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>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>
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<td>None</td>
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<tr>
<td>FC+2SA+440</td>
<td>202°C/min</td>
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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 possess 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

Yet… **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

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

\[ K_{sr} \] – 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.
• In contrast to 704°C, creep crack growth occurs in vacuum at 760°C
• More significant at high $\Delta K \rightarrow$ 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 $K_{\text{surf}}$ as at 704°C
$K_{\text{surf}}$ 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 \( \text{LEFM}_\text{Kmax} \) 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.
Acknowledgment

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