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Experimental Testing and Failure Analysis for High Temperature Plant Environments

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EPSRC Pioneering research and skills

RCNDE UK Research Centre in NDE

HTC High Temperature Centre

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Outline

- Structural Integrity Challenges for Plant Operation
  - High Temperature Operation
  - Flexible Operation
  - Welding and Residual Stress Effects
  - Environmental Effects
- Research Challenges for Current and Future Plant Operation

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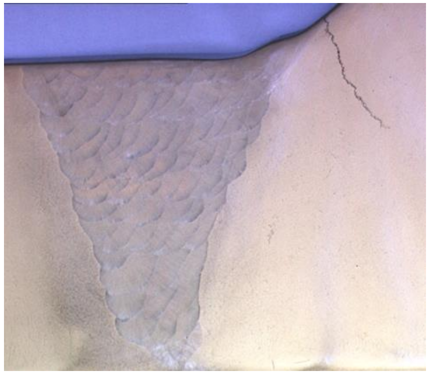
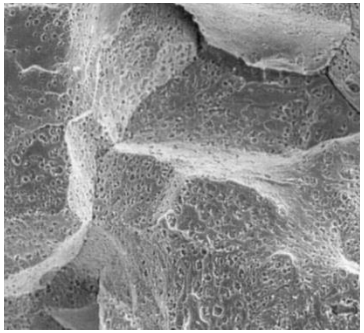
High Temperature Plant Operation

- High operating temperatures is key to exploit power plant efficiency
- Failure of high temperature plant components need needs to be accurately predicted for existing and future plant
- Failure principally due to:
  - Creep and fatigue processes
  - Enhanced by **Residual Stresses**
  - Principally in **Weldments**

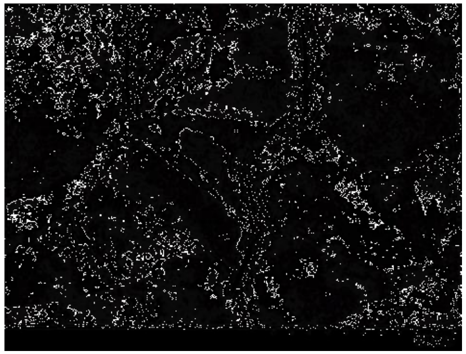


Reheat crack in 316H header component

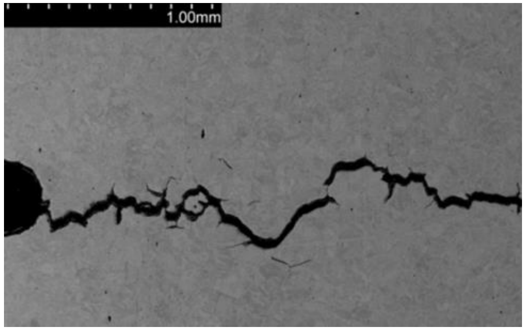
- Significant research into creep deformation and crack growth mechanisms



Grain Boundary Creep Cavitation



Discrete micro cracks



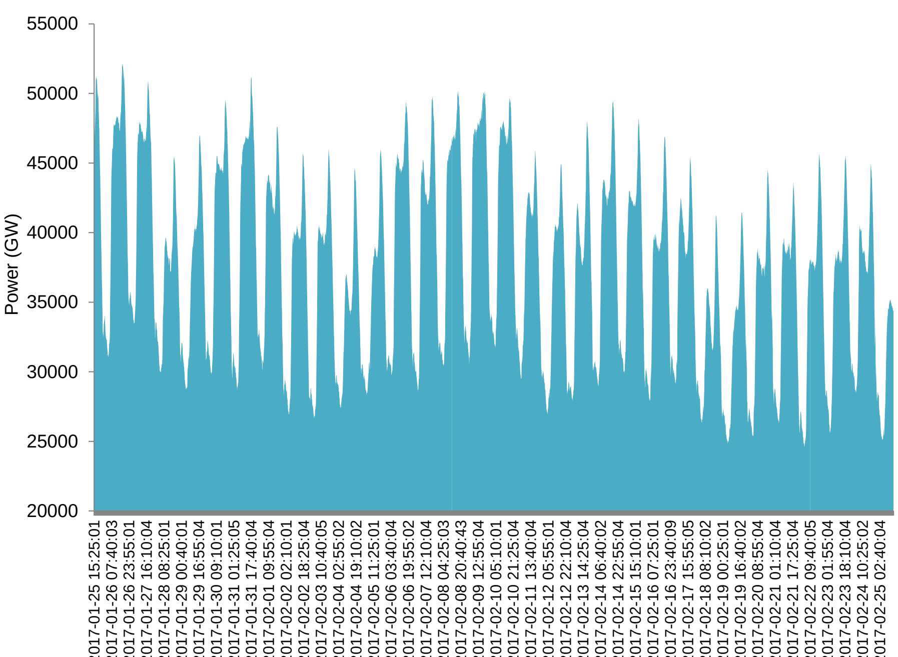
Macroscopic crack growth

In-service failure of a branched connection

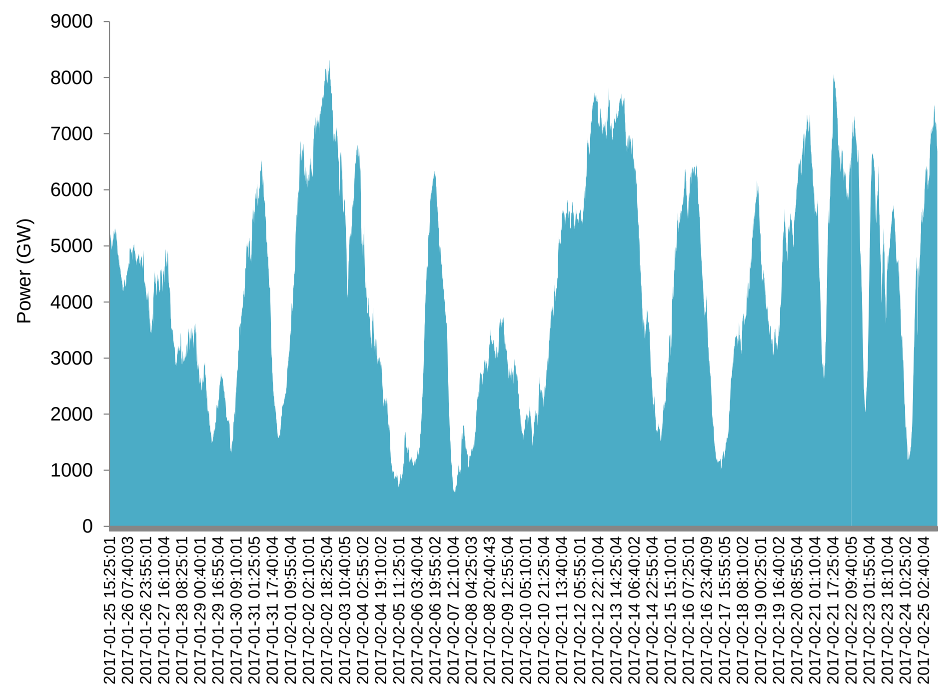
Flexible Plant Operation

- Flexibility is the ability to adapt to dynamic and changing conditions
  - balancing supply and demand by the hour or minute
- Wind energy is a dominant renewable energy source
  - Renewables are intermittent – not easy to forecast availability
  - Need alternative supply to rapidly respond to fluctuations from renewables

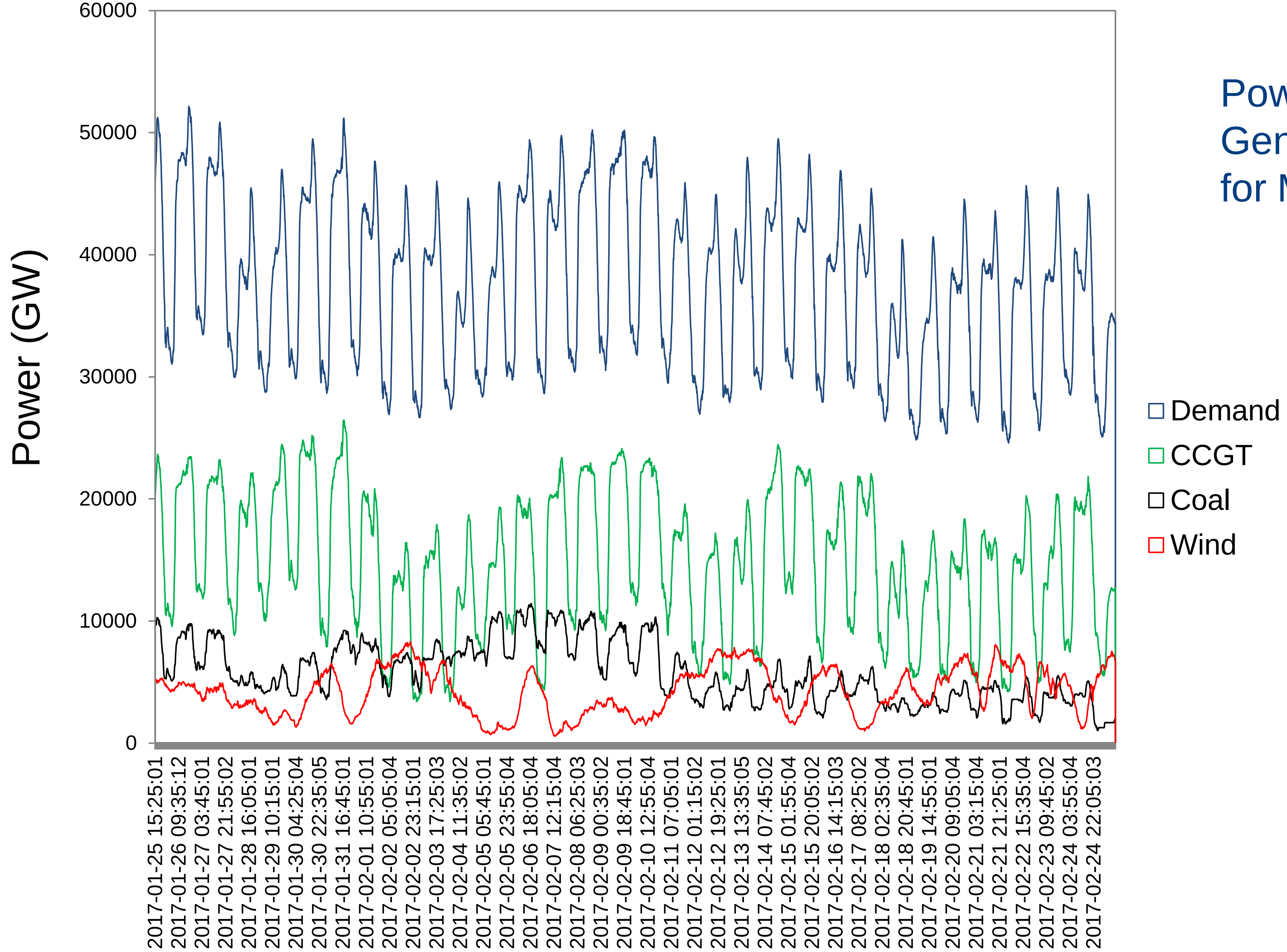
UK Energy demands Jan/Feb 2017



Wind availability Jan/Feb 2017



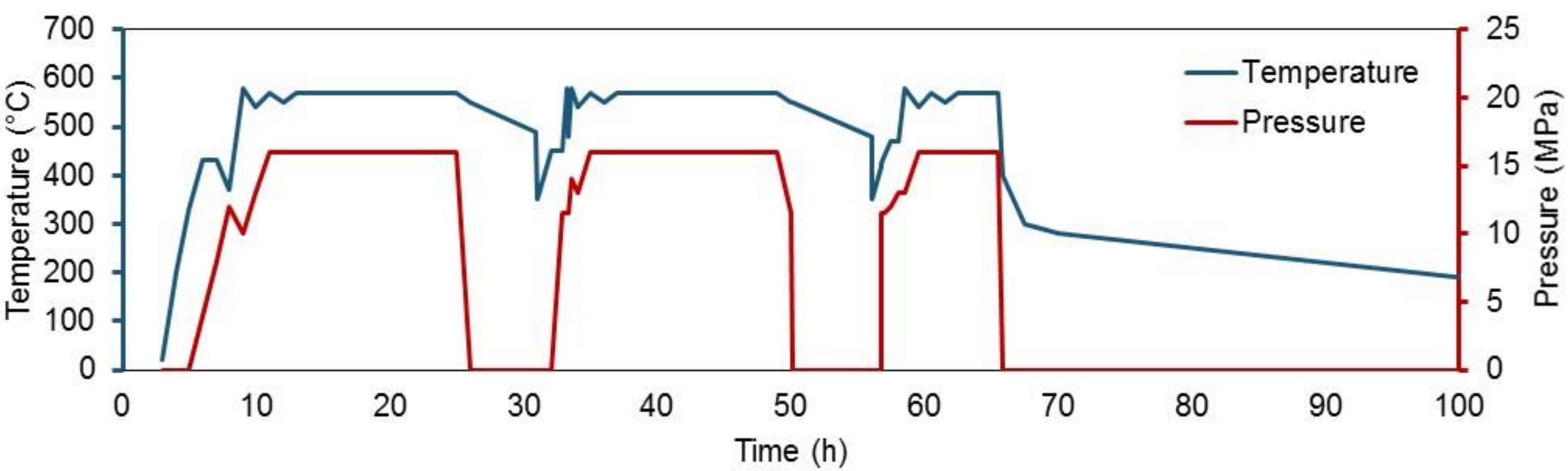
Power Demand and Response



Power Generation for Month

The Issue with Flexing

- Most existing power plant designed for sustained operation at full load to
  - Maximize efficiency
  - Reliability
- The need for flexibility causing
  - more frequent shutdowns when market or grid conditions warrant
  - more aggressive ramp rates (rate of output change)



The Issue with Flexing

- Plant flexing leads to thermal fatigue failures
- Fatigue damage interacts with creep damage to cause
  - **Interactive creep-fatigue** failures
- Next generation plant need to accommodate flexing

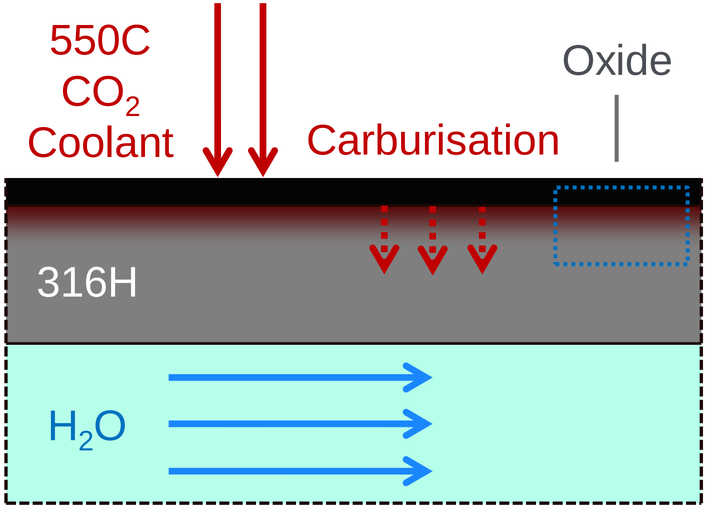
Cracking at pipe penetration due to cyclic operation

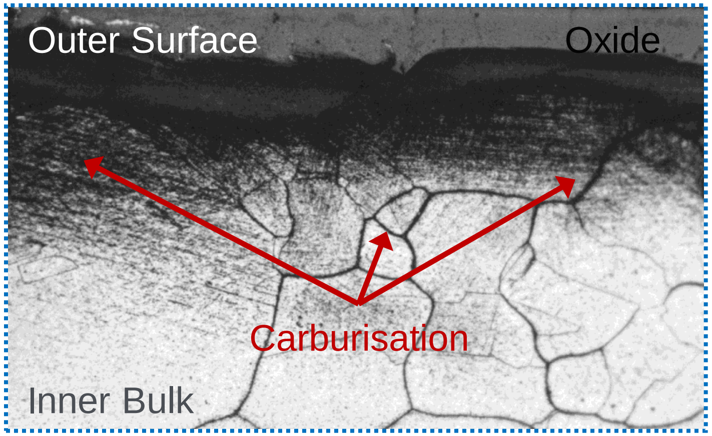
(Courtesy of E.ON)

Cold feedwater introduced to a hot header caused the crack in this economizer header. The cold water created a large through-wall temperature gradient change in temperature during startup and during off-line top-off opportunities. *Courtesy of EPRI*

Environmental Effects : Carburisation

- Advanced Gas Cooled Reactors (**AGR**) Primary coolant gas:
  - **CO_2**, CO, CH_4, H, H_2O
- Stainless Steel 316H components exposed at high temperatures (**550°C**)
  - **Creep**
- Carburisation corrosion forms a **hardened** outer **surface** layer
  - Component cracking.
- **Creep-Carburisation** interaction not considered in defect assessment procedures.





Research Challenges

- Experimental Techniques for Creep Strain Characterisation
  - Parent material and weldments
- Understand and Predict:
  - The role of residual stresses on creep crack initiation and growth
  - Interactive creep-fatigue effects on failure
  - Influence of long-term operation and environment on the integrity of plant components
    - Carburisation for AGR components
- Develop and Implement:
  - Plant monitoring
  - Lifetime prediction techniques

Weld Characterisation

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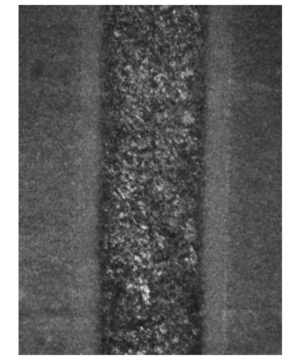
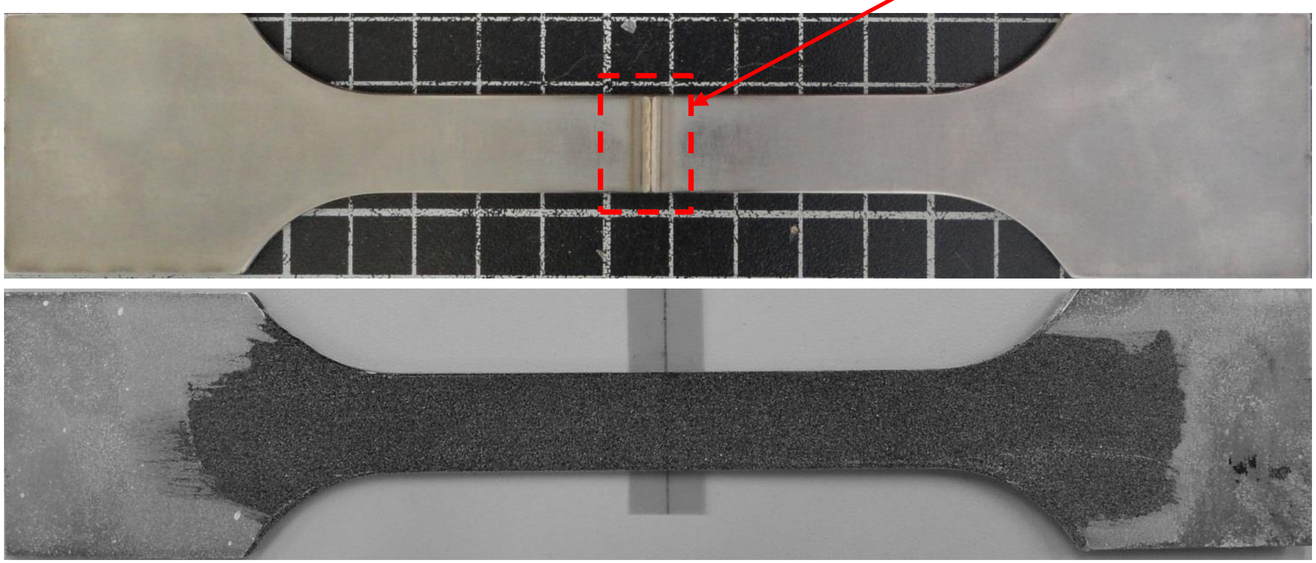
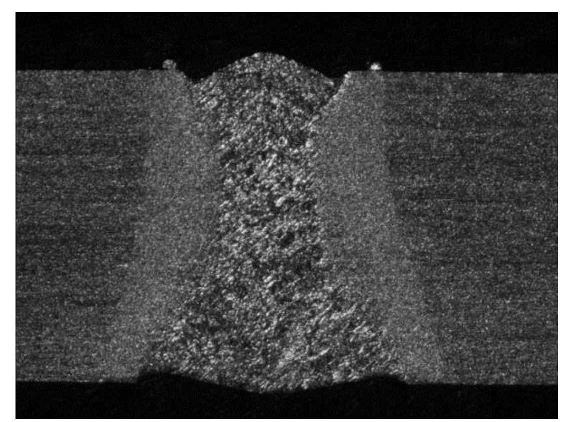
- Components mainly joined by welds
- Complex inhomogeneous microstructures
- Gradient of material properties
  - Parent material
  - Fusion zone
  - Heat effected zone (HAZ)
- Deformation properties characterised
  - Digital Image Correlation



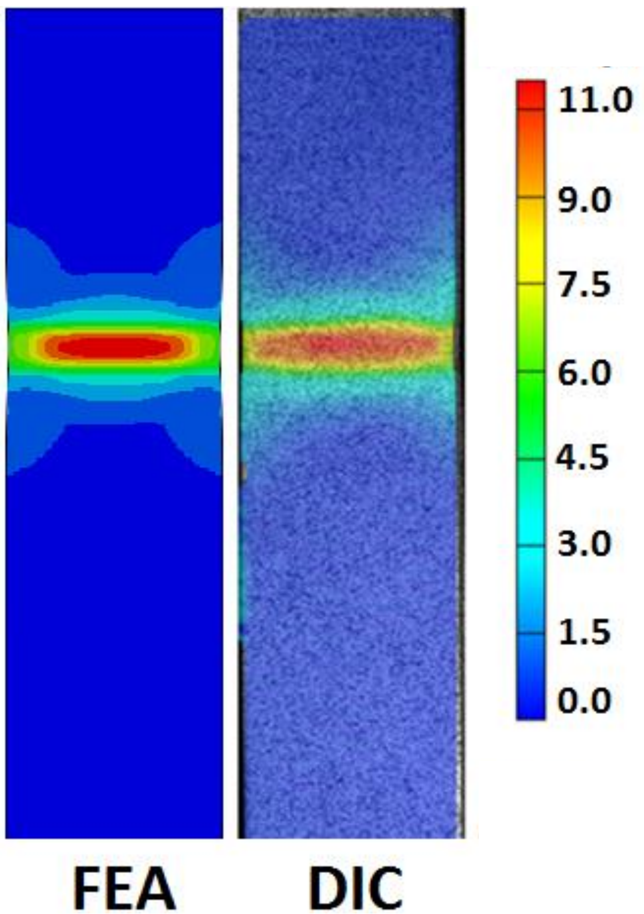
Laser Beam Weld in Aluminium

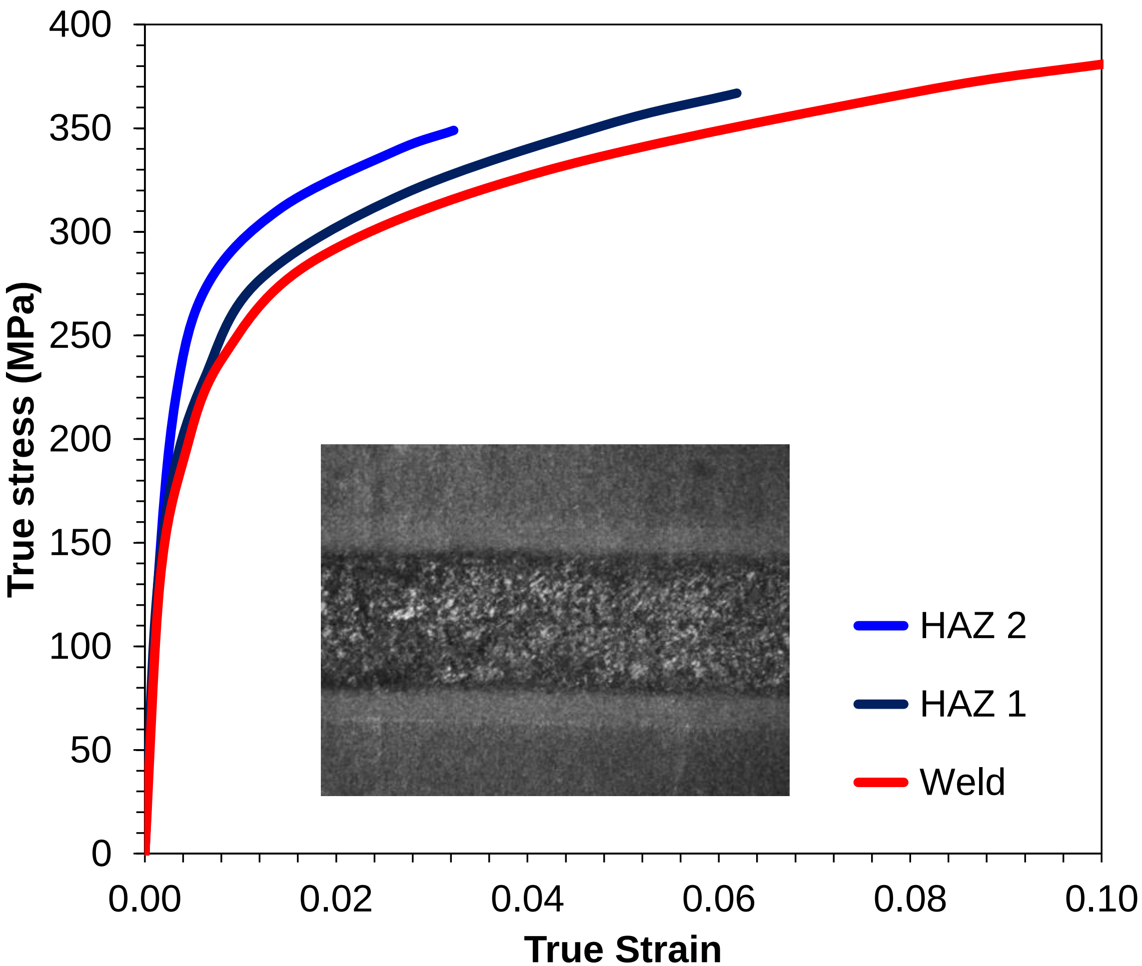




Weld Characterisation

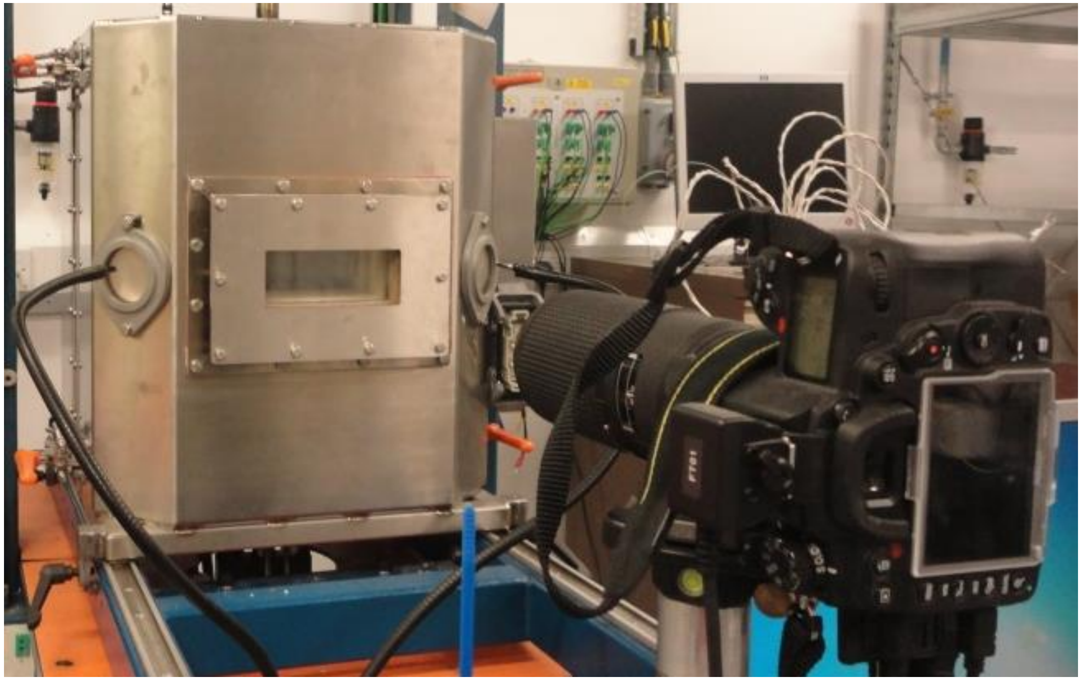
- Inhomogeneous elastic-plastic material properties determined
  - Incorporated in finite element analyses

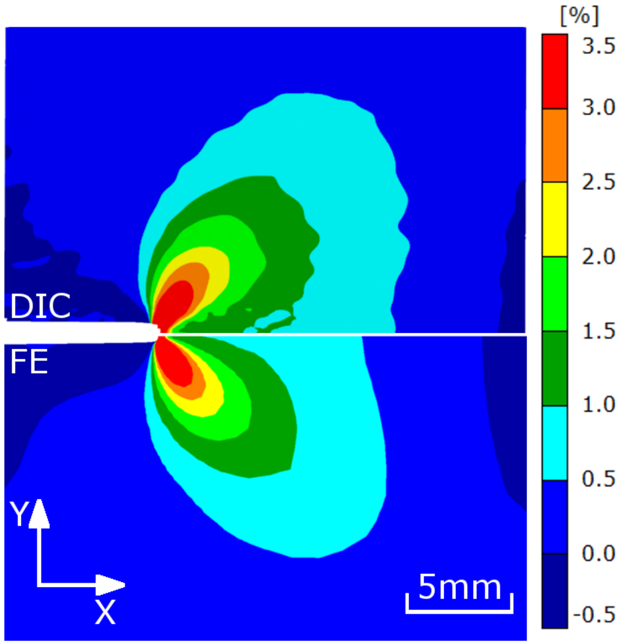




High Temperature DIC

- Custom designed furnace
- 2D or 3D DIC
- Tensile or Fracture Sample
- Time dependent creep strain distribution mapping
- CMOD measurement





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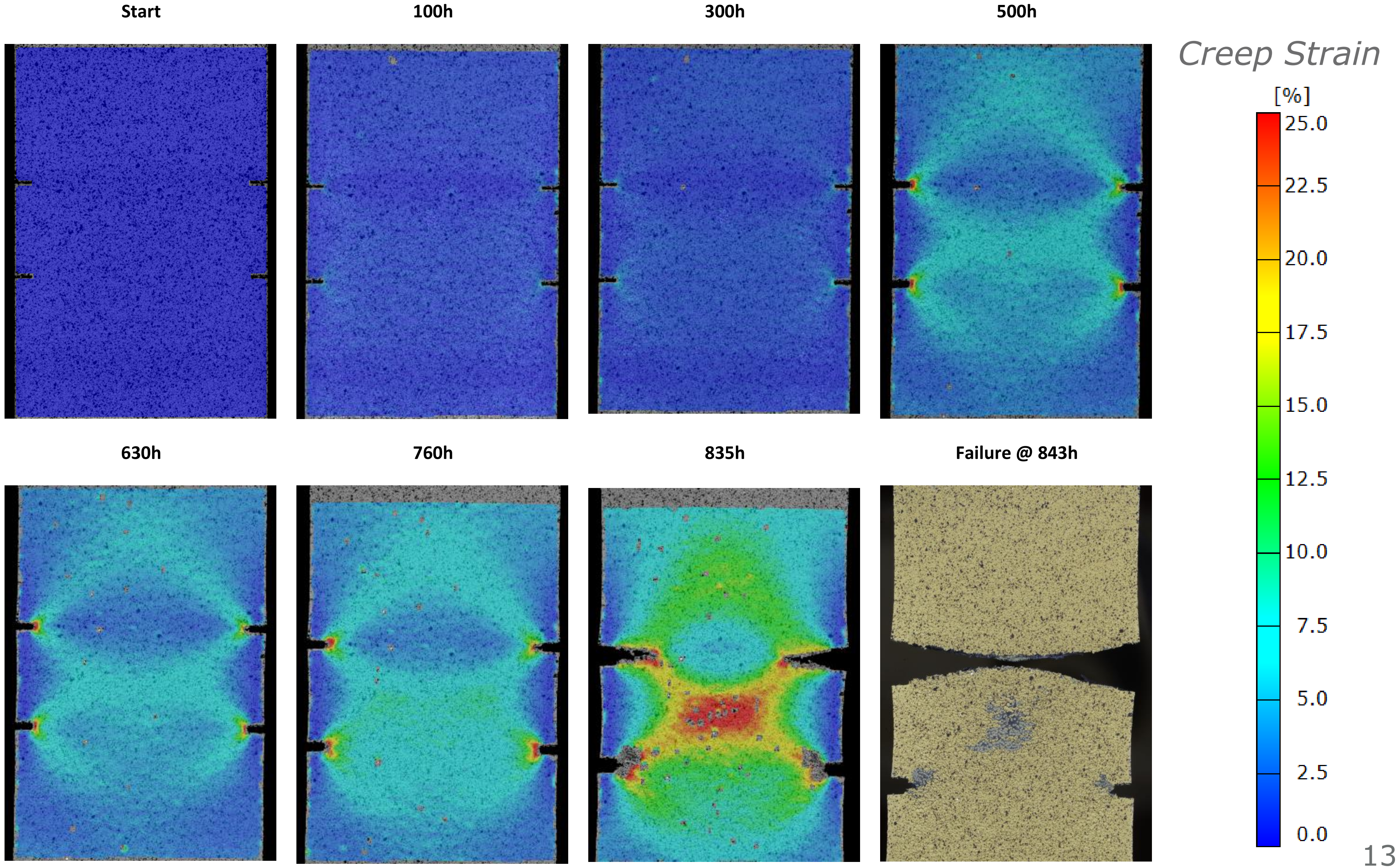
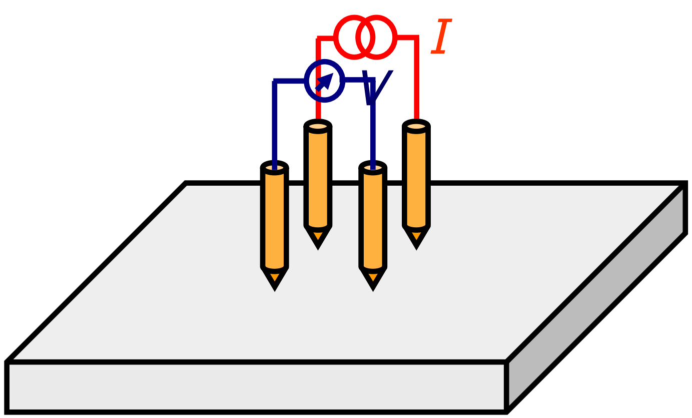
Creep Strain Evolution at 760 °C



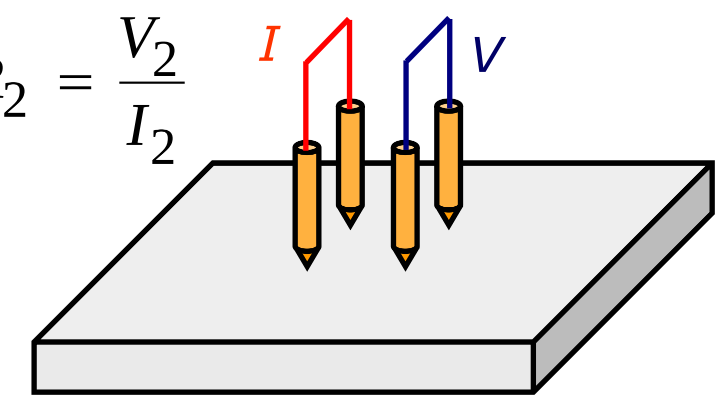
Low Frequency ACPD Strain Measurement Technique

- Technique is based on a square array, directional electrode configuration
- Measures sub-surface
- Small currents (~100 mA) sufficient even in quasi-DC regime
- Phase detection in ACPD provides superior measurements to DC
- Creep can be monitored through variation in the resistance ratio R_1/R_2
- Non-directional thermal effects rejected by calculating the resistance ratio
- Permanently attached probe behaves like strain gauge
- Geometrical variations have larger effect than microstructural changes

$$R_1 = \frac{V_1}{I_1}$$



$$R_2 = \frac{V_2}{I_2}$$



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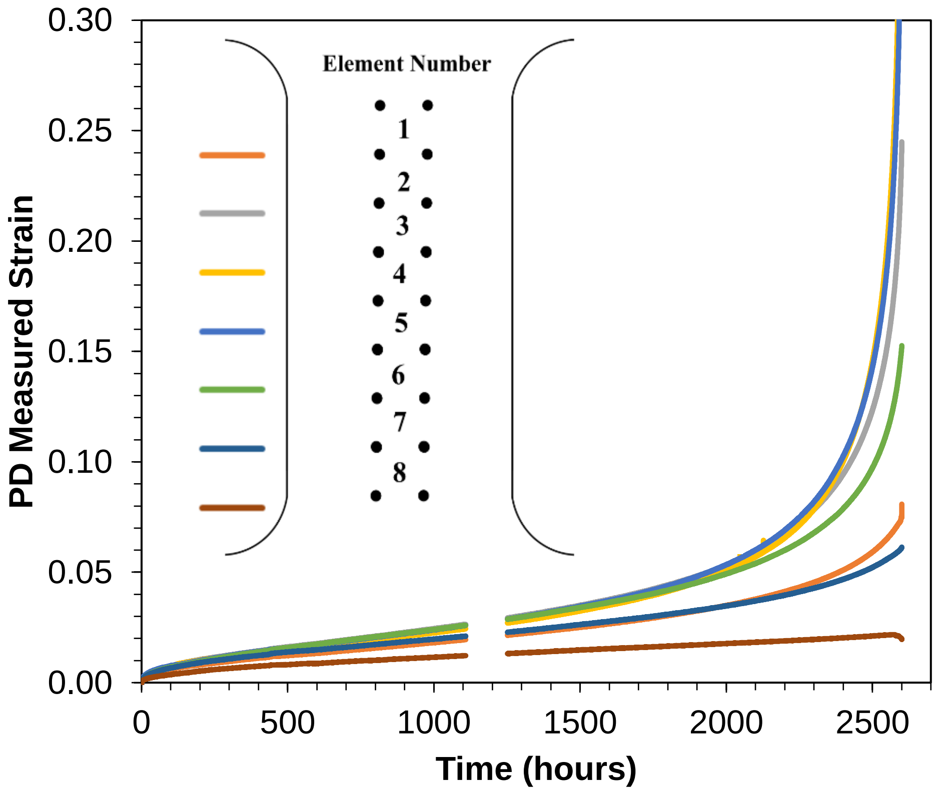
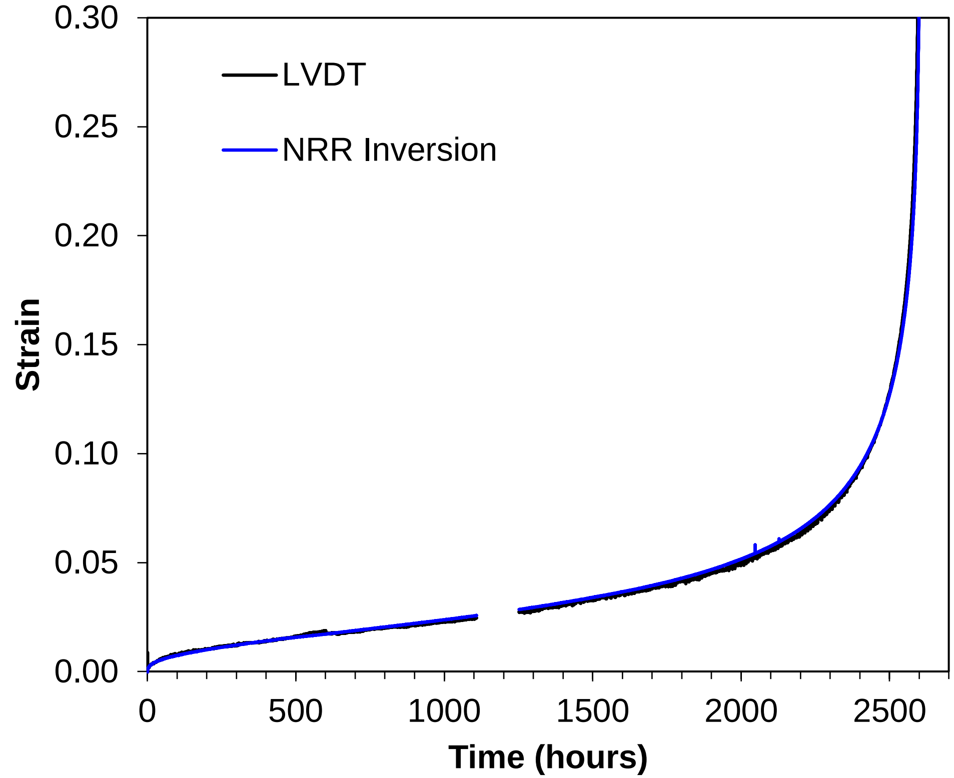
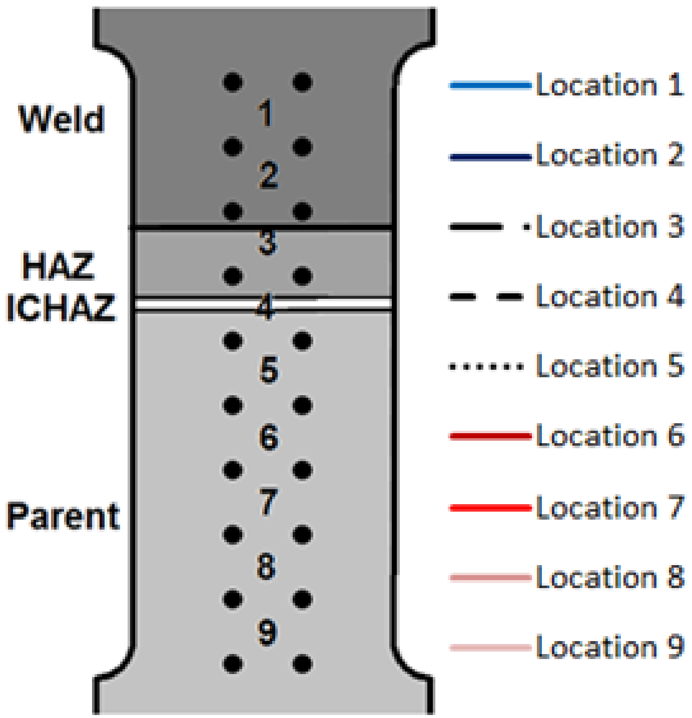
Low Frequency ACPD Strain Measurement



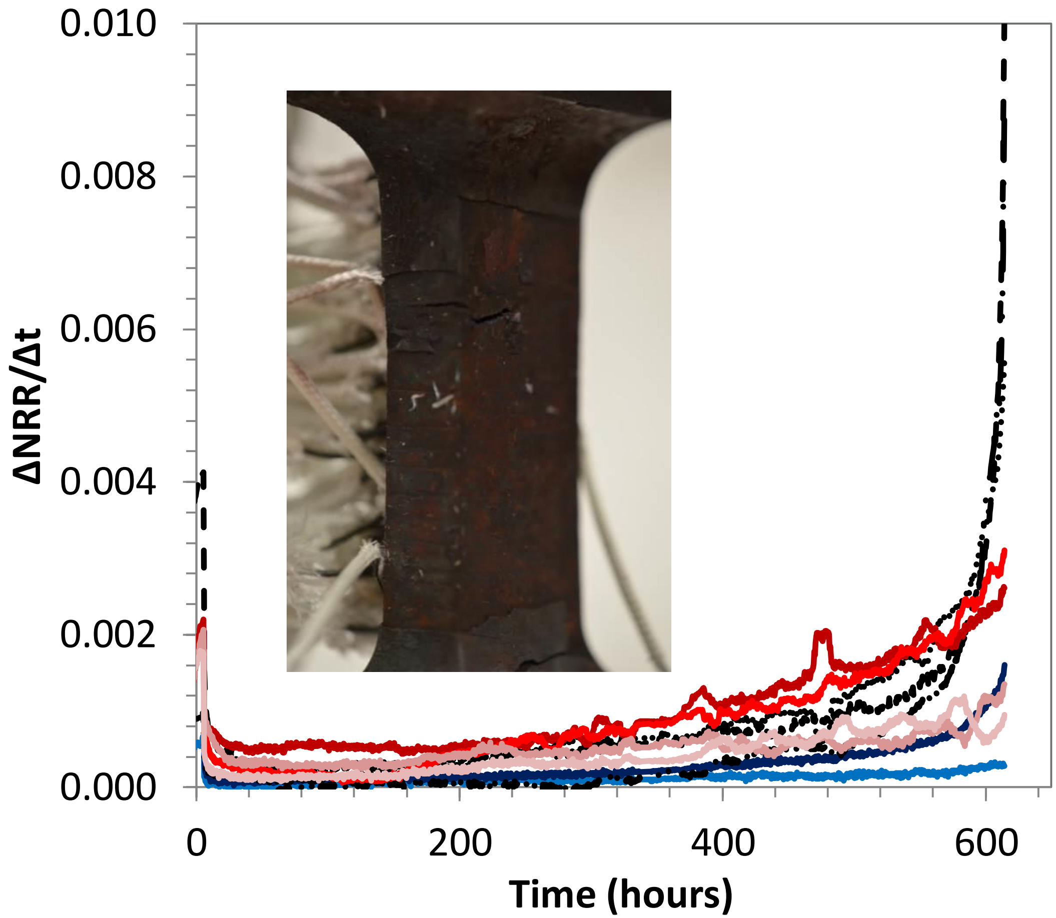


- Local creep strain measurements by PD method
- PD measurements verified by LVDT
  - Average array strain equals the global strain measurement
- Can measure micro-crack formation prior to sample failure

PD Measurement on Welded Sample



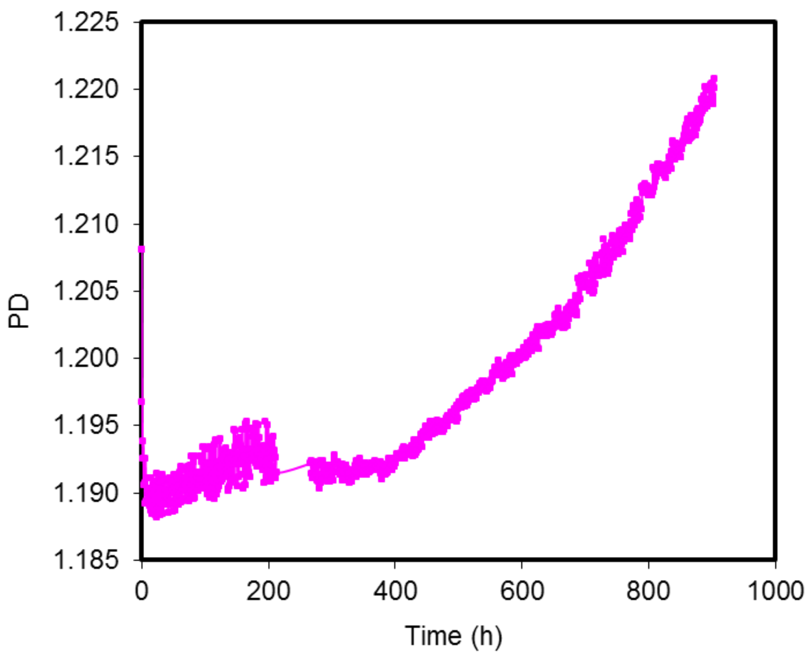
CMV/2.25Cr
80 MPa
625 °C



- Rate of change in resistance clearly indicates onset of failure
- Failure in HAZ region

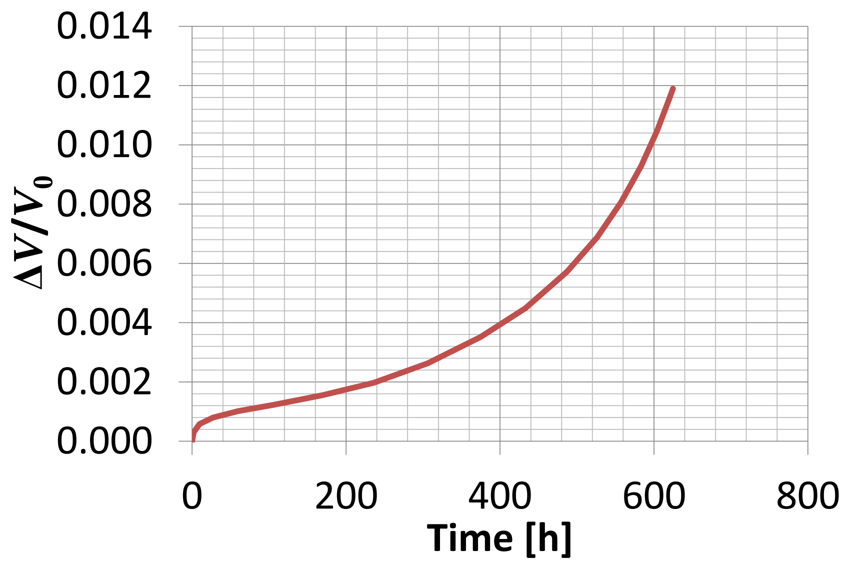
Measuring Crack Initiation and Growth

- Creep crack initiation (CCI) occupies large fraction of a components lifetime
- Verifying CCI models requires accurate experimental measurements
- DCPD often used to monitor crack growth
  - Noisy signals
  - Requires assumptions for CCI point



Measuring Crack Initiation and Growth

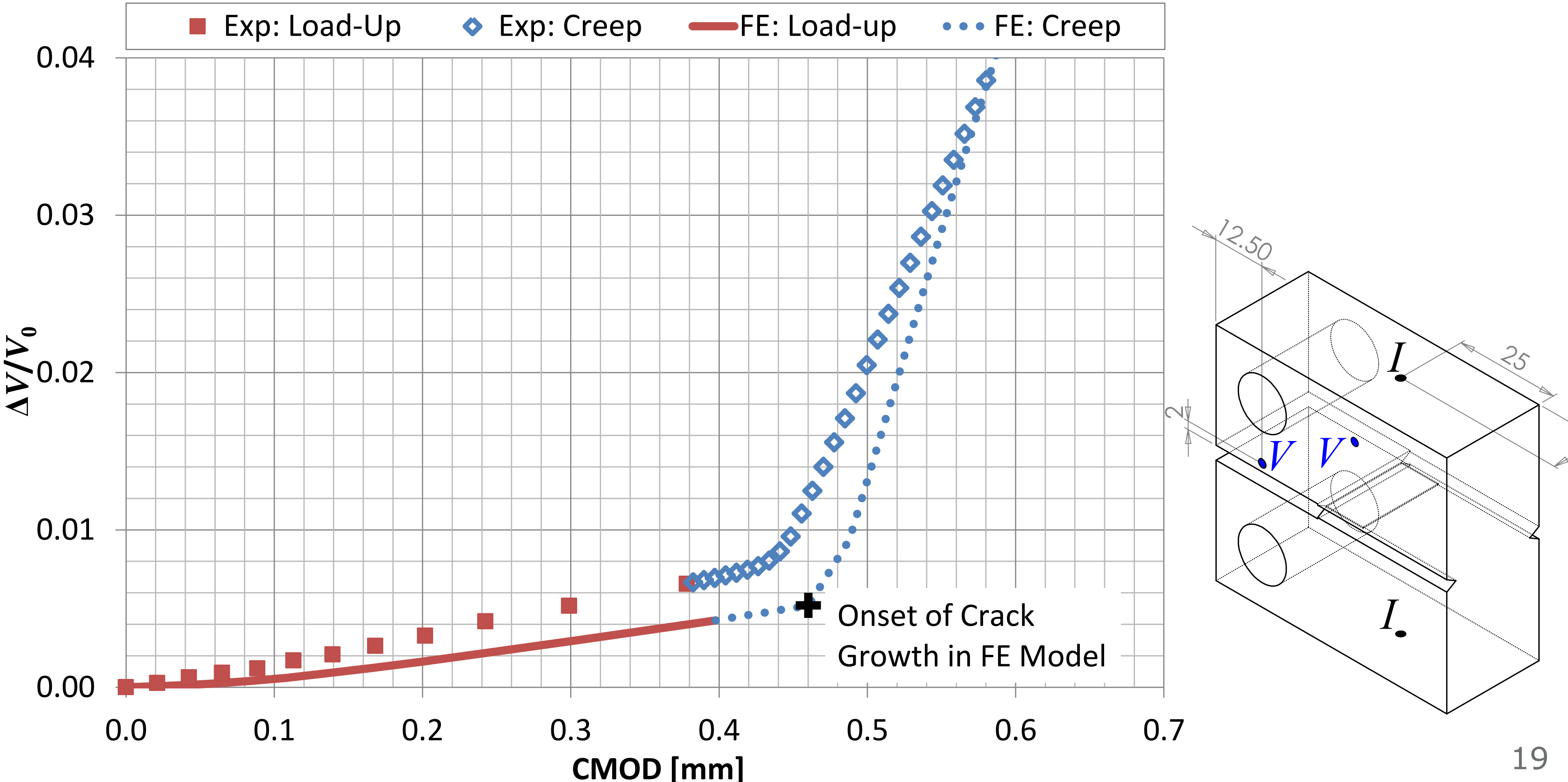
- Issues with current PD measurement technique and standards:
  - Any change in PD after load-up is attributed to crack growth
  - Method does not differentiate between creep strain and crack growth
  - Plasticity can also effect measurements



- Challenges:
  - Reduce the noise in the PD response
  - Identify the point of CCI on the PD response

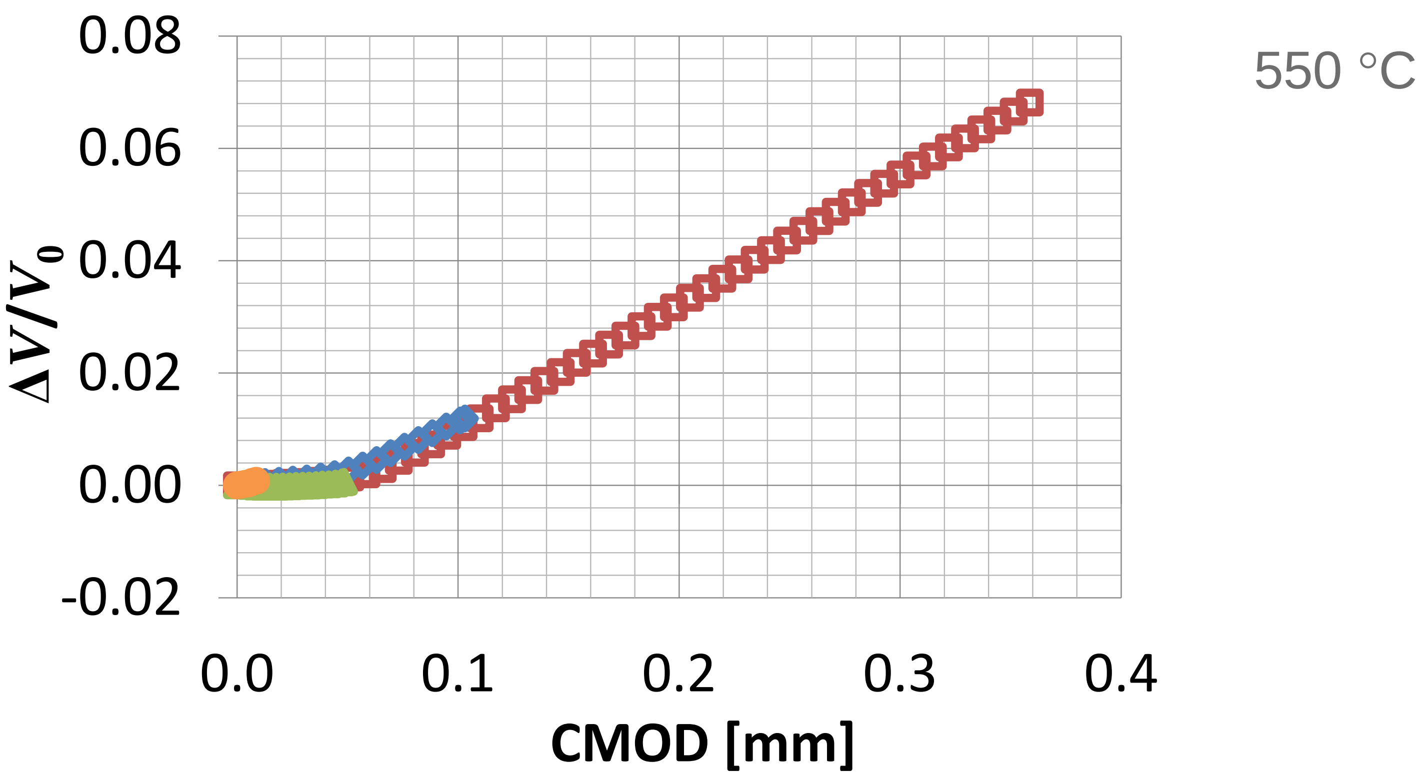
CCI measurement

- Recently demonstrated a point of inflection occurs on a plot of PD vs. CMOD
  - CCI times can be measured more accurately



Experimental Observation of CCI

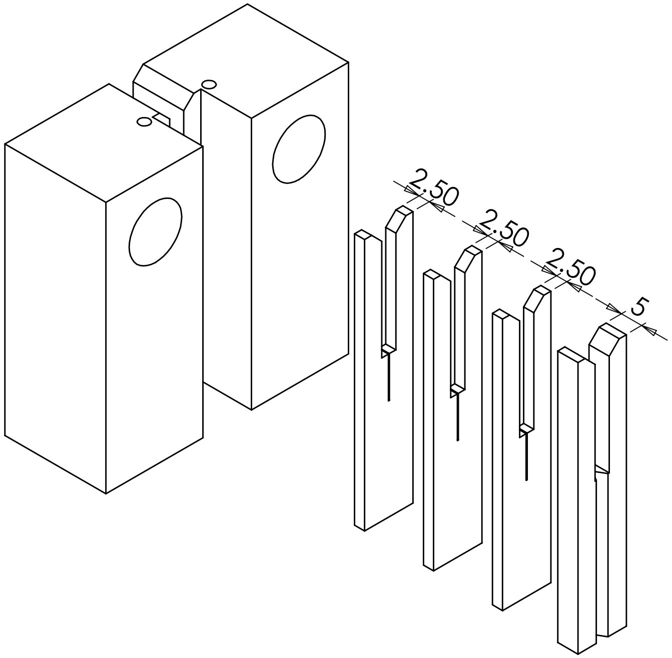
- 4 nominally identical tests on C(T) samples of 316H SS:
  - CCG316_CT01: Significant crack growth
  - CCG316_CT02: Interrupted after 0.2 mm CCG
  - CCG316_CT03: Interrupted at point of inflection
  - CCG316_CT04: Interrupted before point of inflection



Interrupted Tests: CCG316_CT03

Interrupted at point of inflection

- Δa = 0.01 mm
- Δa_{ASTM} = 0.02 mm
- Δa_{NEW} = 0.01 mm



Mid-plane

2.5mm from Mid-plane

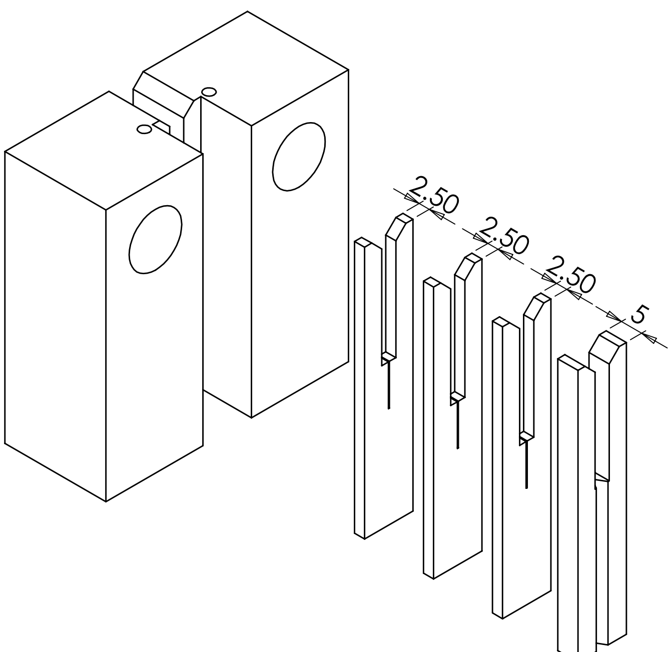
5.0mm from Mid-plane

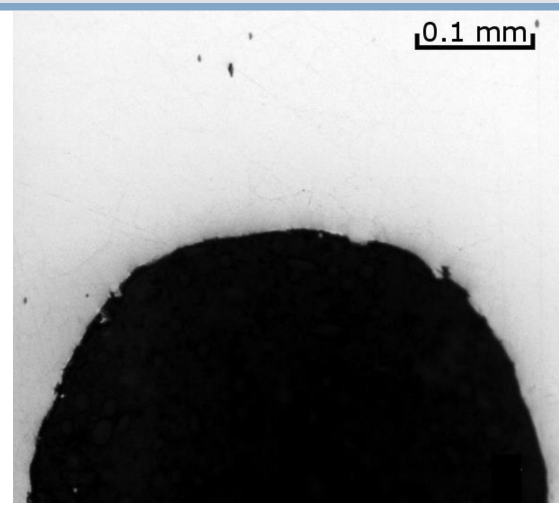
7.5mm from Mid-plane

Interrupted Tests: CCG316_CT04

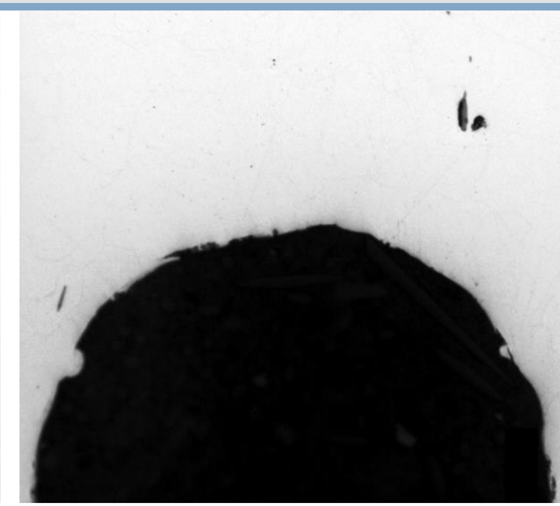
Interrupted before point of inflection

- Δa = 0.00 mm
- Δa_{ASTM} = 0.02 mm
- Δa_{NEW} = 0.00 mm

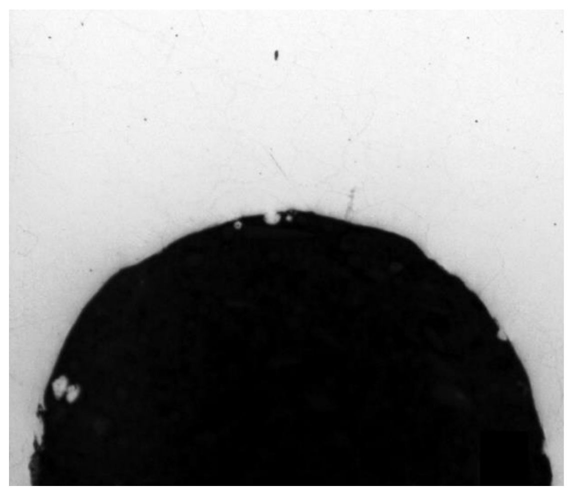




Mid-plane



2.5mm from Mid-plane

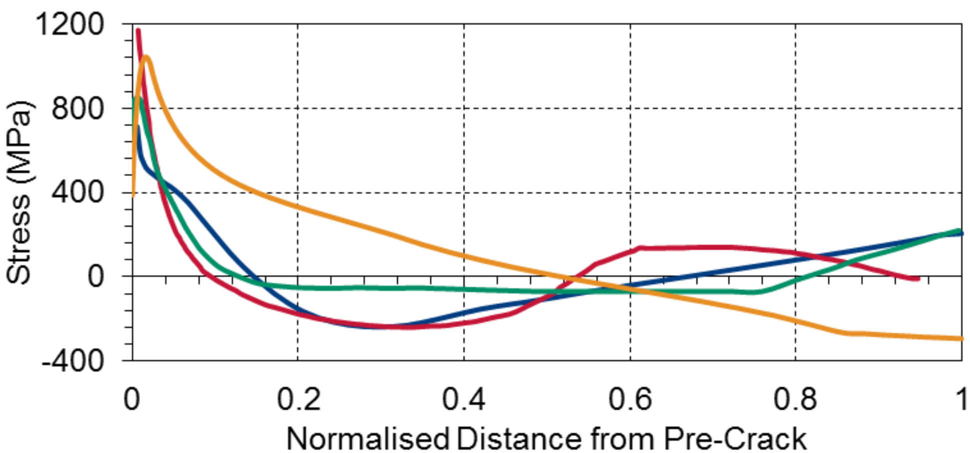


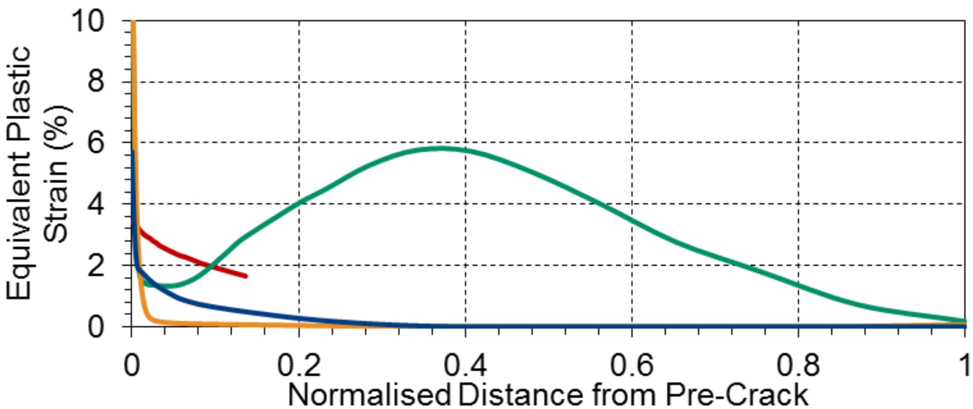
5.0mm from Mid-plane

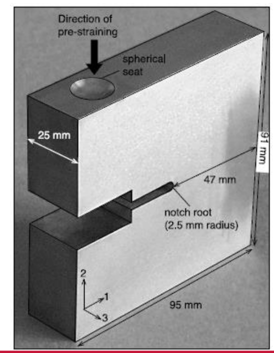
7.5mm from Mid-plane

Role of Residual Stresses on Creep Crack Initiation and Growth

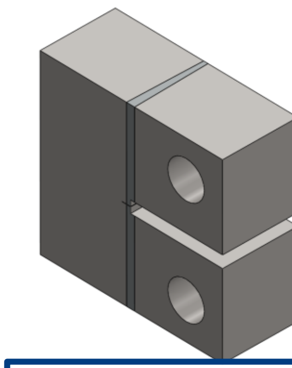
- Range of techniques to introduce residual stress (RS) into test samples
  - Difficult to distinguish role of RS and plasticity



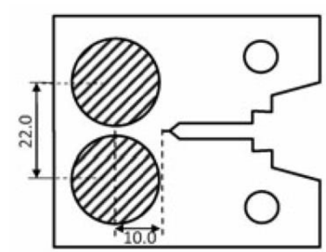




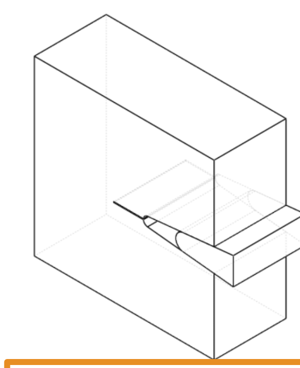
Pre-Compressed



EB Welded



Side Punched

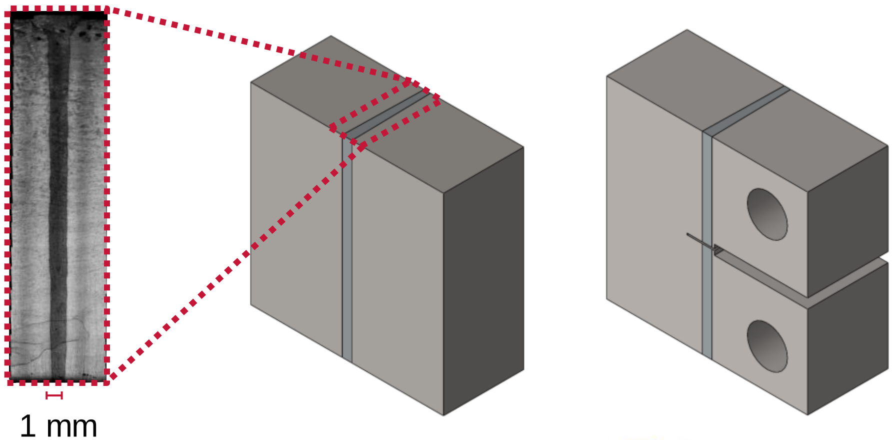


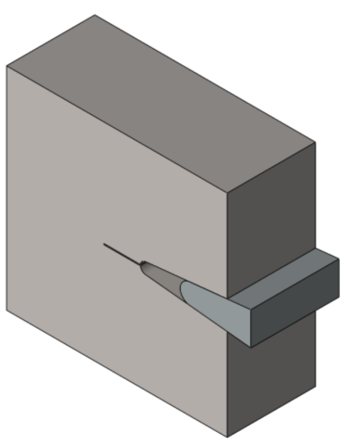
Wedge-Loaded

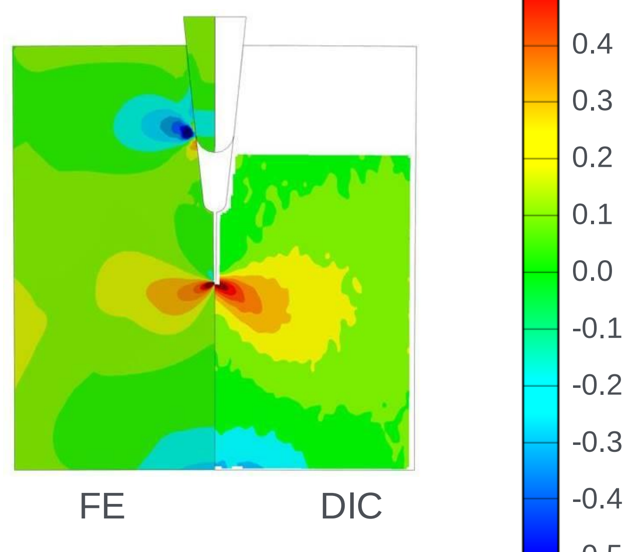
Data for pre-compressed and side punched specimens from: Hossain, S. et al. Fatigue & Fracture of Engineering Materials & Structures, 2011, 34(9), pp. 654-666 Turski, M. et al. Acta Materialia, 2008, 56(14), pp. 3598-3612

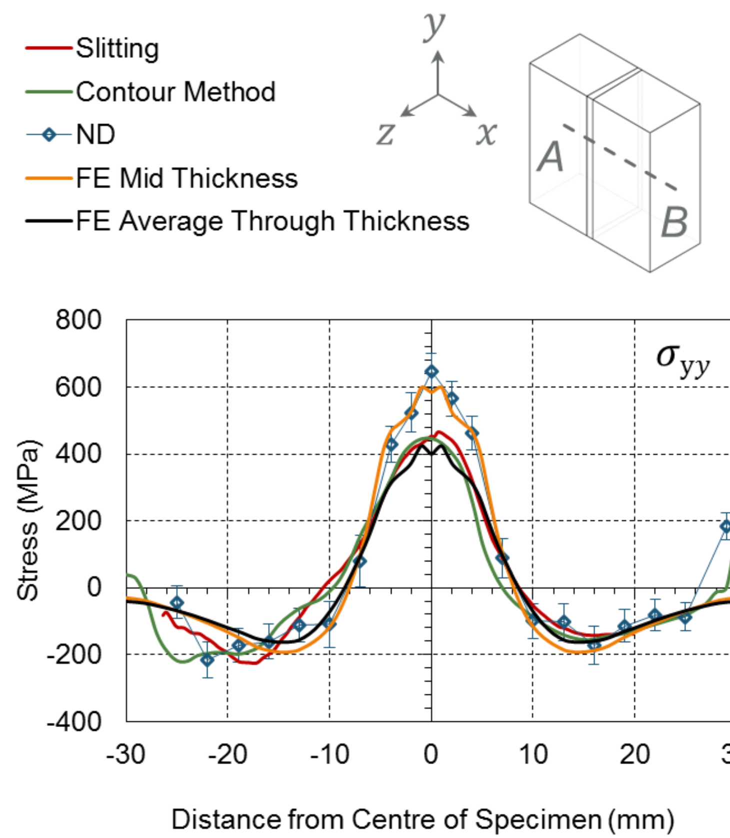
EB and Wedge Loaded Sample

- EB weld – high stress triaxiality
  - Combined loading possible





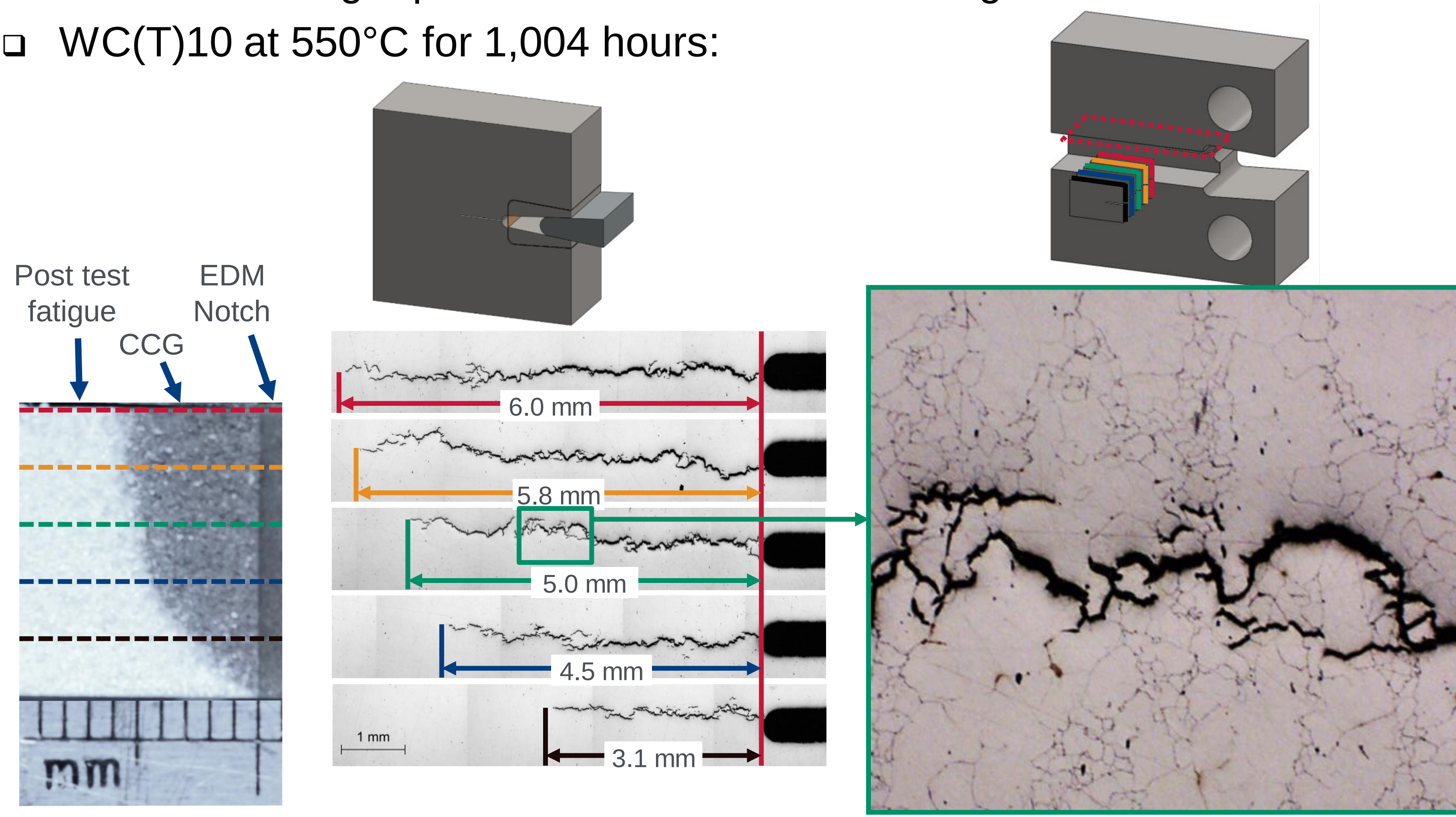




- Wedge doesn't require test machine
- Can easily be tested in environment

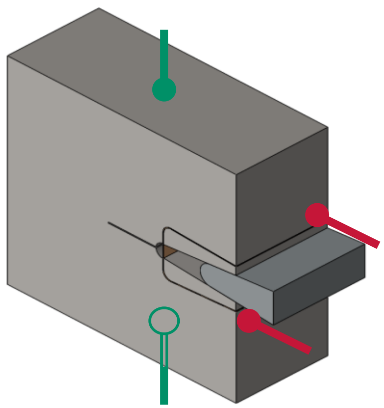
Crack Growth Metallography

- Metallography shows intergranular crack growth
- Crack tunnelling – plane strain conditions and larger K at mid-thickness
- WC(T)10 at 550°C for 1,004 hours:

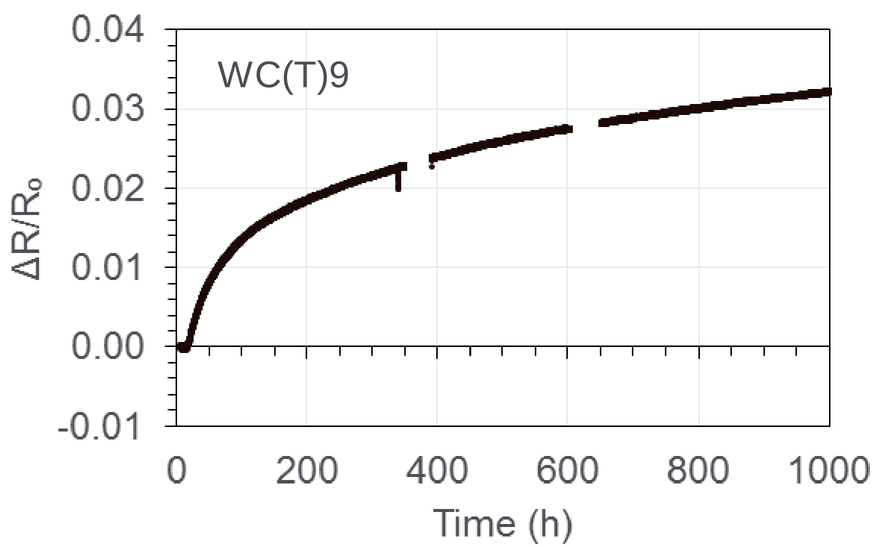


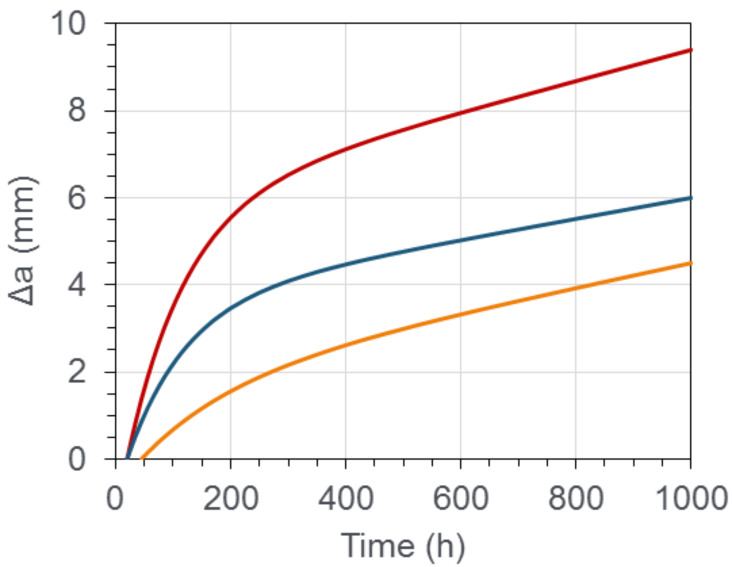
Crack Growth Measurements

- Crack growth measured using low-frequency ACPD system



	Specimen ID	K^s (MPa√m)
(orange line)	WC(T)8	44
(red line)	WC(T)9	47
(blue line)	WC(T)10	44





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Crack Growth Prediction of Wedge Samples in FE

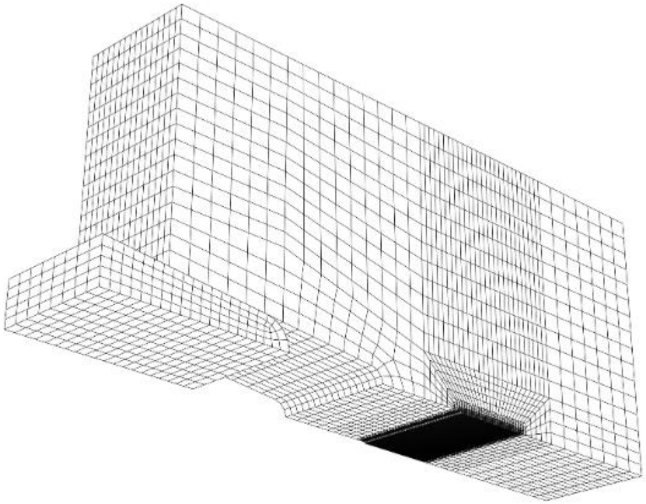
- Creep deformation modelled using RCC-MR model which includes primary and secondary creep regimes
- Implemented in ABAQUS using a CREEP subroutine with time hardening
- Damaged defined by:

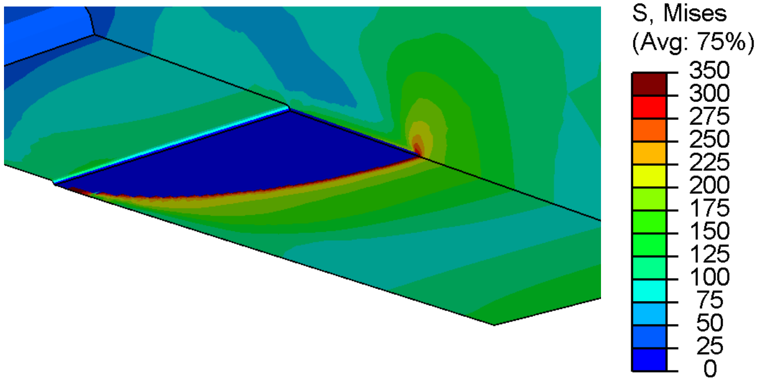
$$D = \int_0^t \frac{\dot{\varepsilon}}{\varepsilon_f^*} dt$$

$$\frac{\varepsilon_f^*}{\varepsilon_f} = \exp\left[p\left(1 - \frac{\sigma_1}{\sigma_{eq}}\right) + q\left(\frac{1}{2} - \frac{3\sigma_m}{2\sigma_{eq}}\right)\right]$$

$$p = 0.15;\ q = 1.25;\ \varepsilon_f = 2.1\%$$

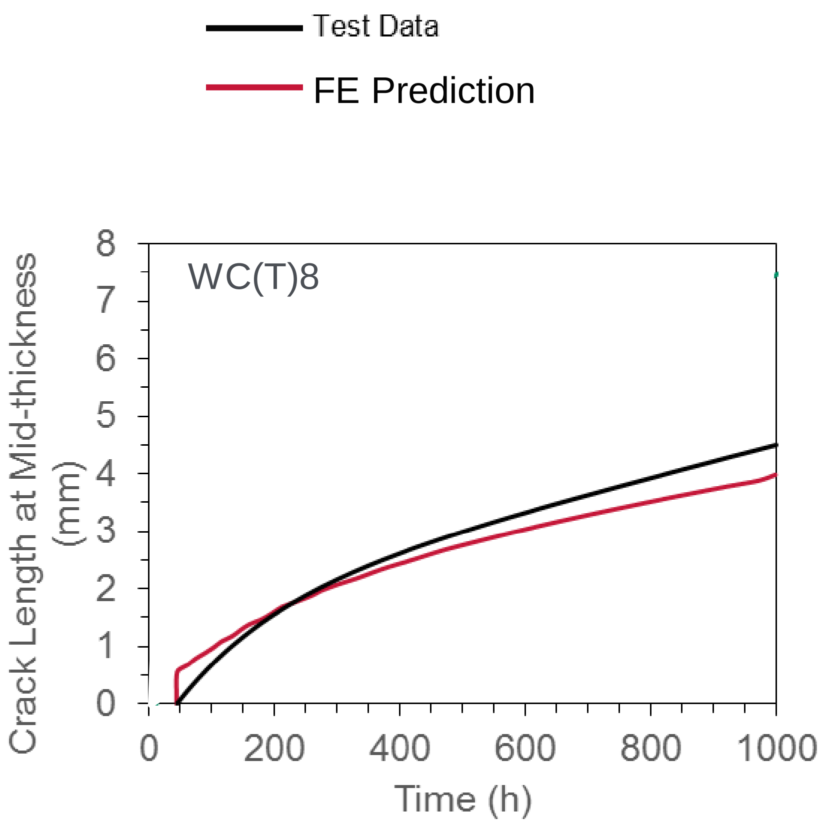
- Once elements are damaged (D = 1), elements are effectively removed by reducing the load bearing capacity using the USDFLD subroutine

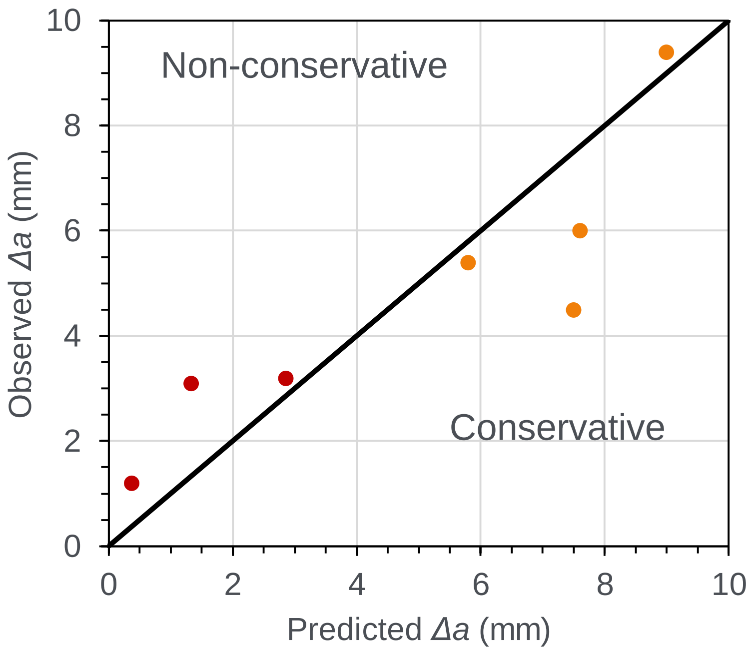




Crack Growth Measurements vs Predictions

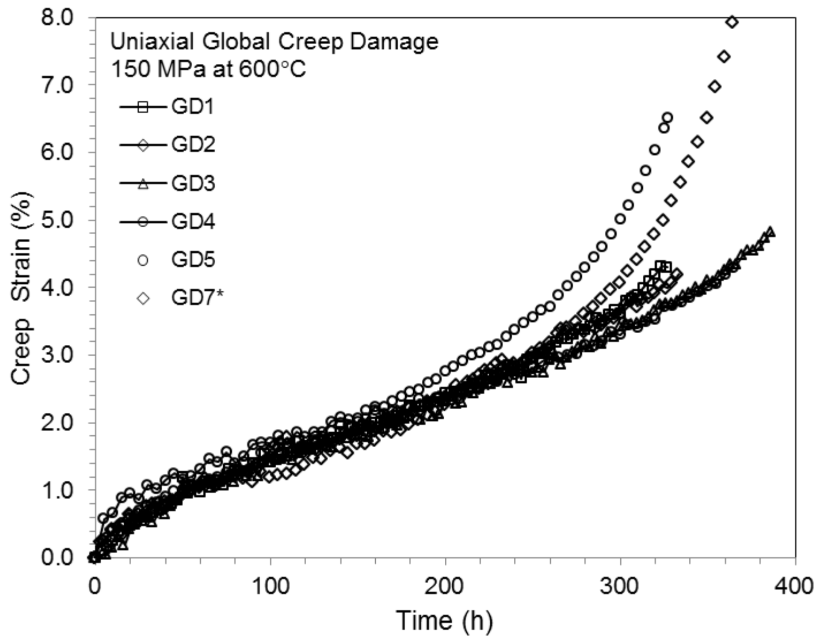
- Crack growth estimates at mid-thickness of the samples compared to measurements in EB welded and wedge loaded C(T) specimens

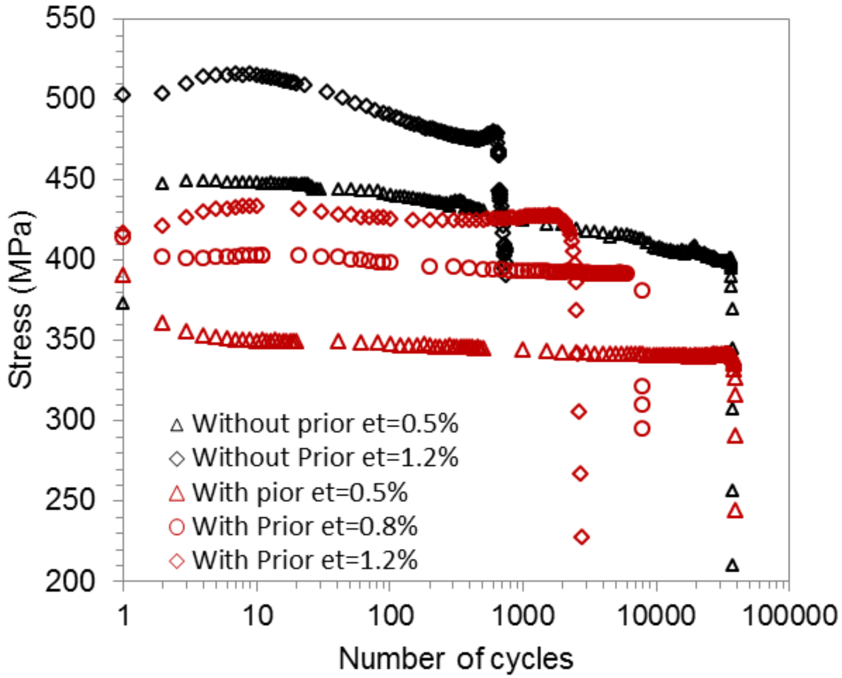




Characterising Creep-Fatigue Deformation

- Perform low-cycle-fatigue test of prior crept sample

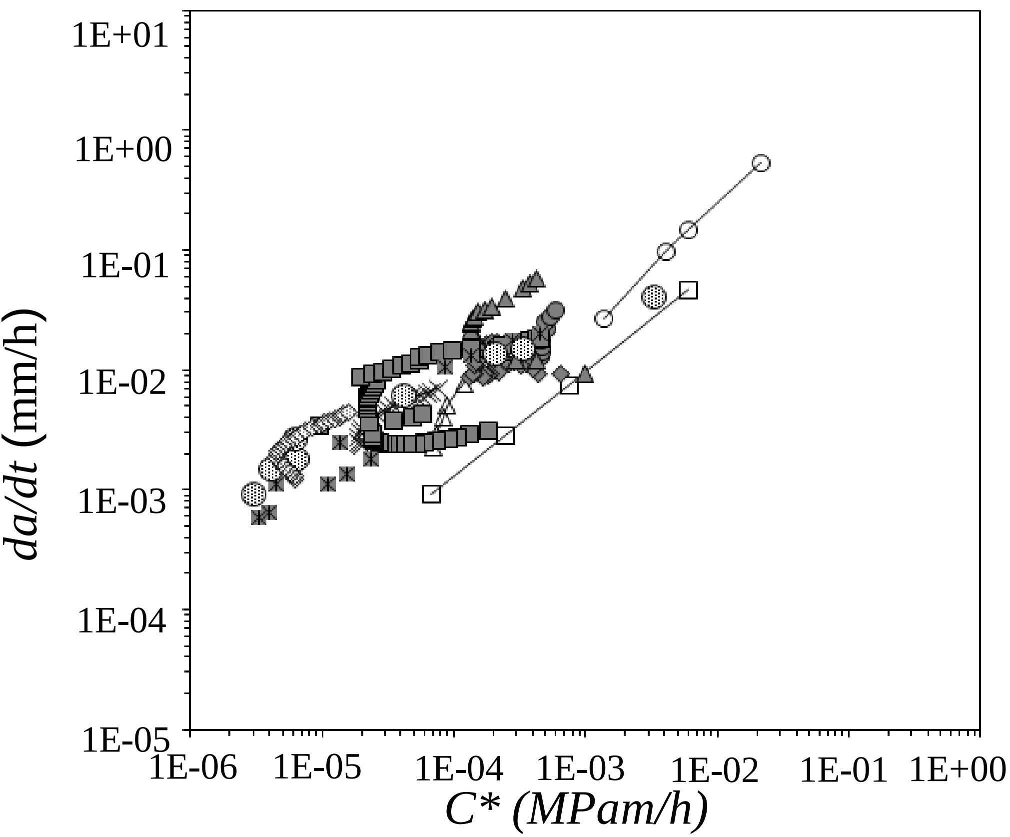




P91 Steel

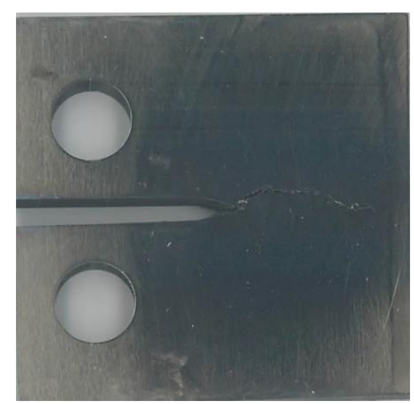
600 °C

Characterising Creep-Fatigue Crack Growth Properties



		T(°C)	f(Hz)	K_{max} (MPa√m)	
◆	CT-B	600	0.0017	25.02	CFCG
●	CT-C1	625	0.0017	22.82	CFCG
▲	CT-C2	625	0.0017	28.83	CFCG
■	CT-A	620	0.0017	25.11	CFCG
✱	A(2011)	625	0.001	8.1	CFCG
◎	A(2011)	625	0.01	10.3	CFCG
◇	M(2013)	600	0.00027	-	CFCG
—○—	A(2011)	600			CCG
—□—	S(2015)	600			CCG
—△—	S(2015)	600			CCG
—×—	M(2013)	600			CCG

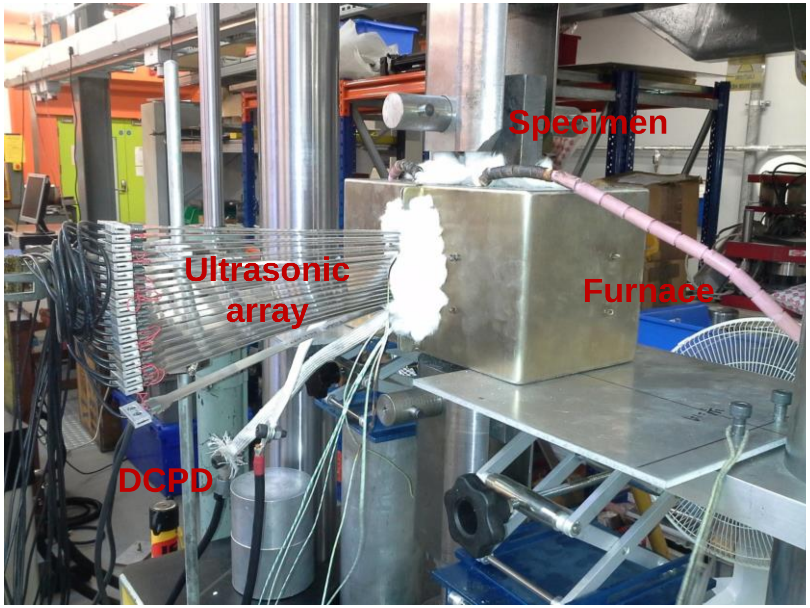
- Creep crack growth accelerated by fatigue loading

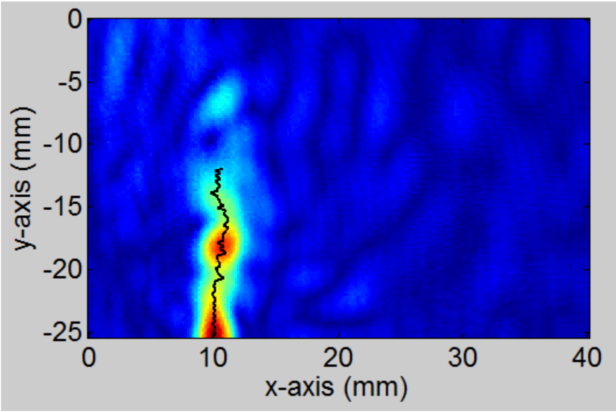


Plant Monitoring Tools

- Techniques developed to monitor creep strain and crack growth

ACPD Creep Strain Monitoring of Plant Components

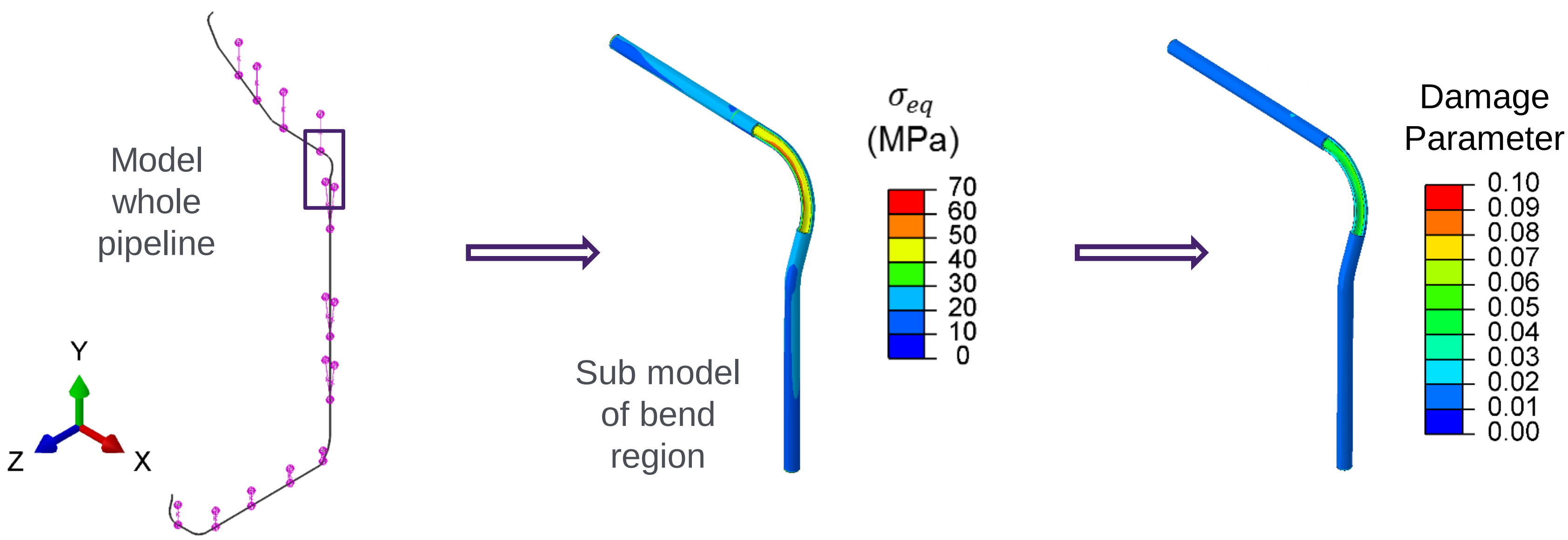




High Temperature Ultrasonic Crack Growth Imaging

Pipeline Life Assessment Tool (PLATO)

- Developing a modelling tool that can be used to predict failure of power plant pipelines
- Estimate pipeline stresses during normal operation and fault conditions
- Automate generation of the FE model, analysis and post-processing to assess accumulation of creep-fatigue damage during service



Sub-Model of Pipe Bend Region

Global Model Deadweight Analysis

Global Model Stress Analysis

Sub-Model Deadweight Analysis

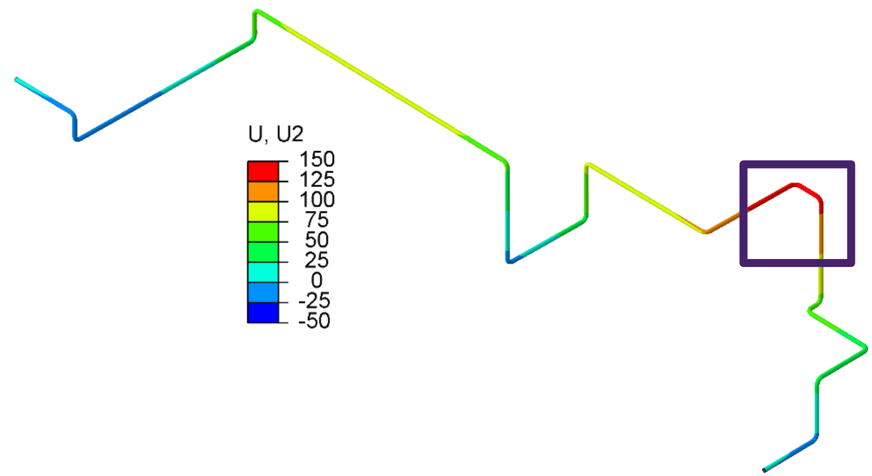
Thermal Model Thermal Analysis

Sub-Model Stress Analysis

Fatigue Assessment

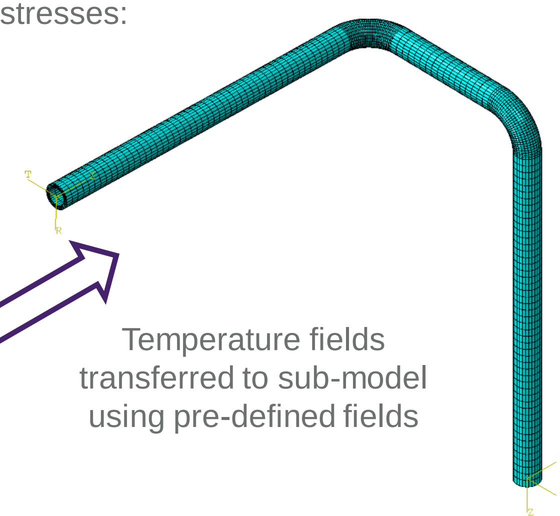
Sub-Model Creep Analysis

Pipeline displacement determined from global model:

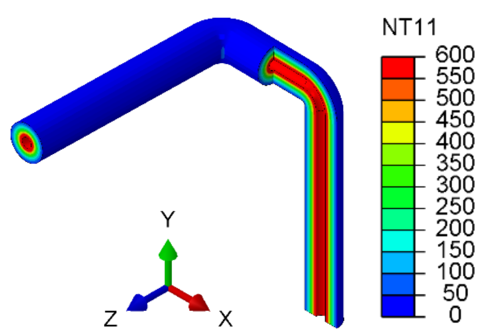


Global model used to define boundary conditions of sub-model

Sub-model to determine pipe stresses:

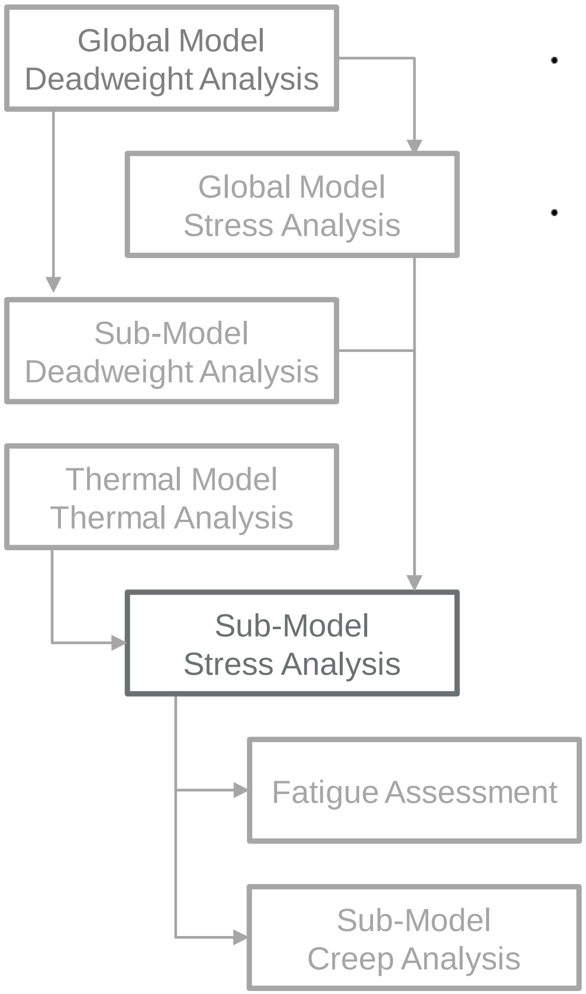


Through thickness temperature variation from thermal model:

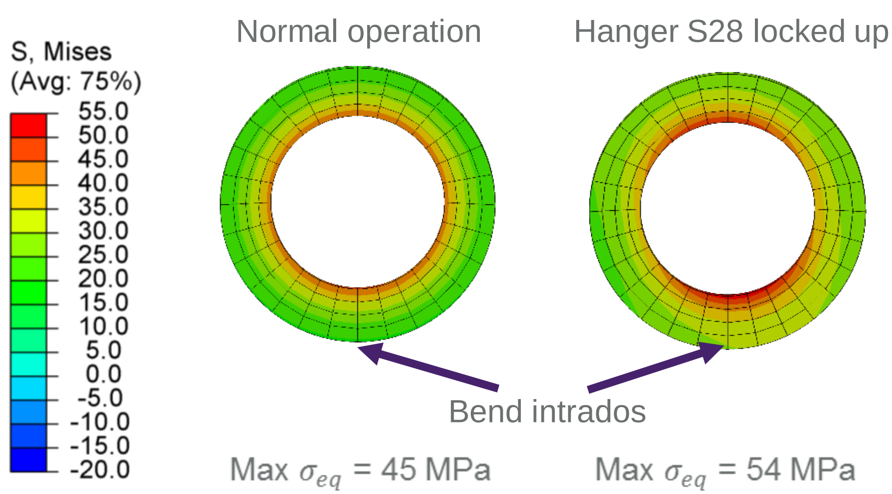


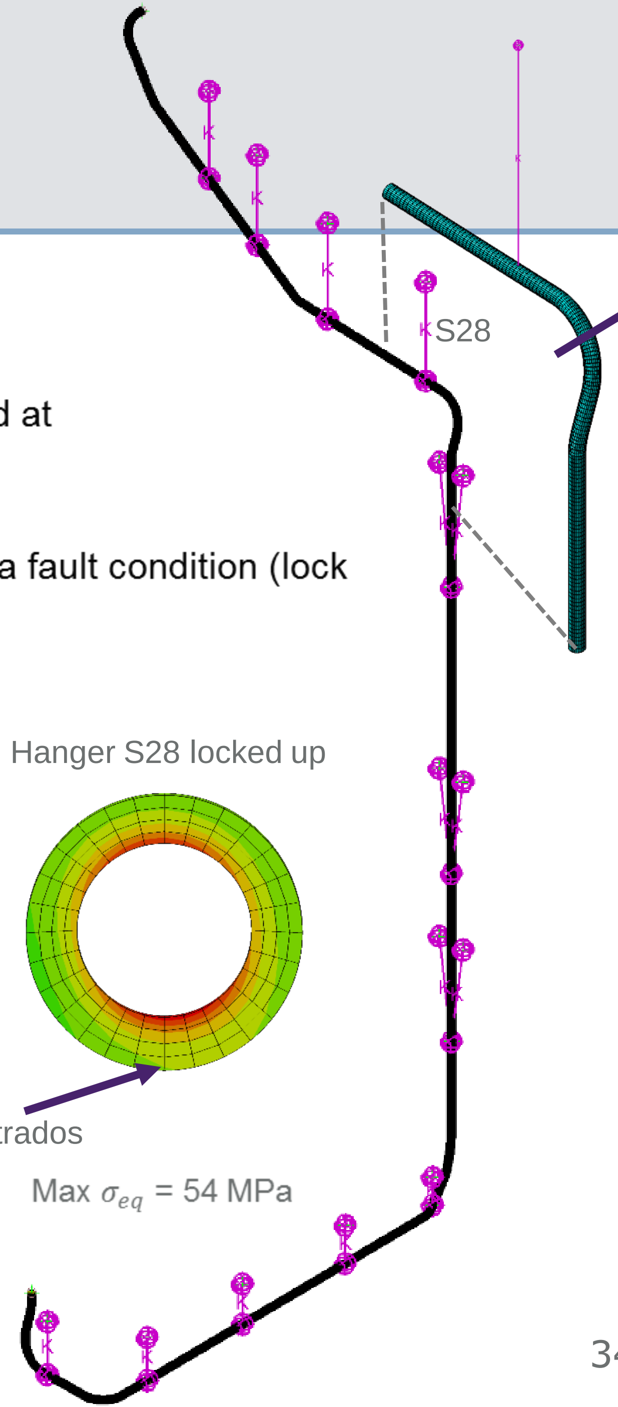
Temperature fields transferred to sub-model using pre-defined fields

Pipe Stresses (1)



- Pipe stresses in bend whilst on load at T = 568°C and P = 16 MPa
- Compare for normal operation and a fault condition (lock up of a nearby hanger)





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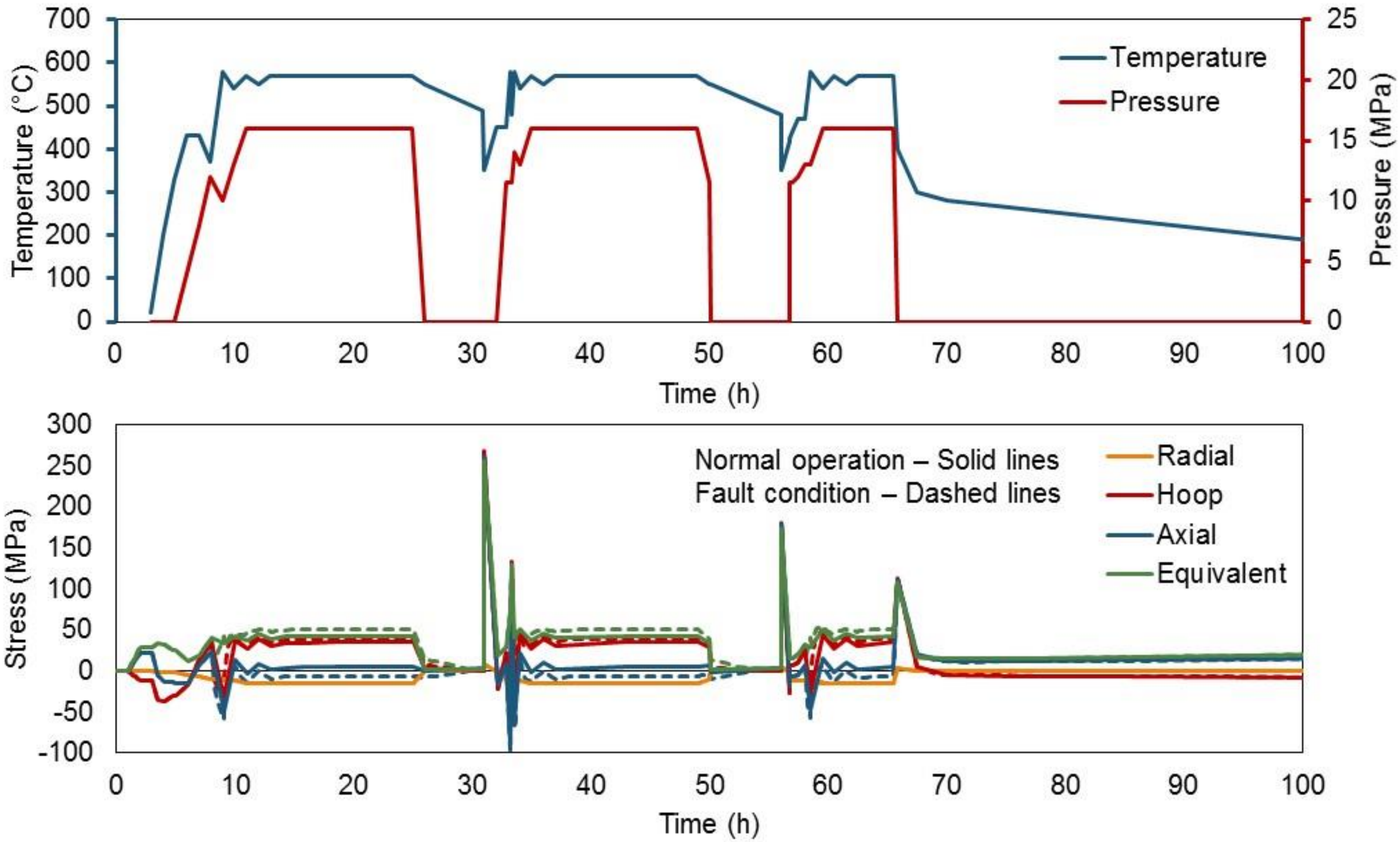
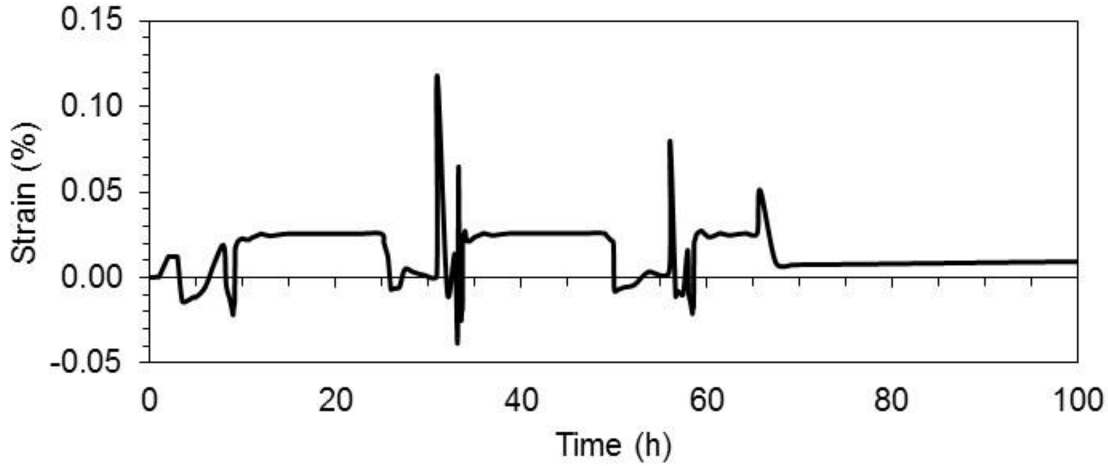
Pipe Stresses (2)



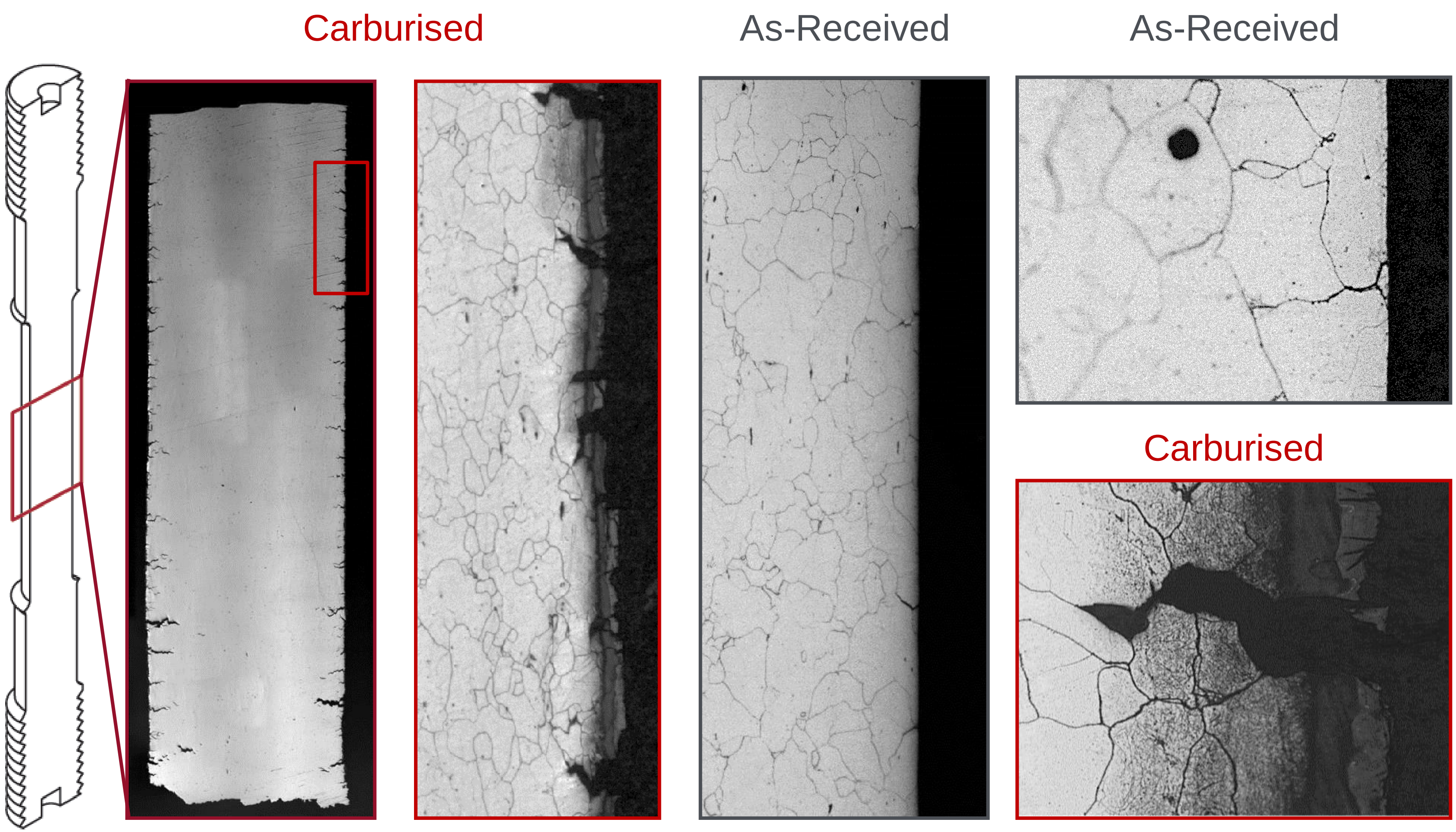
Creep and Fatigue Damage Modelling

- Equivalent strain at bend intrados, inner radius:

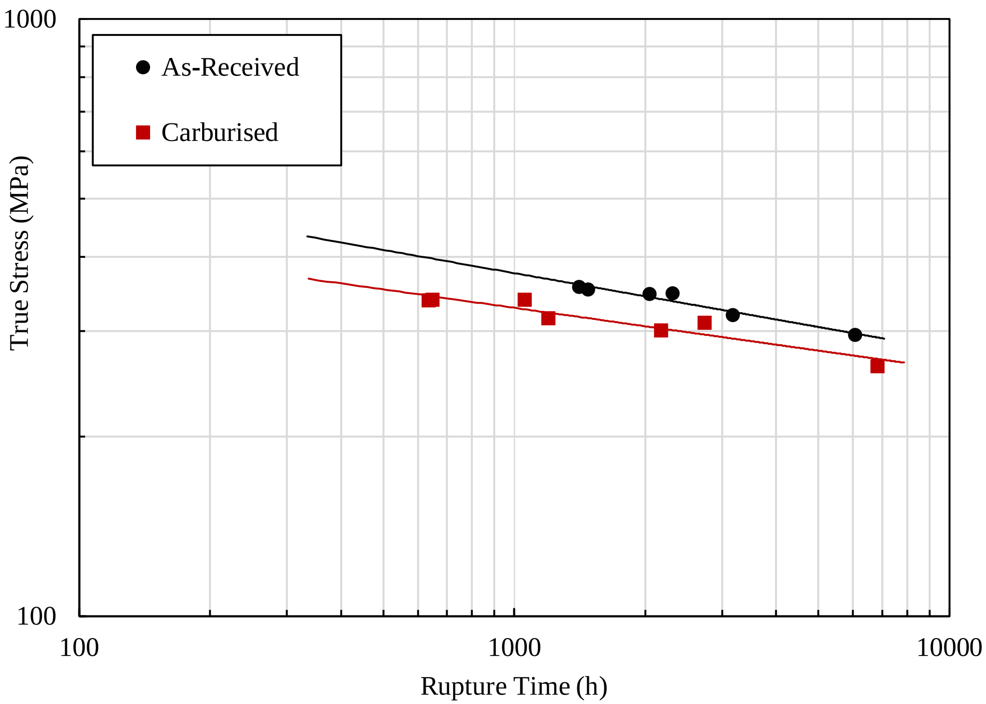


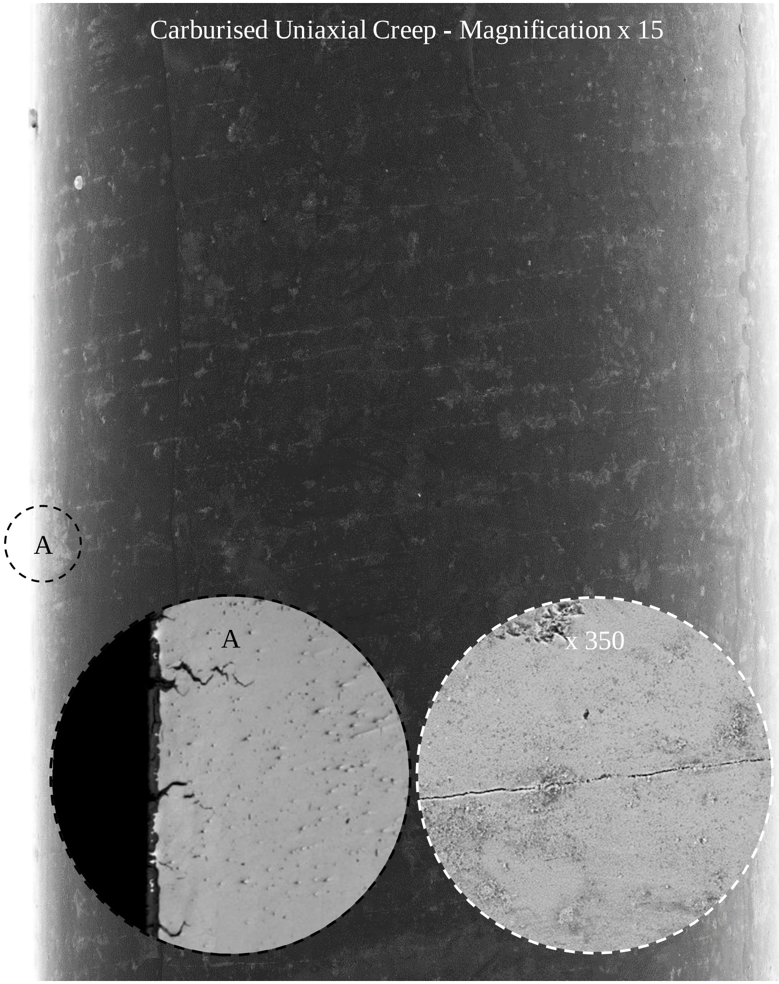
- Fatigue damage, D_f = 8.2 × 10^{-6}, hence > 60,000 cycles to failure
- *Creep damage during 100 hour cycle,* D_c = *9.6 ×* 10^{-6}

Uniaxial Creep Testing – Rupture Life



Carburisation Effects : Creep Strain Rate and Rupture





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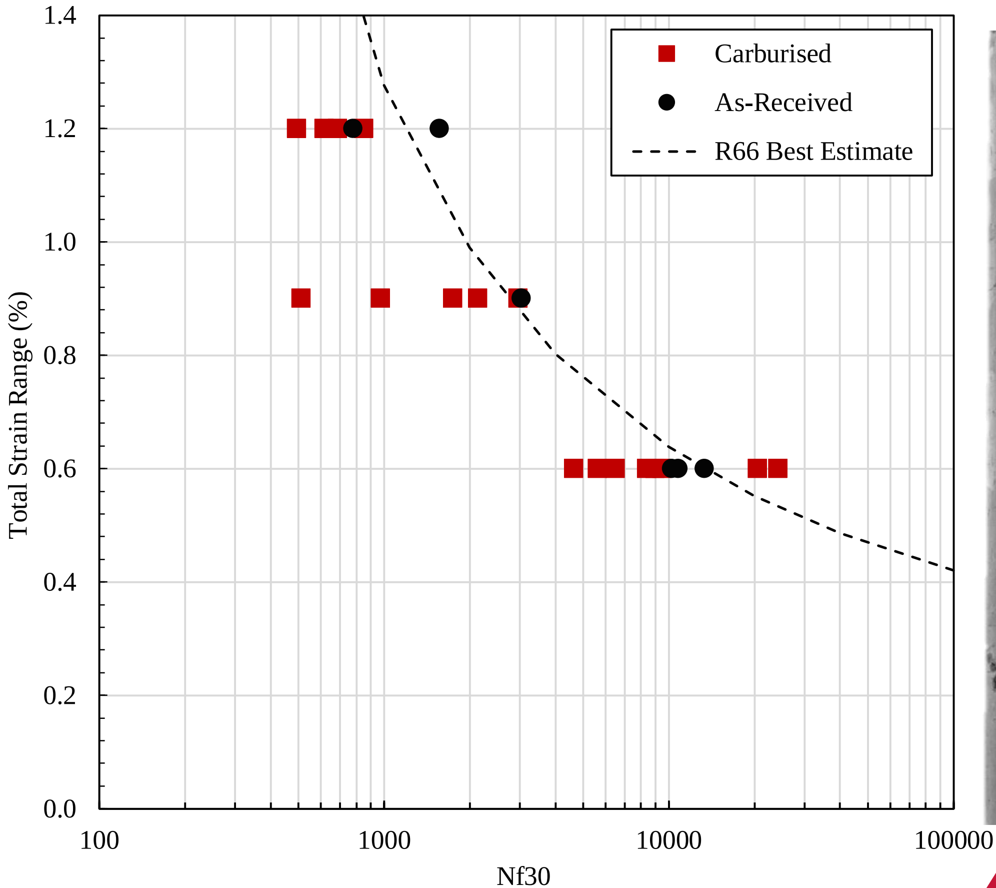
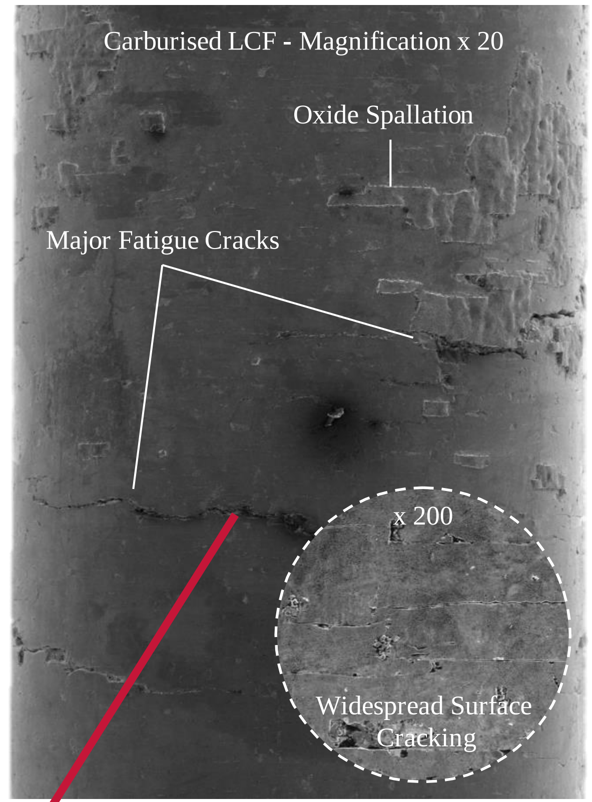
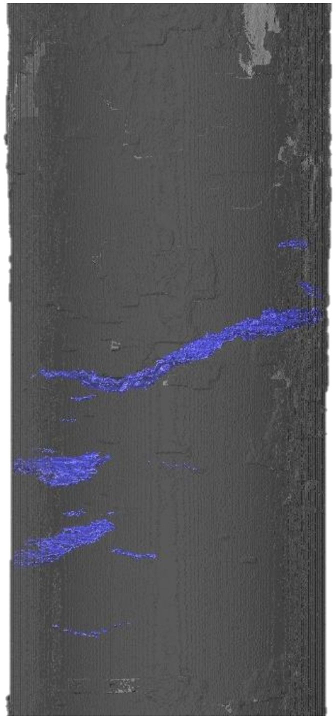
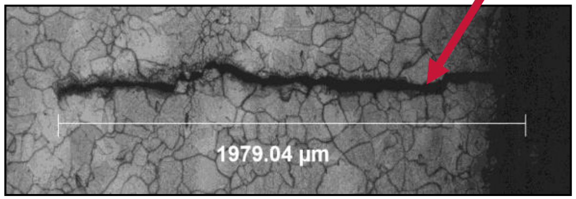
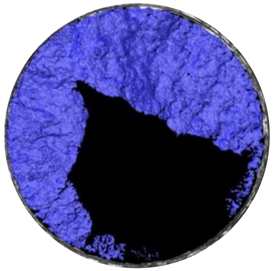
Carburisation – Fatigue Interaction











TOF SIMS Analysis conducted by the University of Manchester

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Summary

- Significant experience in high temperature plant operation
- New challenges due to flexible operation
  - Creep-fatigue interaction effects can be significant and require detailed understanding
- DIC and Low Freq. ACPD Technique provide important information on creep strain development in weldments
- Low Freq. ACPD technique provides more accurate measurement of CCI
- Wedge loaded samples are effective in determining influence of residual stress on CCI and CCG
- CCG can be accurately predicted using FE models
- Plant monitoring tools being developed to monitor creep strain and image crack growth
- FE based Pipeline Life Assessment Tool being developed
- Significant challenges remain in understanding the role of environment effects on creep and creep-fatigue