Multiaxial and Thermomechanical Fatigue of Materials: A Historical Perspective and Some Future Challenges

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Rationale for Multiaxial and Thermomechanical Fatigue

- Structural materials used in engineering applications routinely subjected to repetitive mechanical loads in multiple directions under non-isothermal conditions
- Over past few decades, several multiaxial fatigue life estimation models (stress- and strain-based) developed for isothermal conditions
- Historically, numerous fatigue life prediction models also developed for thermomechanical fatigue (TMF) life prediction, predominantly for uniaxial mechanical loading conditions
- Realistic structural components encounter multiaxial loads and non-isothermal loading conditions, which increase potential for interaction of damage modes. A need exists for mechanical testing and development & verification of life prediction models under such conditions.
Typical Gas Turbine Engine Hot Section Components

- Combustor
- Vane
- Turbine blade
- Turbine disk
Realistic fatigue durability estimation of gas turbine engine components requires consideration of cyclic thermal and multiaxial mechanical loads.
Multiaxial and Thermomechanical Fatigue

- Thermal Fatigue
- Bithermal Fatigue
- Thermomechanical Fatigue

- Isothermal Uniaxial
- Non-Isothermal Uniaxial

- Multiaxial TMF (Simultaneous & Sequential)
  - Simultaneous Loads Multiaxial
  - Sequential Loads Multiaxial
  - Isothermal Multiaxial
Multiaxial and Thermomechanical Fatigue - Scope

• Materials (metallic alloys, polymers, ceramics, composites, and materials with coatings)
  – Structural alloys for aerospace applications (uncoated)
• Fatigue crack initiation and fatigue crack growth
  – Fatigue crack initiation
• Low-cycle versus high-cycle fatigue
  – Low-cycle fatigue (primarily strain-based approaches)
• Deterministic versus probabilistic fatigue life estimation
  – Deterministic fatigue life estimation
• Multiaxial, thermomechanical fatigue – numerous possibilities
  – Some selected examples
• Future challenges in multiaxial thermomechanical fatigue
  – Cumulative fatigue, subcomponents, coatings, composite & functionally graded materials, and residual stresses
Multiaxial and Thermomechanical Fatigue

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- Bithermal Fatigue
- Thermomechanical Fatigue

Non-Isothermal Uniaxial

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- Multiaxial TMF (Simultaneous & Sequential)
  - Simultaneous Loads Multiaxial
  - Sequential Loads Multiaxial
  - Isothermal Multiaxial
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- Bithermal Fatigue
- Thermomechanical Fatigue
  - Simultaneous Loads Multiaxial
  - Sequential Loads Multiaxial
  - Isothermal Multiaxial

Multiaxial TMF (Simultaneous & Sequential)
Thermal Fatigue – Experiments and Life Prediction

Wedge shaped test specimens typically used in fluidized combustion beds to evaluate thermal low-cycle fatigue
Thermal stresses developed during cycling generate inelastic strains, which lead to fatigue cracks.

**Salient features**
- Thermal cycling with an inherent constraint on deformation
- Typically limited or no externally imposed loads
- Mainly deformation controlled
Thermal Fatigue: Life Estimation Model

- Thermal fatigue
  - Inelastic strain range developed during the thermal cycle dictates the fatigue life
  - Manson (1953) and Coffin (1954) working independently developed a power law fatigue life relation

**Manson-Coffin Equation:** \[ \Delta \varepsilon_{in} = C(N_f)^c \]

*Where, \( \Delta \varepsilon_{in} \) is inelastic strain range, \( N_f \) is fatigue life, \( C \) is the Coefficient, And \( c \) is the exponent*

**References:**


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Isothermal Uniaxial Fatigue – Schematic and Life Relations

Manson-Coffin-Basquin relation for deterministic, isothermal low-cycle fatigue life estimation
Isothermal Uniaxial Creep-Fatigue: A Phenomenological Model for Cyclic Life Estimation

Reference: Manson, Halford, and Hirschberg, 1971
Reference: Manson, Halford, and Nachtigall, 1975

Strain Range Partitioning (SRP) Model: Damage from different deformation modes combined with Interaction Damage Rule
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Bithermal Uniaxial Fatigue: Schematics and Salient Features

- **Salient features**
  - Thermal cycling at two temperatures with externally imposed loads
  - Free thermal expansion allowed during temperature changes
  - Effectively two isothermal segments of loading in tension and compression
  - Load controlled with limits on deformation
Bithermal Uniaxial Creep-Fatigue: Schematic Hysteresis Loops

Originally conceived to impose creep in a short time and later viewed as a link between isothermal fatigue and TMF

References: Halford et al., ASTM STP 942, 1987 and Halford et al., ASTM STP 1122, 1991
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Thermomechanical Uniaxial Fatigue: Schematics and Salient Features

- **Salient Features**
  - Simultaneous thermal and mechanical cycling
  - Externally imposed constraint on deformation
  - Temperature and deformation controlled
  - Additional complexity: thermal strain + mechanical strain
Uniaxial Thermomechanical Fatigue (TMF)

- Phasing between mechanical strain and temperature
  - Typically $\theta = 0^\circ$ (in-phase) or $\theta = 180^\circ$ (out-of-phase) [Carden and Slade, 1969]
  - Clockwise and counter clockwise diamonds depending upon application
- Standards for uniaxial TMF testing
  - ASTM E 2368 (2010)
  - ISO FDIS-12111 (2012)
- TMF life estimation approaches
  - Phenomenological models and physical mechanism(s) based models
  - Creep, fatigue, creep-fatigue interaction and oxidation based models
- TMF deformation prediction methods
  - Plasticity and creep deformation models (non-unified)
  - Unified constitutive models

Experimental technique for determining creep strains within an in-phase thermomechanical hysteresis loop
Uniaxial Bithermal and TMF Life Relations for Haynes 188 from Experiments (316 to 760 °C)

Bithermal Fatigue

Tensile Creep In-Phase

Compressive Creep Out-of-Phase

In-Phase

Out-of-Phase

Reference: Halford et al., ASTM STP 1122, 1991

Bithermal fatigue data and deformation behavior used as input to predict thermomechanical fatigue lives
TMF Life Estimations from Bithermal Fatigue Data Using Total Strainrange SRP

TS-SRP Approach

Estimations

Total strain range life curve is established for each specific type of TMF cycle using bithermal fatigue data and simplified flow equations.

Reference: Halford et al., ASTM STP 1122, 1991
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Isothermal Multiaxial Fatigue

- **Multiaxial Loading**
  - Proportional and non-proportional loading (in-phase and out-of-phase loading)
  - Simultaneous versus sequential loading

- **Multiaxial Fatigue Life Correlation Methods**
  - Triaxiality factor based approaches (Davis and Connelly, 1959)
  - Critical plane based approaches (Brown and Miller, 1973)
  - Cyclic hysteretic energy or equivalent parameters (Halford and Morrow, 1962)

References:


Isothermal Fatigue – Types of Multiaxial Loads

- Axial, torsional, and combined axial-torsional loads
  - Relatively simple form of multiaxial loading
  - Thin-walled tubular specimens (trade off between torsional buckling and thin-wall to generate nearly uniform shear stress)
  - ISO/FDIS 1352 (2011)
- Combined torsional and bending loads
  - Torque shafts in automotive applications
  - Relatively lower temperatures and typically high-cycle fatigue
- Combined biaxial loads
  - Thin-walled tubular specimens with internal and/or external pressure (pressure vessels)
  - Cruciform specimens tested in-plane with four independent actuators typically with centroid control
- Combined triaxial loads
  - 3-D version of a cruciform specimen (complicated design and most expensive to fabricate)
  - Primary goal is to evaluate the influence of hydrostatic stress on fatigue life
Examples of Multiaxial Test Specimens

Thin-walled Tubular Specimen and Axial-Torsional Test Rig

Cruciform Specimen and In-plane Biaxial Test Rig

Triaxial Cruciform Specimen for Creep Rupture in Triaxial Tension


References: Bartolotta, Ellis, and Abdul-Aziz, ASTM STP 1280, 1997 & Krause and Bartolotta, ASTM STP 1387, 2000

Reference: Kalluri and Bonacuse, ASTM STP 1092, 1990
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Isothermal, Axial-Torsional, In- and Out-of-Phase Fatigue (Simultaneous Loading), $\lambda = \frac{\gamma_a}{\varepsilon_a}$

- **In-Phase**
  - Phase angle, $\phi = 0^\circ$

- **Out-of-Phase**
  - Phase angle, $\phi = 75^\circ$

- For out-of-phase tests, mechanical phase angle, $\phi = 90^\circ$ is typical
Isothermal Multiaxial Fatigue: Life Estimation

- Multiaxial Fatigue Life Controlling Parameters
  - Phasing of load components (in-phase vs. out-of-phase)
  - Mode of failure (tensile vs. shear) exhibited by the material
  - Temperature

- Four multiaxial fatigue life estimated methods illustrated
  - Von Mises equivalent strain range model
  - Modified multiaxiality factor approach
  - Modified Smith-Watson-Topper Parameter
  - Critical shear plane method of Fatemi, Socie, and Kurath

Applicability of any method is dependent on loading phase, mode of failure exhibited by the material, and temperature
VON MISES EQUIVALENT STRAIN RANGE MODEL

\[
\Delta \varepsilon_{eq} = \frac{\left( (\Delta \varepsilon_{xx} - \Delta \varepsilon_{yy})^2 + (\Delta \varepsilon_{yy} - \Delta \varepsilon_{zz})^2 + (\Delta \varepsilon_{zz} - \Delta \varepsilon_{xx})^2 + \frac{3}{2} (\Delta \gamma_{xy}^2 + \Delta \gamma_{yz}^2 + \Delta \gamma_{zx}^2) \right)^{1/2}}{\sqrt{2(1 + \nu_{eff})}}
\]

\[
\nu_{eff} = \left[ \frac{\Delta \varepsilon \nu_e + \Delta \varepsilon_p \nu_p}{\Delta \varepsilon} \right]
\]

where: \( \Delta \varepsilon_e = \Delta \sigma / E \)

and: \( \Delta \varepsilon_p = \Delta \varepsilon - \Delta \varepsilon_e \)


Von Mises equivalent strain range used in conjunction with effective Poisson’s ratio
Predictions of mechanically out-of-phase tests are higher (unconservative) due to additional hardening.

Reference: Kalluri and Bonacuse, ASME PVP-Vol. 290, 1994, pp. 17-33
MODIFIED MULTIAXIALITY FACTOR APPROACH

\[ MF \Delta \varepsilon_{eq} = MF^{(1-b/c)} B(N_f)^b + C(N_f)^c \]

where,

\[ MF = \frac{1}{2 - TF} ; \quad TF \leq 1 \]

\[ MF = TF ; \quad TF \geq 1 \]

and:

\[ TF = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}} \]


Uniaxial fatigue life relation and cyclic stress strain curve used with Von Mises equivalent strain range and MF
Predictions of mechanically out-of-phase tests are again higher (unconservative) due to additional hardening.
MODIFIED SMITH-WATSON-TOPPER PARAMETER

\[ \frac{\Delta \varepsilon_1}{2} \sigma_1^{\text{max}} = \sigma_f' \varepsilon_f' (2N_f)^{b+c} + \frac{\sigma_f'^2}{E} (2N_f)^{2b} \]

Where,

\( \varepsilon_1 \)  
First principal strain amplitude

\( \sigma_1^{\text{max}} \)  
Maximum stress on the maximum principal strain plane

\( \sigma_f' \)  
Axial fatigue strength coefficient

\( \varepsilon_f' \)  
Axial fatigue ductility coefficient

\( b, c \)  
Exponents of axial elastic and plastic strain-life relations


Modification of the original SWT parameter (1970) for multiaxial fatigue – materials with tensile mode of failure
LIFE PREDICTION: MODIFIED SMITH-WATSON-TOPPER PARAMETER
Haynes 188 at 316°C

Predictions of some torsional and mechanically out-of-phase tests are slightly higher (slightly unconservative)

Reference: Kalluri and Bonacuse, ASME PVP-Vol. 290, 1994, pp. 17-33
CRITICAL SHEAR PLANE METHOD OF FATEMI, SOCIE, AND KURATH

\[
\gamma_{\text{max}} \left(1 + k \frac{\sigma_{\text{n}}^{\text{max}}}{\sigma_y}\right) = \left(1 + \nu_p\right) \frac{\sigma_f}{E} (2N_f)^b + k \frac{1}{2} \left(1 + \nu_p\right) \frac{\sigma_f}{E \sigma_y} (2N_f)^{2b}
\]

\[
+ \left(1 + \nu_p\right) \varepsilon_f (2N_f)^c + \frac{k}{2} \left(1 + \nu_p\right) \varepsilon_f \frac{\sigma_f}{\sigma_y} (2N_f)^{b+c}
\]

Where,

- \(\gamma_{\text{max}}\): Maximum engineering shear strain amplitude
- \(\sigma_{\text{n}}^{\text{max}}\): Maximum normal stress on the maximum shear strain plane
- \(k\): Constant determined from axial and torsional fatigue data
- \(\sigma_y\): Axial yield strength
- \(\sigma_f\): Axial fatigue strength coefficient
- \(\varepsilon_f\): Axial fatigue ductility coefficient
- \(b, c\): Exponents of axial elastic and plastic strain-life relations

References: Socie, 1987 and Fatemi & Socie, 1988
Predictions of mechanically out-of-phase tests are much higher (very unconservative).
Cyclic Hardening in Isothermal, Axial-Torsional, In- and Out-of-Phase Fatigue ($\lambda = \Delta \gamma / \Delta \varepsilon$)

Axial

Shear

In out-of-phase tests, cyclic hardening increases with mechanical phase angle, $\phi$ between axial ($\varepsilon$) and shear ($\gamma$) strains

Reference: Bonacuse and Kalluri, ASTM STP 1184, 1994
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- Sequential Loads Multiaxial

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Isothermal Axial and Torsional Cumulative Fatigue (Sequential Loading)

- Historically, most investigations on cumulative fatigue limited to the same load-types (axial/axial, torsion/torsion, or rotating bending/rotating bending)
- Typical studies involve load order effects within a load-type (high/low or low/high)
- Dissimilar load-types can increase potential for interaction of damage (or mode of cracking)
- Evaluation of both load order and load-type sequencing effects is necessary

References:

Schematics of LCF/HCF and HCF/LCF Cumulative Fatigue Tests on Haynes 188 at 538°C

LCF/HCF

HCF/LCF

Applied Life Fraction: \( n_1/N_1 \); Remaining Life Fraction: \( n_2/N_2 \)
Cumulative Fatigue Life Prediction

• Linear Damage Rule [Palmgren, Langer, and Miner] (LDR):

\[
\left( \frac{n_2}{N_2} \right) = 1 - \left( \frac{n_1}{N_1} \right)
\]

• Nonlinear Damage Curve Approach [Manson and Halford] (DCA):

\[
\left( \frac{n_2}{N_2} \right) = 1 - \left( \frac{n_1}{N_1} \right)^{\left( \frac{N_1}{N_2} \right)^{0.4}}
\]

n_1 and n_2 are Applied Number of Cycles at Load Levels 1 & 2 and N_1 and N_2 are Fatigue Lives at Load Levels 1 & 2, respectively.
Axial ($\Delta \varepsilon_{\text{High}} = 2.0\%$) / Axial ($\Delta \varepsilon_{\text{Low}} = 0.67\%$) Interaction
Haynes 188 at 538°C

For all LCF/HCF data and HCF/LCF data for which $n_1/N_1 > 0.4$, DCA is Better than LDR

Reference: Kalluri and Bonacuse, JAI, Vol. 7, No. 4, 2010
Axial ($\Delta \varepsilon_{\text{High}} = 2.0\%$) / Torsional ($\Delta \gamma_{\text{Low}} = 1.2\%$) Interaction
Haynes 188 at 538°C

For all LCF/HCF data DCA is Better than LDR; However, for HCF/LCF data LDR is Better than DCA

Reference: Kalluri and Bonacuse, JAI, Vol. 7, No. 4, 2010
Torsional ($\Delta \gamma_{\text{High}} = 3.5\%$) / Axial ($\Delta \varepsilon_{\text{Low}} = 0.67\%$) Interaction
Haynes 188 at 538°C

Both for LCF/HCF and HCF/LCF data, when $n_1/N_1 > 0.4$
DCA is Better than LDR

Orientation of Cracks
($\theta = 0°, 10°, 15°$)

Orientation of Cracks
($\theta = 85°$ and $90°$)

Reference: Kalluri and Bonacuse, JAI, Vol. 7, No. 4, 2010

- In Axial Tests, Orientation of Fatigue Crack(s) is Perpendicular to the Maximum Principal Stress Direction ($\theta = 0°$ or $10°$)
- In Torsional Tests, Orientation of Fatigue Crack(s) is Parallel to Maximum Shear Stress Direction ($\theta = 90°$)
Multiaxial and Thermomechanical Fatigue

Thermal Fatigue

Isothermal Uniaxial

Bithermal Fatigue

Non-Isothermal Uniaxial

Thermomechanical Fatigue

Multiaxial TMF (Simultaneous & Sequential)

Simultaneous Loads Multiaxial

Isothermal Multiaxial

Sequential Loads Multiaxial
Multiaxial, Thermomechanical Fatigue

• Torsional, TMF testing
  – Jordan, 1987 (4th Annual SEM Hostile Environments and High Temperature Measurements Conference; Turbine blade superalloy (PWA 1480) tested between 425 to 828 °C)
  – Bakis, Castelli, and Ellis, 1993 (ASTM STP 1191; Hastelloy-X tested between 400 to 600 °C, 600 to 800 °C, 800 to 1000 °C)

• Axial-Torsional TMF testing
  – Bonacuse and Kalluri, [1995 - AGARD Conference]; Kalluri and Bonacuse, [1997, ASTM STP 1280] (Haynes 188 alloy tested between 316 and 760 °C)
  – Brookes et al., 2010 (Materials Science and Engineering A; Near γ-TiAl alloy TNB-15 tested between 400 to 800 °C)
Mechanically In-Phase & Thermally In-Phase (MIPTIP)

Axial Strain

Shear Strain

Temperature [°C]

Time [sec]
Mechanically In-Phase & Thermally Out-of-Phase (MIPTOP)

Axial Strain

Shear Strain

Temperature [°C]

Time [sec]
Mechanically Out-of-Phase & Thermally In-Phase (MOPTIP)

Axial Strain

Shear Strain

Temperature [°C]

Time [sec]

$\varepsilon_{\text{max}}$

$\varepsilon_{\text{min}}$

$\gamma_{\text{max}}$

$\gamma_{\text{min}}$

$T_{\text{max}} = 760°C$

$T_{\text{min}} = 316°C$
Mechanically Out-of-Phase & Thermally Out-of-Phase (MOPTOP)

Axial Strain

Shear Strain

Temperature [°C]

Time [sec]
Deformation Behavior in Mechanically In-Phase Axial-Torsional Fatigue Tests

Axial Strain vs. Shear Strain

Axial Stress vs. Shear Stress

Deformation Behavior in Mechanically Out-of-Phase Axial-Torsional Fatigue Tests

Axial Strain vs. Shear Strain

Axial Stress vs. Shear Stress

Evolution of Maximum and Minimum Stresses in Mechanically Out-of-Phase Axial-Torsional Fatigue Tests

Axial Stress

Shear Stress

Additional Hardening in Axial-Torsional Fatigue Tests

<table>
<thead>
<tr>
<th>Test 1</th>
<th>Test 2</th>
<th>Axial $\Delta\sigma_1-\Delta\sigma_2$ [MPa]</th>
<th>Torsion $\Delta\tau_1-\Delta\tau_2$ [MPa]</th>
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**Additional Hardening from Out-of-Phase Mechanical Cycling**

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<th>Test 2</th>
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**Additional Hardening from Thermal Cycling**

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<td>MIPTOP</td>
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<td>Isothermal MOP</td>
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**Additional Hardening from Combined Out-of-Phase Mechanical and Thermal Cycling**

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<td>MOPTIP</td>
<td>Isothermal MIP</td>
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<tr>
<td>MOPTOP</td>
<td>Isothermal MIP</td>
<td>527</td>
<td>549</td>
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Axial-Torsional TMF loading causes more hardening than Axial-Torsional isothermal loading.
Additional Hardening in Axial-Torsional TMF Tests

760°C mechanically in-phase data used as baseline

Dissimilar mechanical and thermal phasings could synergistically interact to cause additional hardening

Reference: Bonacuse and Kalluri, ASTM STP 1428, 2002
Axial-Torsional TMF Tests: Haynes 188 (316 to 760 °C)

Fatigue Lives For Various Testing Conditions

\[ \Delta \varepsilon = 0.008 \text{ and } \Delta \gamma = 0.014 \]

Thermally in-phase tests yielded lower cyclic lives regardless of the mechanical phasing.

Reference: Kalluri and Bonacuse, ASTM STP 1280, 1997
Multiaxial, Thermomechanical Fatigue -- Some Future Challenges

- Cumulative fatigue under multiaxial, thermomechanical loads
- TMF under biaxial and equi-biaxial ($\lambda = 1$) loading conditions
- Determination of material’s TMF behavior with specimens versus testing subcomponents of structures
- Influence of coatings on structural alloys
- Roles of residual stresses and environment
- Composites and functionally graded materials
Cumulative Fatigue Example: Uniaxial TMF and Isothermal Fatigue

HCF/LCF Interaction at High Temperature

Source: Halford et al., 1983

Cumulative fatigue behavior with out-of-phase TMF LCF and Isothermal HCF under uniaxial loading conditions

Multiaxial, Thermomechanical Fatigue -- Future Challenges

• Thermomechanical fatigue under biaxial and equi-biaxial ($\lambda = 1$) loading conditions (thin-walled tubular specimens with internal/external pressure or cruciform specimens)
  - TMF system for testing cruciform specimens (Scholz, Samir, and Berger, *Proc. of 7th Int. Conf. on Biaxial and Multiaxial Fatigue & Fracture*, Elsevier, 2004)

• Determination of material’s TMF behavior with specimens versus testing subcomponents of structures (scale-up issues and reproducing service conditions)
  - Test conditions are well defined and controlled for a chosen specimen design
  - Tests involving subcomponents are more complex due to the difficulties involved in attaining required temperature profiles and imposing necessary multiaxial loads (design typically accomplished with analysis supplemented with limited testing for validation)
Multiaxial, Thermomechanical Fatigue -- Future Challenges

• Influence of coatings (for example, thermal and environmental barrier coatings) on the multiaxial, TMF life of components
  – LCF and HCF behavior of thick thermal barrier coatings investigated with a high power CO$_2$ laser (Zhu and Miller, NASA TM-1998-206633)
  – Thermal barrier coating / superalloy system tested multiaxial TMF (Bartsch et al., Int. J. of Fatigue, 2008); Thermal gradient mechanical fatigue tests on coated tubular specimens of IN 100 DS superalloy

• Roles of residual stresses and environment on the fatigue crack initiation under multiaxial, thermomechanical loads
  – Depending upon the maximum temperature in the TMF cycle, any existing residual stresses may relax completely. However, at low maximum temperatures and small inelastic strains, residual stresses could influence fatigue life
  – Oxidation plays a significant role and interacts with other damage mechanisms activated by multiaxial loads during TMF. Inert and vacuum environments could exhibit different damage modes under multiaxial TMF.
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Multiaxial Thermomechanical Fatigue (MTMF) can induce additional cyclic hardening and can lower fatigue life significantly compared to uniaxial thermomechanical fatigue and isothermal multiaxial fatigue!

MTMF should be properly evaluated in designing and lifting engineering components!!