

# **The Prediction of Fatigue Crack Propagation in a Friction Stir Welded Specimen Containing a Residual Stress Distribution**

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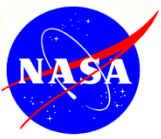
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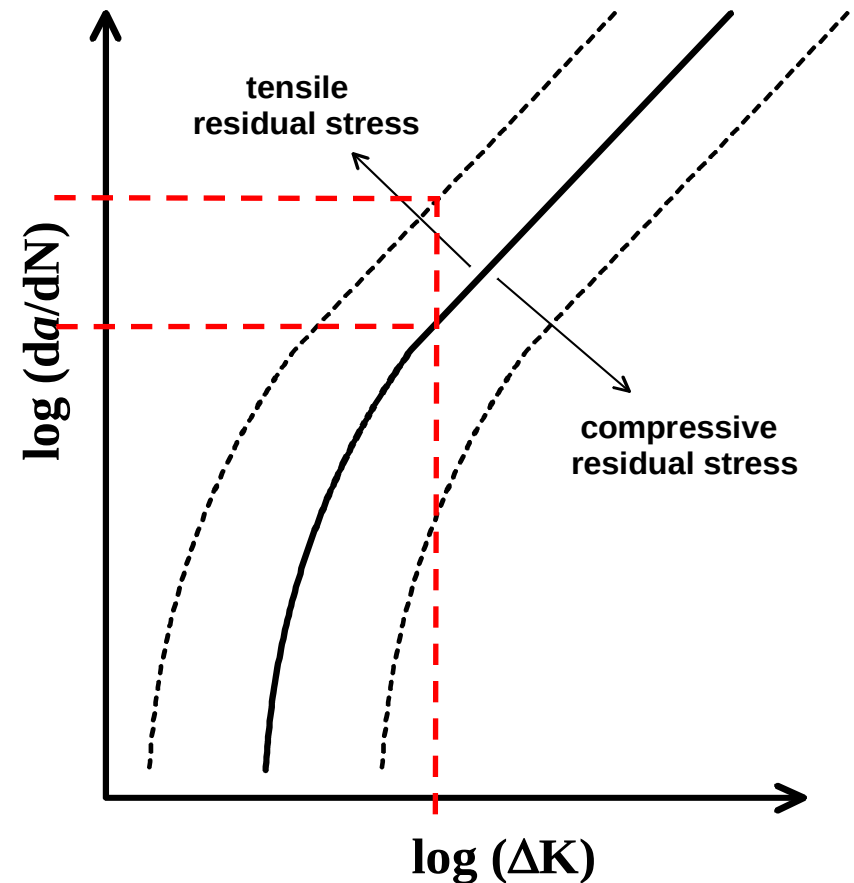
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# Objectives of Study

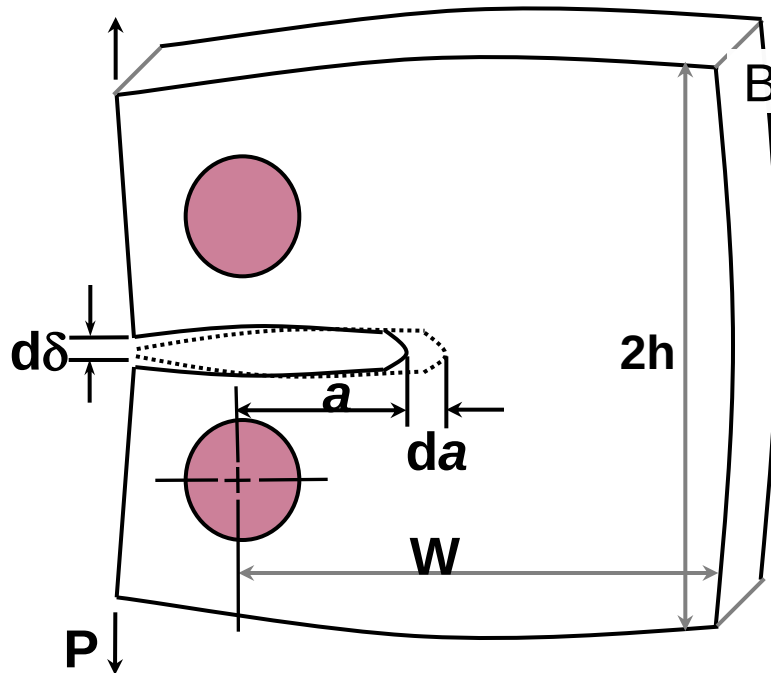


- Need to develop ability to determine residual stresses in specimens
  - How can coupon results be used to understand larger structure?
- Obtain “intrinsic” material behavior by extracting residual stress effects
- What stress state affects the crack tip?
  - $K_{\text{tip}} = K_{\text{applied}} + K_{\text{residual}}$



# Experimental Methods

*Cut-compliance method for front-face displacement measurements*



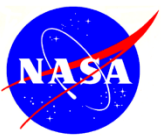
$$K_{res} = \frac{E}{Z(a)} \cdot \frac{d\delta}{da}$$

$Z(a)$  = influence function

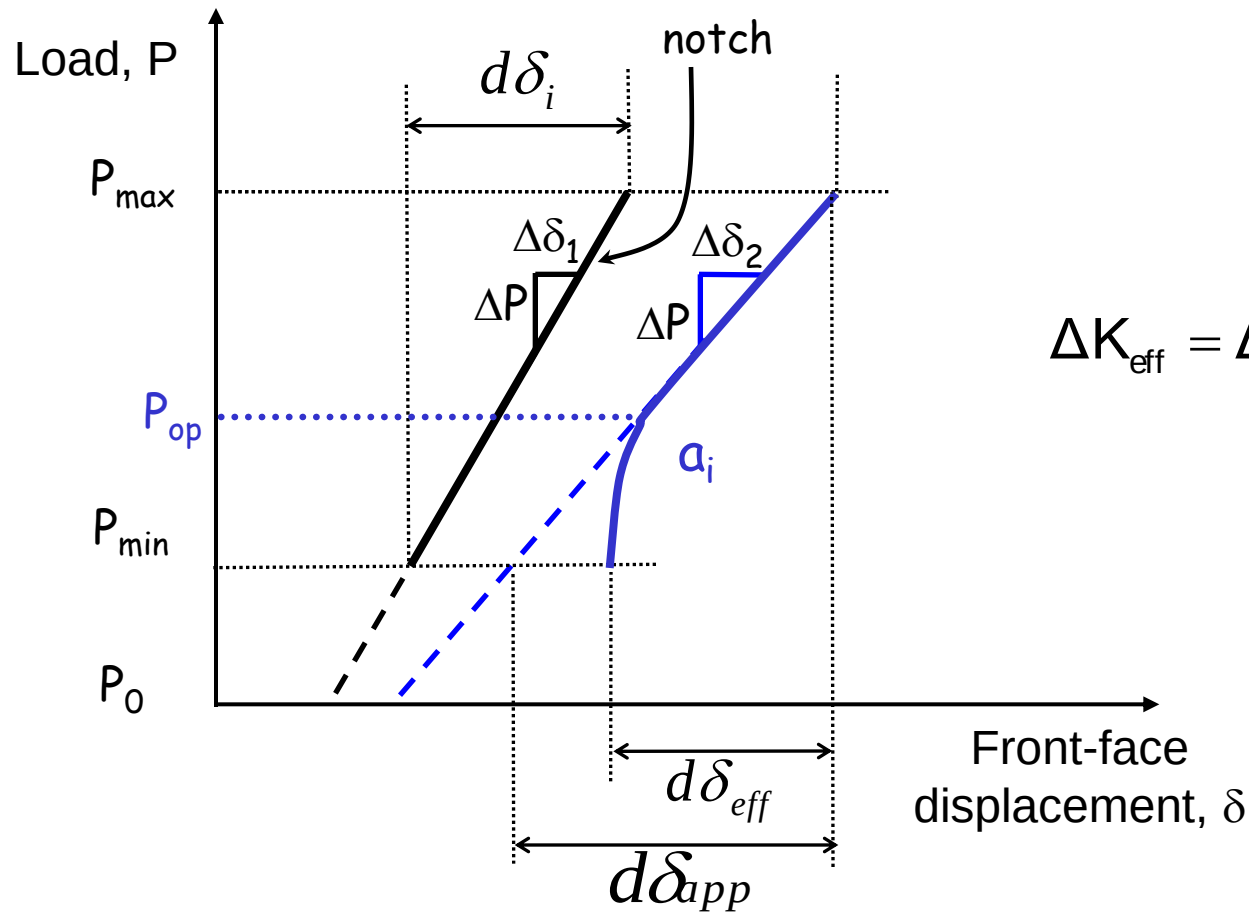
$$Z(a) = \frac{4 \cdot (2W + a) \cdot F_2\left(\frac{a}{W}, \frac{h}{W}\right)}{(W - a)^{3/2}}$$

- Measure changes in notch displacement for incremental changes in crack length  $\Rightarrow K_{res}$  can be calculated
- $Z(a)$  depends on size, geometry, strain measurement location, but not on the residual stress distribution

# Experimental Methods (continued)

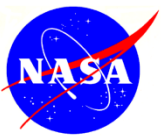


## *Adjusted Compliance Ratio – Determination of Closure*

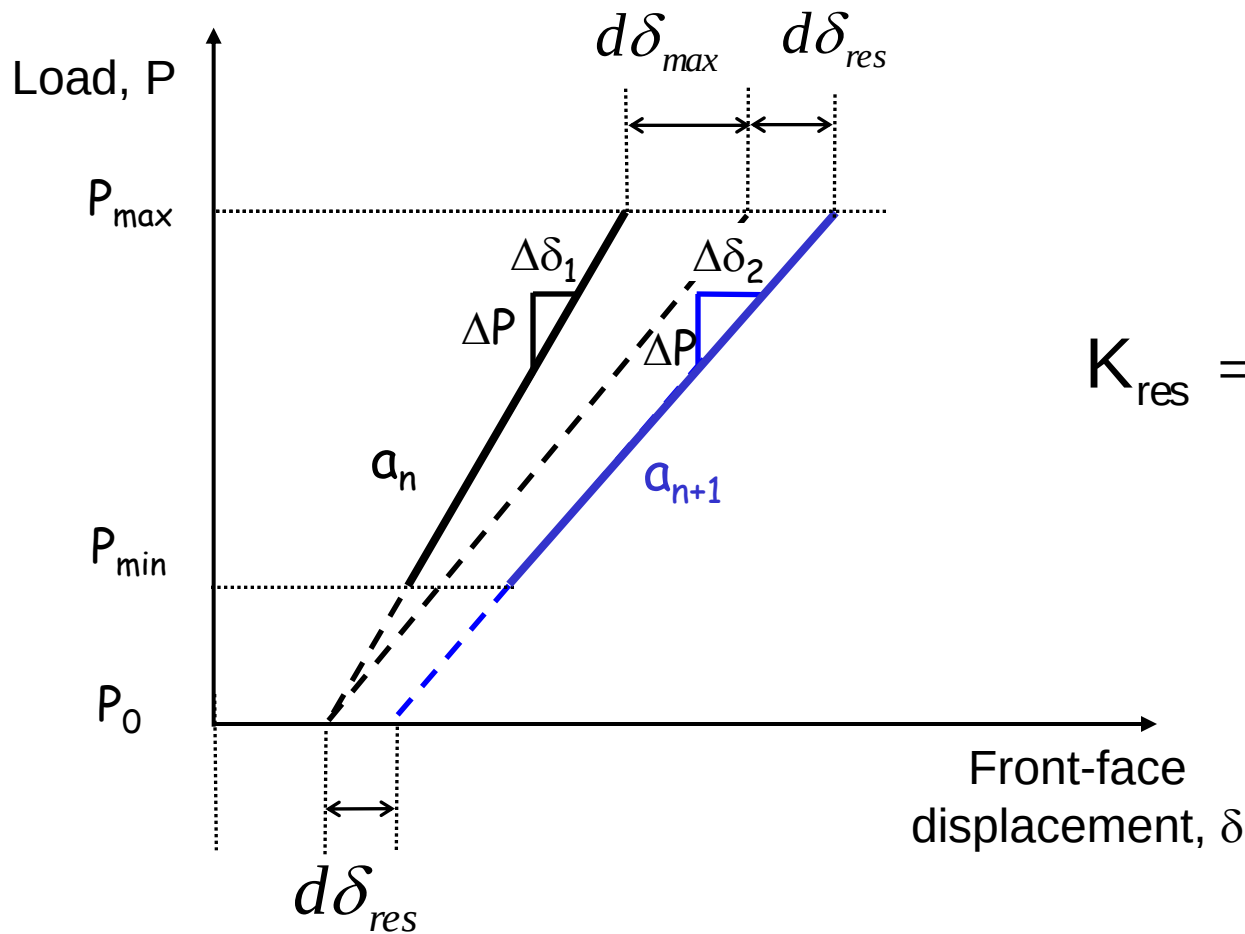


$$\Delta K_{\text{eff}} = \Delta K_{\text{app}} \cdot \frac{d\delta_{\text{eff}} - d\delta_i}{d\delta_{\text{app}} - d\delta_i}$$

# Experimental Methods (continued)



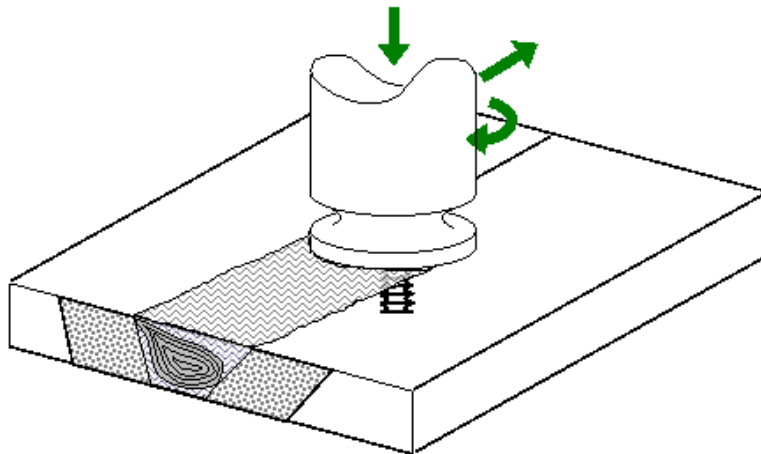
## *Adjusted Compliance Ratio – Determination of Residual Stress*



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

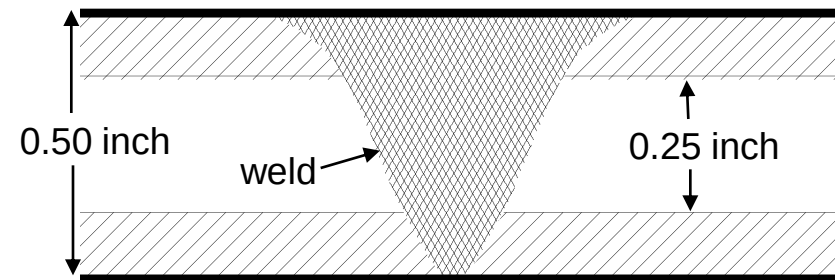
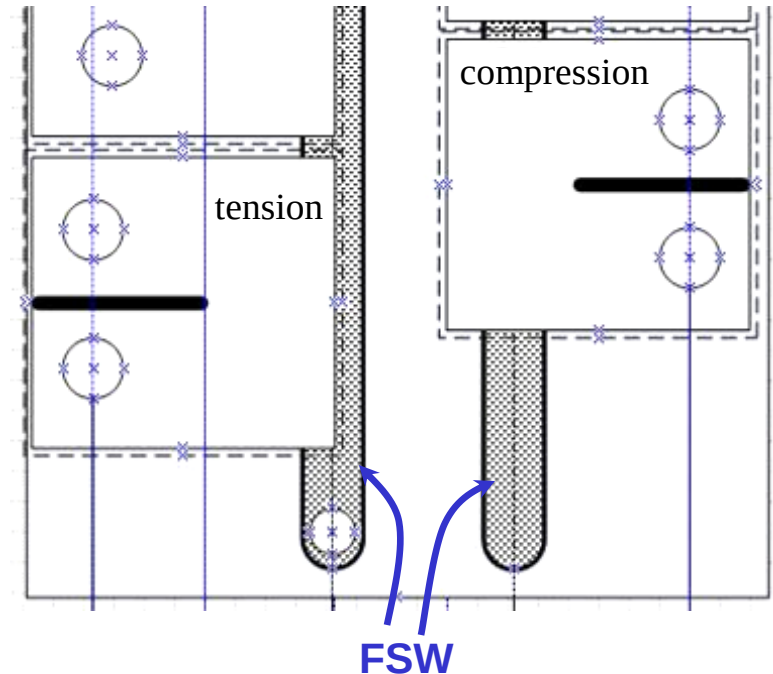
# Test Coupons

- FSW Material
  - Aluminum alloy 2024-T351 plate (1 inch thick)
  - Machined down to 1/2 inch thick before friction stir welded
  - Machined 1/8 inch from each side
  - Final thickness = 1/4 inch
- C(T) Specimen
  - $W = 4$  inch;  $B = 0.25$  inch



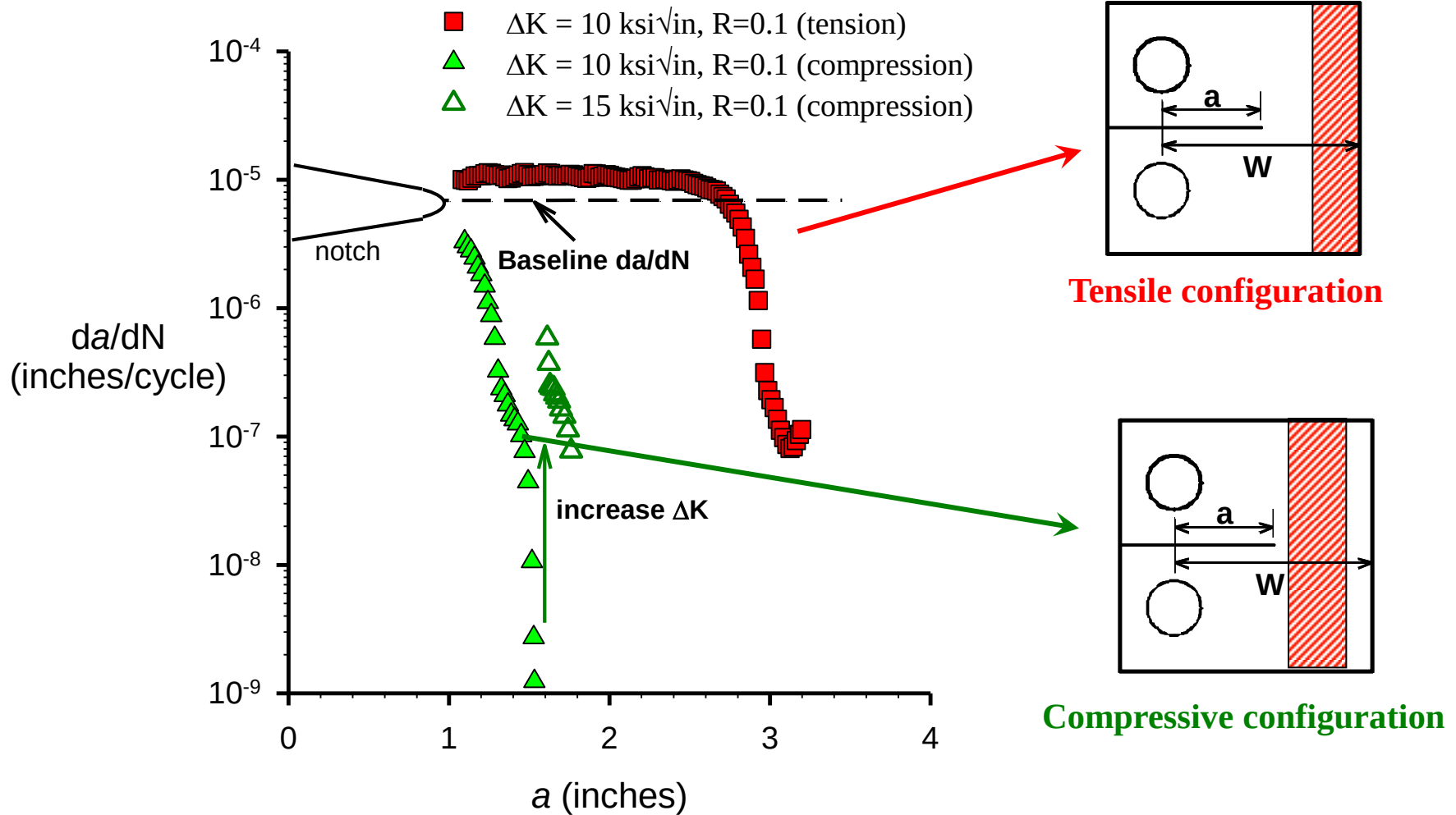
FSW Process

## Specimen Configurations



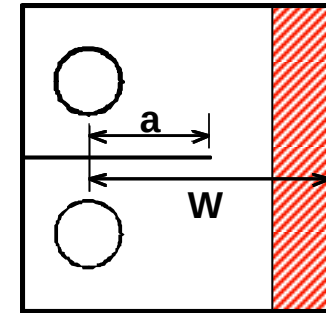
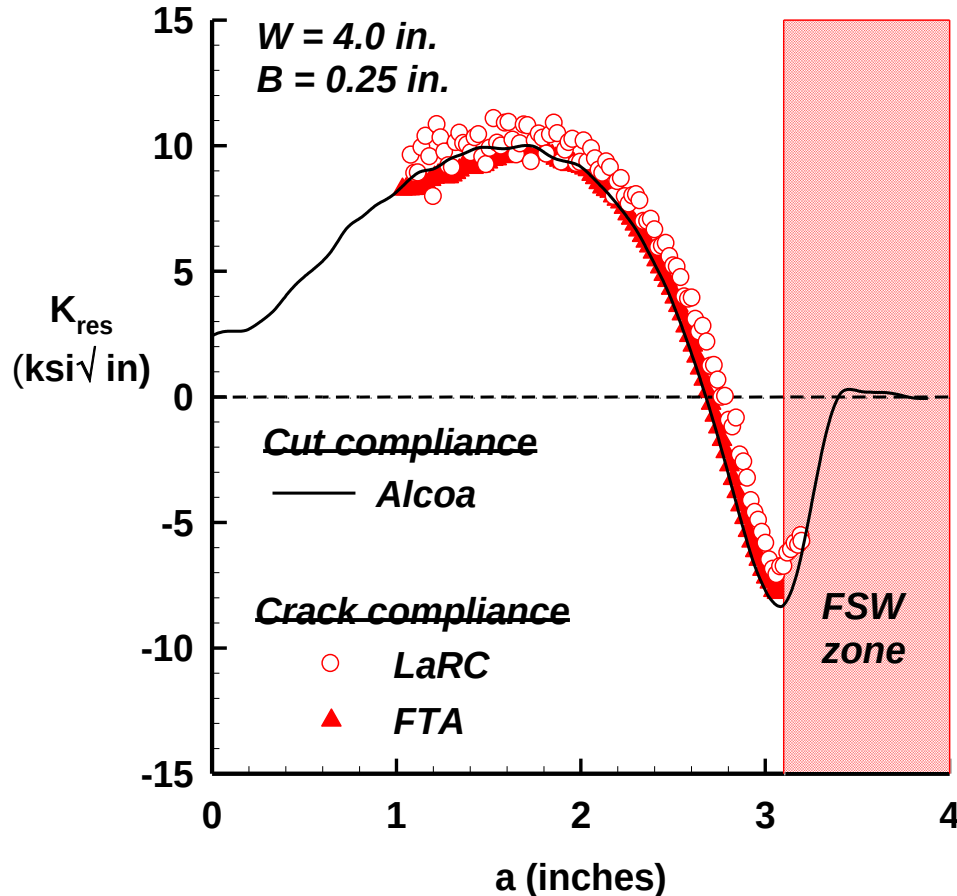
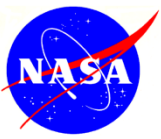
FSW Cross-section

# Variation in FCGR with Crack Length



- Residual stress dramatically affects crack growth rate

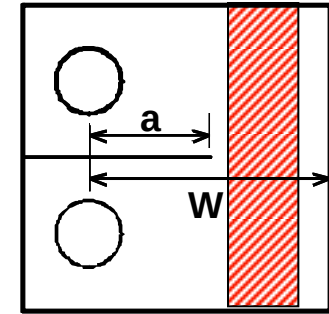
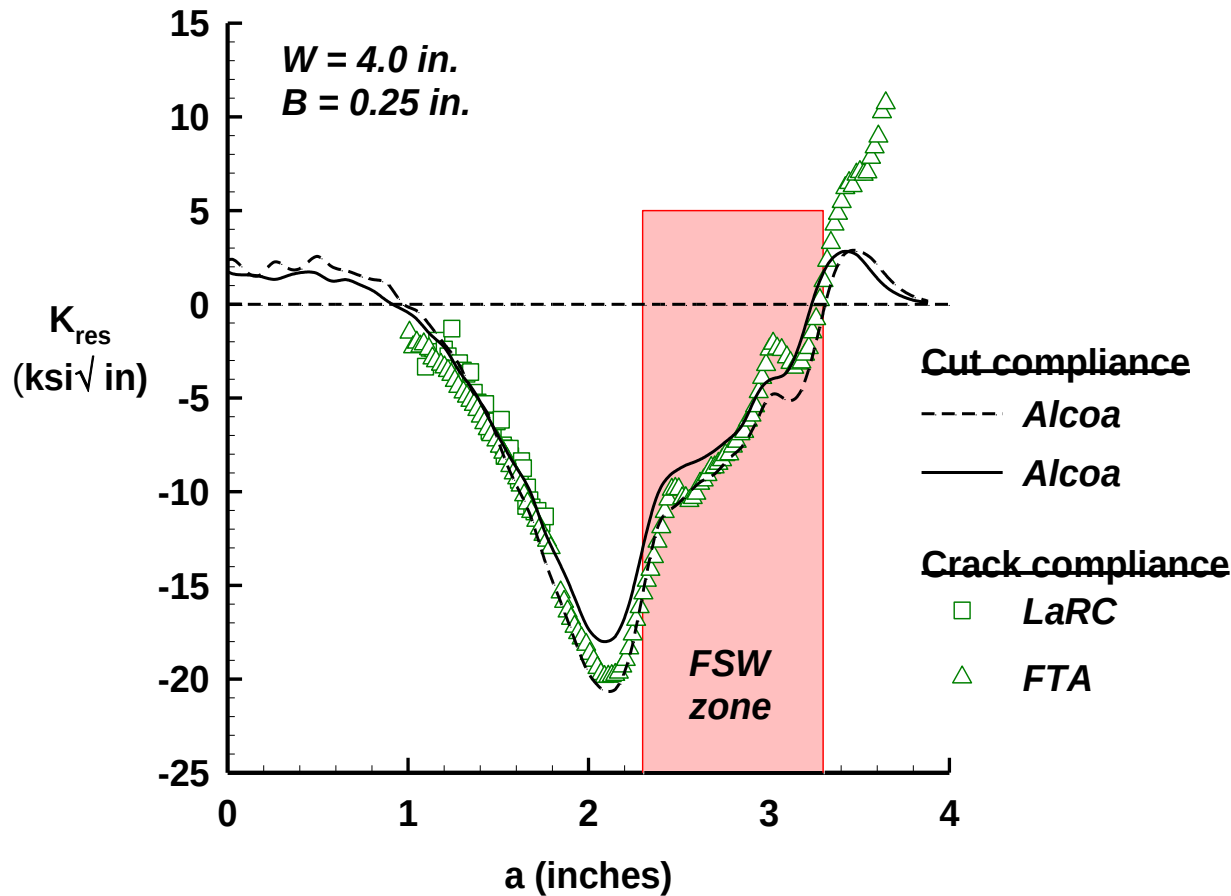
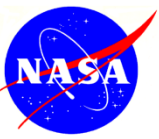
# Experimental Results (Tensile Configuration)



**Tensile configuration**

- Crack compliance method results in consistent results compared to current approaches

# Experimental Results (Compressive Configuration)

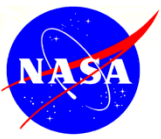


**Compressive configuration**

- Crack compliance results independent of residual stress field
- A robust methodology has been developed (independent of laboratory)

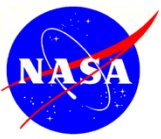
# Residual Stress Effects on FCG

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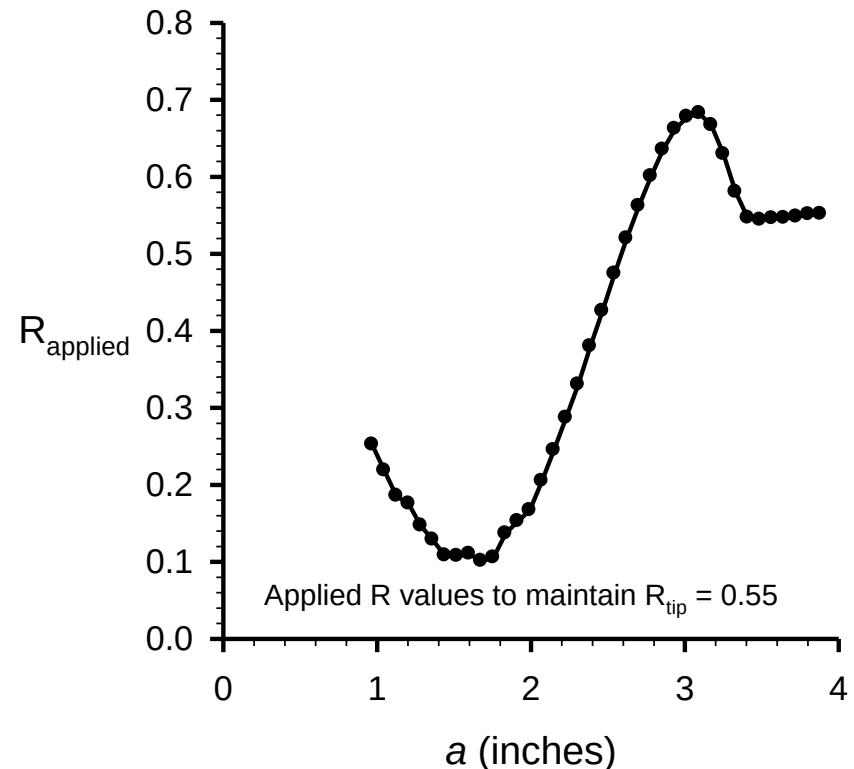
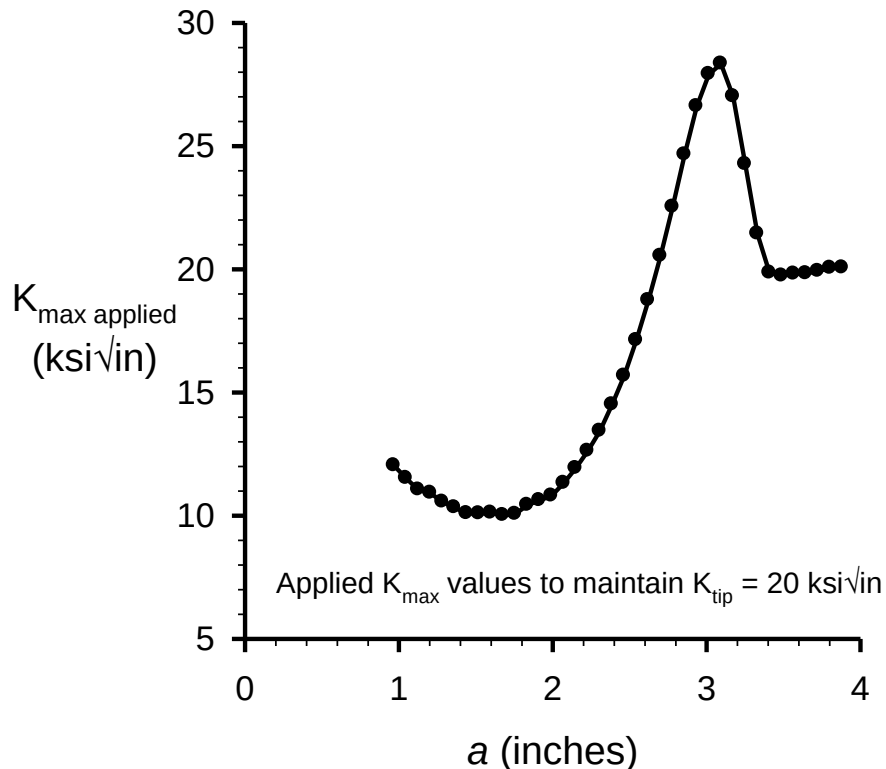


- Hypothesis: Residual stress increases crack-tip mean stress,  $K_{\text{mean}}$ , without affecting  $\Delta K$ . For a given crack-tip loading ( $K_{\text{max tip}}$ ,  $R_{\text{tip}}$ ), the crack growth rate should not depend on residual stress
  - $K_{\text{max tip}} = K_{\text{max residual}} + K_{\text{max applied}}$
- Test: Based on  $K_{\text{residual}}$  data, continuously adjust applied values of  $K_{\text{max}}$  and  $R$  to maintain constant crack-tip load conditions
  - Crack growth rate should remain nearly constant, independent of  $K_{\text{residual}}$

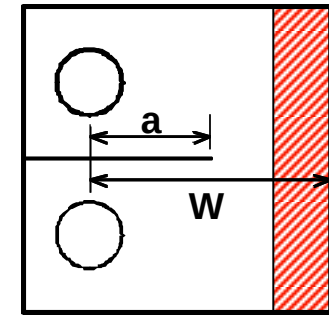
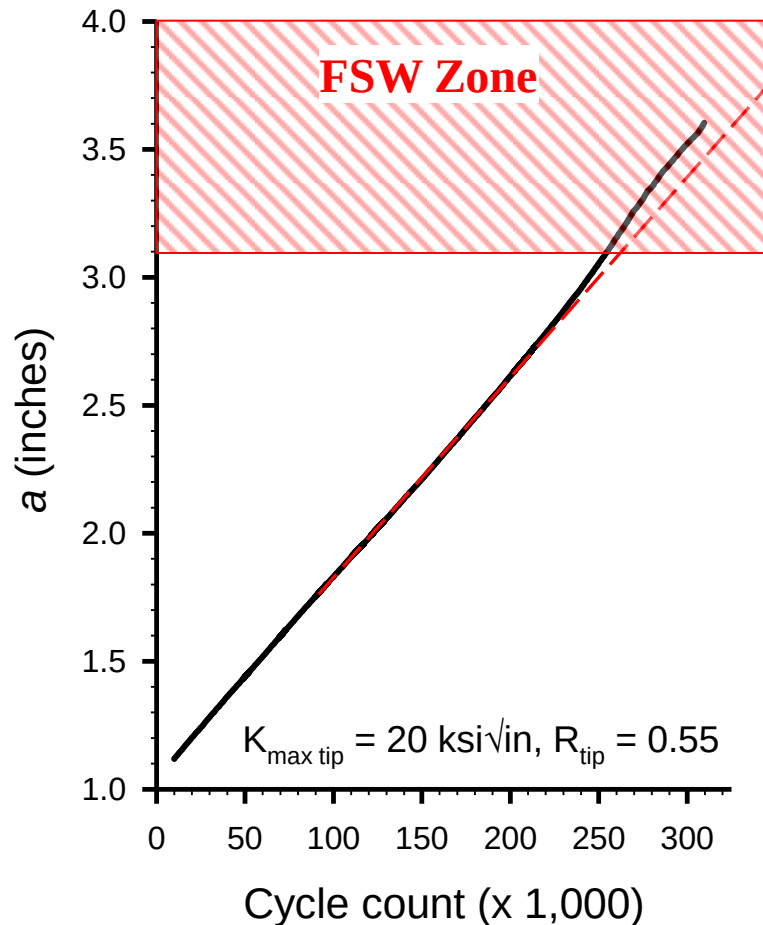
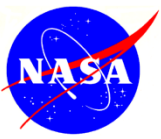
# Constant $K_{tip}$ Testing (Tensile Configuration)



- Applied crack-tip loads to achieve  $K_{max\ tip} = 20\ \text{ksi}\sqrt{\text{in}}$ ,  $R_{tip} = 0.55$



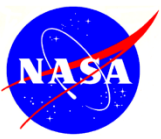
# Constant $K_{tip}$ Testing (Tensile Configuration)



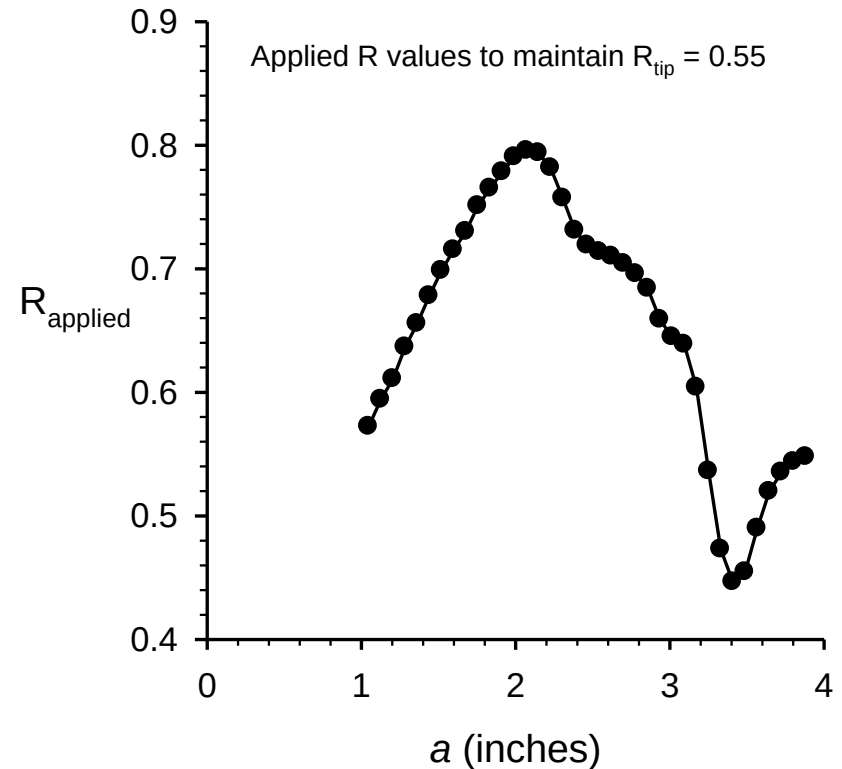
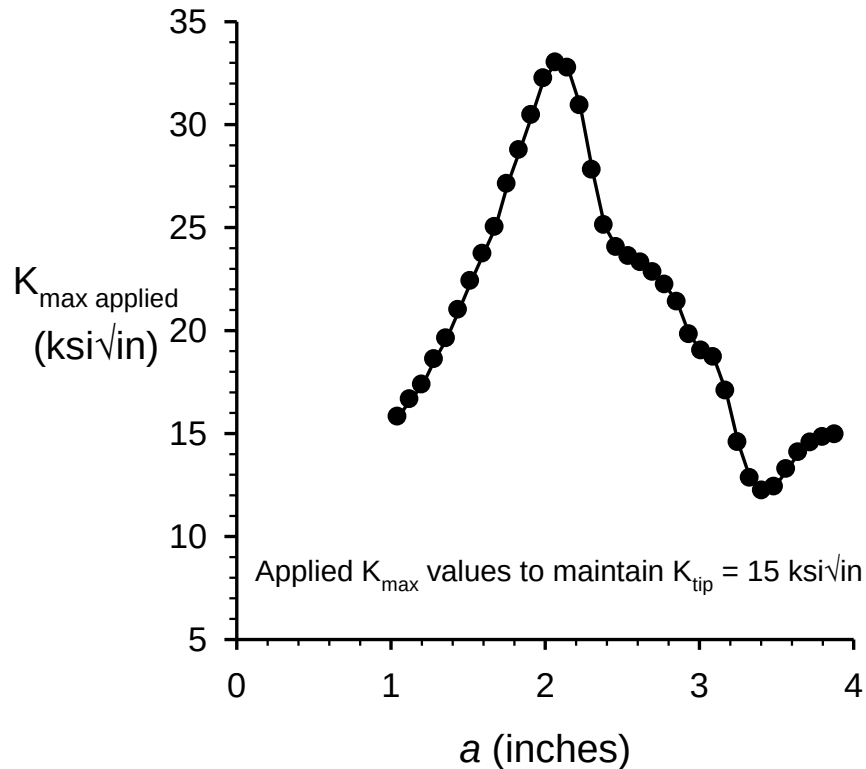
**Tensile configuration**

- Linear crack-length-versus-cycle-count curve indicates constant  $da/dN$
- Slight variation in  $da/dN$  near  $a = 3.5$  inches possibly due to changes in intrinsic FCG properties near the weld

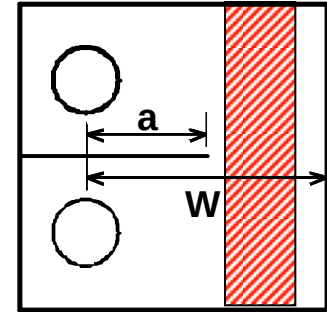
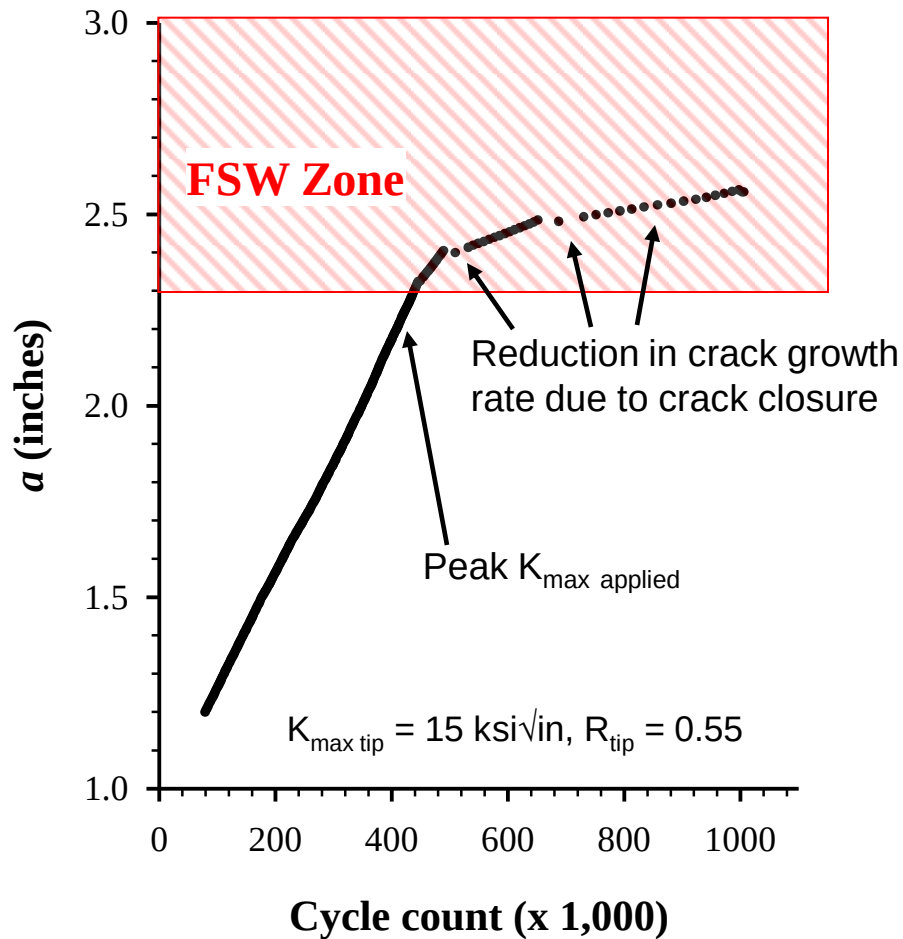
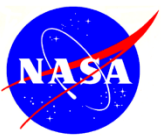
# Constant $K_{tip}$ Testing (Compressive Configuration)



- Applied crack-tip loads to achieve  $K_{max\ tip} = 15\ \text{ksi}\sqrt{\text{in}}$ ,  $R_{tip} = 0.55$



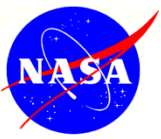
# Constant $K_{tip}$ Testing (Compressive Configuration)



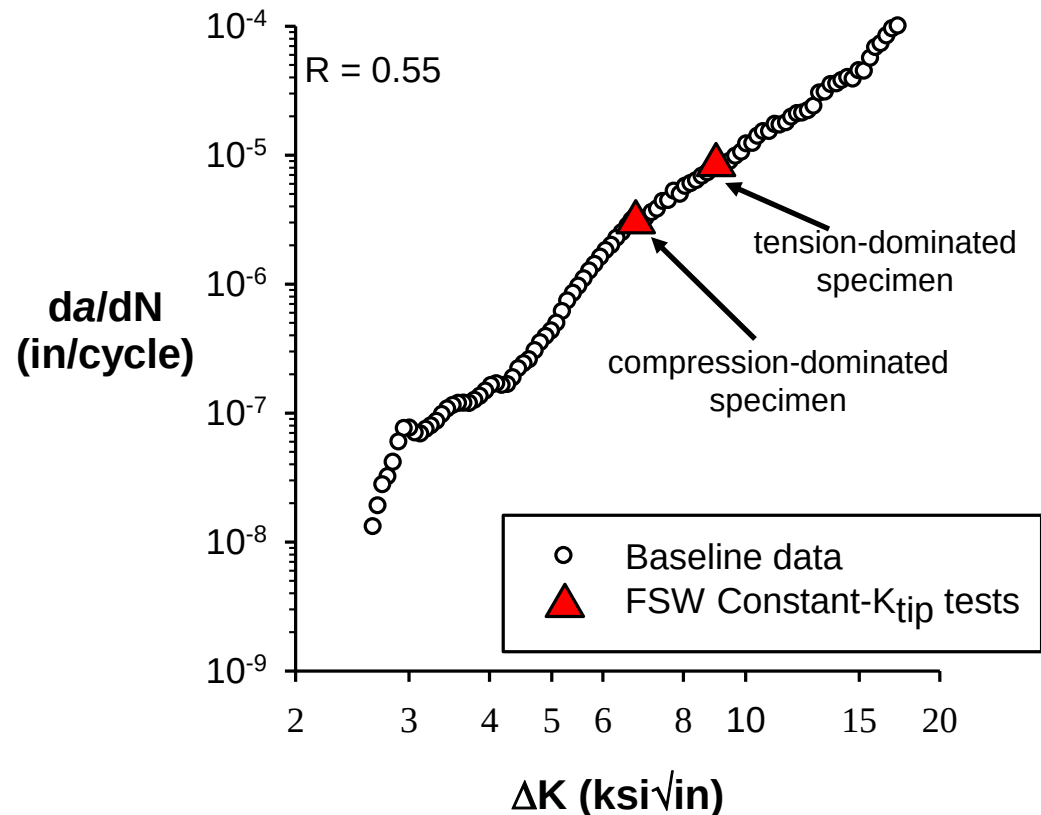
Compressive configuration

- Linear crack-length-versus-cycle-count curve indicates constant  $da/dN$
- Decrease in  $da/dN$  observed at weldment
  - Crack closure

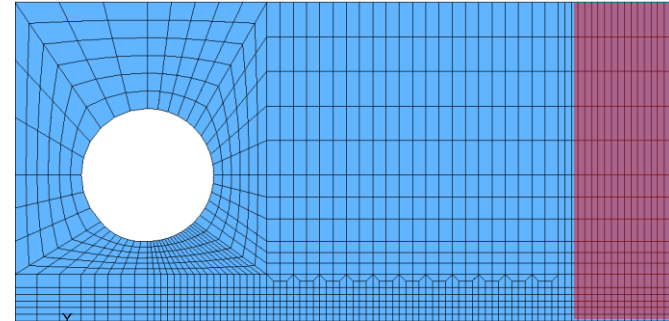
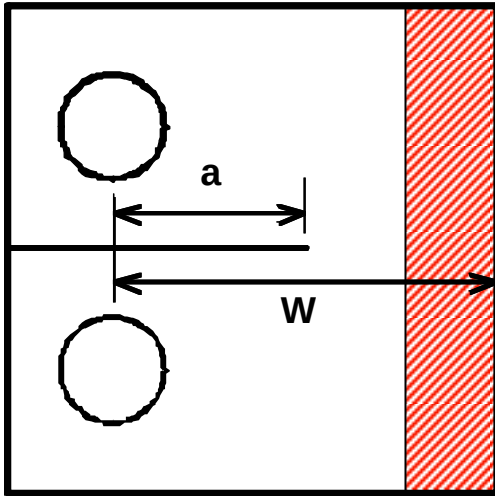
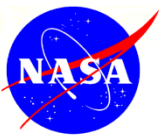
# Comparison with Baseline data



- Constant- $K_{tip}$  results are in good agreement with baseline FCG data
- Same crack growth rates occur for the same crack-tip loading



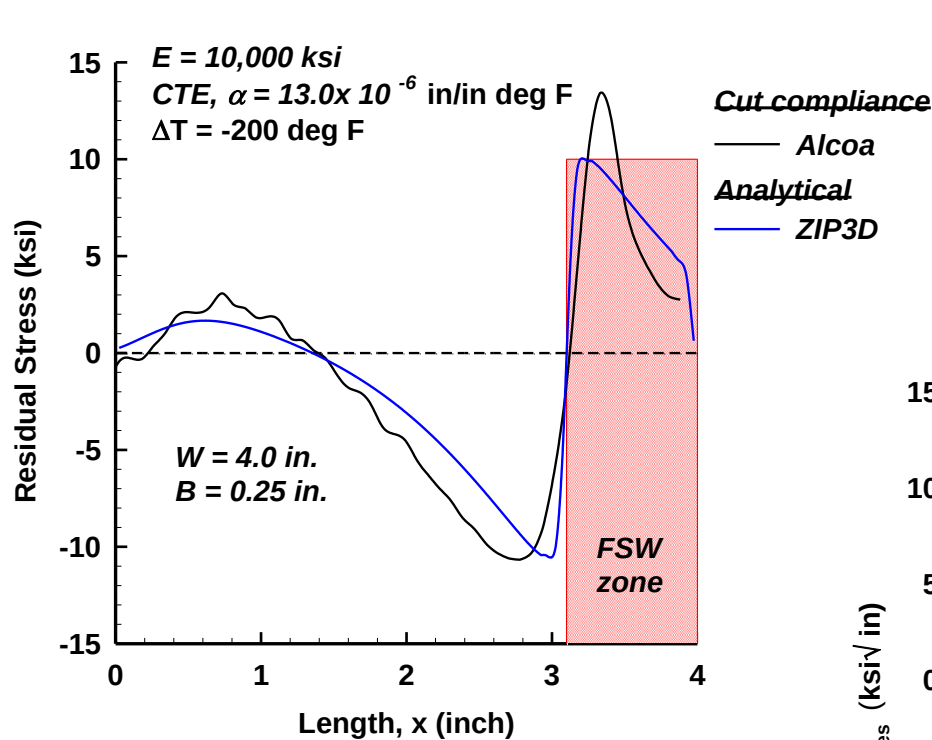
# Experimental and Analytical Configuration



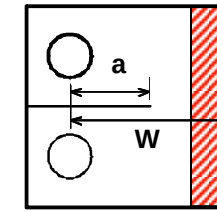
FEM model (1 symmetry plane)

- Establish 3D FEM mesh
  - Elevate temperature of FSW material
  - Cool FSW to room temperature
  - Residual stress developed from thermal contraction
- Thermal residual stress model:  
 $\alpha \cdot \Delta T$
  - Schindler slitting for experimental  $K_{\text{residual}}$

# Residual Stress Distribution

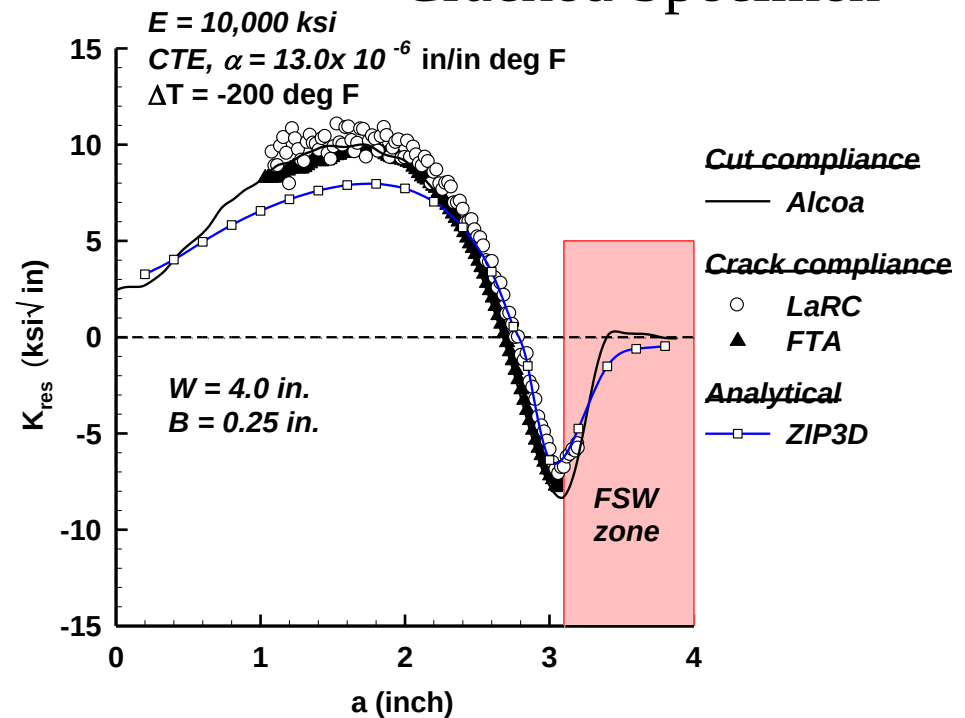


Uncracked Specimen



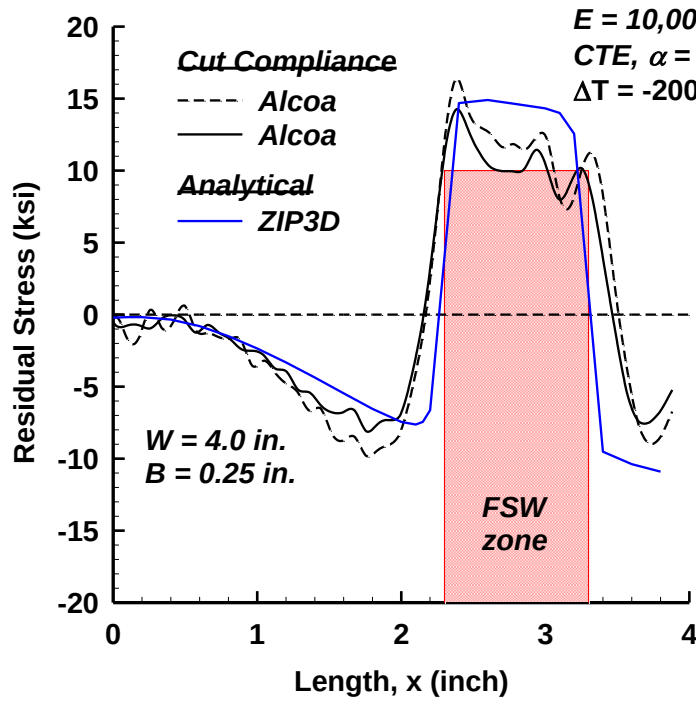
Tensile configuration

## Cracked Specimen

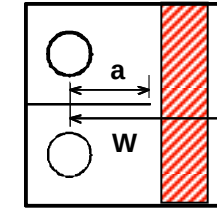


- Thermal residual stress model produces a consistent results compared to experimentally measured methods

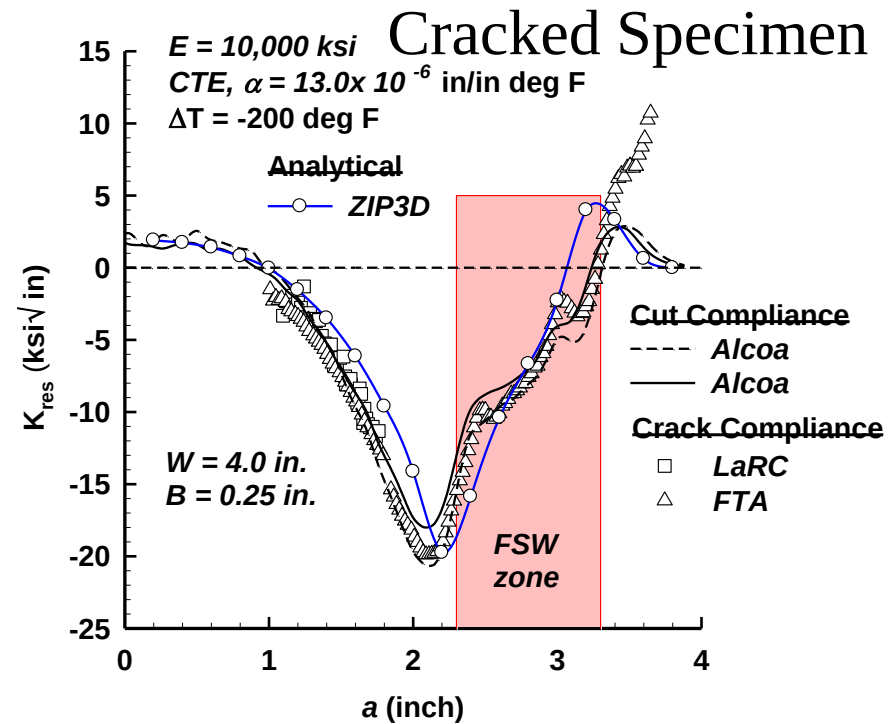
# Residual Stress Distribution



Uncracked Specimen



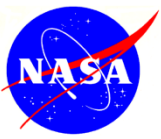
Compressive configuration



- Thermal residual stress model produces a consistent results compared to experimentally measured methods

# Summary

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- Residual stress evaluation of FSW coupons
  - Two compliance-based methods in excellent agreement
    - Cut-compliance
    - Crack-compliance
  - Cut-compliance only provides residual stress data
  - Crack-compliance testing provides:
    - Residual stress data
    - Crack growth rate data
- Preliminary results suggest that residual stress has a “mean stress” like effect on FCGR data
  - $K_{\text{max tip}} = K_{\text{max residual}} + K_{\text{max applied}}$
- Analytical method using thermal residual stress shows excellent agreement with experimental measurements
  - Can analytical method be used to predict residual stress in a structure?
  - Can a 3D FEM analysis including residual stress be used to develop accurate fatigue life predictions for a structure?