THERMO-MECHANICAL FATIGUE CRACK GROWTH IN ADVANCED AEROSPACE ALLOYS

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Euromat 2019

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

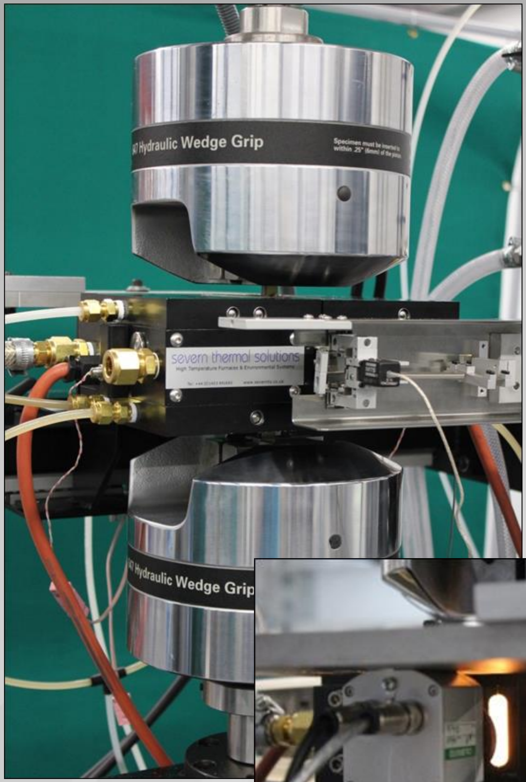
Linkoping University, Sweden.
Modelling and round robin testing

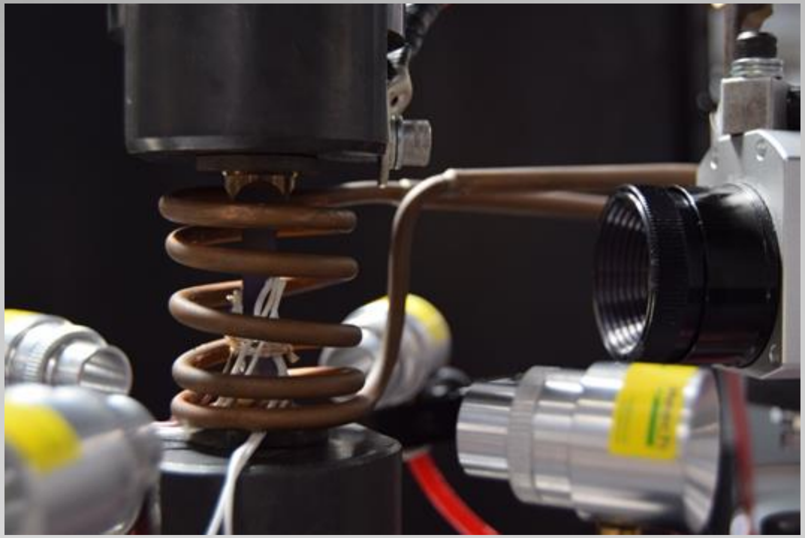
Rolls-Royce plc, UK.
Material and technical support

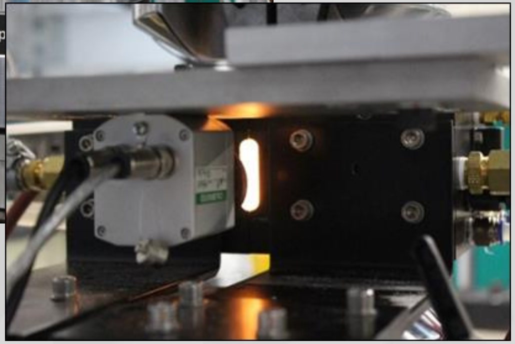
Introduction

- 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



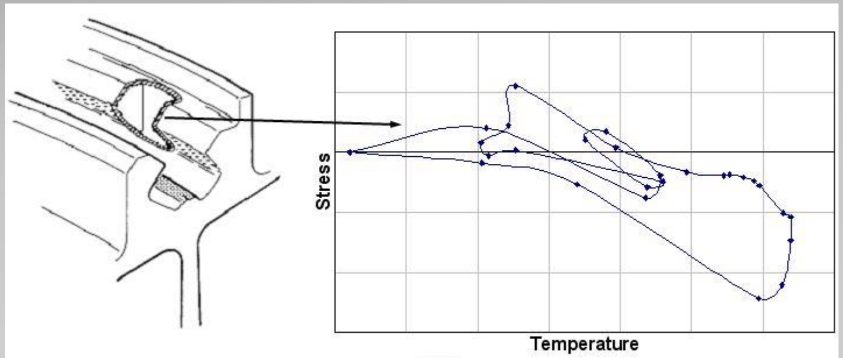




- ASTM E2368-10. Strain Controlled TMF Testing, 2010.
- ISO 12111:2011. Strain-controlled TMF Testing, 2011.
- BAM. CoP Force-Controlled TMF Testing, 2015.

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



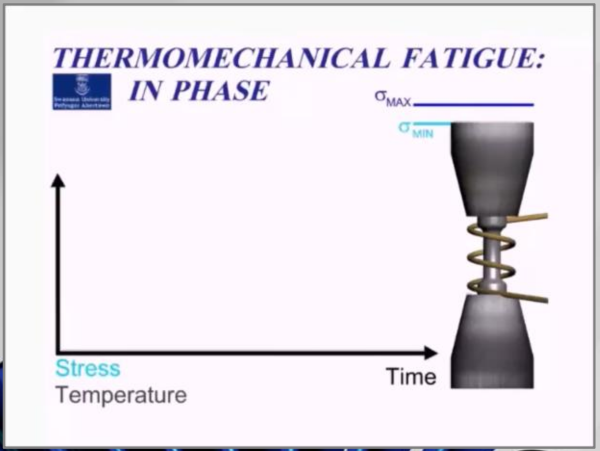
- Extrapolation of isothermal fatigue (IF) results to incorporate these effects show limited success
- Generation of TMF data is required to allow the development of lifing methodologies under TMF loading

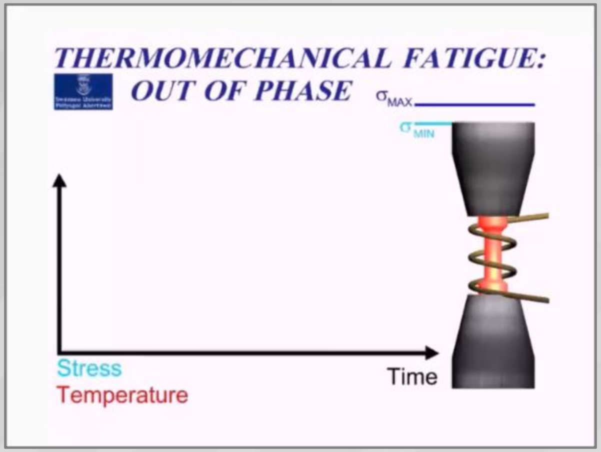
Thermo-Mechanical Fatigue (TMF)

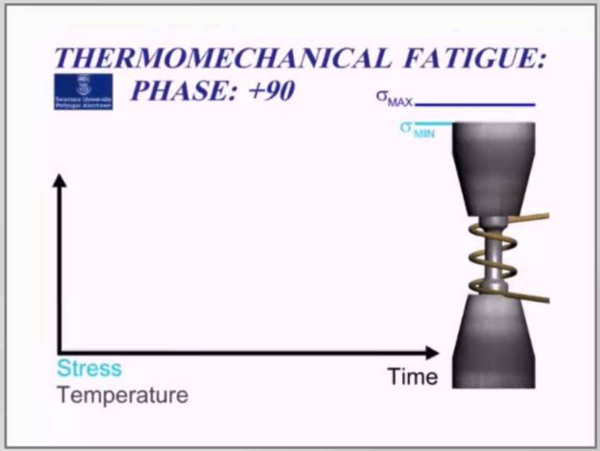
- Diverse mechanisms are involved, Primarily . . .

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

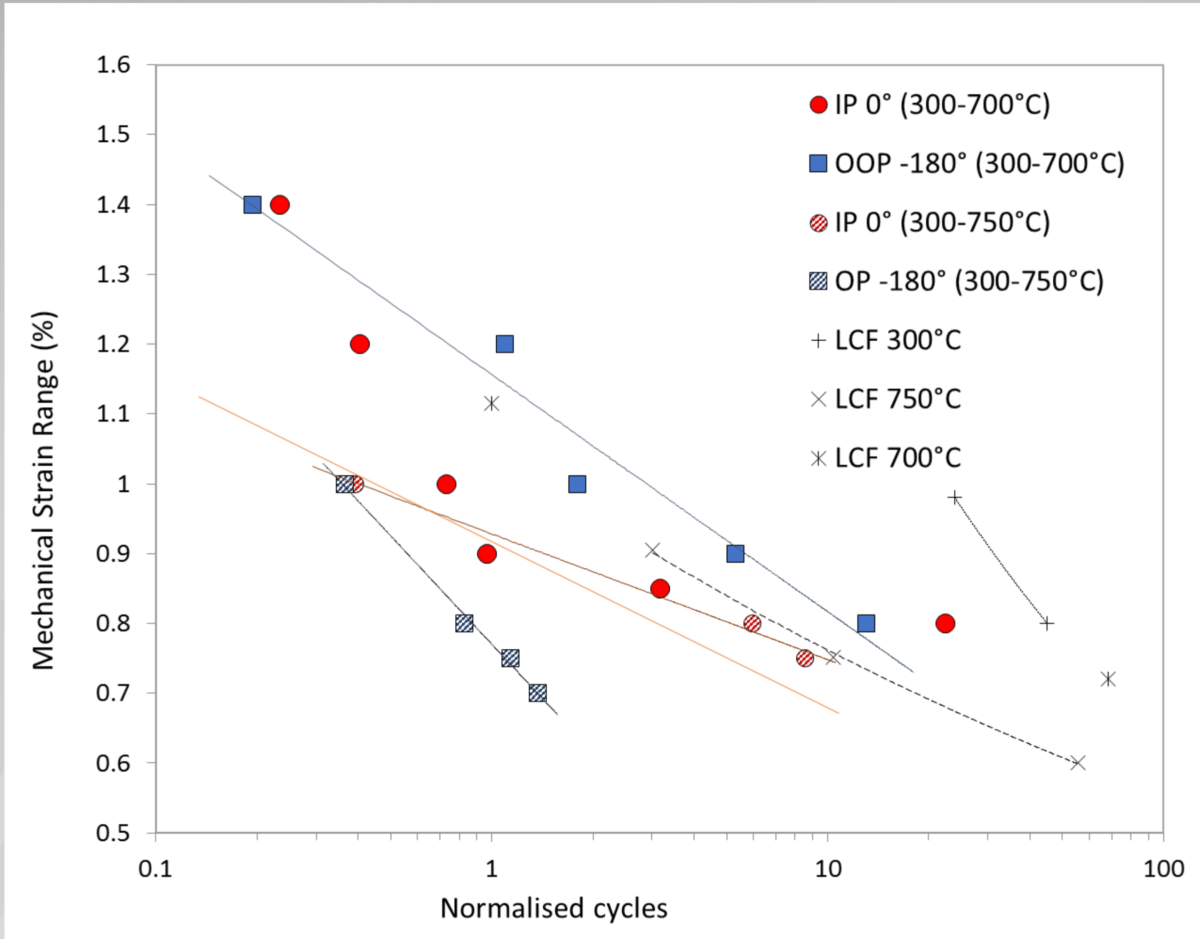






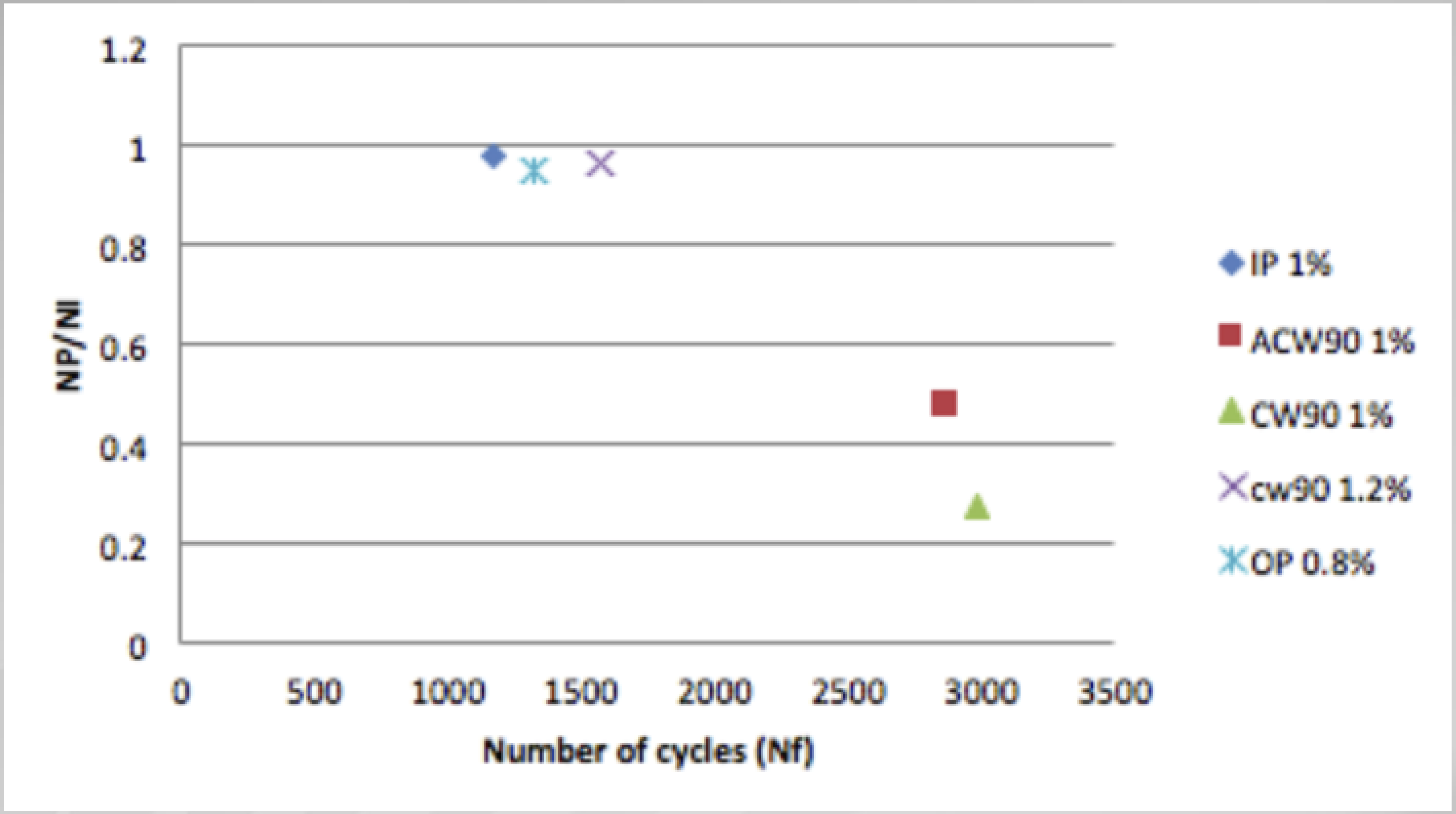
Effect of peak temperature

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



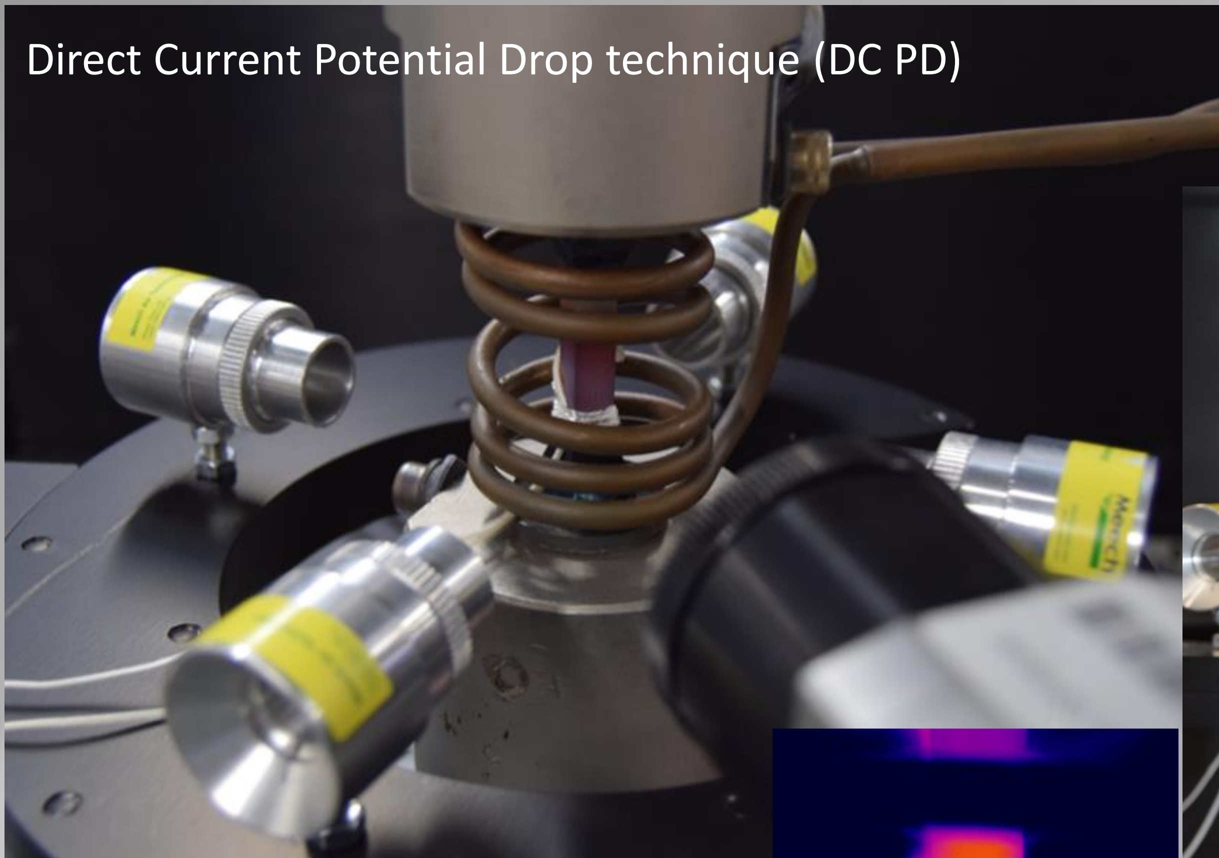
Crack propagation

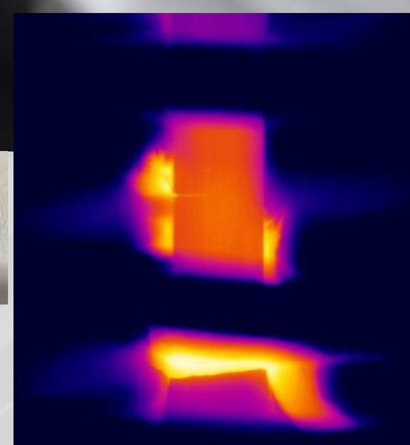
For fatigue lives that are less than 5000 cycles it is not appropriate to consider only crack initiation as the dominant factor in fatigue life.

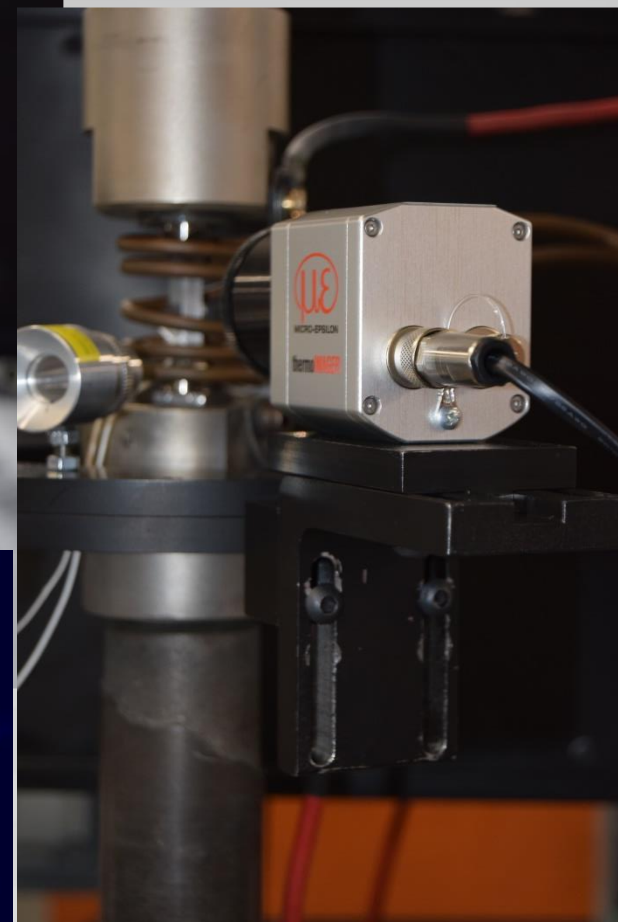


TMFCG Test Development

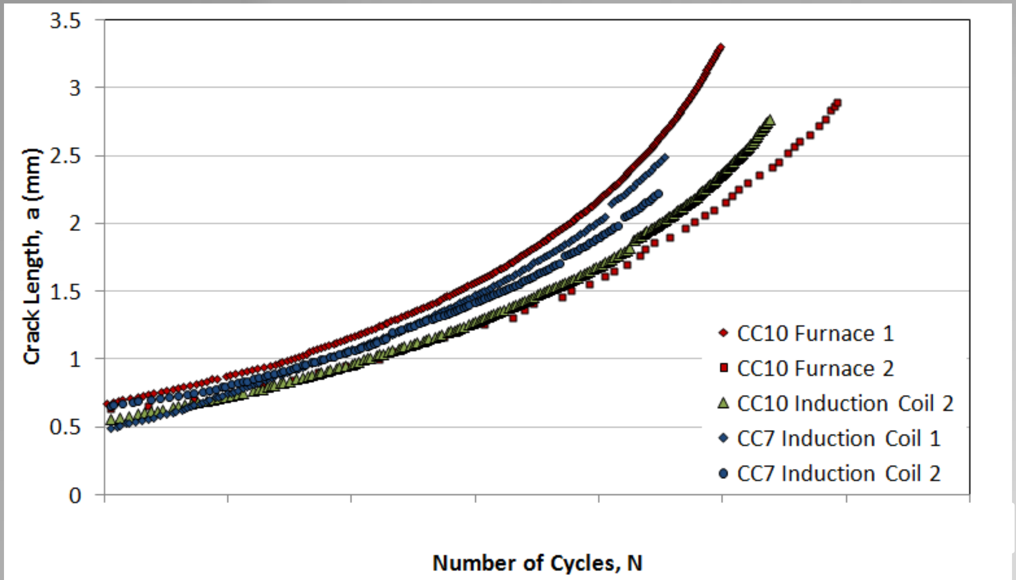
Direct Current Potential Drop technique (DC PD)



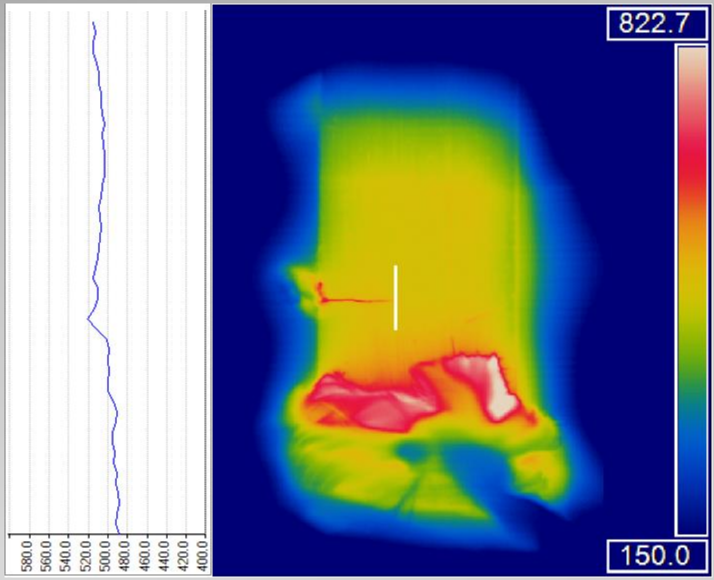




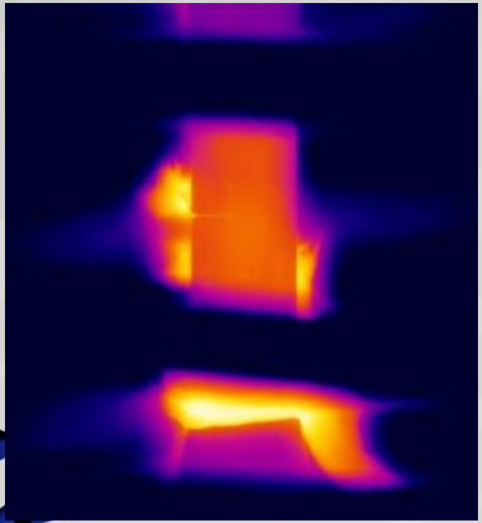
Crack Tip Heating Investigations



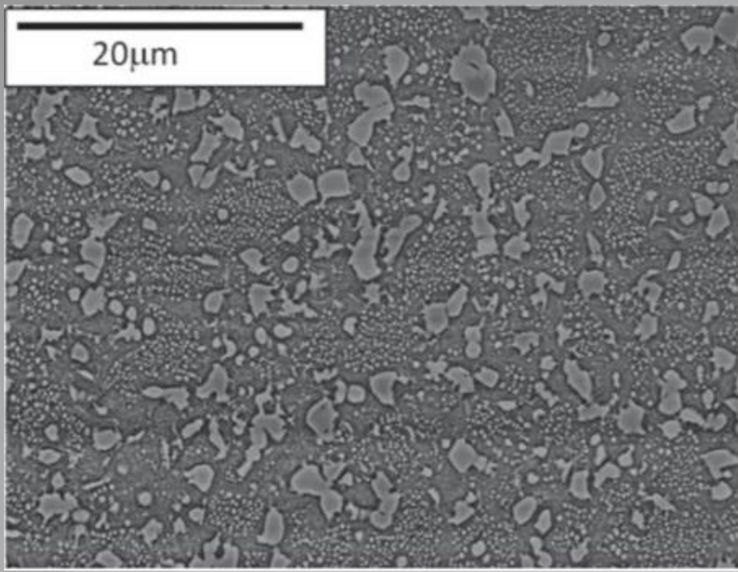
Waspaloy crack length vs. number of cycles: furnace and induction coil comparisons at 650°C, 450MPa and R=0.1.



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



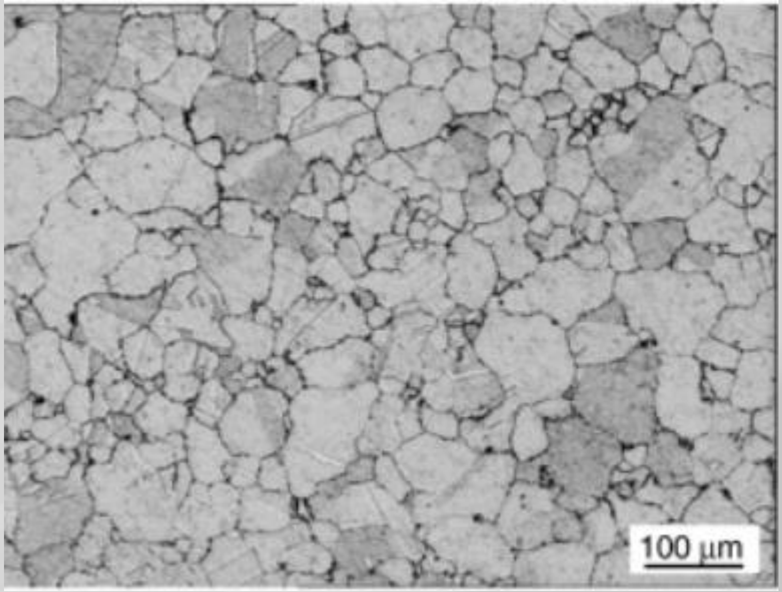
Fine and Coarse grained RR1000



Fine grained RR1000

Coarse grained RR1000

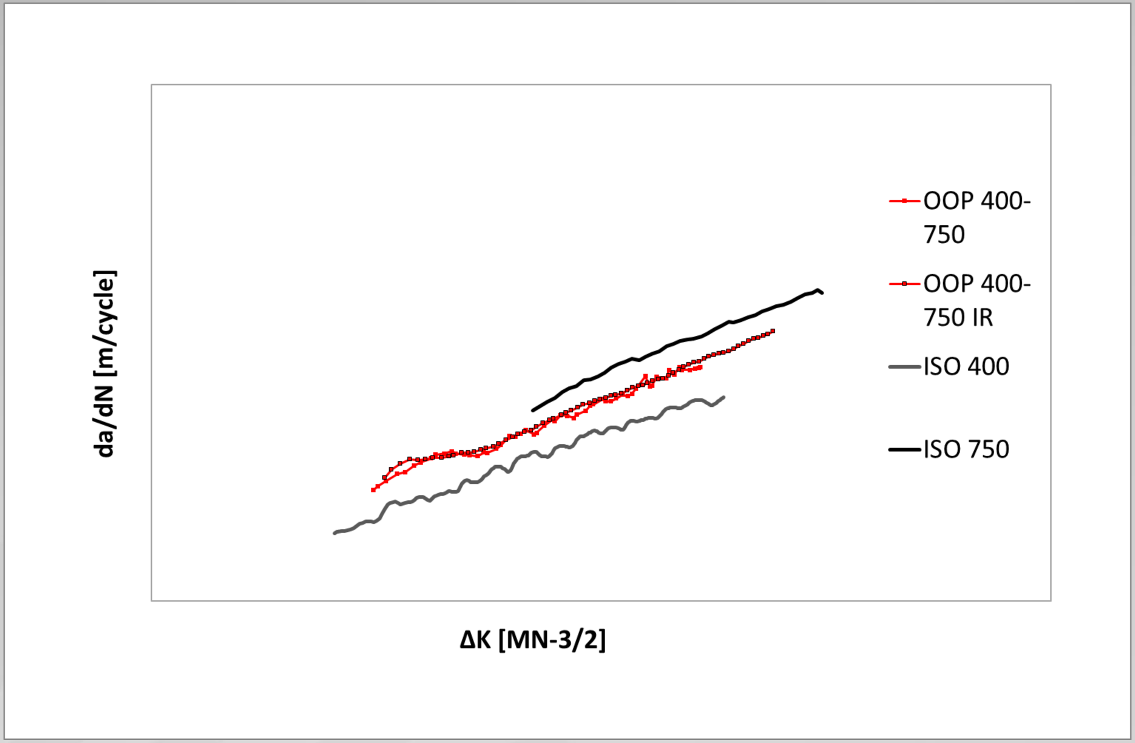
Image courtesy of Li et al, Effects of microstructure on high temperature dwell fatigue crack growth in a coarse grain PM nickel based superalloy, Acta Materialia, Volume 90, 15 May 2015, Pages 355-369



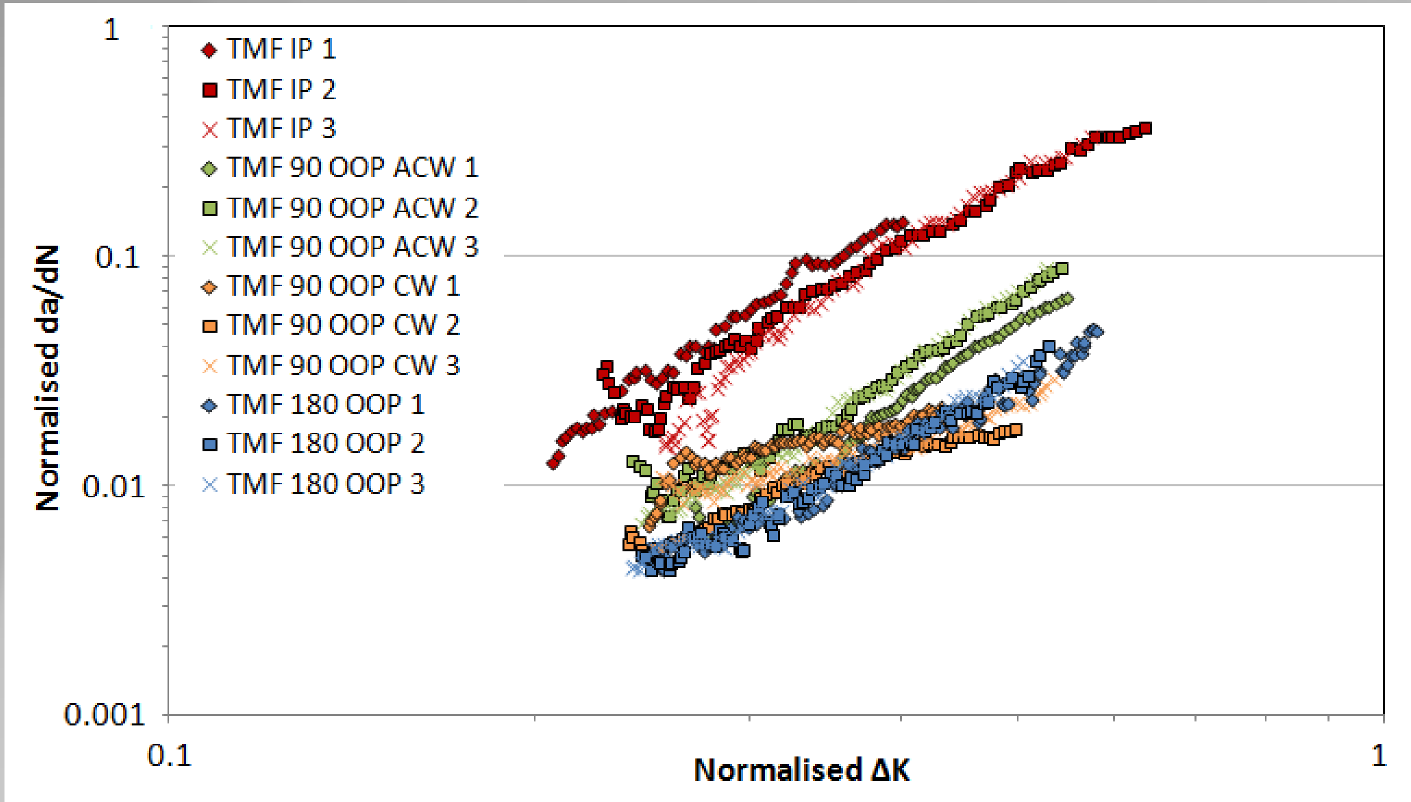
Effect of infra red furnace vs coil

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



FG RR1000 TMF CP

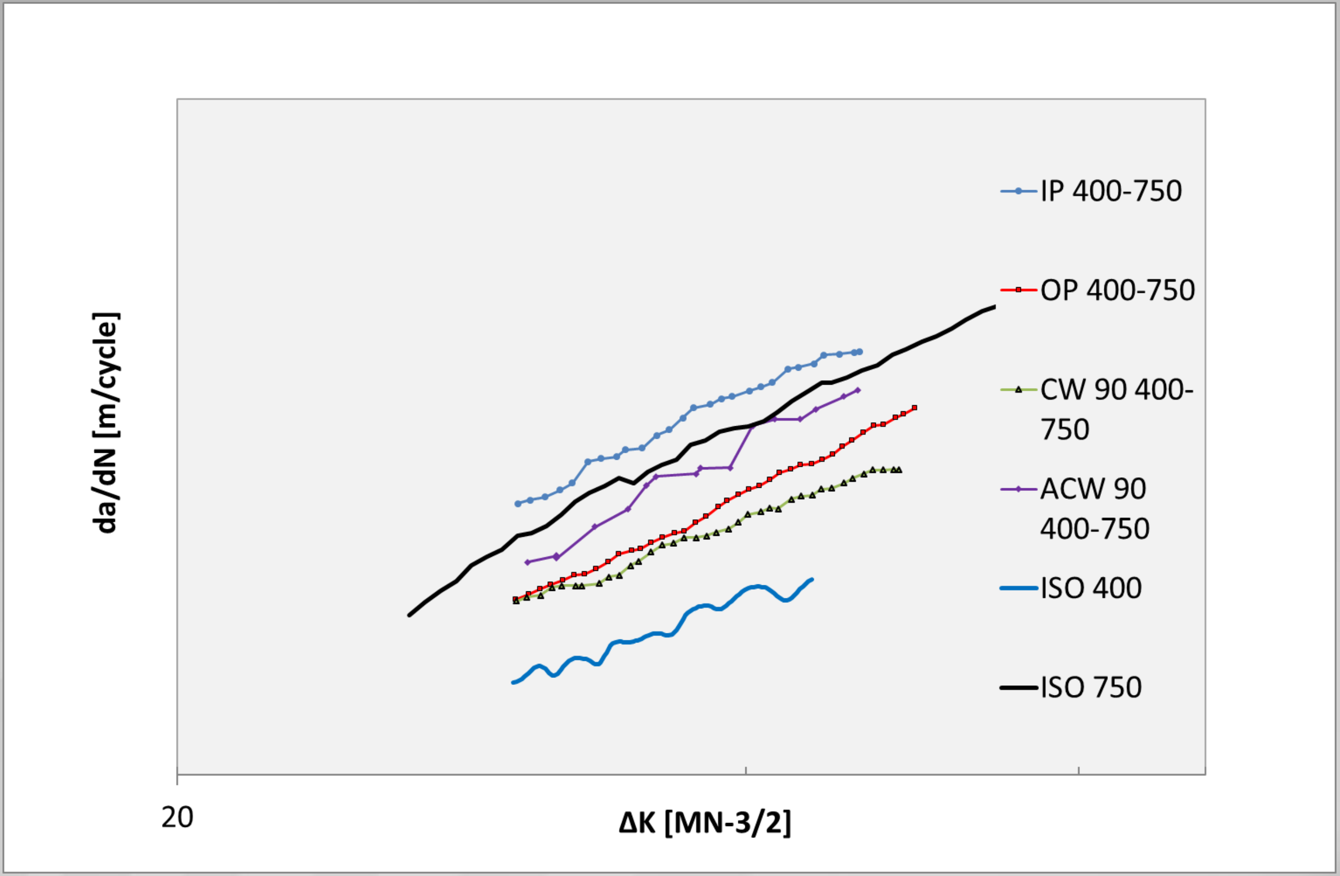


Strong dependence on phase angle

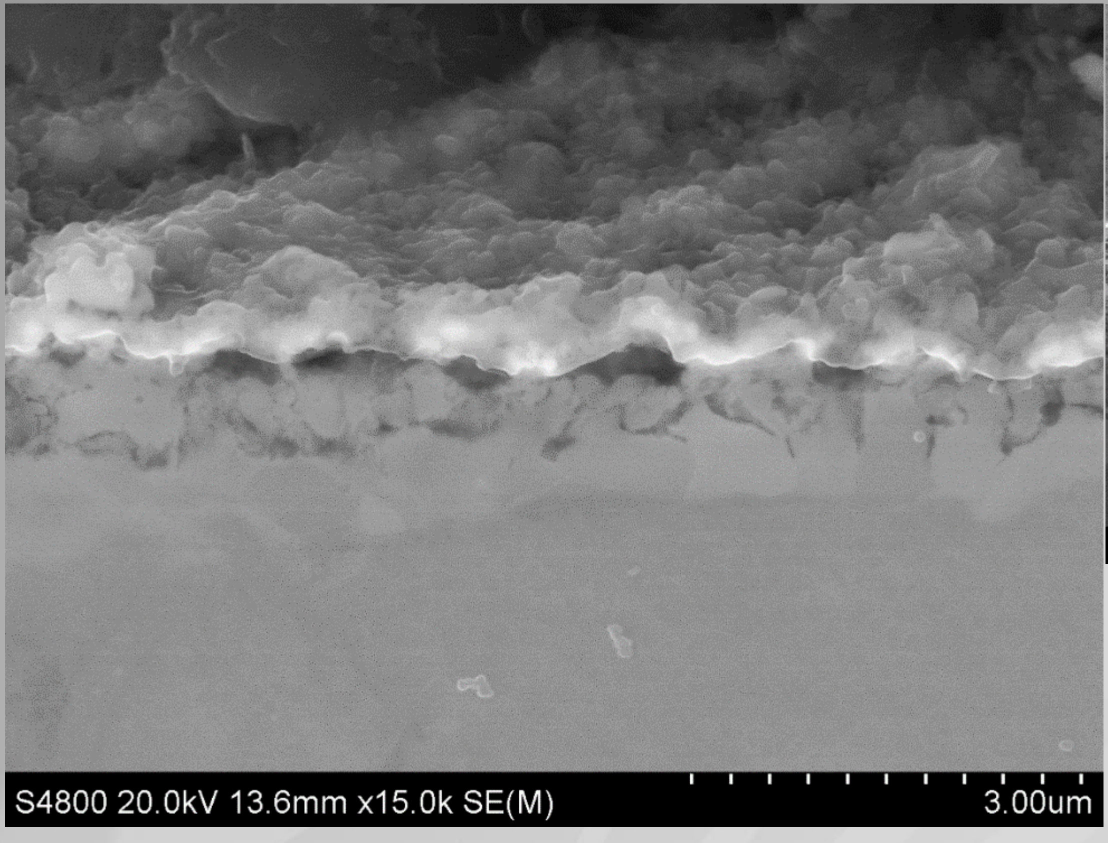
Rates tend to approximate temperature at which peak stress occurs

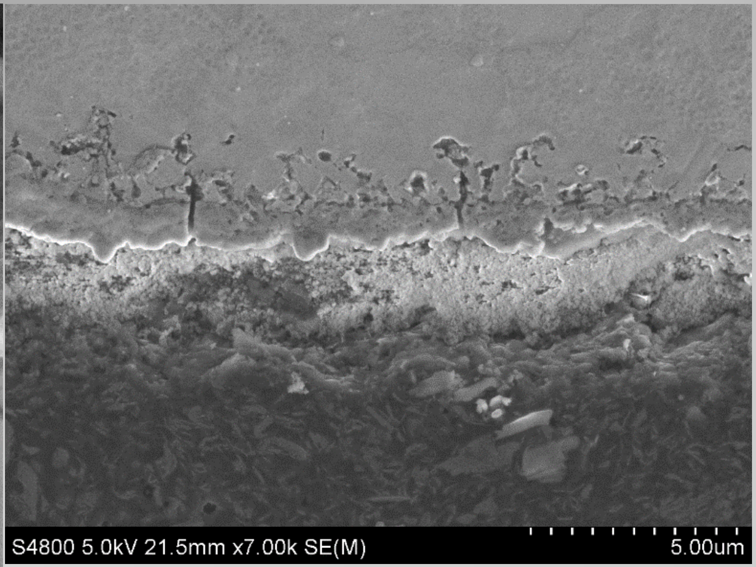
Coarse grain RR1000 crack growth data

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

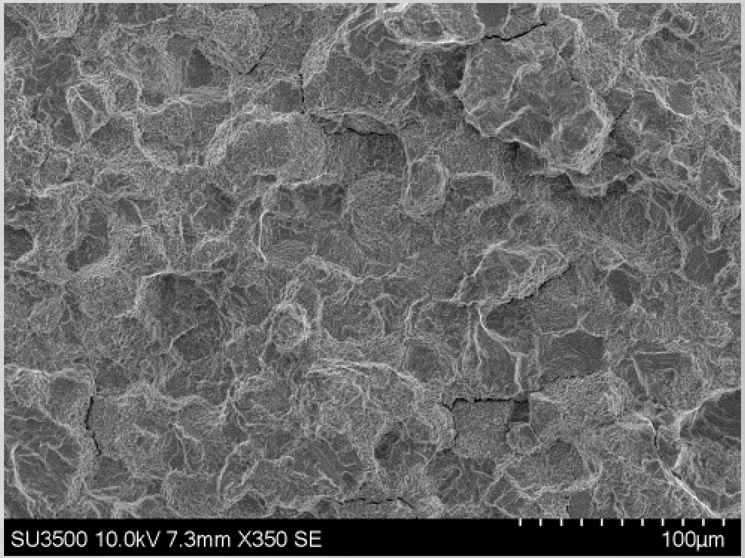


Oxidation damage

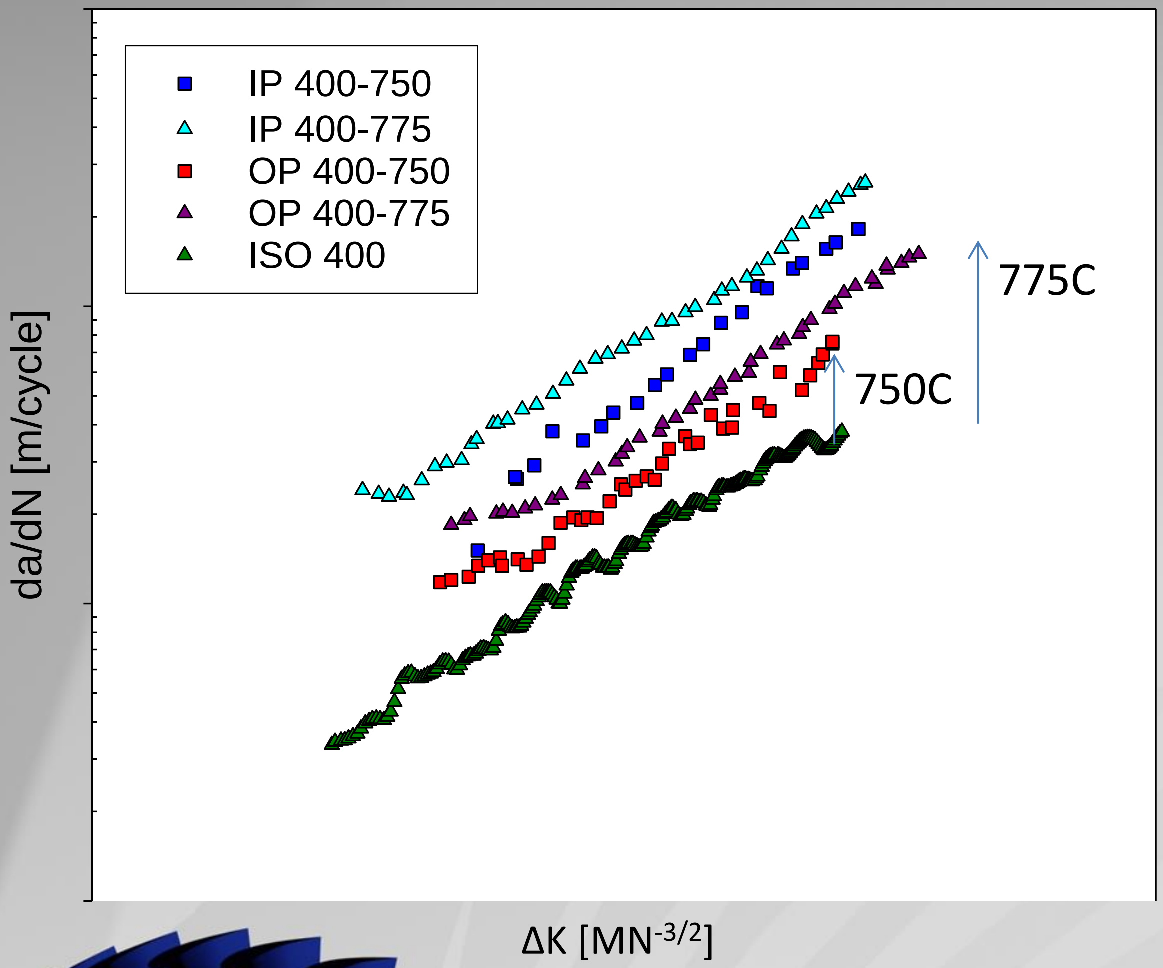




In phase fracture surface



Effects of Peak Temperature

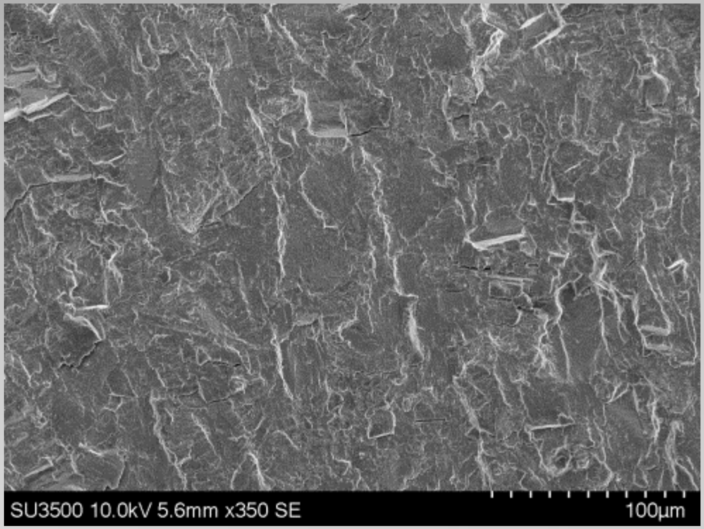


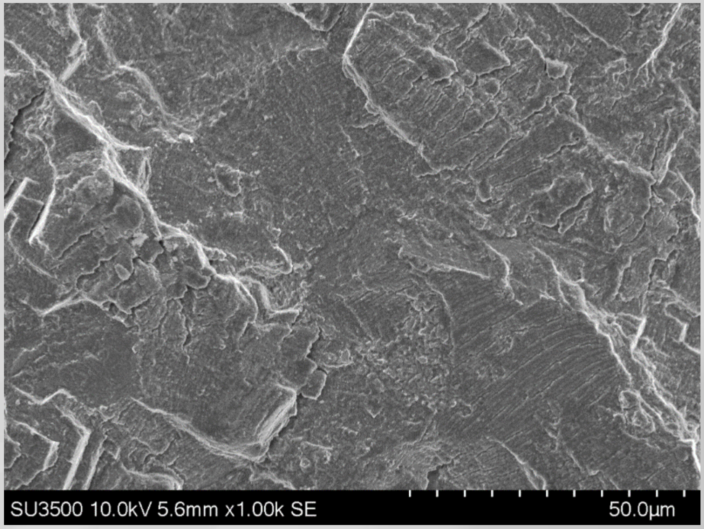
CG RR1000

- **In phase tests show faster rates than equivalent isothermal tests**
- **Dependent on cycle time**
- **In OOP tests increased Tmax influencing TMF CP rates**

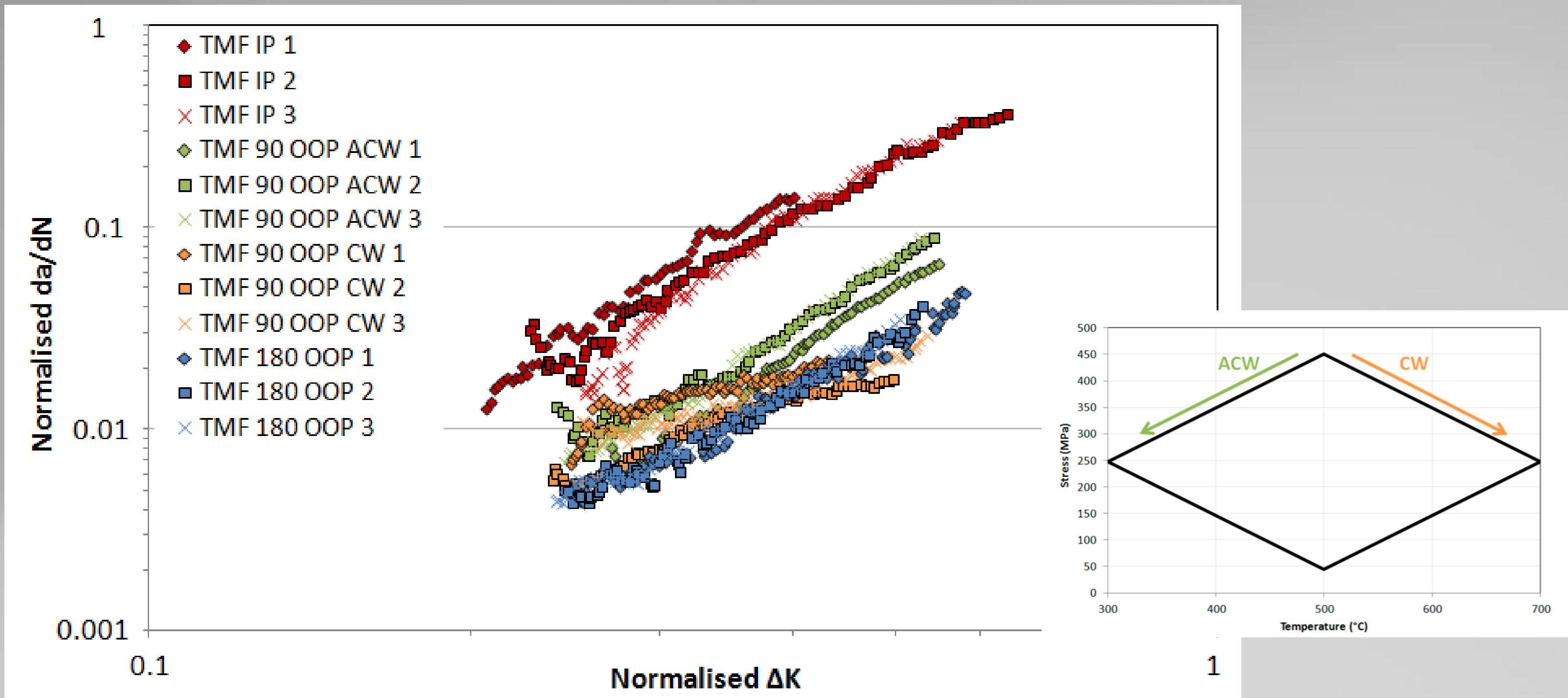
Mechanisms of crack growth in OOP tests

- 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?





FG RR1000 TMF CP

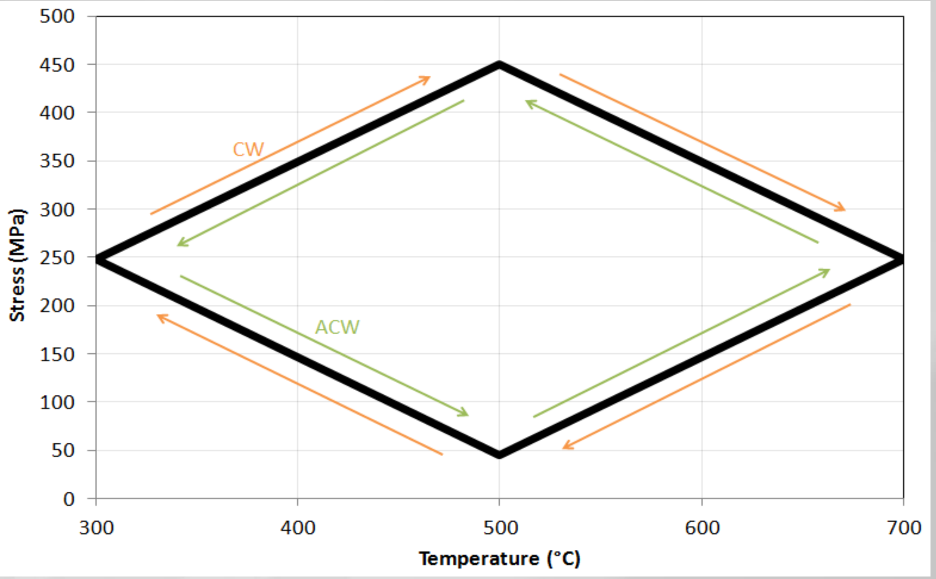


Strong dependence on phase angle

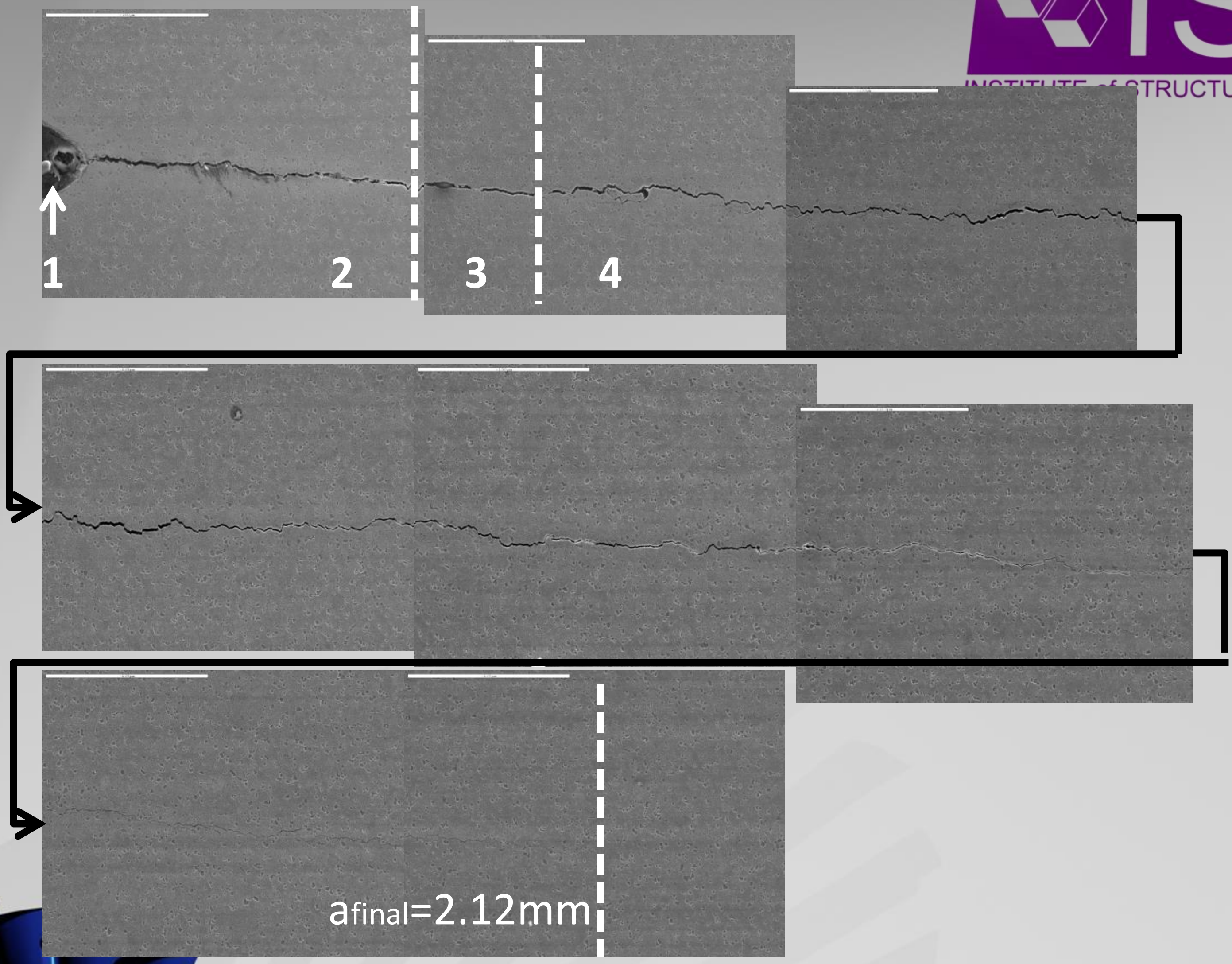
Rates tend to approximate temperature at which peak stress occurs

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 (80 sec) Crack Progression



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

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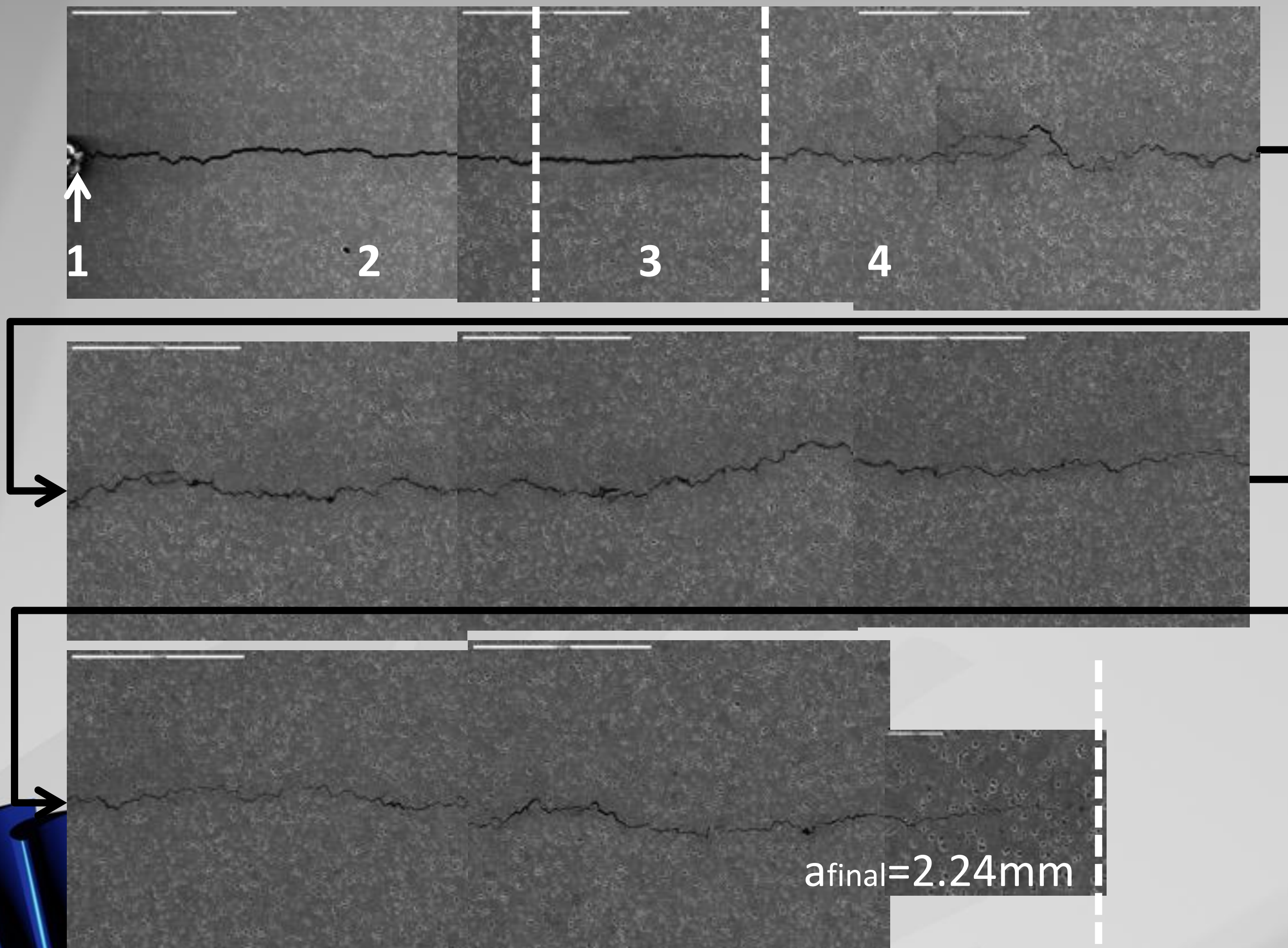
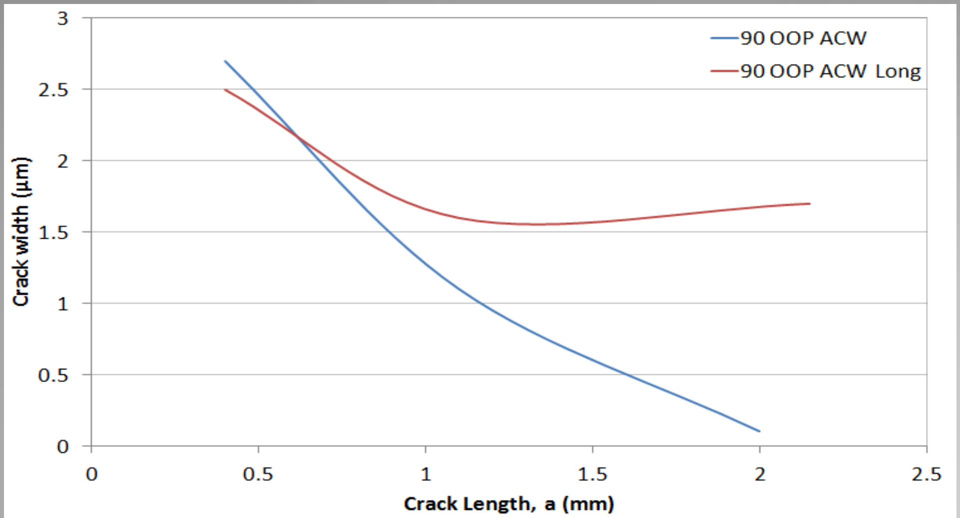


Results: Evidence of Crack Tip Blunting

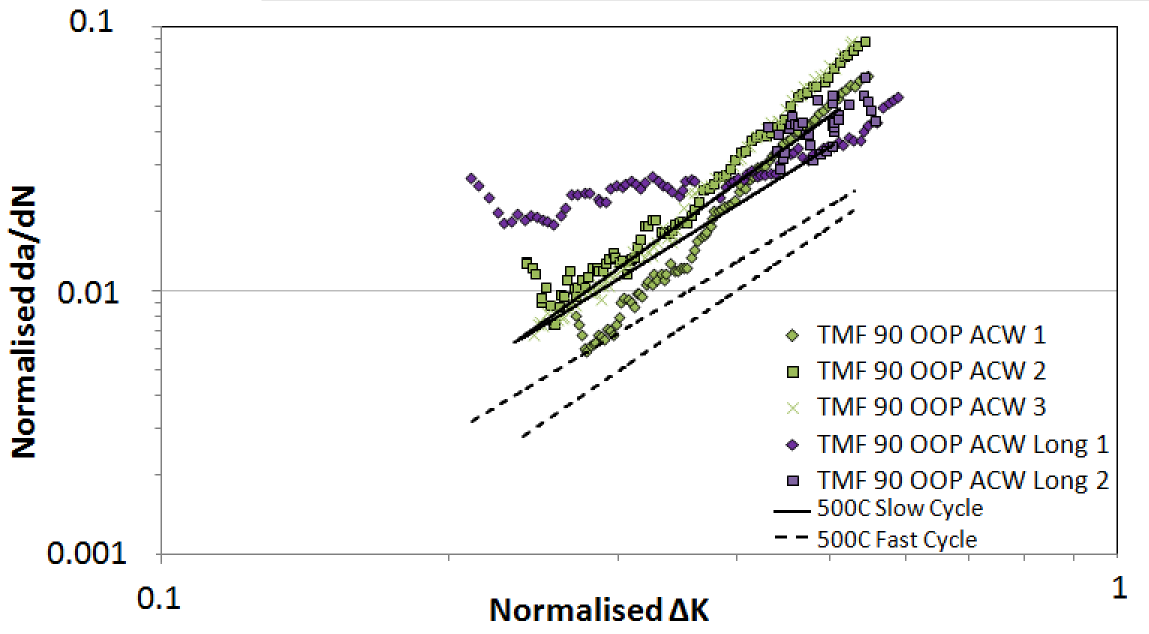


It is clear that the longer cycle results in a wider crack throughout the test

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?

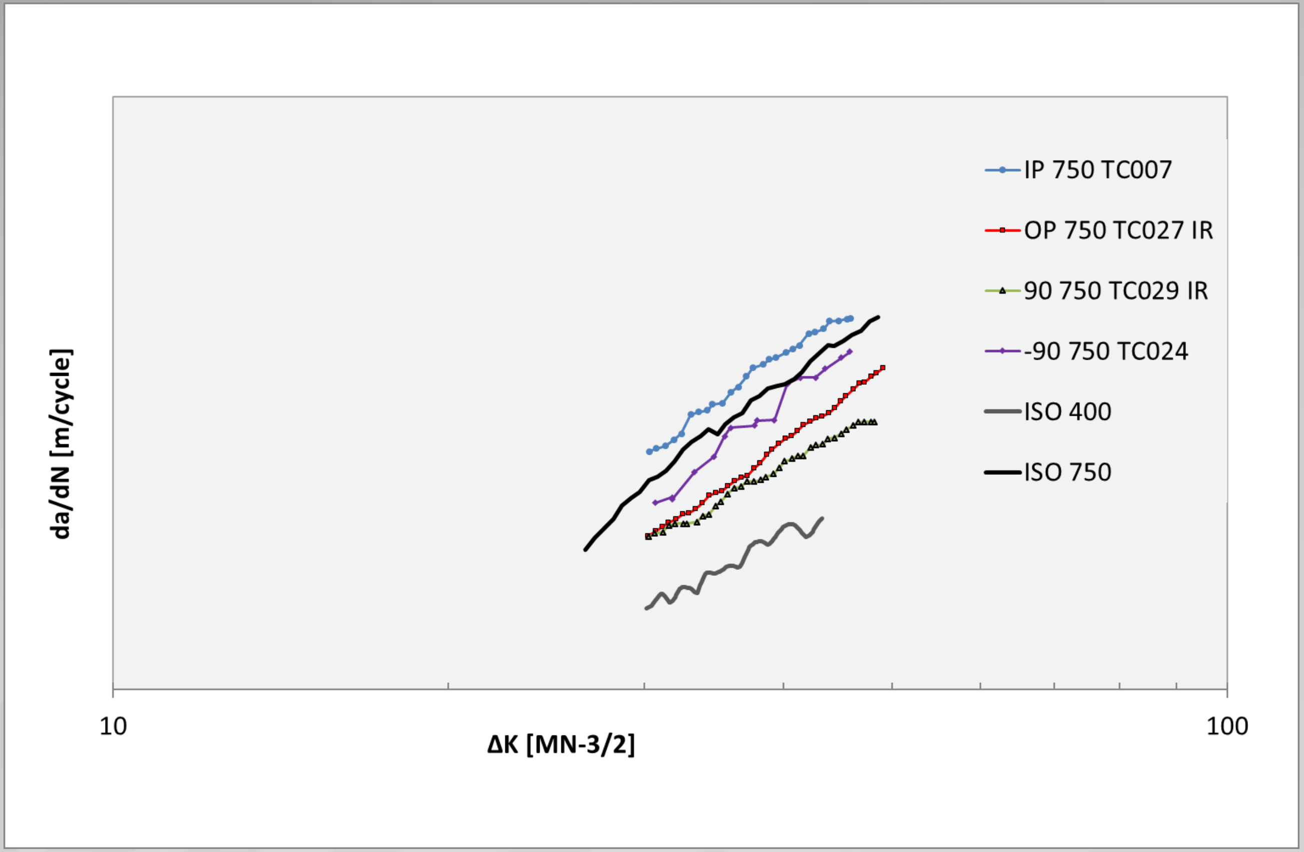


CW and ACW cycles

Accelerated crack growth in ACW 90 cycles

Slow crack growth in CW 90 tests

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.

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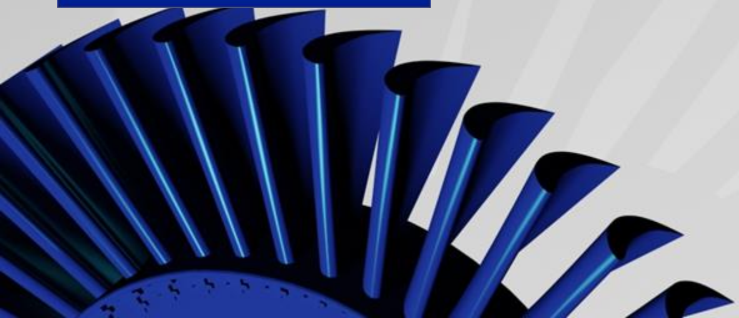
Any Questions?



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