BESPOKE SET UPS FOR THERMO-MECHANICAL FATIGUE TESTING

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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

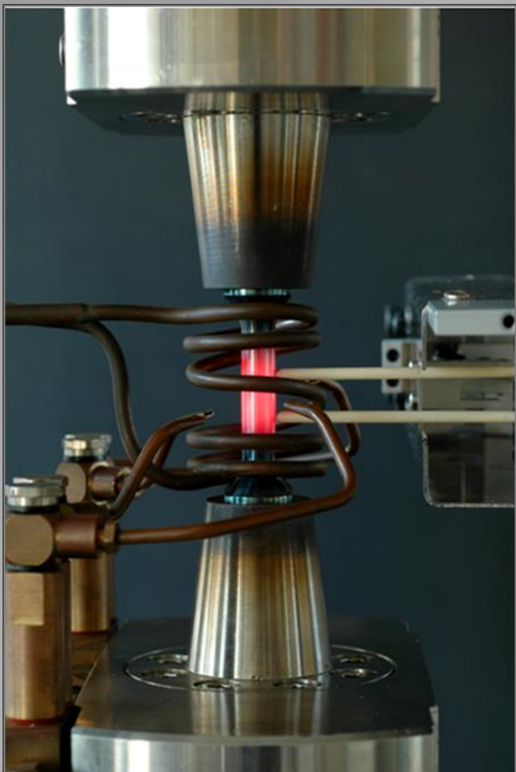
Rolls-Royce plc, UK.
Material and technical support

Introduction

- Swansea University Background in TMF
- Development of test facilities
- TMF total life testing
- Thermography
- TMFCG Test Development
- Crack tip heating investigations
- Lessons learned

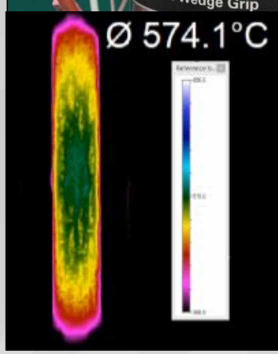
Background in TMF

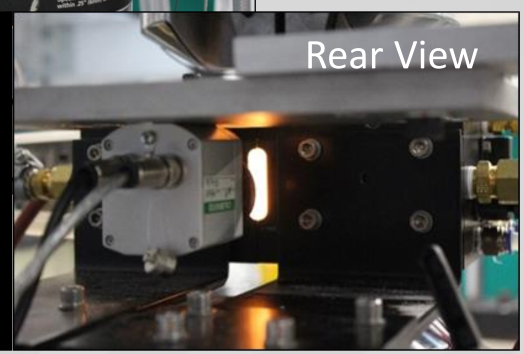
Strain Control - Induction



Pyrometer

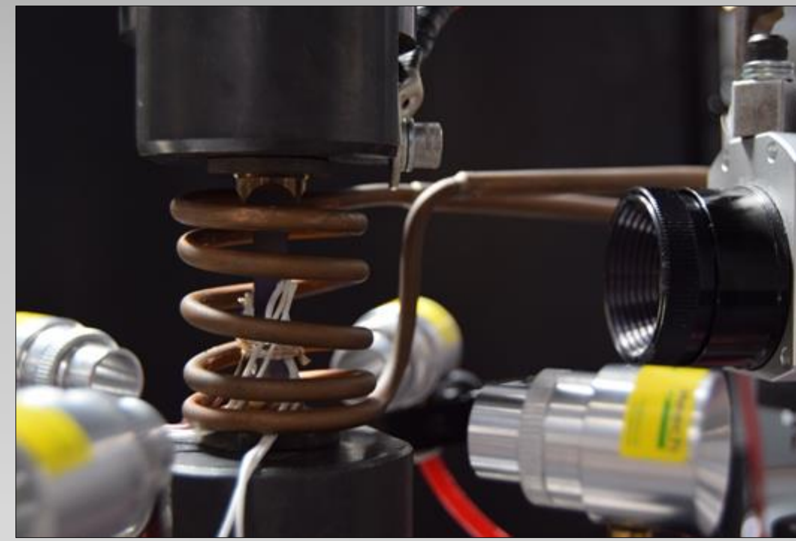
Non Metallic – Lamp Furnace





Thermography

Fatigue Crack Propagation – Induction

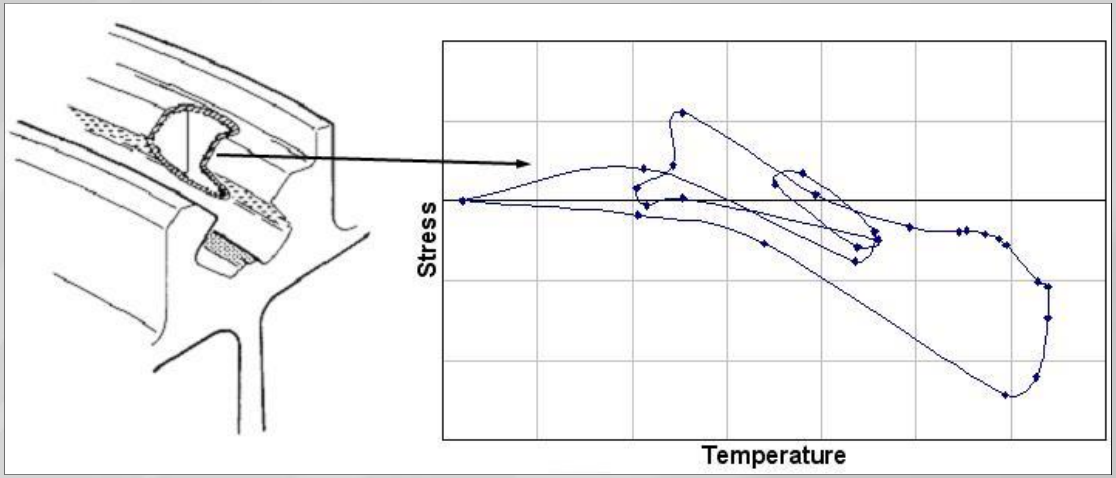


Thermocouple

- *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

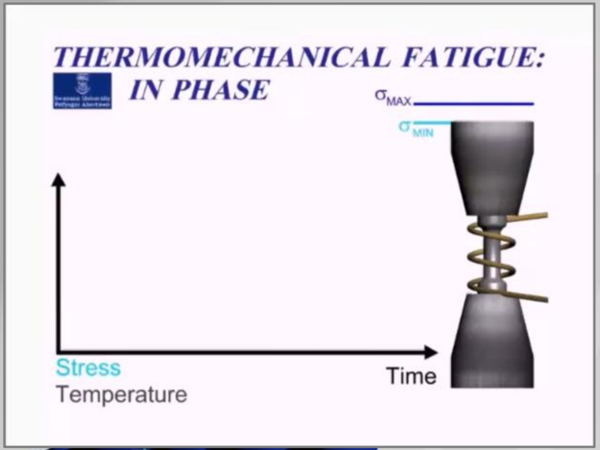


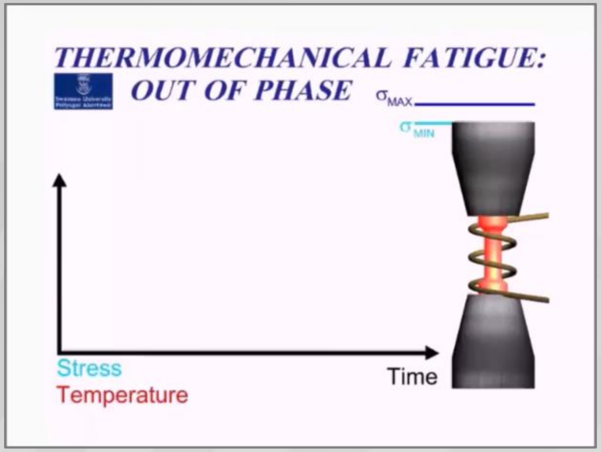
Thermo-Mechanical Fatigue (TMF)

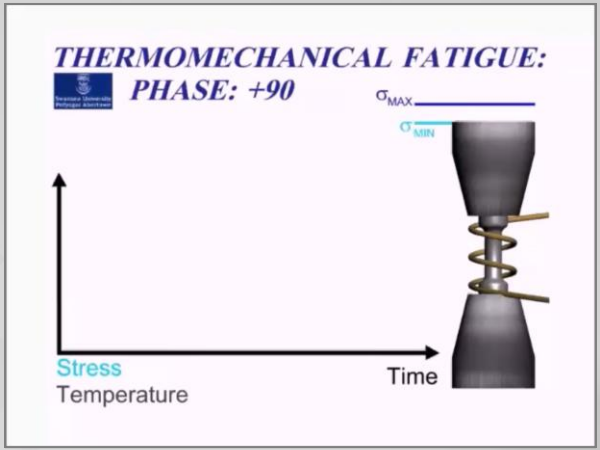
- Diverse mechanisms are involved, Primarily . . .

  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

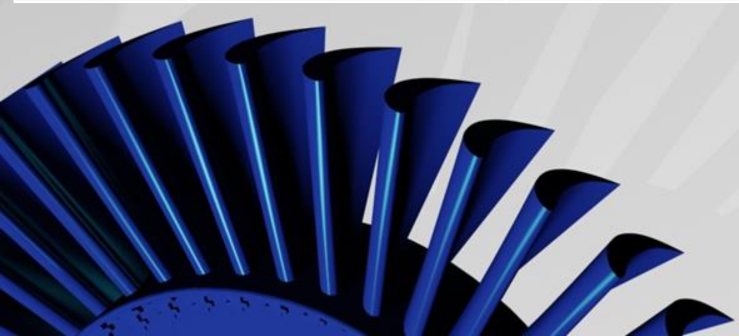






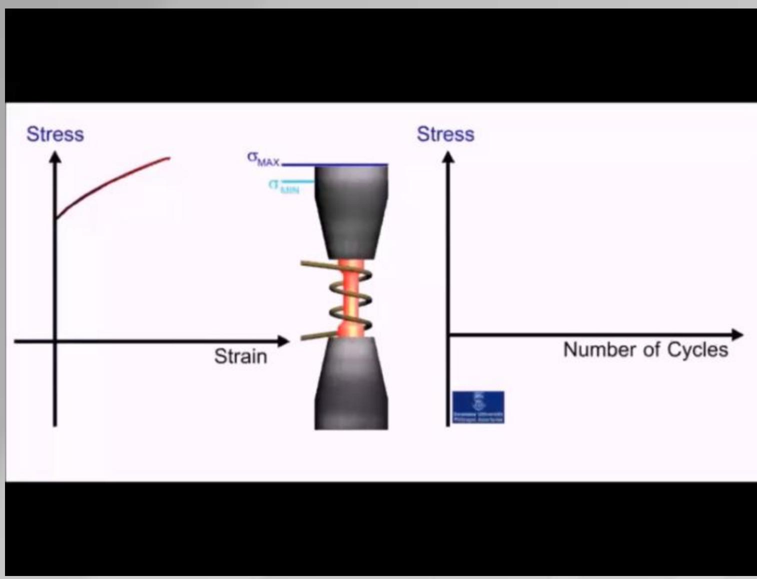
Overview

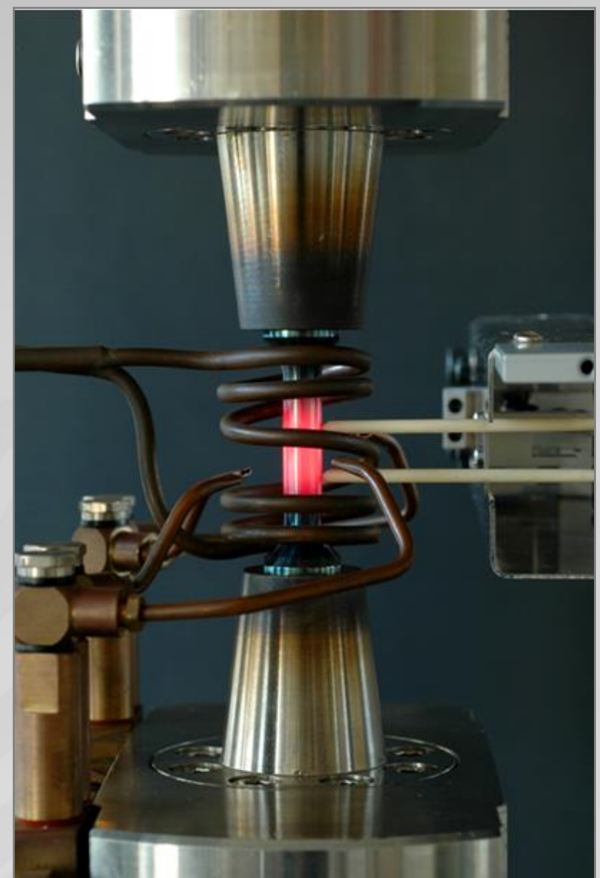
System	TMF Test Type	Heating Method	Temp Control	Max Temp	Max Load	Waveform	Heat/Cooling Max Rate
#1	- Strain Control - Stress Control	Induction	Pyrometer	1150°C	100kN	- Triangular - Trapezoidal - Complex	35°C/S^{-1}
#2	- Crack Growth	Induction	Thermocouple	1150°C	100kN	- Triangular - Trapezoidal	15°C/S^{-1}
#3	- Stress Control (Strain Monitoring)	Infra-Red Lamp (Vertical)	Non-Contact Thermocouple	850°C	100kN	- Saw Tooth	20°C/S^{-1}
#4	- Stress Control - Strain Control - Crack Growth	Infra-Red Lamp (Horizontal)	- Thermography - Thermocouple	850°C	100kN	- Triangular - Trapezoidal - Complex	25°C/S^{-1}

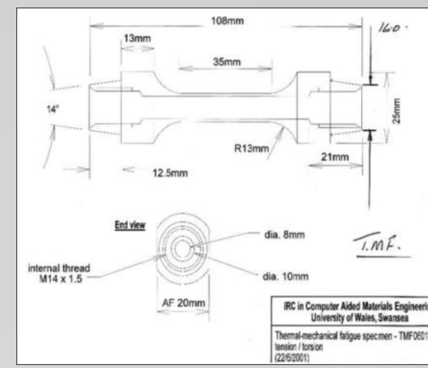


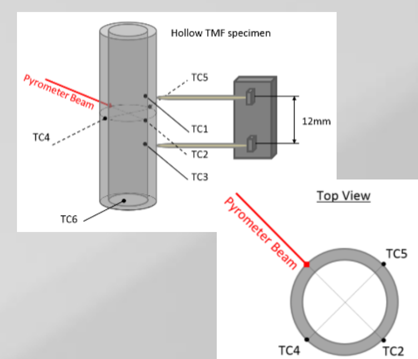
System #1 – ‘Thor’

System	TMF Test Type	Heating Method	Temp Control	Max Temp	Max Load	Waveform	Heat/Cooling Max Rate
#1	- Strain Control - Stress Control	Induction	Pyrometer	1150° C	100kN	- Triangular - Trapezoidal - Complex	35°C/S^{-1}





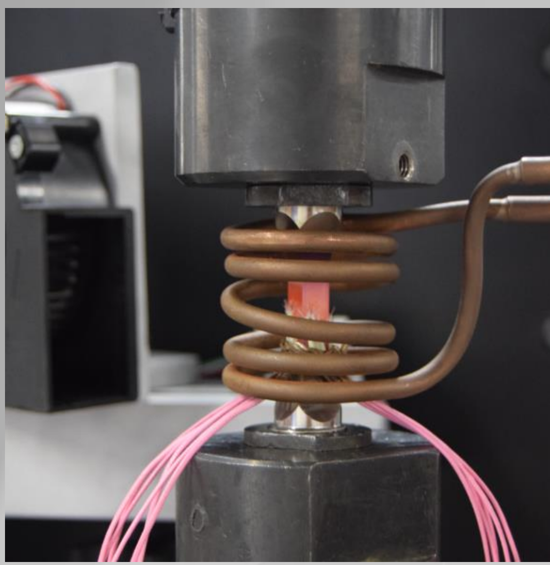


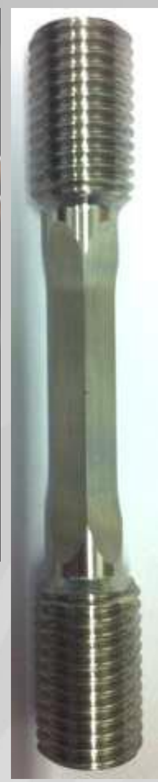


System #2 – ‘Margaret’

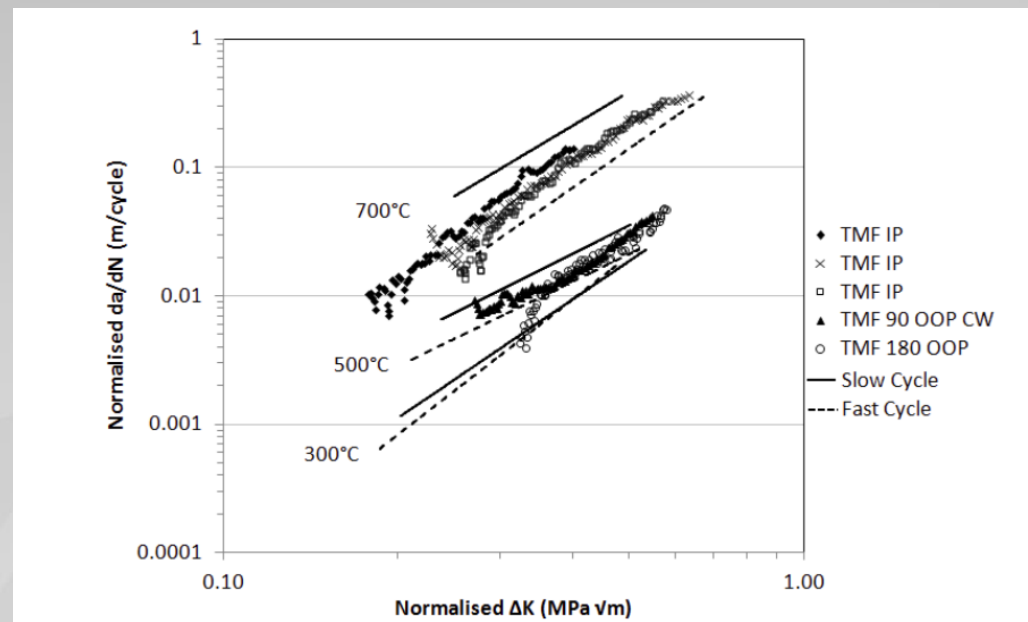
System	TMF Test Type	Heating Method	Temp Control	Max Temp	Max Load	Waveform	Heat/Cooling Max Rate
#2	- Crack Growth	Induction	Thermocouple	1150°C	100kN	- Triangular - Trapezoidal	$15°C/S^{-1}$

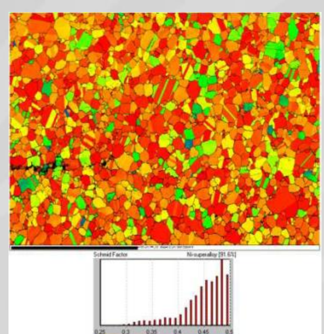
Pretty et al, Advanced Materials Research Vols. 891-892 (2014) pp 1302-1307

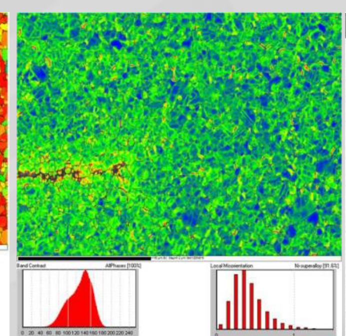


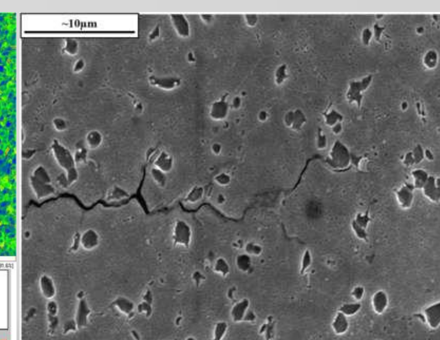


Pretty et al, Materials 2017, 10(1), 34; doi:10.3390/ma10010034



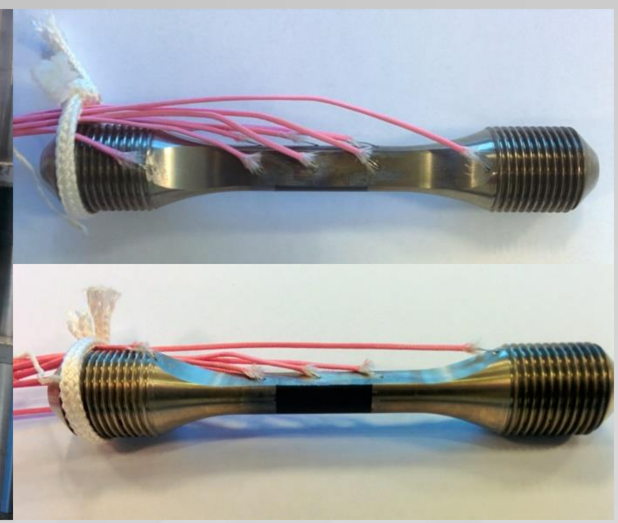


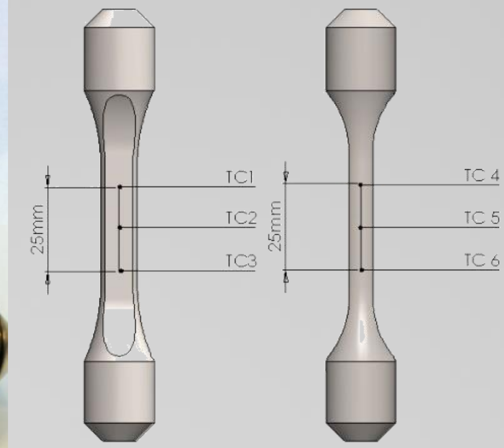




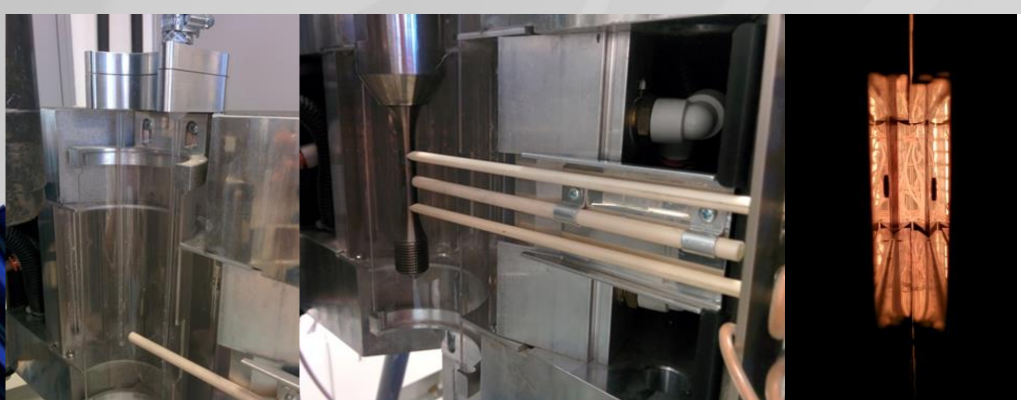
System #3 – 'Hugh'

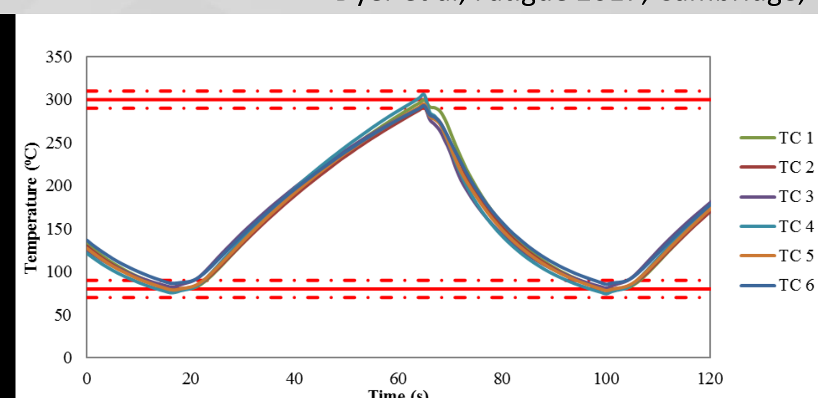
System	TMF Test Type	Heating Method	Temp Control	Max Temp	Max Load	Waveform	Heat/Cooling Max Rate
#3	- Stress Control (Strain Monitoring)	Infra-Red Lamp (Vertical)	Non-Contact Thermocouple	850°C	100kN	- Saw Tooth	20°C/S^{-1}





Dyer et al, Fatigue 2017, Cambridge, UK

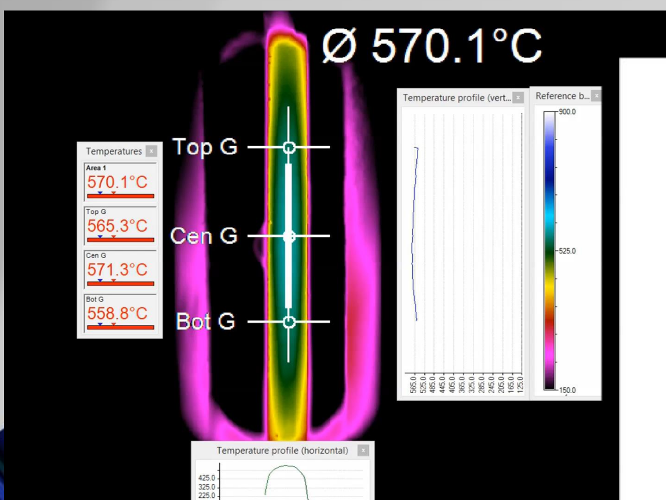


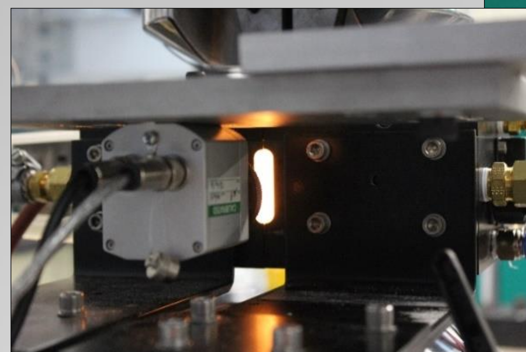


System #4 – ‘Walter’

System	TMF Test Type	Heating Method	Temp Control	Max Temp	Max Load	Waveform	Heat/Cooling Max Rate
#4	- Stress Control - Strain Control - Crack Growth	Infra-Red Lamp (Horizontal)	- Thermography - Thermocouple	850°C	100kN	- Triangular - Trapezoidal - Complex	25°C/S^{-1}

Thermal Gradients			
Horizontal		Vertical	
5mm	15mm	12mm	50mm
~200°C	~400°C	~300°C	~600°C





System #5 – ‘Megatron’

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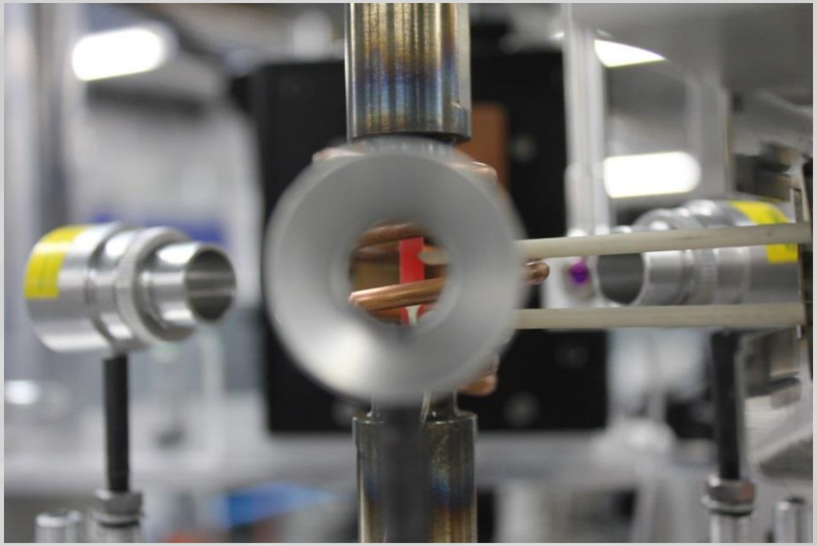
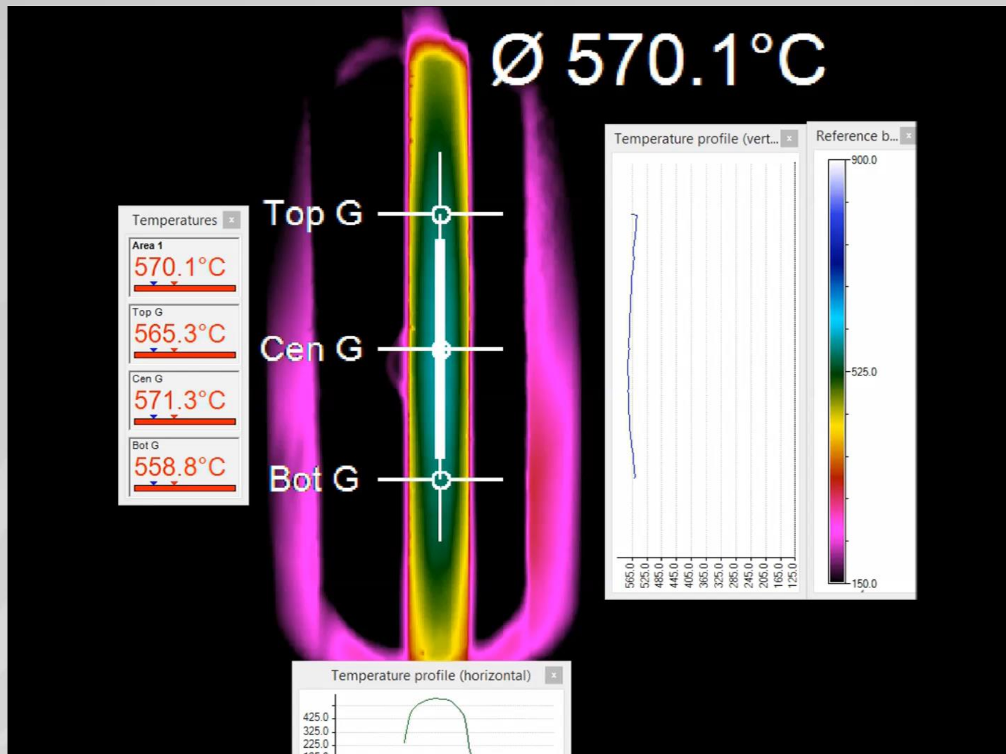


System #5 – ‘Megatron’

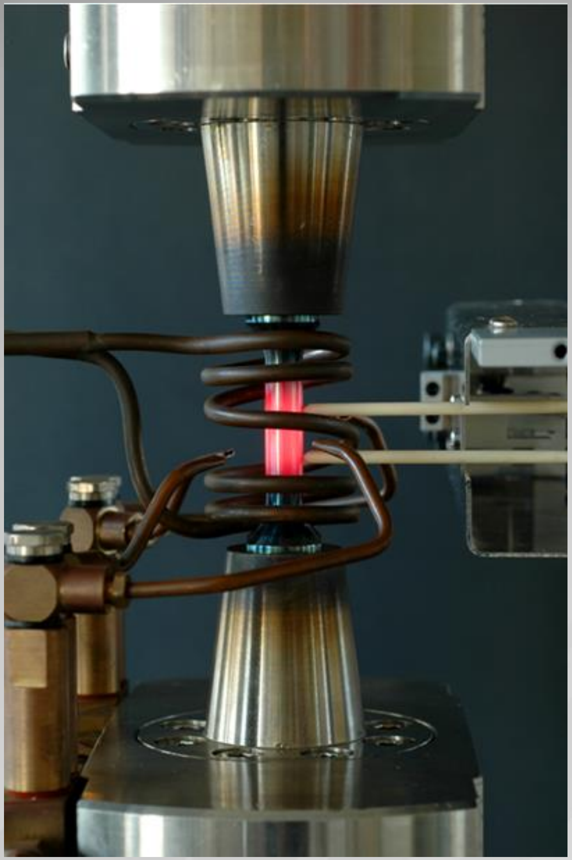
System	TMF Test Type	Heating Method	Temperature Control	Max Temp	Max Heating / Cooling Rate
#5	Stress Control Strain Control Crack Growth	Infra-Red Lamp (Horizontal)	Thermography Thermocouple	1050°C	$25°C/S^{-1}$

Thermal Gradients			
Horizontal		Vertical	
5mm	15mm	12mm	50mm
~250°C	~450°C	~400°C	~750°C

Three Independently Controlled Temperature Zones Through Thermography

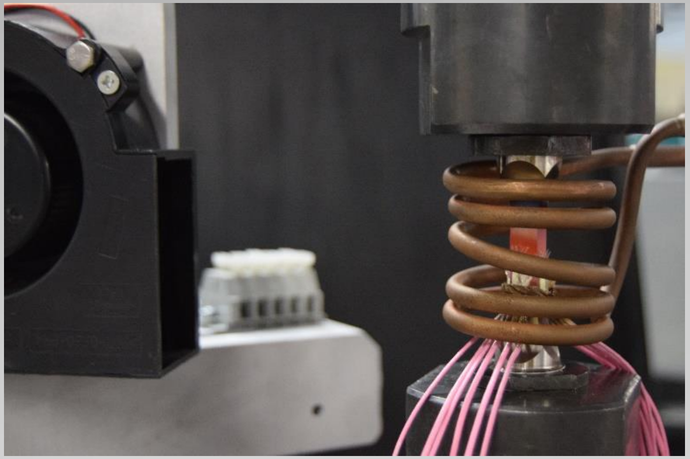


Forced Air Cooling

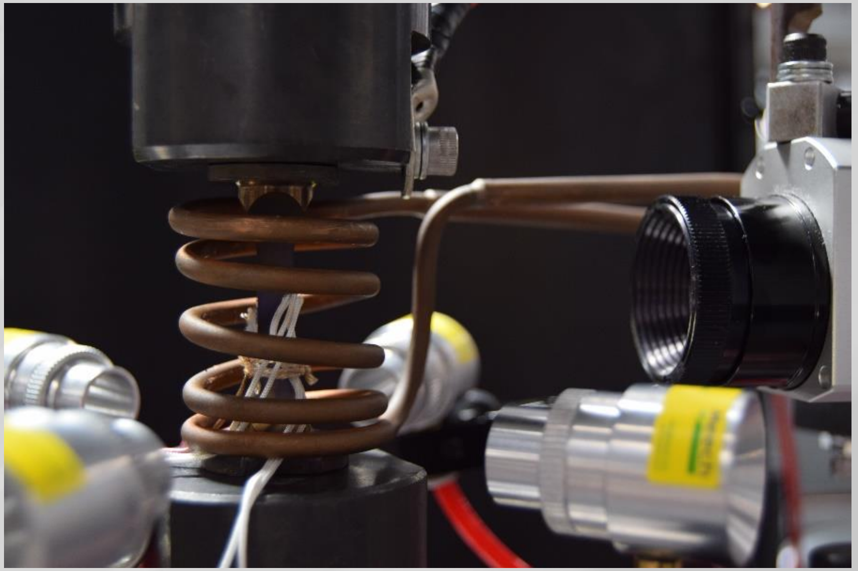


Localised/Focused Cooling

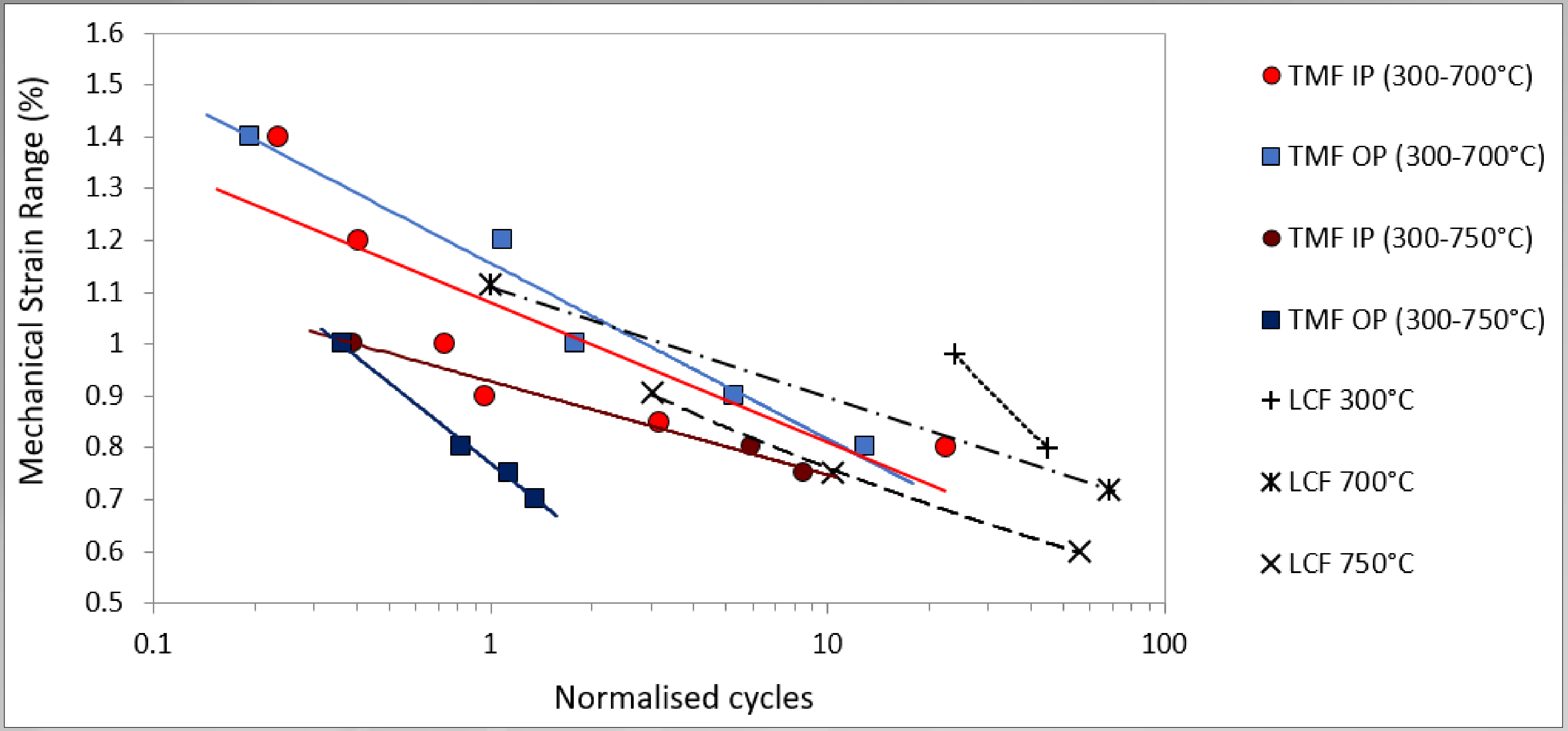
Basic Fan Cooling



Diffuse uniform cooling through air amplifiers



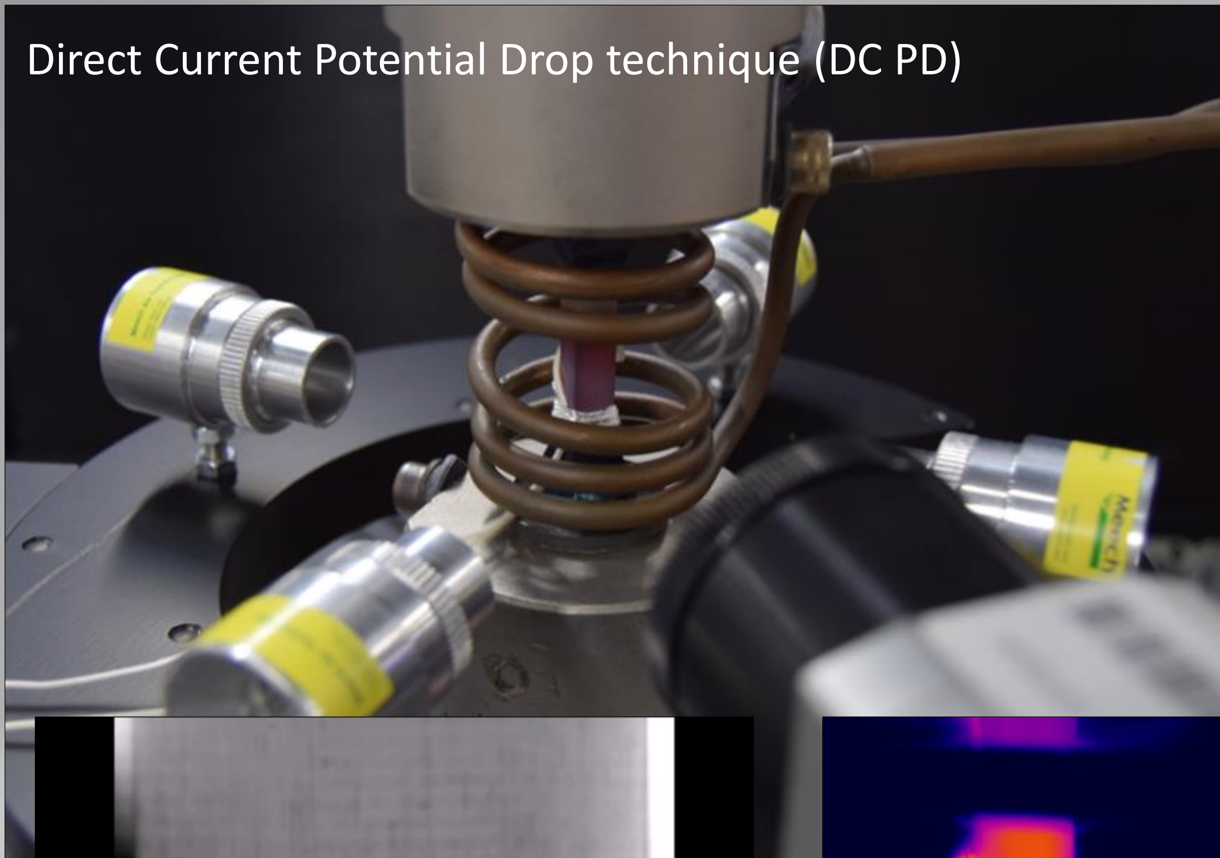
Effect of peak temperature

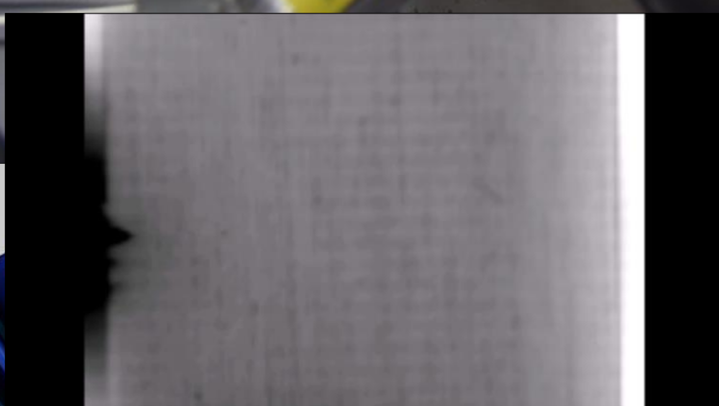


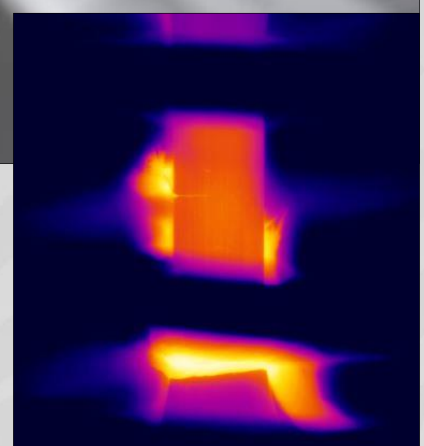
Jones et al. (2017). The influence of phase angle, strain range and peak cycle temperature on the TMF crack initiation behaviour and damage mechanisms of the nickel-based superalloy, RR1000. *IJF* doi:10.1016/j.ijfatigue.2017.01.036

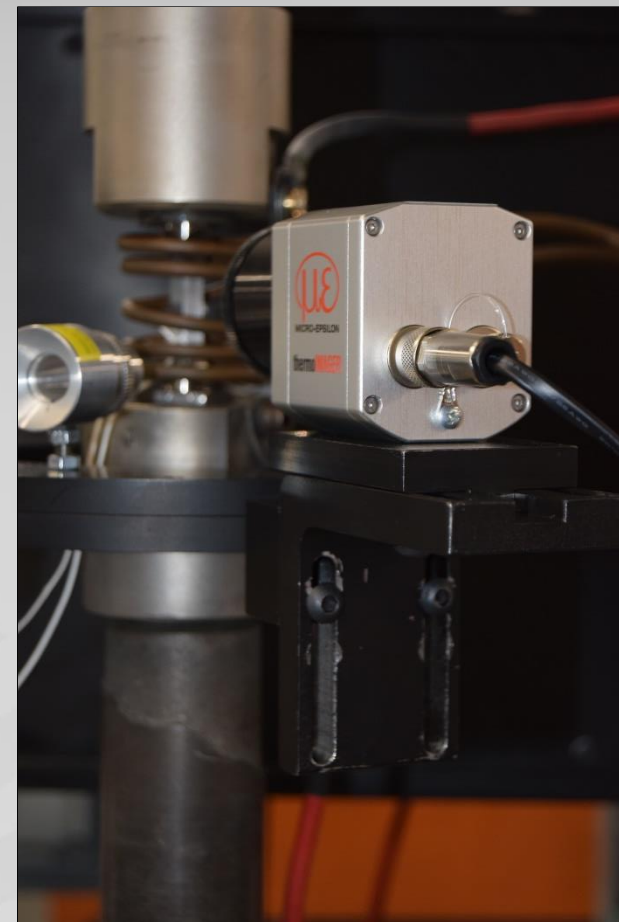
- At 750°C OP data shows a significant decrease in TMF life.
- Likely to be due to increased oxidation effects
- TMF lives consistently shorter than isothermal fatigue lives.

TMFCG Test Development



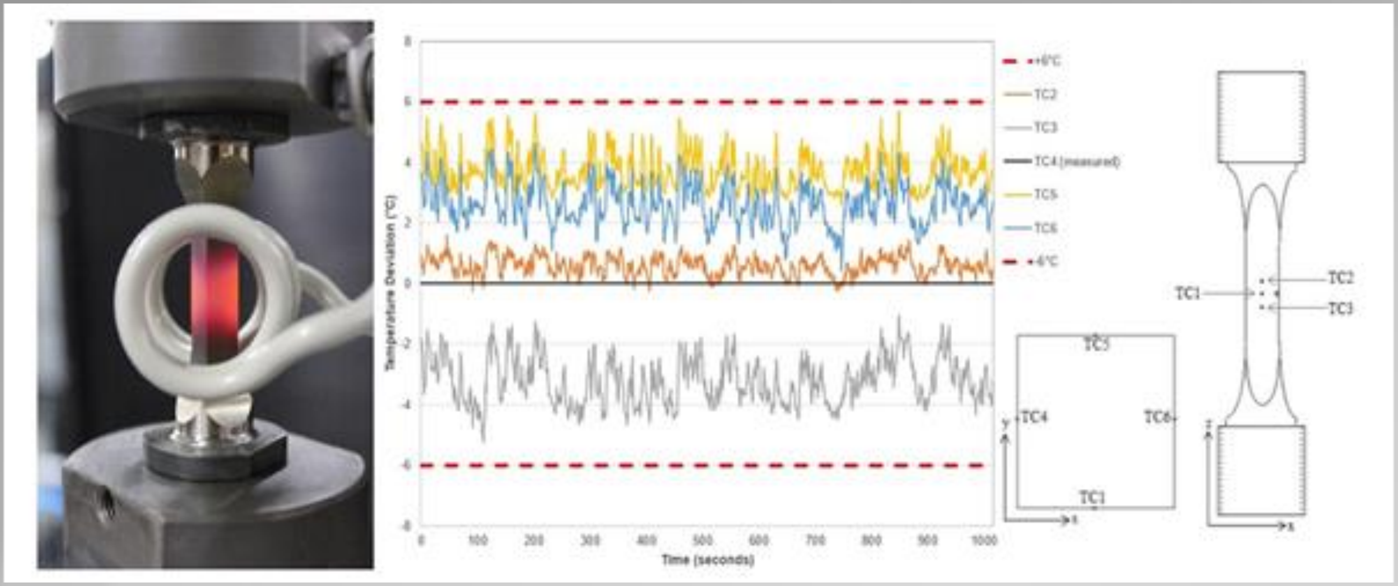


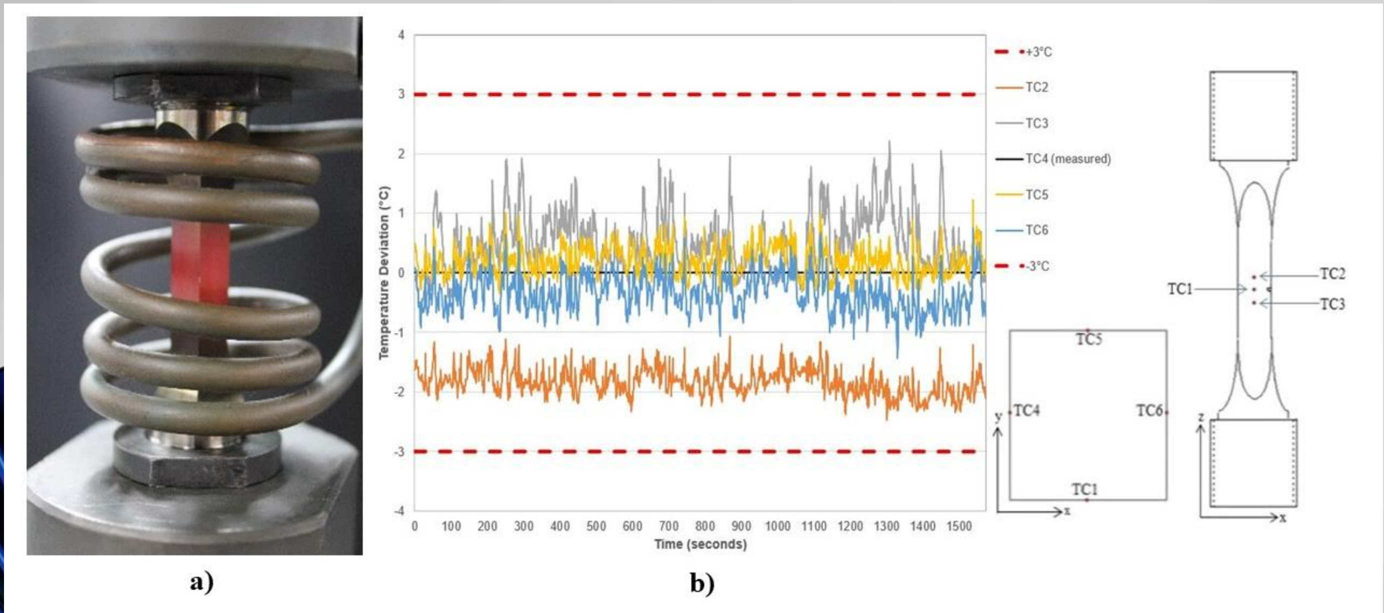




Palmer, J et al (2019). Int. J. Fatigue 121, 208-218. doi:10.1016/j.ijfatigue.2018.12.015

Induction Coil Designs

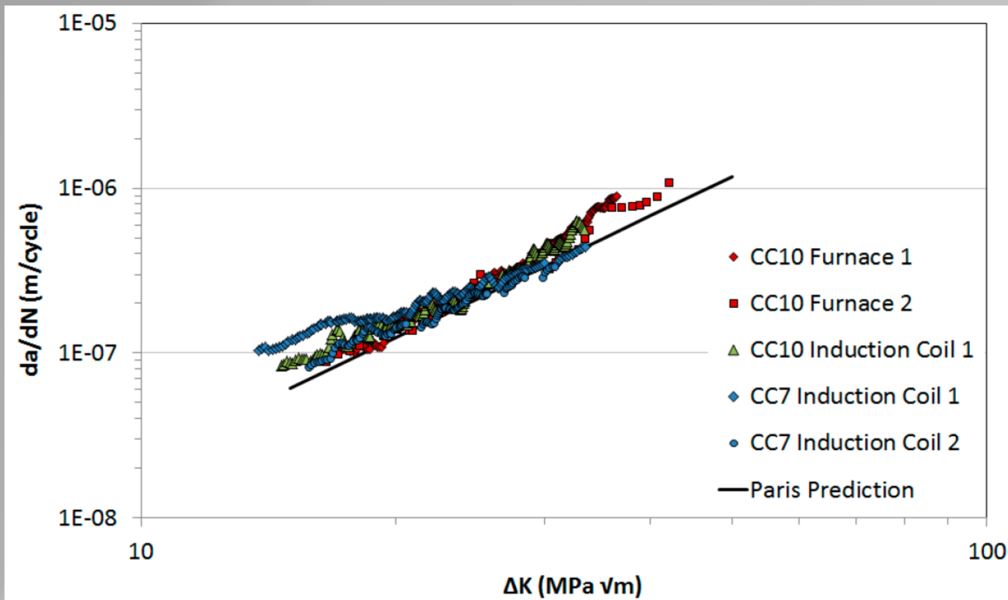




Palmer, J et al (2019). Int. J. Fatigue 121, 208-218. doi:10.1016/j.ijfatigue.2018.12.015

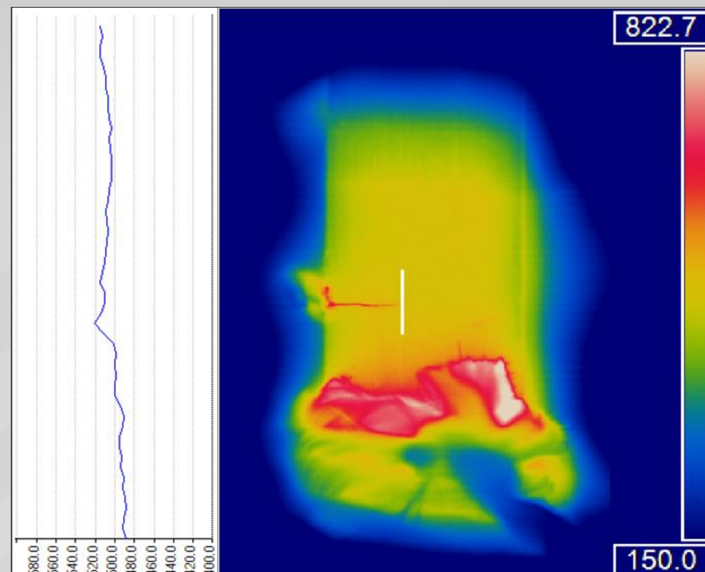
Crack Tip Heating Investigations

Waspaloy crack growth rate vs ΔK: furnace and induction coil comparisons at 650°C, 450MPa and R=0.1.



Pretty et al, Materials 2017, 10(1), 34; doi:10.3390/ma10010034

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

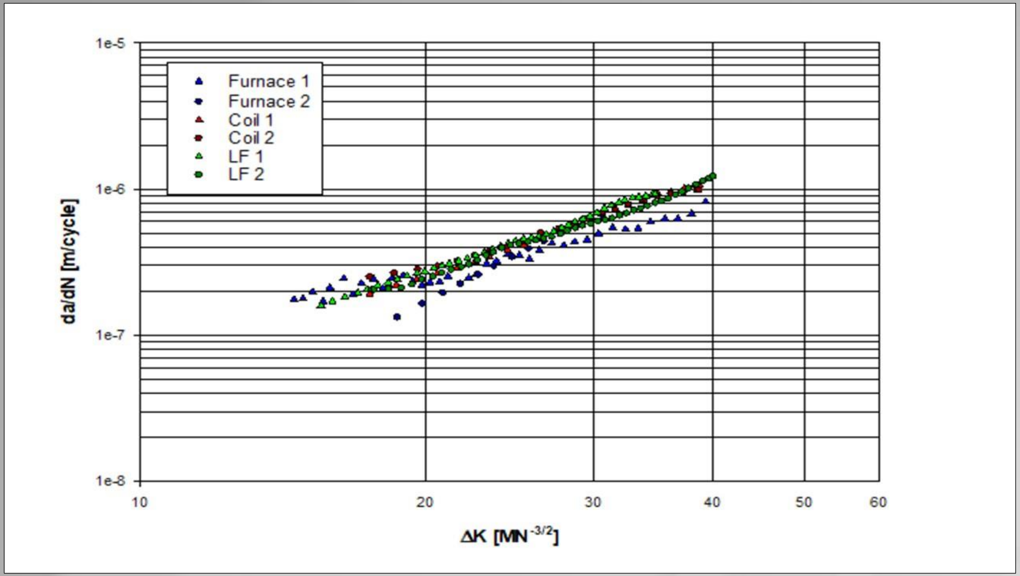


- *ISO 12111:2011. Strain-controlled TMF Testing, 2011. +/-10°C*

Palmer, J et al (2019). Int. J. Fatigue 121, 208-218. doi:10.1016/j.ijfatigue.2018.12.015

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
- 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

Palmer, J et al (2019). Int. J. Fatigue 121, 208-218.
doi:10.1016/j.ijfatigue.2018.12.015

Conclusions

- Crack propagation techniques are developing towards a Code of Practice to enable damage tolerant lifing approaches.
- Thermography control offers potential for highly accurate temperature control across a large volume of material.
- Crack propagation tests in an induction coil show no evidence of crack tip heating.
- Diffuse air flows show more homogeneous cooling and are therefore more appropriate.
- Quartz lamp furnaces should be carefully considered in relation to the thickness of specimens.