Overview of High Temperature and Thermo-mechanical Fatigue (TMF)

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Talk Outline

- Examples of High Temperature Problems
- Basic Terminology at High Temperatures
- Introduction to Constraint : Plasticity and ratchetting, Out of Phase and In phase TMF
- Experimental Techniques at High Temperatures
- Fatigue Lives of Selected Materials under IF and TMF
- Mechanics- Stress-strain Models
- Life Models-Fatigue-Oxidation and Fatigue-Creep Modeling
- Future Directions

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
- Pressure Vessel and Piping

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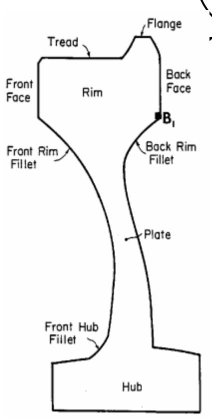
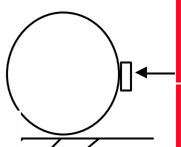
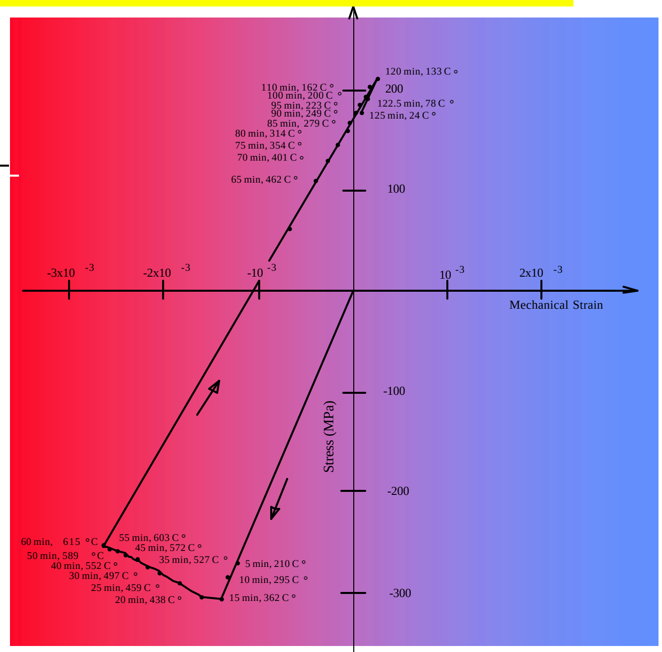
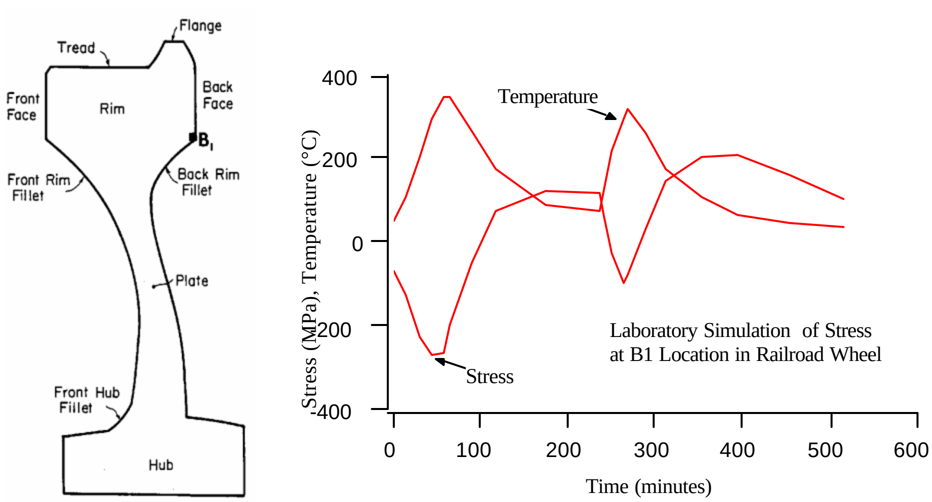
Railroad Wheels under Friction Braking







Schematic of a Railroad Wheel, Strain-Temperature-Stress Changes on the B1 location under brake shoe heating (laboratory simulation based on strain temperature measurements on wheels)



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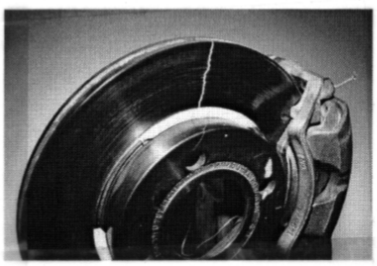
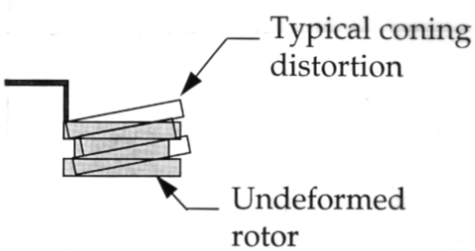
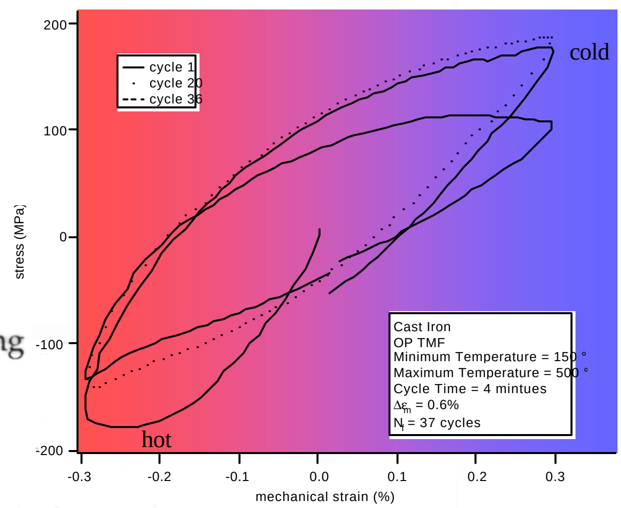
Brake Rotor Cracking







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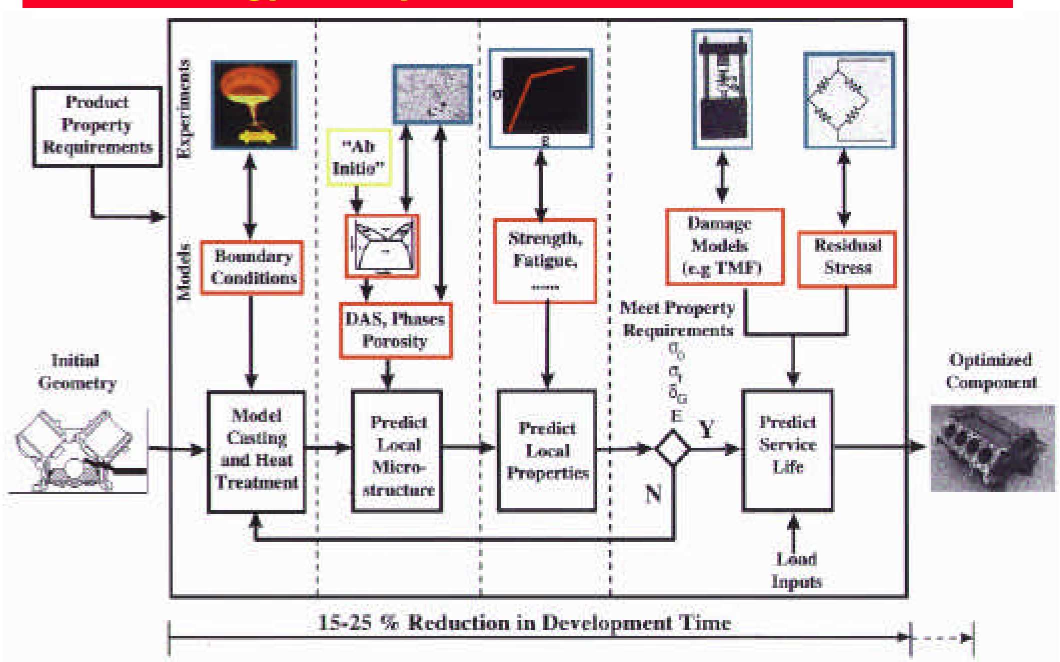
Design-Manufacturing-Life Prediction Methodology for Cylinder Heads and Blocks



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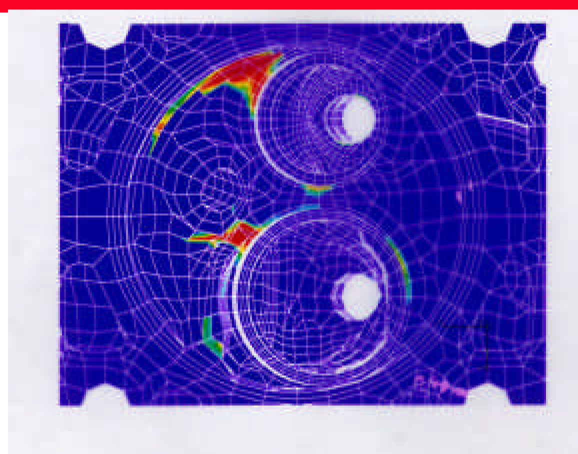
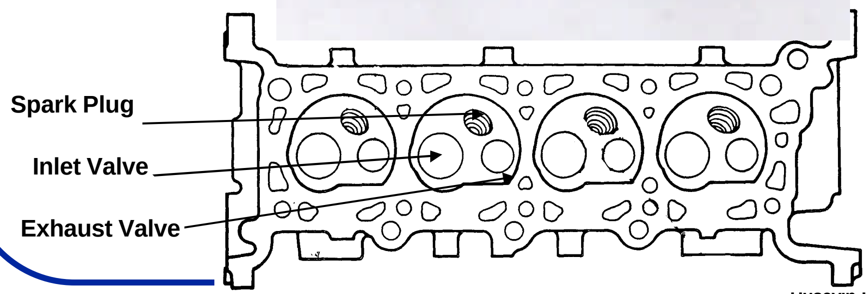
Percentage of Vehicles with Aluminum Engine Blocks and Heads(*)

		1994	2000	2005
Heads				
	Passenger cars	78%	85%	95%
	Light trucks	20%	40%	60%
Blocks				
	Passenger cars	13%	30%	50%
	Light trucks	5%	10%	20%

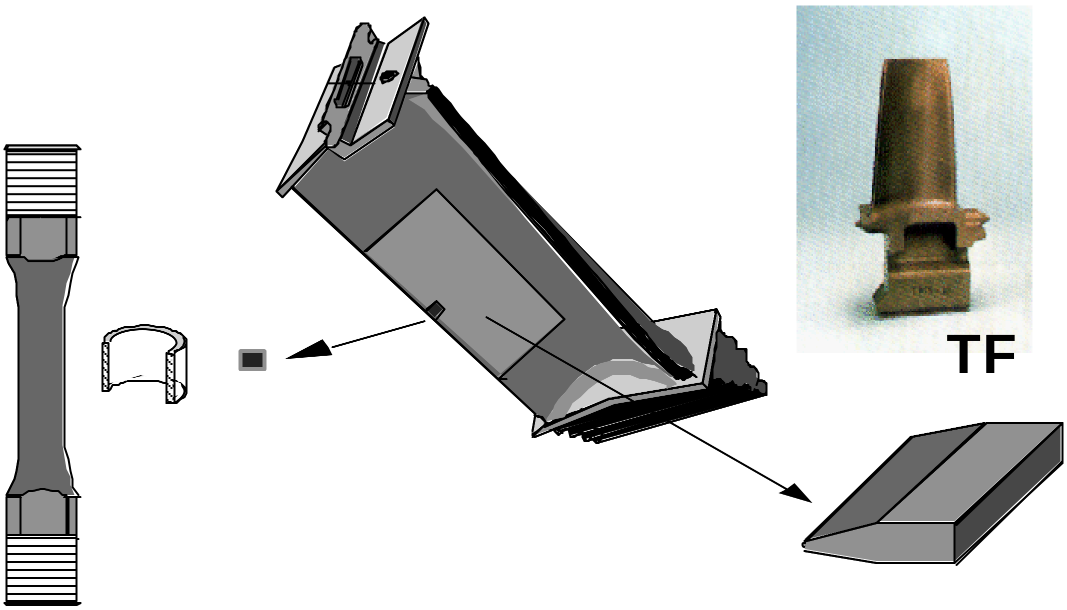
(*) Delphi VIII Study, 1996

Cylinder Heads (FEM and Fatigue Life Contours)

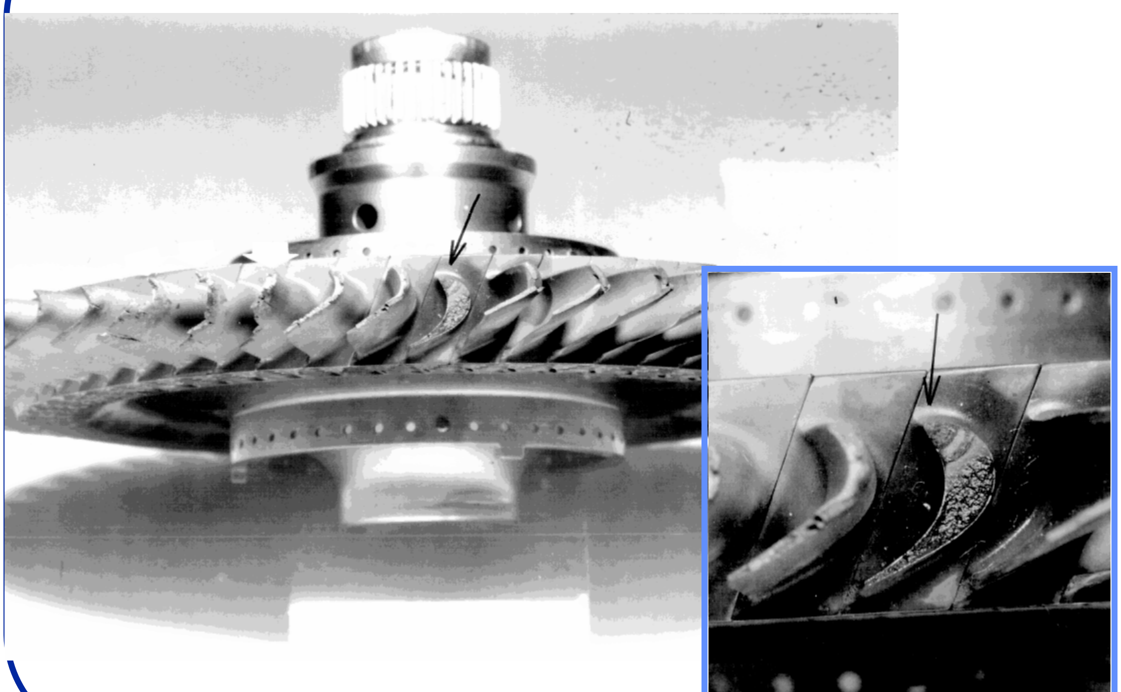




Turbine Blades



Turbine Blades(Thermo-mechanical fatigue failure)



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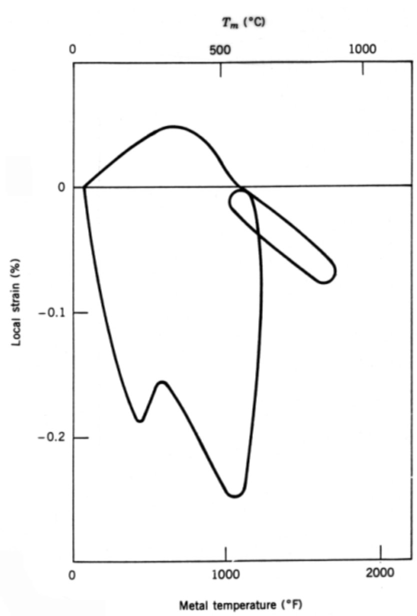
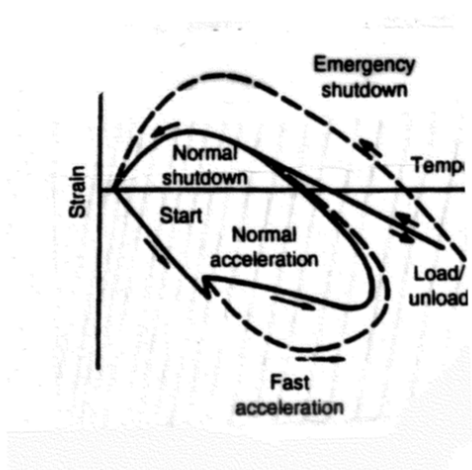
Turbine Blades (strain-temperature variation)





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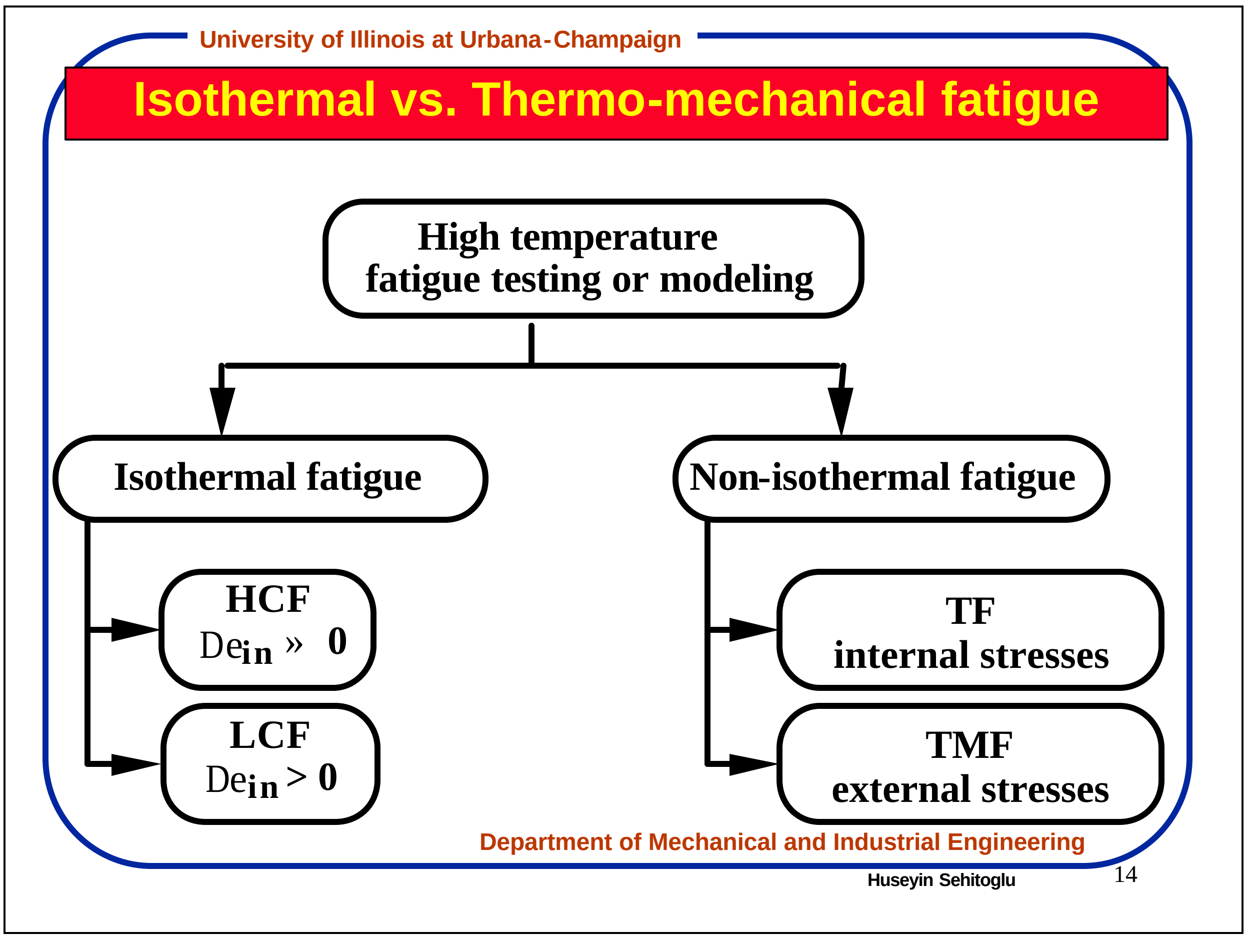
Basic Terminology at High Temperatures

- What is a high temperature problem? Deformation under Constant or Variable Stress at homologous temperatures above 0.35 (T/T_m >0.35 where T_m is melting temperature).
- Stress Relaxation: Decrease in Stress at Constant Strain
- Creep: Increase in Strain at Constant Stress



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Isothermal vs. Thermo-mechanical fatigue
High temperature
fatigue testing or modeling
Isothermal fatigue
Non-isothermal fatigue
HCF
Dein » 0
LCF
Dein > 0
TF
internal stresses
TMF
external stresses
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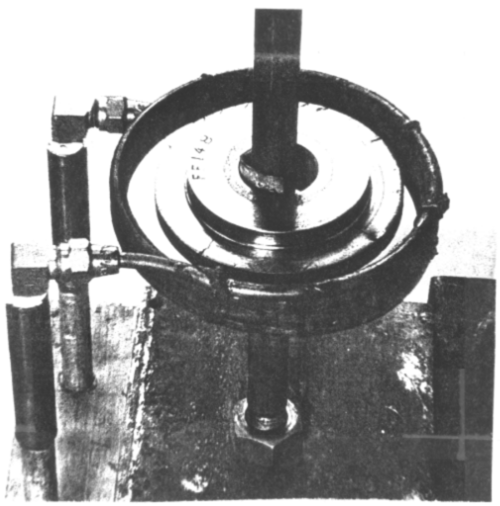
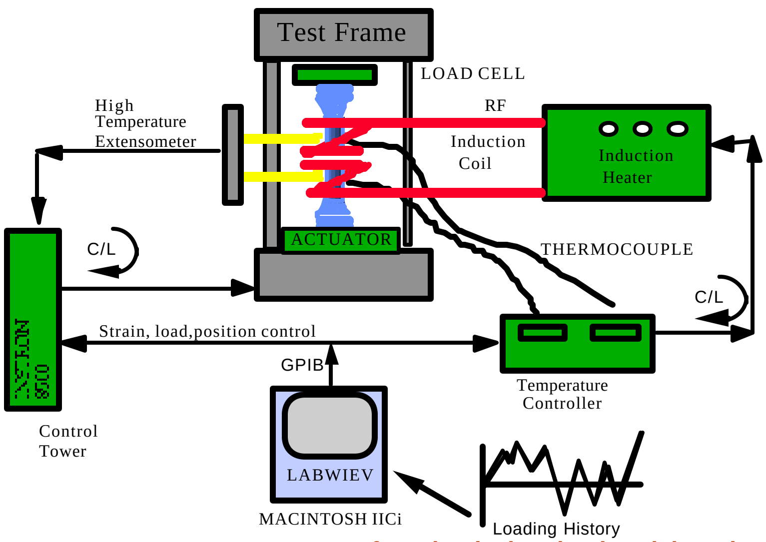
Disk Specimen under TF loading (Simovich)



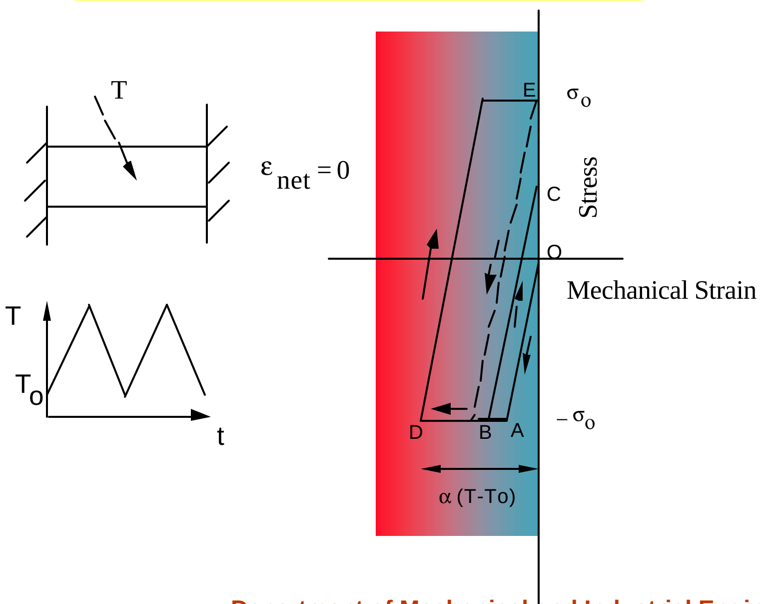
Limitations in our Understanding of High Temperature Material Behavior

- 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.

Experimental Techniques at High Temperatures



Total Constraint



Total Constraint (ctd.)

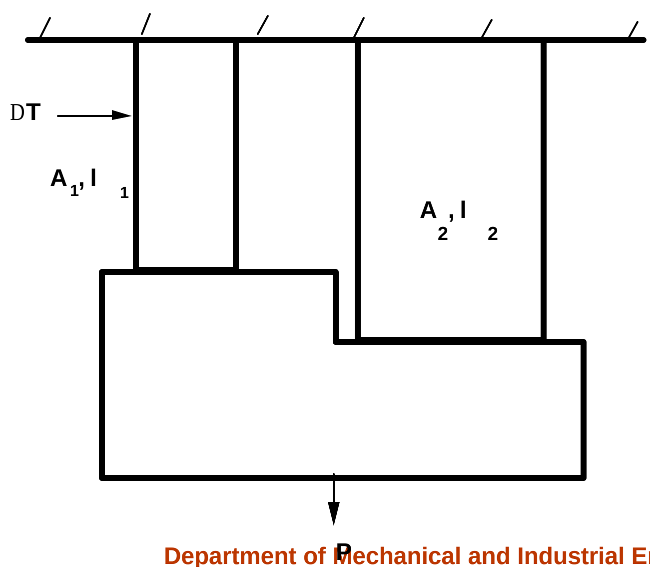
The compatibility equation

$$e_{net} = e_{th} + e_{mech} = a\,(T-T_o) + e_{mech}$$

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

$$e_{mech} = -\,a\,(T-T_o)$$

Two-Bar Model(ctd.)



Simple Relations

- **Equilibrium :** $A_1 \sigma_1 + A_2 \sigma_2 = P$
- **Compatability :** $l_1 \varepsilon_1 = l_2 \varepsilon_2$
- **Strain :**

$$\varepsilon_1 = \varepsilon_{1\,e} + \varepsilon_{1\,in} + \varepsilon_{1\,th}$$

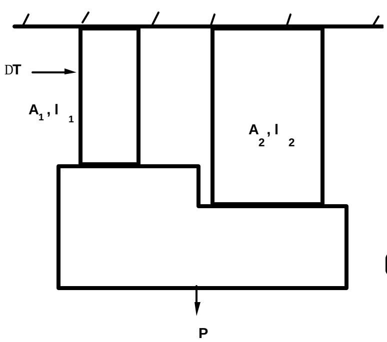
$$\varepsilon_2 = \varepsilon_{2\,e}$$

$$\varepsilon_{1\,th} = \alpha\,(T - T_0)$$

$\varepsilon_{1\,in}$ = inelastic (plastic) strain

$\varepsilon_{1\,e}$ = elastic strain

The Concepts of Total, Partial, Over and Notch Constraint

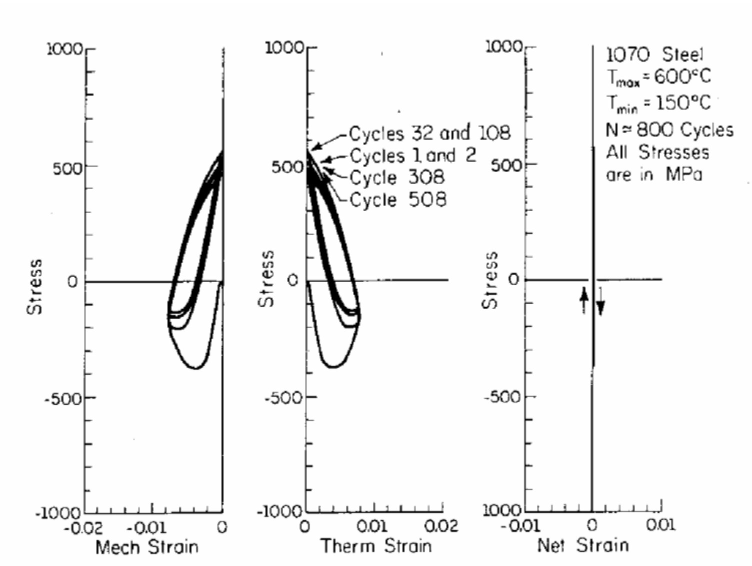


$$\varepsilon_1 = \frac{-\frac{\sigma_1}{E_2}}{C} \;,\; C = \frac{A_2 . l_1}{A_1 . l_2}$$

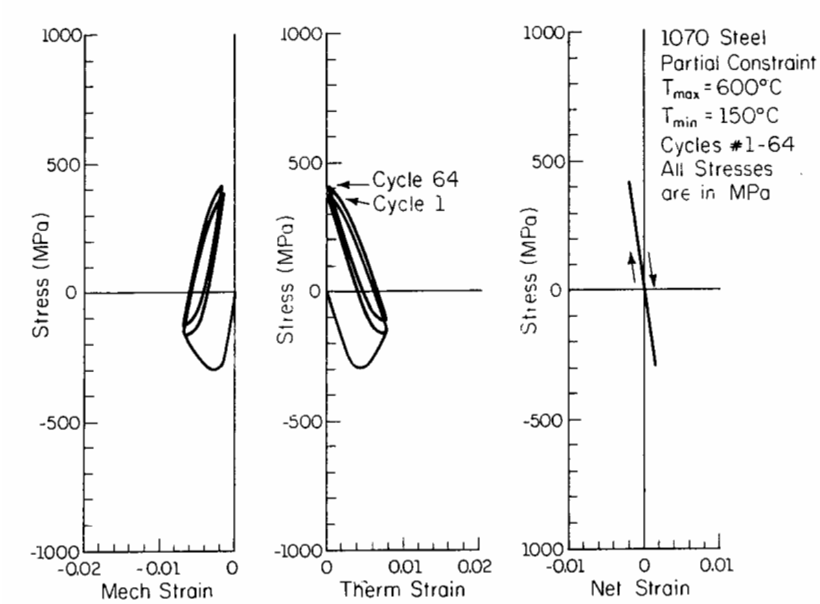
$C \rightarrow \infty$; Total Constraint

$C \rightarrow$ finite ; Partial Constraint

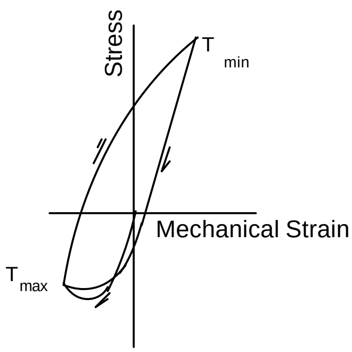
The Stress-strain Response under Total and Partial Constraint



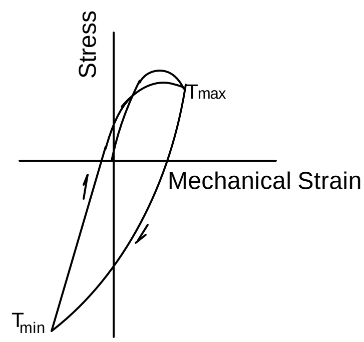
The Stress-strain Response under Total and Partial Constraint (ctd.)



Stress-strain Behavior under Out-of-Phase versus In-Phase

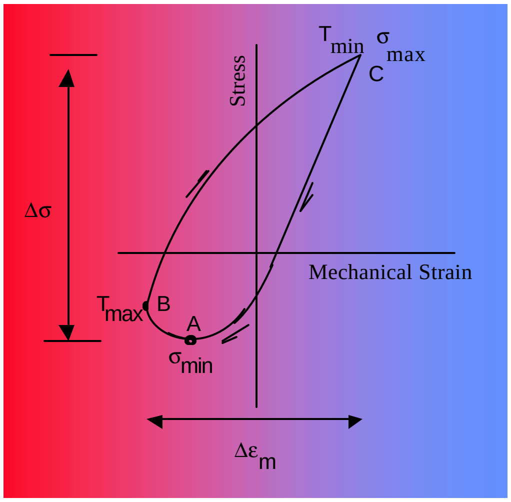


Out-of-Phase TMF Response



In-Phase TMF Response

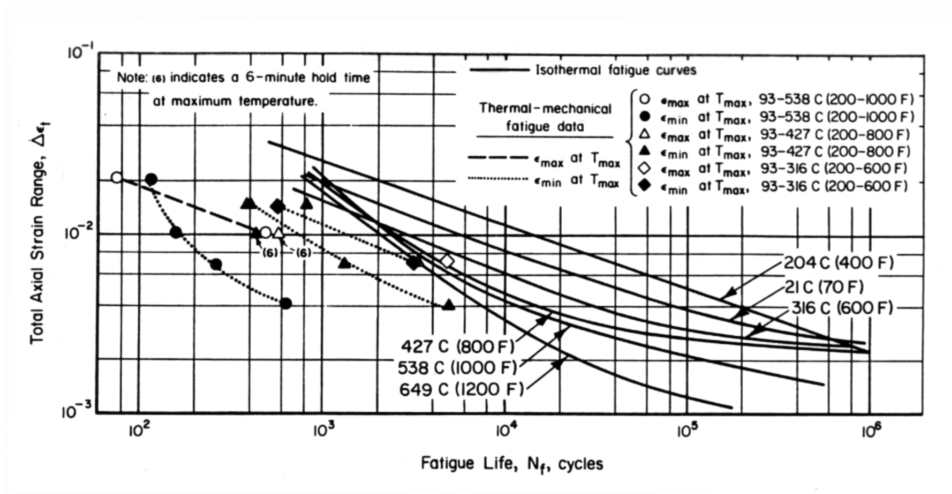
Some Definitions



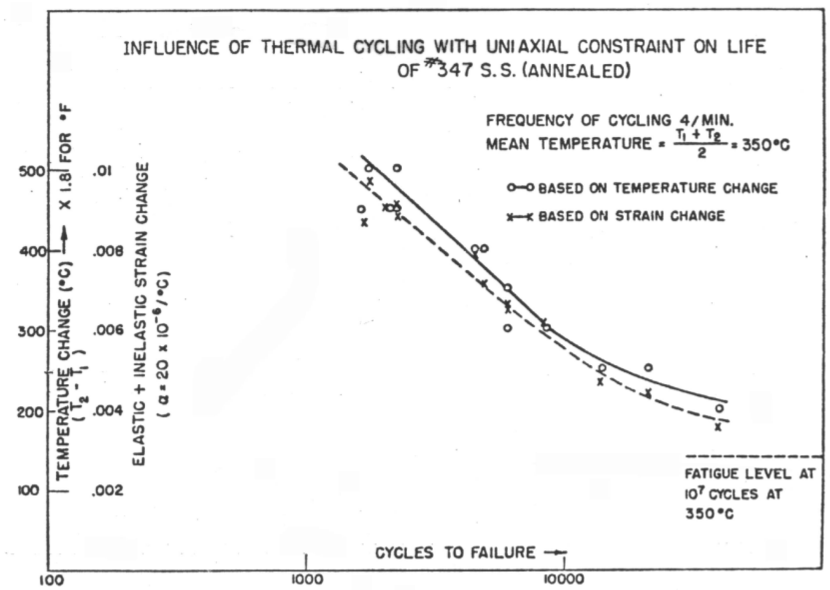
Inelastic Strain range:

$$\Delta\varepsilon_{in} \cong \Delta\varepsilon_m - \left(\frac{|\sigma_B|}{E_B} + \frac{|\sigma_C|}{E_C}\right)$$

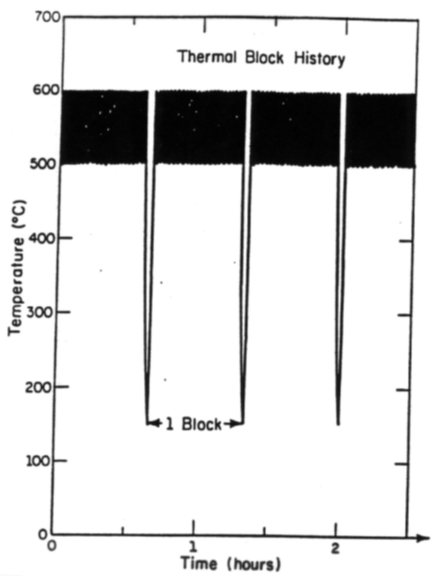
Comparison of TMF IP and TMF OP Tests on 1010 Steel (Jaske's Data)

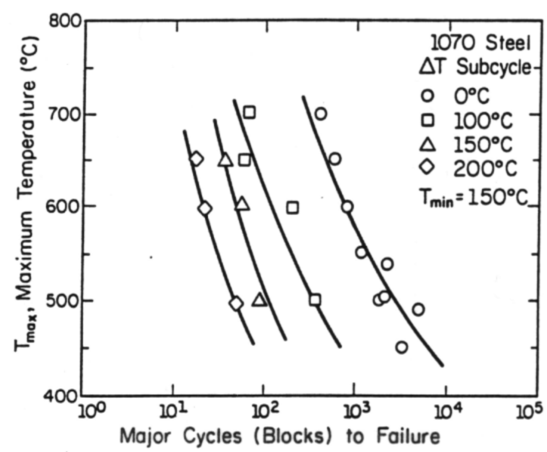


TMF experiments of Coffin



Thermal Block Histories on Steels under Total Constraint





Classification of IF and TMF Studies

- **Metallurgical Studies :**

  (a) Damage Mechanisms (Crack nucleation from slip bands, precipitates, porosities, surface and internal oxidation, grain boundary cavitation)

  (b) Alloy Development

- **Mechanistic Studies :**

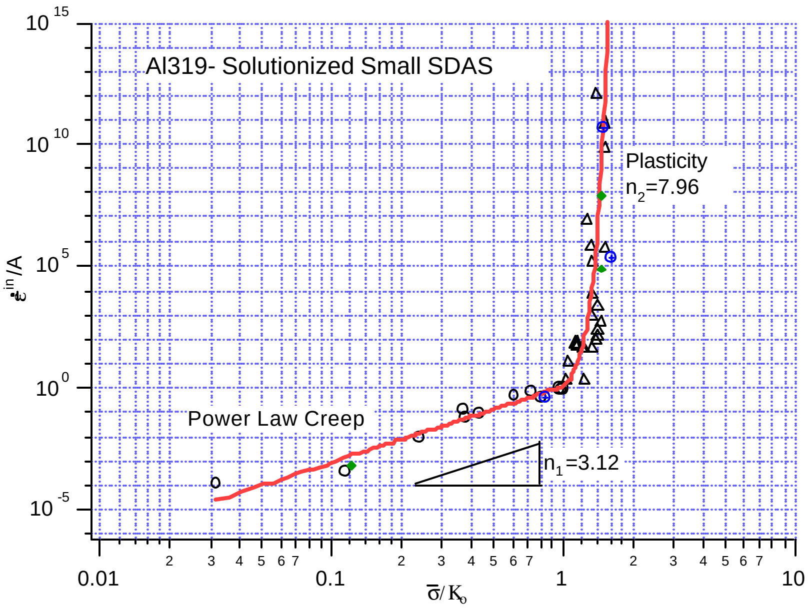
  (a) Constitutive Modeling (phenomenological:non-unified and unified models for stress-strain prediction)

  (b) Life Prediction Modeling (Crack nucleation (stress, strain, time), Crack Growth (Mean stress, crack length)

Classification of IF and TMF Studies (ctd.)

- **Engineering Application :**
  - (a) Material Selection
  - (b) Early Design
  - (c) Residual Life Assesment

Constitutive Modeling-
Experimentally Determined Flow Rule



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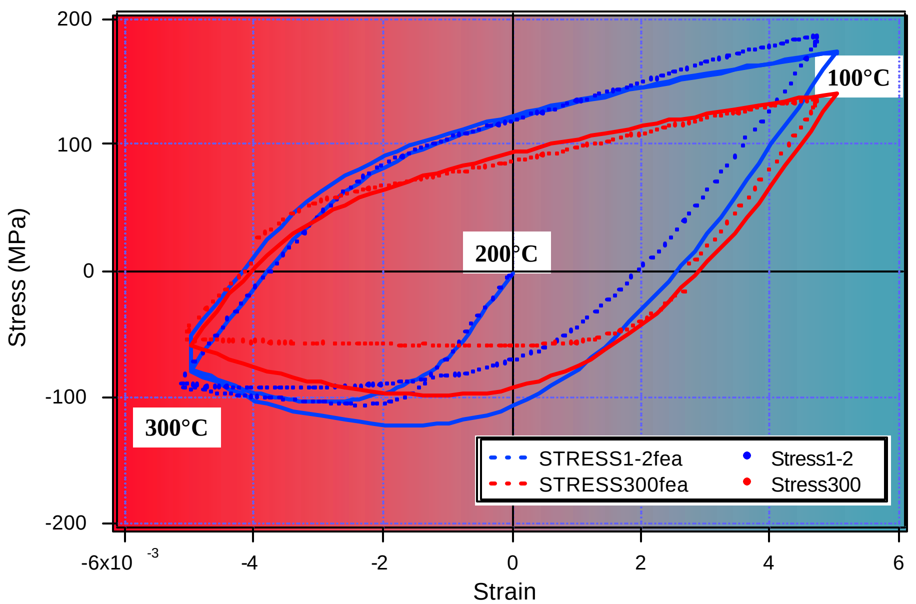
TMF OP 100-300°C 1.0%



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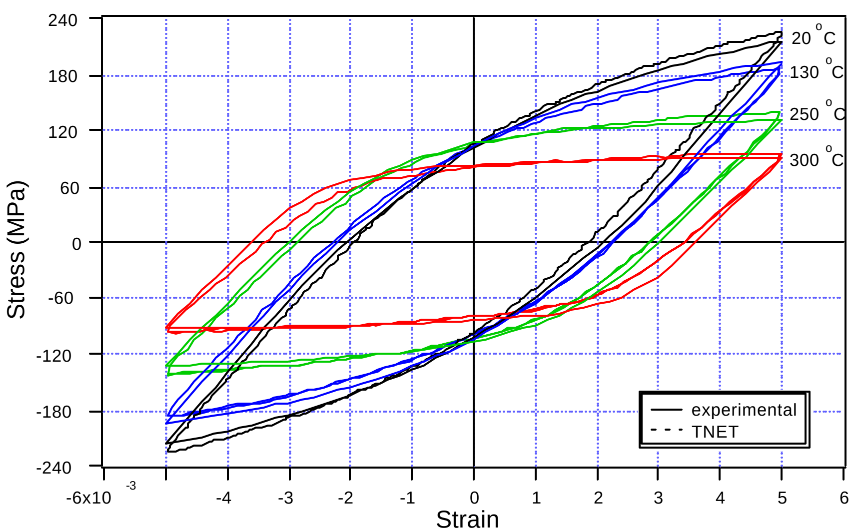
Hysteresis loops for the tests performed at $5x10^{-3}$ s^{-1}



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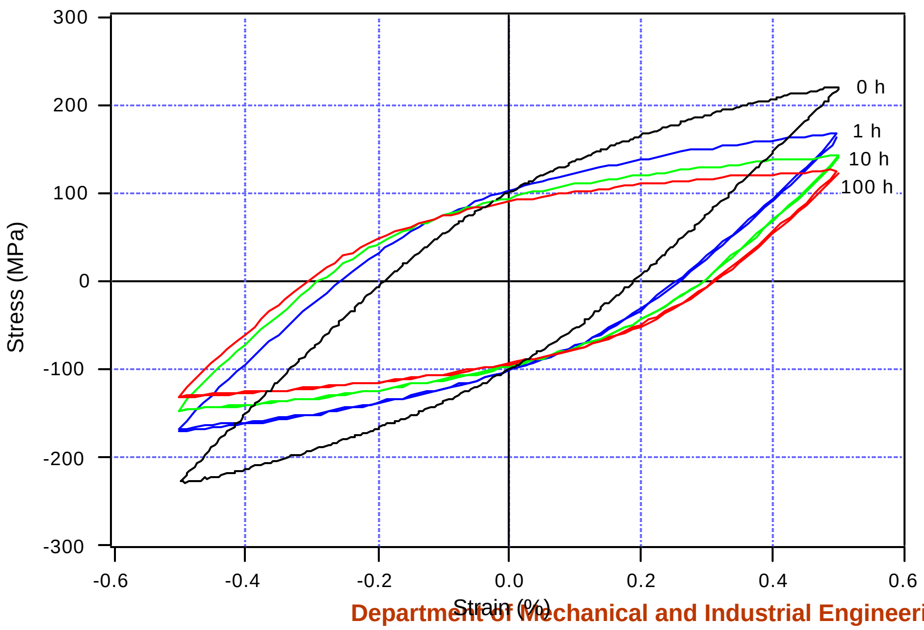
Drag stress recovery

Hyteresis loops at 20°C for the material pre-exposed at 300°C



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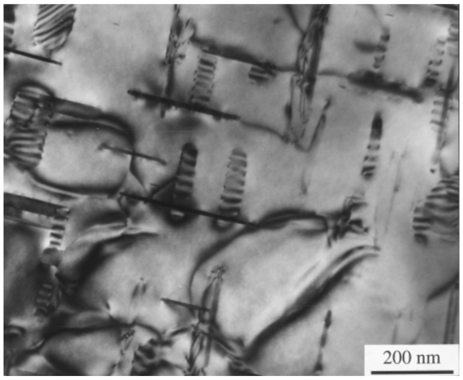
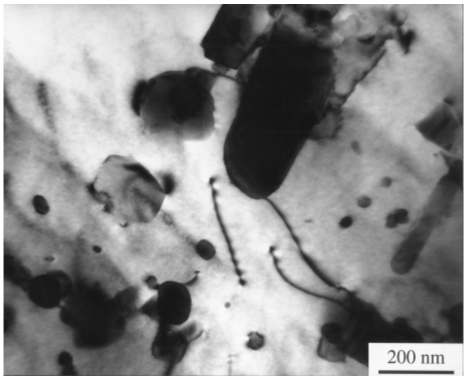
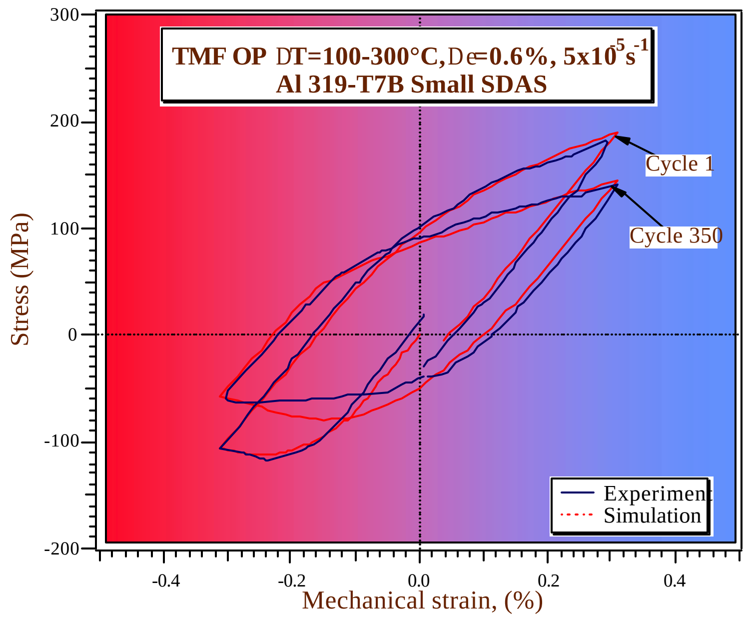
Coarsening of the Precipitates





TMF OP Stress-Strain Prediction



Mechanistic Studies

Constitutive Modeling:

Requirements for a good model:

- **Incorporate strain rate, temperature and mean stress effect on stress-strain response**
- **Incorporate temperature-strain induced changes on material's stress-strain response**

Mechanistic Studies

Constitutive Modeling:

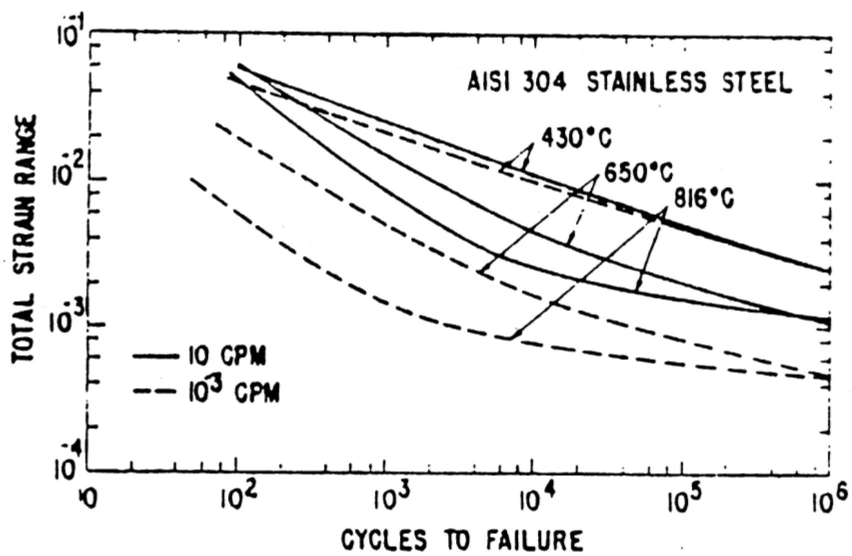
- **Non-unified Plasticity (stress-strain) Models: Plastic strains (time-independent) and creep strains are added.**
- **Unified Creep-Plasticity Models: Plastic strain and creep srain is combined as inelastic strain.**

Life Prediction Modeling

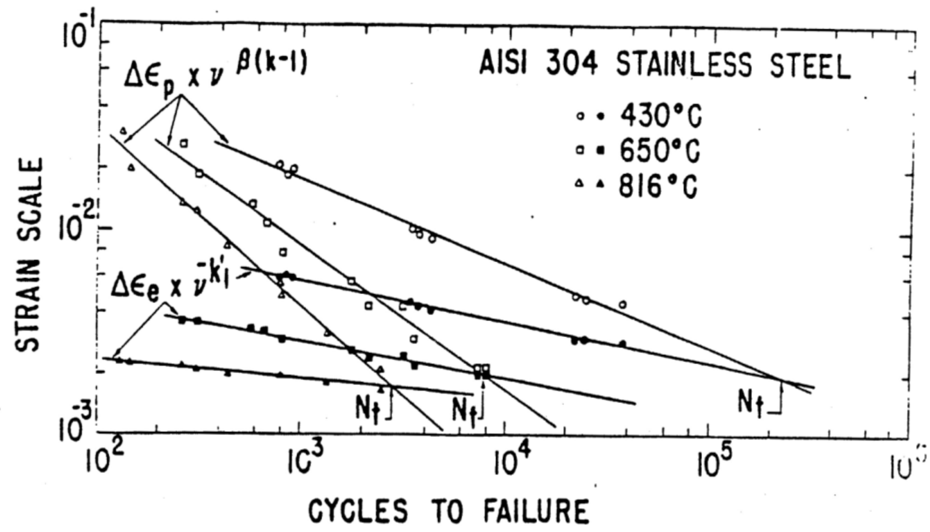
Requirements for a good model:

- **Incorporate stress,strain, thermal expansion, mean stress, stress state effect on life**
- **Predict the effect of temperature, strain rate, metallurgical changes on life.**

Coffin's Approach



Coffin’s Approach (Frequency Modified Life)



Coffin's Approach

Advantages:

(1) Simple to use; accounts for frequency effects

Disadvantages;

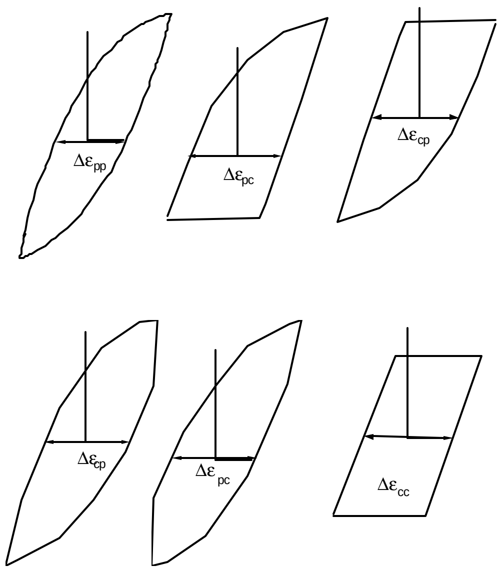
(1) Not sensitive to location of hold time within the cycle (tension or compression).

(2) Does not account for creep damage effects

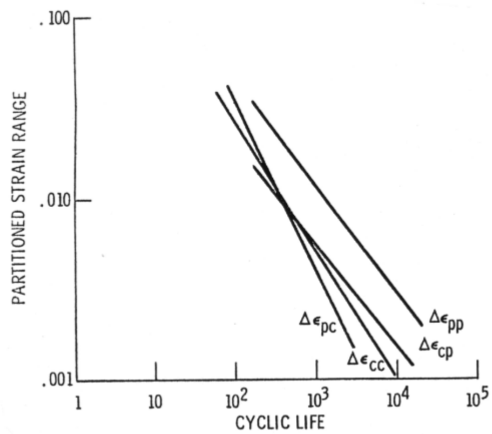
(3) TMF life prediction not explicitly handled.

(4) No stress-strain model

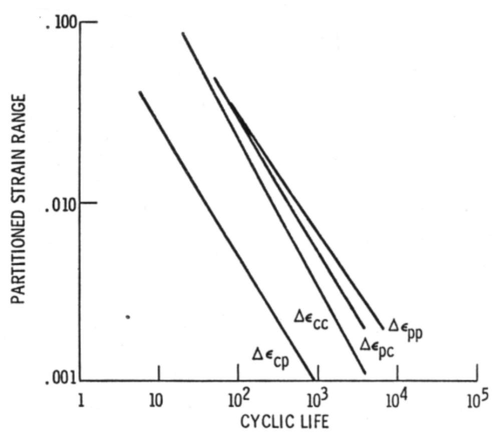
Strain Range Partitioning Method(SRP)



SRP Data on Two Class of Steels (Manson et al.)



· Summary of partitioned strain-life relations. $2\frac{1}{4}$ Cr - 1 Mo steel, 1100 F (865 K).



Summary of partitioned strain-life relations. Type 316 stainless steel, 1300 F (980 K).

SRP Approach

Advantages:

(1) Accounts for location of hold time within a cycle

Disadvantages;

(1) Life curves are often too close, expensive to generate all these curves

(2) Does not account for oxidation/environment effects

(3) TMF Life prediction not explicitly handled.

Development of a Mechanism Based Failure Model (Sehitoglu et al.)

- Damage per cycle is sum of the dominant mechanisms D_{fat}, D_{ox} , D_{creep}.
- The terms in the damage equations should be physically based, specifically, they should be linked to specific experiments, stress-strain behavior and microstructural observations.

Fatigue - Oxidation Models (ctd.)

- **Neu, Sehitoglu, Boismier, Kadioglu, 1987-**

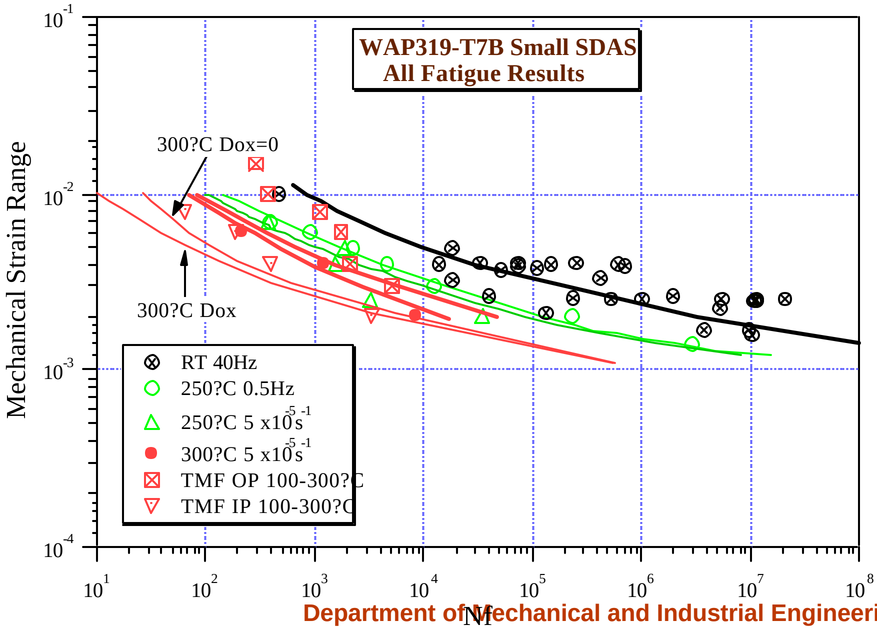
$$\frac{1}{N_f^{ox}} = \left(\frac{h_{cr}\ \delta_o}{B\Phi^{ox}\ K_{peff}}\right)^{-\frac{1}{\beta}} \frac{2\left[\Delta\varepsilon_{mech}^{ox}\right]^{\frac{2}{\beta}+1}}{(\dot{\varepsilon})^{(1-a'/\beta)}}$$

This equation accounts for the strain range at the oxide tip hence the oxide-metal properties the shape of the oxide are included.

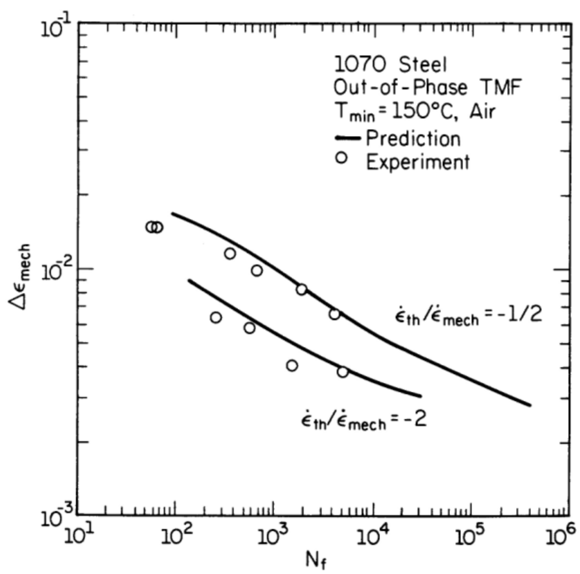
$\Phi^{ox}\ K_{peff}$ **depends on the temperature strain history**

and the temperature- time variation in the cycle.

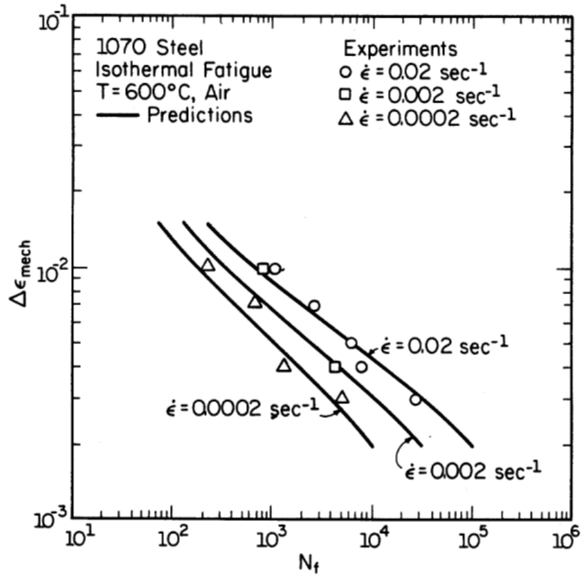
Combined Damage Model Predictions



Combined Damage Model Predictions (1070 Steel)



Combined Damage Model Predictions (1070 Steel)



Combined Damage Model

Advantages:

(1) Accounts for TMF loading.

(2) Damage due to oxidation and creep are included.

Disadvantages:

(1) Requires some time to understand how it all works.

Fatigue Damage Equation

- **Modified Strain-Life Relation**

$$\frac{\Delta e_{mech}}{2} = C' a_0^{\frac{2-b}{2b}} (2N_f^{fat})^{\frac{-1}{b}} + e'_f (2N_f^{fat})^c$$

a_0 - **initial pore size**
C' – **fatigue strength coefficient**
b – **fatigue strength exponent**
e'_f – **fatigue ductility coefficient**
c – **fatigue ductility exponent**

Creep Damage Equation

$$D^{cr} = C_c(m_c - 1)a_0^{m_c - 1}\left\langle \int_0^{tc} \left(\frac{|s_H|}{s_H} \right) \bar{s}^{\,n+1} \exp\left(-\frac{\Delta H}{RT} \right) dt \right\rangle^{m_c}$$

C_c, m_c - empirical constants

ΔH - activation energy

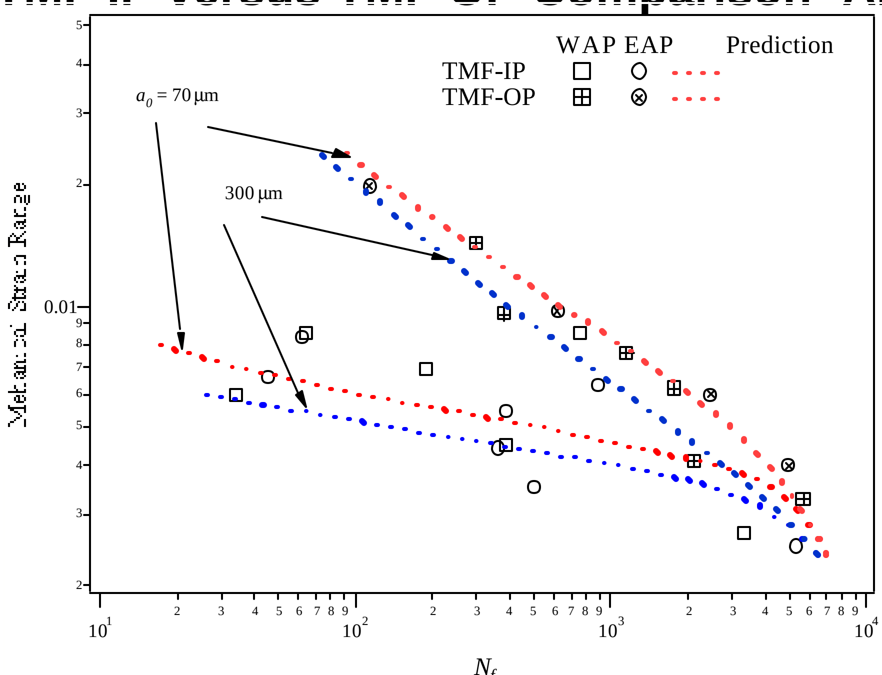
R - universal gas constant

s_H - hydrostatic stress

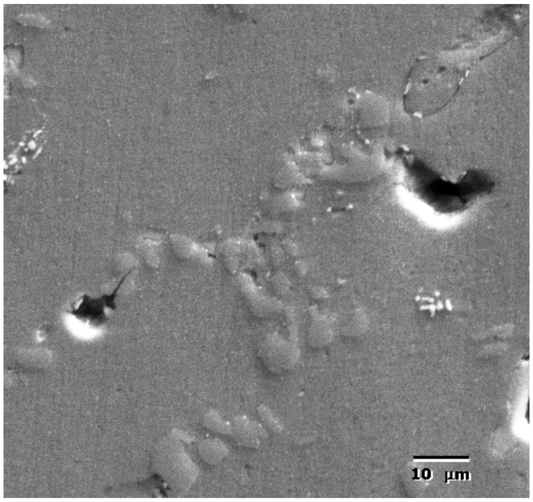
$\bar{s}$ - effective stress

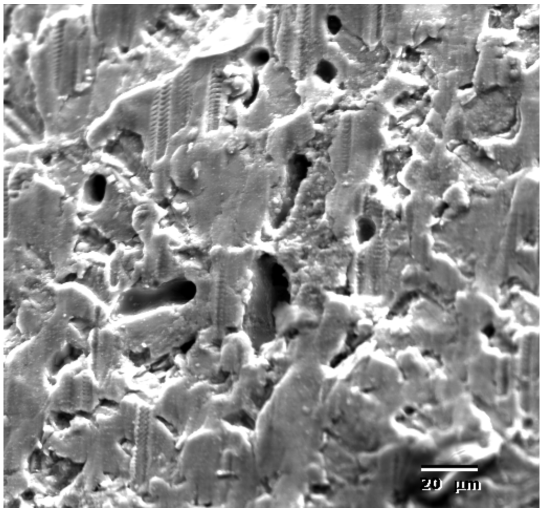
a_0 - initial pore size

TMF IP versus TMF OP Comparison- Al 319



Initial Voids and after TMF IP





Future Directions

- A simple model is developed to predict life for a given mechanical strain range, maximum temperature, and material.

- Given a strain and temperature field in a component, the model can predict the most critical location where crack nucleation will occur.

Future Directions (ctd.)

- Given an elastic strain, temperature history from FEM, the model is able to predict the stresses and plastic strains assuming the mechanical strain is equal to the elastic strain from FEM. This is known as the ‘ strain invariance method’.

- To predict component behavior the model accounts for the initial defect size.