Fatigue Cracks cause turbine disk failure, Sioux City, Iowa, UA 232
Hierarchical Materials-Mechanics Design

Multilevel Microstructure as envisioned by Reamur in 1722

Physics - Materials Science - Mechanical Sciences and Eng. (Mech./Aero/Civi)
Multi-Scale Modeling Approach

Physical Understanding

Turbine Disk

Specimen

Agglomerate of Grains

Microstructural Level

Mesoscale

FCC Unit Cell

Defect Level

Rules for dislocation, motion, and multiplication

First principles simulation

Atomistic scale

Modeling Approach

Atomic Level

Huseyin Sehitoglu

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Department of Mechanical Science and Engineering
Stress Concentrations: Railroad Axles, the Versailles Accident

William John Macquorn Rankine
Born: 2 July 1820 in Edinburgh, Scotland
Died: 24 Dec 1872 in Glasgow, Scotland

Fig 1. Classic appearance of a fatigue cracked railway axle from Glynn, 1844.
Stress-Life Curve

Fatigue life, N (cycles)

Stress range (ksi)

failures
run-outs

Fatigue Limit

Lawrence, 99

Department of Mechanical Science and Engineering
Background: Fatigue Scatter

Problem Statement:
- Observed excessive scatter in the fatigue response of a nickel-based superalloy, Udimet 720.
- Scatter can be linked to the variability in the microstructure

Outstanding Issues:
- Criterion for crack initiation of U720
- How does mis-orientated grains effect the fatigue properties?
- How does a small/large grain within a polycrystalline material (with relatively uniform grain size) effect fatigue life?
Bauschinger Effect and the Presentation of the Fatigue Limit

Fig. 1: Portrait of Johann Bauschinger, born on June 11, 1834, and died on November 25, 1893.

\[
\sigma
\]

\[
\Delta \sigma
\]

\[
\Delta \varepsilon_p \approx 10^{-4}
\]
Cyclic Deformation

(a) Fully annealed
$\Delta \varepsilon = 0.0084$
$2N_f = 8060$ reversals

(b) Partially annealed
$\Delta \varepsilon = 0.0078$
$2N_f = 4400$ reversals

(c) Cold worked
$\Delta \varepsilon = 0.0099$
$2N_f = 2000$ reversals
Incremental Test to Determine Cyclic Stress-Strain Curve

130°C - 5x10⁻³ s⁻¹
Cyclic Stress-Strain Curve

\[
\frac{\Delta \varepsilon}{2} = \frac{\Delta \sigma}{2 E} + \left( \frac{\Delta \sigma}{2 K'} \right)^{1/n'}
\]
Early Observations (A. Ewing, Humphreys, W. Rosenhain, 1899)

Fig. 9. Specimen after 1000 reversals of a stress of 12.4 tons per
sq. inch. × 1600.

Fig. 10. Same after 2000 reversals. × 1000.

Fig. 11. Same after 10,000 reversals. × 1000.

Fig. 12. Same after 40,000 reversals. × 1000.
### Historical Background - Fatigue Crack Initiation

<table>
<thead>
<tr>
<th>Microstructure</th>
<th>Continuum (Phenomenological)</th>
<th>Micromechanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ewing and Humfrey, 1900</td>
<td>Coffin, Manson, 1950</td>
<td>T.H. Lin, T. Mura, 1970</td>
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<tr>
<td>McEvily, 1960</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mughrabi, 1980</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
J. A. Ewing and J. C. W. Humfrey.  

Fig. 9. Specimen after 1000 reversals of a stress of 12.4 tons per sq. inch. × 1000.  

Fig. 10. Same after 2000 reversals. × 1000.
Slip and Cross-slip
Source and Precipitate Interactions
McEvily- Boettner, 1963
Mughrabi and Essman’s Model 1979, 1981, 1986

Model of Extrusions and Intrusions from a Persistent Slip Band

Physically Based and well thought out
• Establishes mechanisms and geometry of PSBs
• Irreversible slip processes:
  – Dynamic equilibrium between dislocation multiplication and annihilation in a PSB
    » Production of vacancies by annihilation of edge dislocations
    » Frank-Read source provided multiplication
  – Randomly distribution
  – Leads to elongation of the PSB
• Estimates surface roughness:

Important Parameters:

\[
R_a = 2F \sqrt{Nb \gamma_{PSB} p_{PSB} h_p}
\]

- \( p_{PSB} \) = ratio of irreversible strain to total strain
- \( \gamma_{PSB} \) = plastic strain amplitude in the PSB
- \( h_p \) = thickness of PSB
- \( \rho_e, \rho_s \) = edge and screw dislocation density
Mura and Tanaka Model, 1981

Micro-mechanical model for crack initiation at a PSB

- Energy balance approach of dislocations
  \[ \Delta U = \frac{1}{2} \Delta \gamma (\Delta \tau - 2k) \]

  where
  \[ \Delta \gamma = \frac{(\Delta \tau - 2k) a^2 \pi (1 - \nu)}{\mu} \]

  Failure criterion:
  \[ U = U_I + U_{II} = 2 n_c \Delta U = 4 a W_s \]

- Results in:
  \[ n_c = \frac{4 \pi (1 - \nu) W_s a^3}{\mu \Delta \gamma^2} \]

  where \( W_s \) is specific fracture energy

- Or can be written as a Coffin-Manson type law which has Hall-Petch type grain size dependency on fatigue strength:

  \[ \Delta \tau = 2k + 2 \sqrt{\frac{\mu W_s}{\pi (1 - \nu) n_c a}} \]
Neumann, 1976, 1990

Misfit-Induced Stress + Negate Surface Tractions

\[ \sigma_{ij}(r) = \sigma_{ij}^a \pm \sigma_{ij}^b + \sigma_{ij}^c(r) \]

Others: Van der Giesen and Needleman, 1995; Brinckmann, 2005.
2. Directly Observe Microstructural Effects

Patriarcha et al. (2013)
Shear Increment on System 10
Potential Energy Of Dislocation
Twin Boundaries (special type of Grain Boundary) as an obstacle to Slip
Motivation

- The GB resistance to slip transmission has a great influence on the stress state associated with the pile-up

Hastelloy X
\[ \Delta \sigma = 750 \text{ MPa} \]
N = 10,000 cycles
Crack Formation

Loading Direction

Fiducial marker

200 µm

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Crack Formation

A N = 1,000 Cycles
No Cracks Observed

B N = 10,000 Cycles
Cracks Observed

C N = 10,000+½ Cycles

Stress
900 MPa
1,000 cycles
10,000 cycles
½ Cycle (Tension)

Ref.
Crack Formation-DIC Strains

Used to Measure DIC Strains (No Cracks)
Crack Formation-DIC Strains

Crack Observations 9,000 Cycles Later

A
N = 1,000 Cycles

B
N = 10,000 Cycles
Crack Formation

N = 10,000+½ Cycles
Crack Formation

N = 10,000+½ Cycles
Crack Formation

\[ \Delta \sigma = 900 \text{ Mpa} \]
\[ N = 900 \text{ Cycles} \]

No Transmission (Shielding)

\[ L_c \]
\[ 50 \mu m \]

\[ \frac{1}{2} \text{ Cycle (Tension)} \]

\[ 900 \text{ Mpa} \]
\[ 50 \mu m \]

\[ N = 10,000 \text{ Cycles} \]
Crack Formation

Possible Slip Transmission | Incident Slip (Schmid Factor) | Possible Transmitted Slip (Schmid Factor) | $|b_r|$ (In terms of lattice spacing $a$)
--- | --- | --- | ---
$b_1 \rightarrow b_2$ | $b_1(1\overline{1}1)[\overline{1}01]$ (0.48) | $b_2(\overline{1}11)[110]$ (0.38) | 0.7
$b_1 \rightarrow b_3$ | $b_1(1\overline{1}1)[\overline{1}01]$ (0.48) | $b_3(111)[\overline{1}0\overline{1}]$ (0.34) | 0.7
Crack Formation

Stress

\[ \text{Stress} \]

900 MPa

Ref.

1,000 cycles

10,000 cycles

\( \frac{1}{2} \) Cycle (Tension)

\[ \Delta \sigma = 900 \text{ Mpa} \]

\[ N = 1,000 \text{ Cycles} \]

\[ \Delta \sigma = 900 \text{ Mpa} \]

\[ N = 10,000 \text{ Cycles} \]

\( \varepsilon_{\text{eff}}(\%) \)

\( L_s \)

\( L_C \)

Slip Transmission

\( 50 \mu m \)

\( 50 \mu m \)
Crack Formation

<table>
<thead>
<tr>
<th>Slip Transmission</th>
<th>Incident Slip (Schmid Factor)</th>
<th>Transmitted Slip (Schmid Factor)</th>
<th>$b_1$ (In terms of lattice spacing $a$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_1 \rightarrow b_2$</td>
<td>$b_1 (\bar{1}11)[110]$ (0.46)</td>
<td>$b_2 (111)[110]$ (0.42)</td>
<td>0.5</td>
</tr>
<tr>
<td>$b_2 \rightarrow b_3$</td>
<td>$b_2 (1\bar{1}1)[110]$ (0.42)</td>
<td>$b_3 (\bar{1}11)[101]$ (0.49)</td>
<td>0</td>
</tr>
</tbody>
</table>
Section Conclusions

- The locations and lengths of fatigue cracks relate to prior strain localizations.
- Strain localization is important but Not enough.
- Deformation in the vicinity of GBs should be considered too.
Slip Transmission and Crack Length

Abuzaid et al. (2013)
Fatigue Scatter Results

- Model - Simulated Specimens
- Model - Average
- U720 Experimental Data
- U720 Data - Average

1000 simulated specimens vs. 84 experimental results
Each simulated specimen takes <30 seconds to construct its microstructure and predict fatigue life for a series of strain ranges

---

Fatigue life is calculated for 300 simulated microstructures at different applied strain ranges.

Process of Fatigue

Stage I crack

Stage II crack

Department of Mechanical Science and Engineering
Opening modes

Mode I: Tensile opening

Mode II: Shear opening

Mixed Mode (I and II)
A gage consists of one subset on each of the crack flanks.
A gage consists of one subset on each of the crack flanks.
Contours of Vertical Displacement (mm). Image: Ti_ktest45xV0007
Stress-Life (Crack Initiation)
Fatigue Crack Initiation

Our Mechanism of Interest: Transgranular facets forming from persistent slip bands (PSBs)
Background: Microstructure

Dense γ' region = finer grains

Sparse γ' region = coarser grains

3000x

4 µm²

12 µm²
Stress- Life Testing 1870-1950s

- Bending Apparatus
- Plastic deformation was ignored.
- Fatigue limit concepts were established.
- Goodman Diagram was used for Mean Stress Correction
Goodman Diagram

Stresses are based on net section.

Test conditions
- Unnotched
  \( K_I = 1.0 \)
- Notched
  \( K_I = 3.0 \)

ASM Handbook
Strain Control Testing 1950-

- Driven by high temperature fatigue problems in aeronautical and nuclear industries (Coffin, Manson)
- Deformation of critical zone controlled by elastic surrounding material.
- Strain-life methodology established in ground vehicle industry
- Coupon testing under strain control became widespread and standardized through ASTM.
Local Strain Approach
Summary of Low Cycle Fatigue Results on Hardened Steels

\[ \frac{\Delta \varepsilon_p}{2\varepsilon_f} \] vs. \[ 2N_f \], Reversals to Failure

Fig. 27b Dimensionless Plastic Strain Amplitude – Fatigue Life Plot for Hardened Steels

Materials:
- SAE 1045, Q & T
  - 705 BHN
  - 595
  - 505
  - 450
  - 380
- SAE 4142, Q & T
  - 670 BHN
  - 560
  - 475
  - 450
  - 380
- SAE 4142, Def.
  - 475 BHN
  - 450
  - 405
- Austempered H-11
  - 655 BHN
- 18% Ni Monel
  - 300 ksi
  - 250
  - 200

Landgraf,67
SAE KeyHole Fatigue Program

Fig. 1.1 - SAE load histories

Transmission History
- RQC-100
- Mon-Ten

Bracket History
- RQC-100
- Mon-Ten

Suspension History
- RQC-100
- Mon-Ten

Crack Initiation Life, Blocks

Maximum Load, KN

Crack Initiation Life, Blocks

Maximum Load, KN
Advent of Fracture Mechanics

- Dates back to the work of Griffith
- Modern fracture mechanics established by George Irwin
- Research focused on establishing crack growth properties
- Material constants such as threshold stress intensity, fracture toughness play a role
Stage I and Stage II Crack Growth

I Sensitive to microstructure and environment

II Paris power Law

III Approaching fracture when $K_{\text{max}} \approx K_C$. 

Lawrence, 99
Modified Power Law Crack Growth Rate Relationship

• Traditional Paris Law

\[ \frac{da}{dN} = C (\Delta K)^m \]

where \( \Delta K = Y \Delta \sigma \sqrt{\pi a} \)

and \( \Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} \)

• Modified Paris Law

\[ \frac{da}{dN} = C (\Delta K_{\text{eff}})^m \]

where \( \Delta K_{\text{eff}} = Y \Delta \sigma_{\text{eff}} \sqrt{\pi a} \)

and \( \Delta \sigma_{\text{eff}} = \sigma_{\text{max}} - \sigma_{\text{open}} \)
Load Ratio

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]

R = 0.05  \hspace{1cm} \text{Tension}

R = -1  \hspace{1cm} \text{Compression - Tension}
Contours of Vertical Displacement (mm). Image: Tiik_test4 XV0007
## Fatigue Design Philosophies

<table>
<thead>
<tr>
<th>Design Methodology</th>
<th>Design Philosophy</th>
<th>Description</th>
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<td>Stress-Life</td>
<td>Safe-Life, infinite-life</td>
<td>Stress-Life</td>
</tr>
<tr>
<td>Strain-Life</td>
<td>Safe-Life, finite-life</td>
<td>Strain-Life</td>
</tr>
<tr>
<td>Fracture Mechanics</td>
<td>Damage Tolerant</td>
<td>da/dN- K</td>
</tr>
</tbody>
</table>
High Temperature Fatigue

“crack initiation and propagation”

• start-up and shut-down operations
  – thermally induced stresses

• **Topics**
  – isothermal vs non-isothermal
  – modern testing methodology
  – damage mechanisms
Experimental Setup
Huseyin Sehitoglu
University of Illinois at Urbana-Champaign

Thermo-mechanical Fatigue Behavior of Materials

Huseyin Sehitoglu, Editor

ASTM STP 1186
Examples of Components Experiencing High Temperatures

- Railroad Wheels undergoing Friction Braking
- Brake Rotors
- Pistons, Valves and Cylinder Heads of Spark-ignition and Diesel Engines
- Turbine Blades and Turbine Disks
- Nuclear Industry-pressure vessels and land based gas turbines
Railroad Wheels under Friction Braking

Stress (MPa) vs. Mechanical Strain

60 min, 615°C
55 min, 603°C
50 min, 589°C
45 min, 577°C
40 min, 552°C
35 min, 527°C
30 min, 497°C
25 min, 459°C
20 min, 438°C
15 min, 362°C
10 min, 295°C
5 min, 210°C
110 min, 162°C
105 min, 200°C
95 min, 223°C
90 min, 245°C
85 min, 279°C
80 min, 314°C
75 min, 354°C
70 min, 401°C
65 min, 462°C
60 min, 615°C
55 min, 603°C
50 min, 589°C
45 min, 577°C
40 min, 552°C
35 min, 527°C
30 min, 497°C
25 min, 459°C
20 min, 438°C
15 min, 362°C
10 min, 295°C
5 min, 210°C
Strain Rate Nomenclature

\[ \dot{\varepsilon} = \frac{\Delta \varepsilon}{2T/4} \]

\[ \dot{\varepsilon} = 2\Delta \varepsilon \cdot v. \]

\[ \dot{\varepsilon}_p = 2\Delta \varepsilon_p \cdot v \]

\[ \Delta \varepsilon_p \]
When materials are strained at temperatures (T > .35 T_m) where T_m is the melting temperature, the material response depends on the strain rate or frequency of loading. Typical examples of rate dependent behavior for 1070 steel at 600°C is indicated. Strain rates of $2 \times 10^{-3}$ 1/s and $2 \times 10^{-6}$ 1/s were considered.
Spherodization (1070 Steel)

- T = 400°C
- T = 600°C

10 μm
Modulus of Elasticity vs. Temperature
Yield Strength vs. Temperature
Nomenclature

IF  Isothermal Fatigue
TF  Thermal Fatigue
TMF Thermo-Mechanical Fatigue
\( \Delta \varepsilon_m, \Delta \varepsilon_{\text{mech}} \)  Mechanical Strain Range
\( \Delta \varepsilon_{\text{th}} \)  Thermal Strain Range
\( \Delta \varepsilon, \Delta \varepsilon_{\text{net}} \)  Net Strain Range
\( \Delta \sigma \)  Stress Range
\( T_{\text{max}}, T_{\text{min}} \)  Maximum, Minimum Temperature in a Cycle
E  Modulus of Elasticity
k  Yield Stress in Shear
\( \nu \)  Poisson's Ratio
\( \bar{\sigma} \)  Von Mises Effective Stress
\( \varepsilon_{\text{in}} \)  Inelastic Strain Rate Tensor
# Nomenclature (ctd.)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>TMF OP</td>
<td>Thermo-Mechanical Fatigue Out-of-Phase</td>
</tr>
<tr>
<td>TMP IP</td>
<td>Thermo-Mechanical Fatigue In-Phase</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>( \dot{\varepsilon} )</td>
<td>Net or Total Strain Rate</td>
</tr>
<tr>
<td>( \dot{\varepsilon}^{\text{th}} )</td>
<td>Thermal Strain Rate</td>
</tr>
<tr>
<td>( \dot{\varepsilon}_{\text{m, mech}} )</td>
<td>Mechanical Strain Rate</td>
</tr>
<tr>
<td>( t_c )</td>
<td>Cycle Time (Seconds, Minutes)</td>
</tr>
<tr>
<td>( f )</td>
<td>Cycle Frequency</td>
</tr>
<tr>
<td>( \varepsilon^{\text{in}} )</td>
<td>Inelastic Strain</td>
</tr>
</tbody>
</table>
Fatigue-Creep Response under Strain and Stress Holds (schematic)
Stress Relaxation and Constant Stress Creep

Stress Relaxation

Constant Stress Creep

Stress vs. Strain

Stress vs. Time

Stress vs. Time

Stress vs. Time
Bree Diagram showing the operating regimes of component behavior

- Reversed Plasticity
  - [Thermo-mechanical Fatigue]
  - (Progressive Distortion)
- Ratchetting
  - (Excessive Distortion)
- Elastic Shakedown
- Elastic [High Cycle Fatigue]

\[
\frac{E \theta \Delta T}{\sigma_y}
\]

\[
\frac{P_n}{P_L}
\]
Ratchetting of the two Bar Structure for 304 Stainless Steel
Ratchetting of the two Bar Structure for 304 Stainless Steel - Simulations
Stress-strain Response (schematics)

Elastic Shakedown

Reversed Plasticity
Cylinder Heads (FEM and Fatigue Life Contours)
Component Testing
Thermal Fatigue Life Prediction

<table>
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<tr>
<th>TFT test</th>
<th>46-210°C</th>
<th>46-230°C</th>
<th>46-250°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>failure</td>
<td>3000</td>
<td>1700</td>
<td>560</td>
</tr>
<tr>
<td>prediction</td>
<td>2312</td>
<td>1415</td>
<td>332</td>
</tr>
</tbody>
</table>

X. Su et al., ASTM STP 1428, 2002.
Turbine Blades
Turbine Blades (Thermo-mechanical fatigue failure)
Temperature capability of gas turbine blade materials

Temperature (°C)


Year

Forged Alloys

SC Alloys

DS Alloys

CC Alloys

INCO 713

Nimonic 80A

IN738LC

IN738

N105

N115

Mar-M002-DS

Mar-M002

CM247LC-DS

SRR99
Environment Effects

Susceptible to the following:

- **Oxidation** – reaction between the material and oxidants present in the hot gas
  - Alloying elements assist in oxidation resistance: Cr, Al, & Y
- **Hot corrosion** – surface reaction with salts deposited from vapor pressure

Superalloys are often coated to resist environmental attacks

1. **Initially coated with MCrAlY** (‘emcrawlee’) or aluminide to improve oxidation resistance
2. **Thermal barrier coating (TBC)** is then applied
   - Ceramic coating with very low thermal conductivity
   - Drop temperature gradient between gas and metal substrate by 200-600°F
   - Typically very thin 8/1000 of an inch
   - Do not prevent oxidation
Thermal Barrier Coatings (TBCs)


Creep Test
Air, 900 °C
\( \sigma = 50 \text{ MPa} \)
\( t = 2 \text{ h} \)

Average Strain = 0.26%

Triple Point
1.19% Strain

Serrated Boundary
1.05% Strain

Haynes 230 Creep Test
Air, 900 °C
\( \sigma = 50 \text{ MPa} \)
\( t = 2 \text{ h} \)

10x Magnification
0.45 μm/pix

Strain (%)

\[ \begin{array}{c}
\text{≥ 1} \\
\text{0.8} \\
\text{0.6} \\
\text{0.4} \\
\text{0.2} \\
\leq 0
\end{array} \]
Basic Terminology at High Temperatures

• What is a high temperature problem? Deformation under Constant or Variable Stress at homologous temperatures above 0.35 (T/Tm > 0.35 where Tm is melting temperature).

• Stress Relaxation: Decrease in Stress at Constant Strain

• Creep: Increase in Strain at Constant Stress
High temperature fatigue testing or modeling

Isothermal vs. Thermo-mechanical fatigue

Isothermal fatigue
- HCF
  - Inelastic strain range \(\sim 0\)
- LCF
  - Inelastic strain range \(> 0\)

Non-isothermal fatigue
- TF
  - Internal stresses
- TMF
  - External stresses
Disk Specimen under TF loading (Simovich)
Total Constraint

\[ \varepsilon_{\text{net}} = 0 \]

Mechanical Strain

Stress

\[ \alpha (T - T_0) \]

\[ \sigma_0 \]

\[ -\sigma_0 \]
The compatibility equation

$$\varepsilon_{net} = \varepsilon_{th} + \varepsilon_{mech} = \alpha (T - T_0) + \varepsilon_{mech}$$

When the net strain is zero and all of the thermal strain is converted to mechanical strain. Then,

$$\varepsilon_{mech} = -\alpha (T - T_0)$$
Two-Bar Model (ctd.)

\[ \Delta T \]

\[ A_1, l_1 \]

\[ A_2, l_2 \]

\[ P \]
Simple Relations

- Equilibrium: \( A_1 \sigma_1 + A_2 \sigma_2 = P \)
- Compatibility: \( l_1 \varepsilon_1 = l_2 \varepsilon_2 \)
- Strain:
  \[
  \varepsilon_1 = \varepsilon_{1e} + \varepsilon_{1in} + \varepsilon_{1th}
  \]
  \[
  \varepsilon_2 = \varepsilon_{2e}
  \]
  \[
  \varepsilon_{1th} = \alpha (T - T_0)
  \]
  \[
  \varepsilon_{1in} = \text{inelastic (plastic) strain}
  \]
  \[
  \varepsilon_{1e} = \text{elastic strain}
  \]
The Concepts of Total, Partial, Over and Notch Constraint

\[ \varepsilon_1 = \frac{\sigma_1}{E_2} \quad , \quad C = \frac{A_2 \cdot l_1}{A_1 \cdot l_2} \]

- \( C \rightarrow \infty \); Total Constraint
- \( C \rightarrow \text{finite} \); Partial Constraint
The Stress-strain Response under Total and Partial Constraint

1070 Steel
$T_{\text{max}} = 600^\circ C$
$T_{\text{min}} = 150^\circ C$
$N = 800$ Cycles
All Stresses are in MPa
The Stress-strain Response under Total and Partial Constraint (ctd.)

1070 Steel
Partial Constraint
$T_{\text{max}} = 600^\circ \text{C}$
$T_{\text{min}} = 150^\circ \text{C}$
Cycles #1-64
All Stresses are in MPa
Turbine Blades (strain-temperature variation)
Thermo-Mechanical Fatigue Cycles

- Simultaneously changing strain and temperature ($T$)
- **In-Phase**: max-strain at max-$T$
- **Out-of-Phase**: max-strain at min-$T$
Diamond (baseball) History

Diagram showing mechanical strain versus temperature and stress versus mechanical strain.
Some Definitions

Inelastic Strain range:

$$\Delta \varepsilon_{in} \approx \Delta \varepsilon_m - \frac{|\sigma_B|}{E_B} + \frac{|\sigma_C|}{E_C}$$
Stress-strain Behavior under Out-of-Phase versus In-Phase

Out-of-Phase TMF Response

In-Phase TMF Response
Comparison of TMF IP and TMF OP Tests on 1010 Steel (Jaske’s Data)
TMF Life

Inelastic Strain Range vs Cycles to Failure

- EAP319
  - 250°C 0.5 hz
  - 250°C 5x10^{-5} s^{-1}
  - 300°C 0.5 hz
  - 300°C 5x10^{-5} s^{-1}

- WAP319
  - TMF OP
  - TMF IP

Graph showing the relationship between inelastic strain range and cycles to failure for different conditions.
Limitations in our Understanding of High Temperature Material Behavior

• Experiments on TMF are missing (difficult, expensive).
• Microstructural damage mechanisms are not well understood.
• Stress-strain (constitutive) models have not been established.
• Proposed failure models have severe drawbacks.