THERMO-MECHANICAL FATIGUE CRACK GROWTH IN ADVANCED AEROSPACE ALLOYS

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Prifysgol Abertawe
Swansea University

Fatigue 2018, Poitiers, France May 30th

Introduction

Swansea University Bay Campus

DevTMF Partners

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.

Swansea University, Wales.
Testing and analysis

Nottingham University, England.
Modelling and round robin testing

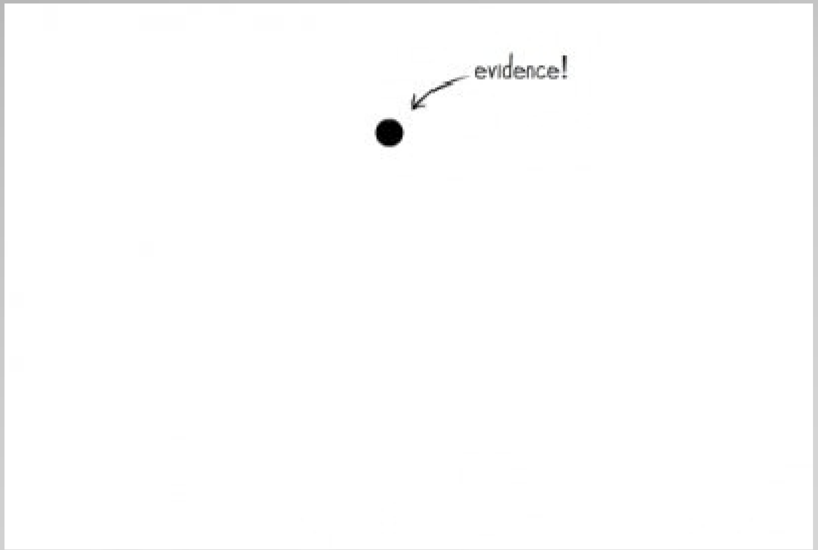
Linkoping University, Sweden.
Modelling and round robin testing

Rolls-Royce plc, UK.
Material and technical support

Introduction

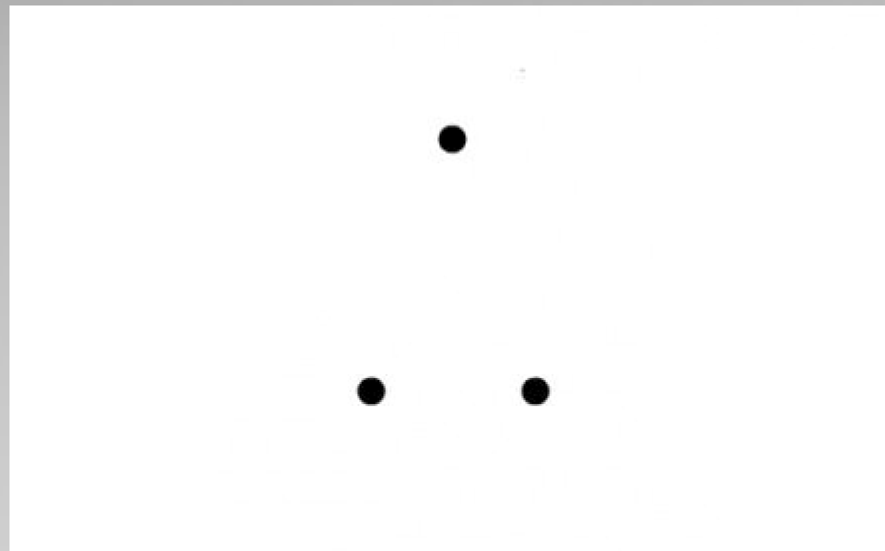
- Swansea University Background in TMF
- TMF total life testing
- Predictive methods
- TMFCG Test Development
- Crack tip heating investigations
- TMFCG Test Results
- Previous Work with Thermography
- TMFCG with Thermography

Science…



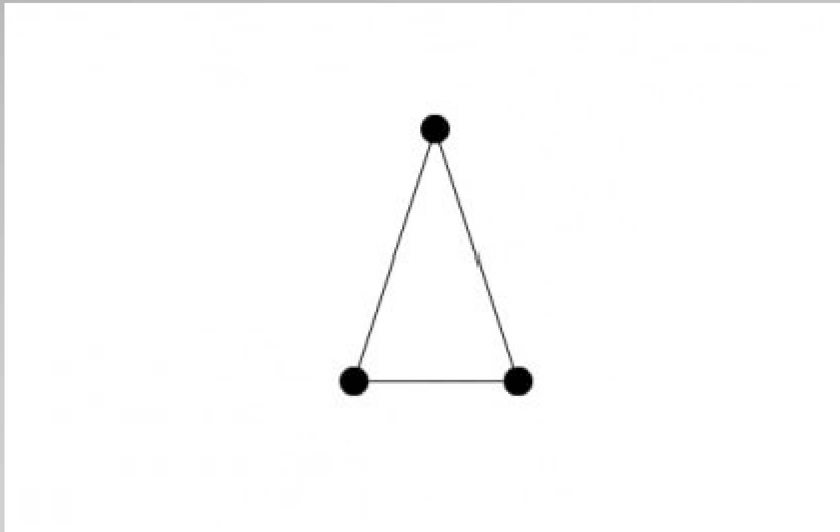
Perform an experiment and it gives us evidence

Science…



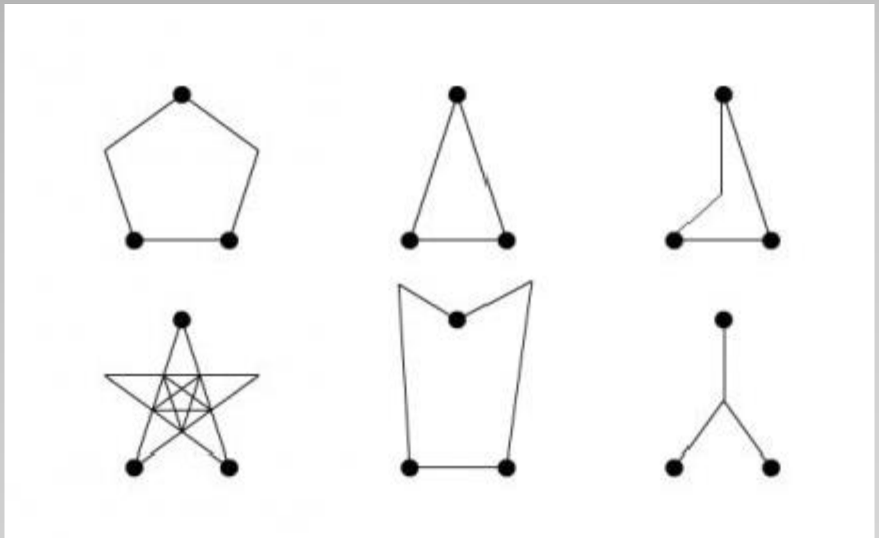
Perform more experiments and gain more evidence

Science…



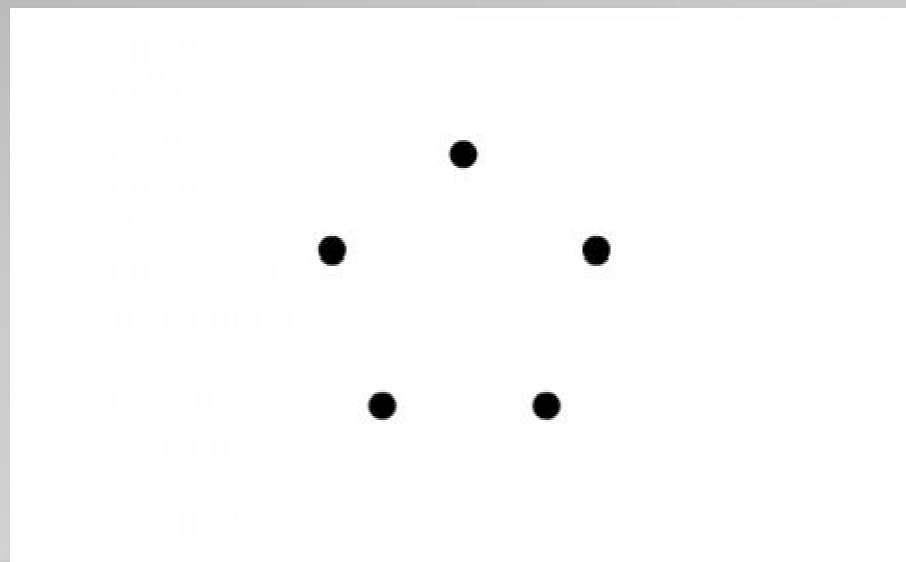
Connect the evidence and come up with a theory

Science…



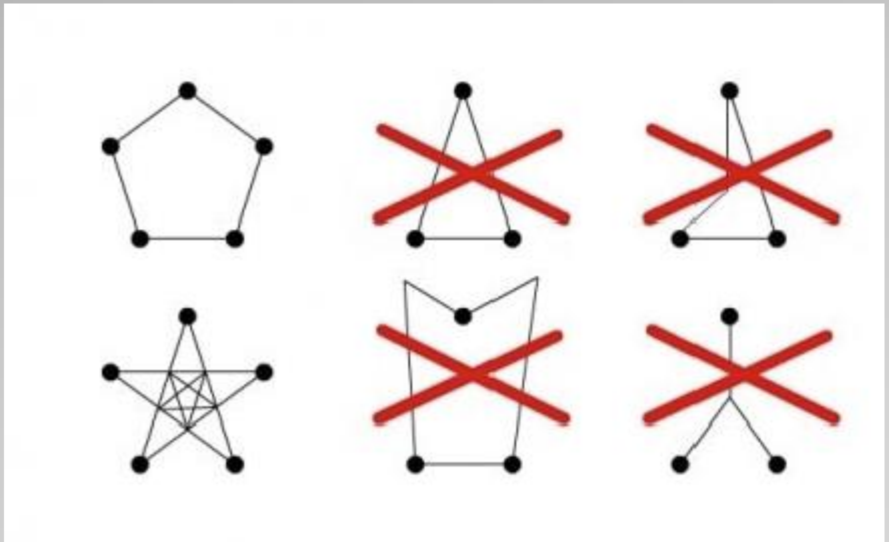
But there can be competing theories

Science…



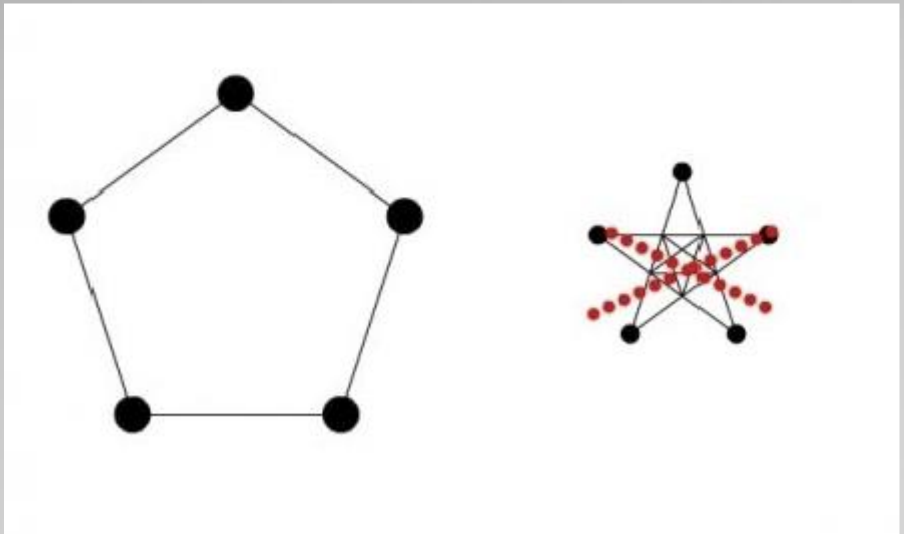
Gather more evidence

Science…



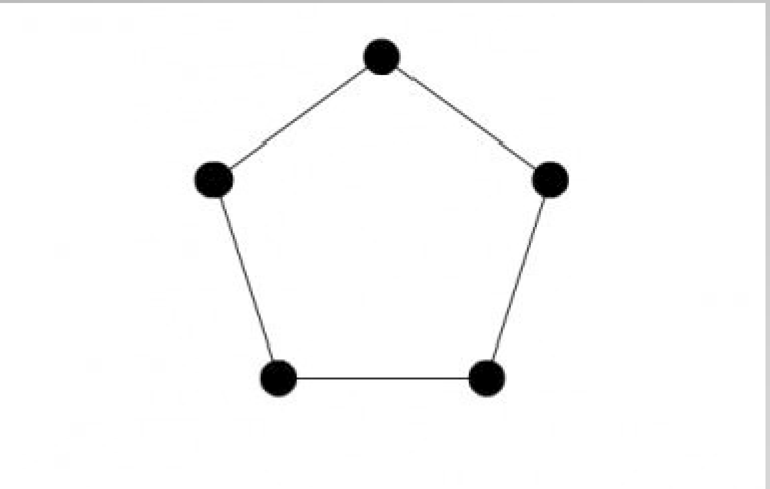
We can eliminate demonstrably incorrect theories

Science…



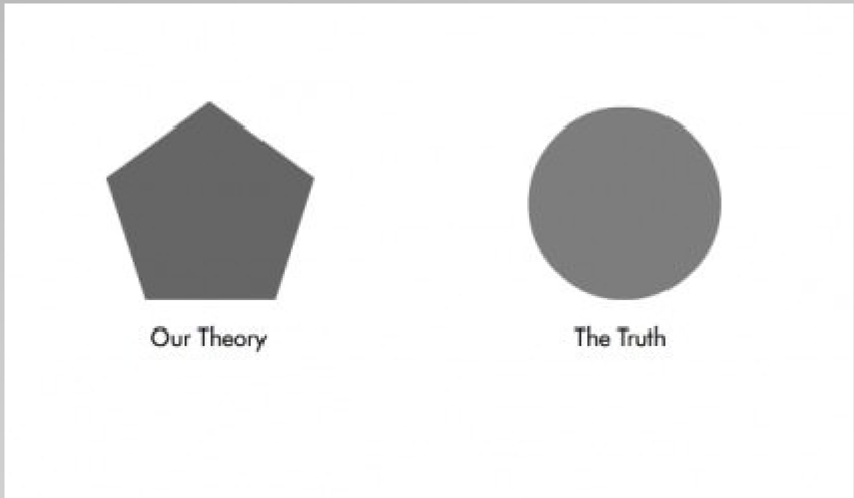
Theories with the least assumptions tend to be true

Science…



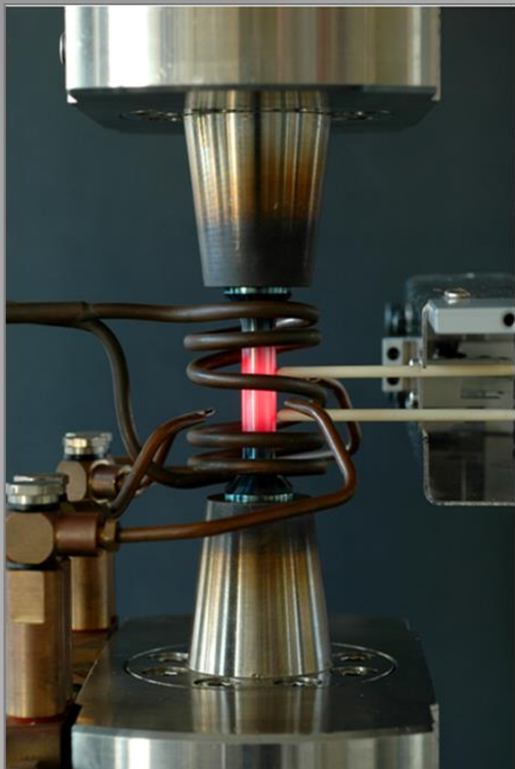
So we tend to focus on theories that have less assumptions

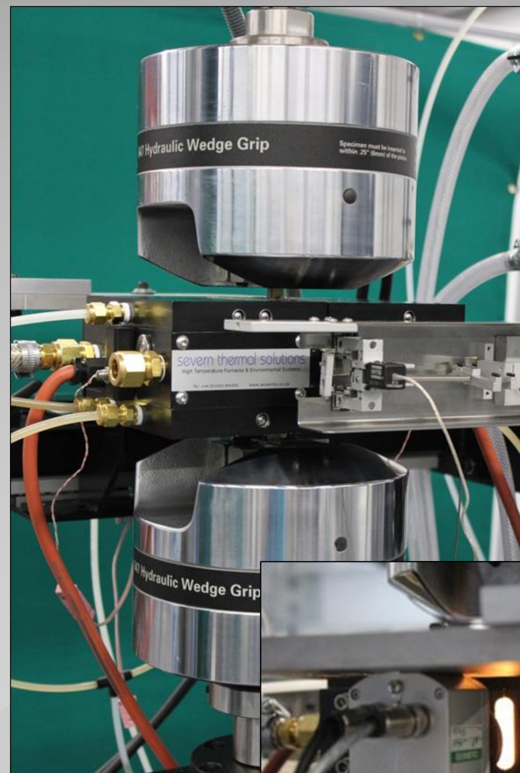
Science…

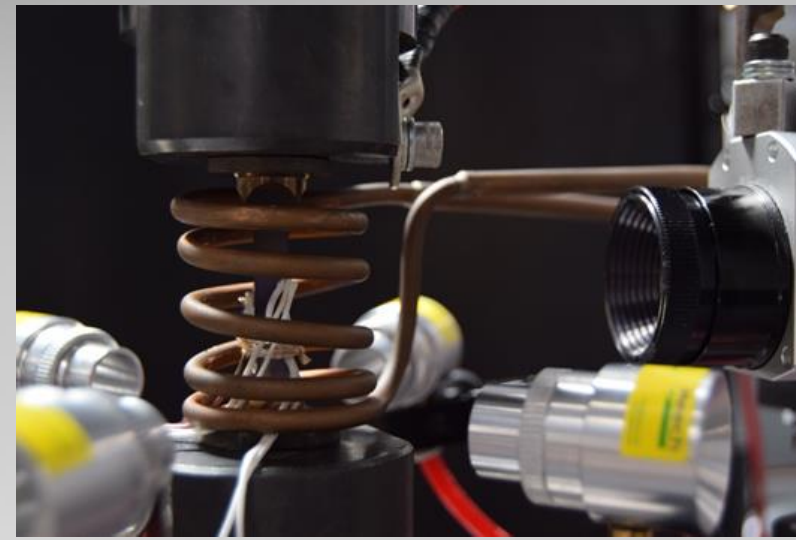


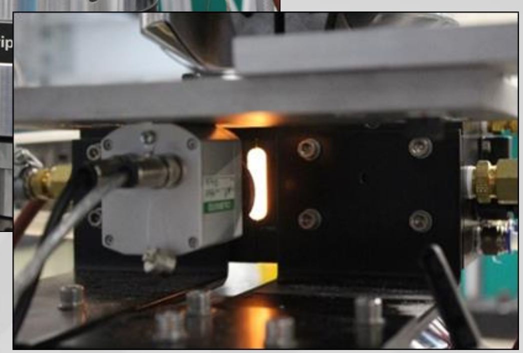
It may not be completely accurate but it's better than competing theories

Background in TMF



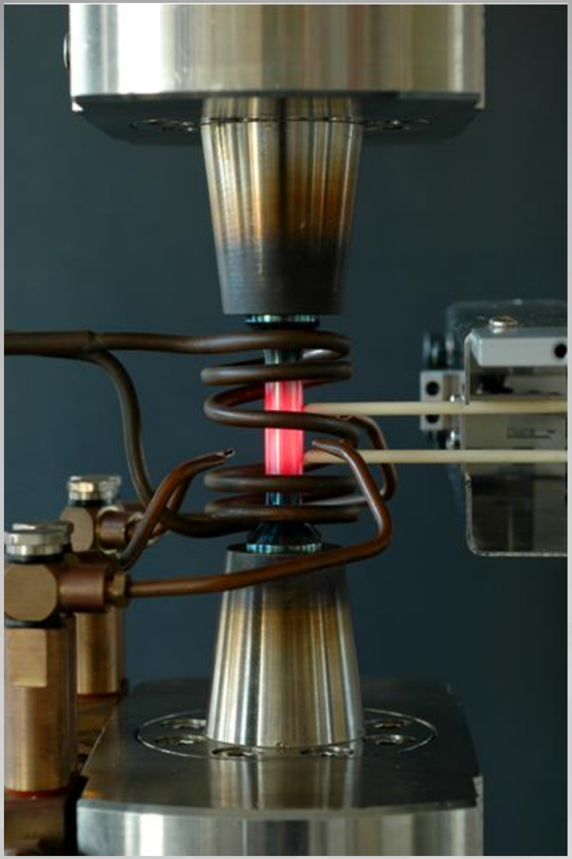






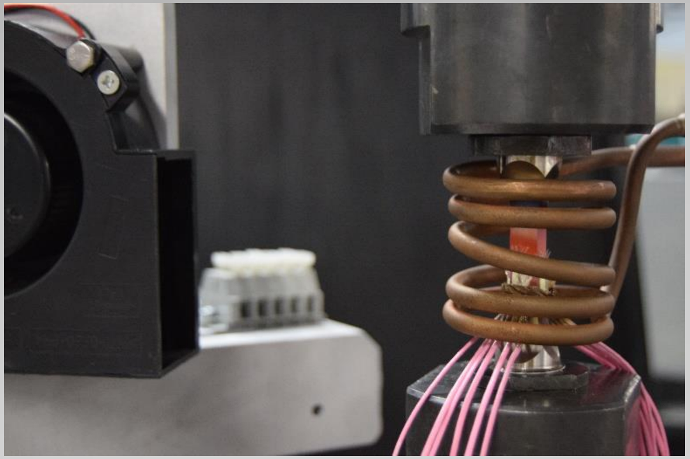
- ASTM E2368-10. Strain Controlled TMF Testing, 2010.
- ISO 12111:2011. Strain-controlled TMF Testing, 2011.
- BAM. CoP Force-Controlled TMF Testing, 2015.

Forced Air Cooling

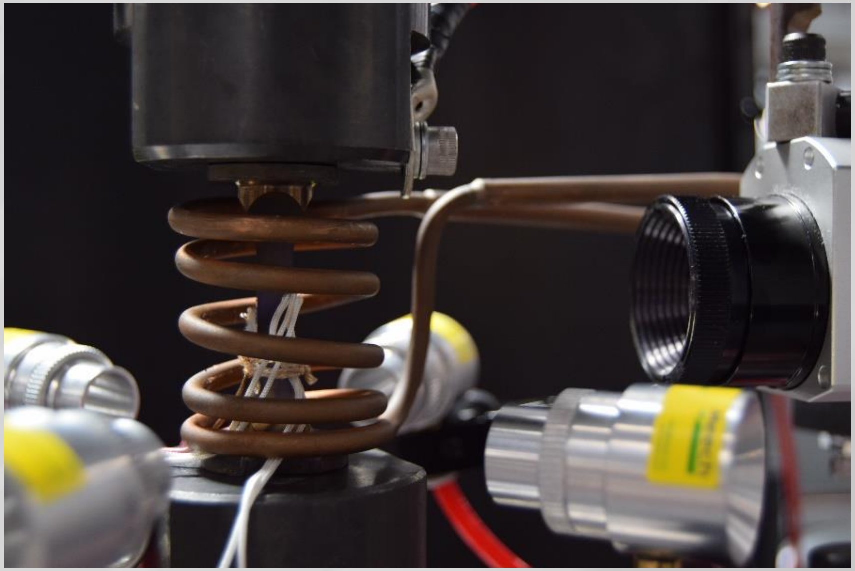


Localised/Focused Cooling

Basic Fan Cooling

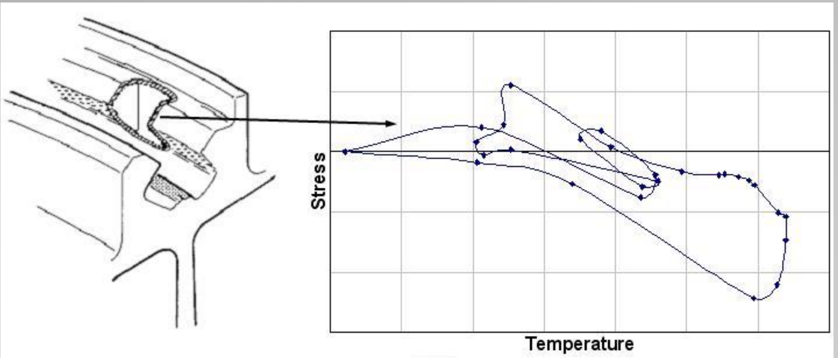


Diffuse uniform cooling through air amplifiers



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



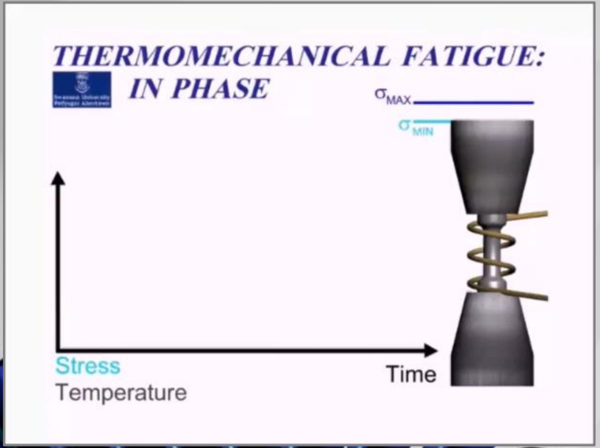
- Extrapolation of isothermal fatigue (IF) results to incorporate these effects show limited success
- Generation of TMF data is required to allow the development of lifing methodologies under TMF loading

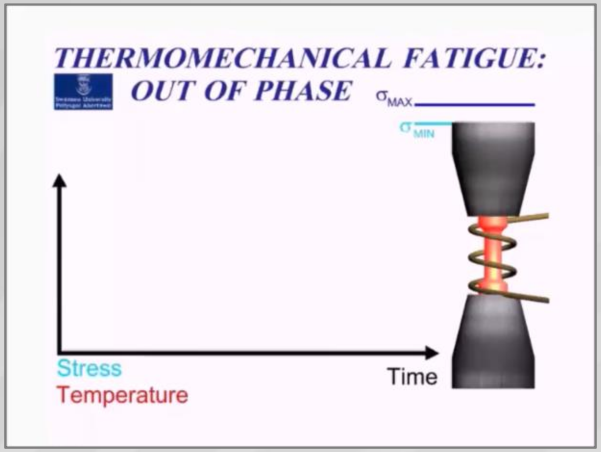
Thermo-Mechanical Fatigue (TMF)

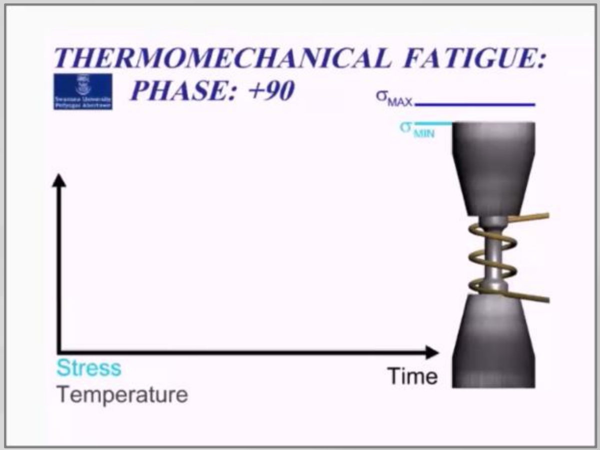
- Diverse mechanisms are involved, Primarily . . .

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
- Resulting in strain R ratios varying between 0 and -∞ depending on the phase angle, ϕ.







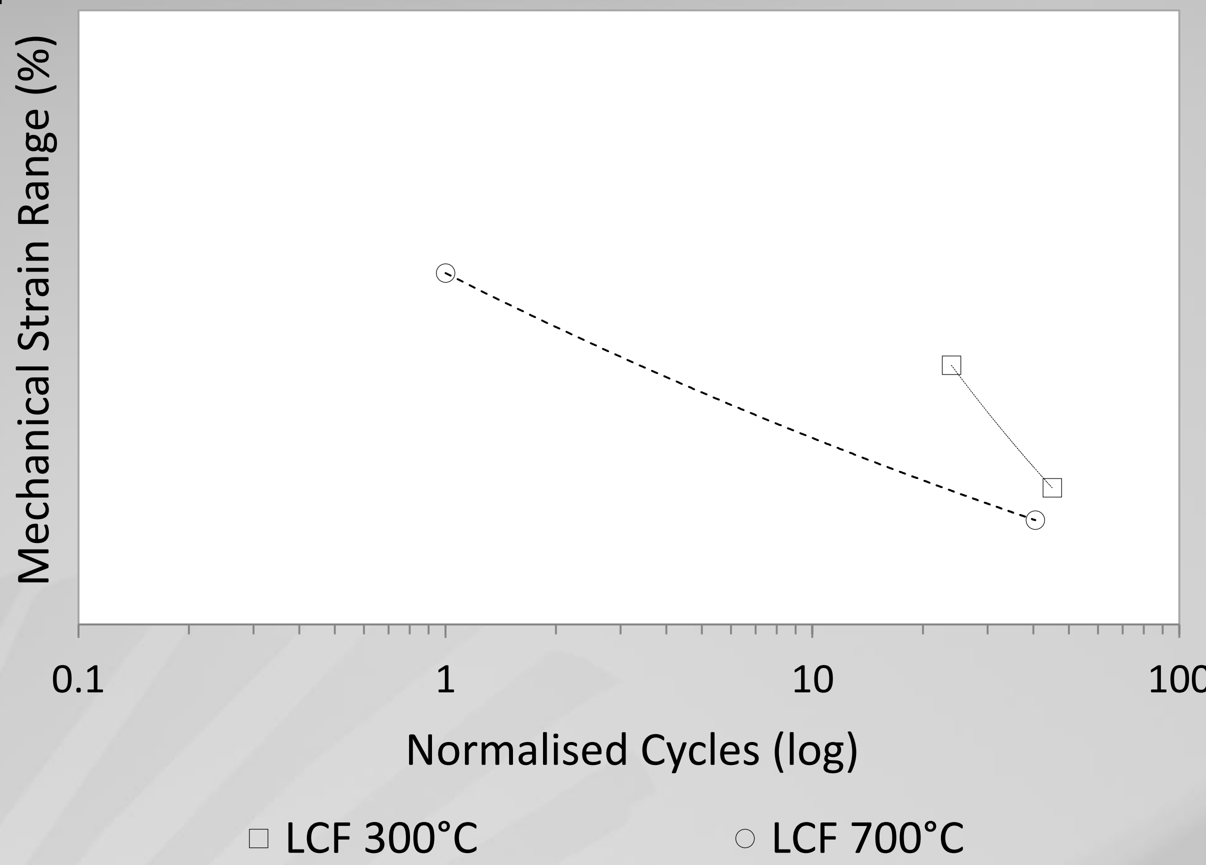
Primary factors affecting TMF life

- R ratio
- Peak strain/stress
- Strain/stress range
- Strain rate
- Environment
- TMAX
- TMIN
- ΔT
- Phase angle
- Loading direction

TMF total life testing

General TMF Life Trends

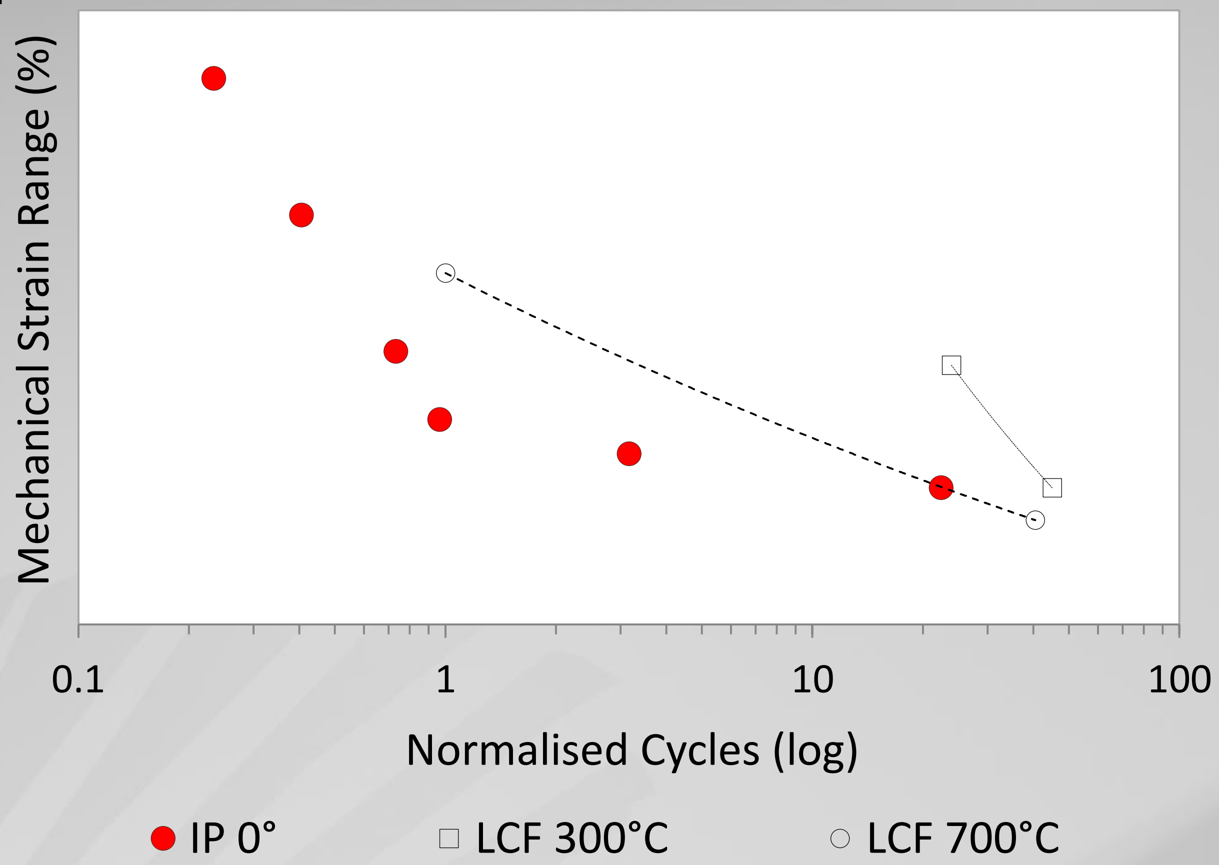
- TMF life ≤ LCF life



Typical RR1000 TMF behaviour

General TMF Life Trends

- TMF life ≤ LCF life
- At Intermediate Δε
  - IP life ≤ OP life
  - IP, INTER-granular cracking



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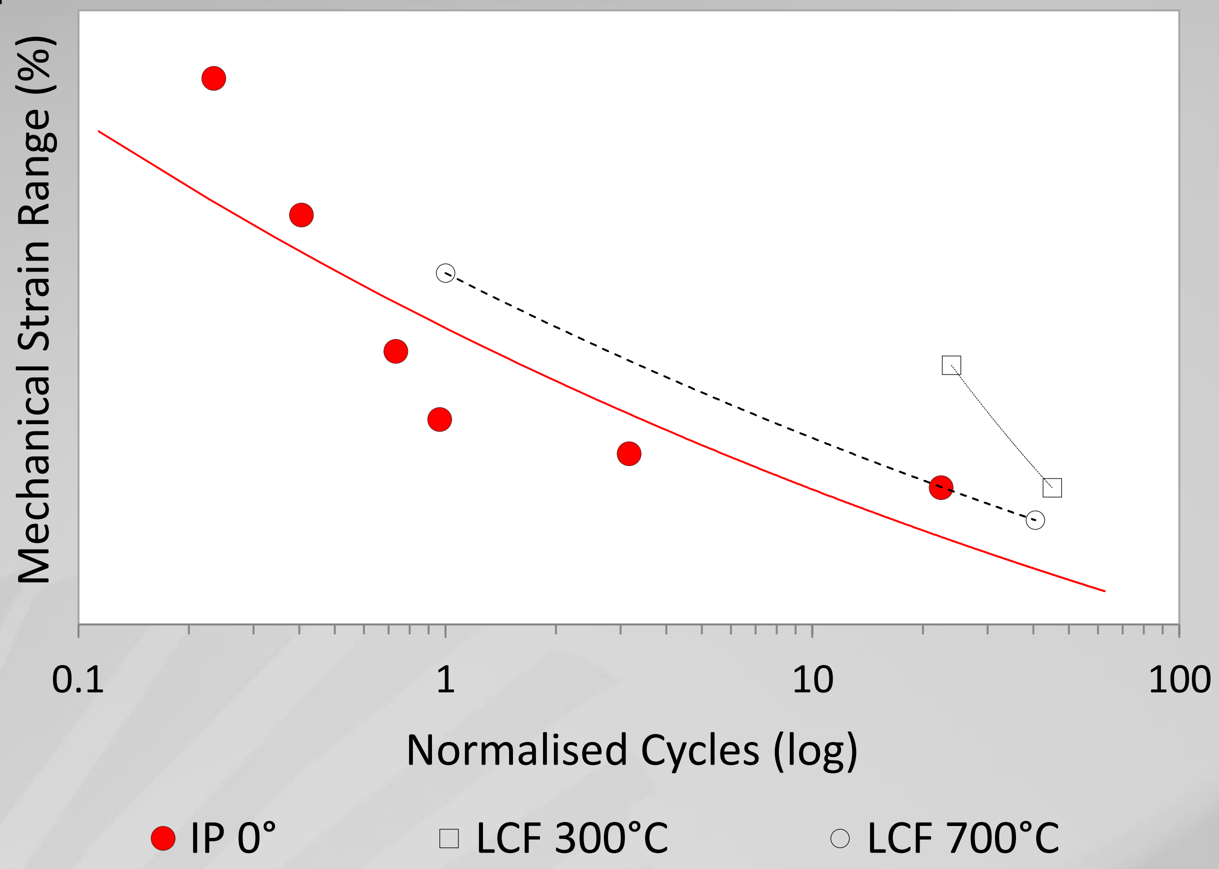

Typical RR1000 TMF behaviour

General TMF Life Trends

- TMF life ≤ LCF life
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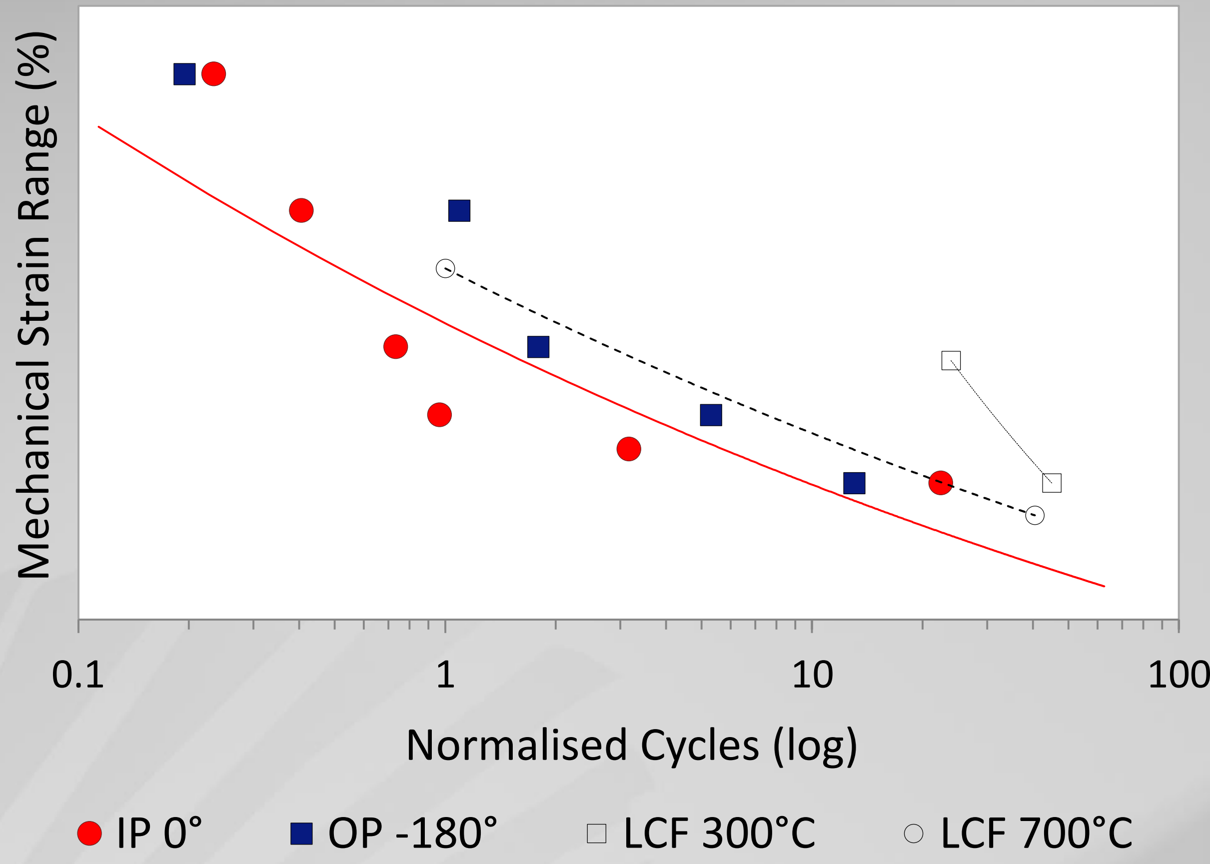
- At Low Δε
  - OP life ≤ IP life
  - OP, TRANS-granular cracking



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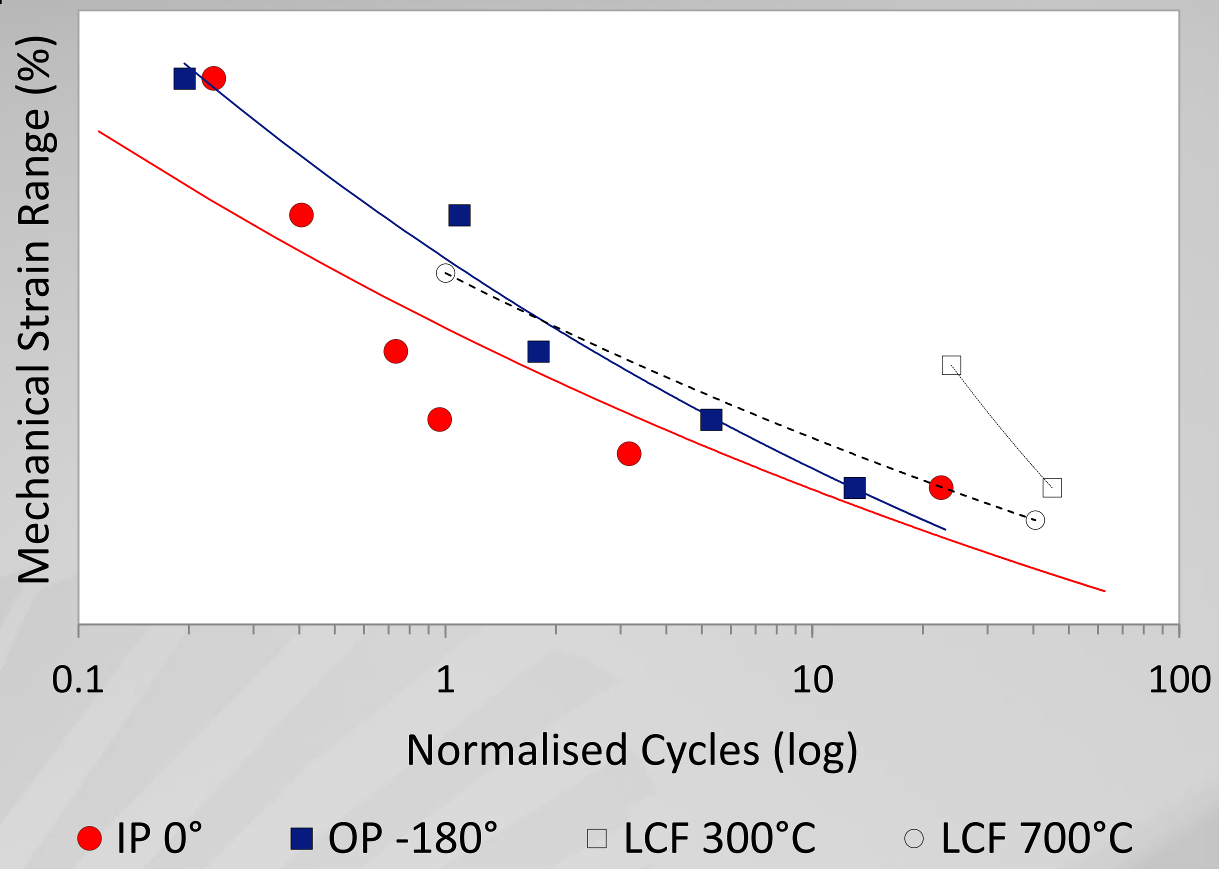
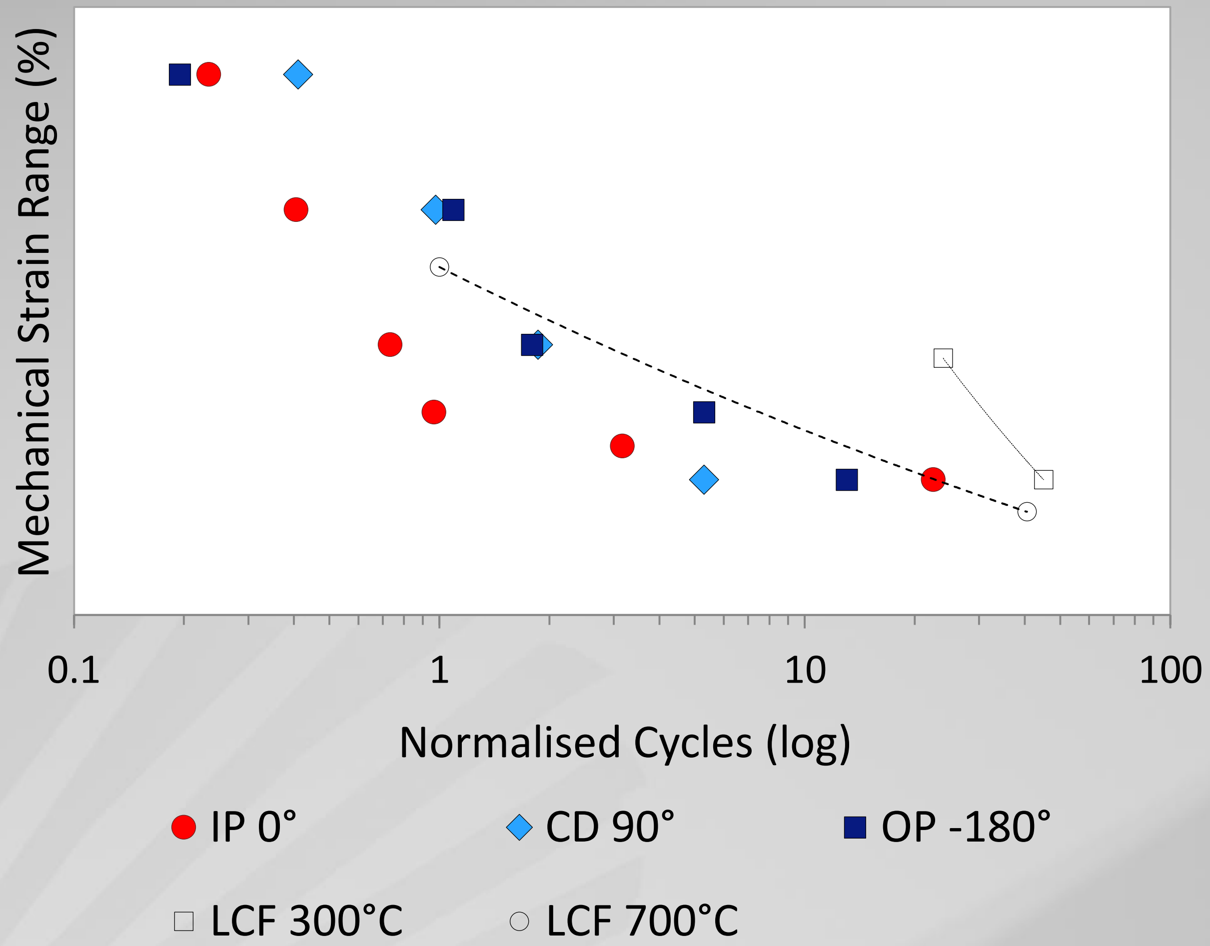


Typical RR1000 TMF behaviour

General TMF Life Trends

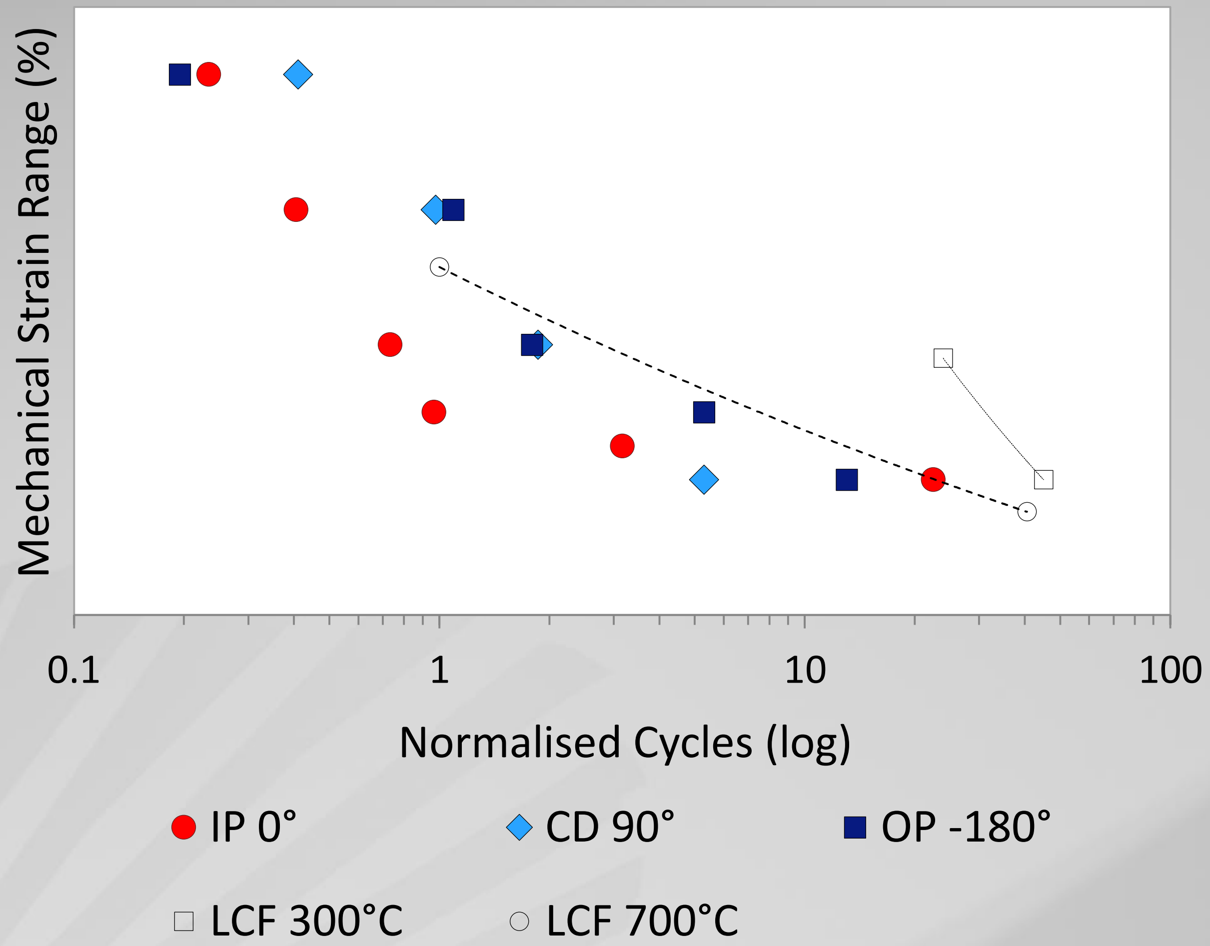
- At Low Δε
  - CD90 life ≤ IP & OP



Typical RR1000 TMF behaviour

General TMF Life Trends

- At Low Δε
    - CD90 life ≤ IP & OP



Typical RR1000 TMF behaviour

General TMF Life Trends

- At Low Δε
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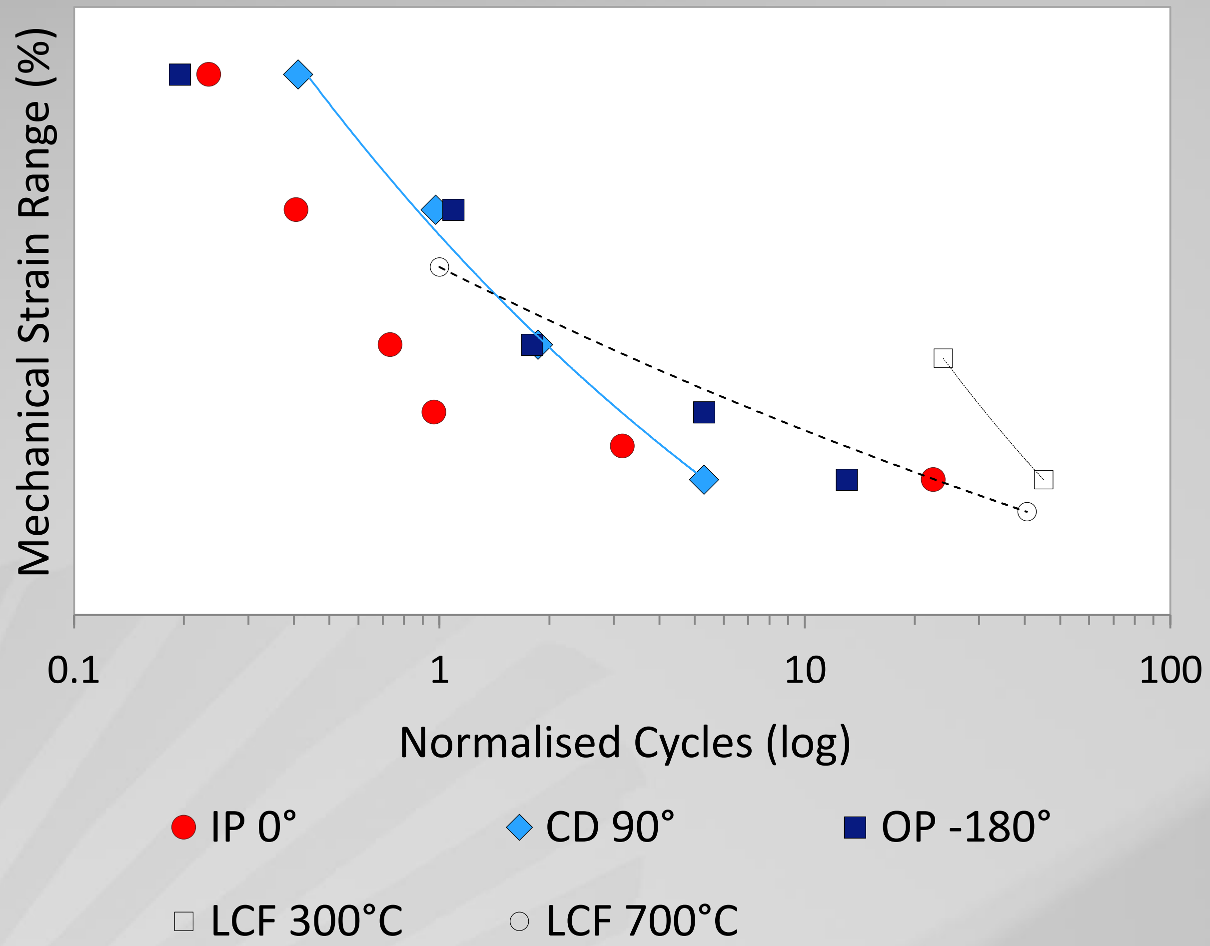
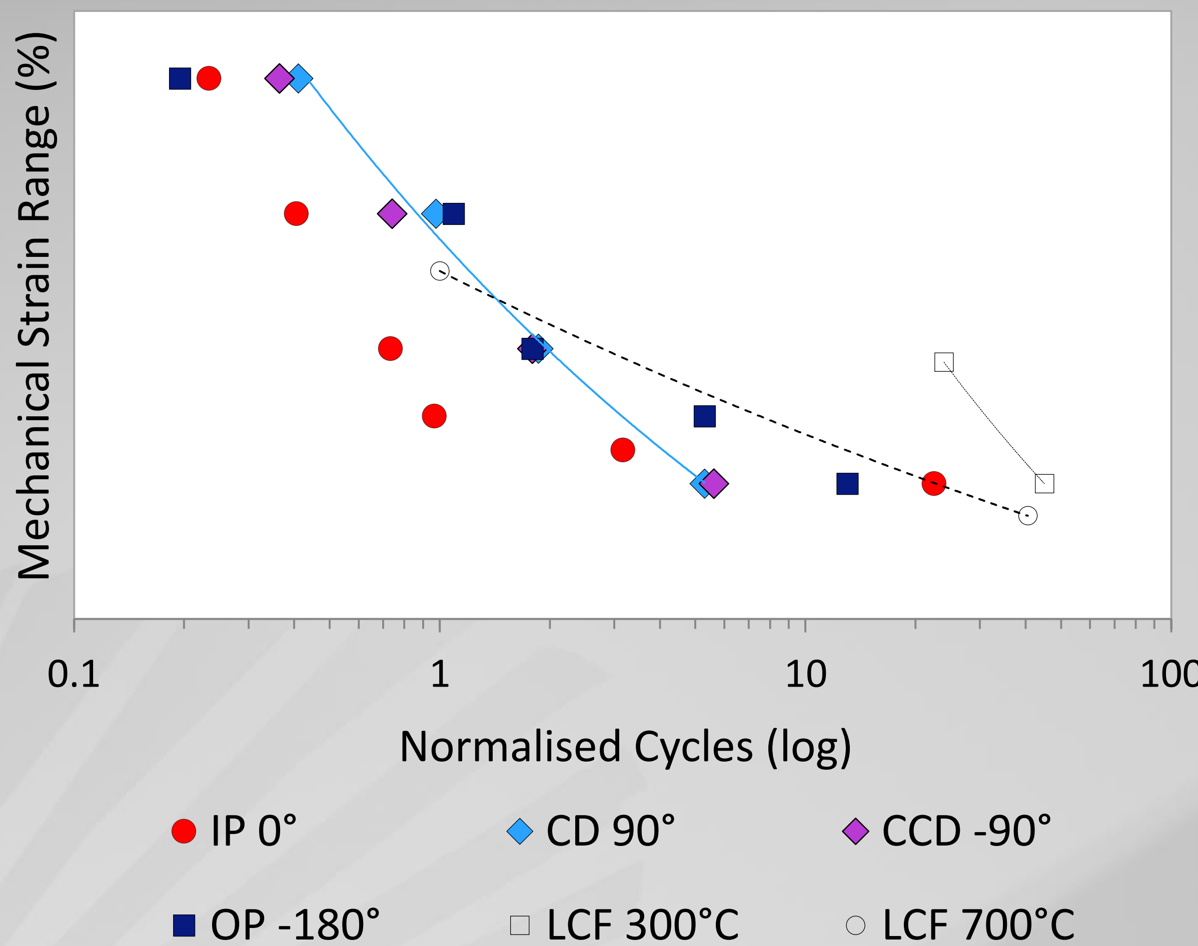


Typical RR1000 TMF behaviour

General TMF Life Trends

- At Low Δε
  - CD90 life ≤ IP & OP
- CD Life ≈ CCD across all strain ranges



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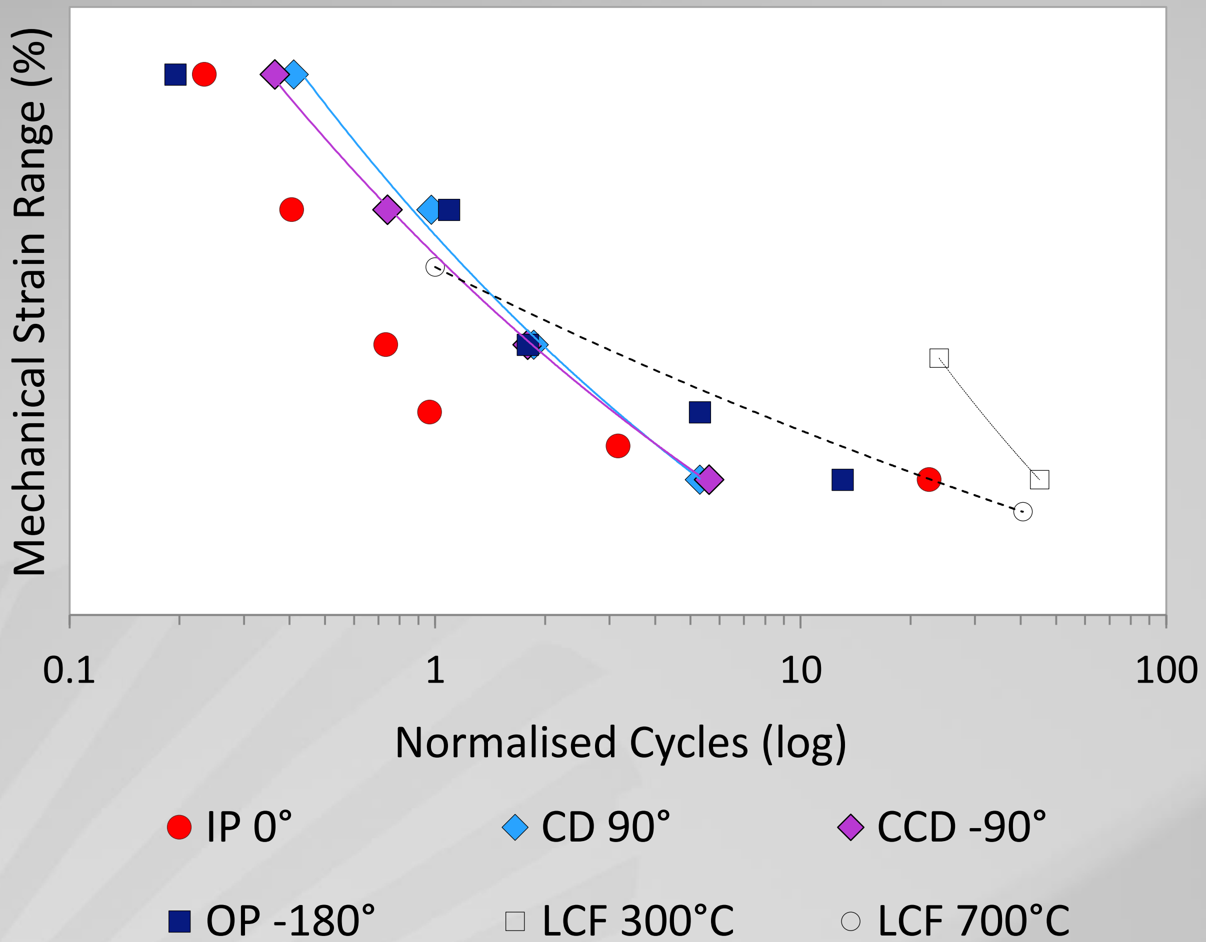
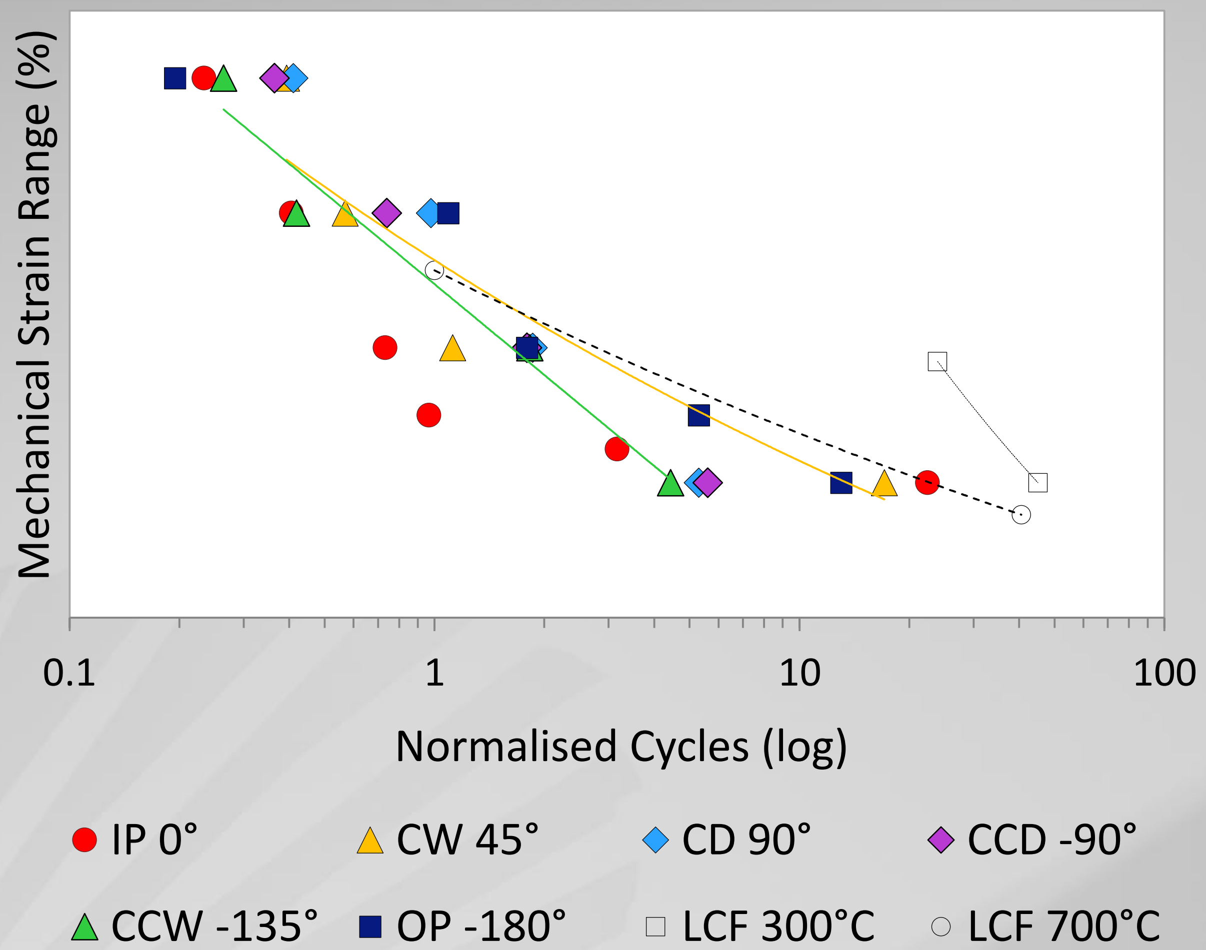


Typical RR1000 TMF behaviour

General TMF Life Trends

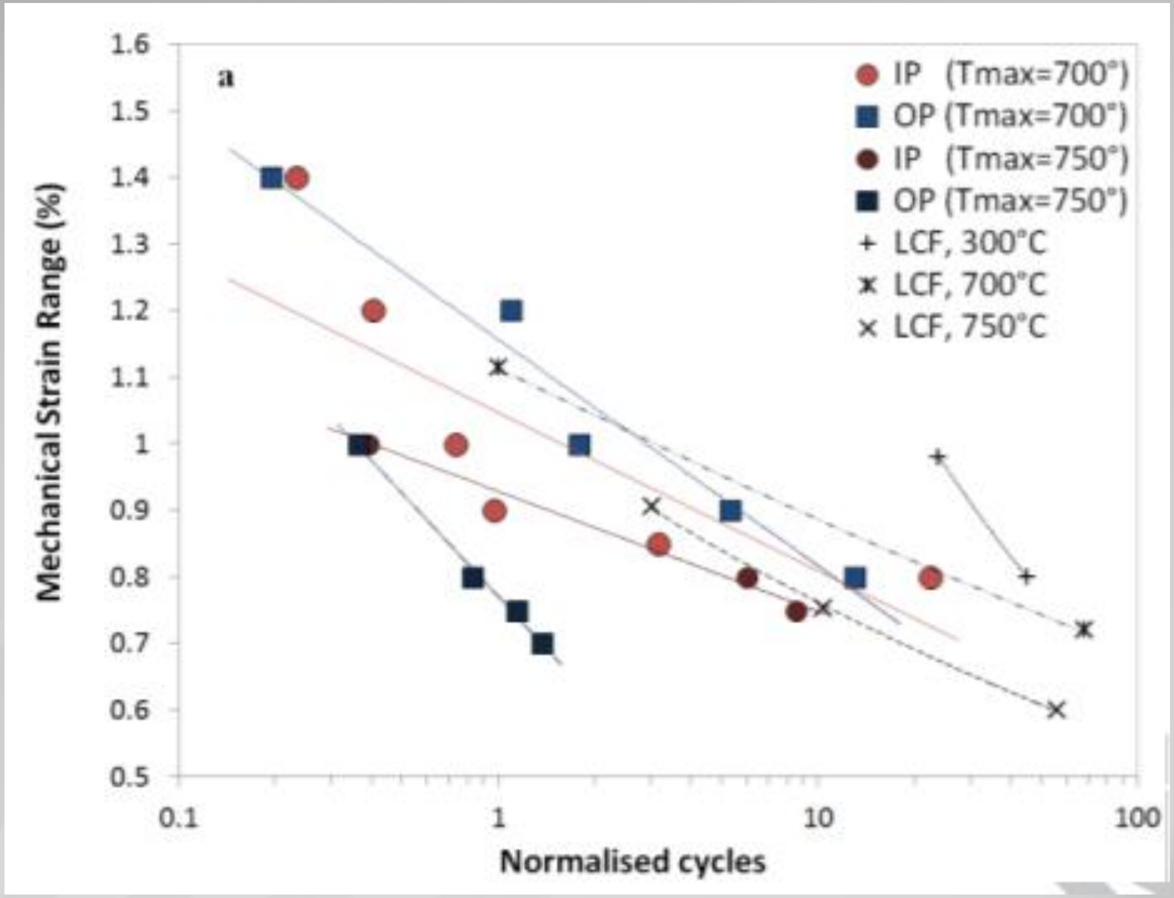
- CW45° loading follows a similar trend to IP loading
- Counter Clockwise -135° loading reduces fatigue life, similar slope to OP loading



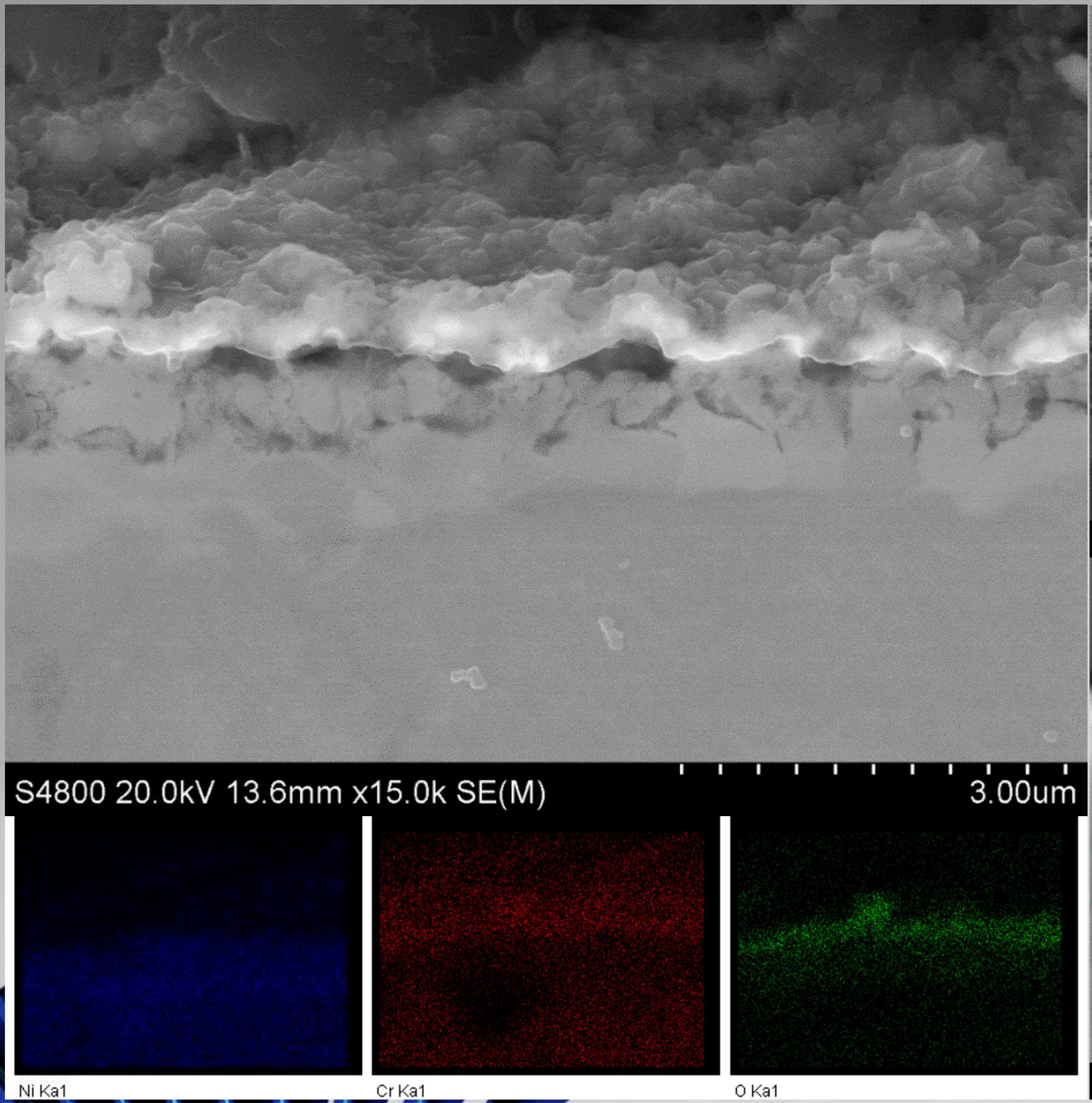
Effect of peak temperature

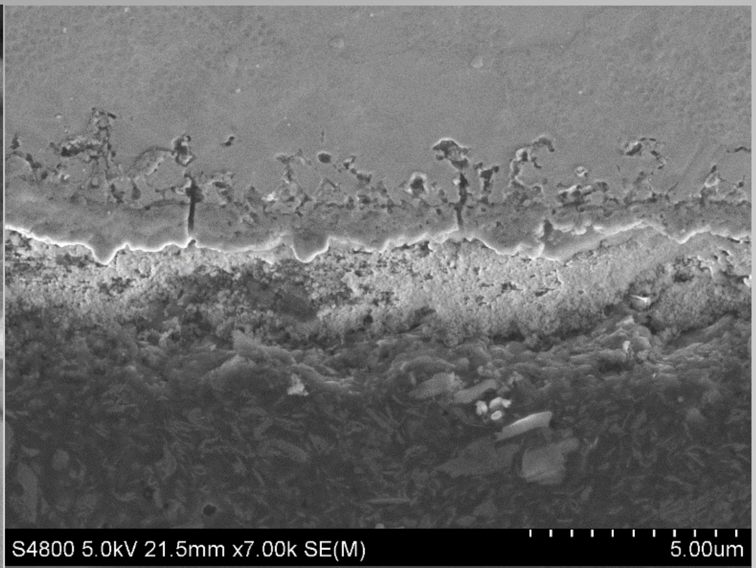
At 750C OOP data shows a significant decrease in TMF life.

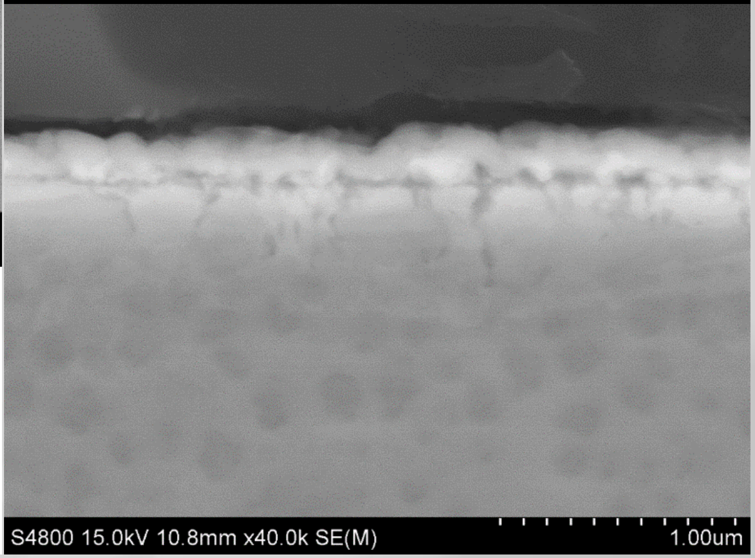
Likely to be due to increased oxidation effects



Oxidation damage

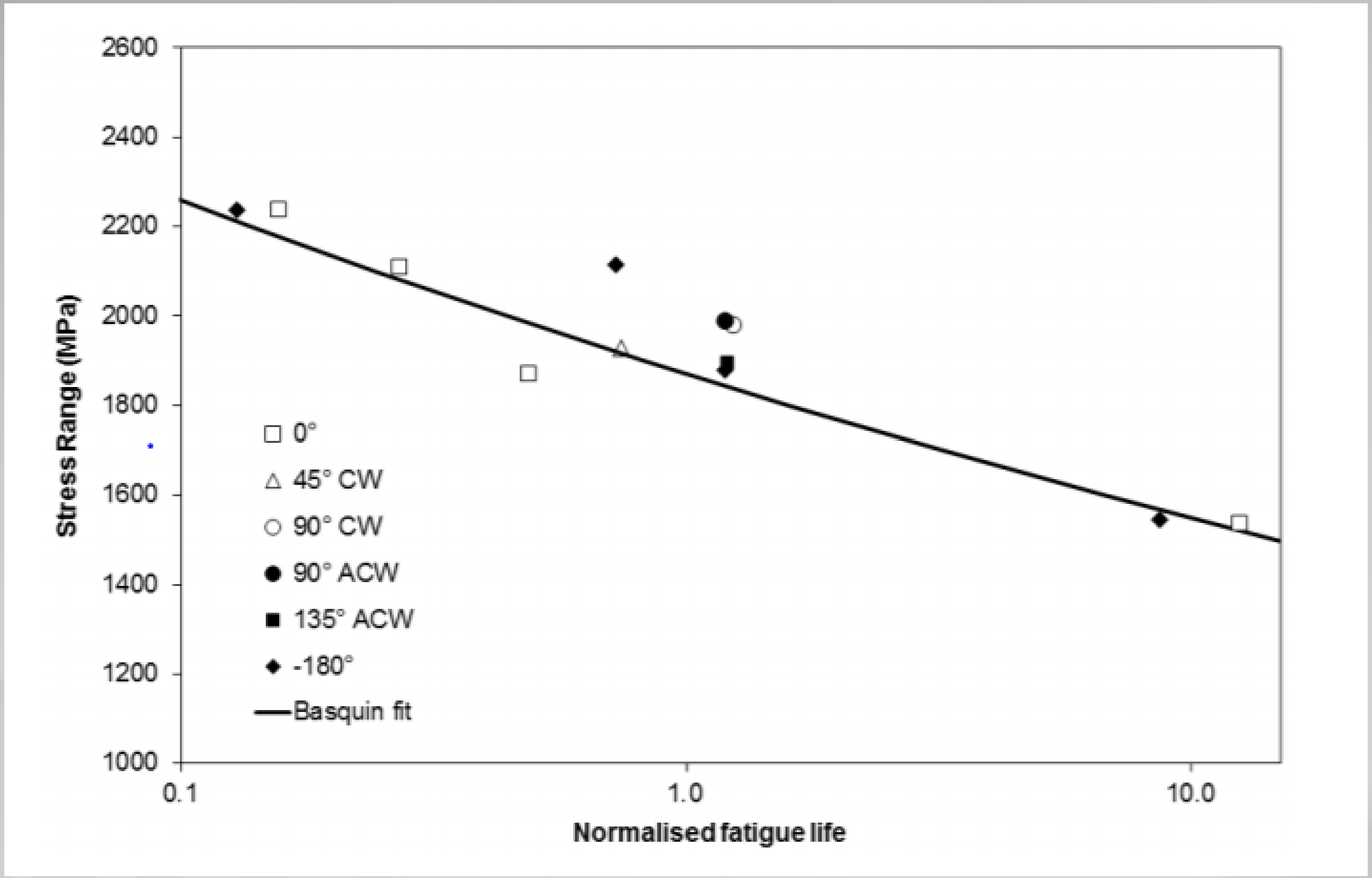






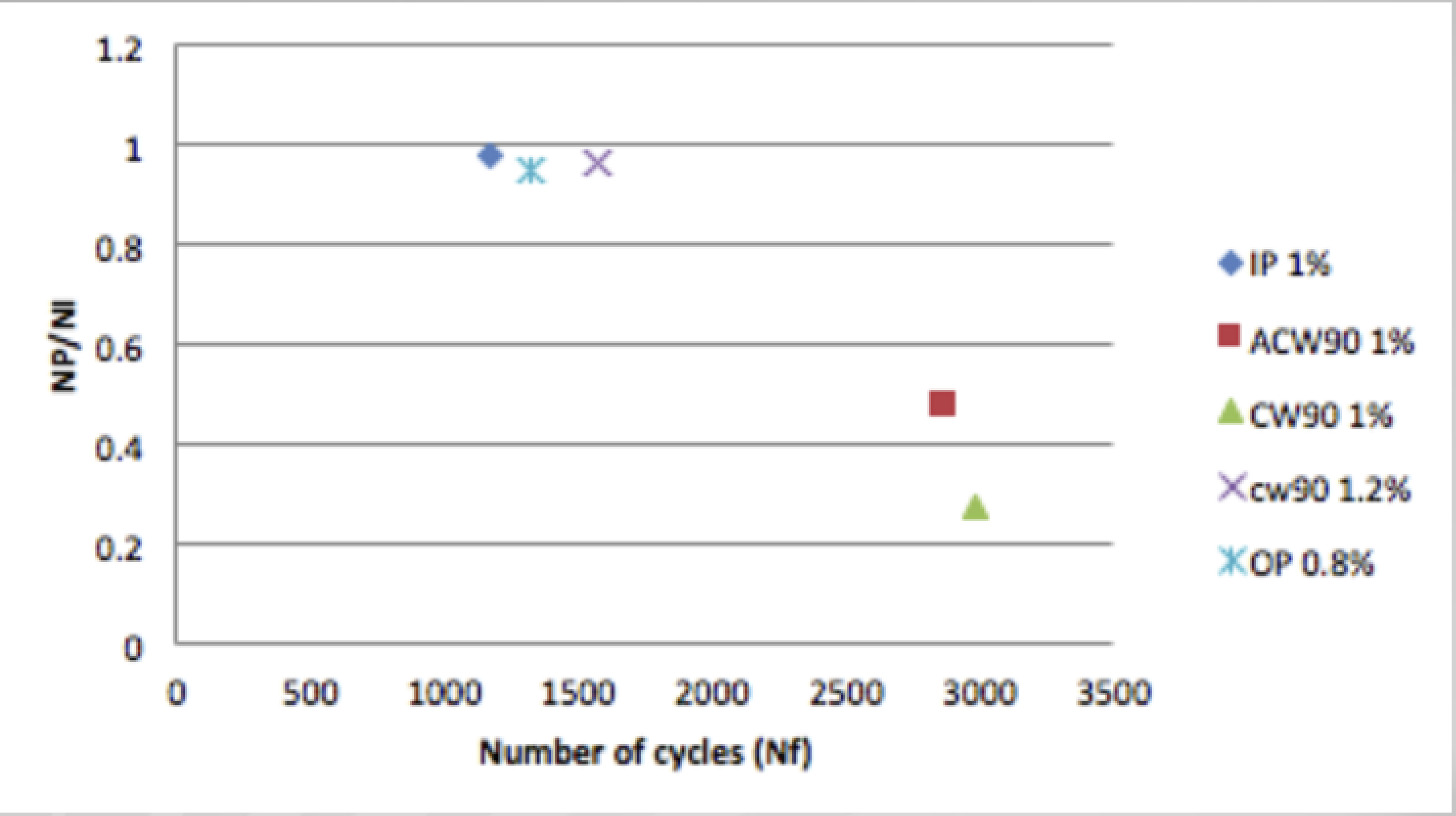
Lifing approaches (Basquin)

Stress based approaches such as Basquin don’t take account of crack propagation



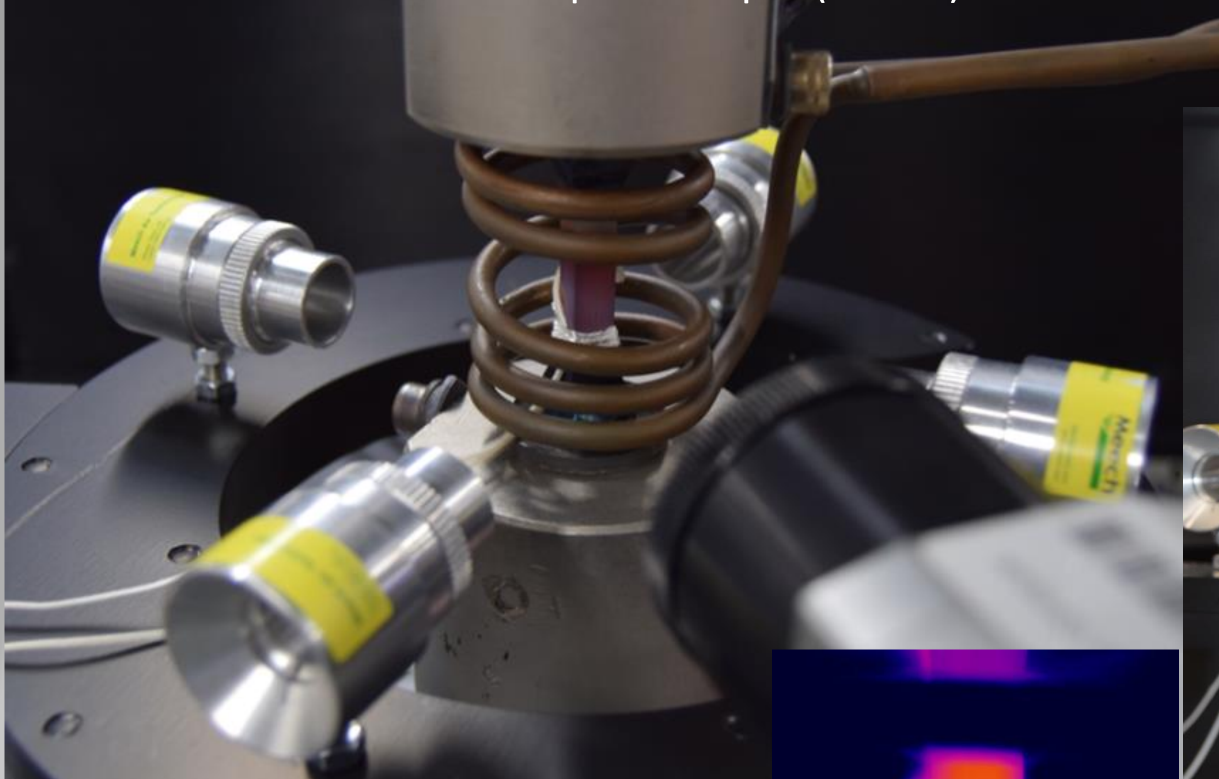
Crack propagation

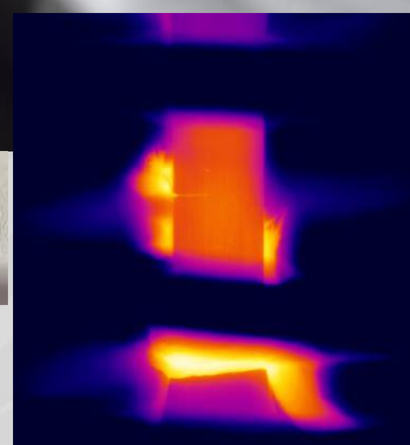
For fatigue lives that are less than 5000 cycles it is not appropriate to consider only crack initiation as the dominant factor in fatigue life.

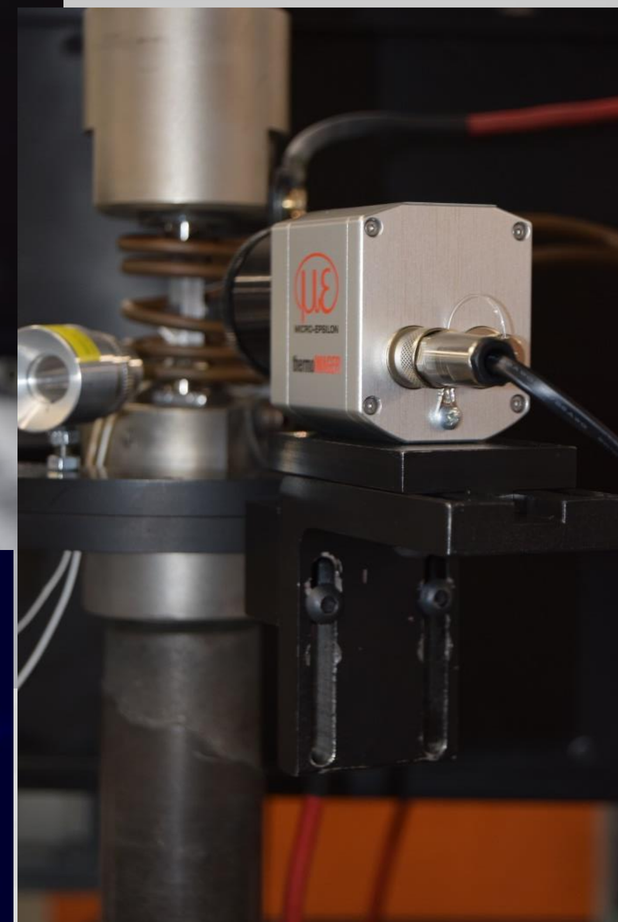


TMFCG Test Development

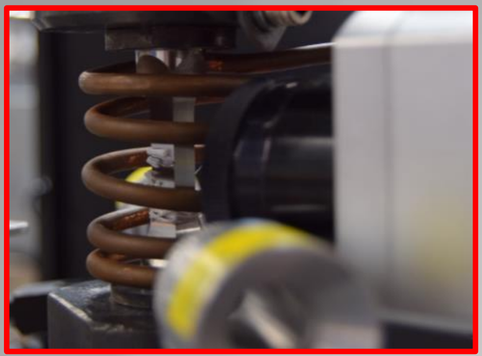
Direct Current Potential Drop technique (DC PD)

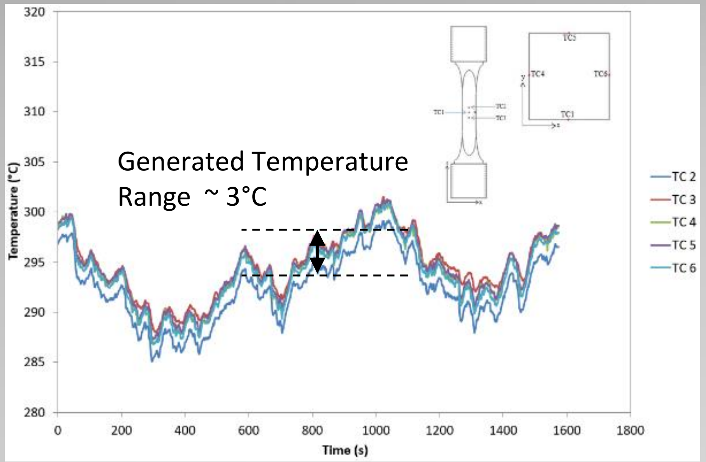


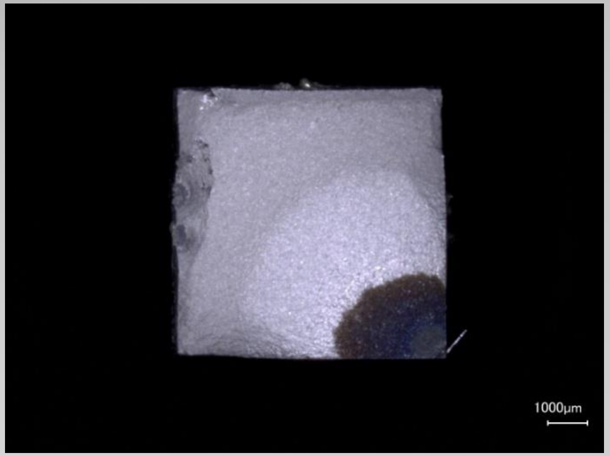


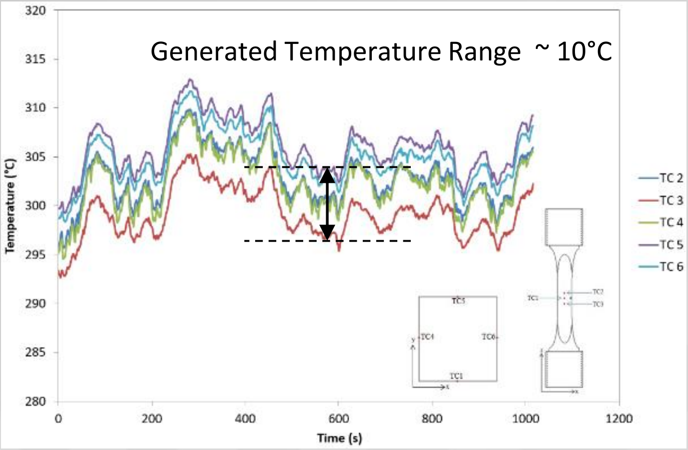


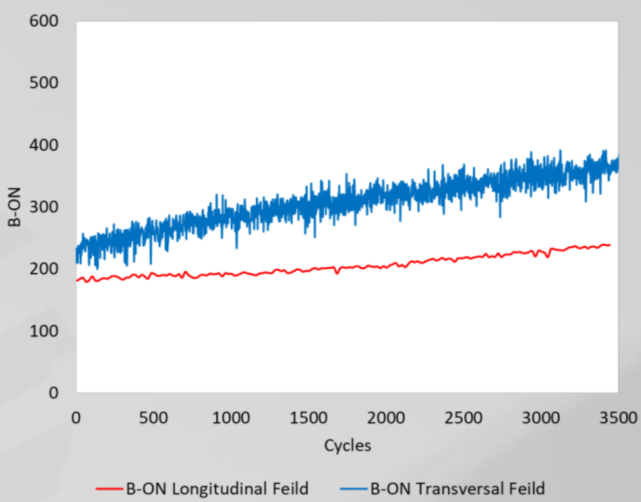
Induction Coil Designs



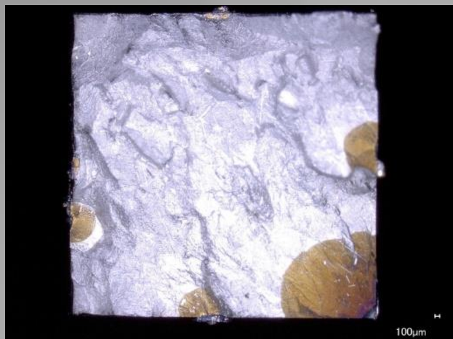






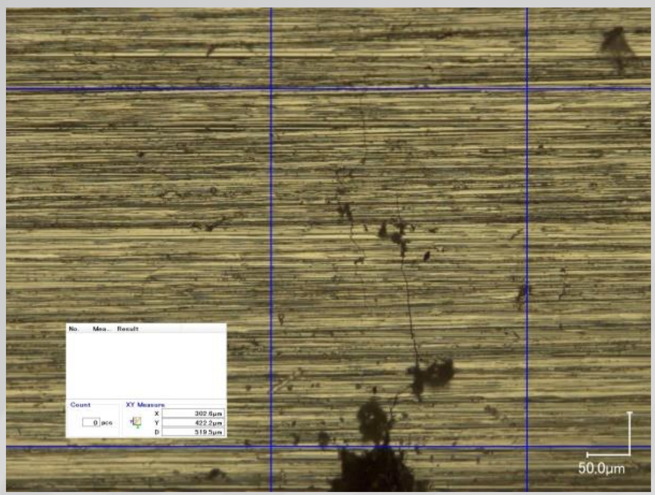


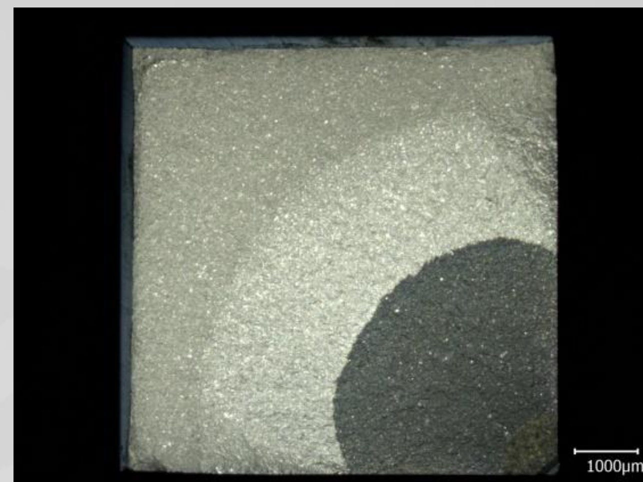
Pre-Crack Procedure



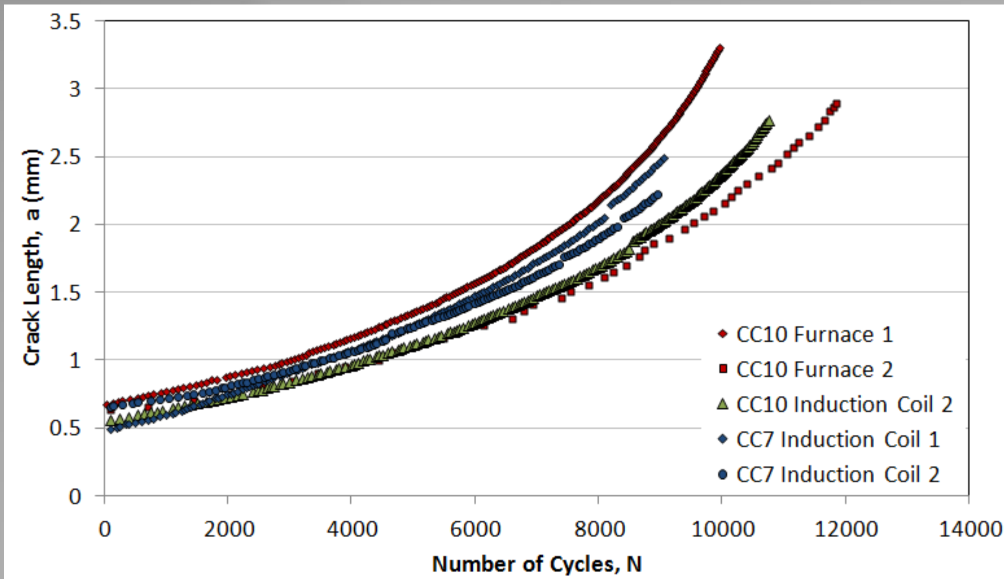
Thermo-Mechanical Fatigue Crack Growth Pre-Cracking

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

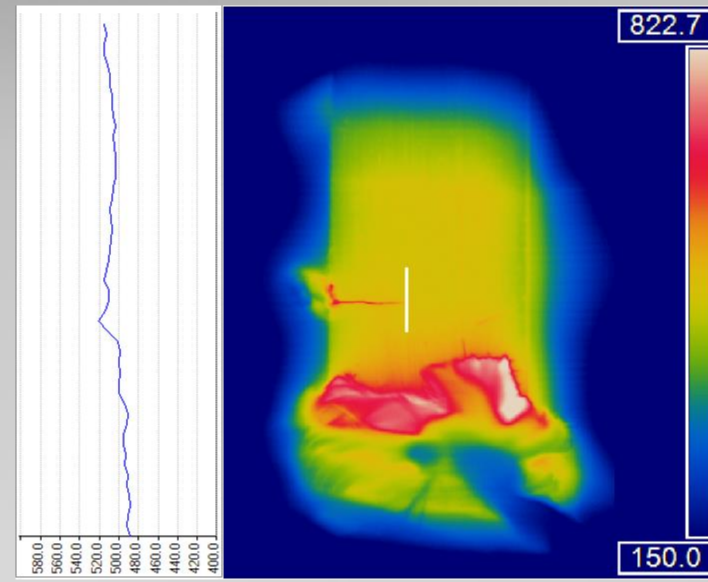




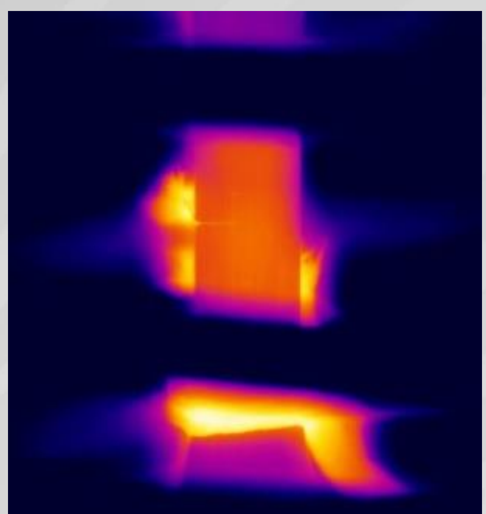
Crack Tip Heating Investigations



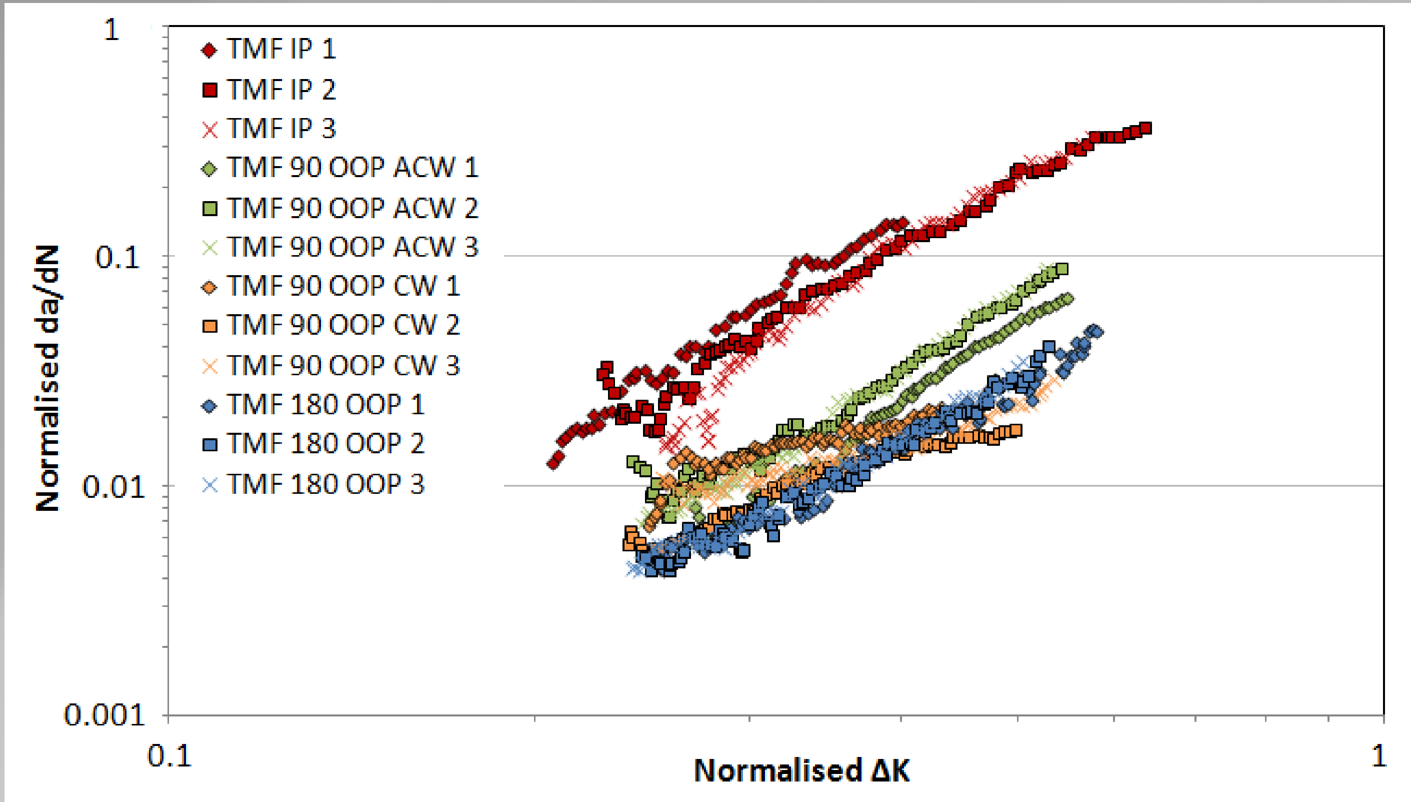
Waspaloy crack length vs. number of cycles: furnace and induction coil comparisons at 650°C, 450MPa and R=0.1.



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



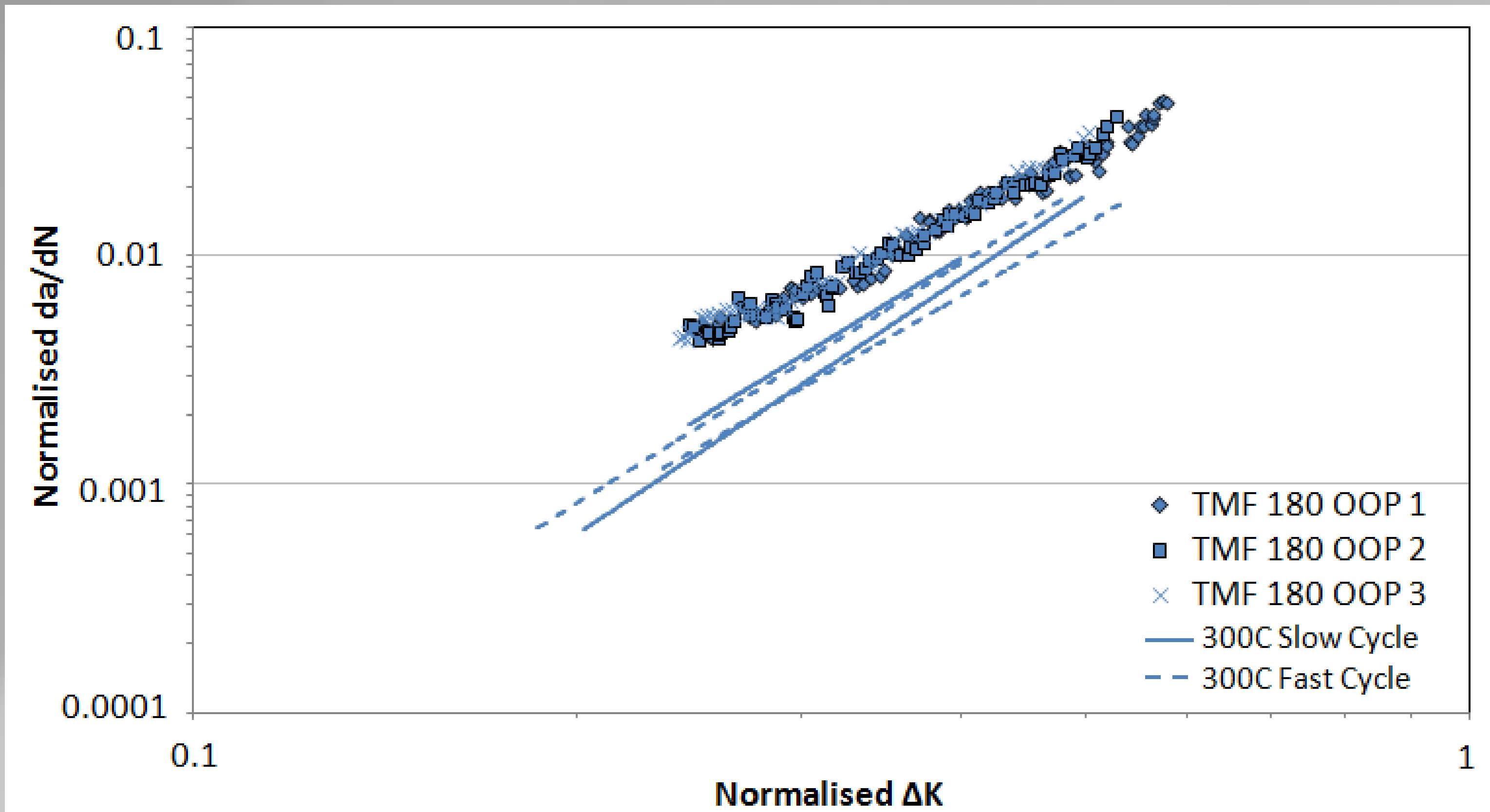
FG RR1000 TMF CP



Strong dependence on phase angle

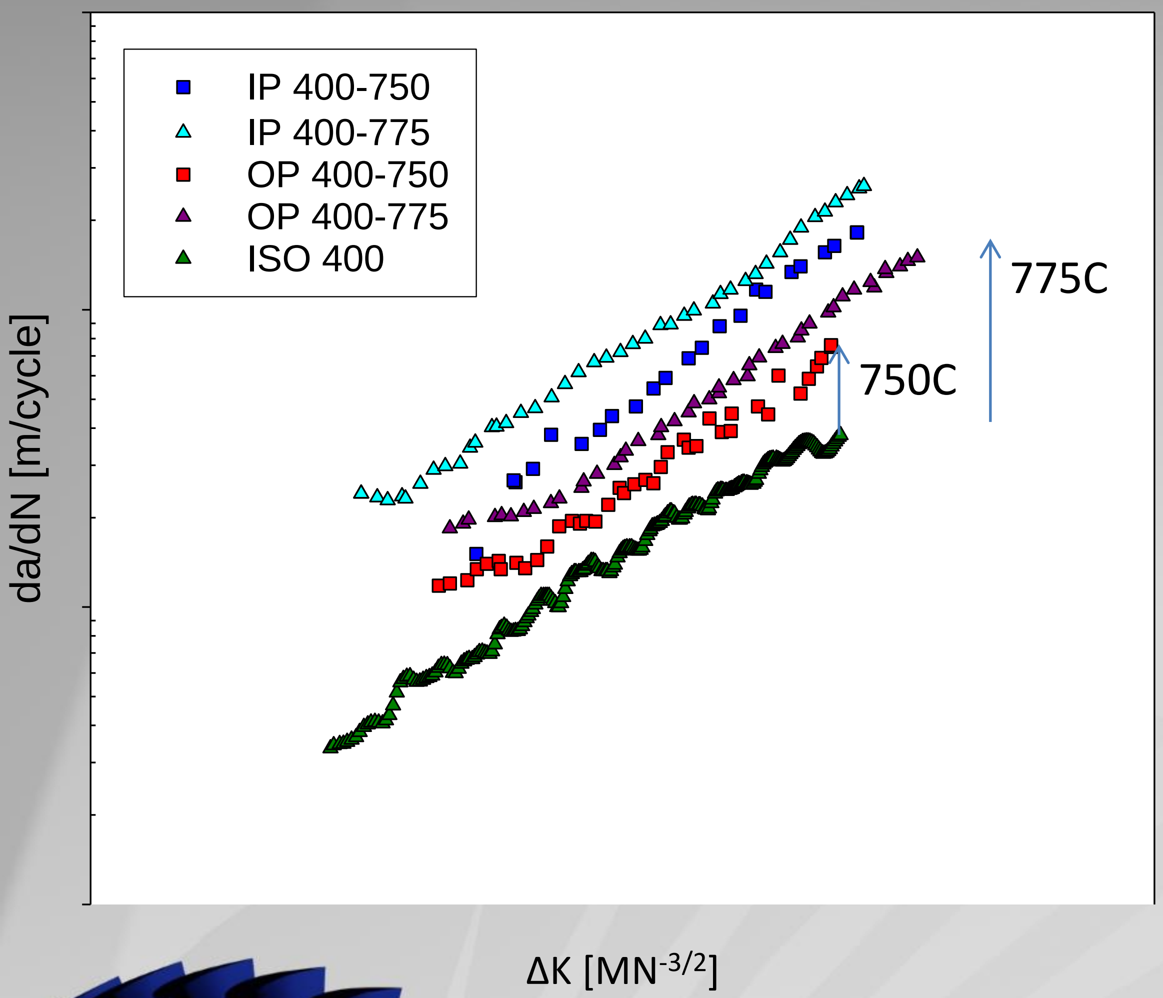
Rates tend to approximate temperature at which peak stress occurs

FG TMF CP



- Slightly accelerated rates in TMF tests at low temperature
- Influence of oxidation

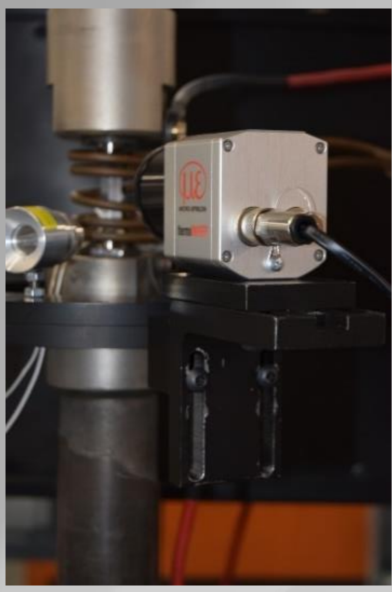
TMFCG Test Results

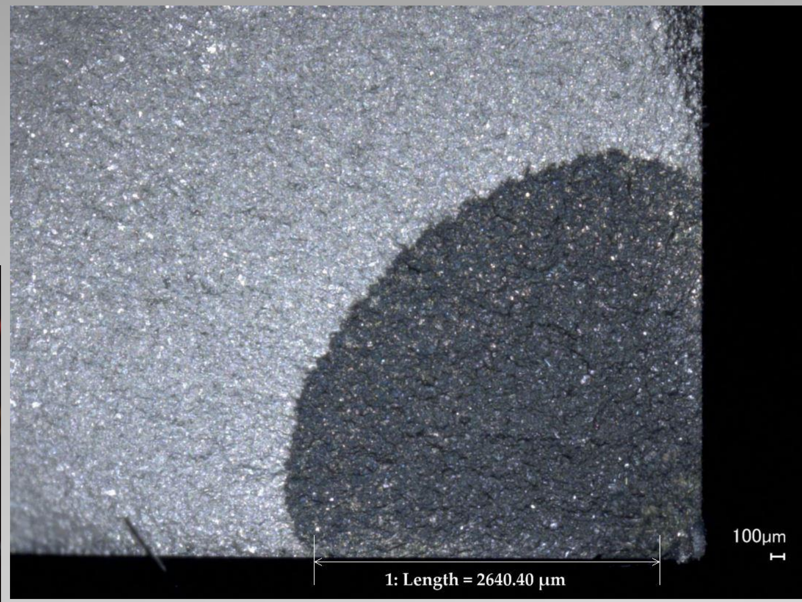


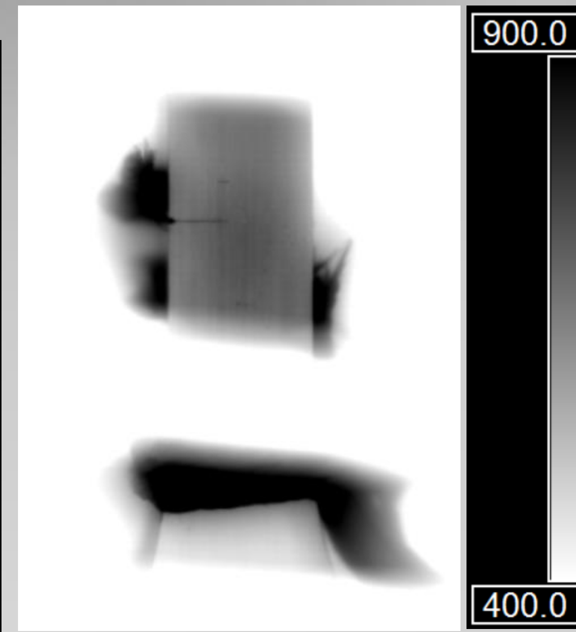
CG RR1000

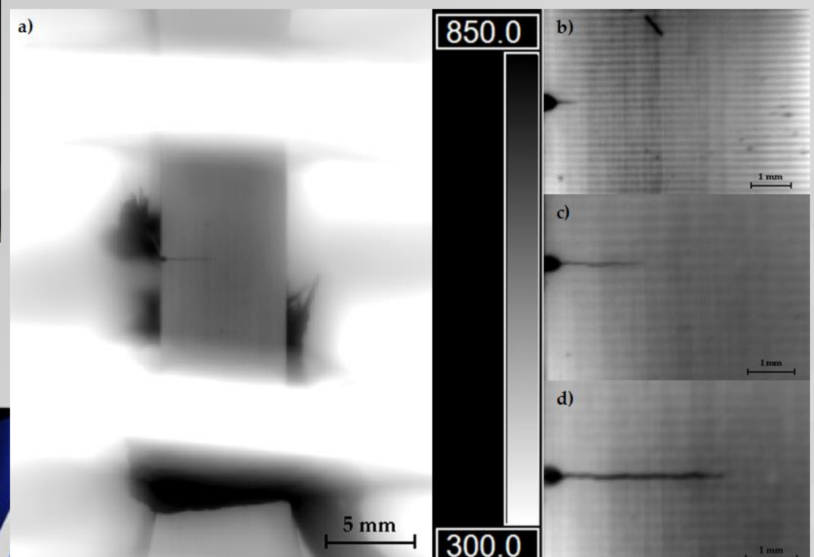
- In phase tests show faster rates than equivalent isothermal tests
- Dependent on cycle time
- In OOP tests increased Tmax influencing TMF CP rates

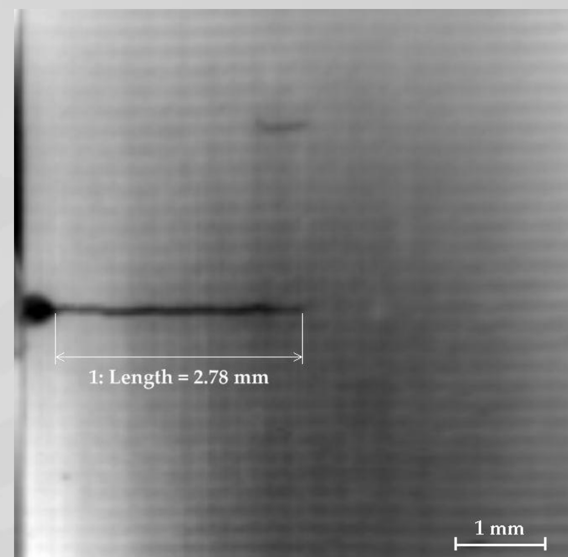
IR Crack Growth Measurements



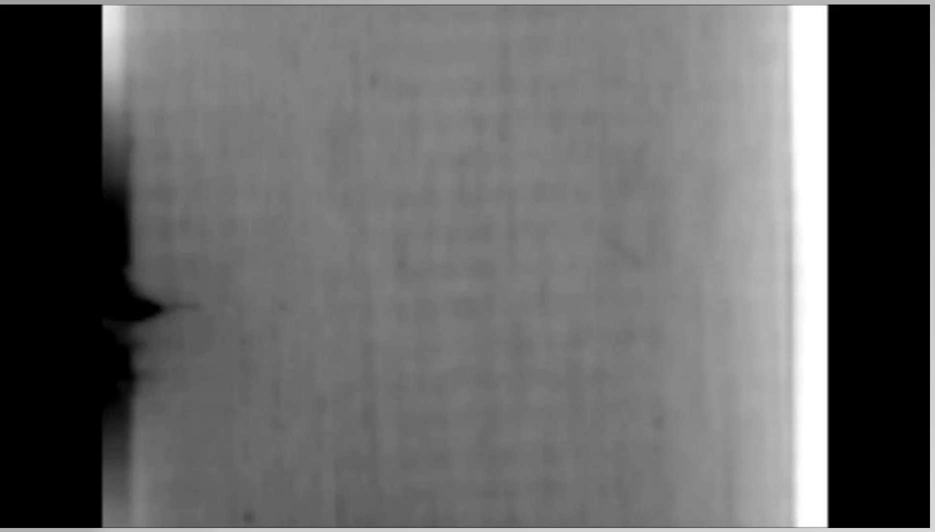


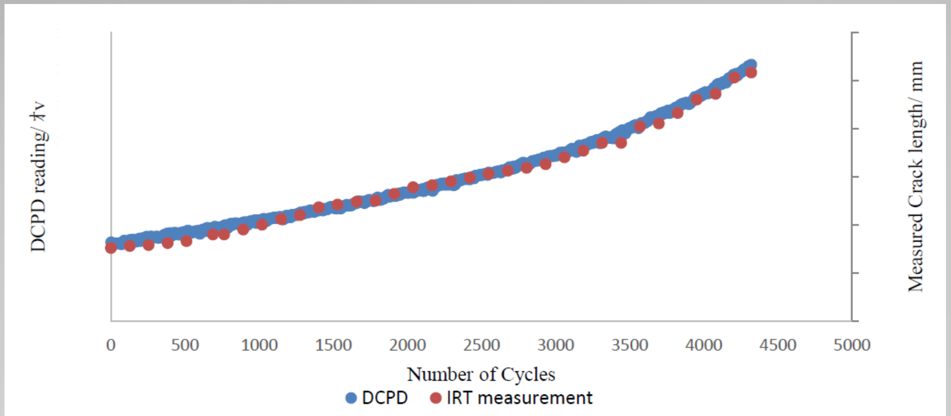


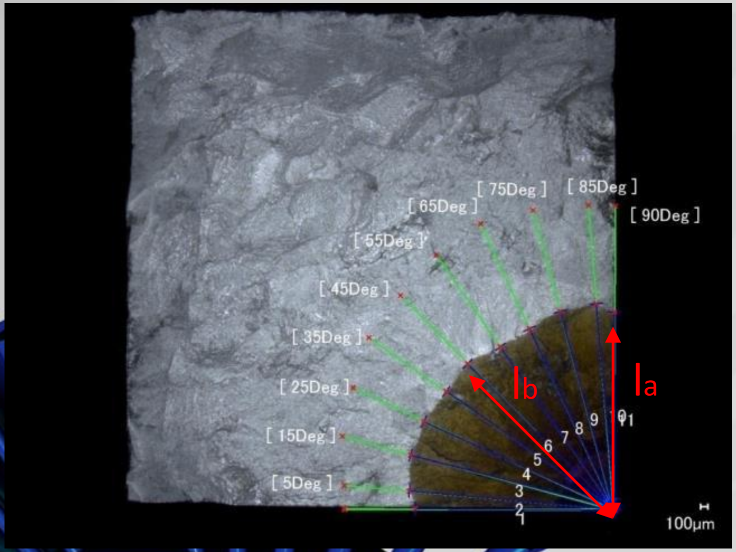




IR Crack Growth Measurements







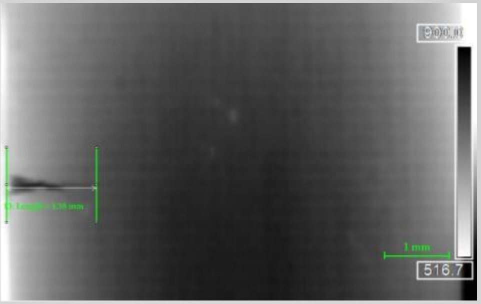


Image of surface crack length 3549 cycles

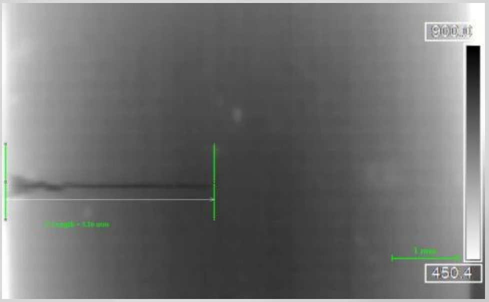


Image of surface crack length after 6549 cycles

Non-Invasive TMFCG

A completely Non-Invasive TMFCG test method

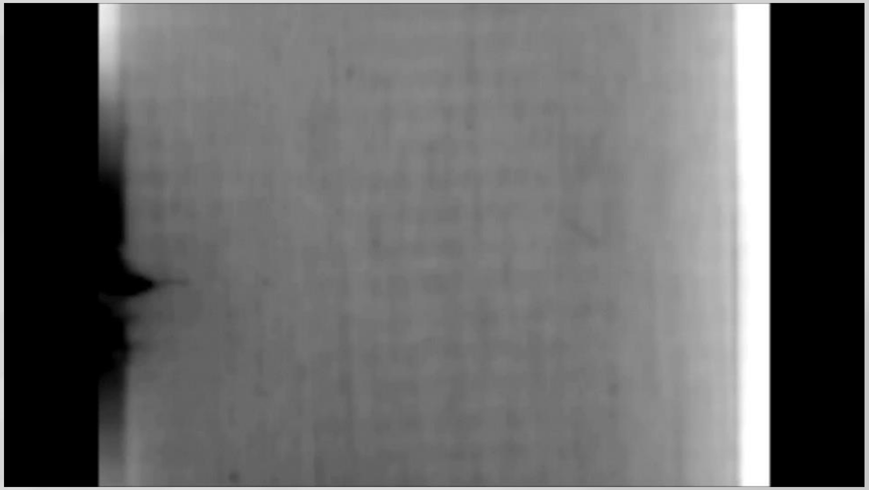
<u>*Advantages*</u> * Avoid complications with thermocouple control

- Crack initiations at welds.
- Thermocouple shadowing and or over/undershooting

J. P. Jones, S. P. Brookes, M. T. Whittaker, R. J. Lancaster and B. Ward. "Non-Invasive Temperature Measurement and Control Techniques under Thermo-Mechanical Fatigue Loading". Materials Science and Technology Journal. 2014.

J. P. Jones, S. P. Brookes, M. T. Whittaker, R. J. Lancaster "Alternative Non-invasive temperature control and monitoring techniques". ASTM, Fourth Symposium on the Evaluation of Existing and New Sensor Technologies for Fatigue, Fracture and Mechanical Testing, 2014.

* Remove complications with PD probe attachments and coil interferences.
* Enables aggressive environmental testing to be carried out



Conclusions

- Engine operating temperatures have increased to the point where Thermo-Mechanical Fatigue (TMF) is now a critical consideration.

- TMF lives are generally reduced from isothermal fatigue at T_{max} irrespective of phase angle.

- Lifing methods based on comparisons with isothermal data at $T_{peak\ stress}$ also fail to offer appropriate predictions.

- Testing methodology for TMF is critical and many traditional techniques should be re-examined.

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

Acknowledgements

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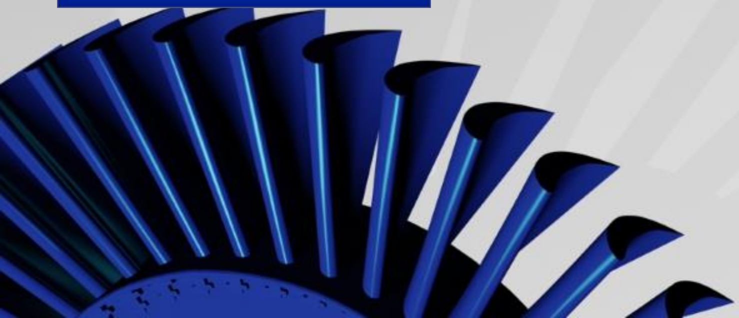
Any Questions?



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