IMPACT OF ENGINE OPERATION ON GAS TURBINE COMPONENT DURABILITY USING DUCTILITY EXHAUSTION

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A CULTURE OF CUSTOMER CARE

Solar Turbines
A Caterpillar Company

CONTENTS

- Introduction
- Ductility Exhaustion and Superalloys
- Operational Stresses in Gas Turbine Components
- The Interaction Between Creep and Fatigue
- Application to Gas Turbine Operation
- Implications for Asset Management

INTRODUCTION

- Reliable operation of gas turbines is key to our customers needs

- Reliability covers a range of potential issues, however material degradation from creep and fatigue presents the most serious of risk

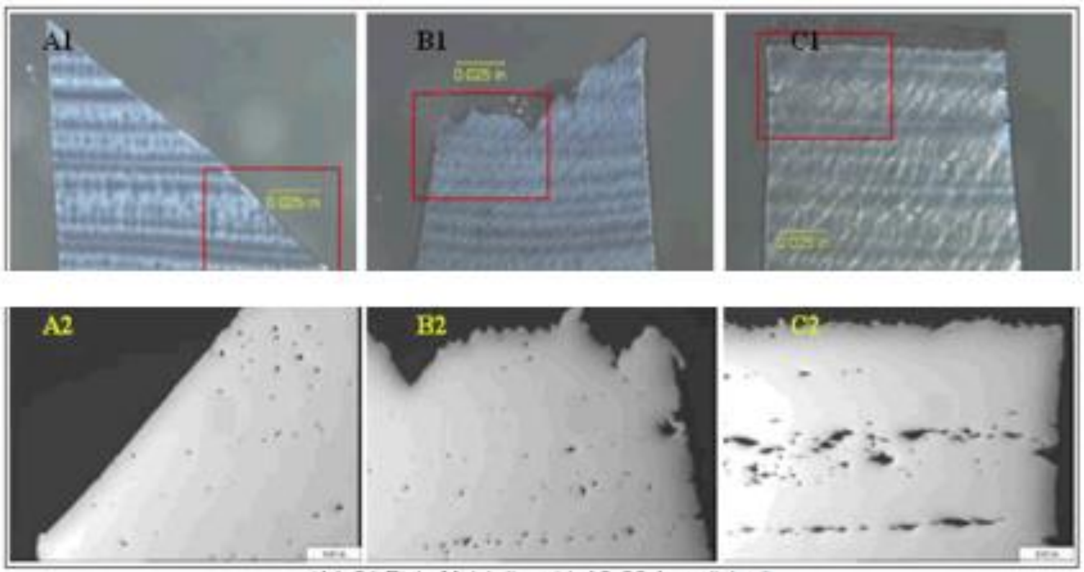
- Industrial gas turbines experience both cyclic loading (variability in operation) and constant loading (extended periods of operation) which leads to both fatigue and creep damage

- The interaction between creep and fatigue can lead to additional damage, which should be considered

- Operational flexibility is important to customers, it is imperative that we understand these interactions in more detail in order to provide better tools for asset management

DUCTILITY EXHAUSTION AND SUPERALLOYS

- What is ductility?
  - Total available strain including plasticity and creep



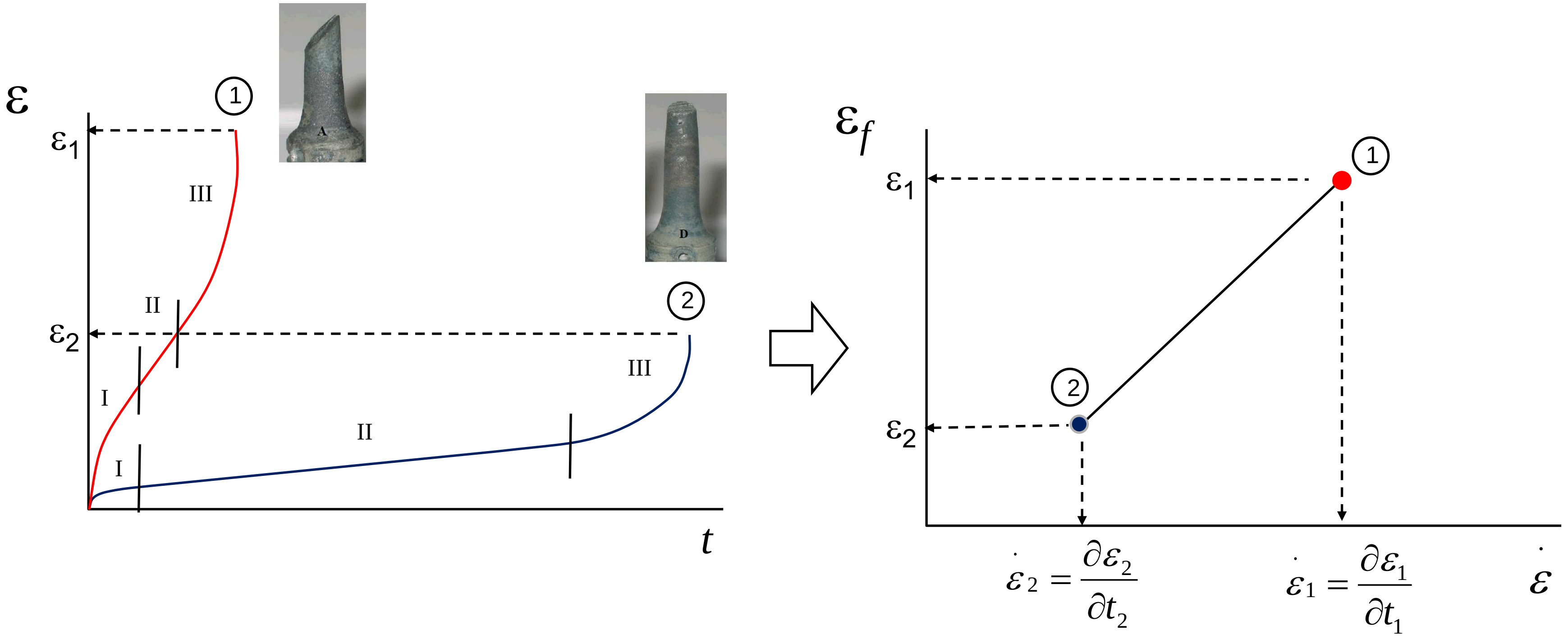
(A1-C1 Etch: Molybdic acid; A2-C2 As-polished)

Dislocation ⇨ Diffusion

  - Differences in failure mode occur due to loading rate

DUCTILITY EXHAUSTION AND SUPERALLOYS

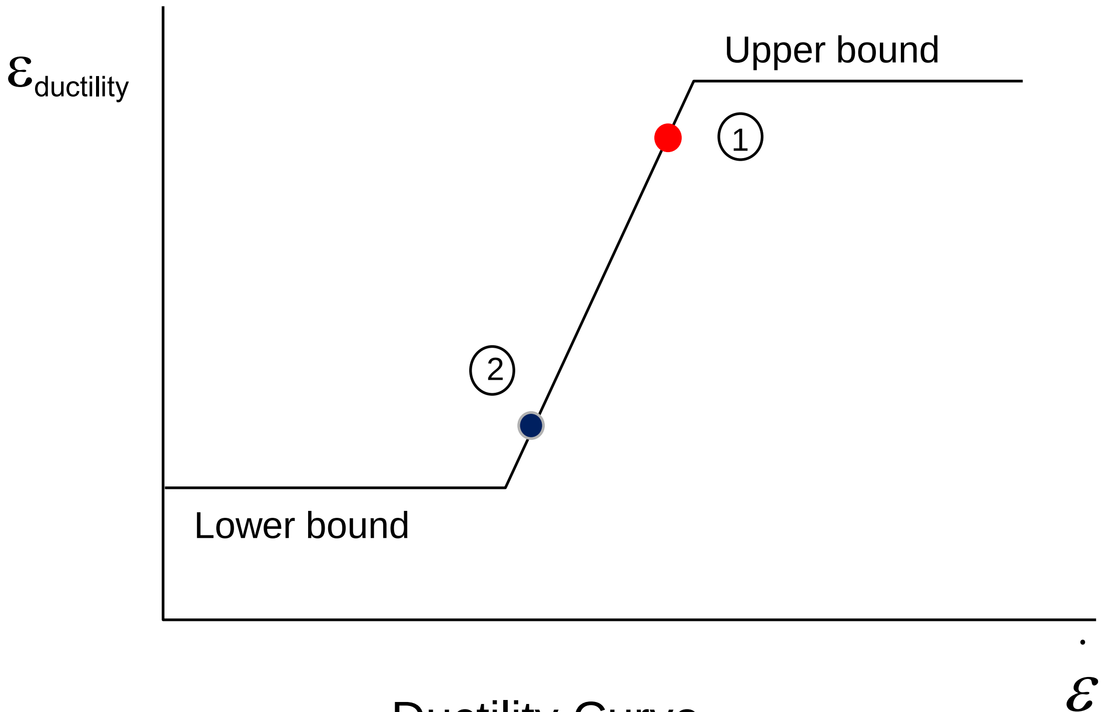
- Ductility is Strain Rate Dependent
  - At high strain rates, damage is driven by dislocations
  - At low strain rates, damage is driven by diffusion



Example of Rate Dependent Ductility

DUCTILITY EXHAUSTION AND SUPERALLOYS

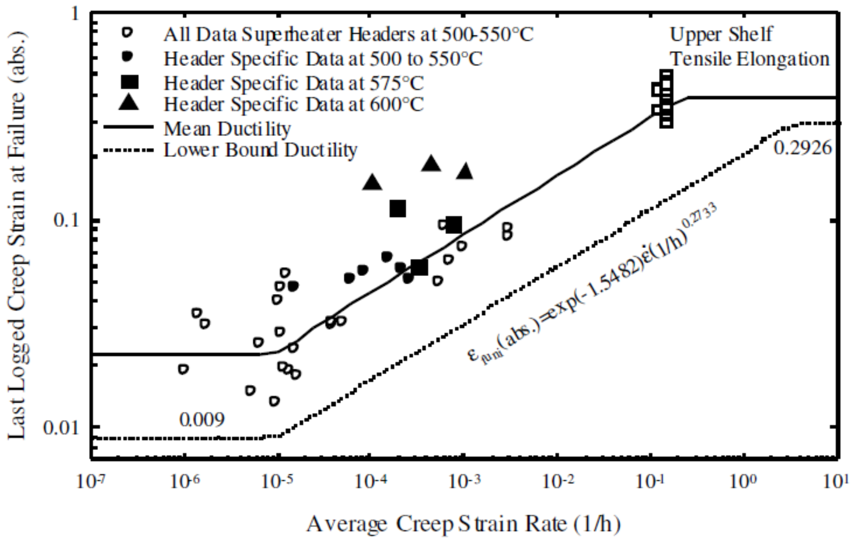
- Ductility Behavior
  - At high strain rates, ductility is high
  - At low strain rates, ductility is low

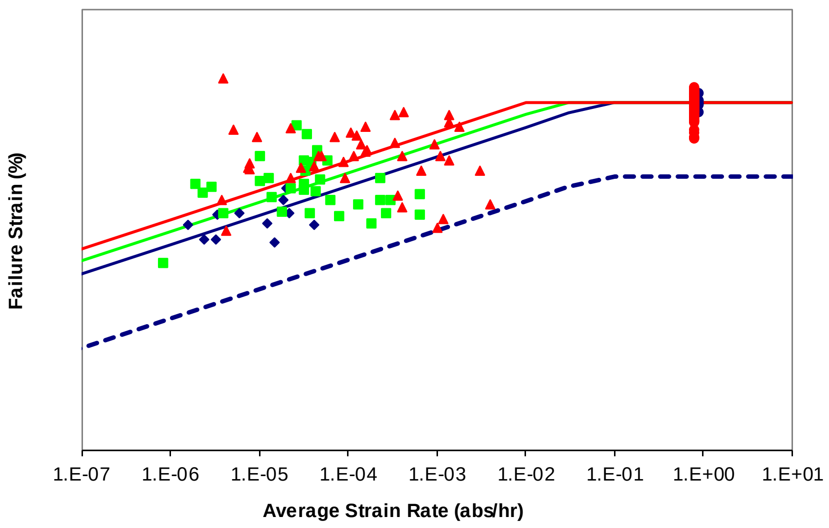


Ductility Curve

DUCTILITY EXHAUSTION AND SUPERALLOYS

- Rate Dependent Ductility in Superalloys
  - Comparing ductility between a typical Superalloy and 316H stainless steel, shows the Superalloy has a higher ductility at lower strain rates, resulting in improved creep resistant
  - This introduces challenges for testing, as lower rate tests tend to require significantly more time



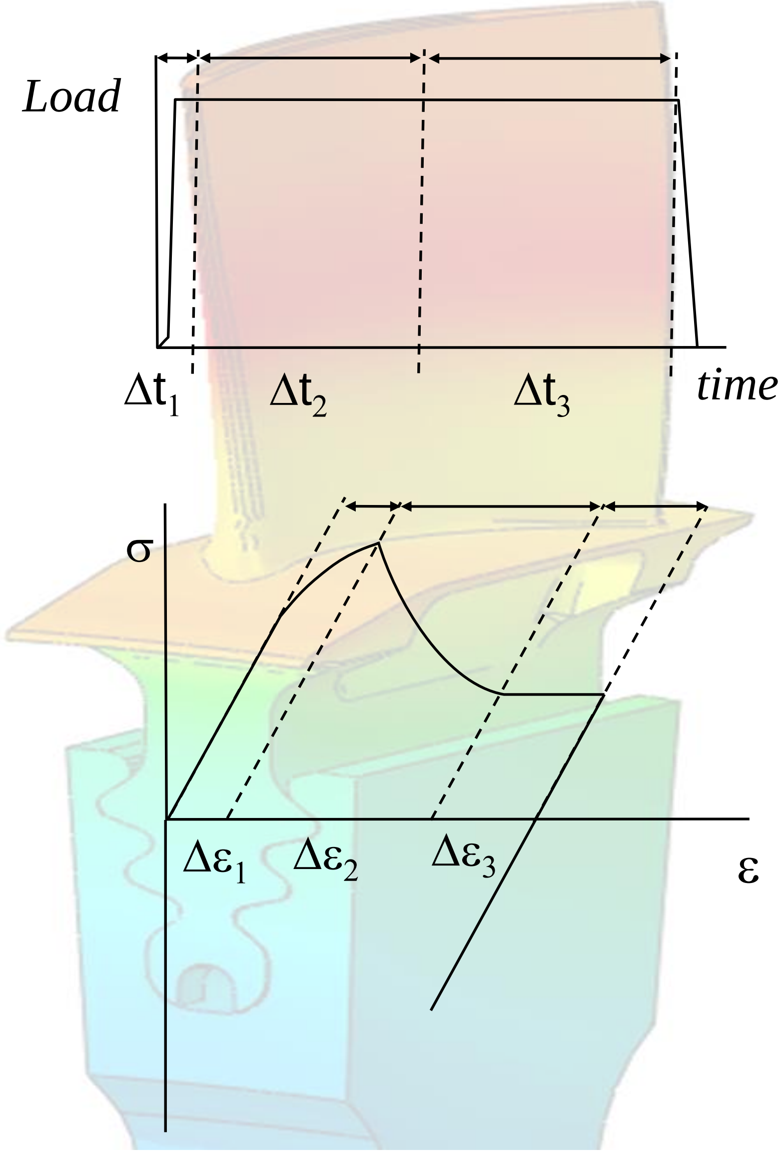


Reference: Spindler, M.W., The Use of Borland Specimens to Reproduce Reheat Cracking in Type 316H, International Conference on High Temperature Plant Integrity and Life Extension, Cambridge, UK, 14th-16th April 2004.

DUCTILITY EXHAUSTION AND SUPERALLOYS

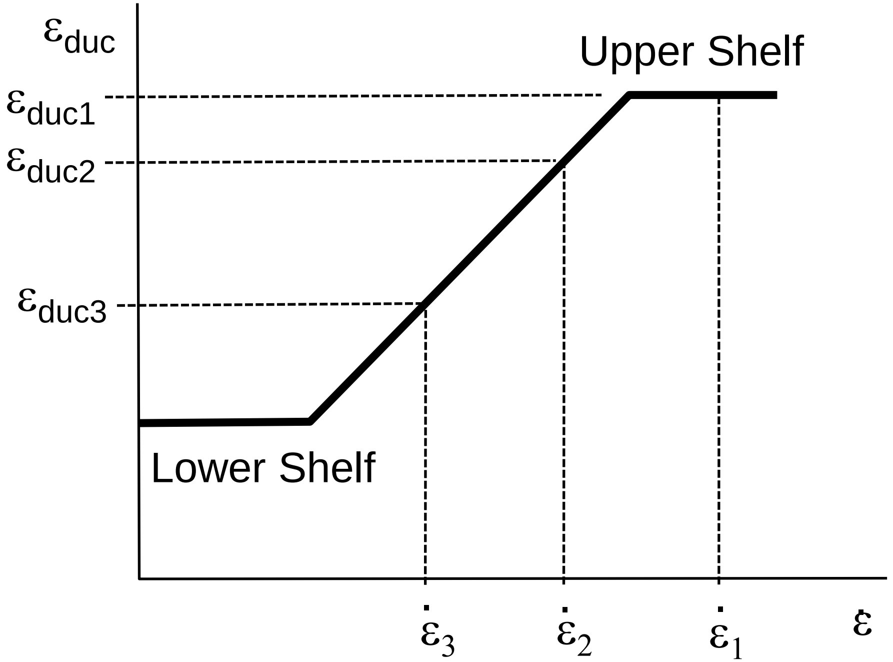
- Using Ductility to Calculate Damage
  - Hot section component experience a range of loads
    - Transient loads during start up and shutdown
    - Constant loads during extended periods of operation
  - The stress-strain response to the load cycle can be used to find the varying strain rates

$$\frac{\Delta \varepsilon}{\Delta t} = \dot{\varepsilon}$$



DUCTILITY EXHAUSTION AND SUPERALLOYS

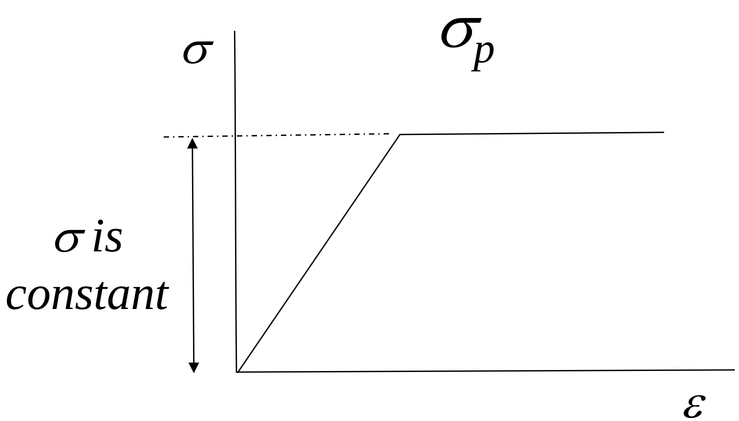
- Using Ductility to Calculate Damage
  - Strain rate can be used to find the available ductility at that rate
  - Damage can then be determined from the incremental strain and the available ductility

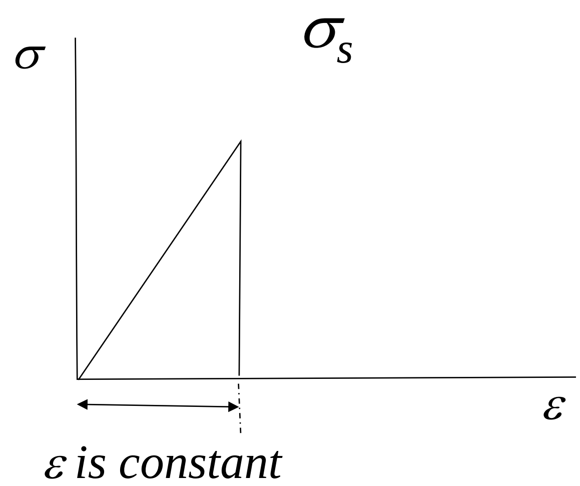


$$\lambda = \int_0^t \frac{\dot{\varepsilon}}{\varepsilon_f(\dot{\varepsilon}, T)} dt$$

OPERATIONAL STRESSES IN GAS TURBINE COMPONENTS

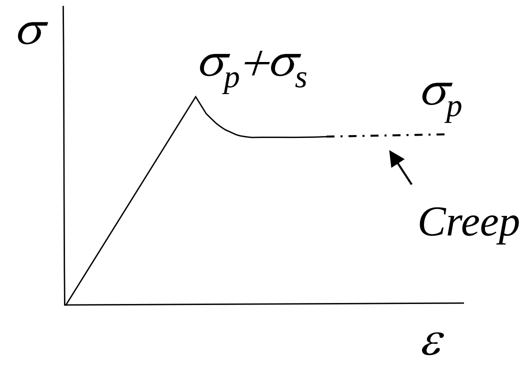
- Hot section components experience two principal load conditions
  - Mechanical loads; resulting in primary stresses (σ_p)
  - Thermal loads; resulting in secondary stresses (σ_s)
- Rotating components, such as disks, are typically dominated by primary stress (speed)
- Static components, such as nozzles, are typically dominated by secondary stresses (temperature)



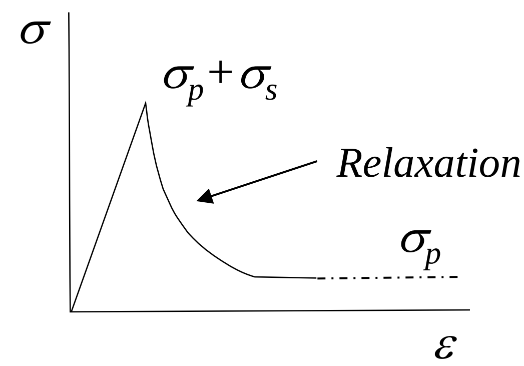


OPERATIONAL STRESSES IN GAS TURBINE COMPONENTS

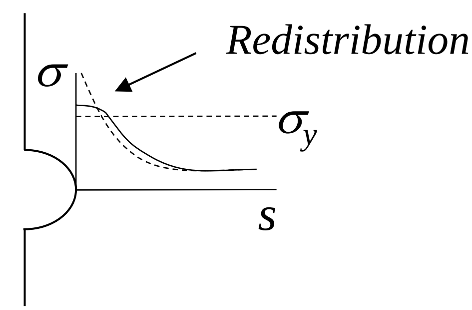
- Primary stresses (σ_p) give rise to forward creep
  - Increasing strain under constant load



- Secondary stresses (σ_s) give rise to stress relaxation
  - Also due to creep, but at constant displacement



- Both primary and secondary stresses can give rise to plasticity, resulting in redistribution of stress and strain

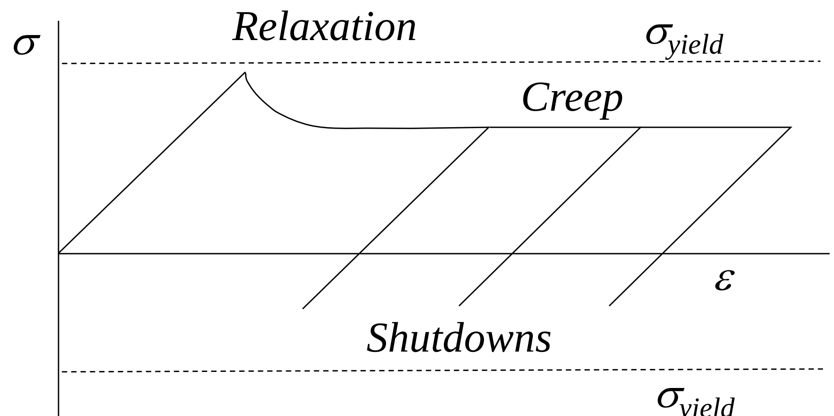


THE INTERACTION BETWEEN CREEP AND FATIGUE

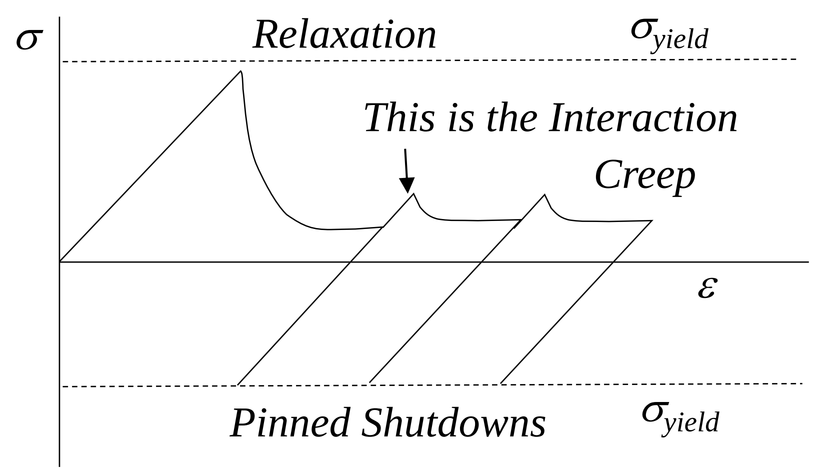
- It is the combination of both primary and secondary stresses which leads to interactions between creep and fatigue

- The potential for interaction is driven by redistribution and relaxation as the peak stresses shakedown

- The interaction can cause perturbations in stress which can lead to increased damage



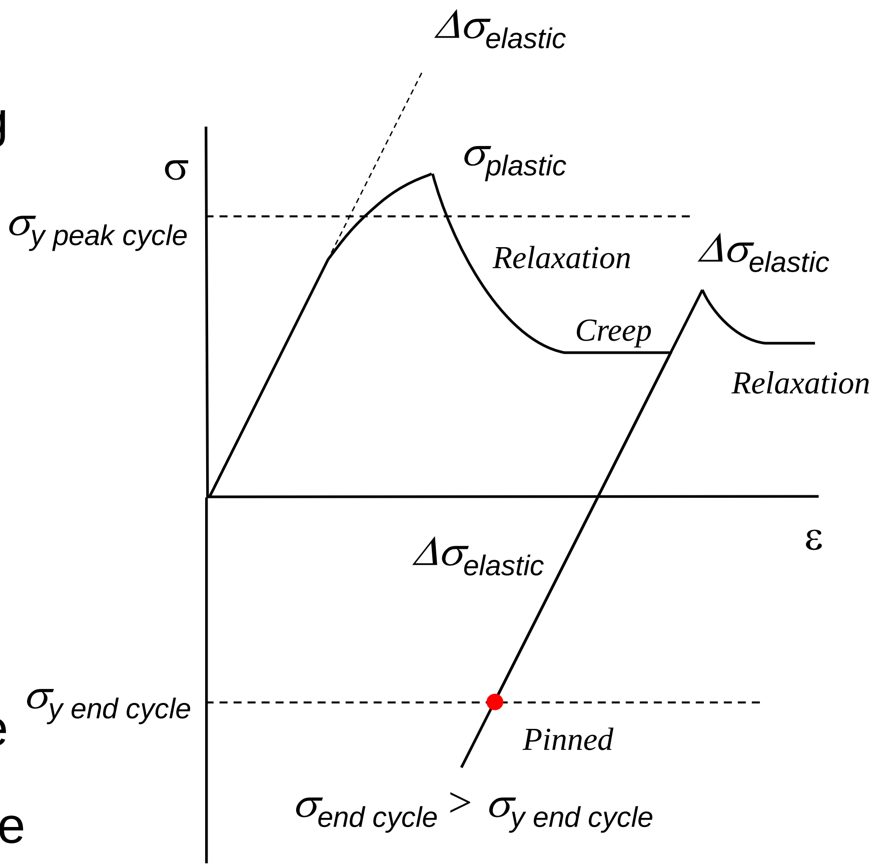
Case A



Case B

THE INTERACTION BETWEEN CREEP AND FATIGUE

- Interaction occurs when creep is perturbed by a cyclic load
- Relaxation and redistribution occur during dwells in the load cycle, resulting in a stress drop
- At the end of the dwell, the stress unloads resulting in a stress which now exceeds yield at the end of the cycle
- There is insufficient energy to cause plasticity at both ends of the cycle, therefore, the stress is “pinned” at yield
- Upon reloading, the elastic stress range is applied perturbing the peak stress leading to further relaxation and damage

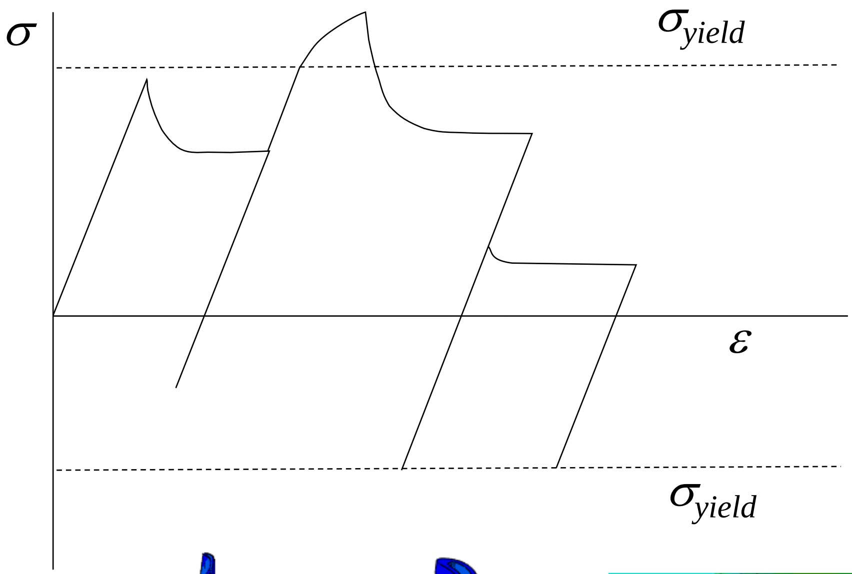


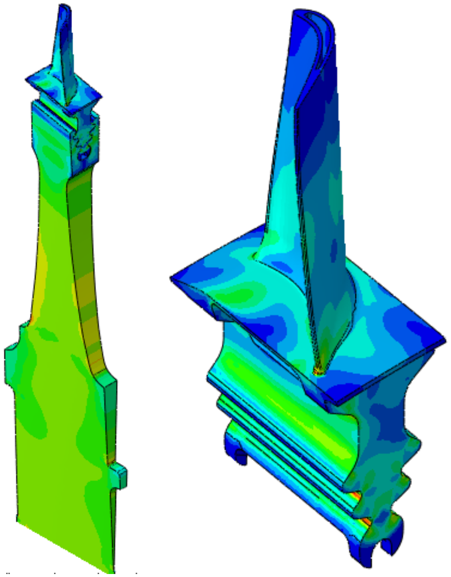
APPLICATION TO GAS TURBINE OPERATION

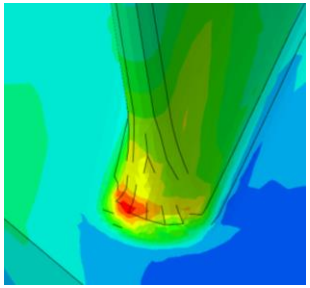
- This Interaction can also occur between different load cycles

- Variation in both the elastic stress ranges and stresses at the start and end of the cycle, can lead to perturbations

- This exaggerates the non linear accumulation of damage over the operation period







SUMMARY

- An approach has been presented which can predict damage from creep and fatigue interaction using ductility exhaustion
- Superalloys exhibit rate dependent ductility, which supports a ductility exhaustion approach
- Interaction between creep and fatigue damage mechanisms can lead to additional damage
- Damage accumulation from creep and fatigue is non linear and path dependent

IMPLICATIONS FOR ASSET MANAGEMENT

- Our common goal is to maximize reliability, availability and operational flexibility
- The continued development of technology is key to achieving this goal
- To support this we must achieve data driven Equipment Heath Management
- Equipment Heath Management is no longer just about hours and cycles, its about real time damage modeling

Thank you