An Investigation of Small-Crack Effects in Various Aircraft Engine Rotor Materials

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• Small fatigue cracks sometimes…
  - Grow at rates faster than anticipated from large-crack data/methods trends
  - Grow at stress intensity factor ranges below the usual large-crack threshold

• The practical engineering challenge is to predict…
  - When this “anomalous” small-crack behavior will occur
  - The actual growth rates of small fatigue cracks on the basis of large-crack data and other appropriate parameters
    - Without having to generate FCG rate data for small cracks, since this is $$$

• A brief investigation was conducted previously to…
  - Survey small-crack effects in a variety of common gas turbine engine rotor materials
  - Critically evaluate one simple engineering model that can be used to correlate small-crack behavior with corresponding large-crack behavior
  - Evaluate the potential significance of the small-crack effect for life prediction
Rotor Materials Studied

• Ti-6Al-4V
  ➢ Lenets et al. (Honeywell)
  ➢ Caton et al. (AFRL)
  ➢ Brown and Taylor

• Ti-6Al-2Zr-4Sn-6Mo
  ➢ Jha et al. (AFRL)

• IMI 685
  ➢ Hicks and Brown

• IN-100
  ➢ Jha et al. (AFRL)

• Astroloy
  ➢ Hicks and Brown

• Udimet 720
  ➢ Kantzos et al. (NASA-Glenn)
Criteria for Data Selection

• Small-crack and large-crack data available for the same heat of material under the same test conditions ($T$ and stress ratio)

• Adequate information available to characterize the large-crack threshold and the smooth specimen endurance limit
  ➢ Or, in the absence of these material property values, the material grain size

• Excluded data (mostly)
  ➢ Microstructurally-small cracks (usually crack size < grain size)
  ➢ Test conditions involving severe elastic-plastic loading conditions (very high stresses and non-negligible general plasticity)

• Focus on engineering analysis methods based on LEFM

• Most small cracks considered in this study would be commonly regarded as “physically-small.”
Small-Crack Analysis Method

- Simple analysis method suggested by El Haddad

\[ \Delta K_{eq} = F(a) \Delta S \sqrt{\pi (a + a_0)} \]

\[ a_0 = \frac{1}{\pi} \left( \frac{\Delta K_{th}}{F \Delta S_\theta} \right)^2 \]
Ti-6Al-4V, $R = 0.1$
Honeywell and AFRL Data

Small-crack vs. large-crack data

EH adjustment on small-crack data
Ti-6Al-4V, $R = 0.5$
Honeywell and AFRL Data

Small-crack vs. large-crack data

EH adjustment on small-crack data
Ti-6Al-4V, $R = -1$
AFRL Data

Small-crack vs. large-crack data

EH adjustment on small-crack data

**Graphs:**
- **Left Graph:**
  - Title: Ti-6Al-4V, $R = -1$
  - Data: Long Cracks (gray), Small Cracks (red)

- **Right Graph:**
  - Title: Ti-6Al-4V, $R = -1$
  - Data: Long Cracks (gray), AFRL Small Cracks (red)
Ti-6Al-4V, $R = 0.2$
Brown and Taylor Data

Coarse-Grained Microstructure

Fine-Grained Microstructure

Ti-6Al-4V, CG (Brown & Taylor)
$R = 0.2$

Ti-6Al-4V, FG (Brown & Taylor)
$R = 0.2$
Ti-6Al-2Zr-4Sn-6Mo, R = 0.1
AFRL Data

Small-crack vs. large-crack data
EH adjustment on small-crack data
IMI 685, $R = 0.1$

Hicks and Brown Data

- IMI 685 has a Widmanstatten alpha + beta colony structure with a large prior beta grain size, and so the relevant microstructural dimension for this microstructure is probably the colony size instead of the grain size.
IN-100, $R = 0.05$

AFRL Data

Small-crack vs. large-crack data

EH adjustment on small-crack data

<table>
<thead>
<tr>
<th>$da/dN$ (in/cyc)</th>
<th>$\Delta K$ (ksi$\cdot$in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-9}$</td>
<td>1</td>
</tr>
<tr>
<td>$10^{-8}$</td>
<td>10</td>
</tr>
<tr>
<td>$10^{-7}$</td>
<td>100</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

167 ksi (Pore) - EH (Pore)
167 ksi (NMP) - EH
174 ksi (Pore) - EH
167 ksi (Pore) - EH 6GS
167 ksi (NMP) - EH 6GS
174 ksi (Pore) - EH 6GS
Long Cracks
Astroloy, $R = 0.1$
Hicks and Brown Data

Coarse-Grained Microstructure
Fine-Grained Microstructure

EH correction based on $a_0 = 6^*GS$
Udimet 720, $R = -0.33$
NASA-Glenn Data

Small-crack vs. large-crack data

EH adjustment on small-crack data

EH correction based on $a_0 = 6 \times GS$
Small-crack vs. large-crack data

EH adjustment on small-crack data

EH correction based on $a_0 = 6 \times GS$
But is the Real Problem Just the Large-Crack Threshold Data?

- So are the large-crack and small-crack data different only because there is something wrong with the large-crack data?
- In particular, are the near-threshold large-crack data suspect because they were generated with conventional load-reduction (LR) test methods?
- Compare small-crack data with large-crack data generated using LR test methods and large-crack data generated using Compression Pre-cracking, Constant Amplitude (CPCA) methods
  - Same heat of material
  - CPCA testing by Ruschau at UDRI
Small Crack Data vs. Large Crack Data (LR and CPCA)

Ti-6Al-4V

$\Delta K$ (ksi $\Delta$ in)

$\text{da/dN (in/cyc)}$
What Difference Does It Make?

- If we used small-crack data/methods instead of large-crack data/methods, what difference would it make in life prediction for practical problems?
- Do a brief simulation study for one material and one $R$ value, considering different initial crack sizes and different stress ranges.
- Look at the ratio of the two predicted life values ($N_{\text{small}}/N_{\text{large}}$) as a function of $a_{\text{initial}}$ and $\Delta\sigma$. 
Tabular and NASGRO Eqn Fits of R = 0.1 Ti-6Al-4V Data

<table>
<thead>
<tr>
<th>da/dN (in/cyc)</th>
<th>10^{-10}</th>
<th>10^{-9}</th>
<th>10^{-8}</th>
<th>10^{-7}</th>
<th>10^{-6}</th>
<th>10^{-5}</th>
<th>10^{-4}</th>
<th>10^{-3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>K (ksi in)</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ti-6Al-4V
R = 0.1

- Tabular Data
- NASGRO Equation
Life Prediction Ratio for El Haddad Approach with Tabular Data

<table>
<thead>
<tr>
<th>Initial crack depth, $a$ (inches)</th>
<th>N_{small crack}/N_{large crack}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.0</td>
</tr>
<tr>
<td>0.002</td>
<td>0.2</td>
</tr>
<tr>
<td>0.004</td>
<td>0.4</td>
</tr>
<tr>
<td>0.006</td>
<td>0.6</td>
</tr>
<tr>
<td>0.008</td>
<td>0.8</td>
</tr>
<tr>
<td>0.010</td>
<td>1.0</td>
</tr>
</tbody>
</table>

$\Delta \sigma = 36$ ksi
$\Delta \sigma = 45$ ksi
$\Delta \sigma = 54$ ksi
$\Delta \sigma = 72$ ksi
$\Delta \sigma = 90$ ksi
$\Delta \sigma = 108$ ksi

Tabular data with $a_0$ in stress intensity factor.
Life Prediction Ratio for El Haddad Approach with NASGRO Eqn

Initial crack depth, $a$ (inches)

$N_{\text{small crack}}/N_{\text{large crack}}$

$\Delta = 36$ ksi

$\Delta = 45$ ksi

$\Delta = 54$ ksi

$\Delta = 72$ ksi

$\Delta = 90$ ksi

$\Delta = 108$ ksi

NASGRO Equation with $a_0$ in stress intensity factor
The NASGRO equation is given by

\[
\frac{da}{dN} = C \left[ \frac{1 - f}{1 - R} \right]^{\Delta K} \left( 1 - \frac{\Delta K_{th}}{\Delta K} \right)^p \left( 1 - \frac{K_{\text{max}}}{K_c} \right)^q
\]

Where the threshold parameter \( \Delta K_{th} \) is described for \( R > 0 \) by the form

\[
\Delta K_{th} = \Delta K_1^* \left( \frac{1 - R}{1 - f[R]} \right)^{(1 + RC_{th}^p)} / (1 - A_0)^{(1 - R)C_{th}^p}
\]

with

\[
\Delta K_1^* = \Delta K_1 \left( \frac{a}{a + a_0} \right)^{1/2}
\]
Small-Crack Effect in NASGRO

Threshold Behavior for various $a/a_0$ values

Curve Parameters
- $S_{max}/S_0 = 0.3$
- $\alpha = 2.5$
- $K_c = 71.2$
- $C = 2 \times 10^{-9}$
- $n = 3$
- $p = 0.25$
- $q = 0.75$
- Yield = 140
- $K_{1c} = 45$
- $A_k = 0.5$
- $B_k = 1$
- $D K_1 = 1.57 \times tfac$
- $C_{th} = 1.04$

Graph showing:
- Fit for $R = 0$, $a/a_0 = 0.04$
- Fit for $R = 0$, $a/a_0 = 0.5$
- Fit for $R = 0$, $a/a_0 = 1$
- Fit for $R = 0$, $a/a_0 = 10$
- Fit for $R = 0$, $a/a_0 = 1000$
Life Prediction Ratio for NASGRO Equation Approach

NASGRO Equation with $a_0$ in threshold term

$N_{\text{small crack}}/N_{\text{large crack}}$

Initial crack depth, $a$ (inches)

$\Delta = 36 \text{ ksi}$

$\Delta = 45 \text{ ksi}$

$\Delta = 54 \text{ ksi}$

$\Delta = 72 \text{ ksi}$

$\Delta = 90 \text{ ksi}$

$\Delta = 108 \text{ ksi}$
\[ \frac{N_{\text{small crack}}}{N_{\text{large crack}}} \text{ for Different } a_0 \text{ Implementations} \]
Ratio of Predicted Lifetimes
With $a_0$ in Threshold or SIF term

NASGRO Equation, life ratio with $a_0$ in threshold
or $a_0$ in stress intensity factor

$N_{\text{small crack (thresh)/small crack (SIF)}}$ vs $a_0$ (inches)

Initial crack depth, $a$ (inches)

- $[]= 36$ ksi
- $[]= 45$ ksi
- $[]= 54$ ksi
- $[]= 72$ ksi
- $[]= 90$ ksi
- $[]= 108$ ksi
Observations: Small-Crack Behavior and Model

- All rotor alloys investigated here exhibited accelerated growth rates when crack sizes were very small. These growth rates tended to merge with large-crack trends as the cracks became larger.

- This behavior does not appear to be explained by difficulties with large-crack threshold test methods.

- The El Haddad correction was generally successful in correlating small-crack and long-crack data, although it (conservatively) overcorrected the small-crack data in some cases.

- When endurance limit data were not available to calculate $a_0$, it appeared reasonable to estimate $a_0$ as a multiple of grain size.
Observations:
Significance of Small-Crack Effects

• For Ti-6Al-4V, small-crack effects are predicted to be significant for life prediction only over a narrow range of very small initial crack sizes (which is dependent on stress range)

• However, within this range, the differences between large-crack and small-crack predictions can be very large (infinite life vs. finite life)

• The magnitude of these differences varies with the specific small-crack model used, but the overall trends are relatively robust

• The generality of these conclusions to other materials has not yet been established
Acknowledgments

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    • Jack Telesman

• Data

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