The Effect Stacking Fault Segregation and Phase Transformations Have on Creep Strength in Ni-based Superalloys

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Ni-Based Superalloys for Turbine Disks
Motivation for Mechanistic Studies

- Material advancements are required to accommodate the higher compressor exit temperatures in jet turbine engines (>700°C near the rotor rim) for improved efficiency and pollution reduction.

- New deformation mechanisms will become dominant at these higher operating temperatures along with a need for improved creep properties in these disk alloys.

- New understanding and materials will be needed for future advancements
Deformation Mechanisms in Superalloys

**Disk Alloys**

- **T < 700° C**
- Athermal γ' shearing by 1/2<110> dislocations

**Y Phase (FCC)**

**Y' Phase (L1_2)**

**Blade Alloys**

- **T > 900° C**
- Climb By-Pass of γ' by individual 1/2<110> dislocations

*Epishin and Link (2008)*
Deformation Mechanisms in Superalloys

**Disk Alloys**
- T<700°C
  - Athermal γ' shearing by 1/2<110> dislocations

**Novel mechanisms:**
- Stacking Fault Cutting
- Microtwinning
- Stacking Fault Ribbons

**Blade Alloys**
- T>900°C
  - Climb By-Pass of γ' by individual 1/2<110> dislocations

**Diffusion mediated creep deformation**

*Epishin and Link (2008)*
Segregation along superlattice stacking faults has been observed in numerous Ni and Co-based superalloys.
New insight into alloy effects:

- Segregation of $\gamma$ formers in ME3 promotes microtwinning
- Formation of $\eta$ phase at faults in ME501 inhibits microtwinning and improves creep strength
Does the observed $\chi$ ($\text{Co}_3\text{W}$) or $\gamma$ phase transformations along SISFs have any impact on creep properties?

CMSX-4 (high W content)*

*Smith et al. 2018
Material Preparation

<table>
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<tr>
<th>Alloy</th>
<th>Cr</th>
<th>Co</th>
<th>Al</th>
<th>Ti</th>
<th>Nb</th>
<th>Mo</th>
<th>Ta</th>
<th>W</th>
<th>Zr</th>
<th>B</th>
<th>C</th>
<th>Ni</th>
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<tbody>
<tr>
<td>LSHR</td>
<td>12.5</td>
<td>20.4</td>
<td>3.5</td>
<td>3.5</td>
<td>1.5</td>
<td>2.7</td>
<td>1.5</td>
<td>4.3</td>
<td>0.05</td>
<td>0.03</td>
<td>0.045</td>
<td>Bal</td>
</tr>
<tr>
<td>ME3</td>
<td>13</td>
<td>21</td>
<td>3.4</td>
<td>3.8</td>
<td>0.8</td>
<td>3.7</td>
<td>2.4</td>
<td>2.1</td>
<td>0.05</td>
<td>0.02</td>
<td>0.05</td>
<td>Bal</td>
</tr>
</tbody>
</table>

The two alloys are microstructurally comparable!
Creep Testing of ME3 and LSHR

Creep tests were performed at 760°C under a stress of 552MPa.

LSHR has consistently performed better in creep compared to ME3 in this temperature regime. Why?
No notable differences in active deformation modes could be discerned between the two alloys.
Segregation along SISFs in ME3 and LSHR

Ordered contrast exists along SISFs in LSHR but not ME3
Segregation along SISFs in ME3 and LSHR

Ordered contrast exists along SISFs in LSHR but not ME3
Segregation along SISFs – ME3

Confirmed γ phase nucleation along SISFs in ME3

Co, Cr Segregation
Ni, Al Depletion
Segregation along SISFs - LSHR

Confirmed $\chi$ phase nucleation along SISFs in LSHR

Co, W, Cr Segregation
Ni, Al Depletion
Stacking Fault Ribbon Formation

\[
\frac{a}{3} < 112 > (SISF) + \frac{a}{6} < 112 > (APB) + \frac{a}{6} < 112 > (SESF) + \frac{a}{3} < 112 > = a < 112 >
\]


Stacking Fault ribbons are a major source of primary creep strain in this temperature regime for single crystal superalloys

C.M.F. Rae and R.C. Reed. Acta Materialia. 2007

What effects will \( \gamma \) or \( \chi \) phase formation along SISFs have on this shearing process?
Ni$_3$Al $\gamma'$ cells with an APB were created to explore the effect SISF segregation has on the formation of the trailing APB.

Relaxed energies were compared when a W, Mo, or Cr atom were away from the APB or on the APB.
Phase Transformation Softening – γ Phase

γ phase formation along SISF promotes stacking fault ribbon shear.
Phase Transformation Strengthening – $\chi$ phase

$\chi$ phase formation along SISF inhibits stacking fault ribbon shear

Co, W segregation

APB Energy

Al-site

Energy Difference (eV)
Conclusions

• Significant differences between ME3 and LSHR creep strain rates exist even though the microstructural differences between the two alloys are negligible.

• Slight differences in overall chemistry between the two alloys can result in notable differences in stacking fault segregation. LSHR displayed the formation of Co₃W χ phase along intrinsic stacking faults in γ’ precipitates. In contrast, ME3 displayed the formation of a Co and Cr-rich γ phase along the same fault type.

• This formation of the Co₃W phase along these intrinsic stacking faults represents a novel phase transformation strengthening mechanism, by inhibiting the shear of a<112> stacking fault ribbons.

• Alloy design is alive and aided by advanced characterization and modeling techniques.

• Future work: Can the strengthening η and χ phase transformations be optimized and combined in future Ni-base disk alloy compositions?
Acknowledgements

Questions?

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