THERMO-MECHANICAL FATIGUE CRACK GROWTH IN ADVANCED AEROSPACE ALLOYS

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Prifysgol Abertawe
Swansea University

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Introduction

Swansea University Bay Campus

DevTMF. This project has received funding from the *European Union's Horizon 2020 research and innovation programme* and Joint Undertaking Clean Sky 2 under grant agreement No 686600.

DevTMF Partners

Swansea University, Wales.
Testing and analysis

Nottingham University, England.
Modelling and round robin testing

Linkoping University, Sweden.
Modelling and round robin testing

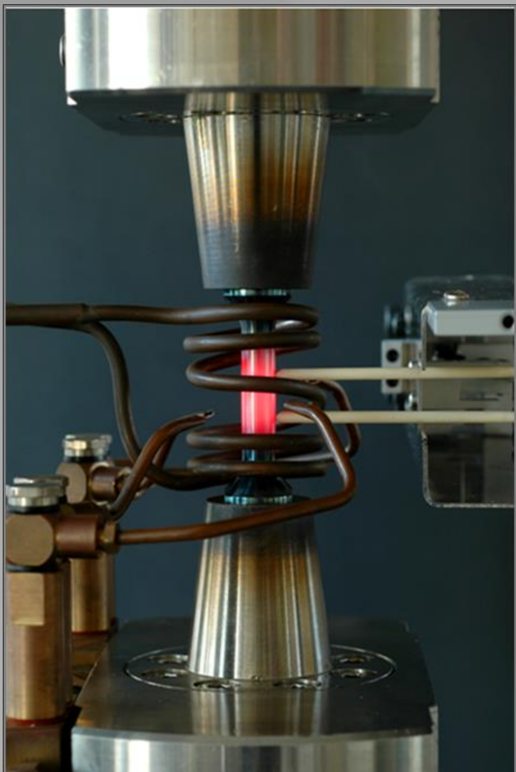
Rolls-Royce plc, UK.
Material and technical support

Introduction

- Swansea University Background in TMF
- TMF total life testing
- TMFCG Test Development
- Crack tip heating investigations
- TMFCG Test Results
- Phase angle effects
- Damage mechanisms

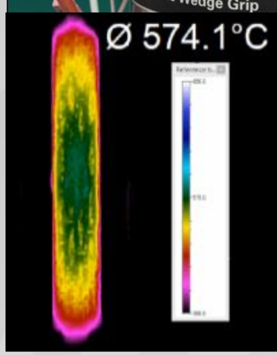
Background in TMF

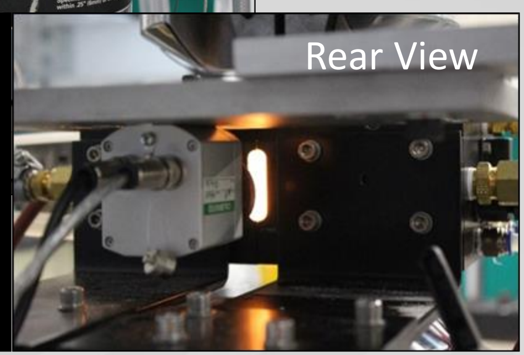
Strain Control - Induction



Pyrometer

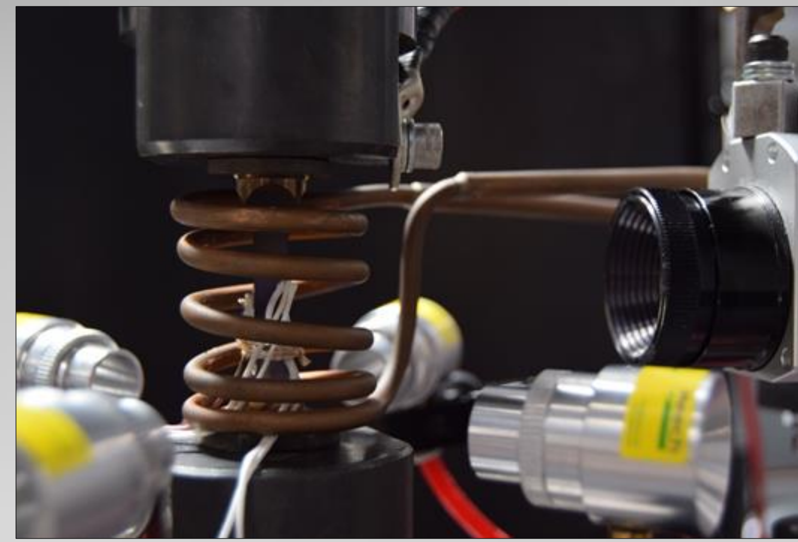
Non Metallic – Lamp Furnace





Thermography

Fatigue Crack Propagation – Induction

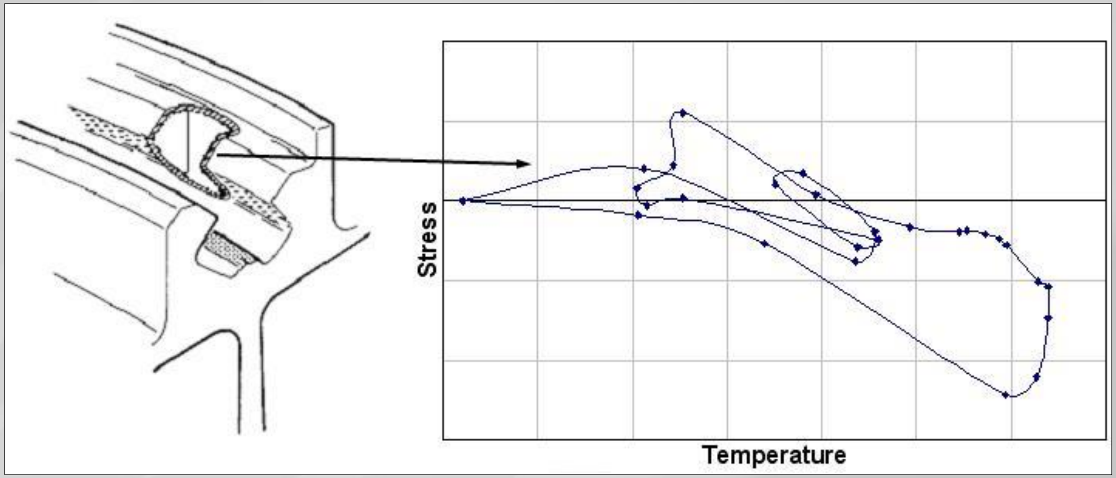


Thermocouple

- *ASTM E2368-10. Strain Controlled TMF Testing, 2010.*
- *ISO 12111:2011. Strain-controlled TMF Testing, 2011.*
- *BAM. CoP Force-Controlled TMF Testing, 2015.*

Industrial Motivation

- Increased turbine entry temperatures
- Thinner disc rims and advanced cooling systems leading to larger thermal gradients
- Complex loading regimes within the gas turbine leading to diverse phasing between temperature and strain
- Extrapolation of isothermal fatigue (IF) results to incorporate these effects show limited success
- Generation of TMF data is required to allow the development of lifing methodologies under TMF loading

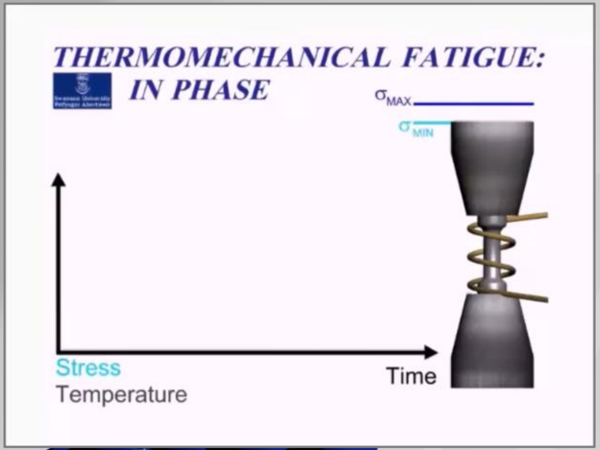


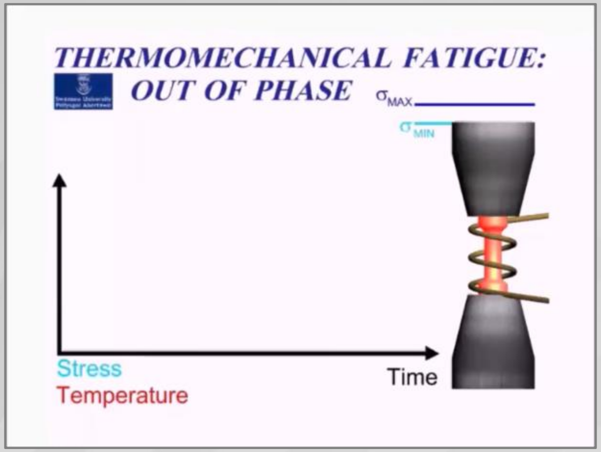
Thermo-Mechanical Fatigue (TMF)

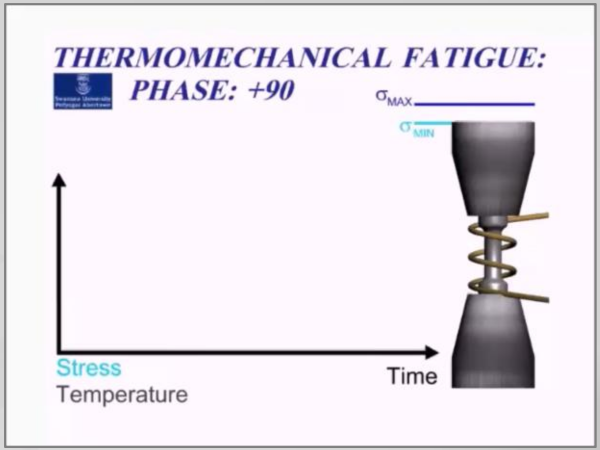
- Diverse mechanisms are involved, Primarily . . .

  Fatigue   Creep   Oxidation

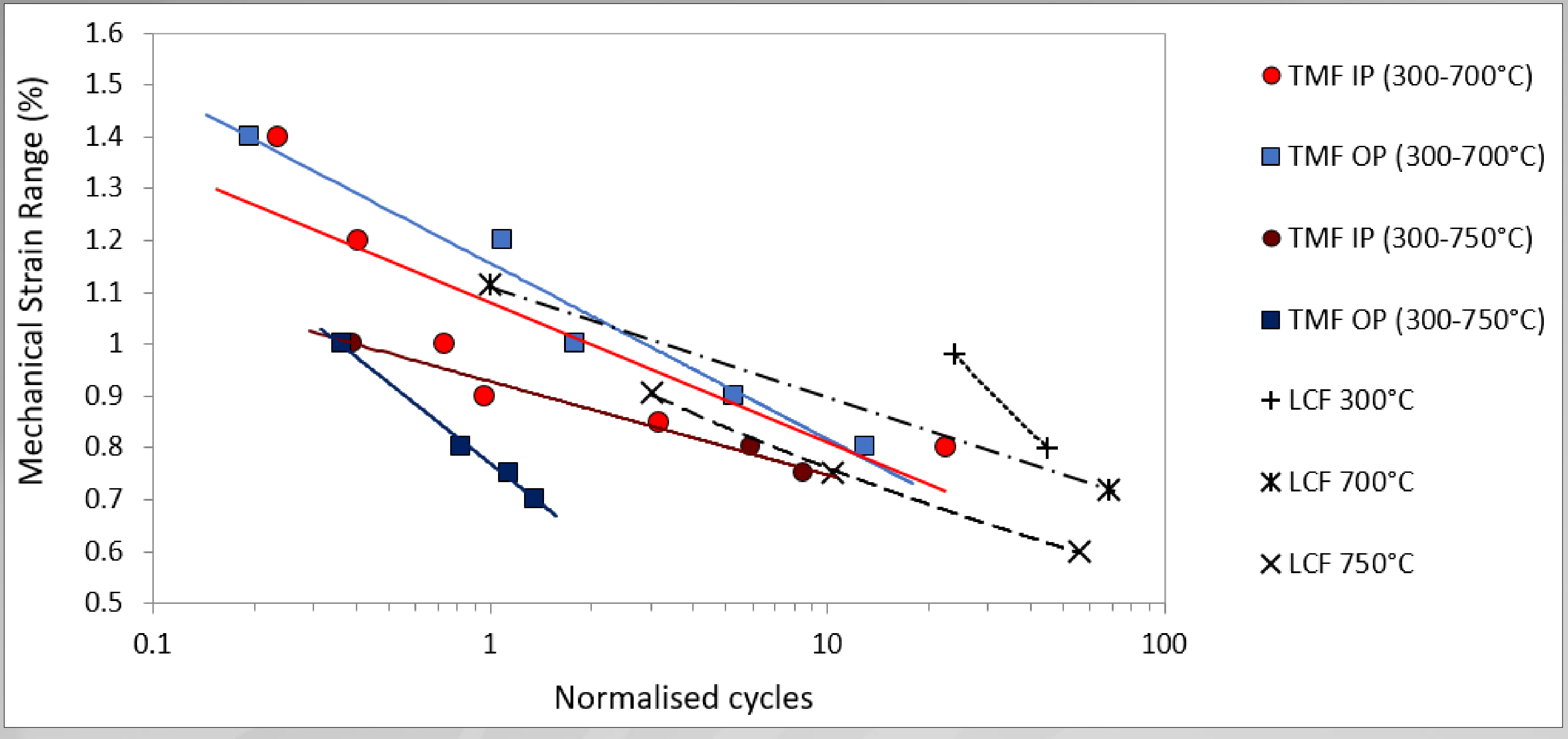
- TMF loading can be more damaging than isothermal fatigue at an equivalent T_{max}
- Complex interaction within diverse *phase angles* between peak temperature and strain range





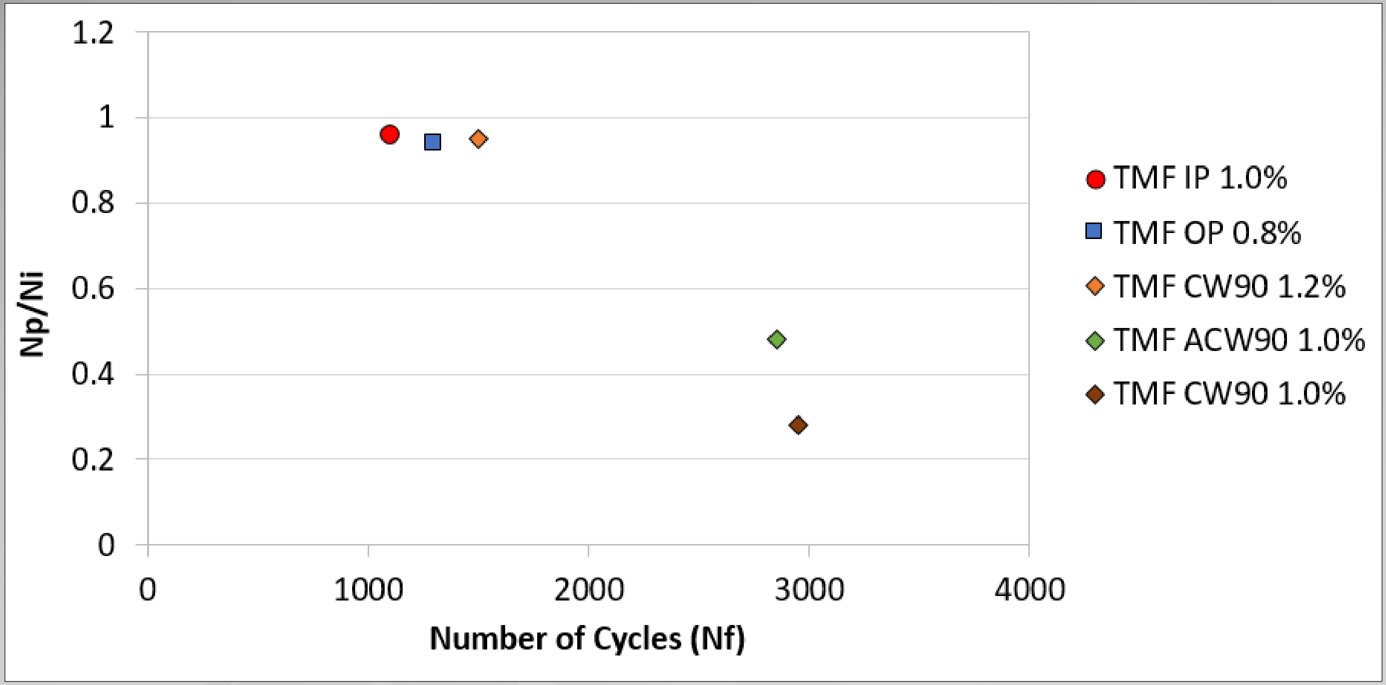


Effect of peak temperature



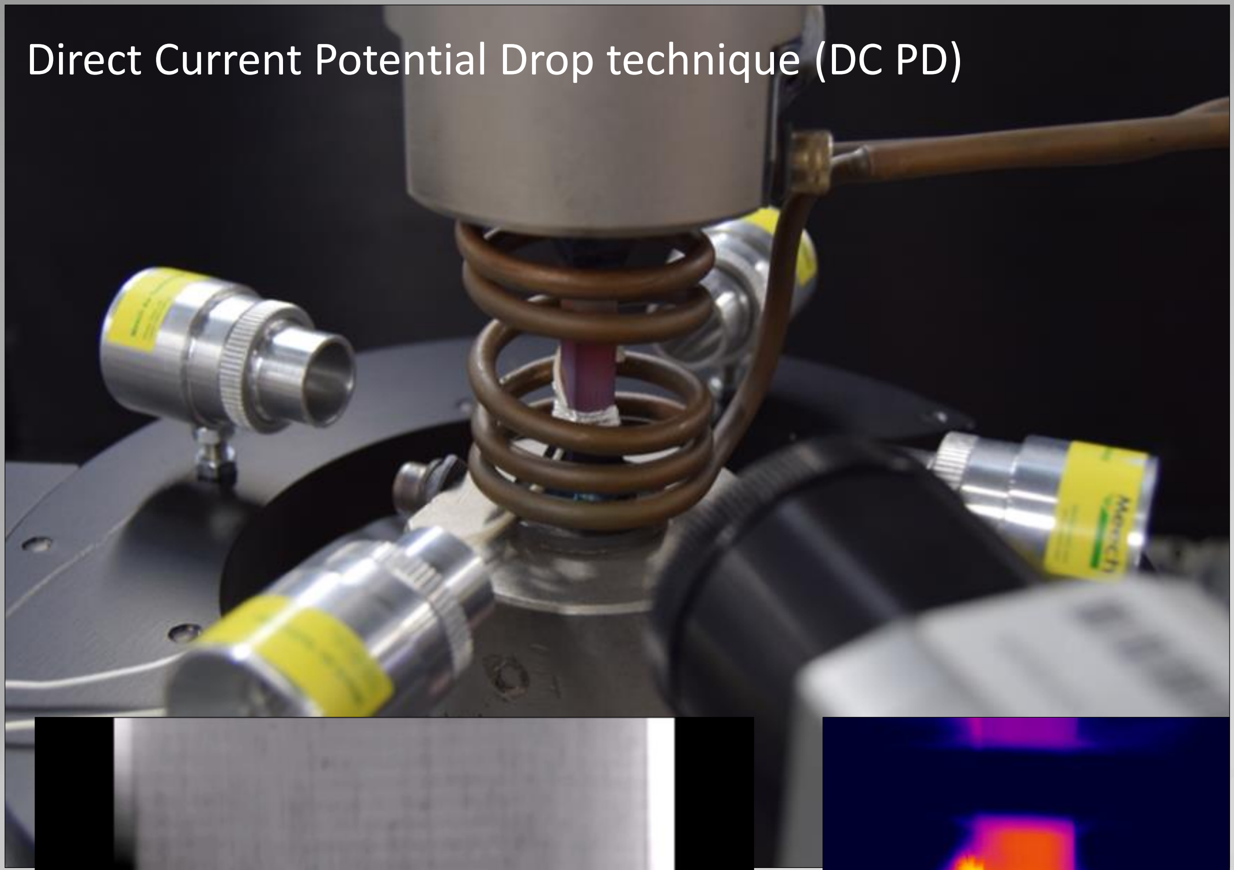
- At 750°C OP data shows a significant decrease in TMF life.
- Likely to be due to increased oxidation effects
- TMF lives consistently shorter than isothermal fatigue lives.

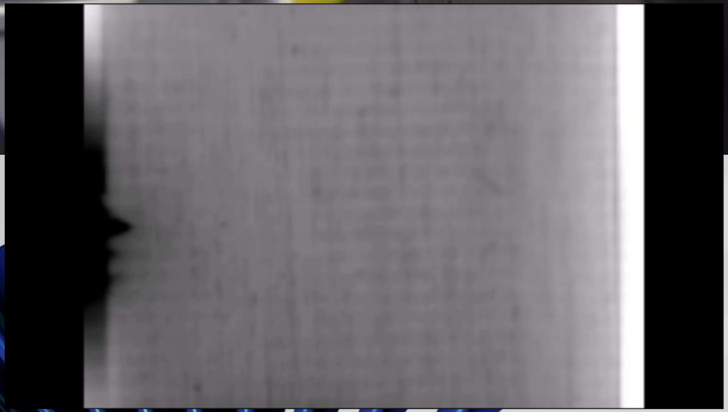
Crack propagation

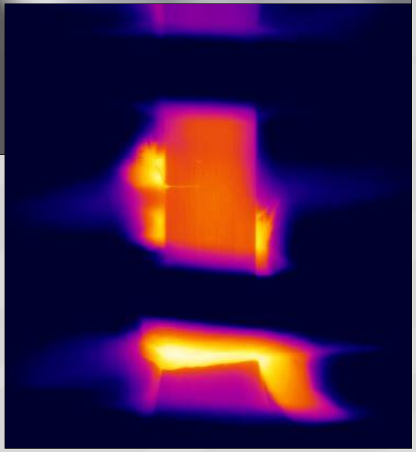


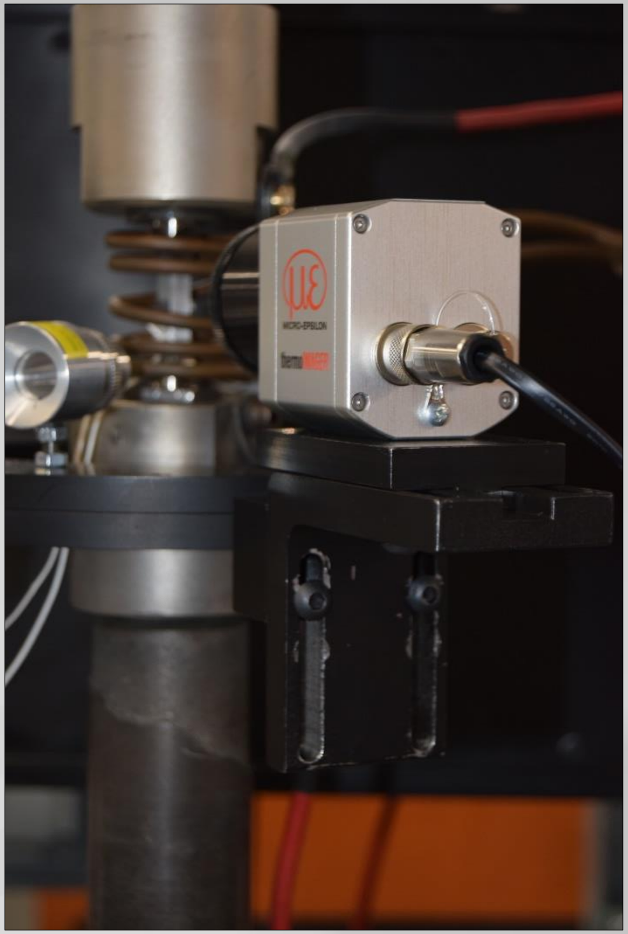
- For fatigue lives that are less than 5000 cycles it is not appropriate to consider only crack initiation as the dominant factor in fatigue life.

TMFCG Test Development



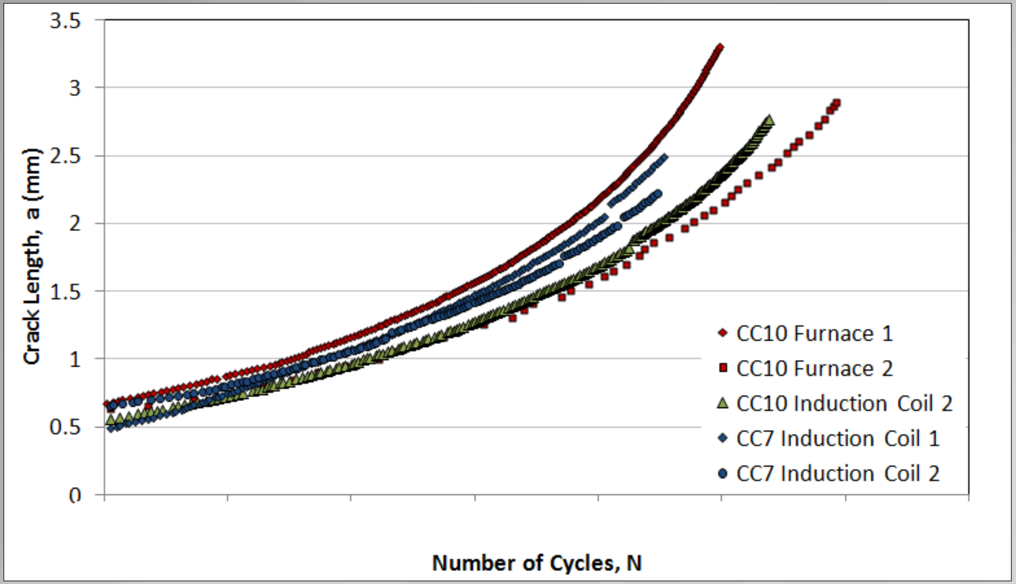




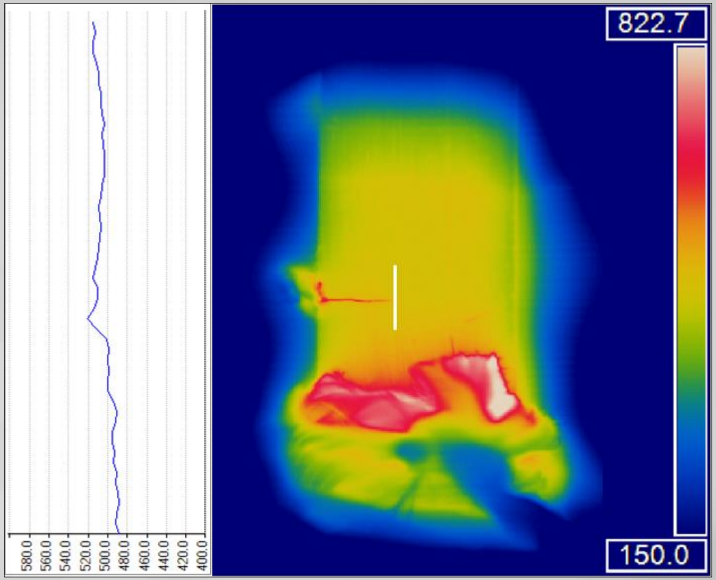


Crack Tip Heating Investigations

Waspaloy crack length vs. number of cycles: furnace and induction coil comparisons at 650°C, 450MPa and R=0.1.

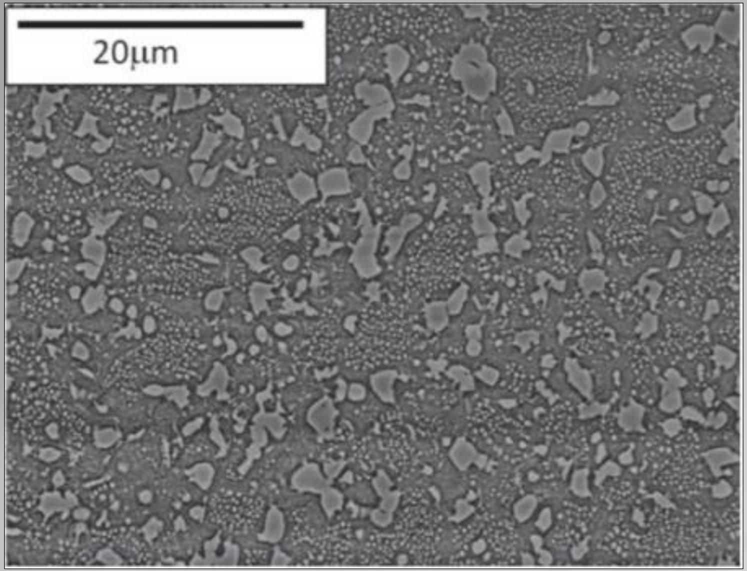


Ti6246 with crack plane at 500°C. Profile indicates no effect of crack tip heating.



Fine and Coarse grained RR1000

Fine grained RR1000



Coarse grained RR1000

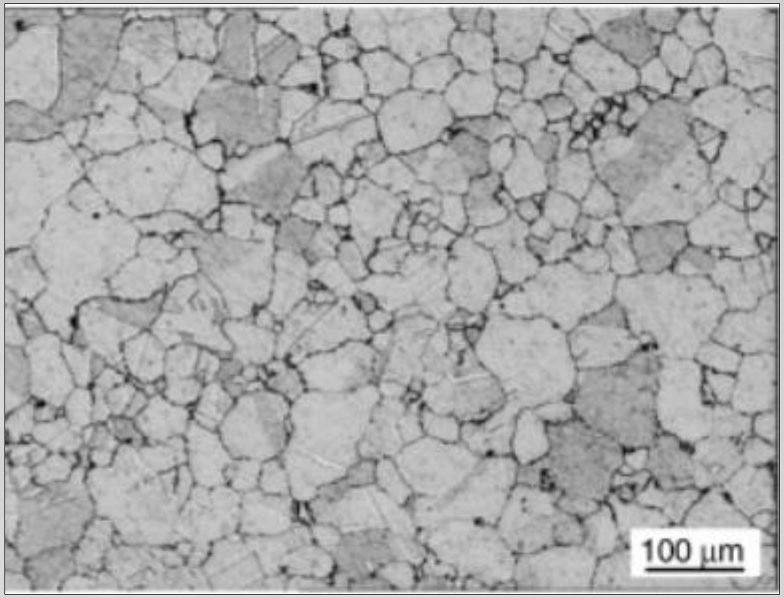
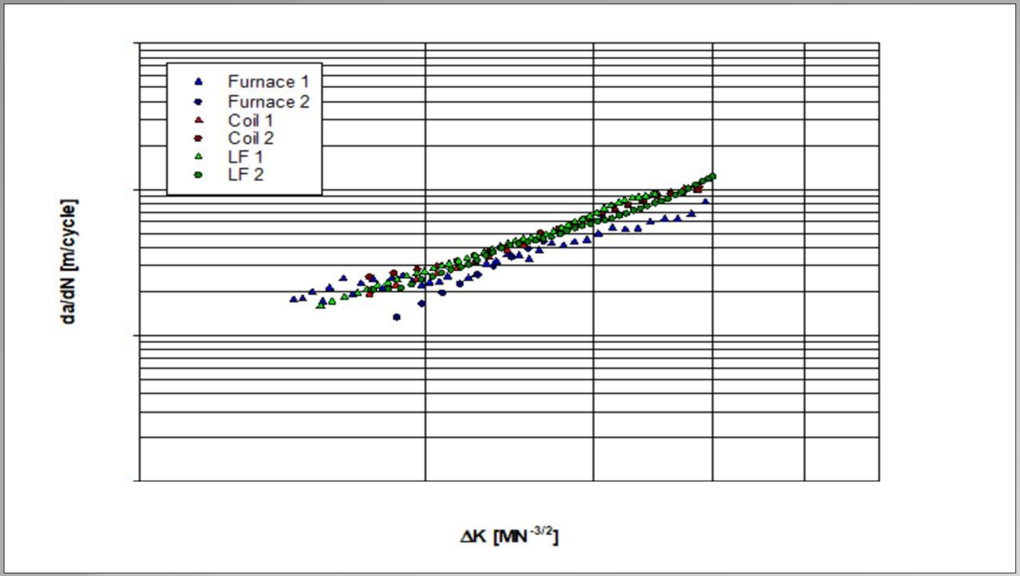


Image courtesy of Li et al, Effects of microstructure on high temperature dwell fatigue crack growth in a coarse grain PM nickel based superalloy, Acta Materialia, Volume 90, 15 May 2015, Pages 355-369

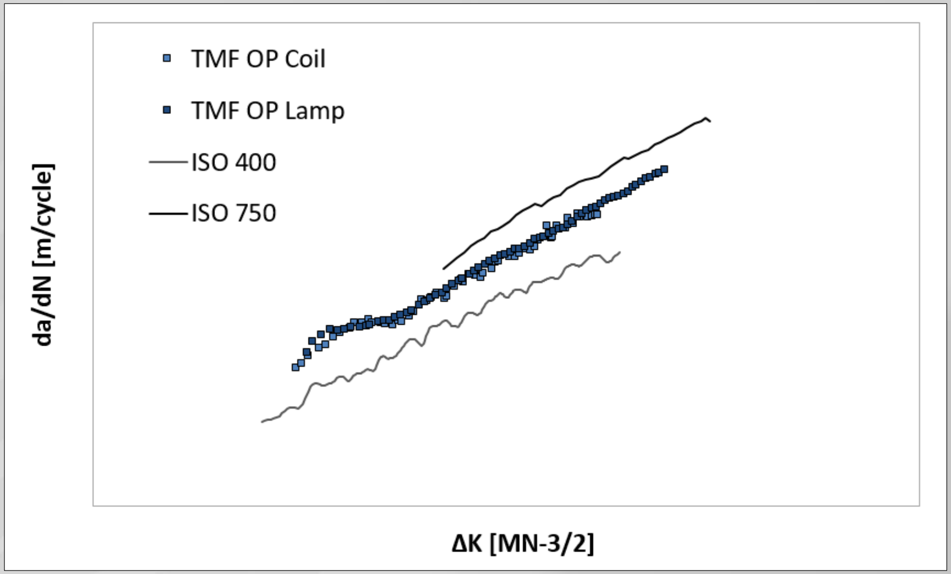
Effect of Lamp Furnace vs Induction Coil

Isothermal



- Ti-6246 corner crack specimens tested at the same isothermal conditions, using three different heating methods
- Crack growth rates are consistent across heating methods

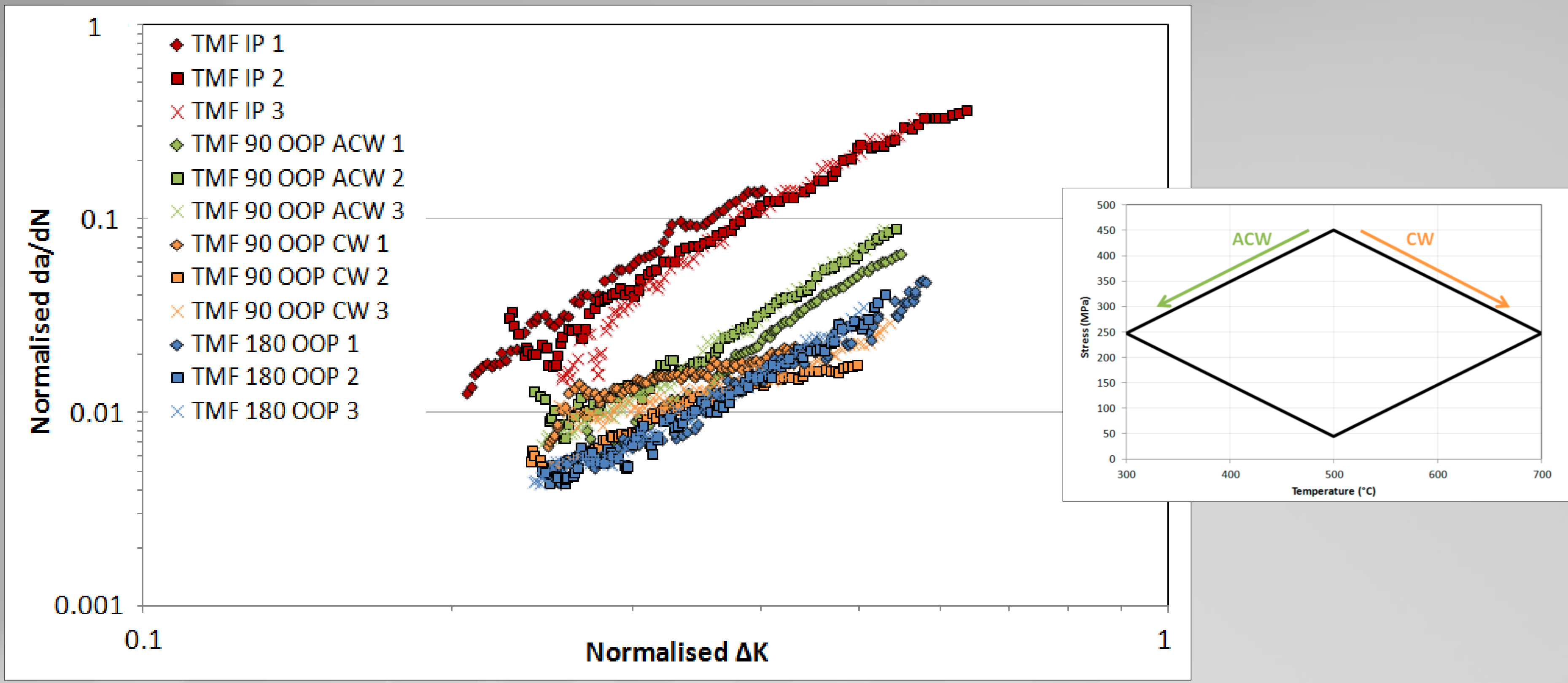
Out of Phase TMF



- For out of phase tests no evidence seen of variability in crack growth rate based on method
- Similar results in IP tests but more variability in growth rates overall

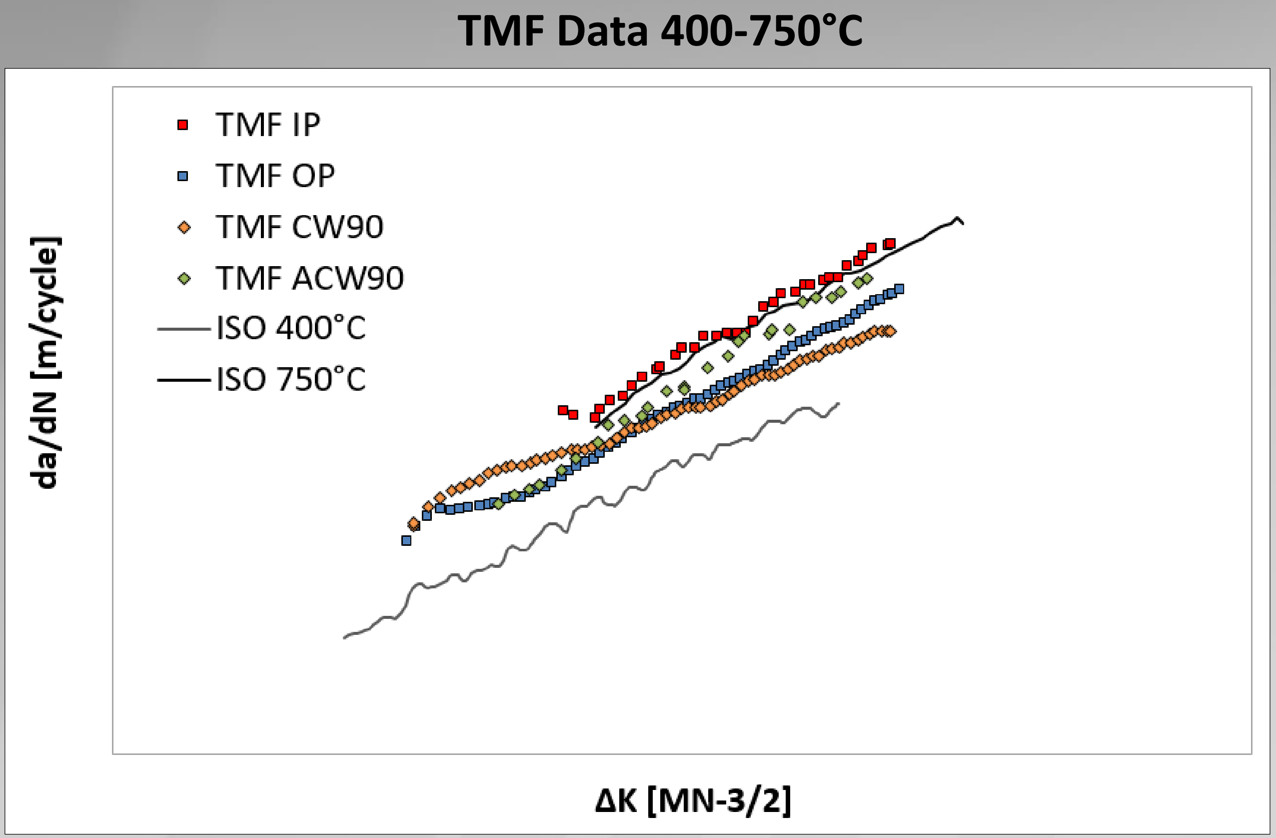
Fine Grained RR1000 TMF CP

TMF Data 300-700°C



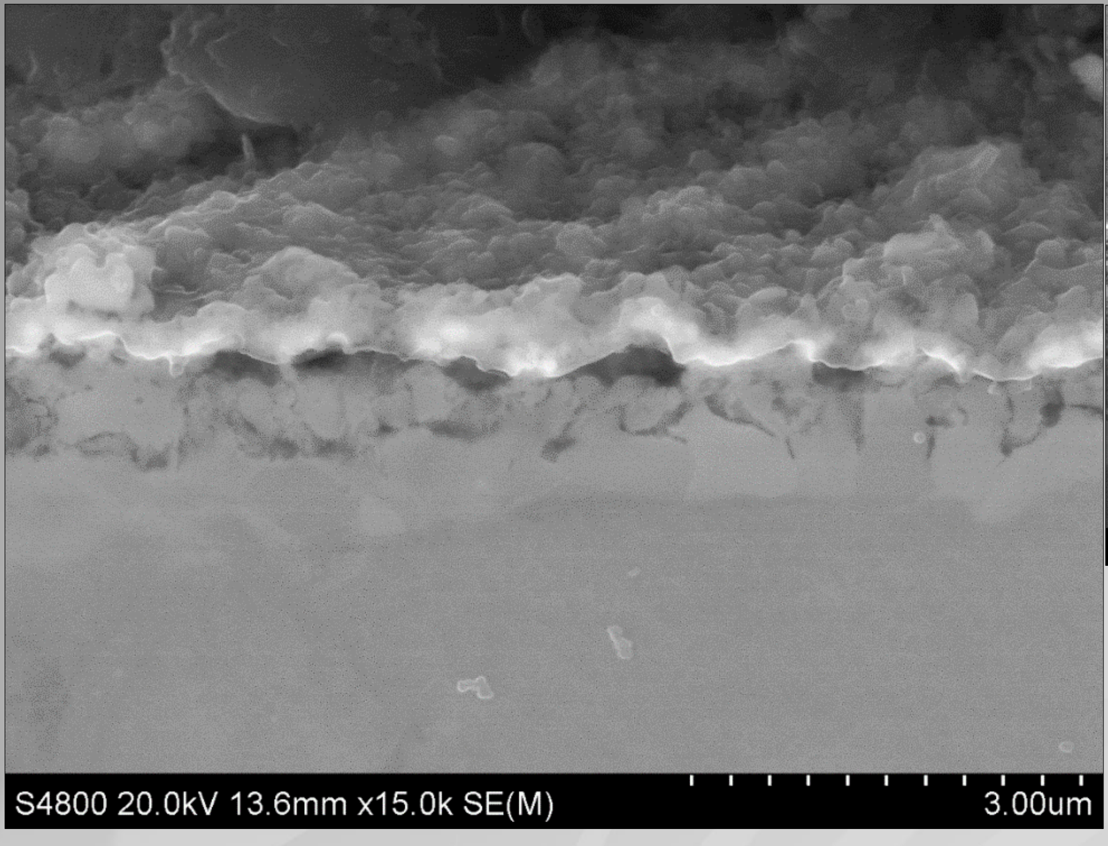
- Strong dependence on phase angle
- Rates tend to approximate temperature at which peak stress occurs

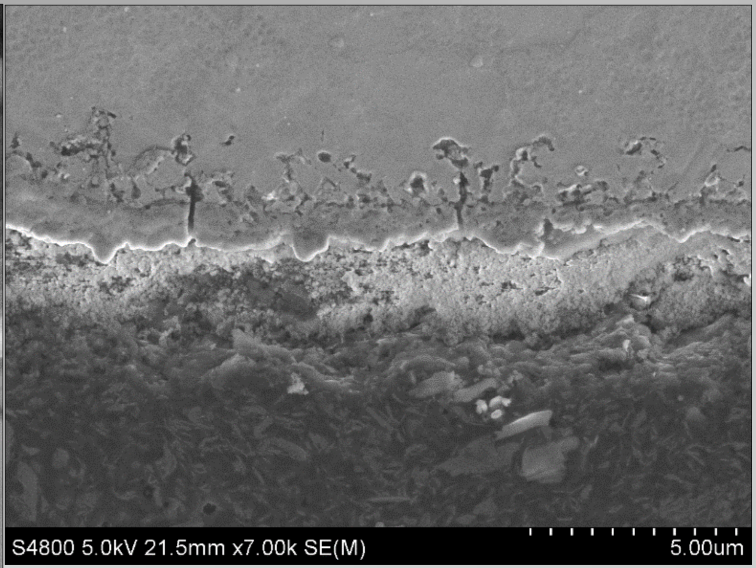
Coarse Grained RR1000 TMF CP



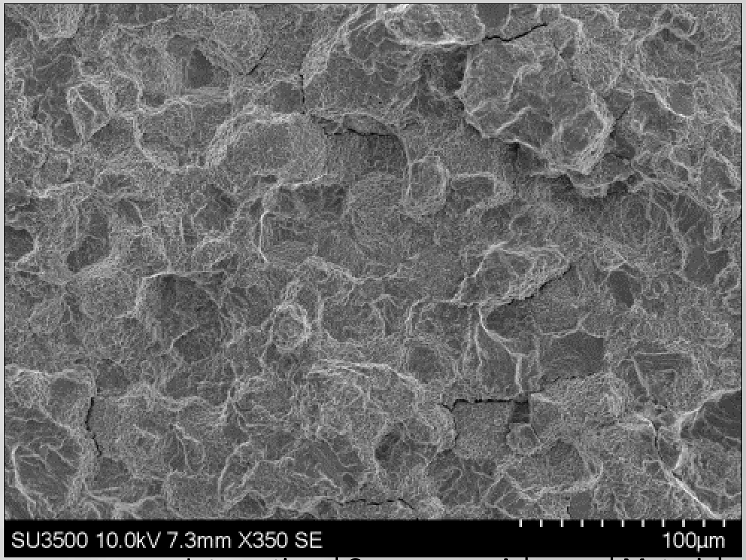
- Phase angle effects are significant in the alloy
- TMF crack growth rates exceed isothermal rates at peak temperature
- Cycle direction is also important

Oxidation damage

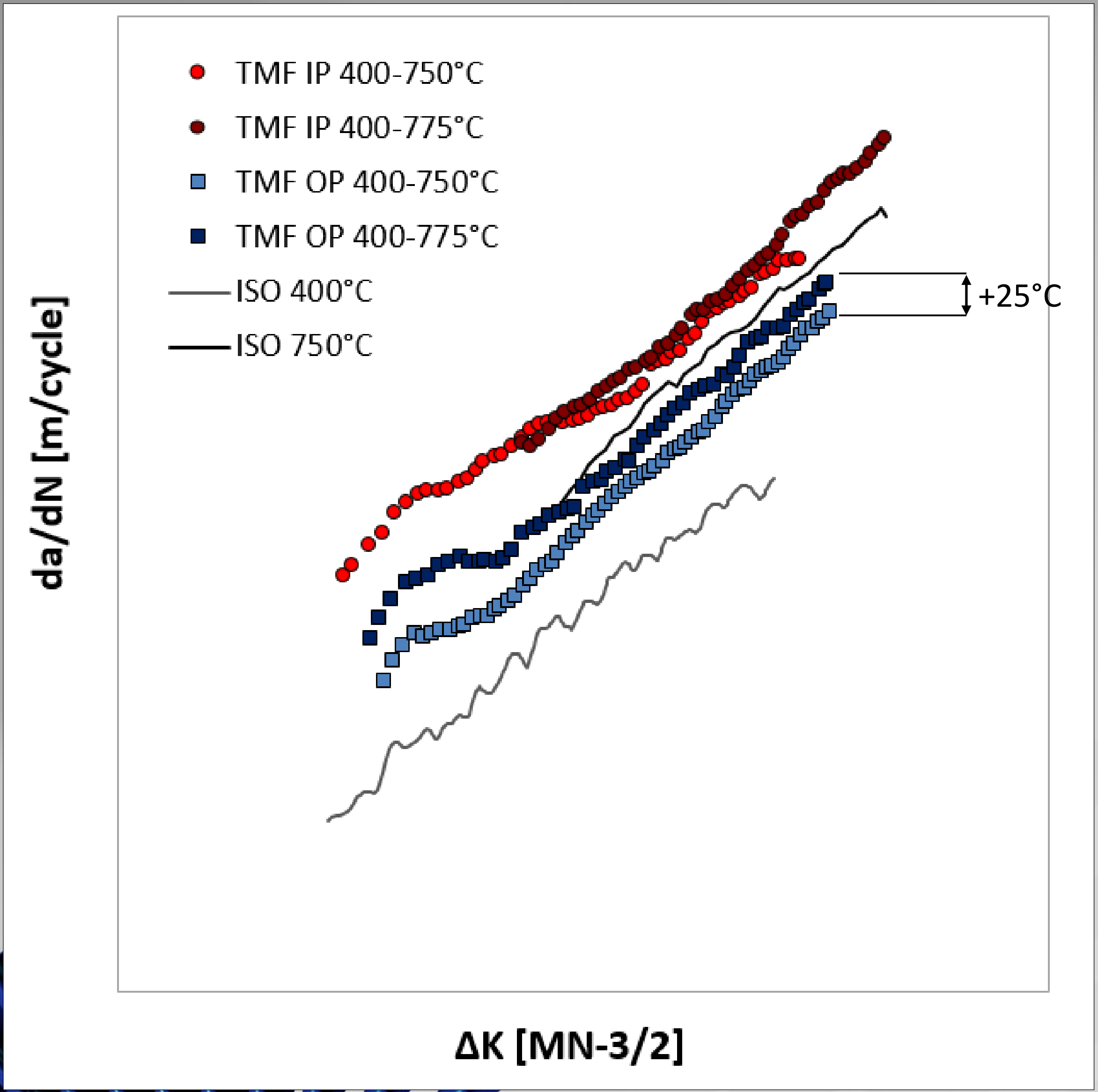




- TMF In-Phase fracture surface



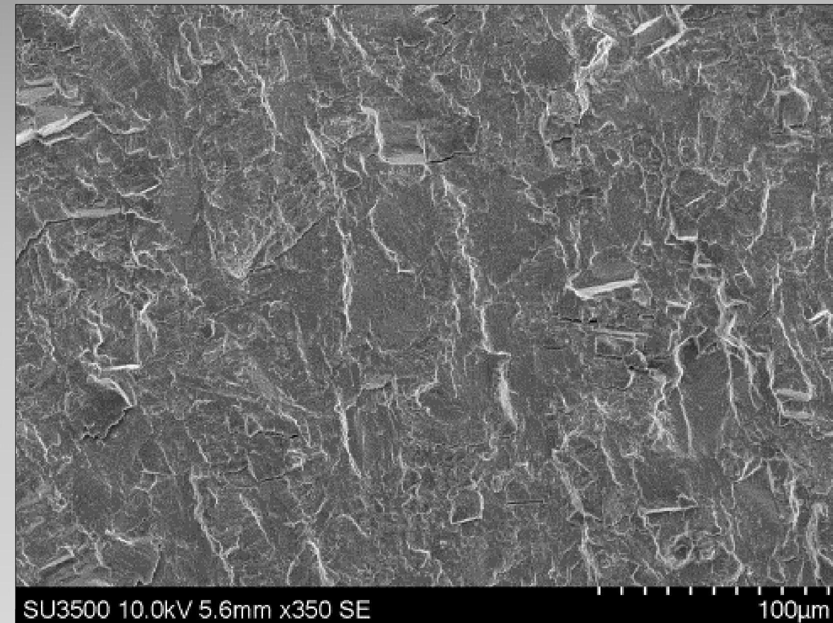
Effects of Peak Temperature

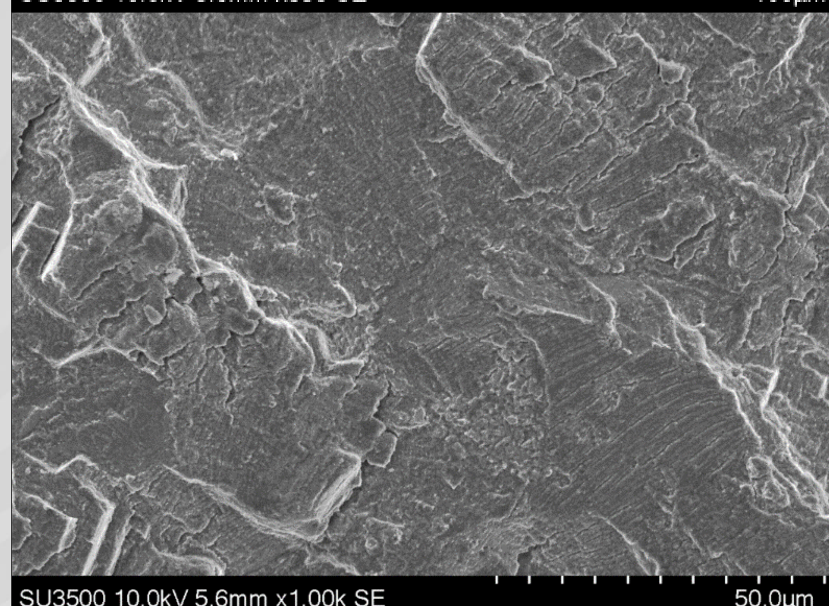


- TMF CG RR1000
- In phase tests show faster rates than equivalent isothermal tests
- Dependent on cycle time
- In Out of Phase tests increased Tmax influencing TMF CP rates

Mechanisms of crack growth in OP tests

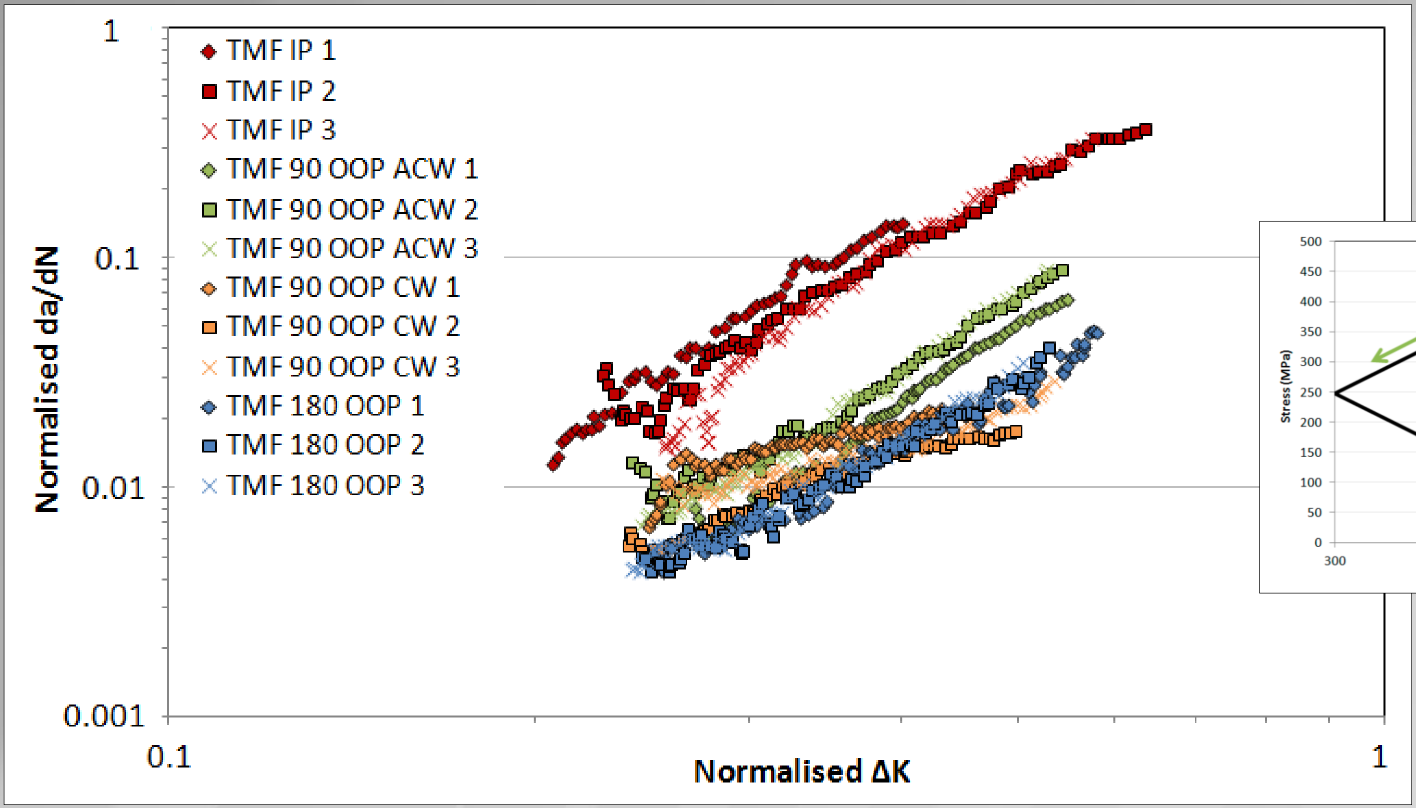
- Transgranular failure indicates minimal effect of oxidation
- Acceleration with increased peak temperature must be due to alternative mechanism
- Compressive stresses at crack tip relieved during high temperature portion of cycle?
- Increased temperature – increased relaxation
- More relaxation leads to greater tensile strain and higher increment of crack growth?

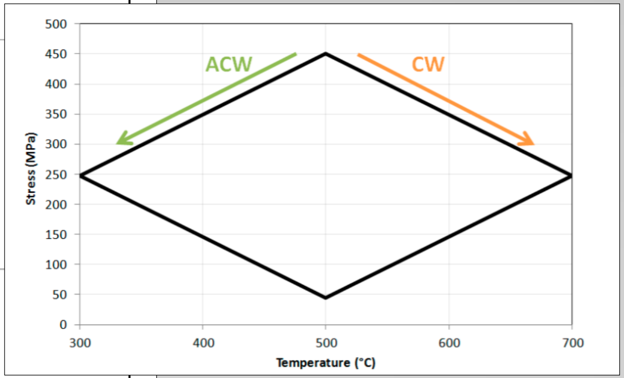




Fine Grained RR1000 TMF CP

TMF Data 300-700°C

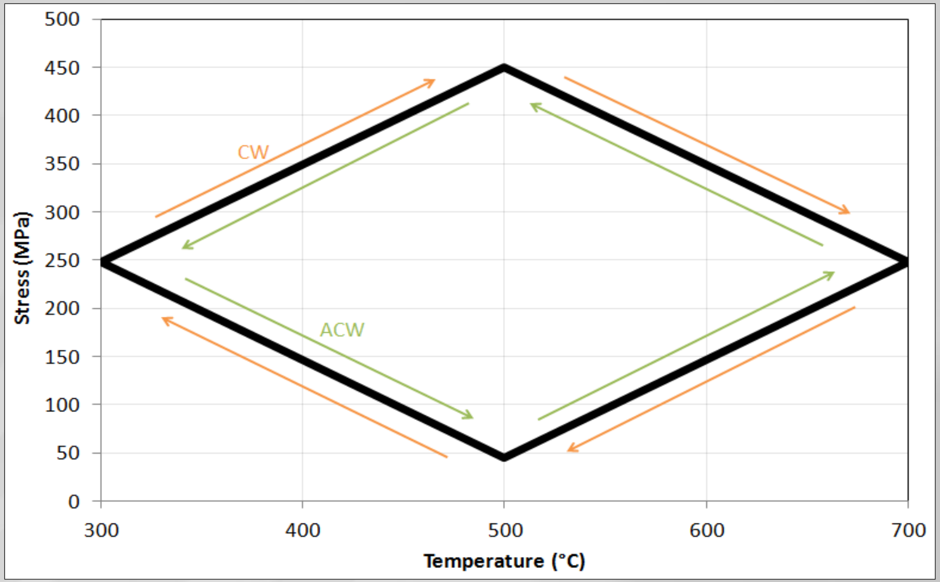




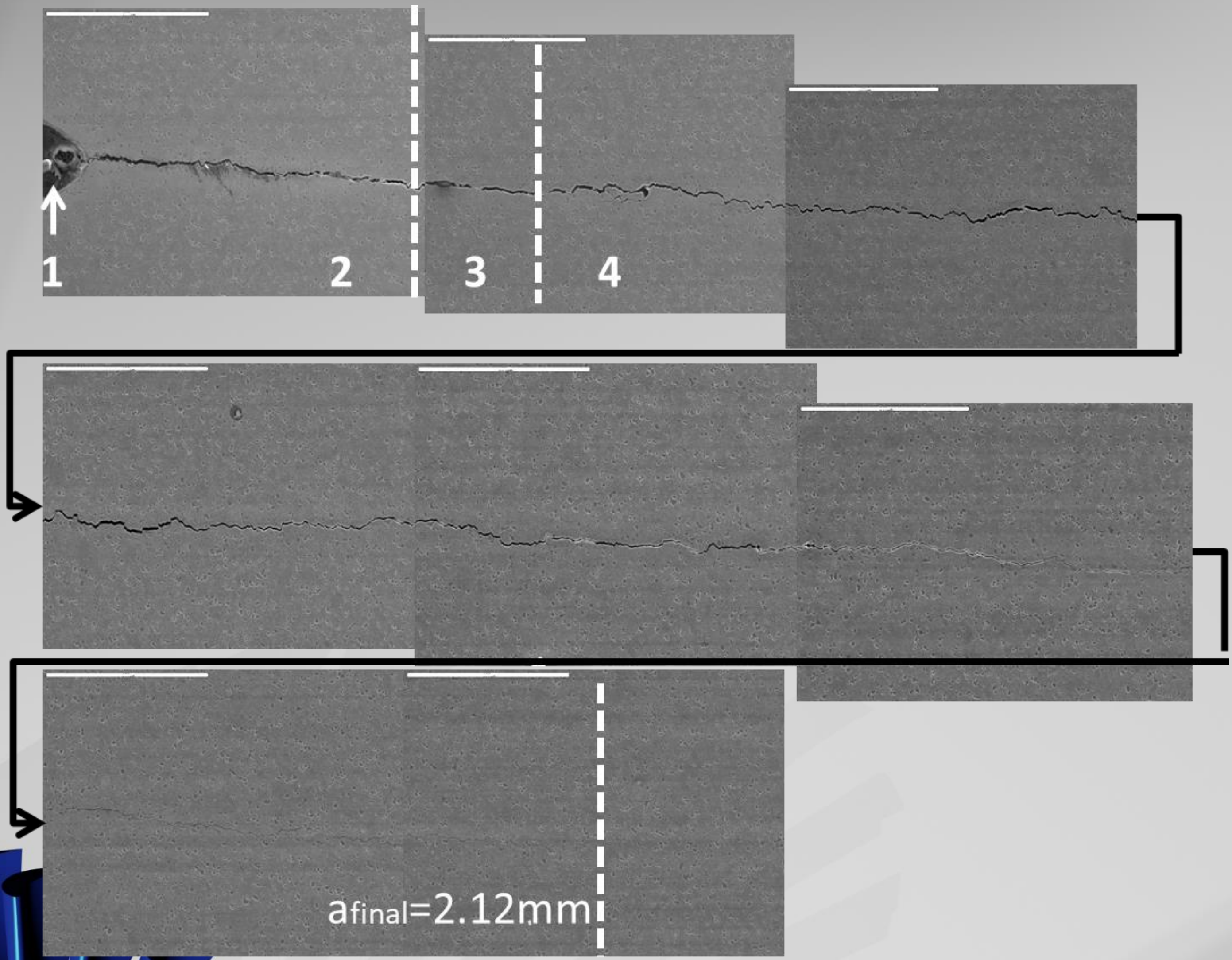
- Strong dependence on phase angle
- Rates tend to approximate temperature at which peak stress occurs

Results: 90° OOP CW vs. ACW theory

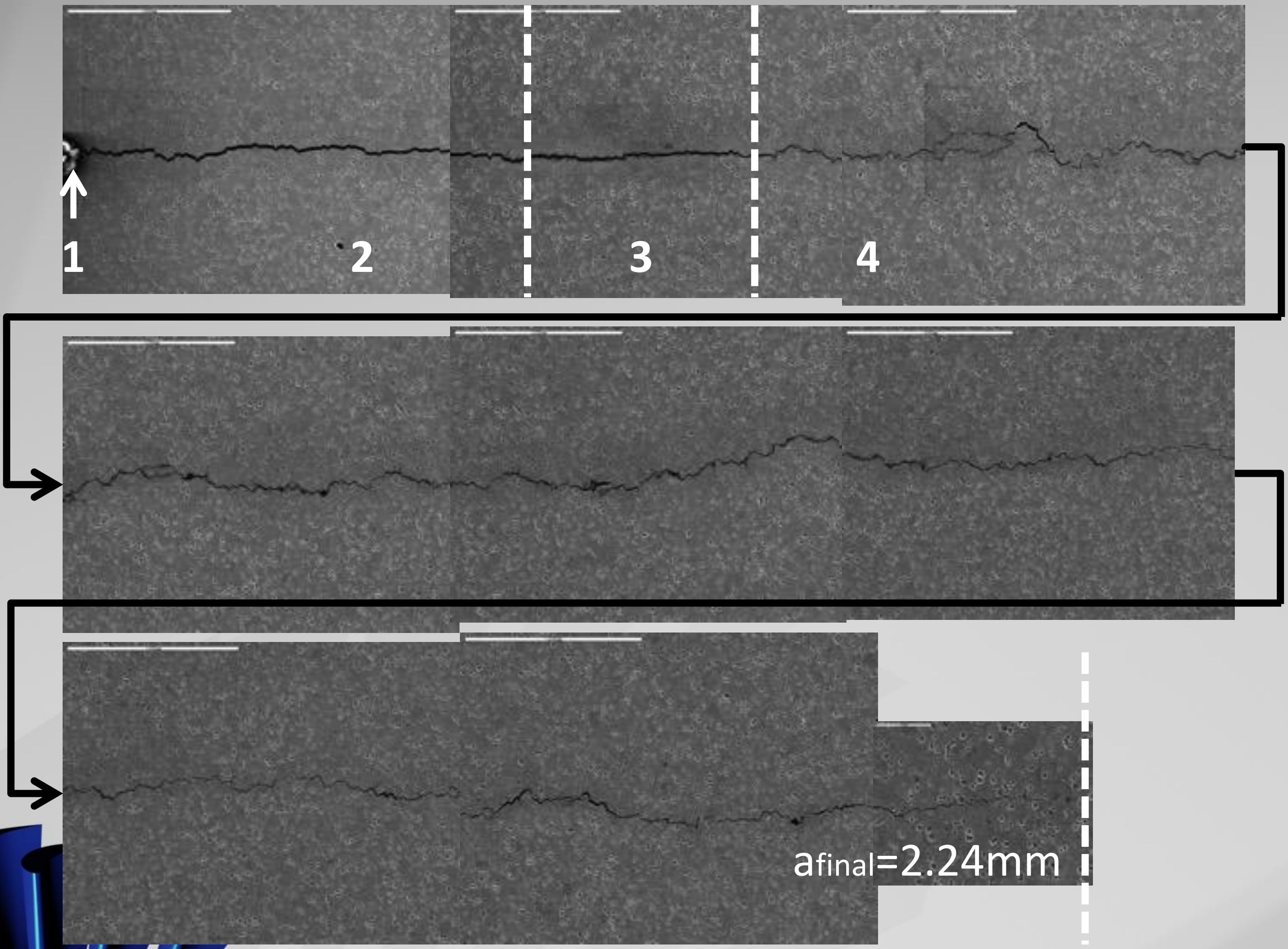
- **CW:**
  - Unloaded at high temperatures which oxidises crack tip because there is no crack growth so oxides reach a few grains beyond tip
  - Loads the oxidised crack tip so crack grows along oxidised grain boundaries causing more of an intergranular failure
- **ACW:**
  - Unloaded at low temperatures so there is no/less oxidation
  - Loaded at higher temperatures so creating new surfaces and preventing oxidation of crack tip causing dynamic transgranular failure i.e. Crack growth faster than oxidation process
- **Theory to the test:**
  - 500 second cycle TMF OOP90° ACW test to manipulate mechanism
  - Check if oxidation surpasses crack growth rate for intergranular failure



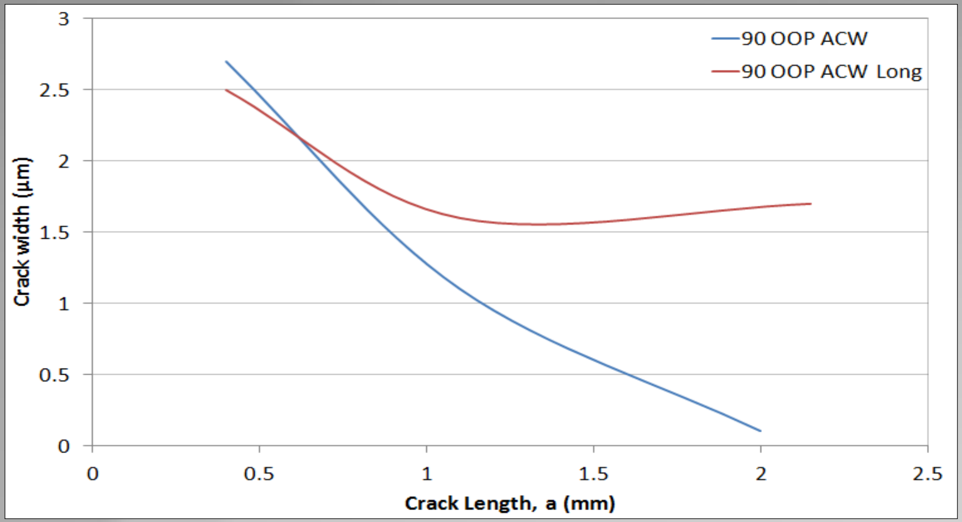
Results: 90° OOP ACW (80s) Crack Progression



Results: 90° OOP ACW (500s) Crack Progression

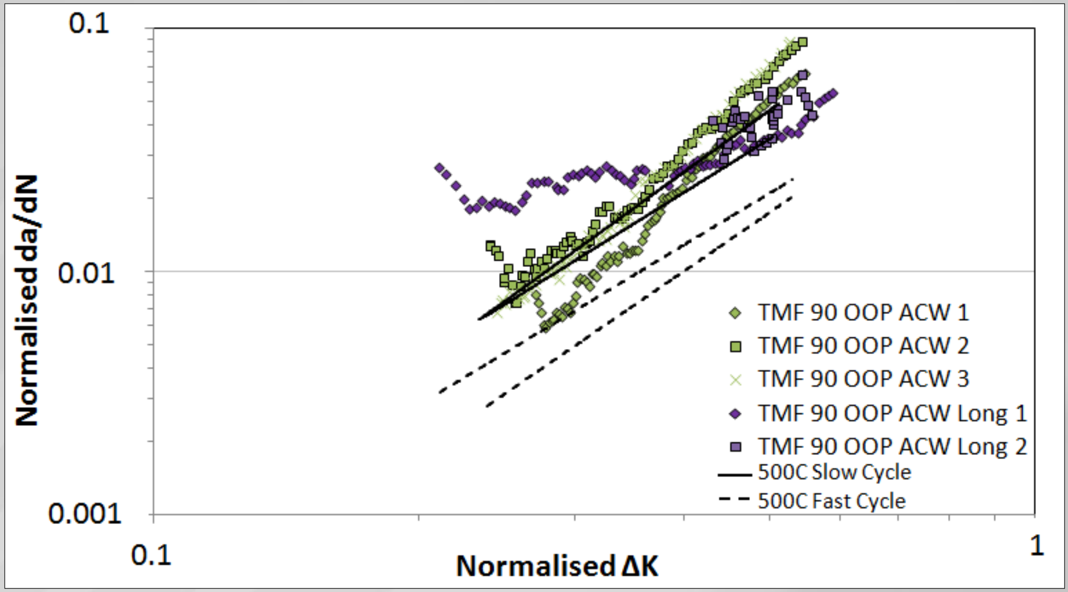


Results: Evidence of Crack Tip Blunting



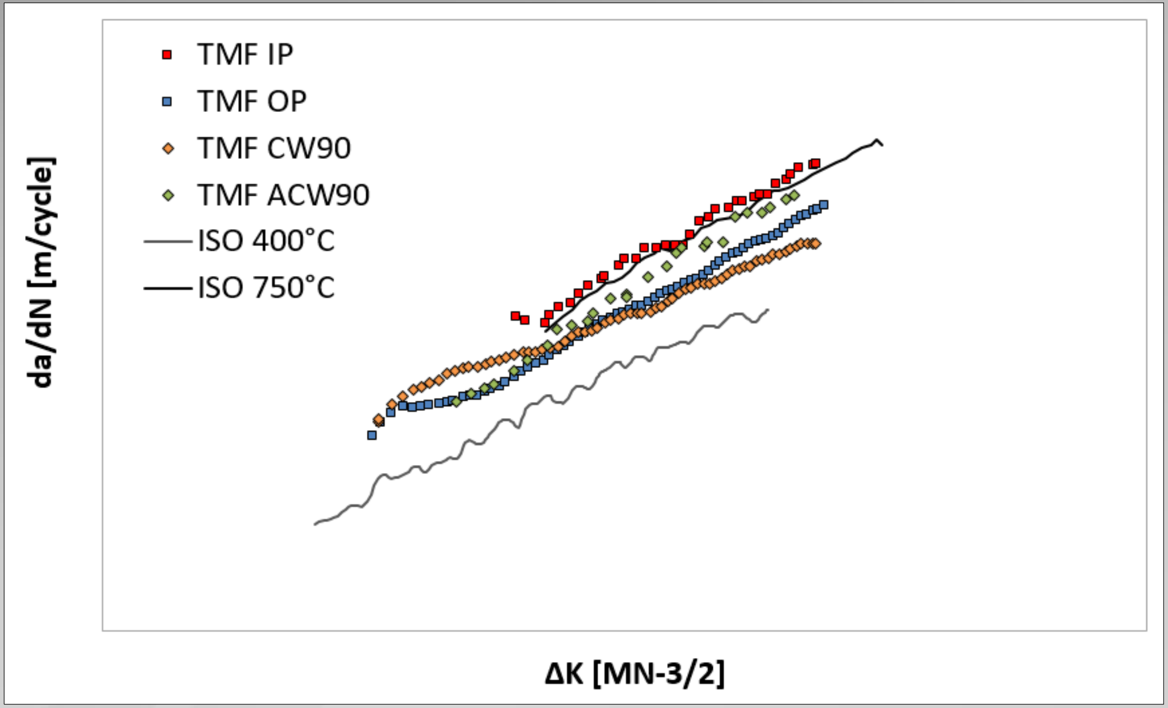
- It is clear that the longer cycle results in a wider crack throughout the test
- Flat gradient of the Paris curve supports this crack tip blunting theory

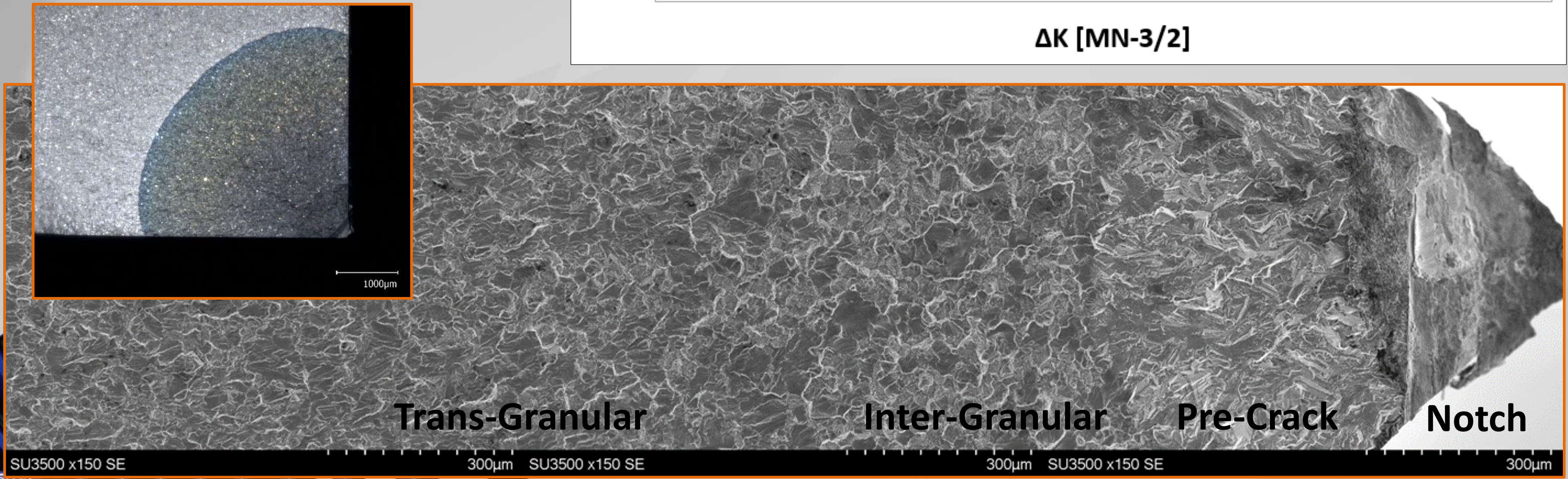
- The crack growth is retarded by the reduced stress concentration at the crack tip
- Is this due to oxidation layers on the upper and lower surfaces of the crack?



CW and ACW Diamond 90 cycles

- Accelerated crack growth in **ACW 90 cycles**
- Slow crack growth in **CW 90 cycles**
- Often a low gradient is seen early in the test (oxidation dominated) giving way to an increased gradient as dynamic failure takes over





Conclusions

- Crack propagation techniques are developing towards a Code of Practice to enable damage tolerant lifing approaches.

- Significant differences in TMF cycles due to phase angle occur in both fine grain and coarse grain material

- In phase tests dominated by oxidation damage

- Out of phase tests influenced by stress relaxation of compressive stresses around the crack tip. Higher temperatures promote more relaxation which leads to a greater increment of crack growth.

- CW and ACW cycles can be very sensitive to oxidation and rates may depend on cycle times.

Acknowledgements

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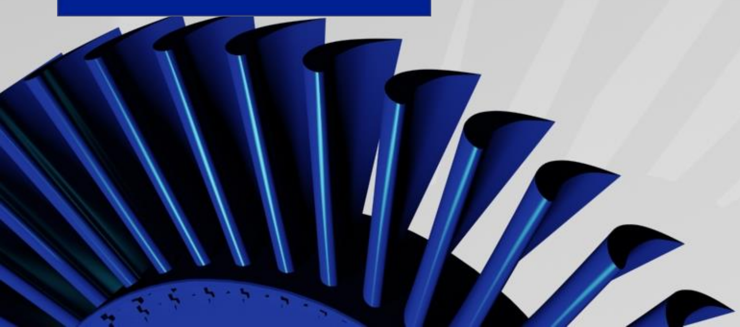
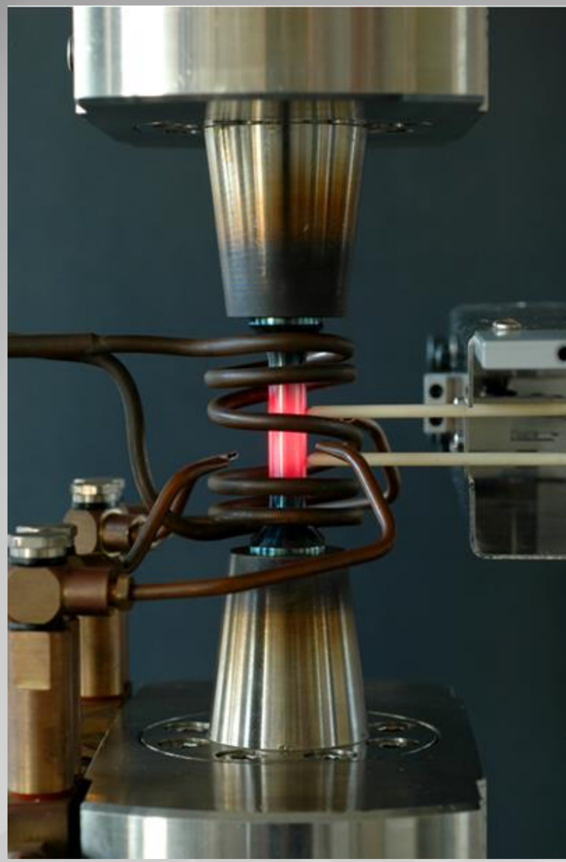
Any Questions?

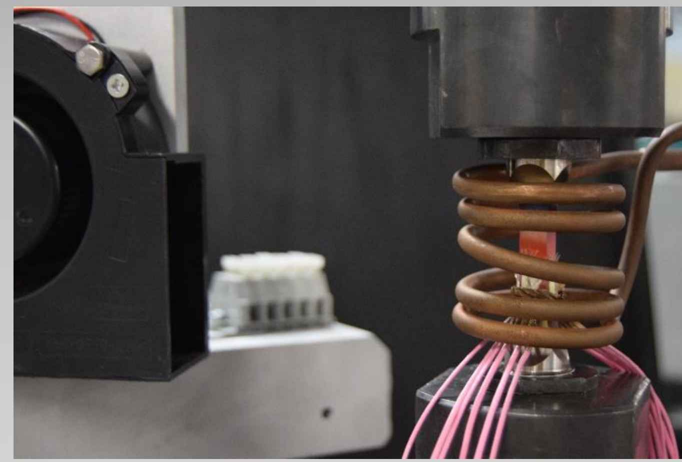


Forced Air Cooling



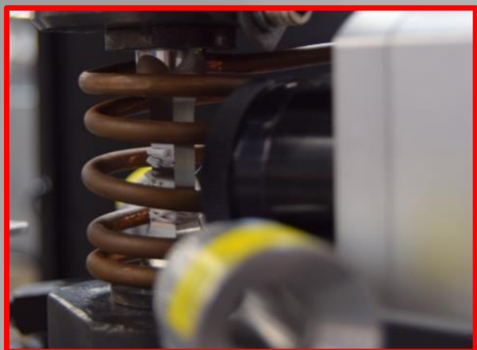
Localised/Focused Cooling

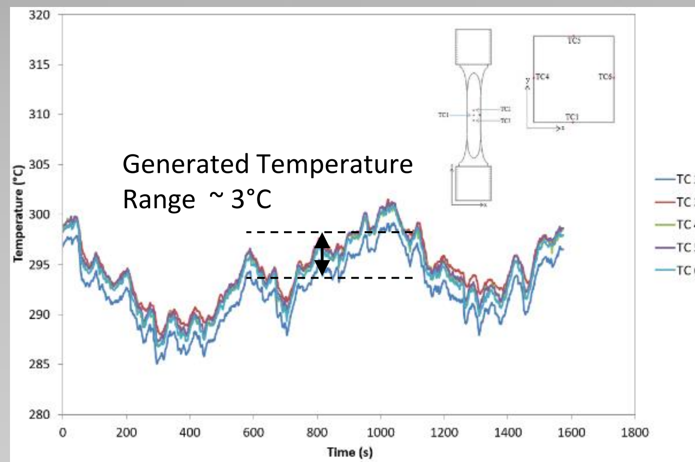
Basic Fan Cooling

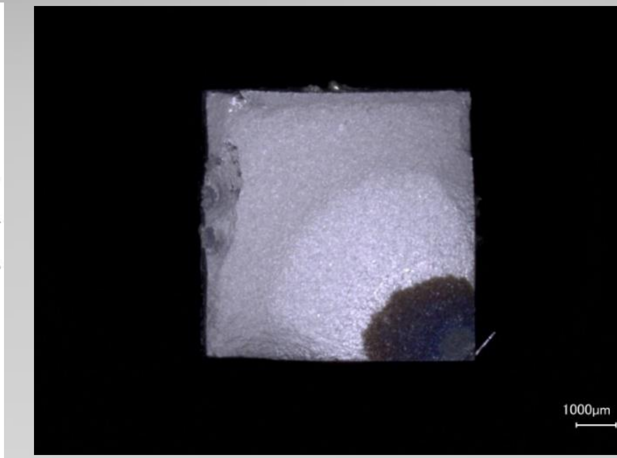


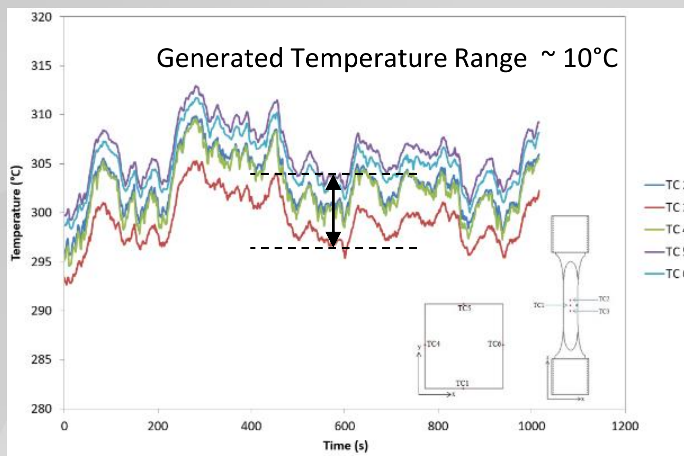
Diffuse uniform cooling through air amplifiers

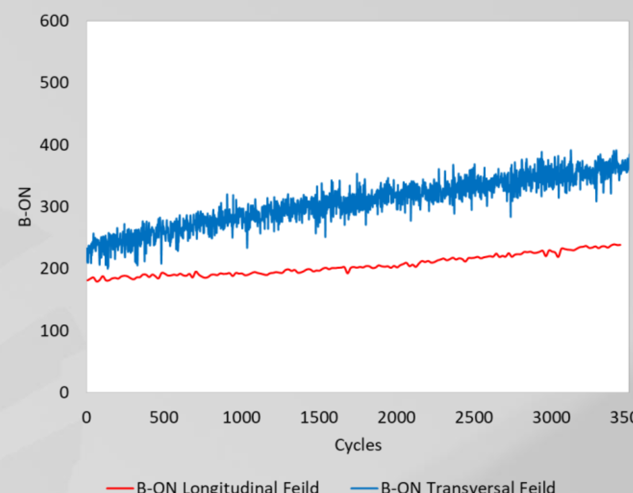
Induction Coil Designs



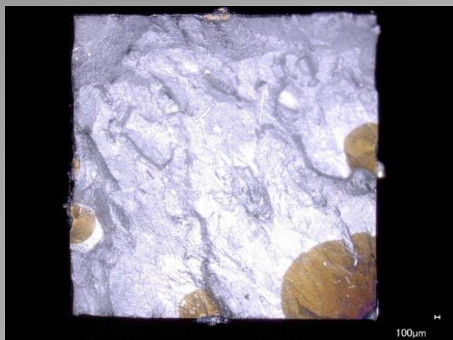


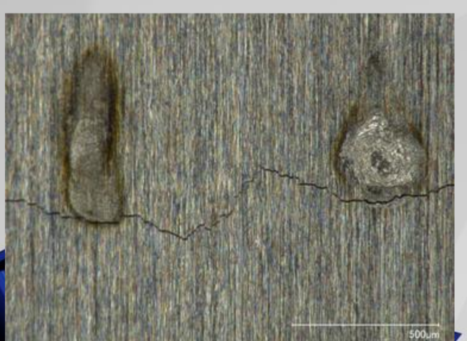






Pre-Crack Procedure





Thermo-Mechanical Fatigue Crack Growth Pre-Cracking

Stage	Temperature (°C)	Waveform	Frequency (Hz)	Stress (MPa)	Duration (µv)
1	Ambient	Sine	5	600	25
2	Ambient	Sine	5	500	50
3	Ambient	Sine	1	500	75