PREDICTION OF LOWER BOUND FRACTURE TOUGHNESS IN THE TRANSITION TEMPERATURE REGION BY $T_{33}$-STRESS

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2012/7/25
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  – Predict lower bound $J_c$ for TST

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  – Predict lower bound $J_c$ for TST
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■ Summary and Future Plans
Background
Background: Size effect on $J_c$

- Fracture toughness $J_c$: test specimen size effect

Temperature

Fracture toughness

$K_{lc}$

$J_{c\text{ shallow}} > J_{c\text{ deep}}$

Deep crack

Shallow crack

Lower-shelf Region

Transition Region

Upper-shelf Region
Background: Size effect on $J_c$

- “Planar” size effect on $J_c$
  - Differences in crack tip constraint
  - $T$-stress (Larsson & Carlsson, Rice)
  - Hancock et al., O’Dowd, ...
    - $T_{11} > 0$

- Mechanical issue
Test Specimen Thickness effect on $J_c$ (1)

• Test Specimen Thickness (TST) effect on $J_c$
  – Wallin
    • $J_c \propto B^{-1/2}$
  – Anderson et al.
    • Weakest Link (WL) Model

• Material issue
Test Specimen Thickness effect on $J_c(2)$

- **Contradiction**
  - $J_c \propto B^{-1/2}$: $J_c \rightarrow 0$ for $B \rightarrow \infty$

- **TST effect on actual flaw**
  - **Not clear**: definition of $B$?

- **Meshii et al.**
  - Out-of-plane constraint issue
  - Mechanical parameter: $T_{33}$

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Previous Results for S55C (1)

• Fracture toughness test
  – 0.55% carbon steel S55C at R.T.

  CT: \( B/W = 0.25 \sim 0.5 \)

  3PB: \( B/W = 0.25 \sim 0.5 \)

• \( P-V_g \) curve
  – \( P_c/P_Q > 1.1 \text{ } \rightarrow K_{IC} \text{ invalid} \)
  – \( J_c \) for \( P_c \) evaluated by E1820
  – \( K_c : K \) for \( P_c \)

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Previous Results for S55C (2)

- Exp: (S55C*)

$$J_c \propto B^{-1/2}$$

$$K_c = 66 \text{ MPa m}^{1/2}$$

Previous Results for S55C (3)

- Exp & FEA: (S55C*)

\[ J_c \propto |T_{33c}|^{1/2} \]
Background

Motivation

– Predict lower bound $J_c$ for TST
Motivation

- Anderson et al.
  - Contradiction: $J_c \to 0$ for $B \to \infty$

- Meshii et al.
  - Correlated with $T_{33}$: $J_c \propto |T_{33}|^{1/\gamma}$

Predict lower bound $J_c$ for TST & Solve the contradiction
Failure Criterion

• ‘Planar’ Failure Criterion
  – Ritchie et al.
  – Shih

  \( \sigma_{22} \geq \sigma_{22c} \) at \( l_c \)

  – Dodds et al.
    • Critical distance: \( l_c = 4 \delta_t \)
    • Quantified \( a/W \) effects on \( J_c \)

• Out-of-plane TST issue

\( J_{SSV} = J_{SSV_r} \)
Background

Motivation
– Predict lower bound $J_c$ for TST

FEA
– Derivation of failure criterion for S55C
Elastic-Plastic FEA
Standard CT Specimen

• Model
  – 1/4 symmetry (CT, B/W = 0.5, a/W = 0.5)
  – Side groove: removing constraint
  – Circular hole $\rho = 0.004$ mm

• Material
  – J2-incremental plasticity
  – Ramberg-Osgood
    $$n = 6.9, \alpha = 1.61, \sigma_0 = 428 \text{ MPa} \quad \frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha \left( \frac{\sigma}{\sigma_0} \right)^n$$

• Maximum load
  – $K_{c \text{S55C}} = 66$ MPa m$^{1/2}$ (30 load steps)

• Solver: WARP3D
  – Focused on thickness center value
Derivation of Failure Criterion for S55C

- **Standard CT specimen**: $K_c \text{S55C} = 66 \text{ MPa m}^{1/2}$

- Crack tip opening displacement $\delta_t$: 0.04 mm
- Crack opening stress $\sigma_{22} (\theta=0)$ distribution

**CT specimen, W=25 mm, B/W=0.5**

$\sigma_{22c} = 1530 \text{ MPa}$

Failure criterion: $(l_c = 0.16 \text{ mm}, \sigma_{22c} = 1530 \text{ MPa})$
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– Validation of failure criterion to out-of-plane TST issue
Validation of failure criterion for out-of-plane TST issue

- Elastic-plastic FEA for non-standard test specimen

CT specimen

3PB specimen

\( B/W = 0.5 \)

\( B/W = 0.4 \)

\( B/W = 0.25 \)
Validation of failure criterion for out-of-plane TST issue

1. Step 1: Large Stain FEA for 1/2TCT ($B/W=0.4$)

$K_{\text{max}} = 1.1 \times K_{c\ S55C}$

$P_{\text{max}} @$

$\sigma_{22}(\theta=0)$ distribution at specimen thickness center for each load step

$\sigma_0 = 428 \text{ MPa}, \alpha = 1.61, n = 6.9$

$E = 206 \text{ GPa}, \nu = 0.3$

Increasing Load

load step 1

load step 10

load step 30

$B = W = 0.4$

Large Strain FEA
Validation of failure criterion for out-of-plane TST issue

Step 2: Extract $\sigma_{22} (\theta = 0)$ values at $l_c = 0.16$ mm

$\sigma_{22} (\theta=0)$ at the critical distance $l_c = 0.16$ mm

<table>
<thead>
<tr>
<th>load step $i$</th>
<th>$P_i/P_{max}$</th>
<th>$\sigma_{22i}$ MPa ($l_c=0.16$ mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.900</td>
<td>1529.0</td>
</tr>
<tr>
<td>16</td>
<td>0.908</td>
<td>1542.4</td>
</tr>
</tbody>
</table>

$\sigma_0 = 428$ MPa, $\alpha = 1.61$, $n = 6.9$
$E = 206$ GPa, $\nu = 0.3$
Validation of failure criterion for out-of-plane TST issue

- **Step 3: Derive fracture load:** \( P_{c\text{ FEA}} \)

<table>
<thead>
<tr>
<th>load step ( i )</th>
<th>( P_i/P_{\text{max}} )</th>
<th>( \sigma_{22, i} ) MPa (( l_c=0.16 ) mm)</th>
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</table>

\( \sigma_{22\, c}=1530 \) MPa

\[
P_{c\text{ FEA}} = \frac{P_{i+1} - P_i}{\sigma_{22\, i+1} - \sigma_{22\, i}} \cdot (\sigma_{22\, c} - \sigma_{22\, i}) + P_i
\]

- **Step 4: Estimate** \( K_{c\text{ FEA}} \)

\[
K_{c\text{ FEA}} = \frac{P_{c\text{ FEA}}}{\sqrt{B B_N W}} f_{CT} \left( \frac{a}{W} \right)
\]
Validation of failure criterion for out-of-plane TST issue

- Estimated $K_c^\text{FEA}$ for other CT & 3PB specimens

$K_c^\text{FEA}$: almost constant for TST

Failure criterion ($l_c$, $\sigma_{22c}$) applicable

Out-of-plane TST issue
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FEA
- Derivation of failure criterion for S55C
- Validation of failure criterion to out-of-plane TST issue
- Predict lower bound $J_c$ for TST
Prediction of Lower Bound $J_c$

- **Non-standard 3PB specimen**
  \[(B/W=0.25\sim0.5; \ 0.75\sim2.0)\]

- **Failure criterion** ($l_c=0.16\ \text{mm}$, $\sigma_{22c}=1530\ \text{MPa}$)

\[
\begin{array}{c|c|c|c|c|c|c|c|c|c|c|c|c}
\hline
B/W & 0.25 & 0.4 & 0.5 & 0.75 & 1.0 & 1.25 & 1.5 & 1.75 & 2.0 \\
\hline
J_c^{\text{FEA}} & \circ & \triangle & \square & + & \diamond & < & \triangledown & & \\
\hline
\end{array}
\]

Lower bound $J_c$ obtained for $B/W \geq 1.5$
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Prediction of Lower Bound $J_c$ with $T_{33}$-stress

- **Model**
  - 1/4 symmetry
  - Side groove: removing constraint
  - $W=25$ mm, $B/W=0.25~2.0$
  - Singular element: $\Delta l/a=0.0016$

- **Load:** $K_0=1$ MPa m$^{1/2}$

- **Values at specimen center**
  - $K,T_{11}$: little change
  - $T_{33}$: significant change
  - $T_{33}$: a bound value for $B/W \geq 1.5$

\[ \beta_{kk} = \frac{T_{kk} \sqrt{\pi a}}{K_0} \quad (k = 1, 3) \]
Prediction of Lower Bound $J_c$ with $T_{33}$-stress

- Lower bound $J_c^{\text{FEA}}$ predicted by $T_{33}$-stress

![Graph showing prediction of lower bound $J_c$ with $T_{33}$-stress](image)
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■ Summary and Future Plans
Summary & Future Plans

• The ‘planar’ failure criterion
  – Applicable for out-of-plane TST issue
• Lower bound $J_c$ for S55C: $B/W \geq 1.5$
• Lower bound $J_c$ could be predicted by $T_{33}$-stress

Next study plan…
  – Validate the lower bound $J_c$ by fracture toughness test
  – Numerical study for different materials and test specimens
  – Correlate test specimen $J_c$ with actual flaw
$\sigma_{22}$ distribution ($\theta = 0$) at $K_c = 66$ MPa m$^{1/2}$

CT-W=25 mm-B/W=0.25 ~ 0.5
$\sigma_{22}$ distribution ($\theta = 0$) at $K_{c,S55C}=66$ MPa m$^{1/2}$

CT-W=25 mm-$B/W=0.25 \sim 0.5$

$\sigma_{22}/\sigma_0$

$l_c=4\delta_t$

$r/a$

$B/W$

- 0.25
- 0.4
- 0.5

$(l_c=0.16$ mm, $\sigma_{22c}=1530$ MPa)
CT-W=25 mm-B/W=0.5-a/W=0.5

S55C: $\sigma_0= 428$ MPa, $\alpha =1.61$, $n=6.9$, $E=206$ GPa

$K_c\ \text{S55C} = 66$ MPa m$^{1/2}$

**$J$ values at thickness center:**

![Graph showing J values](image)
CT-W=25 mm-$B/W=0.5-a/W=0.5$

S55C: $\sigma_0= 428$ MPa, $\alpha =1.61$, $n=6.9$, $E=206$ GPa

$K_{cS55C} = 66$ MPa m$^{1/2}$

**$J$ values in thickness direction:**

[Diagram showing thickness center and free surface with a graph plotting $J_{c, FEA}$ vs. $x_3/(B_N/2)$]
3PB-W=25 mm-B/W=0.5-a/W=0.5

$E=206$ GPa, $\nu=0.3$

Elastic FEA results in thickness direction:

- Free surface
- Thickness center

![Graph showing Elastic FEA results in thickness direction with labels for $K/K_0$, $\beta_{11}$, and $\beta_{33}$.

$K/K_0$, $\beta_{11}$, and $\beta_{33}$ markers are shown with corresponding values on the graph.

$x_3/(B_N/2)$ axis is labeled with values from 0 to 1.
Q: Why TST effect on $J_c$ could be expressed by $T_{33}$-stress?

A: Out-of-plane $\varepsilon_{33}$ at specimen thickness center

Elastic:

Elastic-plastic:
Q: Why the normalized lower bound $J_{c\, FE A}$ is not equal to plane strain $J$.

A: Full plastic 2D $J$ solution according to the method by EPRI, in this work, we conducted 3D FEA for 3PB specimen.
Q: How do you distinguish between shallow cracked specimen and deep cracked specimen?

A: By now, no standard could be follow.

However, in Dodds et. al’s works, they defined $a/W = 0.15$ and $a/W=0.5$. 

Shallow crack $a/W=0.15$  
Deep crack $a/W=0.5$
Q: What is the new point of view in your works?

A: Anderson et al.: material issue

Meshii et al.: mechanical issue

$J_c \propto B^{-1/2}$

$B/W = 0.5$

Increasing $B$

$\log J_c \cdot \log B$

$W = \text{constant}$

$\cdot J_c \propto |T_{33c}|^{1/2}$

Lower bound $J_c$

$f(T_{33})^{38}$

large $B/W$

lower bound
Q: In elastic-plastic FEA, how did you define the keyhole size $\rho$ at the crack tip?

A: McMeeking & Parks: $\text{CTOD} \geq 5\rho$. In this work, $\text{CTOD}/\rho \geq 10\rho$

$\delta_t$: Crack tip opening displacement; CTOD

\begin{align*}
\rho & \quad \text{keyhole size at the crack tip} \\
\Delta & \quad \text{Crack tip opening displacement} \\
R & \quad \text{radius of the tube} \\
a & \quad \text{crack length}
\end{align*}
Q: The $\sigma_{22c}$ value of the failure criterion obtained in this work is very large.

A: For three dimensional cracks, considering triaxial stress state, the equivalent Mises stress was below the true tensile stress $\sigma_B$.

\[
\sigma_{Mises} = \sqrt{\left(\sigma_1 - \sigma_2 \right)^2 + \left(\sigma_2 - \sigma_3 \right)^2 + \left(\sigma_3 - \sigma_1 \right)^2}
\]

\[
\sigma_{Mises} < \sigma_B
\]

CT specimen, $W=25$ mm, $B/W=0.5$

$\sigma_{22c} = 1529.5$ MPa

$l_c = 1.6$ mm