Constructing a Validated Deformation Mechanism Map using Low Temperature Creep Strain Accommodation Processes for Waspaloy (a Nickel-Based Superalloy)

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Introduction

Jet Engine

Land-based Gas Turbine

Main criterion for design and inspection: Temperature and load dependent Creep Rate
<table>
<thead>
<tr>
<th>Mechanisms</th>
<th>Rate Equation ([\text{s}^{-1}])</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dislocation Climb</td>
<td>(\dot{\varepsilon} = AD\frac{\alpha_b}{kT} \left(\frac{G}{\delta}\right)^{4.5})</td>
<td>(A \approx 10^6)</td>
</tr>
<tr>
<td>Diffusional Creep</td>
<td></td>
<td>(G = \text{shear Modulus})</td>
</tr>
<tr>
<td>Nabarro-Herring (Bulk)</td>
<td>(\dot{\varepsilon} = BD\frac{\alpha_b}{kT} \left(\frac{G}{B}\right)^{2} \left(\frac{\sigma}{G}\right))</td>
<td>(B \approx 30)</td>
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<tr>
<td></td>
<td></td>
<td>Threshold Stress (\approx 10^{-7} G)</td>
</tr>
<tr>
<td>Coble (Grain Boundary)</td>
<td>(\dot{\varepsilon} = CD \left(\frac{D_{\alpha_b}}{kT}\right) \left(\frac{G}{B}\right)^{2} \left(\frac{\sigma}{G}\right))</td>
<td>(C \approx 30)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(B \approx 30)</td>
</tr>
<tr>
<td>Ashby-Verrall</td>
<td>(\dot{\varepsilon} = FD\frac{\alpha_b}{kT} \left(\frac{G}{B}\right)^{2} \left(\sigma - \sigma_1\right) \left[1 + \frac{\delta}{\alpha} \left(\frac{D_{\alpha_b}}{D}\right)\right])</td>
<td>(F \approx 100)</td>
</tr>
<tr>
<td>(Diffusional Accommodated Flow)</td>
<td></td>
<td>Threshold Stress (\approx G\frac{\delta^2}{\alpha})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\delta = \text{GB thickness})</td>
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<tr>
<td></td>
<td></td>
<td>Threshold Stress (= \sigma_1 = \frac{\alpha f}{\varepsilon})</td>
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<tr>
<td></td>
<td></td>
<td>(\Gamma = \text{GB freeenergy})</td>
</tr>
<tr>
<td>Grain Boundary Sliding</td>
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<td></td>
</tr>
<tr>
<td>Controlled by GB Diffusion</td>
<td>(\dot{\varepsilon} = HD_{\alpha_b}\frac{\alpha_b}{kT} \left(\frac{G}{B}\right)^{2} \left(\frac{\sigma}{G}\right))</td>
<td>(H \approx 8 \times 10^5)</td>
</tr>
<tr>
<td>Controlled by Lattice Diffusion</td>
<td>(\dot{\varepsilon} = LD\frac{\alpha_b}{kT} \left(\frac{G}{B}\right)^{2} \left(\frac{\sigma}{G}\right))</td>
<td>(L \approx 10^7)</td>
</tr>
<tr>
<td>Haper-Dorn</td>
<td>(\dot{\varepsilon} = MD\frac{\alpha_b}{kT} \frac{\sigma}{G} \left(\frac{G}{B}\right)^{2} \left(\frac{\sigma - \sigma_{\text{limb}}}{G^2}\right))</td>
<td>(M \approx 10^{-11})</td>
</tr>
<tr>
<td>Complex Engineering Alloy</td>
<td>(\dot{\varepsilon} = AD\frac{\alpha_b}{kT} \left(\frac{G}{B}\right)^{q} \left(\frac{\lambda + r}{b}\right)^{q-1} \left(\frac{\sigma - \sigma_{\text{GB}}}{{\sigma}_{\text{limb}}}\right))</td>
<td>(A \approx 10^6)</td>
</tr>
<tr>
<td>(GBS in Presence of Precipitates)</td>
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<tr>
<td></td>
<td></td>
<td>(q = 1) (without particles)</td>
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<tr>
<td></td>
<td></td>
<td>(q = 2) (discrete particles)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(q = 3) (continuous network of particles)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\lambda : \text{interlodge spacing})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(r : \text{average grain boundary ledge height})</td>
</tr>
</tbody>
</table>
Deformation Mechanisms Map (DMM)

- Plastic flow is a kinetic process (vs. defined Yield point)
  Controlled by competition between the activation energies over time
  \[ \dot{\gamma} = f(\sigma_s, T, S_i, P_i) \]

- Frost and Ashby et. al. (1982):
  Assumed: state and property does not change over time

Five groups of kinetic processes

1. Dislocation Glide
2. High Temperature Creep
3. Low Temperature Creep
4. Nabarro-Herring Creep
5. Coble Creep
Initial DMM for Superalloys:

Grain boundary sliding significantly contributes to creep rate

Alloy’s DMM is very different from pure metal

Stress Assisted Vacancy Migration

[Mueller & Ashby et. al. 1982]

Grain Boundary Sliding

[Mohammad & Langdon et. al. 1979]
Modified DMM:

Ashby’s Diffusional Creep is different from

1- Grain Boundary Sliding
2- Interface Reaction Controlled Diffusional Creep

If diffusion is active, GB is not the perfect source or sink for vacancies in complex alloys

[Image: Before deformation, After deformation]

[Koul & Castillo 1993 – Inconel 738LC]
Dominance of GBS Confirmed Superalloys:

- The quantitative assessment of the variation of the minimum creep as a reciprocal of the square of the grain size indicates the dominance of GBS.
- GBS is accommodated by dislocation creep (slip) adjacent to the grain boundaries leading to shearing, boundary migration and dissolution of precipitates and the formation of denuded zones.
- Grain boundaries are not good sources and sinks of stress-created vacancies due to segregation of impurities at the grain boundaries. This effect will be more prominent in cast engineering alloys because of decreased grain boundary surface area relative to forged alloys.
- Herring-Nabarro creep is limited to simple metals.

[Wardsworth et al, 2002]
Further Modification on DMM:

Studied Different Engineering Alloys:

GBS dominates the creep deformation

And

Not the common interpretation of diffusional creep

[Wu et al 2009]
Recent Modification on DMM:

Further subdivide the GBS

1- GBS + W-type Cracking
2- GBS + Cavitations + GI

[Banerjee & Koul 2011]
Constructing DMM:

As Minimum requirement;
Numerical techniques together with short term creep tests (PLC) as well as long term creep tests (GBS)

\[
\dot{\varepsilon} = \varepsilon_{gbs} + \varepsilon_{ig}
\]

\[
D_{gbs} = D_{0c}\exp \left( \frac{-Q_c}{RT} \right)
\]

\[
\varepsilon_{gbs} = HD_{gbs} \left( \frac{Gb}{kT} \right) \left( \frac{b}{d} \right)^2 \left( \frac{\sigma}{G} \right)^2
\]

\[
D_{ig} = D_{0v}\exp \left( \frac{-Q_v}{RT} \right)
\]

\[
\varepsilon_{ig} = AD_{ig} \left( \frac{Gb}{kT} \right) \left( \frac{\sigma - \sigma_0}{G} \right)^{4.5}
\]

\[
G = (88.75 - 0.0256 \times T) \times 10^9 \ [Pa]
\]
Data Collection and PLBD:

Average Grain Size 42 micron

[Chamanfar, Jahazi, 2012]

Waspaloy
GS 30 -50

[Lasalmonie et al, 1986]

[National Research Council Canada, 2009]
[Oak Ridge National Laboratory, Lockheed Martin, 2000]
[University of Nottingham, 1997]
[Denmark Riso National Laboratory & Germany Metallgesellschaft A G, Metall-Laboratorium, 1993]
Computational Model for DMM:

\[ \dot{\varepsilon} = \varepsilon_{gbs} + \varepsilon_{ig} \]

\[ \varepsilon_{gbs} = HD_{gbs} \frac{Gb}{kT} \left( \frac{b}{d} \right)^2 \left( \frac{\sigma}{G} \right)^3 \]

\[ \varepsilon_{ig} = AD_{ig} \frac{Gb}{kT} \left( \frac{\sigma - \sigma_0}{G} \right) \]

\[ D_{ig} = D_{0i} \exp \left( \frac{-Q_v}{RT} \right) \]

\[ D_{gbs} = D_{0c} \exp \left( \frac{-Q_c}{RT} \right) \]

\[ G = (88.75 - 0.0256 \times T) \times 10^9 \text{ [Pa]} \]

H = \(8 \times 10^{16}\)

A = \(5 \times 10^{55}\)

[uOttawa, LPTi, 2012]
Open-source R-Project with standard package for computation, Lattice package, and 4D Contour plot for visualization.

[uOttawa, LPTi, 2013]
A Validated Deformation Mechanisms Map using Low Temperature Creep Strain Accommodation Processes for Waspaloy

Expected Transition

[uOttawa, LPTi, 2013]
Conclusion & Remarks:

• A rationale and methodology for constructing DMM has been summarized.

• Unlike the traditional Ashby type DMM with diffusional creep, GBS is considered dominant at lower as well as higher temperature.

• The GBS regime is further subdivided to w-type and r-type cracking although the transition is not well understood.

• A mathematical algorithm has been developed to compute the data for DMM over wide range of stresses and temperatures. This DMM is calibrated to Waspalloy by using experimental data including GBS and PLC, PLBD.

• Grain size effect appears but is not validated.

• This type of DMM is now practically in use for the creep life prediction of GT components and forms the basis of patented prognostic systems.
Thank You

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