Creep, fatigue and environmental interactions and their effect on crack growth in superalloys

J. Telesman, T.P. Gabb, L.J. Ghosn, T. Smith

NASA Glenn Research Center – Cleveland, OH

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Presentation Overview

• Complex interactions of creep/fatigue/environment control dwell fatigue crack growth (DFCG) in superalloys.

• Crack tip stress relaxation during dwells significantly changes the crack driving force and influence DFCG.

• Linear Elastic Fracture Mechanics, $K_{\text{max}}$, parameter unsuitable for correlating DFCG behavior due to extensive visco-plastic deformation.

• Magnitude of remaining crack tip axial stresses controls DFCG resistance due to the brittle-intergranular nature of the crack growth process.

• Proposed a new empirical parameter, $K_{\text{srf}}$, which incorporates visco-plastic evolution of the magnitude of remaining crack tip stresses.

• Previous work performed at 704°C, extend the work to 760°C.
Material: Low Solvus High Refractory (LSHR) P/M nickel-base disk alloy

<table>
<thead>
<tr>
<th>Wt. %</th>
<th>Al</th>
<th>B</th>
<th>C</th>
<th>Co</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Nb</th>
<th>Ta</th>
<th>Ti</th>
<th>W</th>
<th>Zr</th>
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</thead>
<tbody>
<tr>
<td>LSHR</td>
<td>3.5</td>
<td>.03</td>
<td>.045</td>
<td>20.4</td>
<td>12.3</td>
<td>2.7</td>
<td>Bal.</td>
<td>1.5</td>
<td>1.5</td>
<td>3.5</td>
<td>4.3</td>
<td>0.05</td>
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</tbody>
</table>

Four Supersolvus Heat Treatments Evaluated

<table>
<thead>
<tr>
<th>Condition</th>
<th>Cooling Rate (°C/min)</th>
<th>Aging Treatment</th>
<th>Thermal Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC+2SA</td>
<td>202°C/min</td>
<td>855°C/4 h +775°C/8h</td>
<td>None</td>
</tr>
<tr>
<td>SC+2SA</td>
<td>72°C/min</td>
<td>855°C/4 h +775°C/8h</td>
<td>None</td>
</tr>
<tr>
<td>FC+2SA+440</td>
<td>202°C/min</td>
<td>855°C/4 h +775°C/8h</td>
<td>815°C-440 h</td>
</tr>
<tr>
<td>SC+2SA+440</td>
<td>72°C/min</td>
<td>855°C/4 h +775°C/8h</td>
<td>815°C-440 h</td>
</tr>
</tbody>
</table>

Testing performed at 704 °C and 760°C

**Baseline FCG Testing:**
- Cyclic FCG in Air and Vacuum; 0.333 to 30 Hz
- Dwell FCG in Air and Vacuum; 90 sec hold at $\sigma_{\text{max}}$
- Specimen Geometry: Surface Flaw (KB bar)

**Baseline Stress Relaxation Testing:**
- Strained to 1% total strain
- Stress relaxation measured for 100 h.
- Specimen: Cylindrical (4.05 mm diam.)
Separating Environmental Effects from Stress Relaxation

- All four conditions show faster cyclic FCGR in air than in vacuum – environmental debit.
- All conditions exhibited similar FCG resistance behavior but environmental effect is smaller at higher frequency.
- Assume these conditions posses similar *intrinsic* environmental resistance.
- Any differences in their dwell FCG resistance are then due to stress relaxation effects.
At 704°C:

- 90 sec dwell FCG rates in vacuum same as cyclic FCG in vacuum – **No Dwell Debit**

- Creep crack growth does not contribute towards dwell crack growth

- An order of magnitude increase in DFCG in air due to environmental damage
• Brittle-intergranular failure mode was operative in air for 90 sec dwell.

• Only transgranular failure mode operative in vacuum. No evidence of grain boundary sliding or microvoid coalescence found (classical creep crack growth did not directly contribute to DFCG).

• Grain boundaries are strong! Cracks avoid growth along grain boundaries when environmental embrittlement or creep mechanisms are not operative.
• Four heat treatments: similar env. resistance → 10x difference in DFCG.

• “Creepier heat treatments” i.e. slower cooling rates and thermal exposures improve DFCG resistance.

• Environmental resistance similar – DFCG differences due to stress relaxation.

• LEFM Kmax parameter unsuitable for correlating visco-plastic influenced DFCG response.
• Stress relaxation stresses decrease with slower cooling rates and ↑thermal exposure.

• Remaining stresses closely correlate with dwell fatigue crack growth

  *Classical creep propagation mechanisms DO NOT contribute to crack growth*

• Why is magnitude of remaining stresses important? **What governs the relationship?**

*Remaining Stress = Relaxation Stress*
DFCG Failure Mechanism

- Cracks grow through brittle-intergranular process controlled by crack tip tensile stress
- Magnitude of crack tip tensile stress controls DFCG propagation rates
- Stress relaxation behavior sets the magnitude of crack tip tensile stresses
- Strong, yet indirect relationship between stress relaxation and DFCG behavior

Embrittled crack tip region – Interrupted 90s dwell tests
New Empirical Parameter for Modeling Dwell Crack Growth in Air

Approach: Use stress relaxation results to simulate and normalize the differences in the crack tip tensile stresses under visco-plastic conditions

\[ K_{srf} = \frac{K_{max}}{SRF} \]

- \( K_{srf} \) – modified stress intensity factor normalized by \( SRF \)
- \( K_{max} \) – Applied LEFM stress intensity factor during dwells

\[ SRF = \left( \frac{\sigma_0}{\sigma_m} \right)^4 \]

- SRF= stress relaxation factor
- \( \sigma_0 \)= remaining stress at the onset of steady state creep (highest remaining stress condition)
- \( \sigma_m \)= remaining stress for other conditions – onset of steady state creep

\[
\dot{\varepsilon} = A\sigma^{n1}t^m + B\sigma^{n2}
\]

- \( n2 = 4 \) (steady state creep component per the relaxation fit)
New Empirical Parameter for Modeling Dwell Crack Growth in Air

Plots of $da/dt$ vs $K_{\text{max}}$ and $K_{\text{srf}}$: 704°C

- New $K_{\text{srf}}$ parameter able to compensate for a 10x spread in DFCG rates using standard LEFM parameter.
DFCG in Vacuum and Air – Behavior at 760°C

- In contrast to 704°C, creep crack growth occurs in vacuum at 760°C.
- More significant at high ΔK → increase in crack tip plasticity.

- DFCG in air 100x faster than in vacuum.
- Environmental degradation is predominant… Ksrf approach may still be applicable.
Comparison of Microstructural Damage Mechanisms

704°C – 90 sec; Vacuum

- High Kmax

- Lower T.; DFCG=Cyc FCG;
- No evidence of creep damage
- Transgranular failure mode

760°C – 90 sec; Vacuum

- High Kmax

- High Temp; DFCG > CFCG
- Slow DFCG
- Grain boundary creep cavitation

760°C – 90 sec; Air

- High Kmax

- High T; DFCG>>CFCG
- Fast DFCG
- Environmentally induced intergr. failure mode dominant
- Inadequate time for creep cavitation
Identical methodology used to calculate $K_{srf}$ as at 704°C

$K_{srf}$ correlated DFCG within 2X for FC+2SA and SC+2SA (no exposures)

Other two conditions experienced likely specimen mixup at the vendor…No agreement between stress relaxation repeats, sorting out the issues…
Conclusions

- A new empirical parameter, $K_{srf}$, proposed to correlate DFCG in superalloys.

- The new parameter modifies LEFM$_{K_{\text{max}}}$ parameter by accounting for differences in visco-plastic evolution of the magnitude of remaining crack tip axial stresses.

- Magnitude of remaining crack tip axial stresses controls DFCG resistance due to the brittle-intergranular nature of the crack growth process.

- The parameter works well at 704°C and looks promising even at 760°C.

- Creep crack growth mechanisms are active at 760°C but are still considerably lower than the environmentally induced DFCG debit.
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