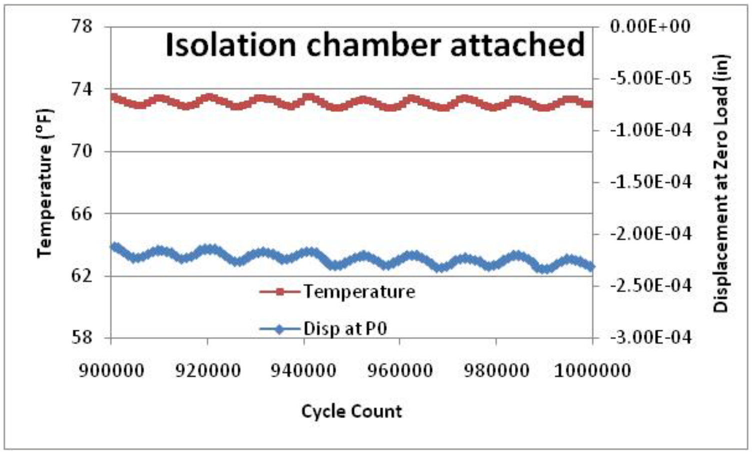
Effect of Temperature on Displacement at Zero Load for M(T)



Without the isolation chamber, a cyclic temperature of ~5 °F is indicated (due to cycling of HVAC unit).

A corresponding change in displacement at zero load is also noted.

Effect of Temperature on Displacement at Zero Load for M(T)

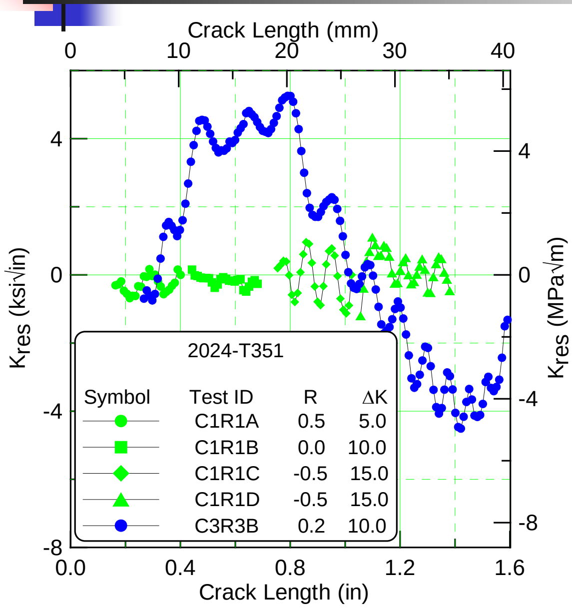


With the isolation chamber, a cyclic temperature of ~1 °F is indicated.

A corresponding change in displacement at zero load is also noted.

Displacement temperature sensitivity is 0.000015 inch/°F.

$K_{residual}$ Profile (Neutral and FSW) without temperature compensation



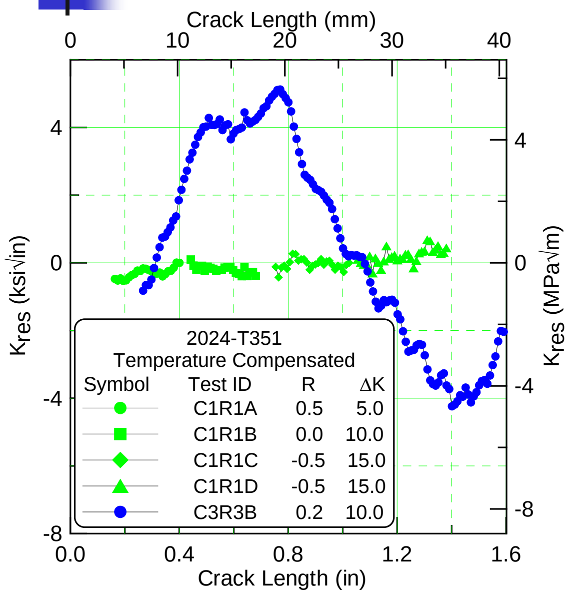
$K_{residual}$ determination without temperature compensation.

Scatter in $K_{residual}$ measurement is significant even though temperature fluctuation is ~ 1 °F or less.

Base material (green symbols)

FSW (blue symbols)

$K_{residual}$ Profile (Neutral and FSW) with temperature compensation

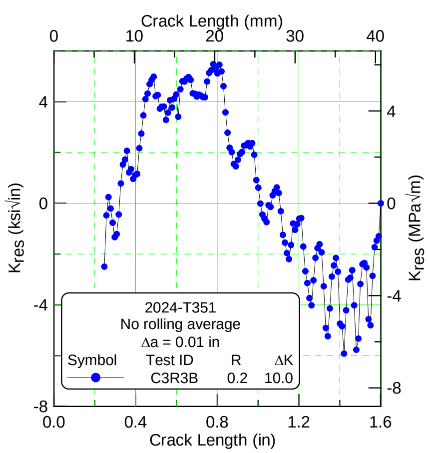


$K_{residual}$ determination with temperature compensation.

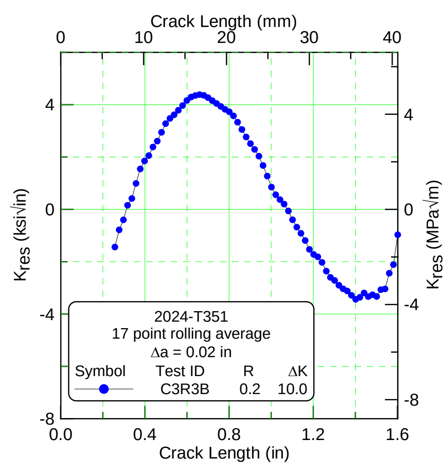
Most of the scatter is removed by accounting for temperature variation.

Impact of using rolling average and change in Δa increment

No rolling average, Δa = 0.01 inch



17 point rolling average, Δa = 0.02 inch



Summary of M(T) Geometry Considerations

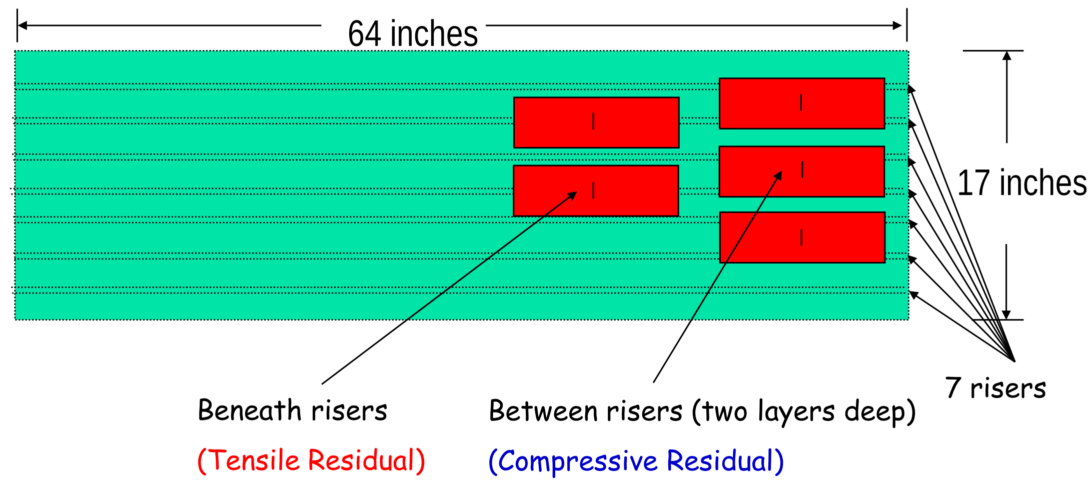
- The determination of $K_{residual}$ for M(T) samples requires greater precision than for C(T) samples, pushing the limits of commercially available displacement transducers.
- Temperature compensation can be used to reduce scatter and variability in the $K_{residual}$ measurements.
- Alternatively, selection of the appropriate Δa increment as well as the appropriate rolling average can be used to reduce scatter in the measurements.

Two Advanced Application Examples

1. FCGR variability in 7075-T6511 extrusion is the result of residual stress. Consistent results are indicated when extrusion location is accounted for. Benefit: Knowledge of residual stress pattern could be used for optimum location of fastener holes.

2. "Designer" material has potential for improved life as demonstrated and accounted for by using Crack-Compliance methodology. Benefit: Optimization of local or global residual stress distribution is easily verified experimentally.

Example 1: 7075-T6511 Sample Extraction



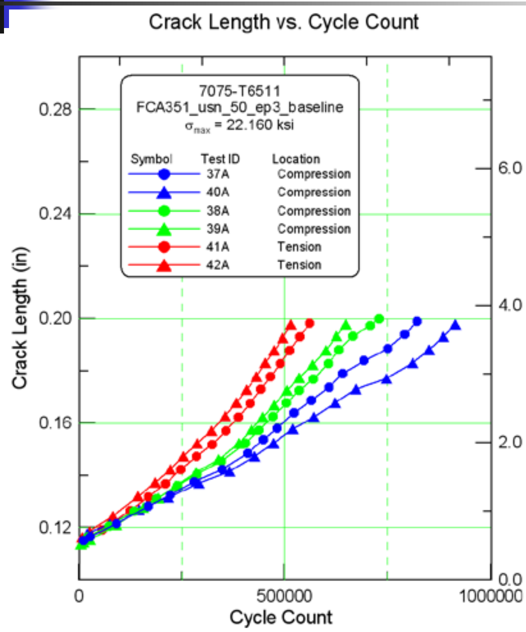
Example 1: Test Plan

- Part A: Spectrum loading out to a = 0.2 inches using common spectrum to show relative crack growth rate variation

- Part B: Constant ΔK beyond a = 0.2 inches to establish steady-state crack growth rate response and capture K residual measurements

- Show correlation between trend in crack growth rate and K residual measurements.

Example 1:
Part A – Spectrum Loading



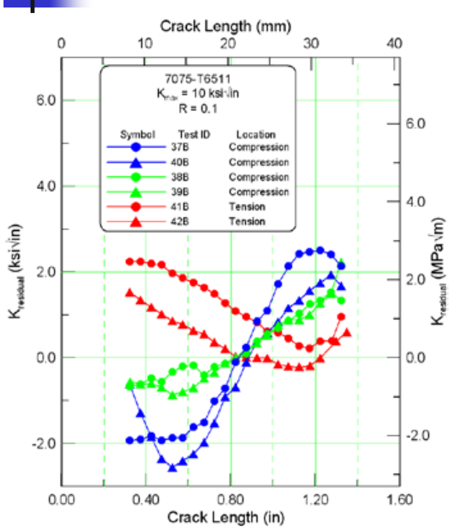
Three categories of behavior:

High compressive residual stress

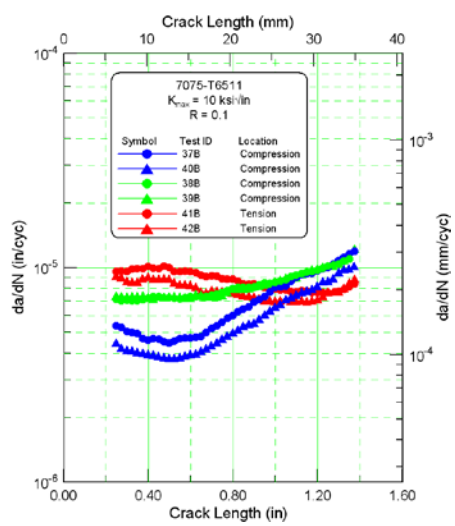
Low compressive residual stress

Tensile residual stress

Example 1:
Part B – Constant ΔK FCGR



$K_{residual}$



da/dN

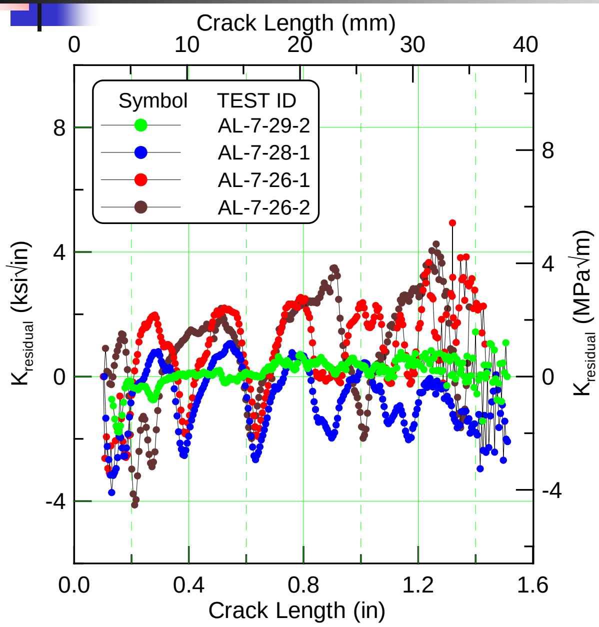
Example 2:
7075-T6 1/8” Thick Plate

Example 2:
Test Plan

Test ID	Dowel force/linear inch	Groove spacing
AL-7-29-2	none	none
AL-7-28-1	8,333 lbf	0.25 inch
AL-7-26-1	10,000 lbf	0.25 inch
AL-7-26-2	10,000 lbf	0.40 inch

A cyclic load of 6,000 lb, R = 0.1 applied to all samples

Example 2: $K_{residual}$ versus Crack Length



Four categories of behavior:

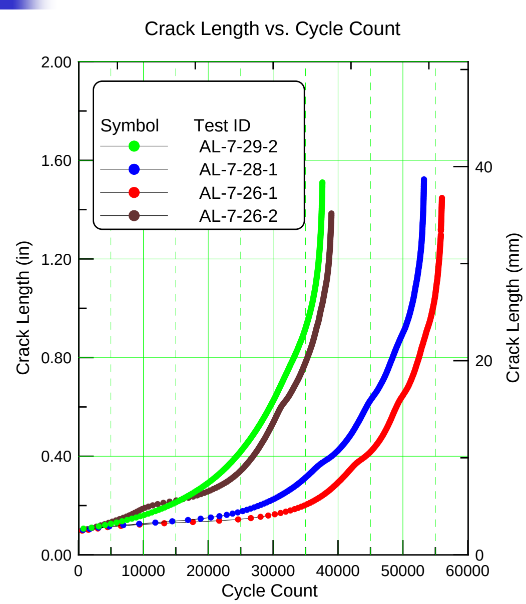
Base line - neutral residual stress

0.25 " groove spacing - intermediate groove forming force

0.25 " groove spacing - higher groove forming force

0.40 " groove spacing - higher groove forming force

Example 2: Crack Length versus Cycle Count



Four categories of behavior:

Base line - neutral residual stress

0.25 " groove spacing - intermediate groove forming force

0.25 " groove spacing - higher groove forming force

0.40 " groove spacing - higher groove forming force

Summary and Conclusions

- The Crack Compliance technique has been validated analytically and experimentally.
- The practical application of the methodology requires precise signal stability and linearity -- far beyond that necessary for standard fatigue crack growth rate experiments.
- The technique offers the potential to explore the beneficial or detrimental effects of residual stress by simultaneously measuring $K_{residual}$ and fatigue crack growth rates.

7.3 The Fundamentals of Constant K_{MAX} Test for Generating the Master Curve

The Fundamentals of the Constant K_{max} Test for Generating the Master Curve

By:
Keith Donald
Fracture Technology Associates

Mark James
Alcoa Technical Center

Introduction

- ACR combined with K_{max} sensitivity offers a novel approach to material characterization by utilizing a "Master Curve".
- A "Master Curve" can also be generated using a series of constant K_{max}, decreasing ΔK tests without the need to measure closure or use compliance.
- A fixed stress ratio prediction can be made from the normalized curve. The process is suitable for predicting some forms of small crack behavior from constant K_{max} tests.
- The well-behaved and characterized 2024-T351 from the ASTM Round Robin program was used for this example.

K Normalization (for small cracks)

Master curve (from constant K_{max} tests above closure)

$$K_{norm} = \Delta K^{1-n} \bullet K_{max}{}^{n}$$

Any stress ratio can then be predicted knowing value of n

$$\Delta K = K_{norm}(1-R)^{n}$$

Common Testing Parameters

- Material: 2024-T351 (0.375 in thick)
- Environment: Lab Air (75 deg F, RH = 40 %)
- Orientation: L-T
- Stress Ratio: 0.1, 0.7
- Constant K_{max}:5, 10, 15, 20, 25 ksi√in
- Frequency: 16-20 Hz

Four Sample Types

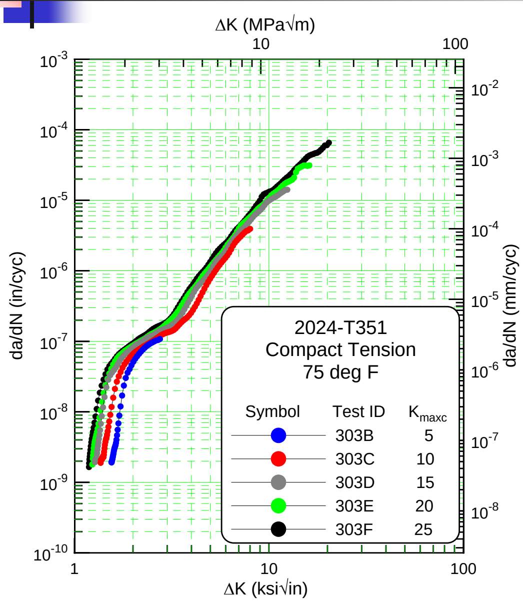
Compact Tension, C(T)

Middle Crack Tension, M(T)

Corner Crack Tension, CC(T)

Single Edge Notch Tension, SEN(T)

K_{max} effect (C(T), $\Delta K_{applied}$)



K_{max} = 5, 10, 15, 20, 25

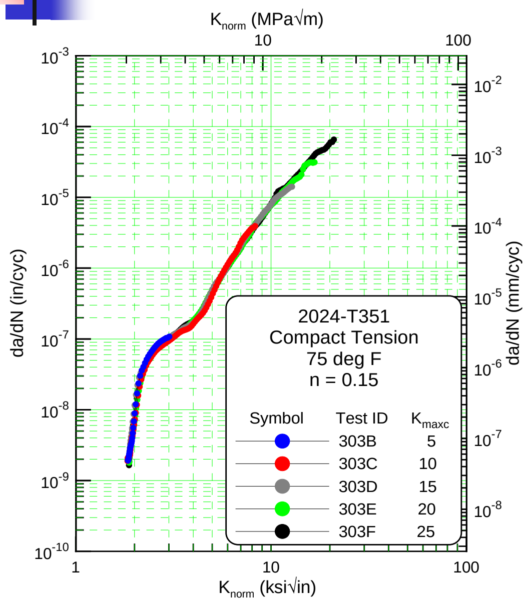
K-gradient = -15 1/in.

Steep gradients provide quick tests and all tests were conducted on one sample

All data plotted are closure free. Stress ratio at threshold from R = 0.7 to 0.95.

Note shift to the left as K_{max} is increased

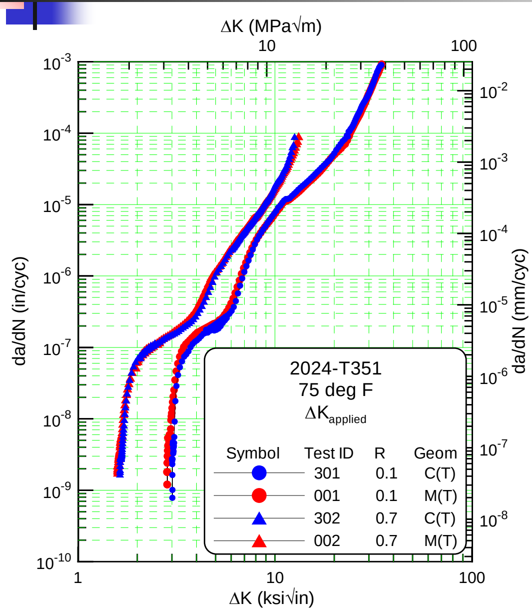
K_{max} effect (C(T), K_{norm})



A K_{max} sensitivity exponent = 0.15 was used to collapse the data

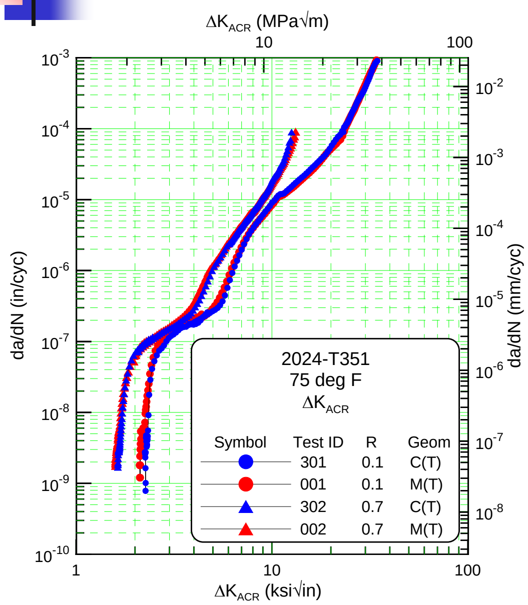
Five tests fall on a single "master curve".

FCGR data ($\Delta K_{applied}$, R=0.1, 0.7)



M(T) and C(T) samples are in good agreement at both stress ratios.

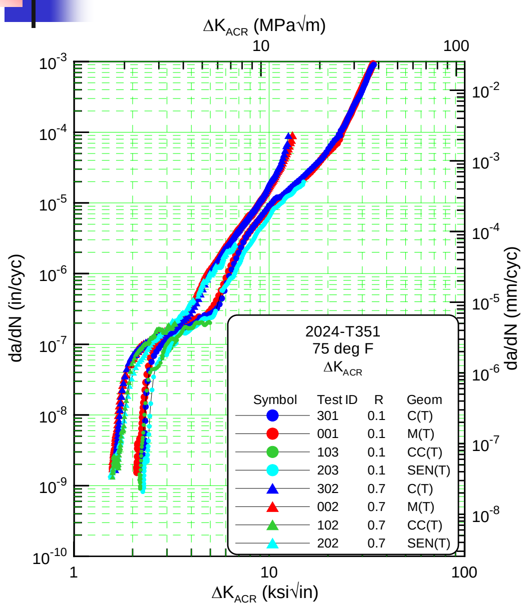
FCGR data (ΔK_{ACR}, R=0.1, 0.7)



ACR method is applied to low R data only.

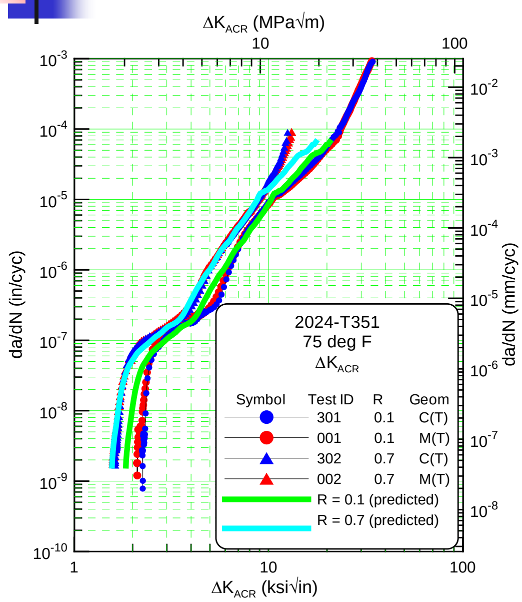
(high R is already closure free)

ΔK_{ACR} compared with small/short crack data



Small/short crack data agree with closure corrected long crack data.

Master curve from constant K_{max} tests used to predict constant R data



Constant K_{max} tests provide lower bound prediction.

Predicted curves based only on K_{max} input data

K_{max} exponent = 0.15

Summary and Conclusions

- A series of constant K_{max}, decreasing ΔK tests can be used to generate a master curve.
- Closure corrected (ACR) "long" crack samples can be used to predict "small/short" crack behavior.
- The master curve from the constant K_{max} tests can also be used to predict "small/short" crack behavior (no ACR measurements required).

7.4 ASTM DRAFT STANDARD FOR ACR WITH REFERENCES

APPENDIX X4. RECOMMENDED PRACTICE FOR DETERMINATION OF ACR-BASED STRESS-INTENSITY FACTOR RANGE

X4.1 Introduction

X4.1.1 This appendix describes the Adjusted Compliance Ratio (ACR) method to estimate the effects of remote closure. Remote closure refers to crack tip shielding as a result of contact in the crack wake away from the crack tip (**11**). This is in contrast to other shielding mechanisms near to the crack tip such as plasticity. The ACR method is based on the same measurement signals that are used for the opening force method in Appendix X2, which describes a method to estimate the 2% crack opening force.

X4.2 Scope

X4.2.1 This appendix covers the experimental determination of the ACR-based crack driving force during tests of the specimens outlined in this test method, subjected to constant amplitude or K-control methods, and based on procedures recommended in this standard. The ACR method builds on the opening force method of closure determination as well as compliance method of crack size determination, so familiarity and conformity with Appendix X2 and Annex A5 of this standard are assumed.

X4.3 Terminology

X4.3.1 *Definitions*—Definitions of terms specific to this appendix are given in this section. Other terms used in this appendix are defined in the main body of this test method.

X4.3.1.1 *open-crack compliance,* C_o [LF^{-1}] – the open-crack compliance for the specimen at a given crack size.

X4.3.1.1.1 *Discussion* – for the purposes of this appendix, all compliance values may be expressed as either EvB/P or v/P, where E is elastic modulus, v is displacement between two points, B is specimen thickness, and P is force. The former is dimensionless, while the latter has dimensions of LF^{-1}. For consistency with Appendix X2, all compliances in this appendix are assumed to be calculated as $C = v/P$.

X4.3.1.2 *secant compliance,* C_s [LF^{-1}] – the secant compliance for the specimen at a given crack size as defined by the secant of the unloading compliance curve between the maximum force and minimum force.

X4.3.1.3 *initial open-crack compliance,* C_{oi} [LF^{-1}] – the notch open-crack compliance before a crack has formed.

X4.3.1.4 *initial secant compliance,* C_{si} [LF^{-1}] – the notch secant compliance before a crack has formed.

X4.3.1.5 *adjusted compliance ratio,* U_{ACR} – a dimensionless parameter representing the ratio of secant to open-crack compliances, both adjusted by the initial compliance.

X4.3.1.6 *stress-intensity factor range based on adjusted compliance ratio,* ΔK_{ACR} [$FL^{-3/2}$] – in fatigue, the stress-intensity factor range computed using the Adjusted Compliance Ratio method.

X4.4 Significance and Use

X4.4.1 The method of determining ΔK_{ACR} presented in this appendix provides an engineering approximation that has been used in various ways to predict crack growth **(2,3)** and compare material performance **(4,5,6)**. The method has been used for removing remote closure effects associated with microstructure or residual stress **(4,5)** and has been used in conjunction with a power law equation to collapse data to a unique curve **(1,6)**, which can then be transformed into design curves **(6)**.

NOTE 1—Some materials and loading situations may exhibit strong near-tip closure effects (i.e. due to oxide formation, etc). In this case the ACR method may not be suitable.

X4.5 Basis for Determination of Driving Force by the ACR Method

X4.5.1 The ACR method has been shown to be independent of measurement location for experimental measurements along the crack plane behind the crack tip **(1)** and for an analytical evaluation along the load line **(8)**, which provides a foundation for using the same algorithm for front-face clip-gage and back-face strain-gage. Additional research was performed to investigate a relationship between remote crack wake interference and the crack-tip cyclic strain **(9)**. An inter-laboratory round robin was performed as part of the second round robin on closure measurement **(10)** based on the measured force-displacement traces collected in the second round robin on closure measurement.

X4.5.2 The ACR method focuses on the displacement or strain range between maximum and minimum force due to crack closure rather than the point of deviation in linearity of the force versus displacement/strain curve. Although the opening force, P_{op}, is not used directly in the calculation of ACR values, accurately determining the opening force is essential to guarantee that the linear slope of the fully open crack is achieved. The same precautions regarding apparatus and data quality given in the opening force method are equally applicable to the ACR method. Therefore, adherence to the procedures specified in sections X2.5 through X2.8 of Appendix X2 are necessary for the proper determination of ACR.

X4.6 Apparatus

X4.6.1 The procedure requires no new hardware beyond what is necessary to evaluate P_{op} in Appendix X2 of this standard. However, the apparatus should be capable of recording the secant compliance as outlined below in addition to the open crack compliance and other quantities specified in test method E647.

X4.7 Recommended Procedure—Determination of Driving Force by the ACR Method

X4.7.1 *Data Collection*

X 4.7.1.1 The ACR method is intended to be implemented in the context of a computer monitored or controlled fatigue crack growth rate test that meets the requirements of this test method. In a typical implementation, a digital data acquisition system is used to collect the cyclic force and associated front-face clip gage displacement data on a periodic basis. These data are tabulated and used to determine the open-crack compliance, crack size, and stress-intensity factor as a function of elapsed cycle count; then these data are subjected to numerical analysis to determine the crack growth rate as a function of stress-intensity factor. In the ACR method, an additional quantity is saved. Each time that the open-crack compliance and other quantities are calculated, the secant compliance must also be calculated using the end points of the force-displacement data. Figure 1 contains a schematic of two force-displacement curves – one for the notch before the crack forms and one for a current crack configuration after the crack has formed and grown. For the current crack, Figure 1 indicates the opening force, P_{op}, which defines the lower bound for the linear portion of the force-displacement curve, and the open-crack compliance, C_o, which is calculated by fitting a straight line to the upper linear part of a force-displacement curve. The secant compliance, C_s, is the slope drawn between the upper and lower coordinates of the force versus displacement curve for a given loading cycle, as shown in Figure 1, and is computed from maximum and minimum values of force and displacement as follows:

$$C_s = \frac{v_{max} - v_{min}}{P_{max} - P_{min}}, \qquad \textbf{(1)}$$

where:

P_{max} = maximum value of applied force,
P_{min} = minimum value of applied force,
V_{max} = value of crack opening displacement at P_{max}, and
V_{min} = value of crack opening displacement at P_{min}.

X4.7.1.2 When back-face strain is used, the secant compliance can be defined as:

$$C_s = \frac{\varepsilon_{\max} - \varepsilon_{\min}}{P_{\max} - P_{\min}} , \qquad \textbf{(2)}$$

where:

ε_{max} = value of back surface strain at P_{max} and
ε_{min} = value of back surface strain at P_{min}.

X4.7.1.3 The ACR method adds one new quantity, the secant compliance, to the table of data that will be subjected to numerical analysis.

X4.7.2 *Results Calculation*

X4.7.2.1 After data collection the ACR method values are calculated as follows:

X4.7.2.2 The initial values of open-crack compliance, C_{oi}, and secant compliance, C_{si}, must be calculated. These are the respective average values associated with the notch before crack formation. The number of cycles necessary for averaging may be dependent on the magnitude and range of the signals as well as signal quality. One approach is to review the respective compliance values, for instance as a plot of compliance versus cycles or compliance versus crack length. Then identify an initial range for each that represents average response for cycles applied before crack growth has occurred. In addition, Note A5.1 contains guidance for averaging data in terms of crack length increment that may be useful for averaging the initial values of open-crack and secant compliances here.

X4.7.2.3 For each recorded value of the open-crack and secant compliances the U_{ACR} value is calculated as follows:

$$U_{\mathrm{ACR}} = \frac{C_{oi}}{C_{si}} \cdot \frac{C_s - C_{oi}}{C_o - C_{oi}} , \qquad \textbf{(3)}$$

where the ratio of C_{oi}/C_{si} compensates for a possible bias in the secant or open-crack compliances because of signal conditioning noise or nonlinearity.

NOTE 2—Experience has shown that, under most circumstances, the difference between C_{oi} and C_{si} is less than 0.5%. An analysis of error limits for typical clip-gage displacement and force indicates that a nearly 1% difference between the compliances may be possible when the force and displacement errors are combined. Thus, a ratio of C_{oi}/C_{si} outside the range $0.99 \leq C_{oi}/C_{si} \leq 1.01$ may indicate poor data quality or excessive nonlinearity in one or both of the transducer signals that should be investigated. Note that frequency effects, such as nonlinearity as a result of electronic filtering effects or increased noise caused by resonant frequencies can influence the quality of ACR data.

NOTE 3—The value of U_{ACR} is theoretically undefined until crack advance occurs because C_s, C_o, and C_{oi} will initially be nominally equal to each other. In practice, for high-speed digital systems, enough data collection and testing variability occur for this not to create difficulties numerically. However, the recommended practice is to use the crack formation period to calculate the initial values of the open crack and secant compliances and use the crack growth period to calculate the U_{ACR} and ΔK_{ACR} values.

X4.7.2.4 The driving force, ΔK_{ACR}, is calculated as follows:

$$\Delta K_{\mathrm{ACR}} = U_{\mathrm{ACR}} \cdot \Delta K_{\mathrm{fr}} , \qquad \textbf{(4)}$$

where ΔK_{fr} is the full range stress-intensity factor as calculated for each data point and as discussed in Section 3, Terminology.

X4.8 Data Quality Requirement

X4.8.1 The procedure has no new data quality or hardware requirements beyond what are necessary to evaluate P_{op} in Appendix X2 of this standard.

X4.9 Report

X4.9.1 The following information should be reported:
X4.9.1.1 All items in section X2.9 of Appendix X2.
X4.9.1.2 The initial open-crack compliance before a crack has formed, C_{oi}.
X4.9.1.3 The initial secant compliance before a crack has formed, C_{si}.
X4.9.1.4 All calculated values of the open-crack compliance, C_o.
X4.9.1.5 All calculated values of the secant compliance, C_s.
X4.9.1.6 All calculated values of the adjusted compliance ratio, U_{ACR}.
X4.9.1.7 All calculated values of the ACR stress-intensity factor range, ΔK_{ACR}.

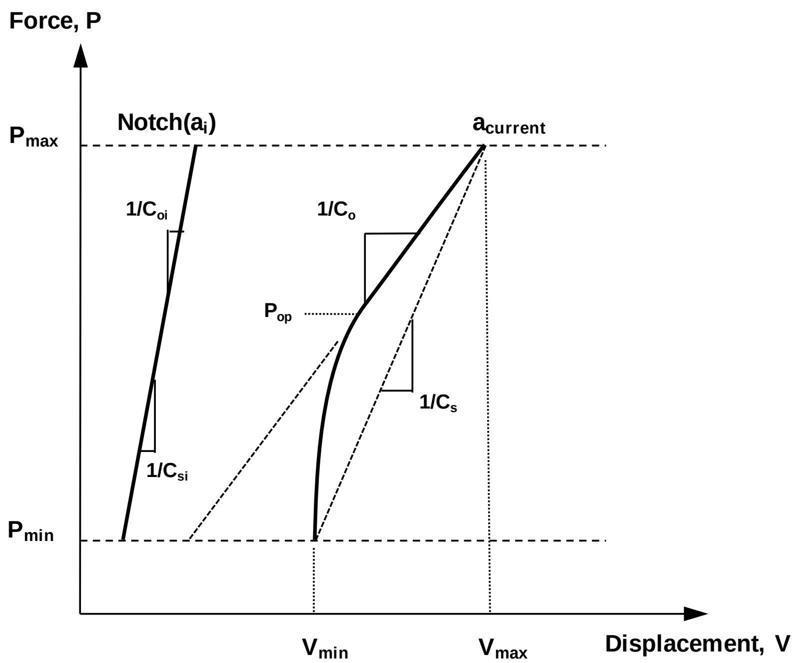


Figure X4.1—Schematic of force-displacement records showing critical parameters for the ACR method.

New References Added to E647 (to be renumbered)

1. Donald, J. K., Bray, G. H., Bush, R. W., "An Evaluation of the Adjusted Compliance Ratio Technique for Determining the Effective Stress Intensity Factor," *29th National Symposium on Fatigue and Fracture Mechanics, ASTM STP 1332*, T. L. Panontin, S. D. Sheppard, Eds., American Society for Testing and Materials 1998.
2. Brockenbrough, J. R. and Bray, G. H., "Prediction of S-N Fatigue Curves Using Various Long-Crack Derived ΔKeff Fatigue Crack Growth Curves and a Small Crack Life Prediction Model," *Fatigue and Fracture Mechanics, 30th Volume*, ASTM STP 1360, P. C. Paris and K. L. Jerina, Eds., ASTM International, West Conshohocken, PA, West Conshohocken, PA, 1999, pp. 388–402.
3. H. R. Zonker, G. H. Bray, K. George, and M. D. Garratt , "Use of ACR Method to Estimate Closure and Residual Stress Free Small Crack Growth Data," *Journal of ASTM International*, July/August 2005, Vol. 2, No. 7.
4. Diana A. Lados, Diran Apelian, Paul C. Paris, J. Keith Donald, "Closure mechanisms in Al–Si–Mg cast alloys and long-crack to small-crack corrections," *International Journal of Fatigue* 27 (2005) 1463–1472.

5. J. Keith Donald and Diana A. Lados, "An integrated methodology for separating closure and residual stress effects from fatigue crack growth rate data," *Fatigue Fract Engng Mater Struct* 30, 223-230, 2006.
6. Ball, D. L., "The Influence of Residual Stress on the Design of Aircraft Primary Structure" Seventh International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics, R.W. Neu, K.R.W. Wallin, S.R. Thompson, Eds., ASTM International, West Conshohocken, PA, 2007.
8. Diana A. Lados, Diran Apelian, and J. Keith Donald, "Fracture mechanics analysis for residual stress and crack closure corrections," *International Journal of Fatigue* 29 (2007) 687–694.
9. Donald, J. K., Connelly, G. M., Paris, P. C., and Tada, H., "Crack Wake Influence Theory and Elastic Crack Closure Measurement," *Fatigue and Fracture Mechanics: 30th Volume, ASTM STP 1360*, P. C. Paris and K. L. Jerina, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2000, pp. 185-200.
10. Donald, J. K. and Phillips, E. P., "Analysis of the Second ASTM Round Robin Program on Opening Load Measurement Using the Adjusted Compliance Ratio Technique," *Advances in Fatigue Crack Closure Measurement and Analysis: Second Volume, ASTM STP 1343*, R. C. McClung, J. C. Newman, Jr., Eds., American Society for Testing and Materials, 1997.
11. Ritchie, R. O., "Crack Tip Shielding in Fatigue," Fifth International Conference on Mechanical Behavior, China, 1987.