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

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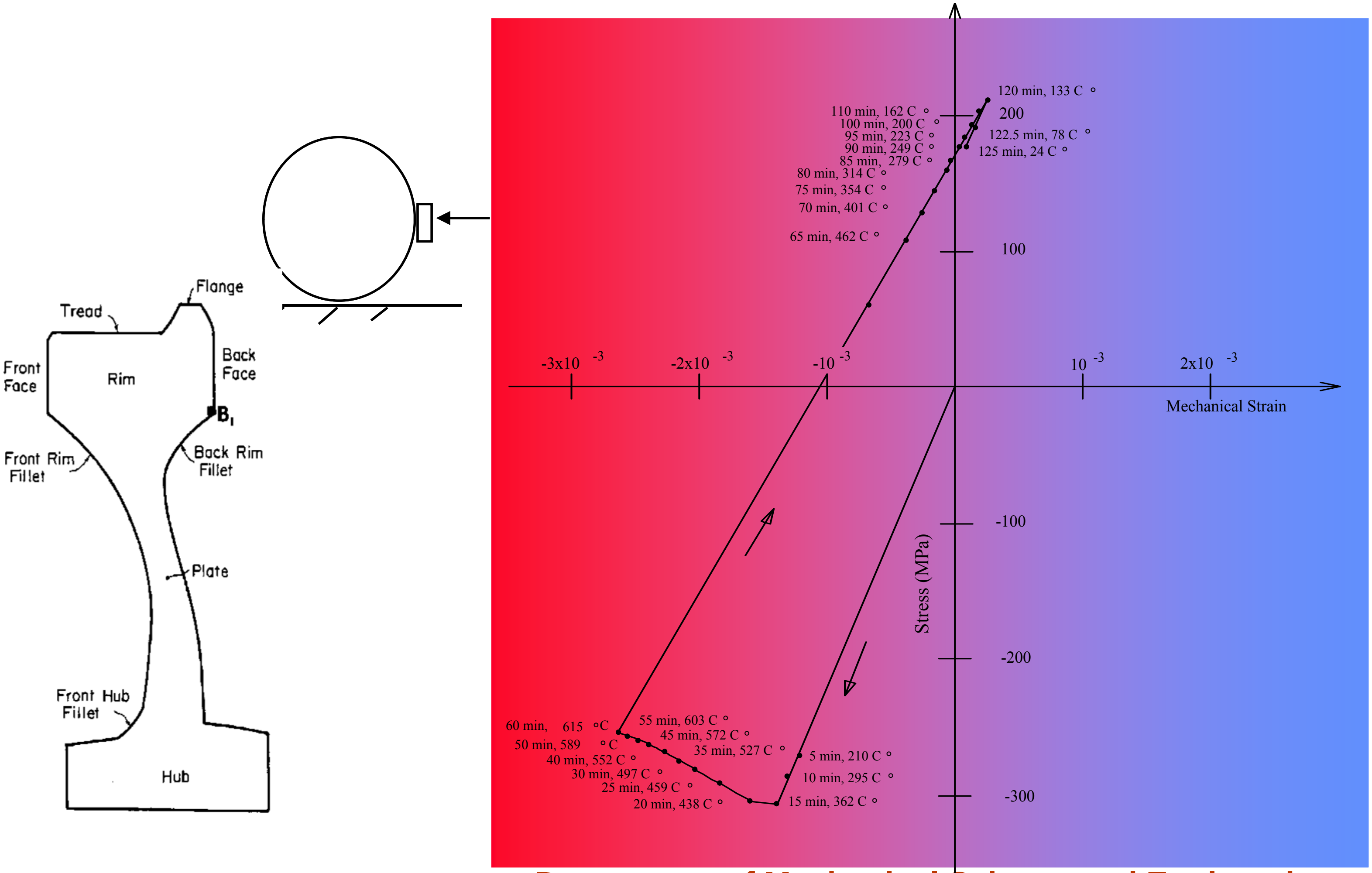
Talk Outline

- 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

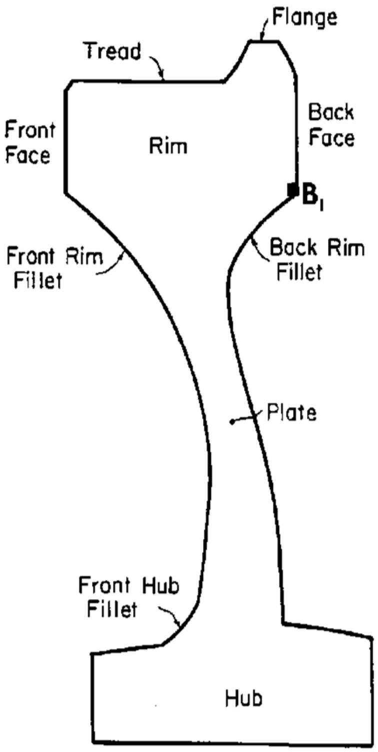
Examples of Components Experiencing High Temperatures

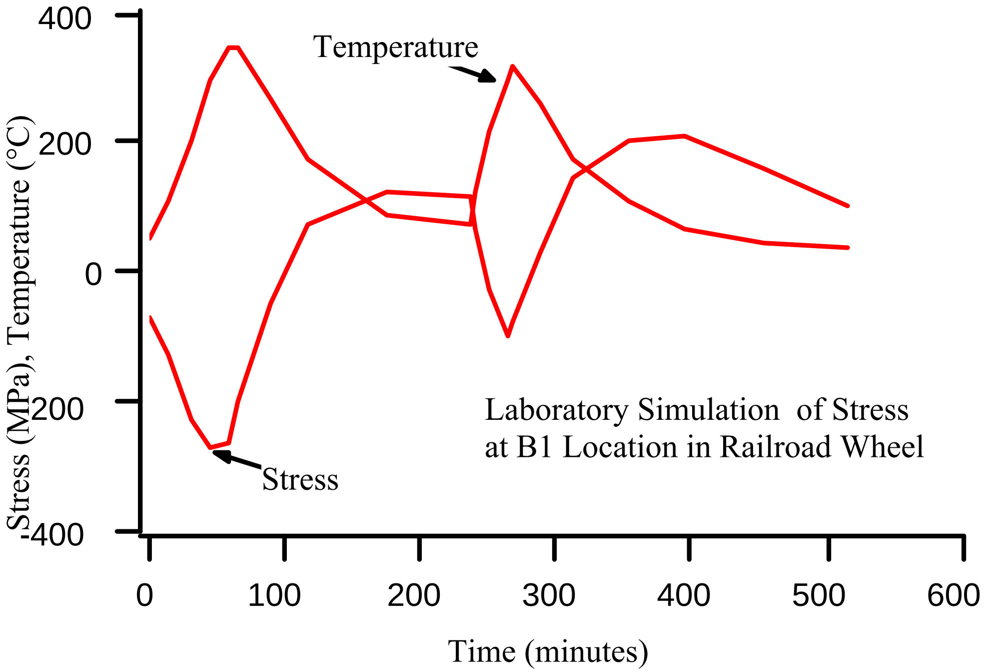
- Railroad Wheels undergoing Friction Braking
- Brake Rotors
- Pistons, Valves and Cylinder Heads of Spark-ignition and Diesel Engines
- Turbine Blades and Turbine Disks
- Pressure Vessel and Piping

Railroad Wheels under Friction Braking



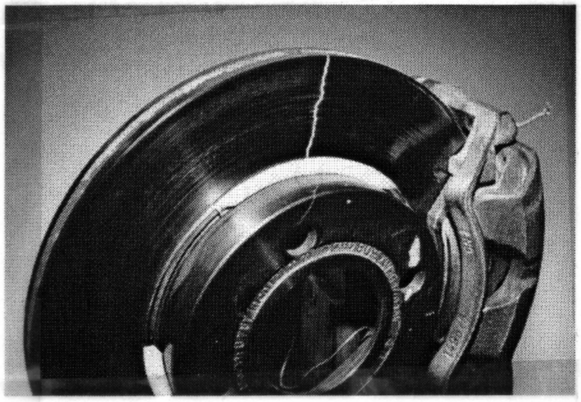
Schematic of a Railroad Wheel, Strain-Temperature-Stress Changes on the B1 location under brake shoe heating (laboratory simulation based on strain temperature measurements on wheels)

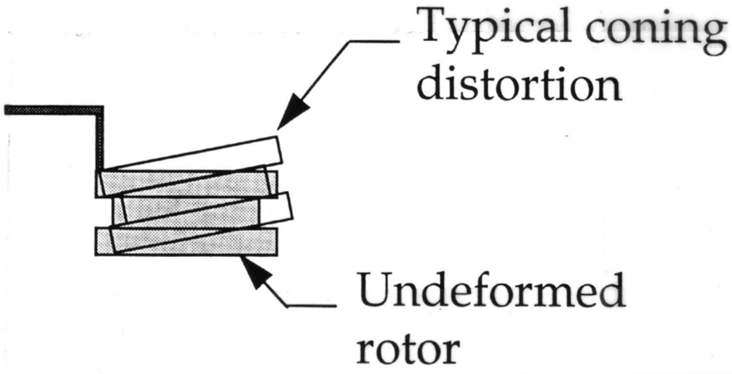


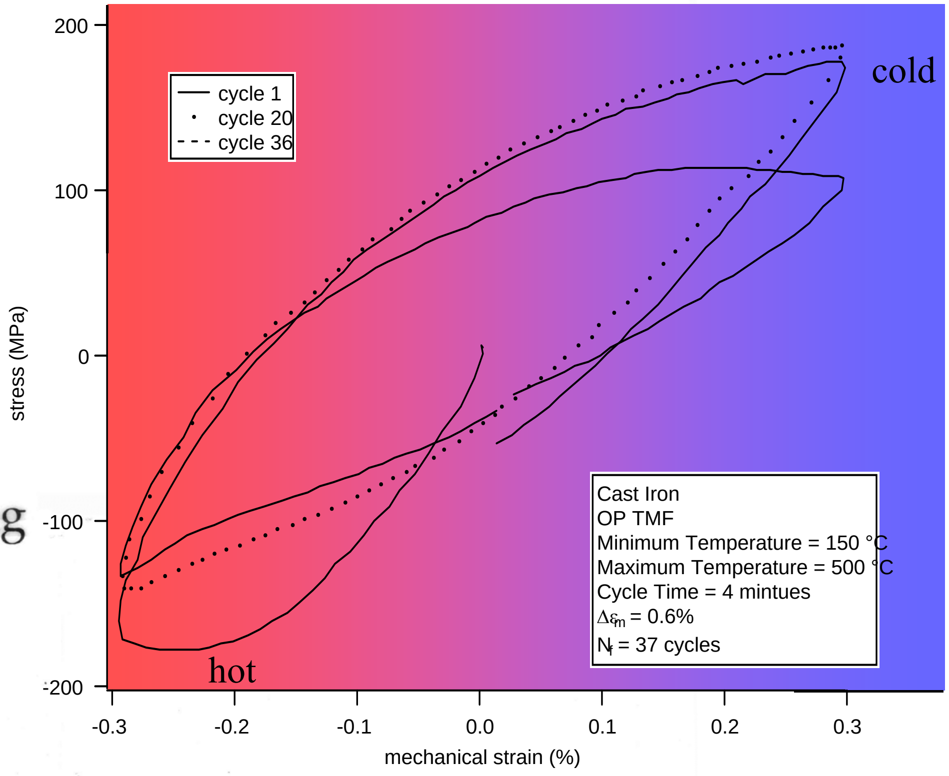


Laboratory Simulation of Stress at B1 Location in Railroad Wheel

Brake Rotor Cracking

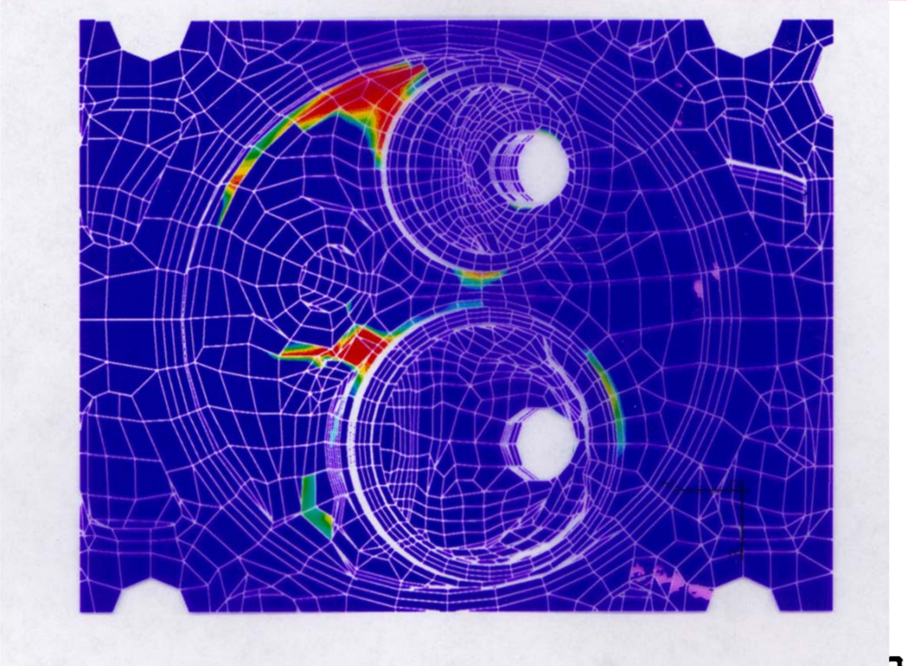


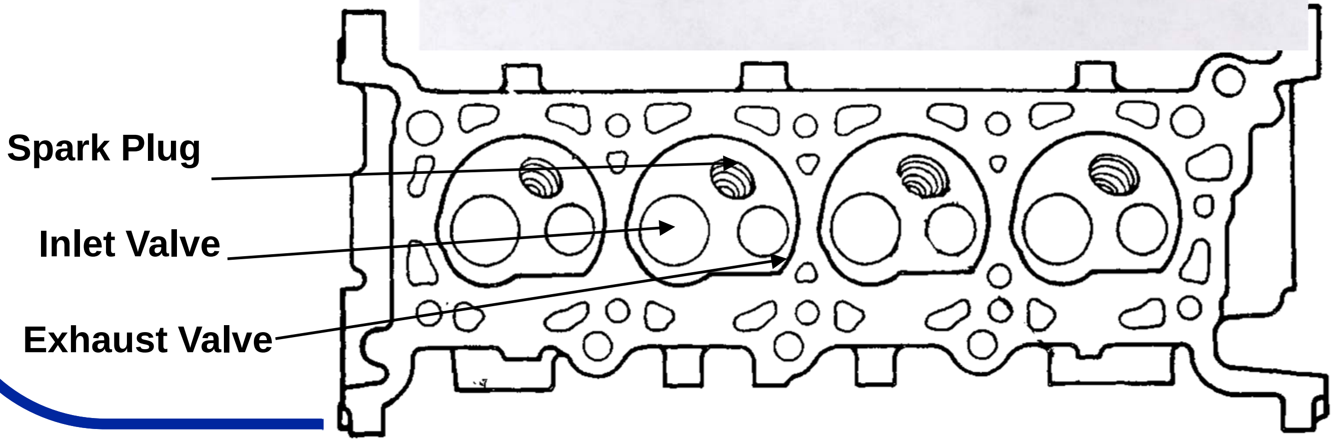




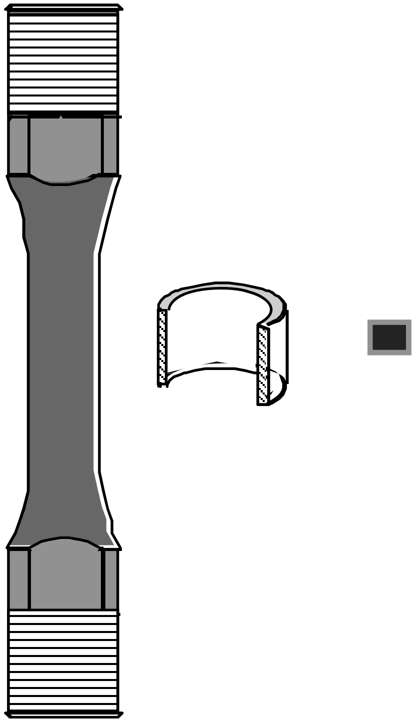
Cast Iron
OP TMF
Minimum Temperature = 150 °C
Maximum Temperature = 500 °C
Cycle Time = 4 mintues
$\Delta\varepsilon_m$ = 0.6%
N_f = 37 cycles

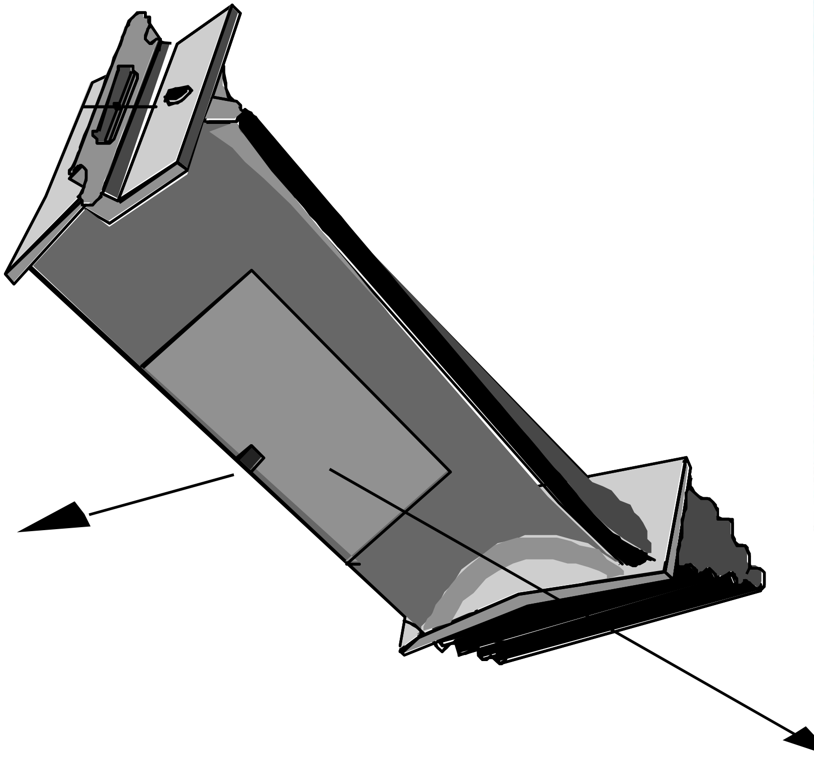
Cylinder Heads (FEM and Fatigue Life Contours)

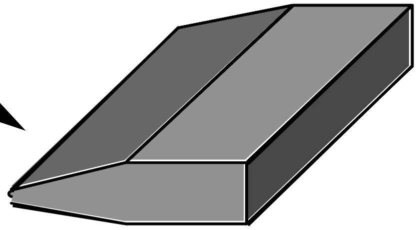




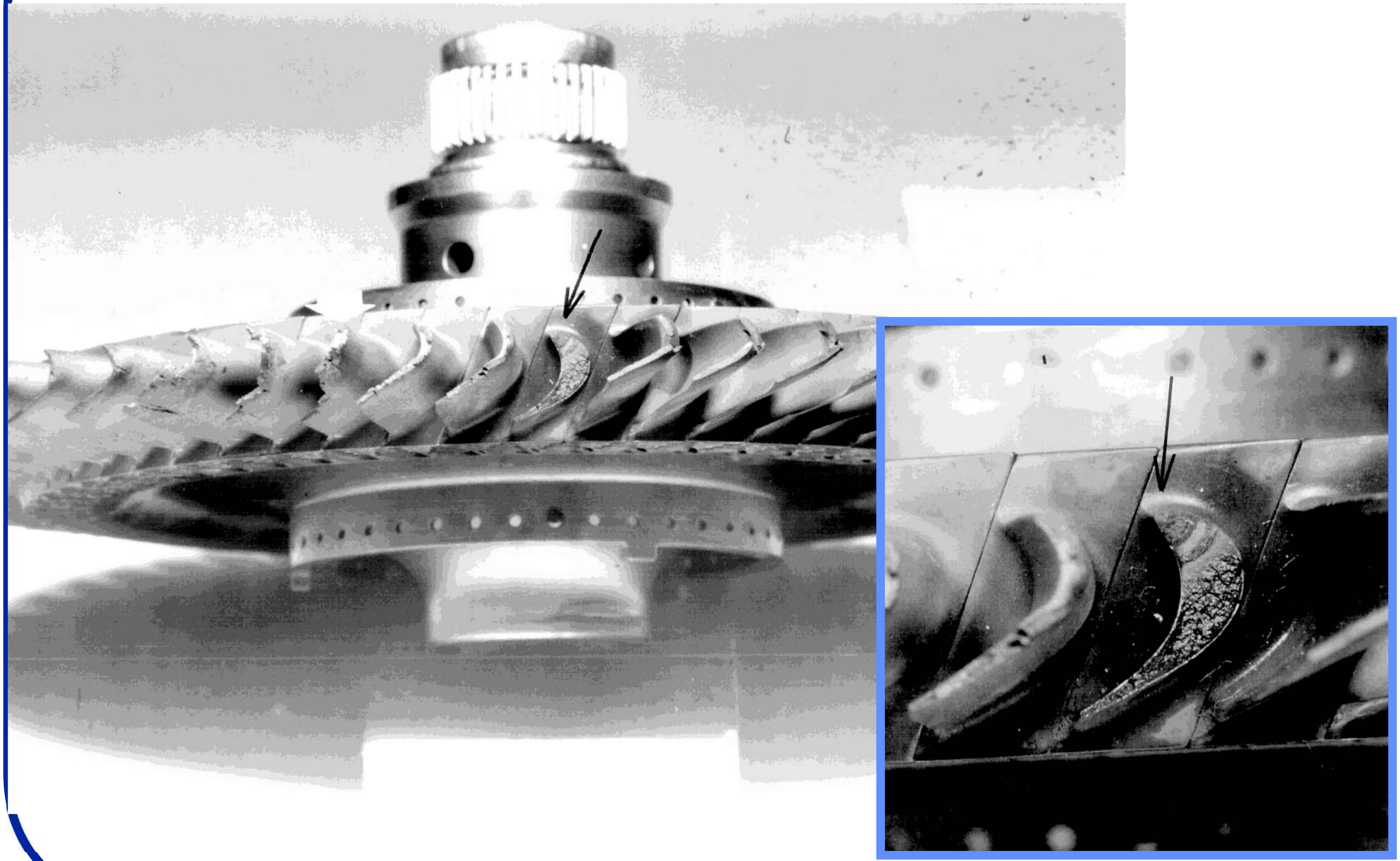
Turbine Blades



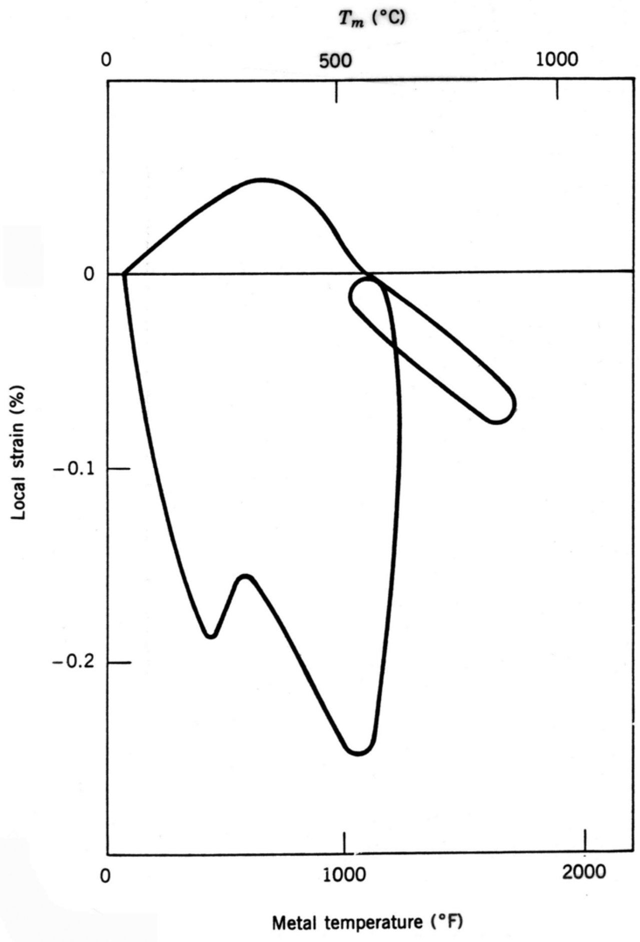


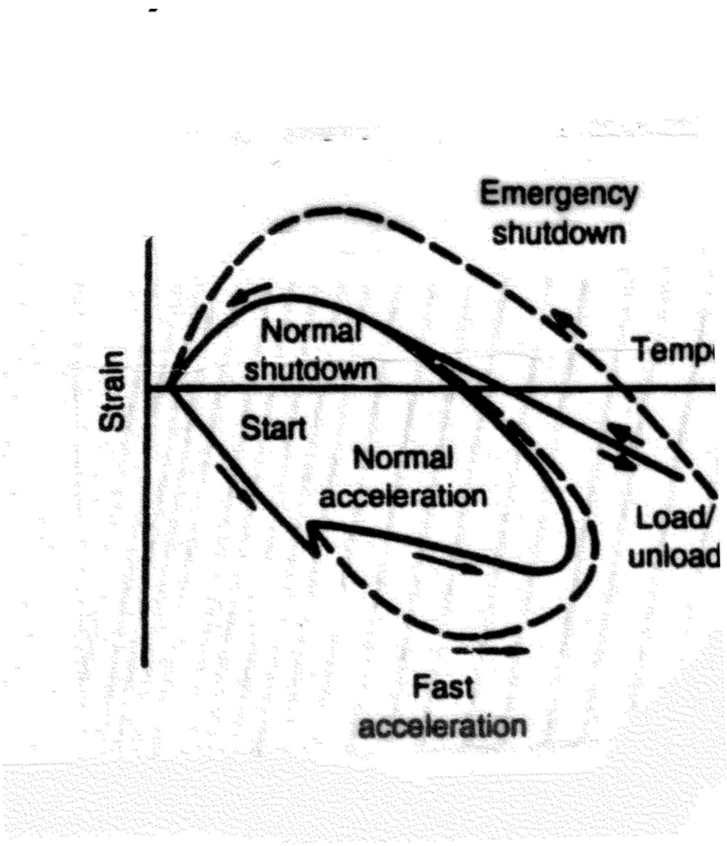


Turbine Blades(Thermo-mechanical fatigue failure)



Turbine Blades (strain-temperature variation)

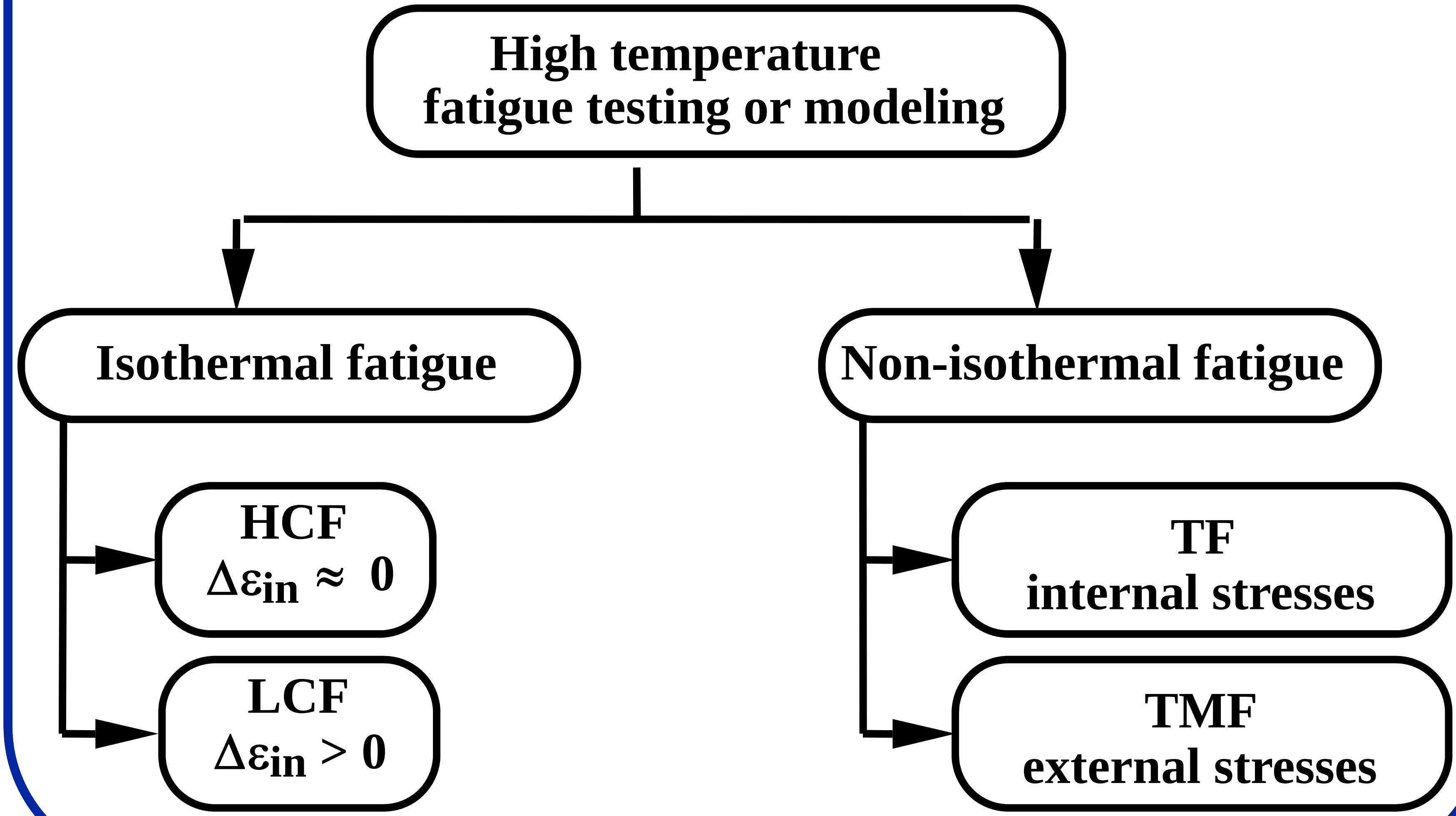




Basic Terminology at High Temperatures

- 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

Isothermal vs. Thermo-mechanical fatigue



High temperature fatigue testing or modeling

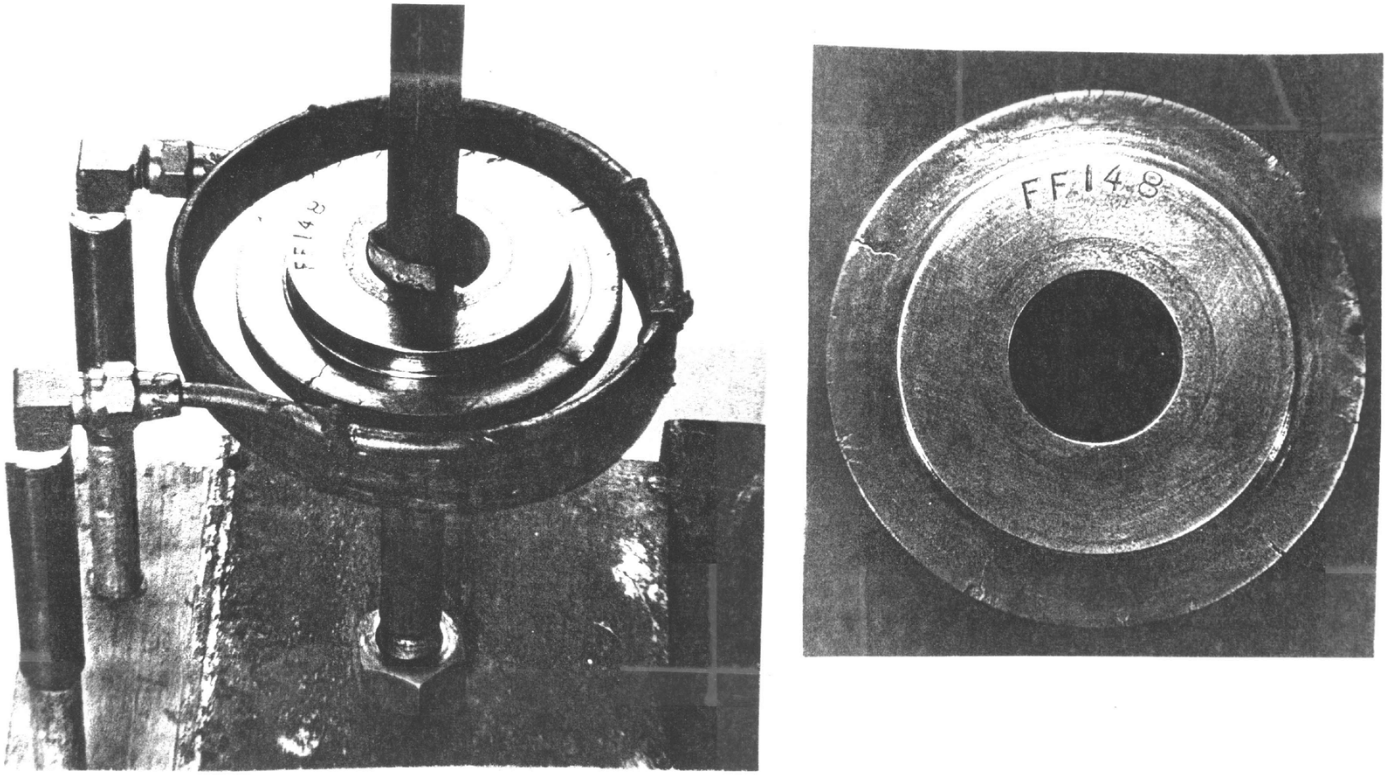
Isothermal fatigue

- **HCF** $\Delta\varepsilon_{in} \approx 0$
- **LCF** $\Delta\varepsilon_{in} > 0$

Non-isothermal fatigue

- **TF** internal stresses
- **TMF** external stresses

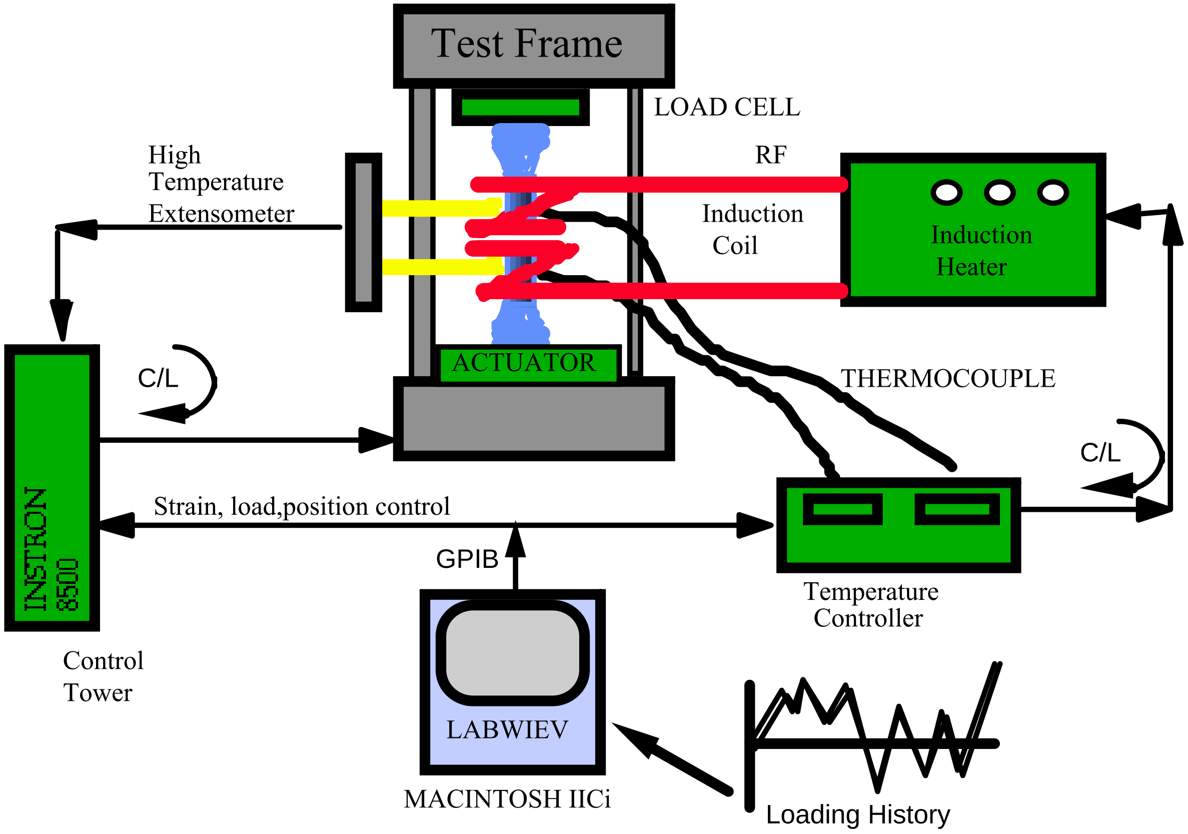
Disk Specimen under TF loading (Simovich)



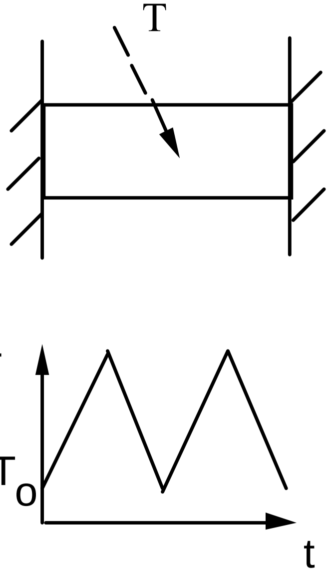
Limitations in our Understanding of High Temperature Material Behavior

- 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.

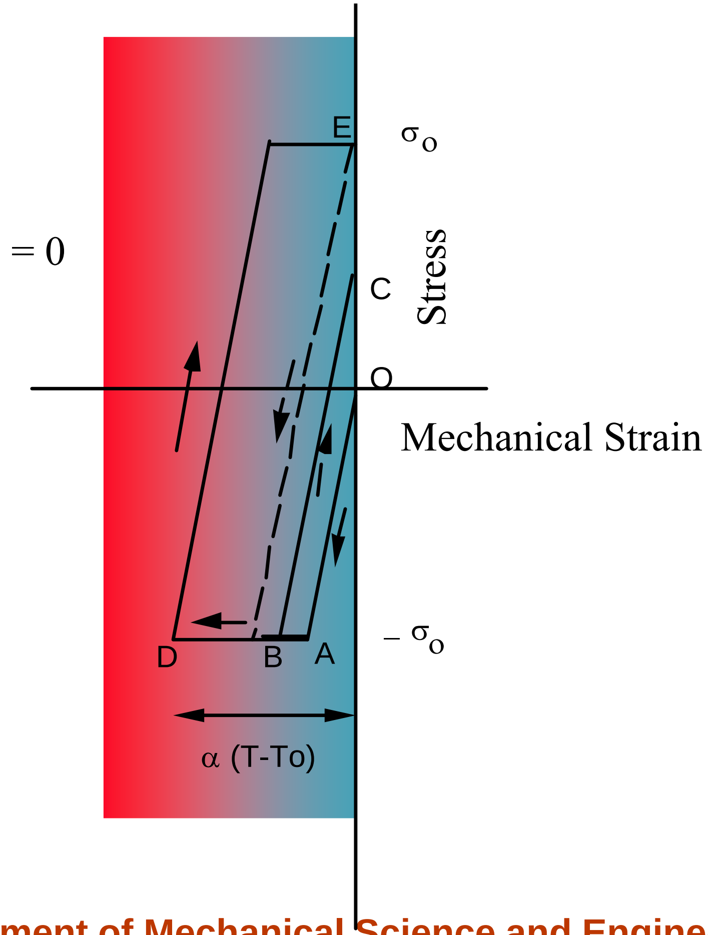
Experimental Techniques at High Temperatures



Total Constraint



$\varepsilon_{net} = 0$



Total Constraint (ctd.)

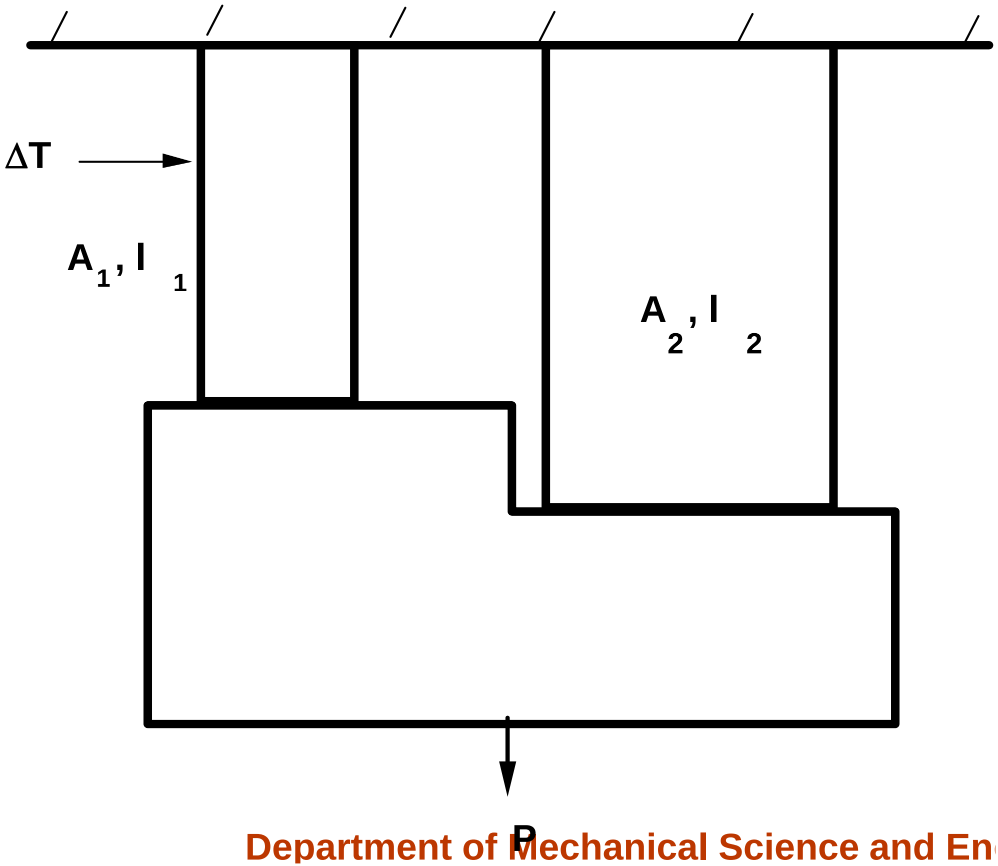
The compatibility equation

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

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

$$\varepsilon_{mech} = -\,\alpha\,(T-T_o)$$

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 :

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

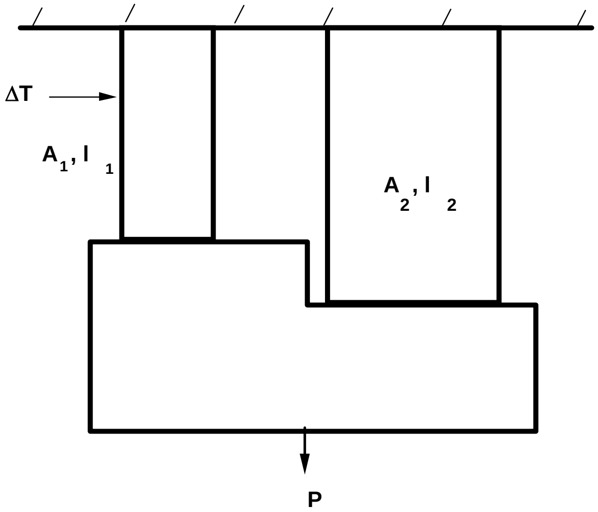
$$\varepsilon_2 = \varepsilon_{2\,e}$$

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

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

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

The Concepts of Total, Partial, Over and Notch Constraint

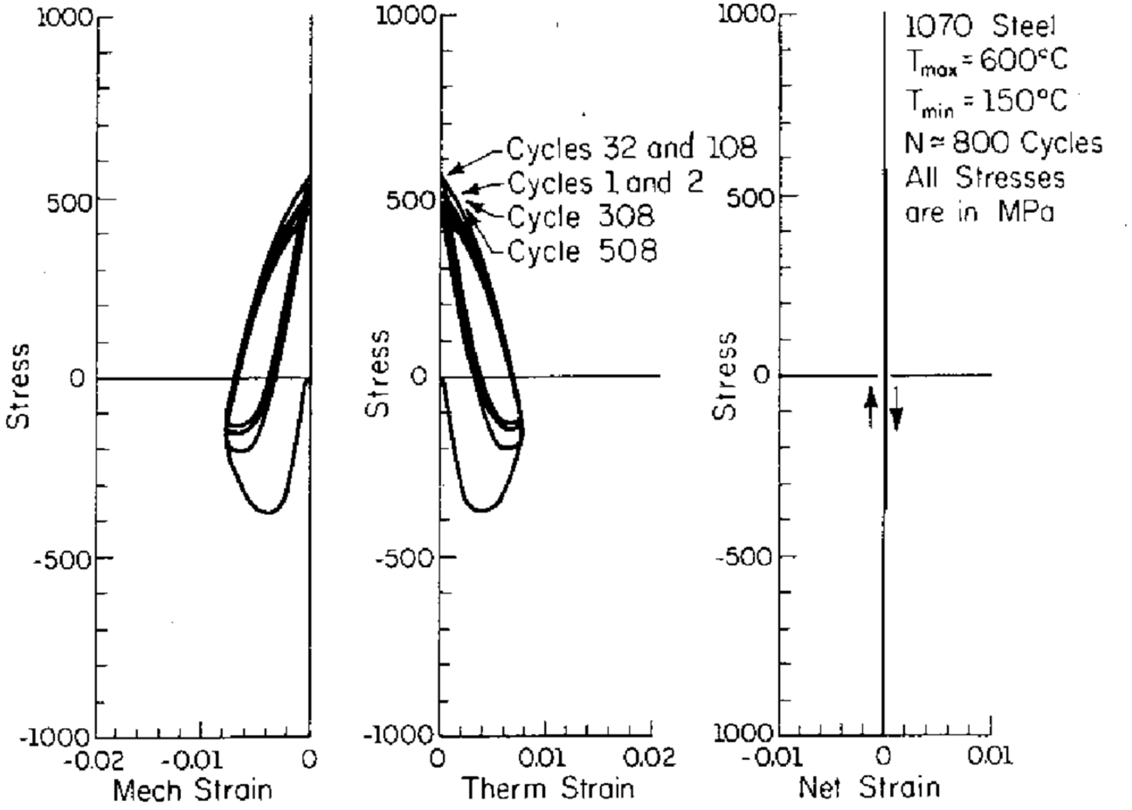


$$\varepsilon_1 = \frac{-\frac{\sigma_1}{E_2}}{C} \;, \quad C = \frac{A_2 . l_1}{A_1 . l_2}$$

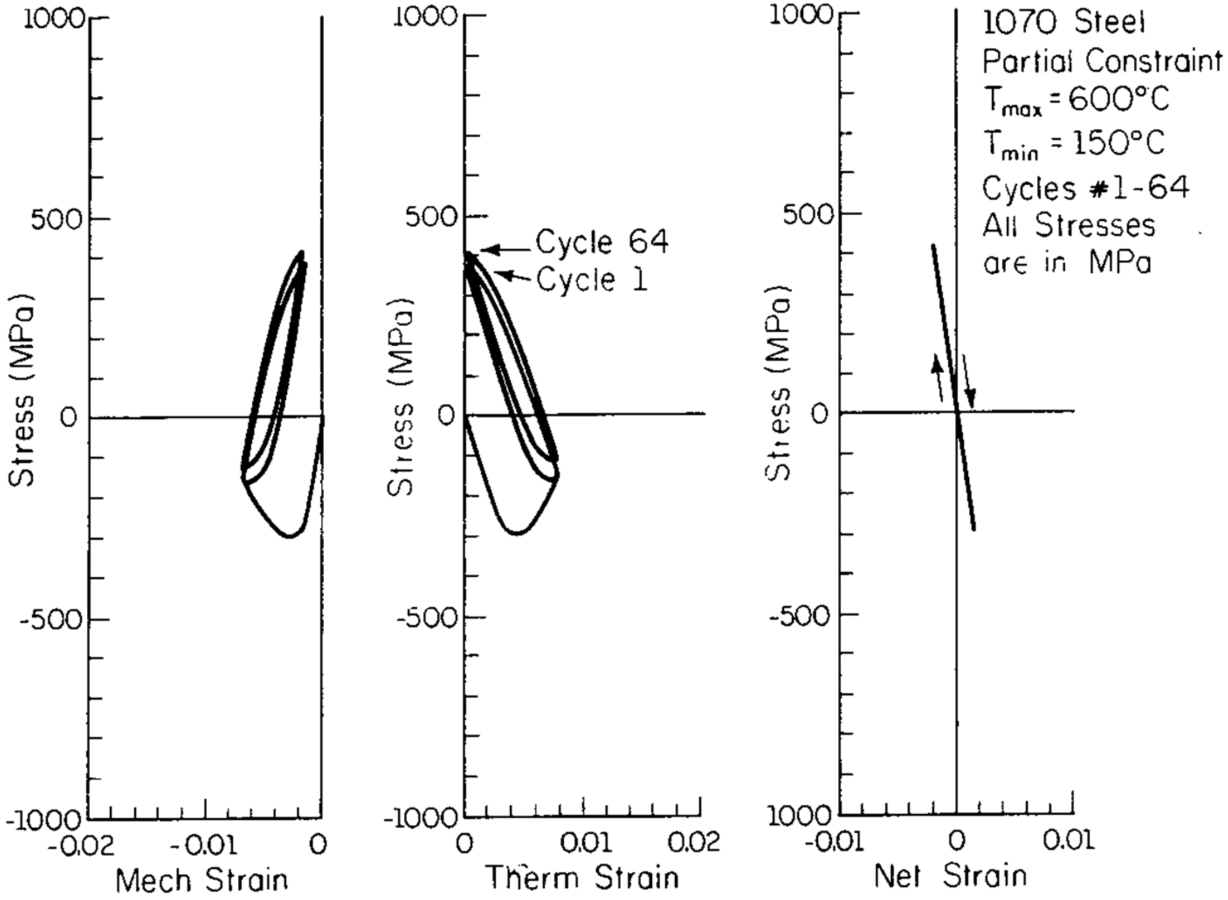
$C \rightarrow \infty$; Total Constraint

$C \rightarrow$ finite ; Partial Constraint

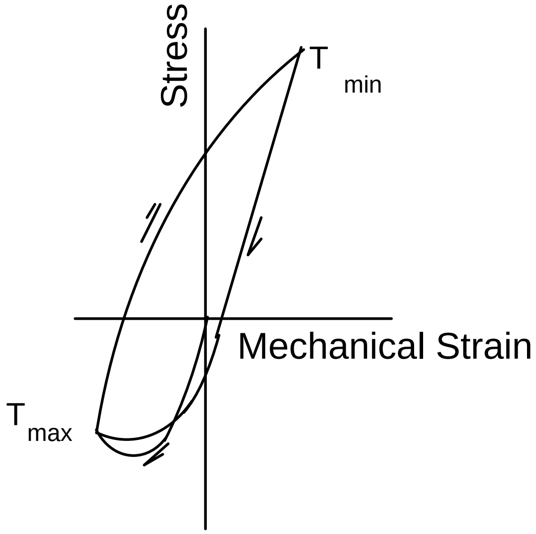
The Stress-strain Response under Total and Partial Constraint



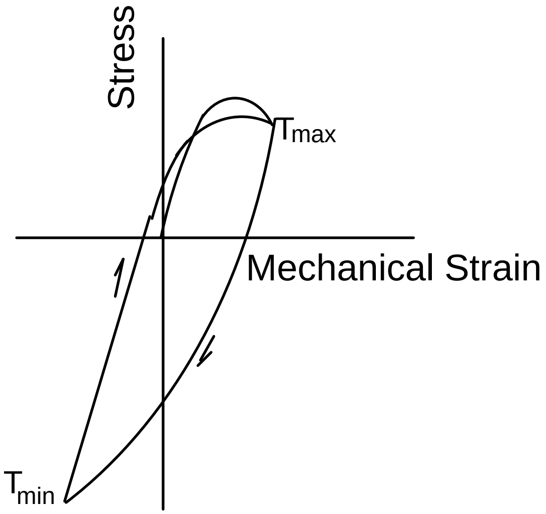
The Stress-strain Response under Total and Partial Constraint (ctd.)



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

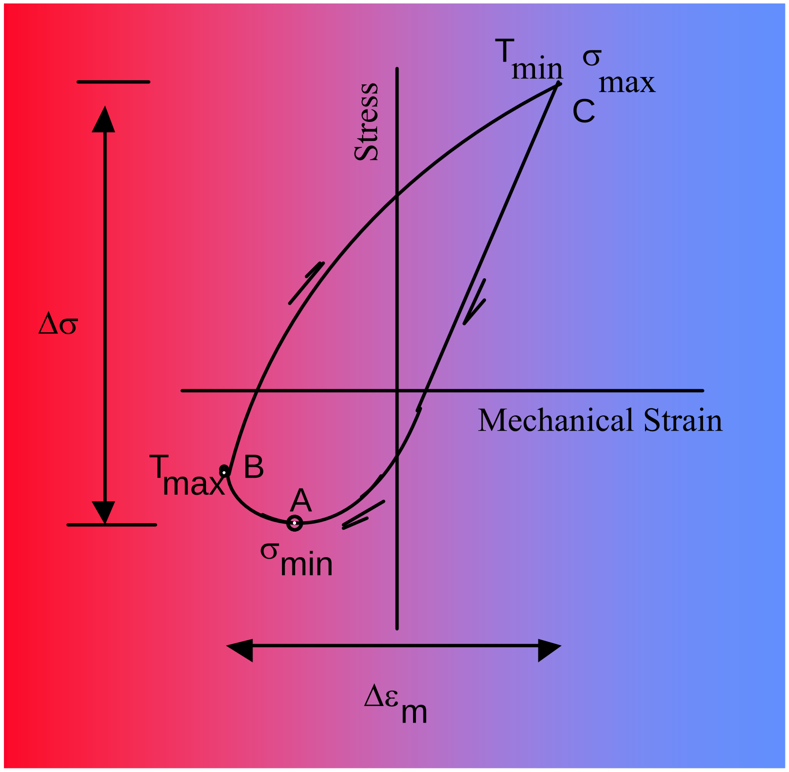


Out-of-Phase TMF Response



In-Phase TMF Response

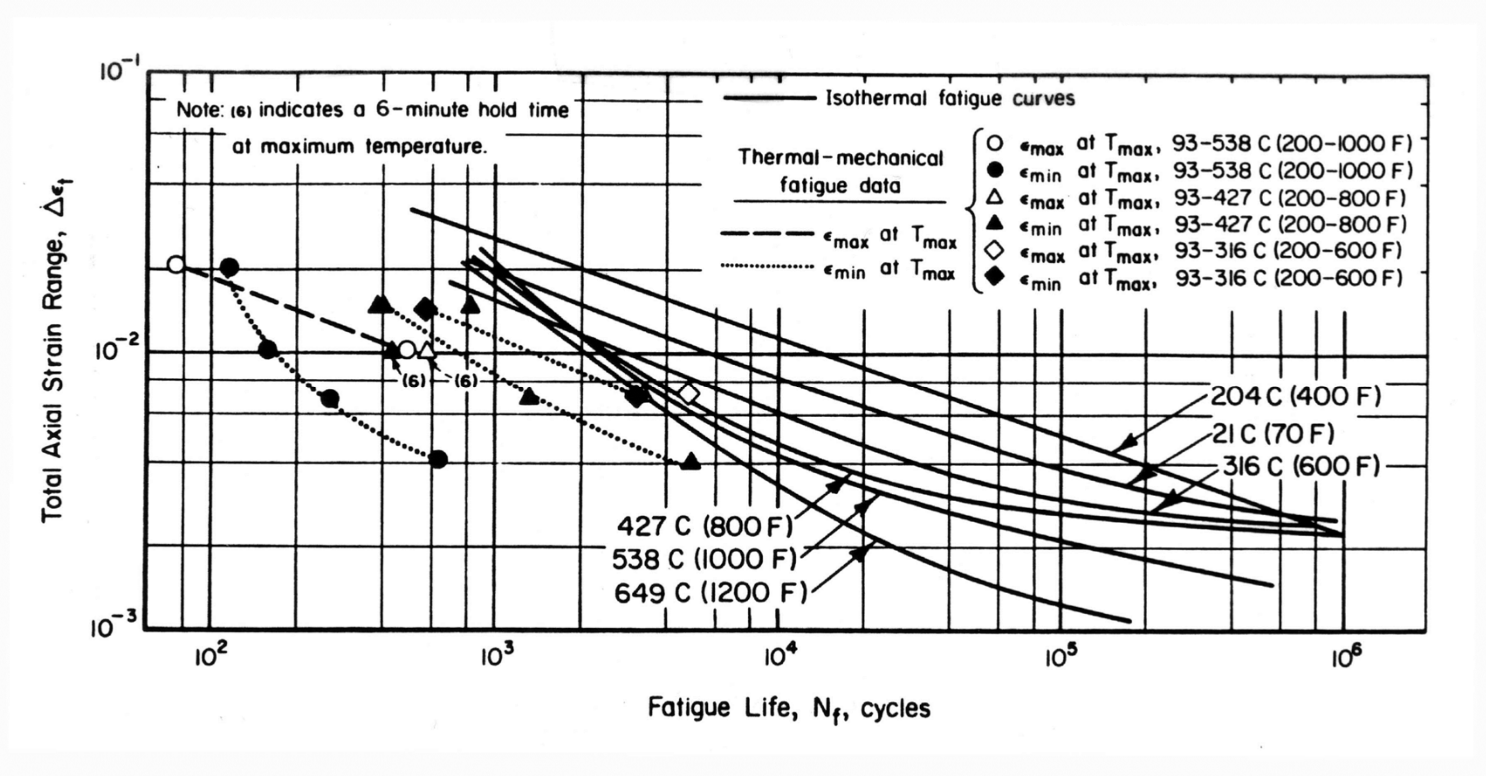
Some Definitions



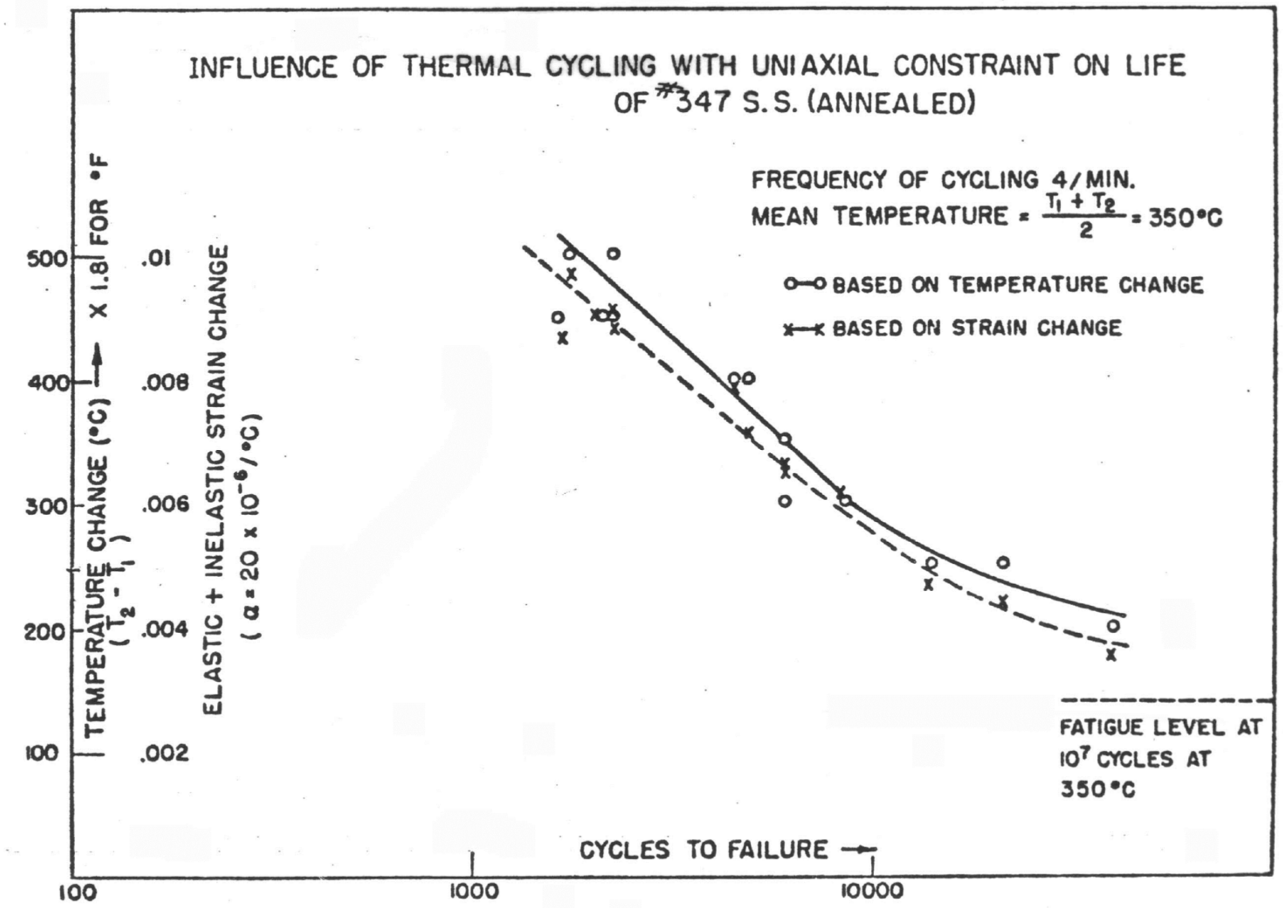
Inelastic Strain range:

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

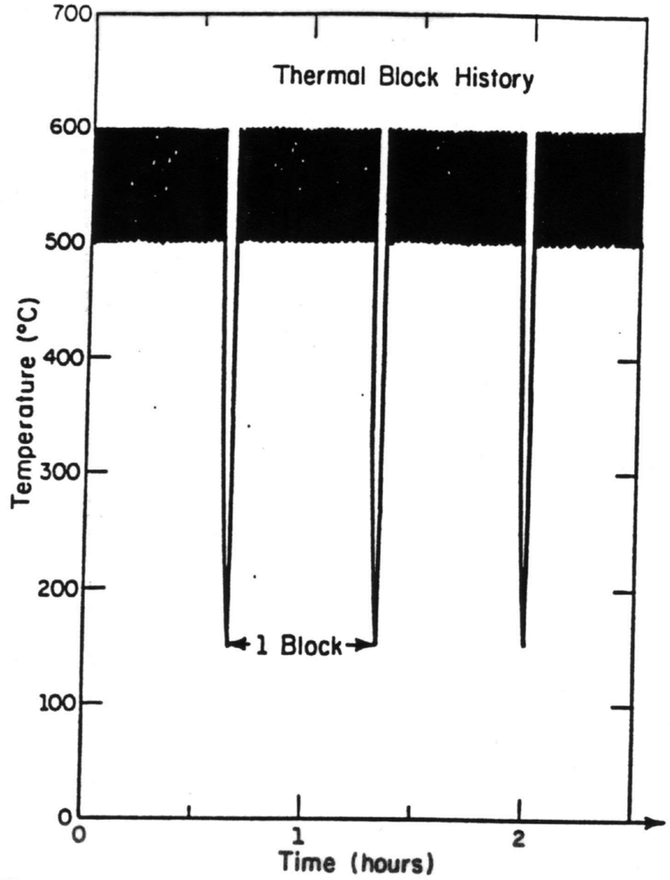
Comparison of TMF IP and TMF OP Tests on 1010 Steel (Jaske's Data)

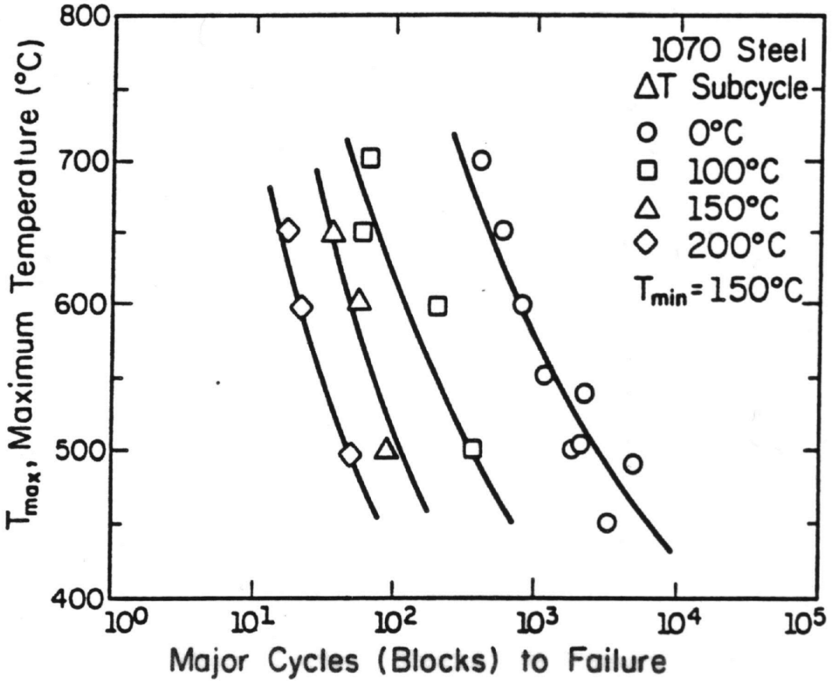


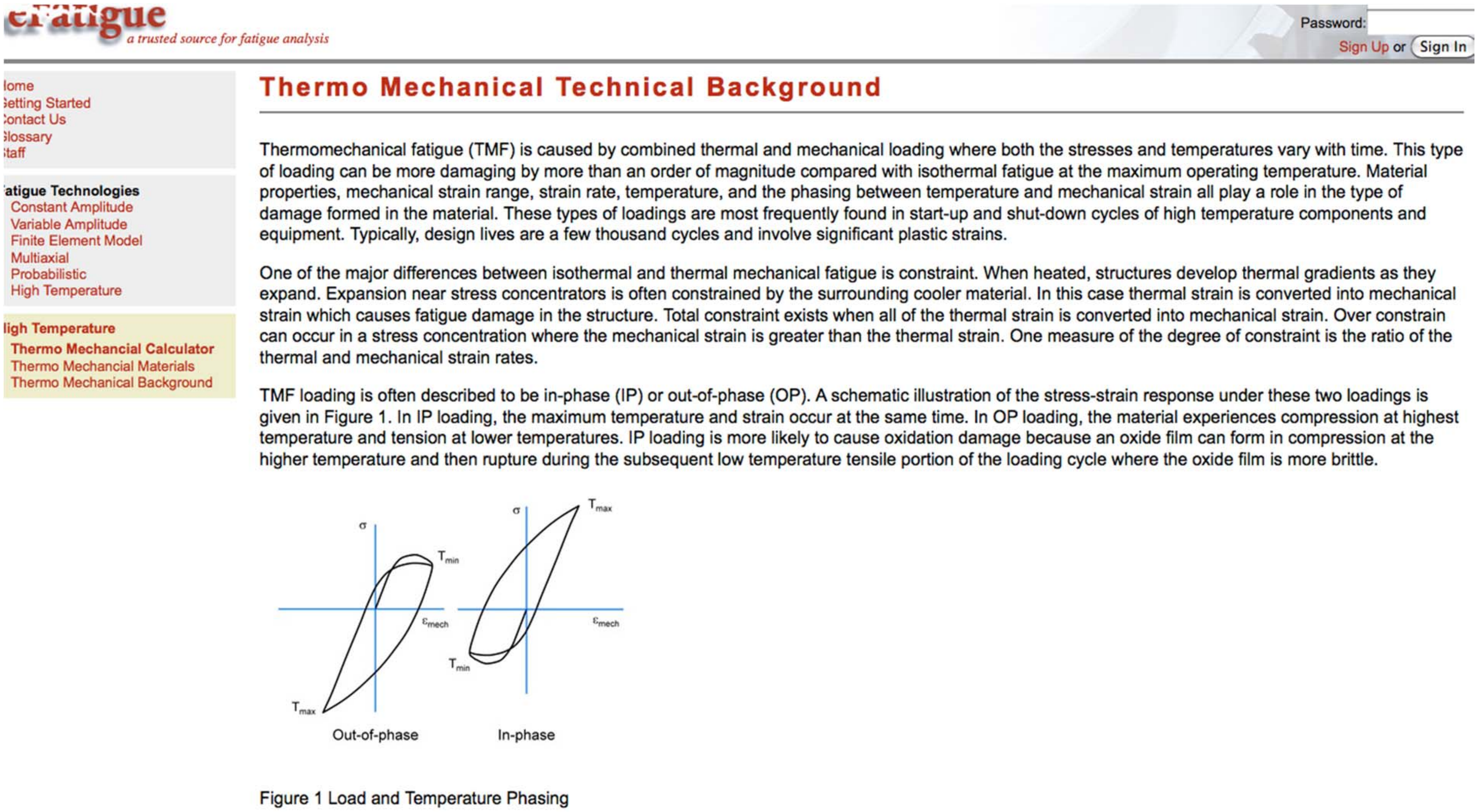
TMF experiments of Coffin



Thermal Block Histories on Steels under Total Constraint







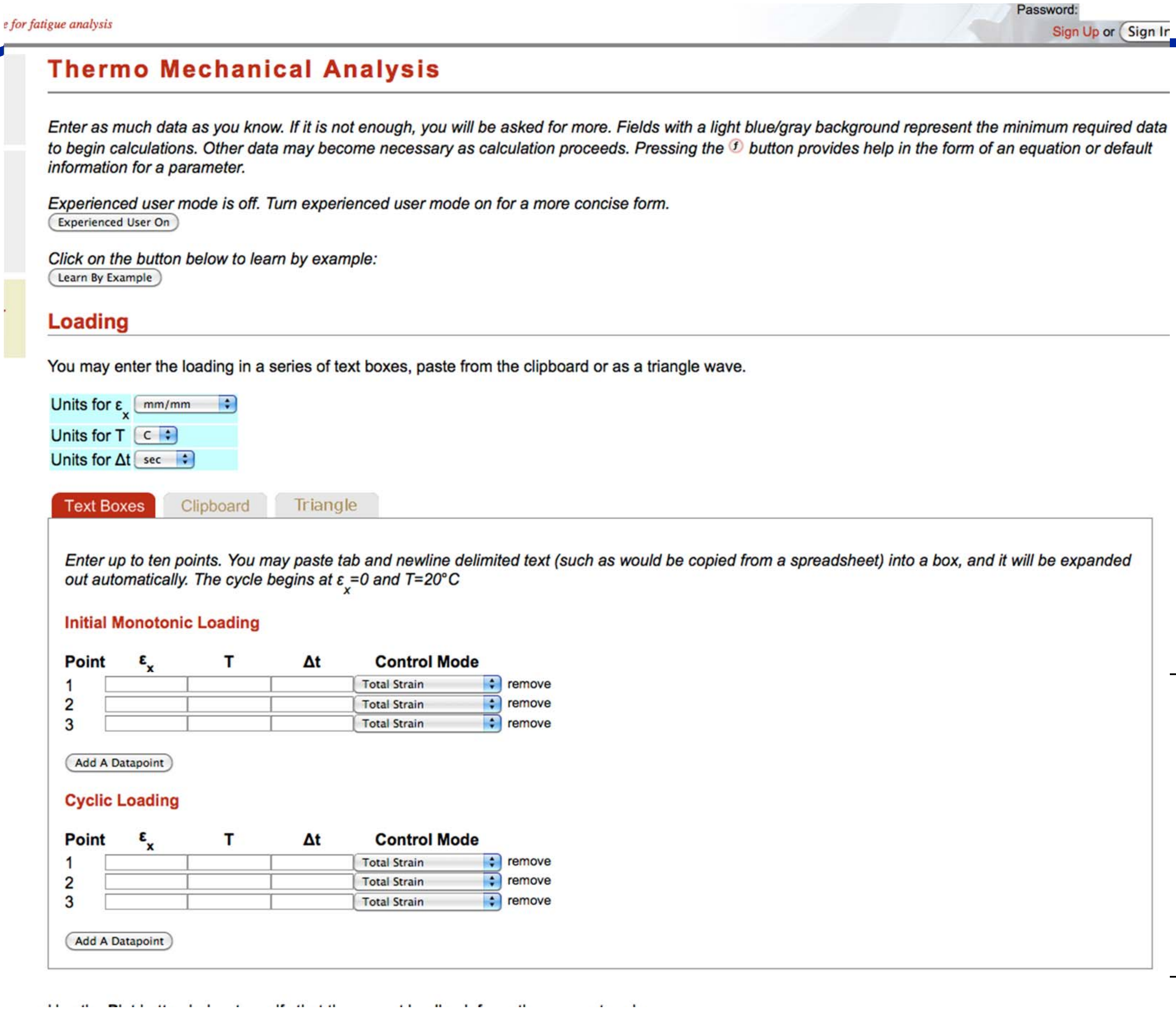
Thermo Mechanical Technical Background

Thermomechanical fatigue (TMF) is caused by combined thermal and mechanical loading where both the stresses and temperatures vary with time. This type of loading can be more damaging by more than an order of magnitude compared with isothermal fatigue at the maximum operating temperature. Material properties, mechanical strain range, strain rate, temperature, and the phasing between temperature and mechanical strain all play a role in the type of damage formed in the material. These types of loadings are most frequently found in start-up and shut-down cycles of high temperature components and equipment. Typically, design lives are a few thousand cycles and involve significant plastic strains.

One of the major differences between isothermal and thermal mechanical fatigue is constraint. When heated, structures develop thermal gradients as they expand. Expansion near stress concentrators is often constrained by the surrounding cooler material. In this case thermal strain is converted into mechanical strain which causes fatigue damage in the structure. Total constraint exists when all of the thermal strain is converted into mechanical strain. Over constrain can occur in a stress concentration where the mechanical strain is greater than the thermal strain. One measure of the degree of constraint is the ratio of the thermal and mechanical strain rates.

TMF loading is often described to be in-phase (IP) or out-of-phase (OP). A schematic illustration of the stress-strain response under these two loadings is given in Figure 1. In IP loading, the maximum temperature and strain occur at the same time. In OP loading, the material experiences compression at highest temperature and tension at lower temperatures. IP loading is more likely to cause oxidation damage because an oxide film can form in compression at the higher temperature and then rupture during the subsequent low temperature tensile portion of the loading cycle where the oxide film is more brittle.

Figure 1 Load and Temperature Phasing



Thermo Mechanical Analysis

Enter as much data as you know. If it is not enough, you will be asked for more. Fields with a light blue/gray background represent the minimum required data to begin calculations. Other data may become necessary as calculation proceeds. Pressing the ⓘ button provides help in the form of an equation or default information for a parameter.

Experienced user mode is off. Turn experienced user mode on for a more concise form.

Click on the button below to learn by example:

Loading

You may enter the loading in a series of text boxes, paste from the clipboard or as a triangle wave.

Units for ε_x: mm/mm
Units for T: C
Units for Δt: sec

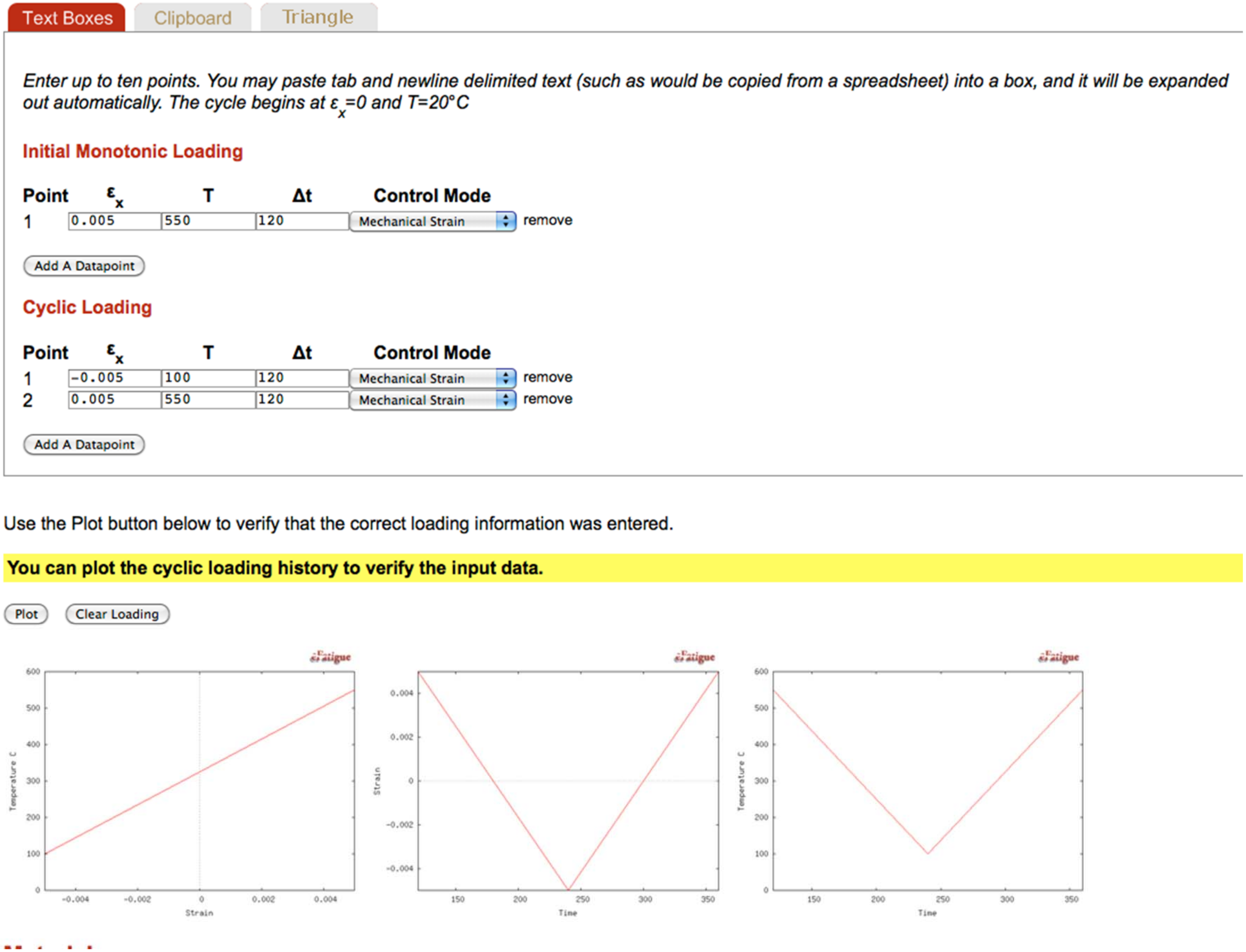
Enter up to ten points. You may paste tab and newline delimited text (such as would be copied from a spreadsheet) into a box, and it will be expanded out automatically. The cycle begins at ε_x=0 and T=20°C

Initial Monotonic Loading

Point	ε_x	T	Δt	Control Mode	
1				Total Strain	remove
2				Total Strain	remove
3				Total Strain	remove

Cyclic Loading

Point	ε_x	T	Δt	Control Mode	
1				Total Strain	remove
2				Total Strain	remove
3				Total Strain	remove



Enter up to ten points. You may paste tab and newline delimited text (such as would be copied from a spreadsheet) into a box, and it will be expanded out automatically. The cycle begins at $\varepsilon_x=0$ and T=20°C

Initial Monotonic Loading

Point	ε_x	T	Δt	Control Mode	
1	0.005	550	120	Mechanical Strain	remove

Cyclic Loading

Point	ε_x	T	Δt	Control Mode	
1	-0.005	100	120	Mechanical Strain	remove
2	0.005	550	120	Mechanical Strain	remove

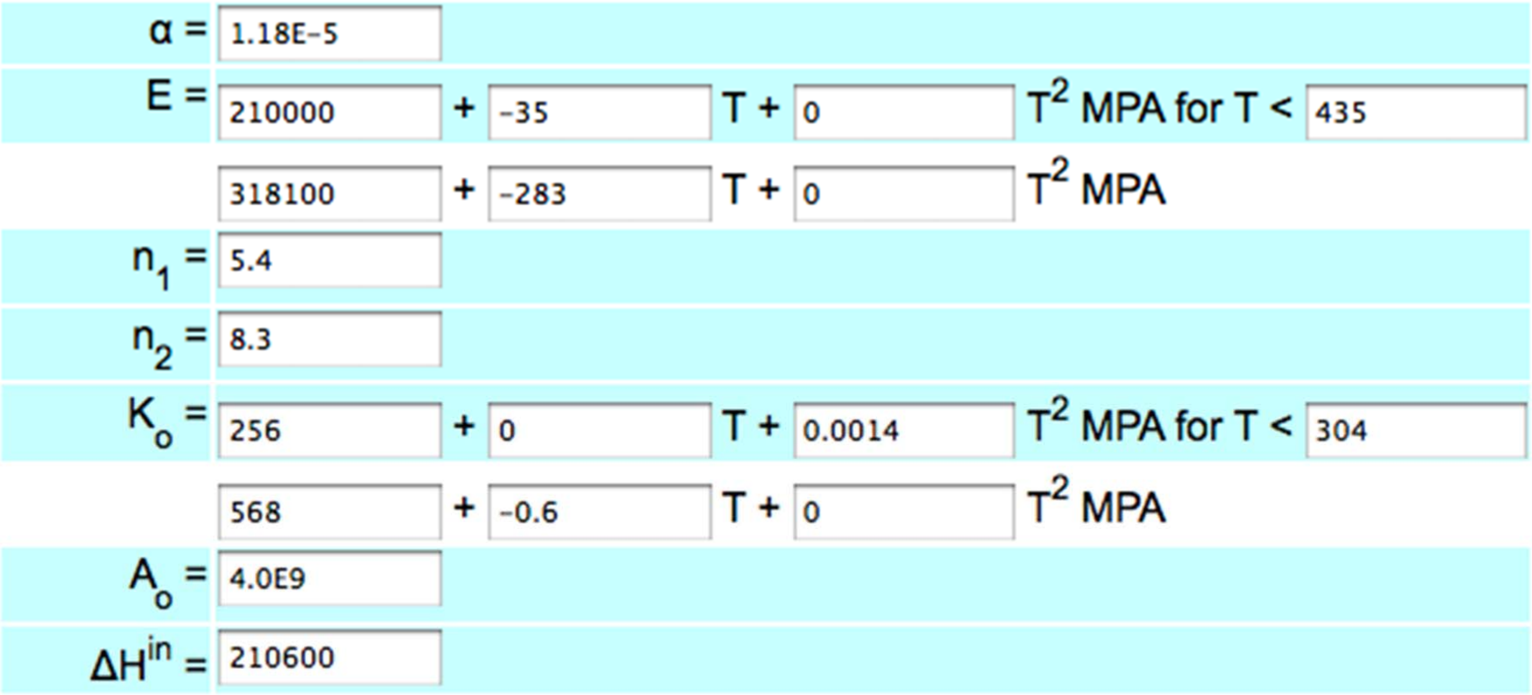
Use the Plot button below to verify that the correct loading information was entered.

You can plot the cyclic loading history to verify the input data.

Department of Mechanical Science and Engineering

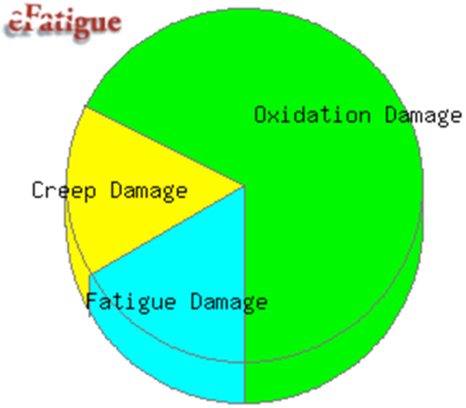
Stress Strain Properties

$$\dot{\varepsilon}^{in} = \left\{ \begin{array}{ll} A_o \left(\frac{\bar{\sigma}}{K_o}\right)^{n_1} \exp\left(\frac{-\Delta H^{in}}{RT}\right) & \left(\frac{\bar{\sigma}}{K_o}\right) \leq 1 \\ \hline A_o \exp\left[\left(\frac{\bar{\sigma}}{K_o}\right)^{n_2} - 1\right] \exp\left(\frac{-\Delta H^{in}}{RT}\right) & \left(\frac{\bar{\sigma}}{K_o}\right) \geq 1 \end{array} \right\}$$

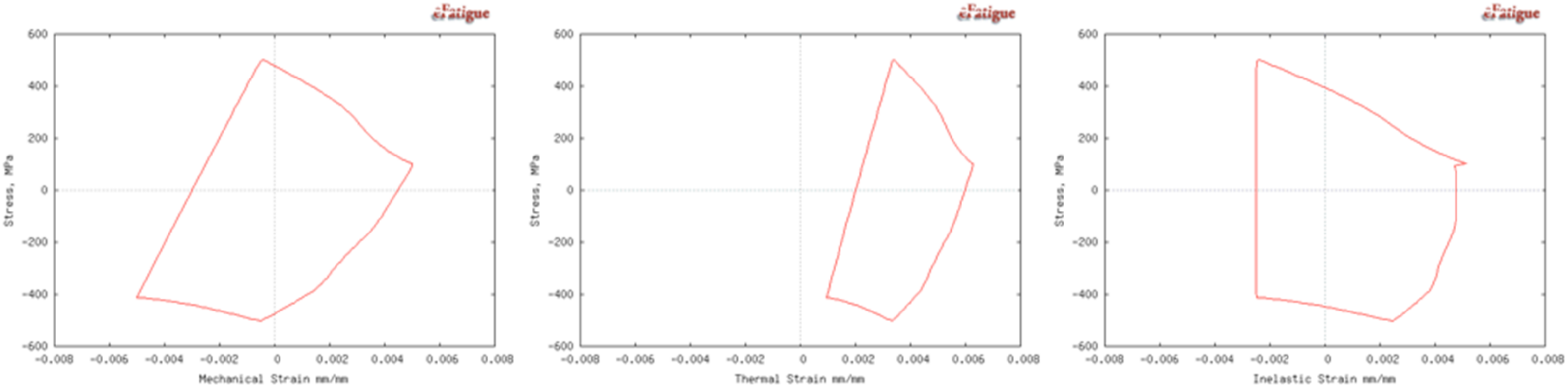


α =	1.18E-5						
E =	210000	+	-35	T +	0	T^2 MPA for T <	435
	318100	+	-283	T +	0	T^2 MPA	
n_1 =	5.4						
n_2 =	8.3						
K_o =	256	+	0	T +	0.0014	T^2 MPA for T <	304
	568	+	-0.6	T +	0	T^2 MPA	
A_o =	4.0E9						
ΔH^{in} =	210600						

A pie chart showing the relative damage for each failure mechanism is given first.

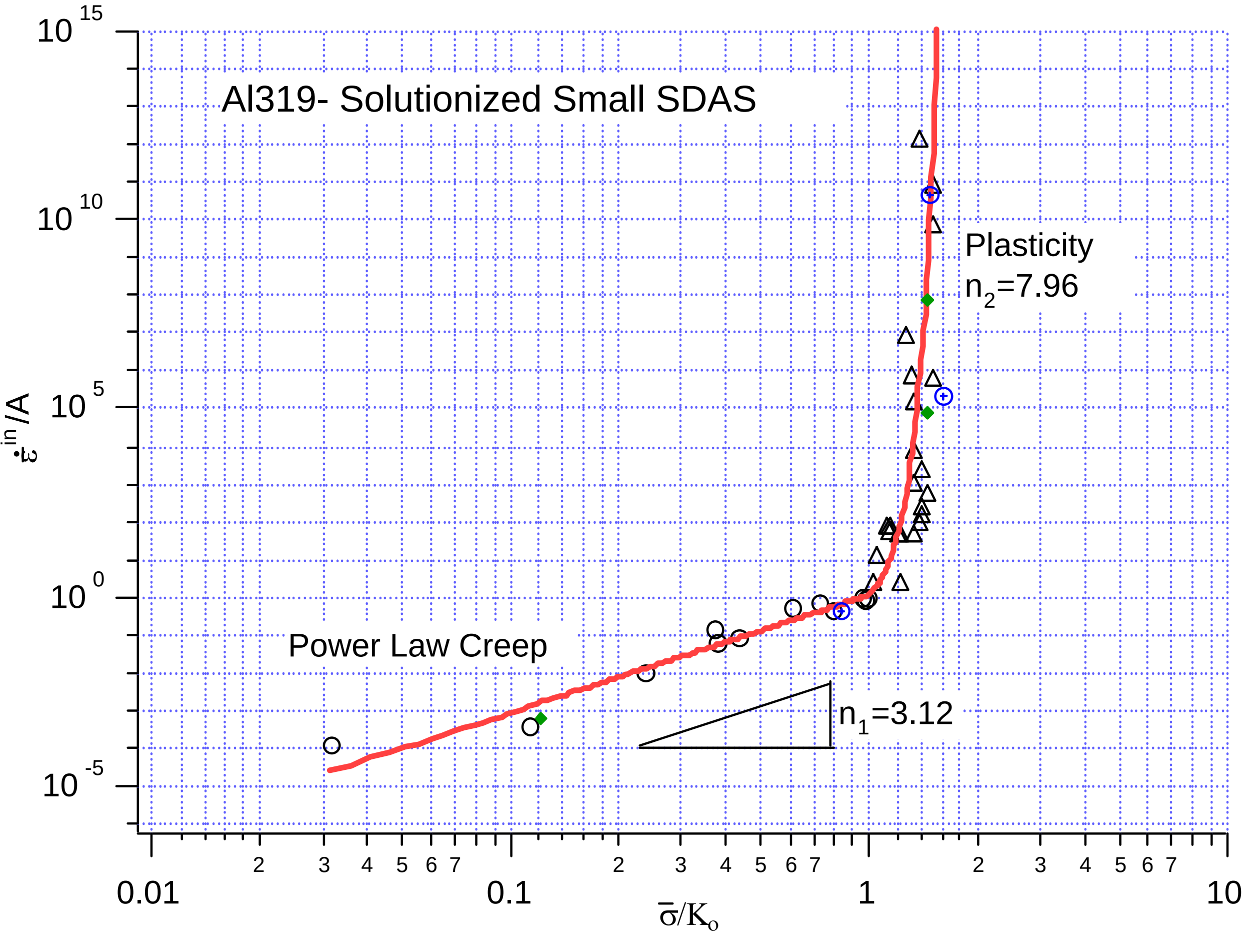


Stress strain plots are given next for mechanical strain, thermal strain, and inelastic strain vs stress.

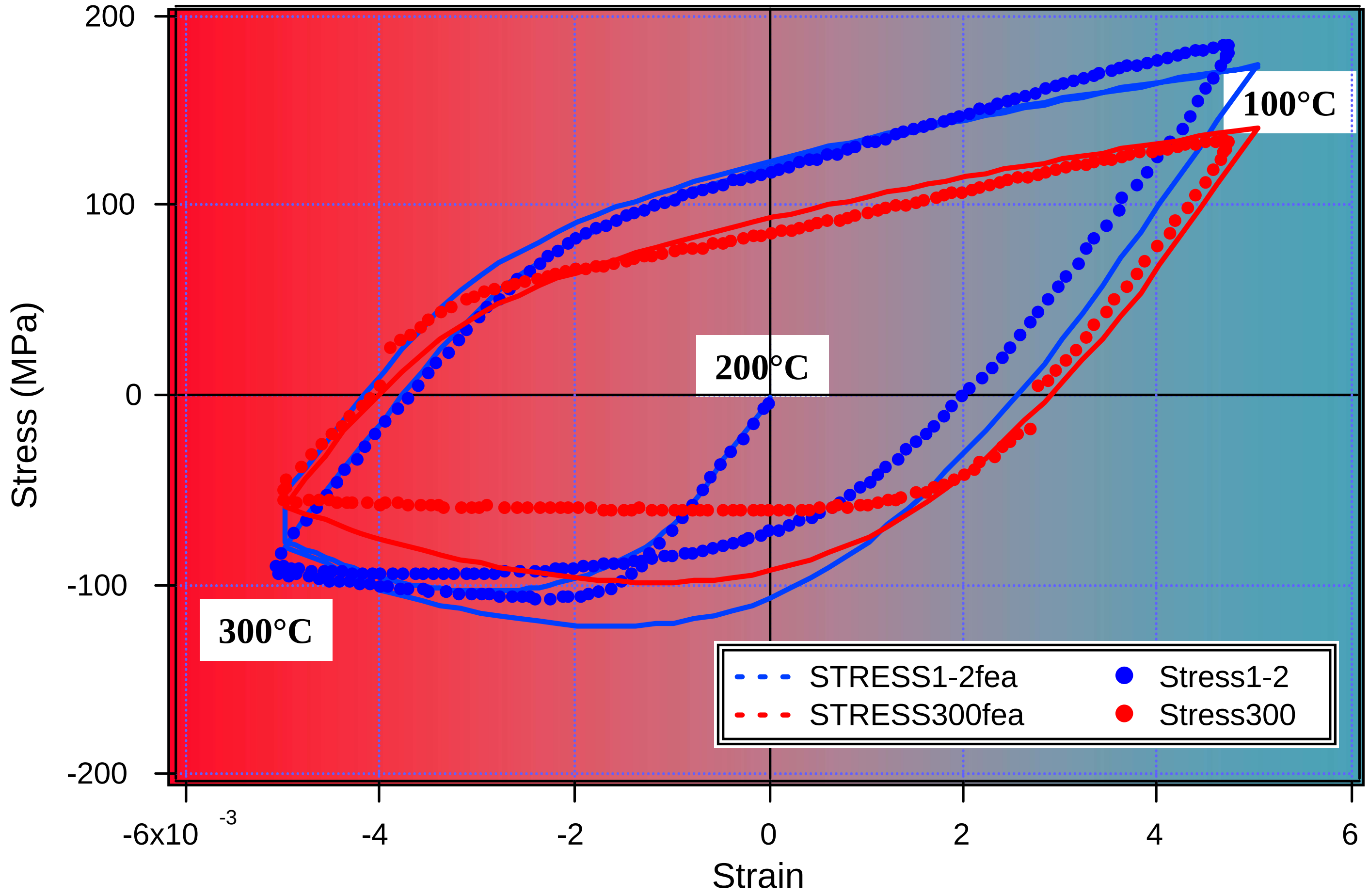


Numerical data for the stress strain plots is available in a tab delimited format that can be used with the clipboard or saved as a text file.

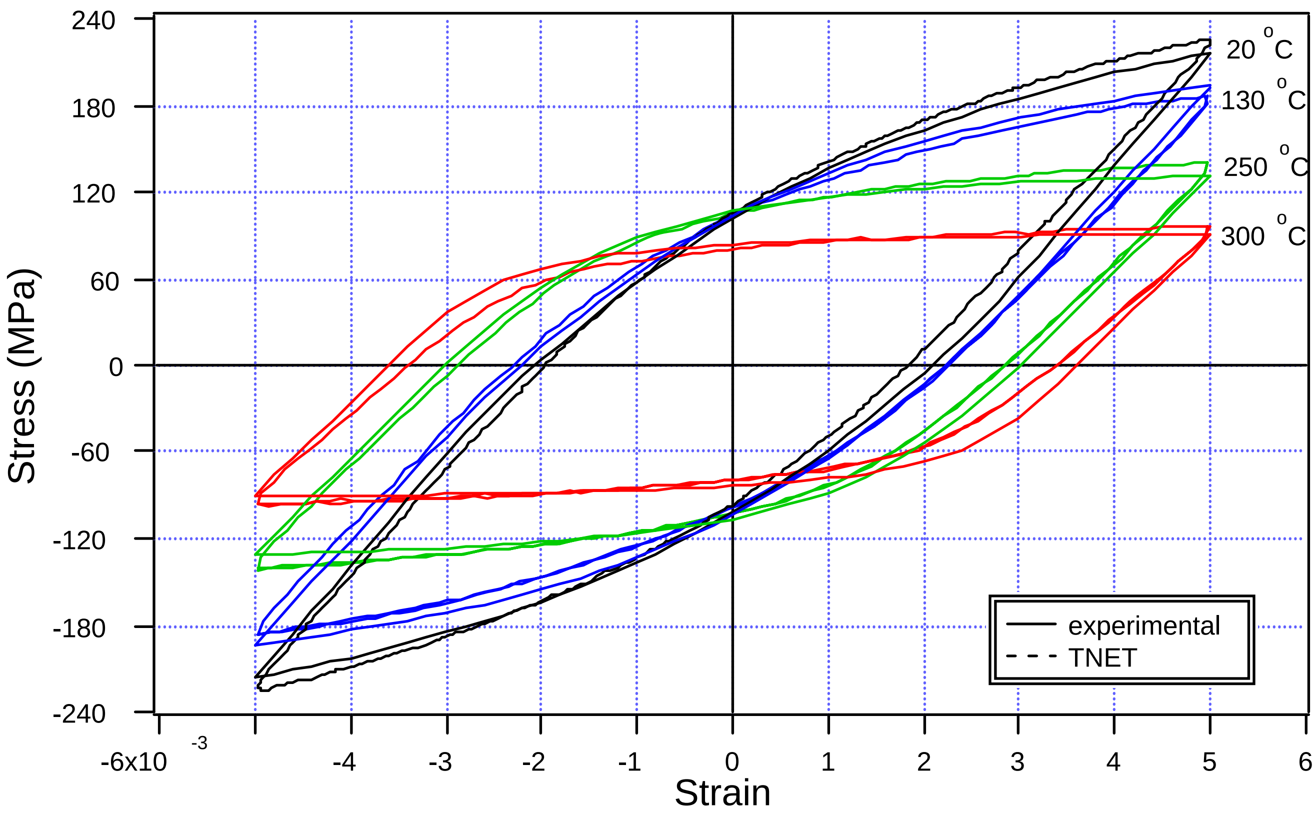
Constitutive Modeling- Experimentally Determined Flow Rule



TMF OP 100-300°C 1.0%

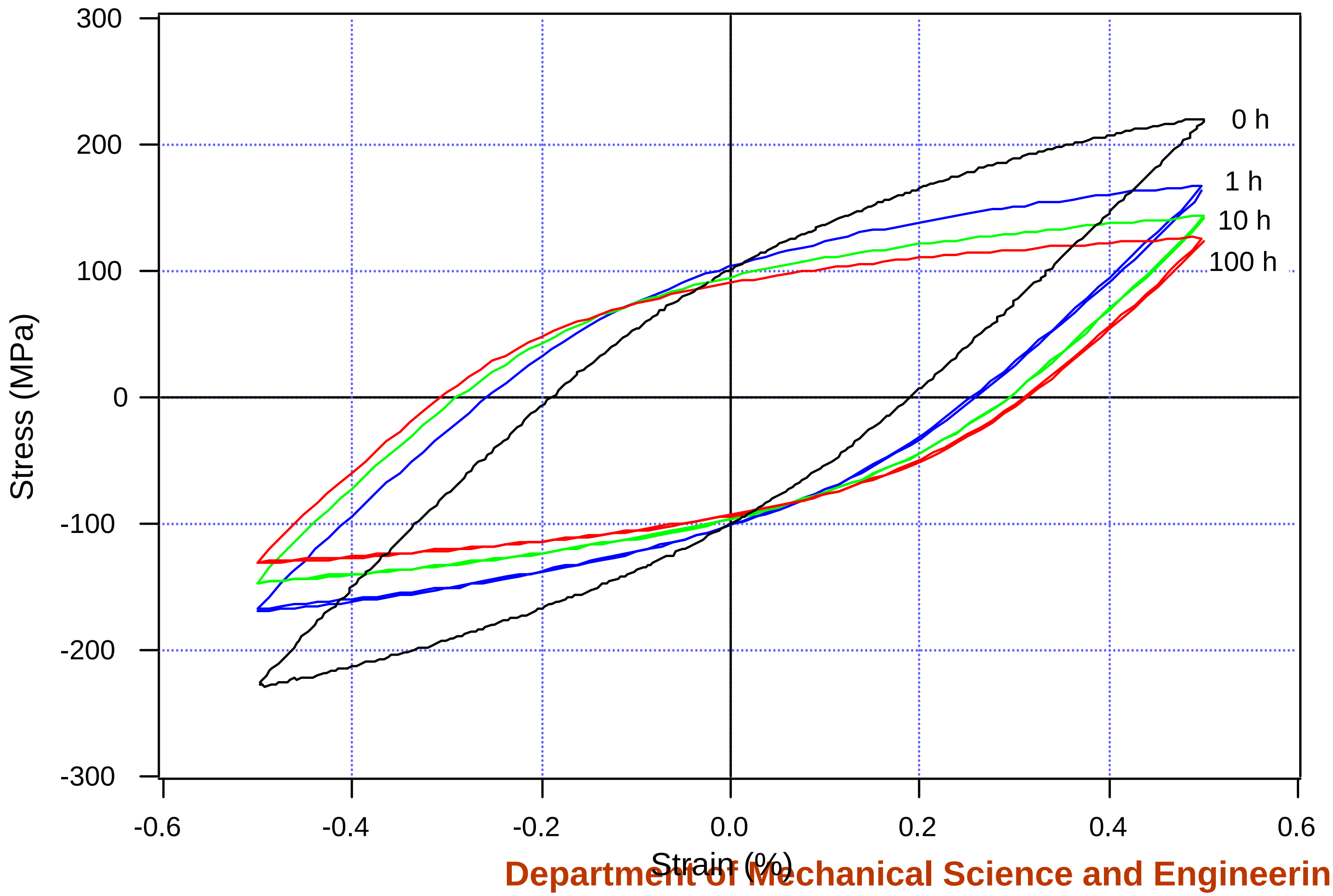


Hysteresis loops for the tests performed at 5×10^{-3} s^{-1}

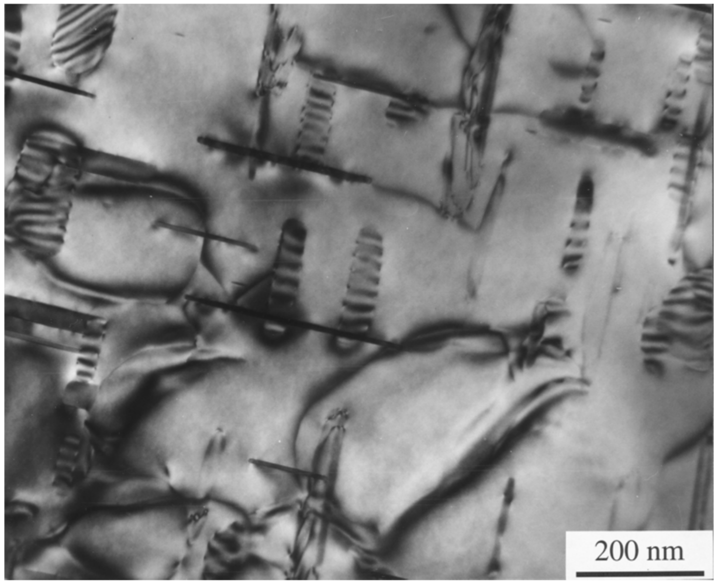


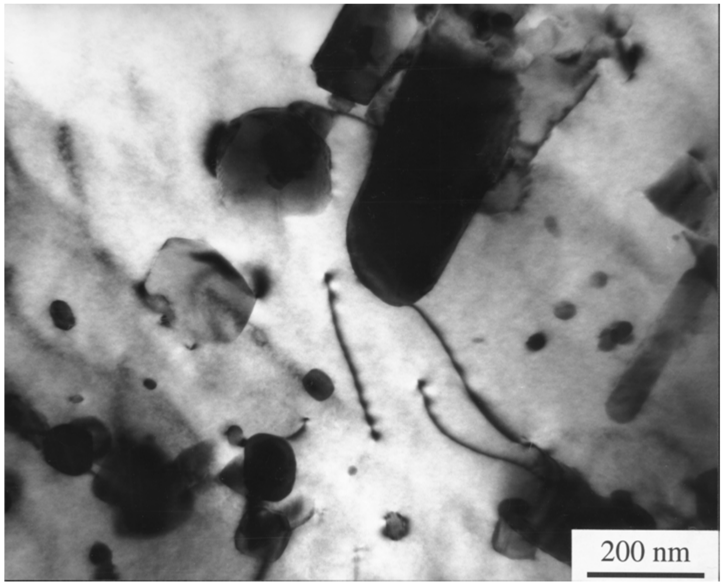
Drag stress recovery

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

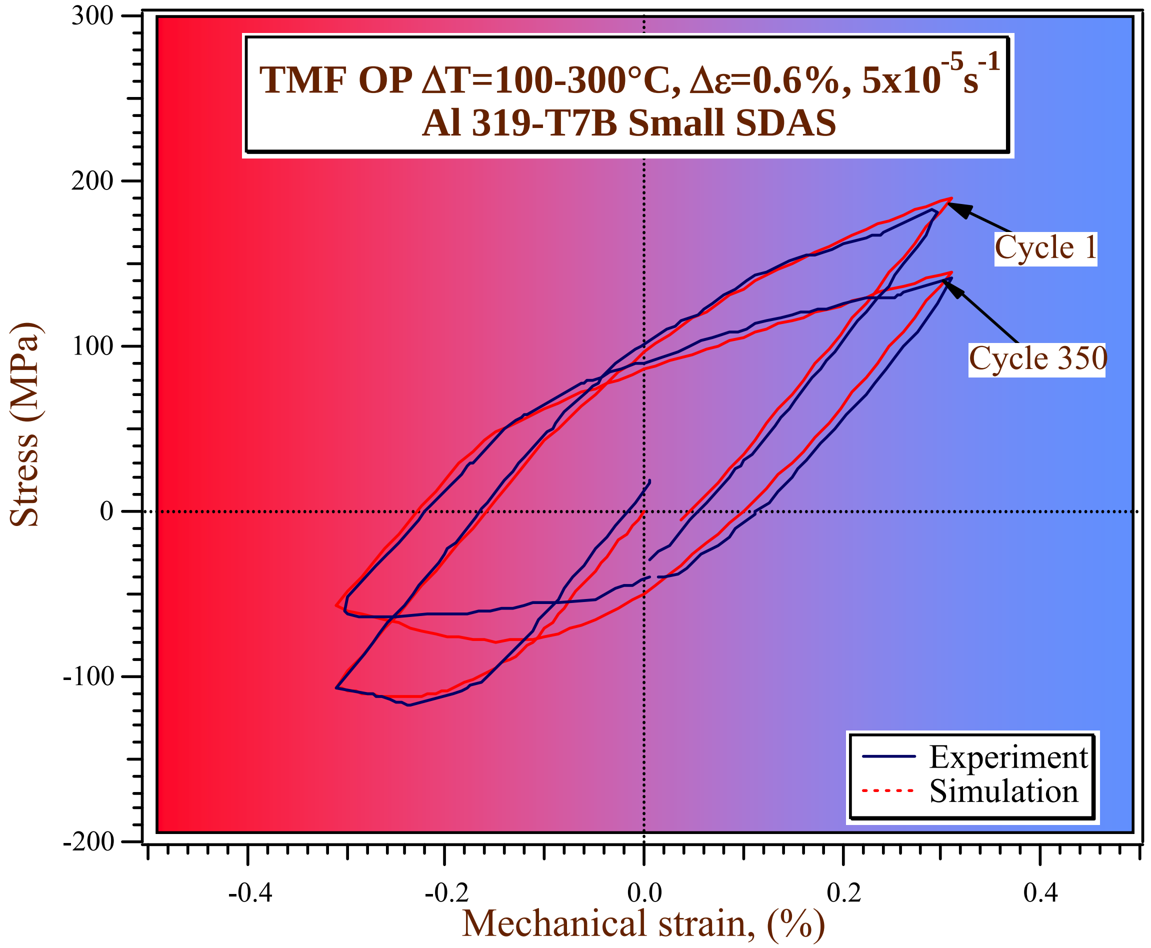


Coarsening of the Precipitates





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:

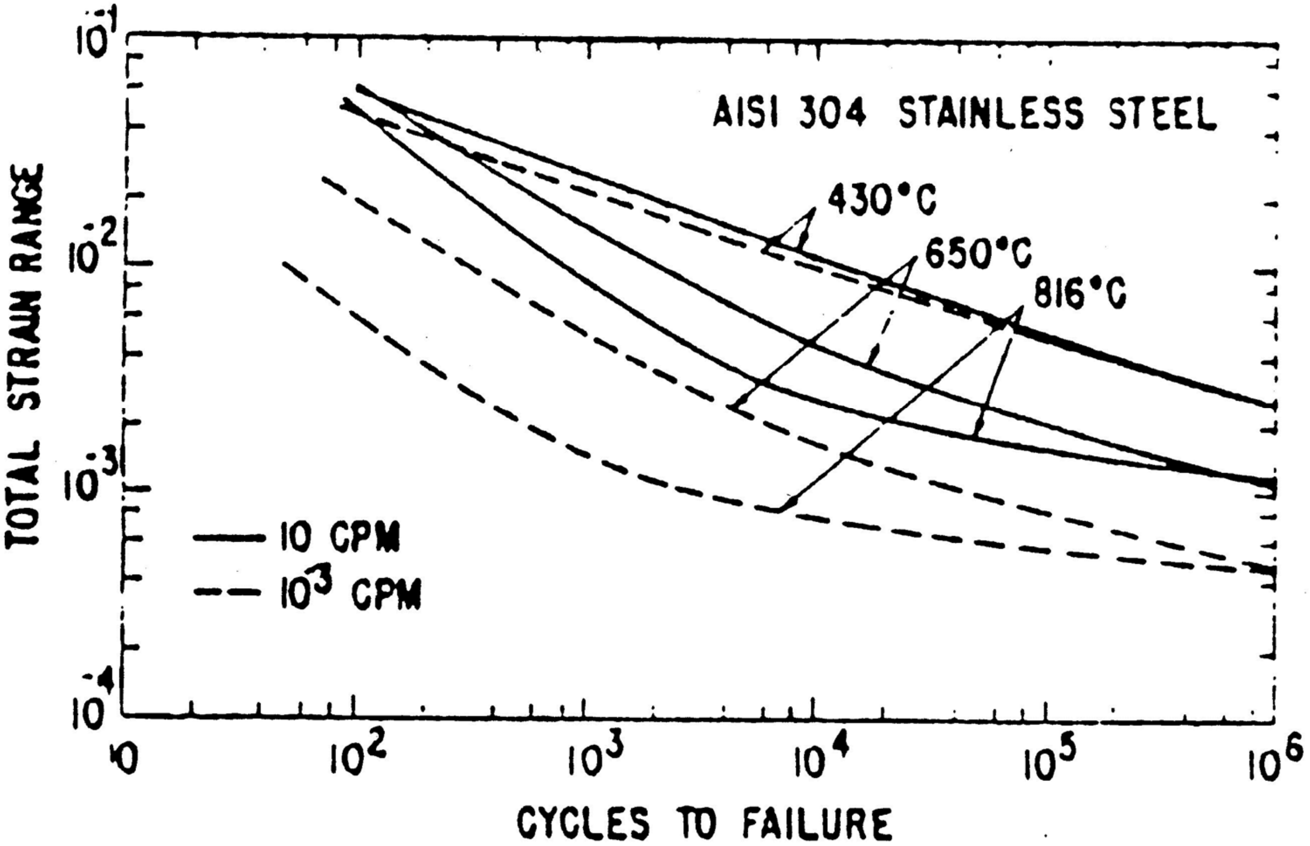
- **Non-unified Plasticity (stress-strain) Models: Plastic strains (time-independent) and creep strains are added.**
- **Unified Creep-Plasticity Models: Plastic strain and creep srain is combined as inelastic strain.**

Life Prediction Modeling

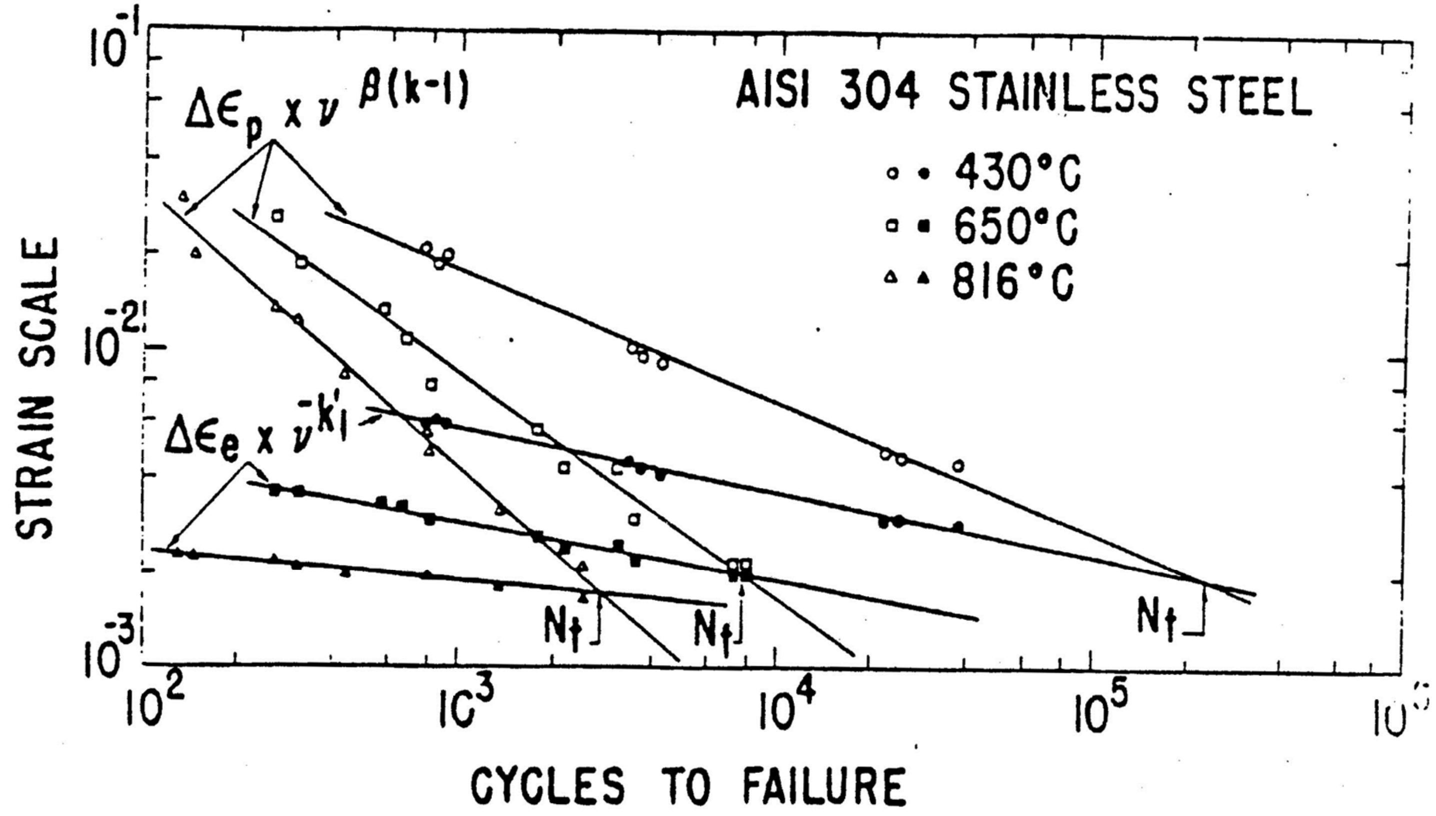
Requirements for a good model:

- **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;

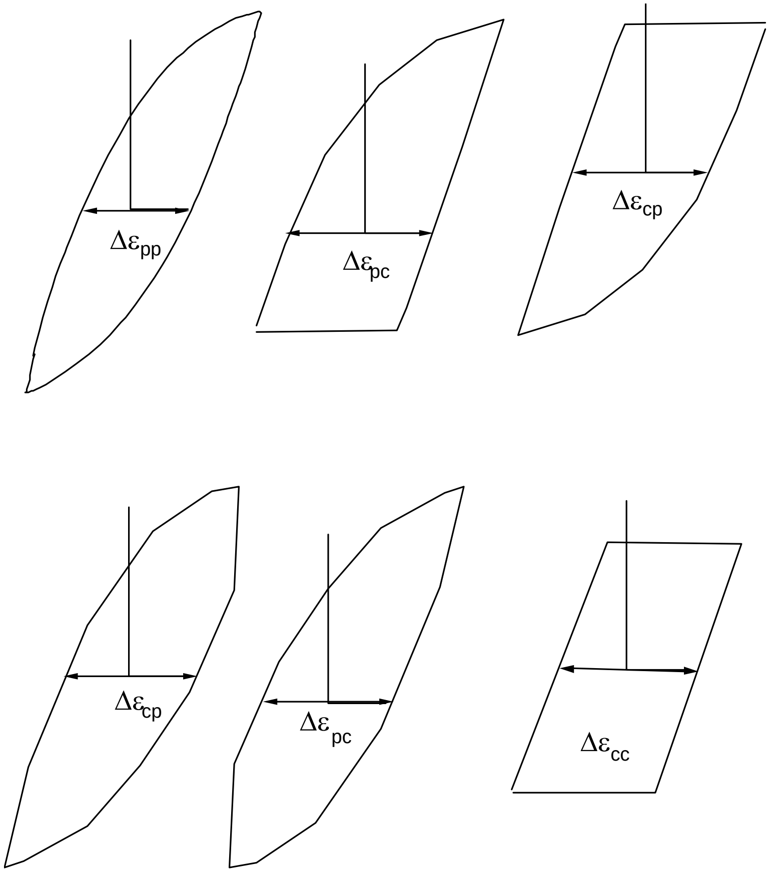
(1) Not sensitive to location of hold time within the cycle (tension or compression).

(2) Does not account for creep damage effects

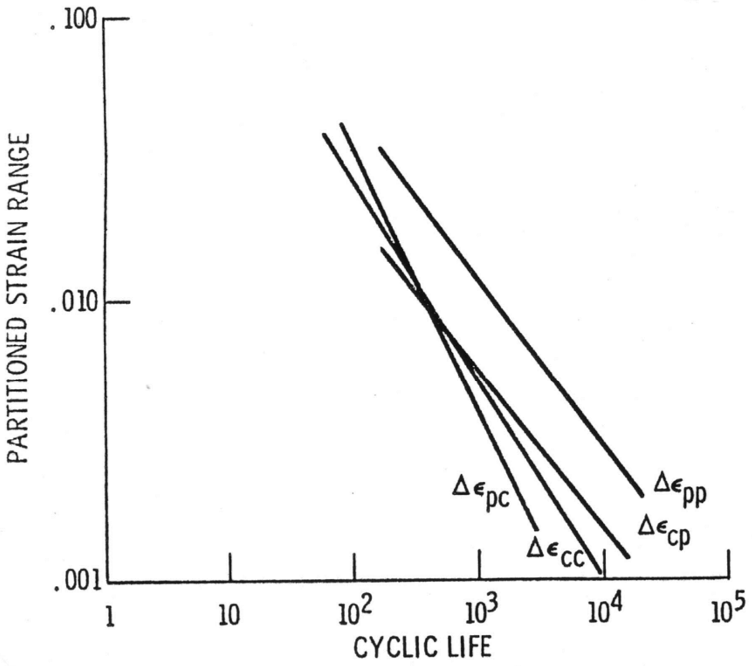
(3) TMF life prediction not explicitly handled.

(4) No stress-strain model

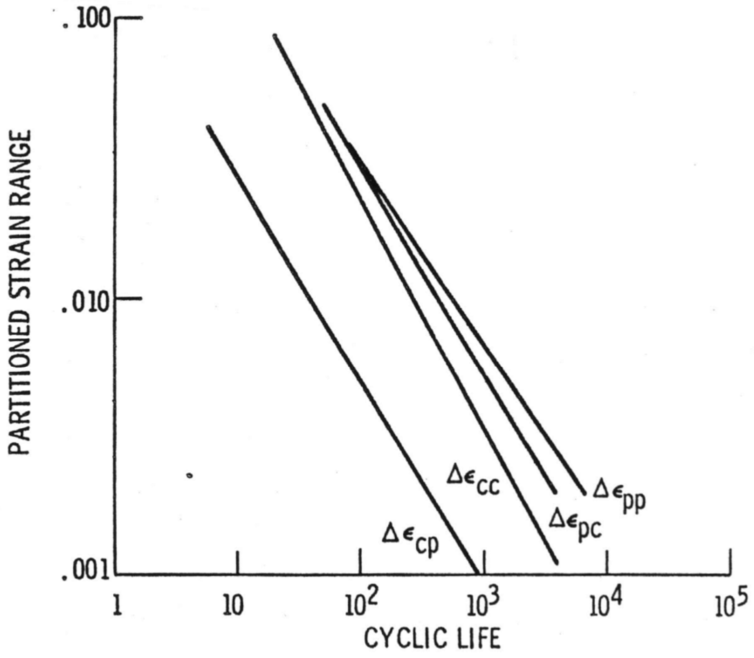
Strain Range Partitioning Method(SRP)



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-**

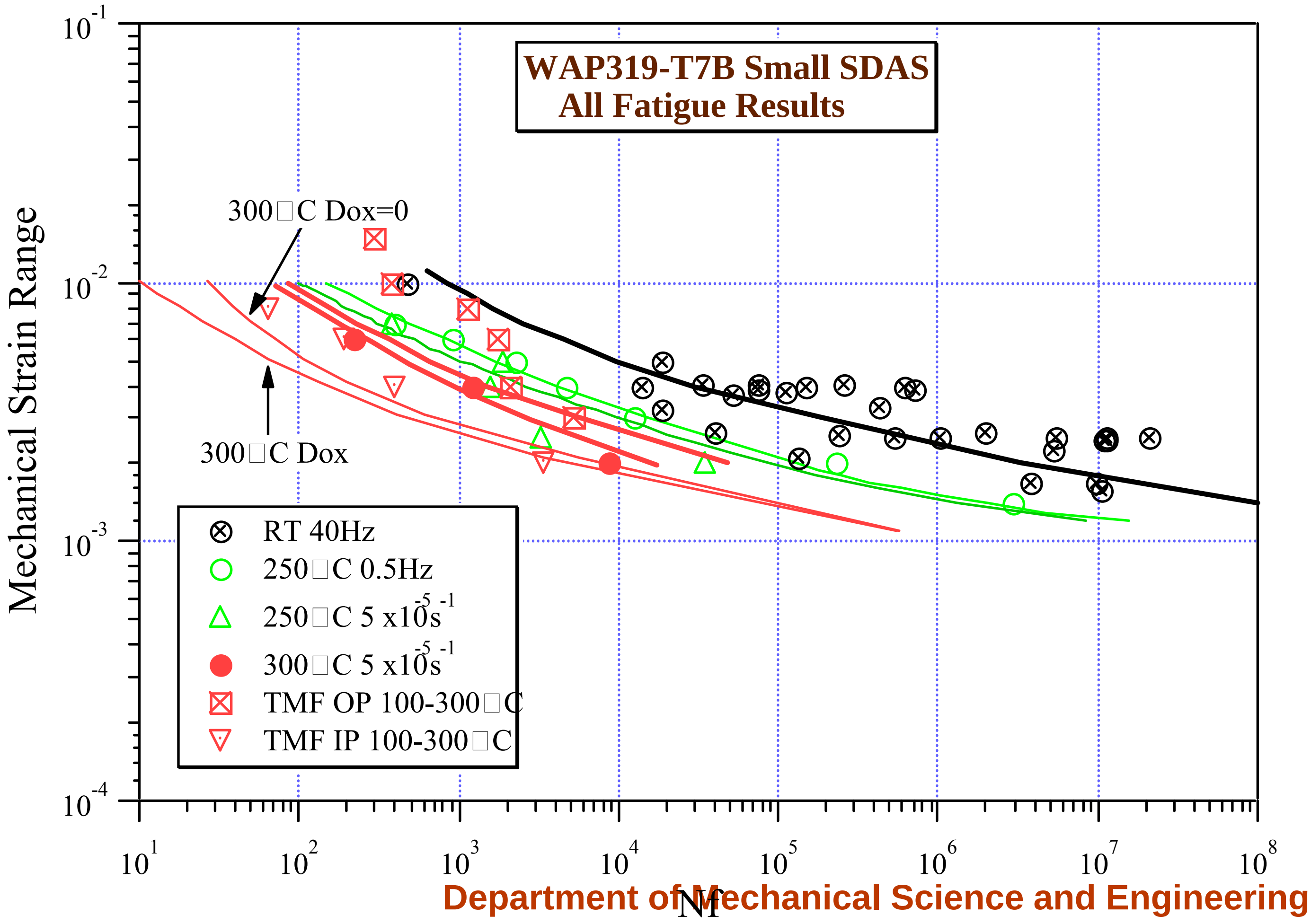
$$\frac{1}{N_f^{ox}} = \left(\frac{h_{cr} \ \delta_o}{B \Phi^{ox} \ K_{peff}} \right)^{-\frac{1}{\beta}} \ \frac{2 \left[\Delta \varepsilon_{mech}^{ox} \right]^{\frac{2}{\beta}+1}}{\left(\dot{\varepsilon} \right)^{(1-a'/\beta)}}$$

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

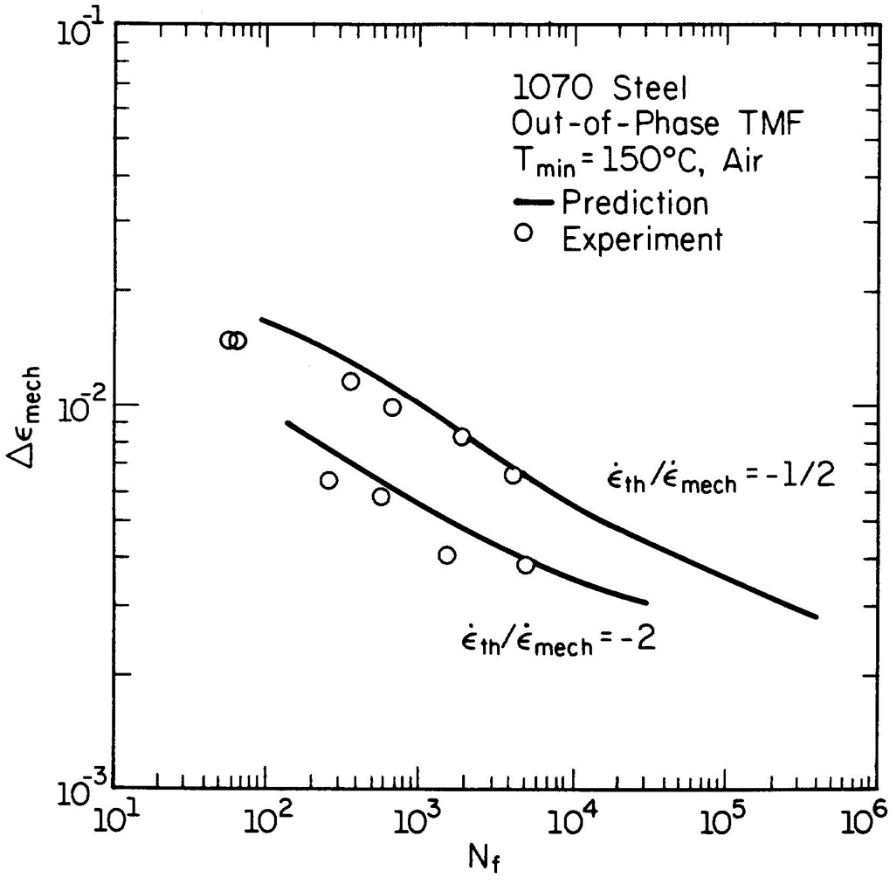
$\Phi^{ox} \ K_{peff}$ **depends on the temperature strain history**

and the temperature- time variation in the cycle.

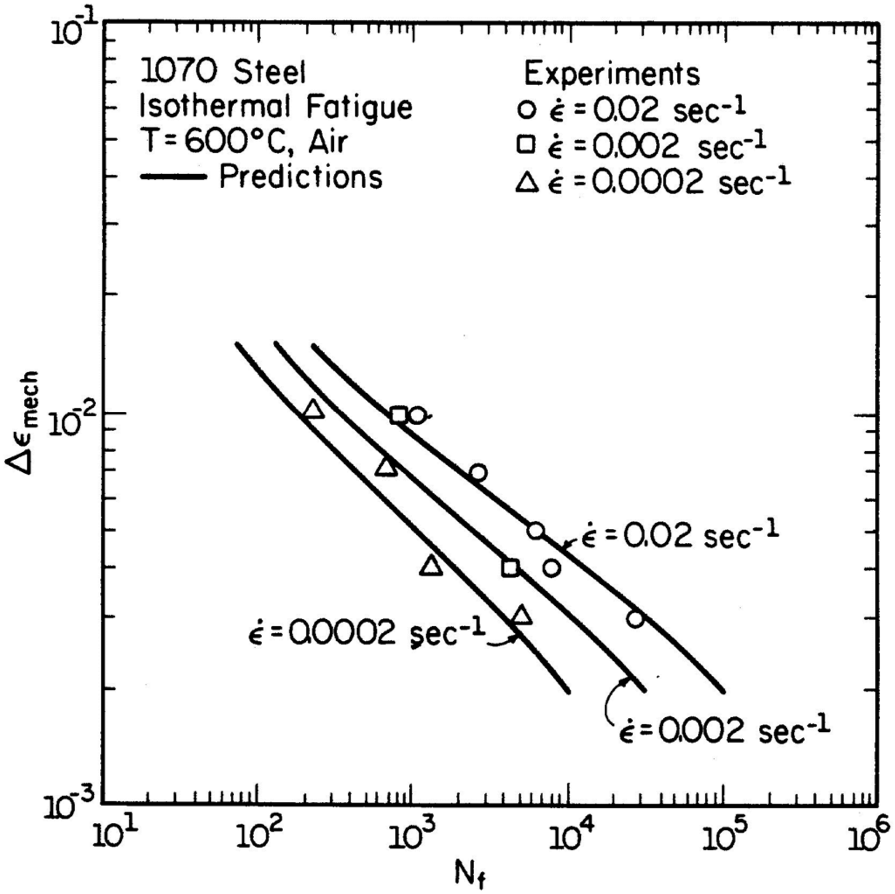
Combined Damage Model Predictions



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**

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

a_0 - initial pore size

C' – fatigue strength coefficient

b – fatigue strength exponent

ε_f' – fatigue ductility coefficient

c – fatigue ductility exponent

Creep Damage Equation

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

C_c, m_c **- empirical constants**

ΔH **- activation energy**

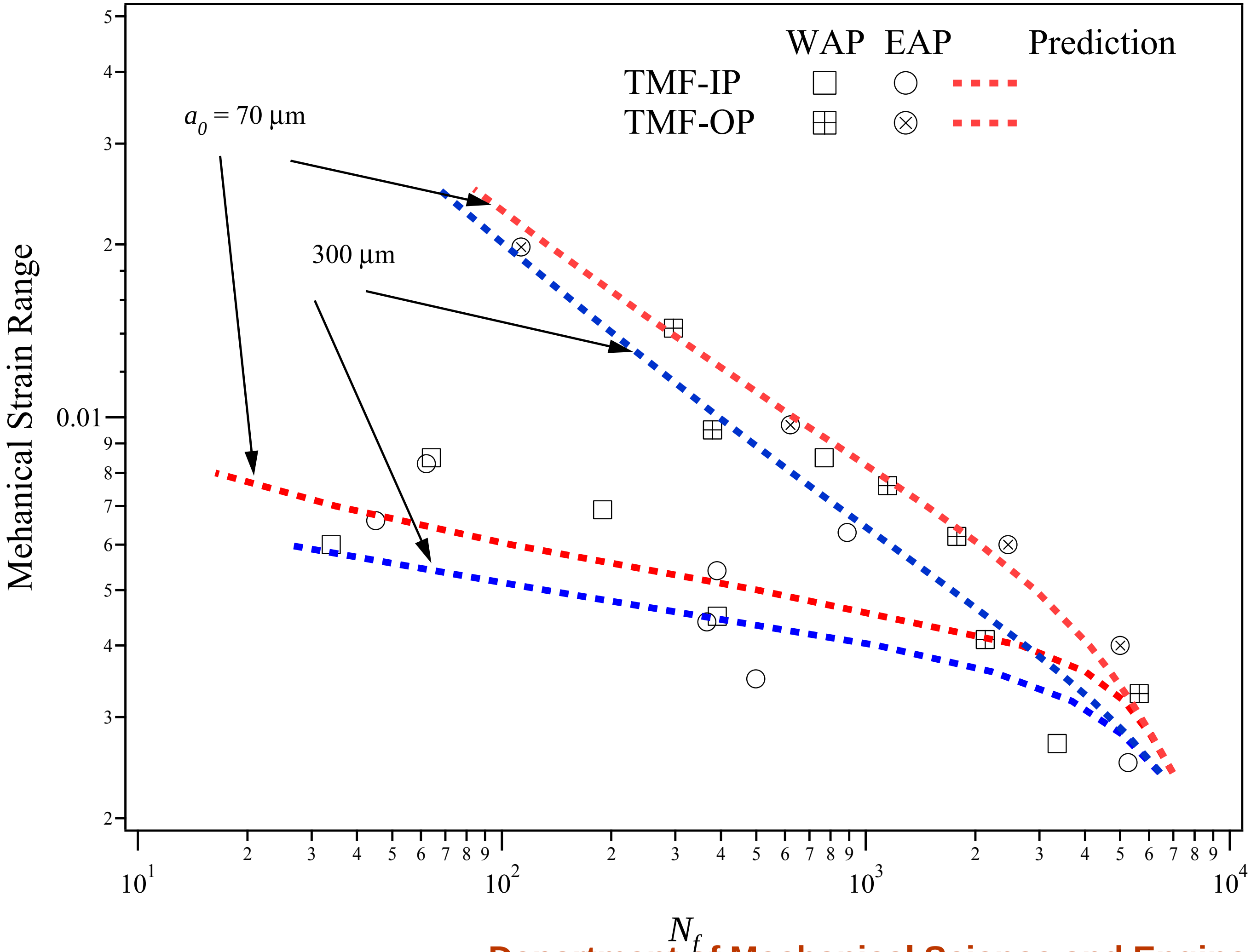
R **- universal gas constant**

σ_H **- hydrostatic stress**

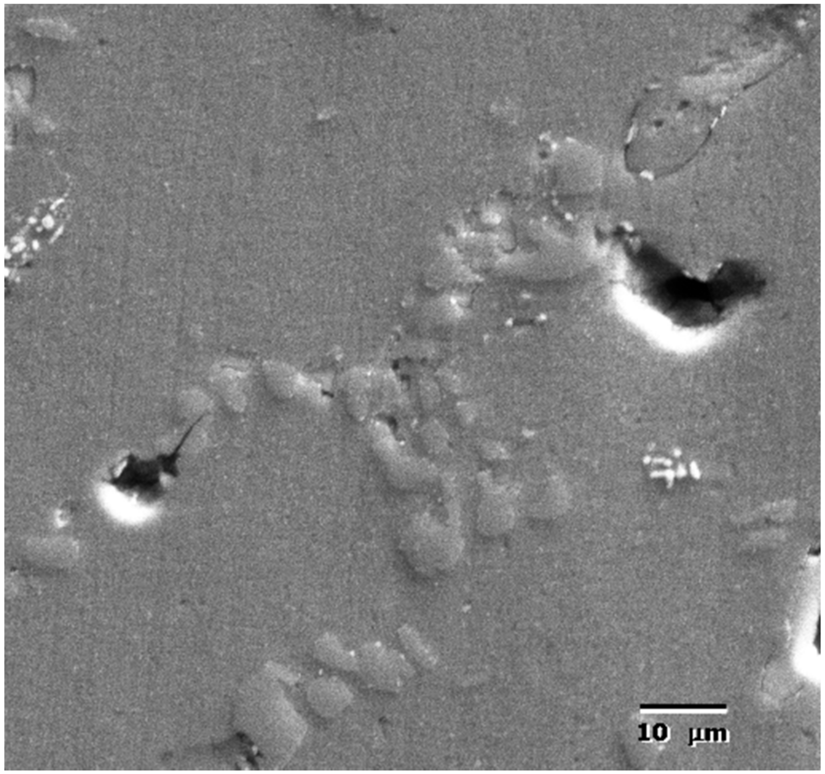
$\bar{\sigma}$ **- effective stress**

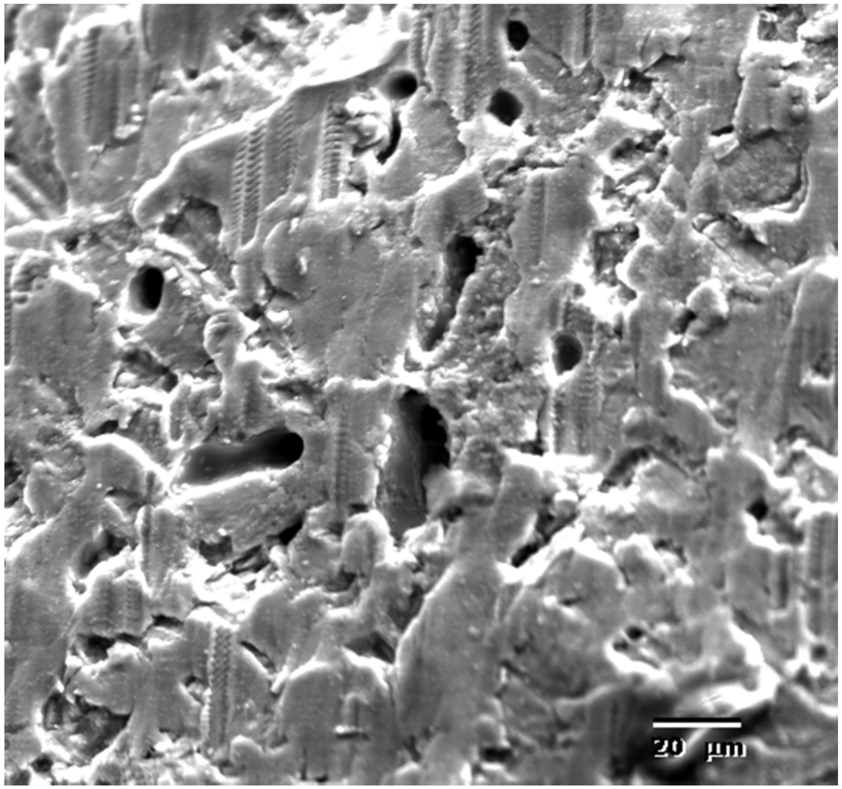
a_0 **- initial pore size**

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.