Challenges involved in implementing and maintaining high temperature control accuracy during complex mechanical testing.

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Introduction

Swansea University Bay Campus

DevTMF Partners

DevTMF. *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

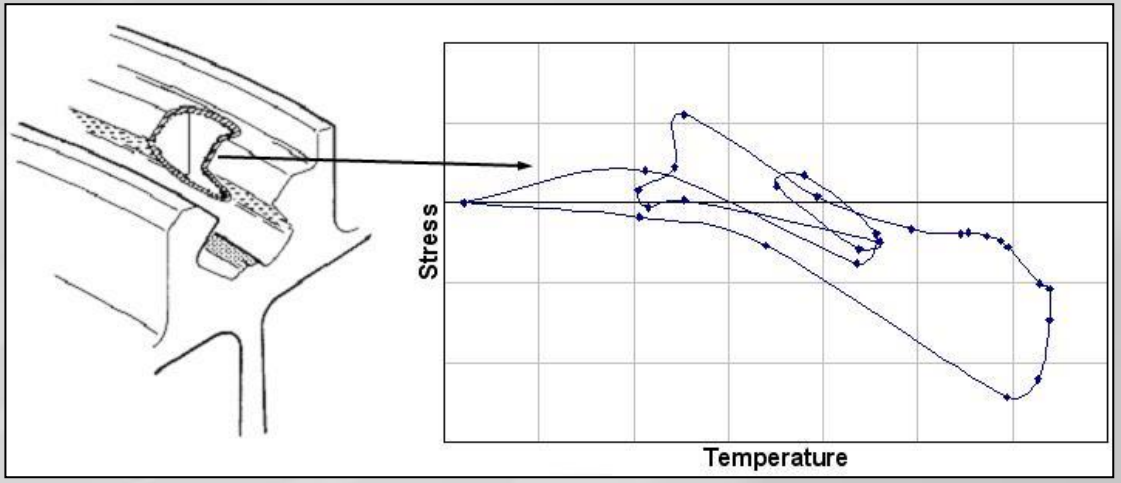
Rolls-Royce plc, UK.
Material and technical support

Content

- Background in thermo-mechanical fatigue (TMF)
- Need for accurate high temperature control
- Typical induction coil TMF testing setups
- Thermocouple complications
- Alternative thermocouple control options
- Thermography control
- Alternative heating - Lamp furnace
- Non-invasive control complications
- Advantages of thermography control

Background in thermo-mechanical fatigue (TMF)

- Increased turbine entry temperatures
- Thinner disc rims and advanced cooling systems leading to larger thermal gradients
- Complex loading regimes occur within the gas turbine leading to diverse phasing between temperature and strain known as thermo-mechanical fatigue (TMF)
- 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

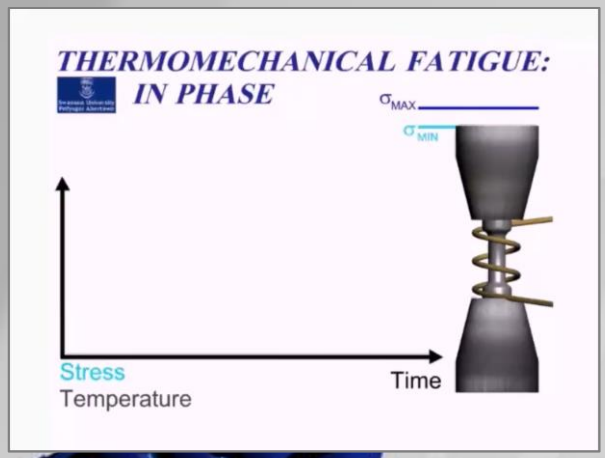


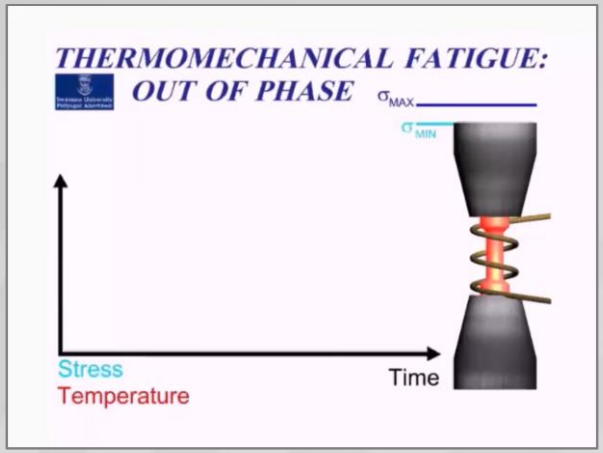
Need for accurate high temperature control

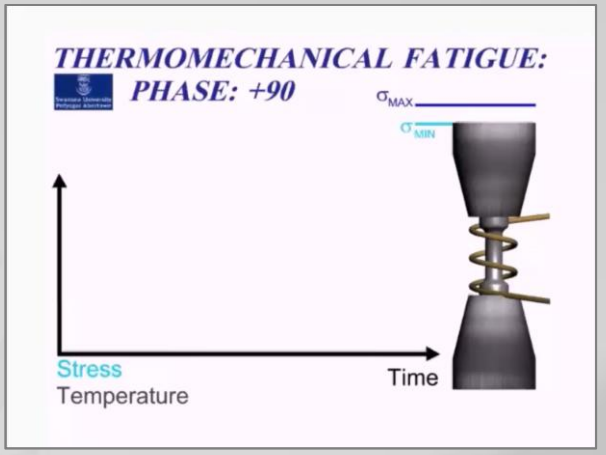
- Diverse mechanisms are involved, Primarily . . .

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



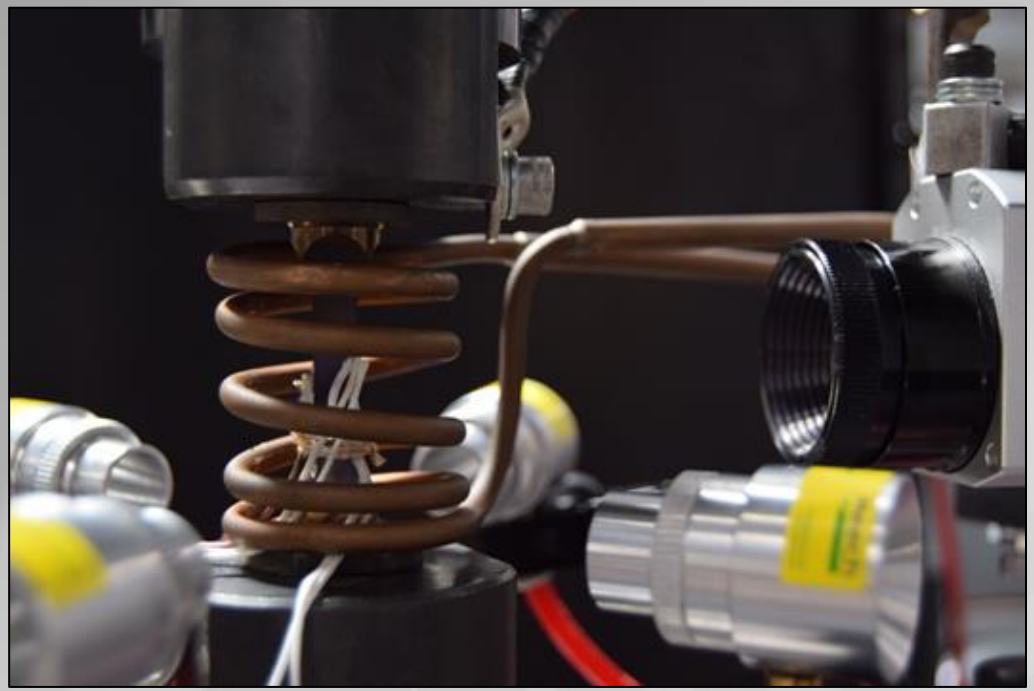




- *ASTM E2368-10. Strain Controlled TMF Testing, 2010.*
- *ISO 12111:2011. Strain-controlled TMF Testing, 2011.*
- *BAM. CoP Force-Controlled TMF Testing, 2015.*

Typical induction coil TMF testing setups

Fatigue Crack Propagation – Induction

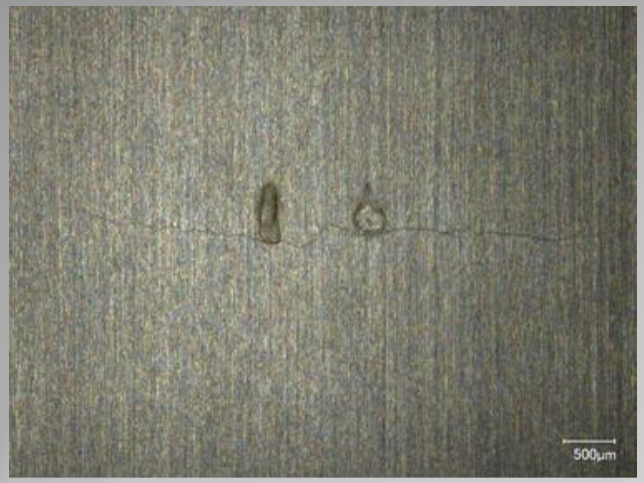


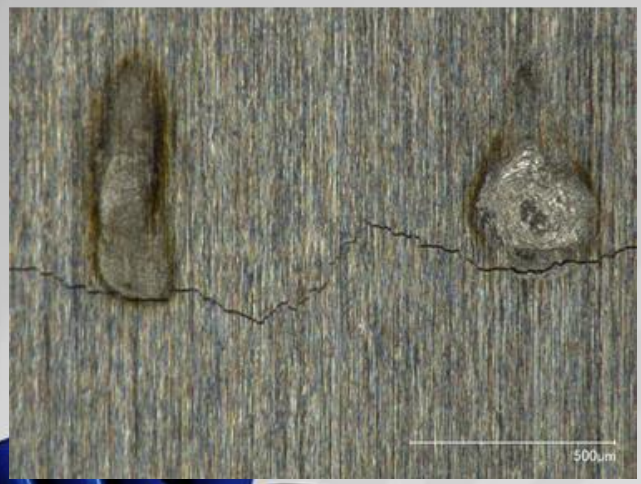
Thermocouple

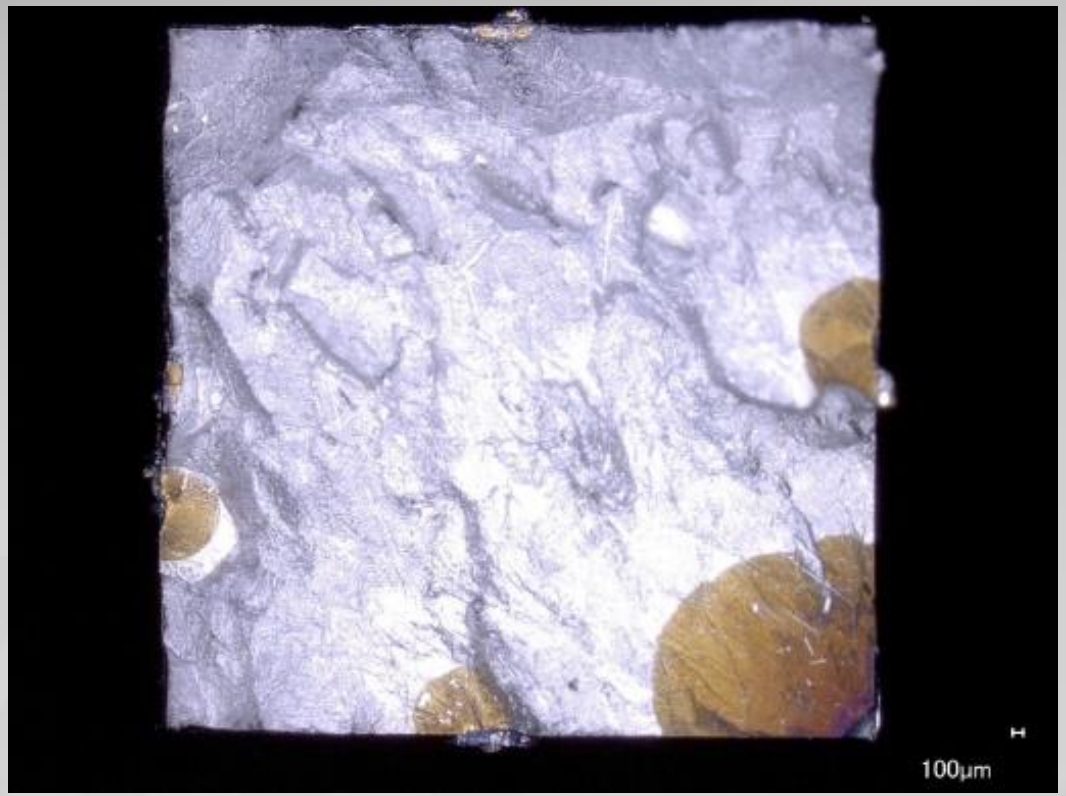
Strain Control - Induction

Pyrometer

Thermocouple complications

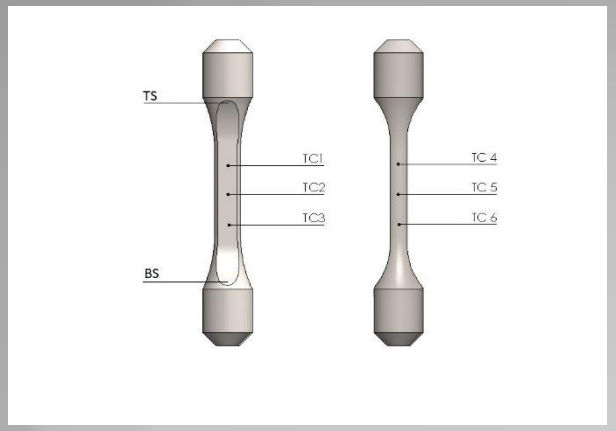




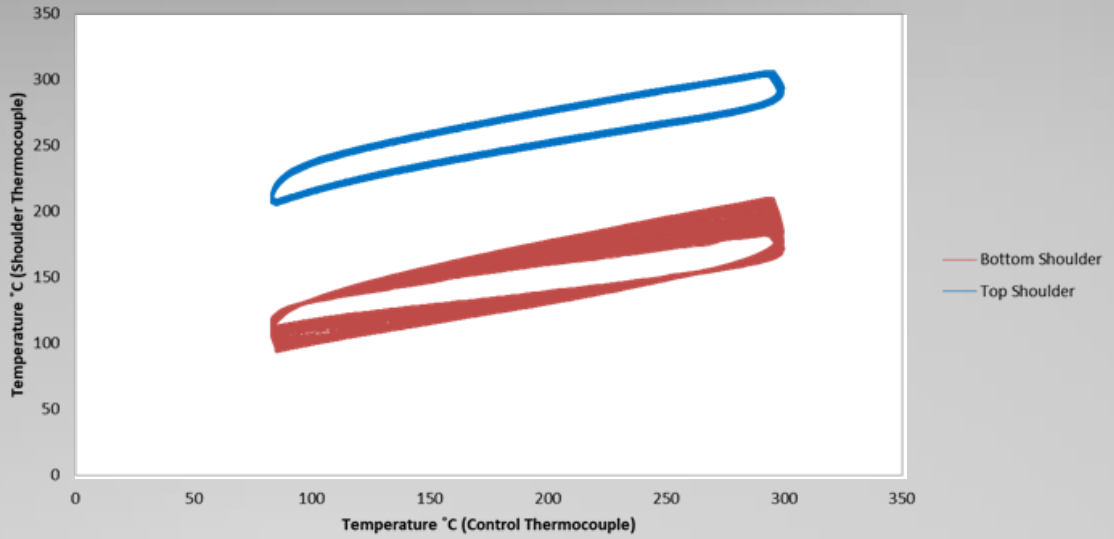


Alternative thermocouple control options

Shoulder Thermocouple Control

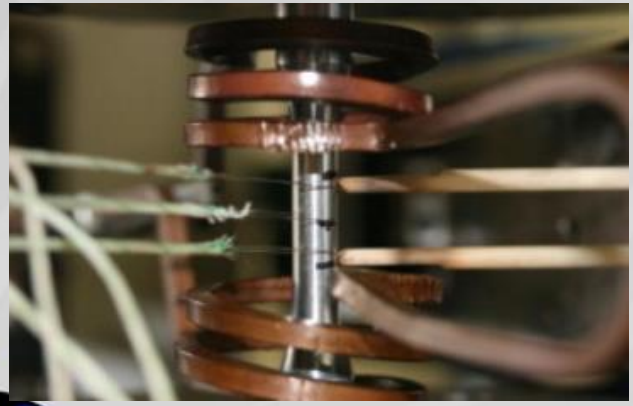


Specimen schematic showing the locations of the 6 thermocouples during the profiling stage (Front and back views).



Thermal response at the specimen shoulders. Shoulder temperature plotted against TC2 centre gauge control thermocouple.

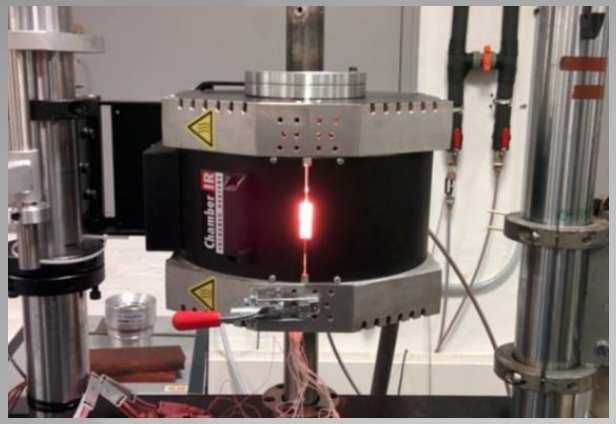
Ribbon Thermocouple Control

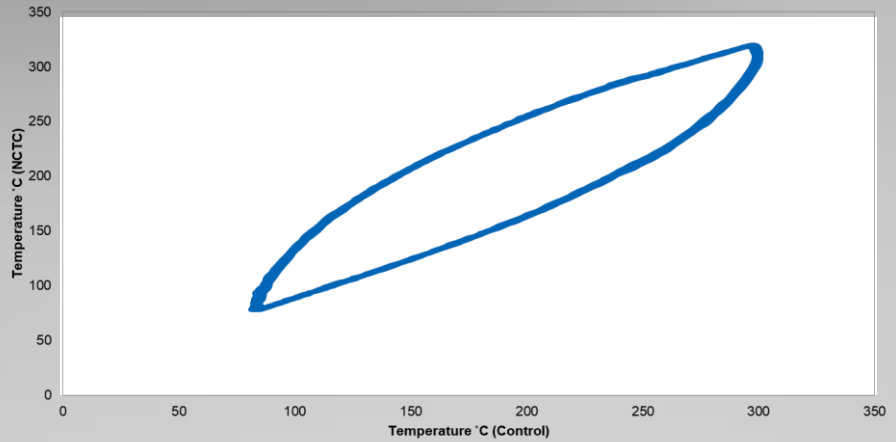


M. Azadi, M. M. Shirazabad, Heat treatment effect on thermo-mechanical fatigue and low cycle fatigue behaviors of A356.0 aluminum alloy, Materials & Design, Volume 45, 2013, Pages 279-285, ISSN 0261-3069.

Alternative thermocouple control options

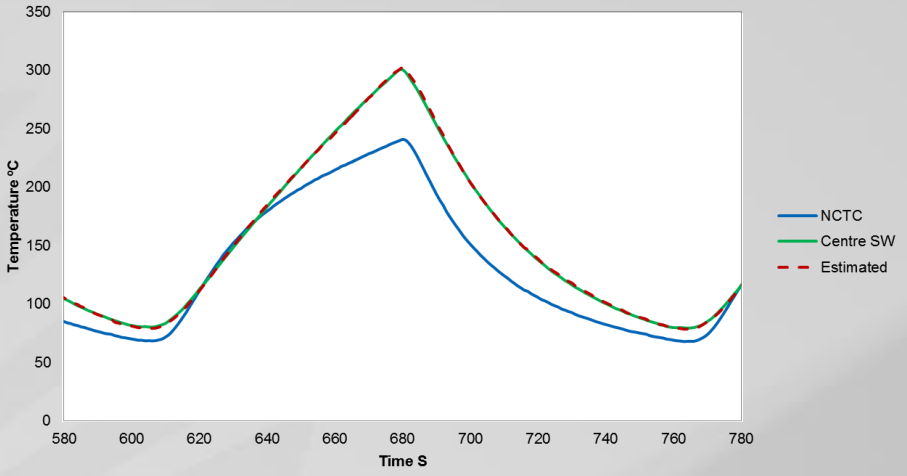
Lamp Furnace





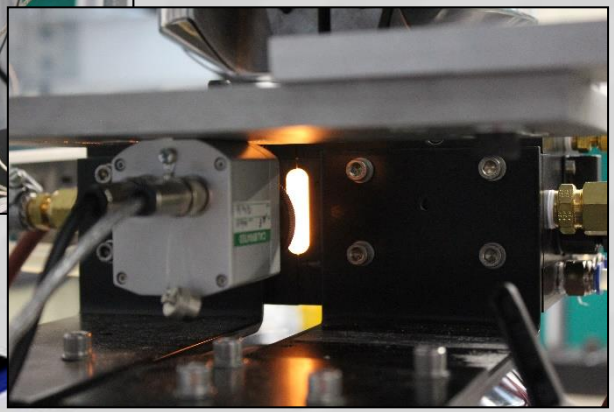
Relationship between the control (centre gauge) thermocouple and the close proximity mounted thermocouple.

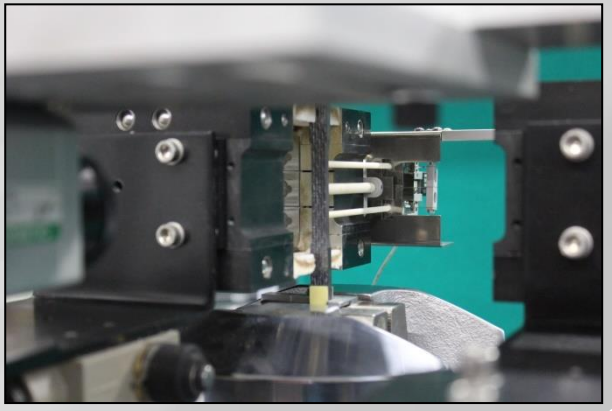
Close proximity (Non-Contact) thermocouple mount



TMF Profile indicating the temperature read from the non-contact (close proximity) thermocouple (NCTC). This allows derivation of an estimated relationship for the specimen surface temperature which shows close correlation to the spot welded thermocouple at the centre of the gauge length (Centre SW).

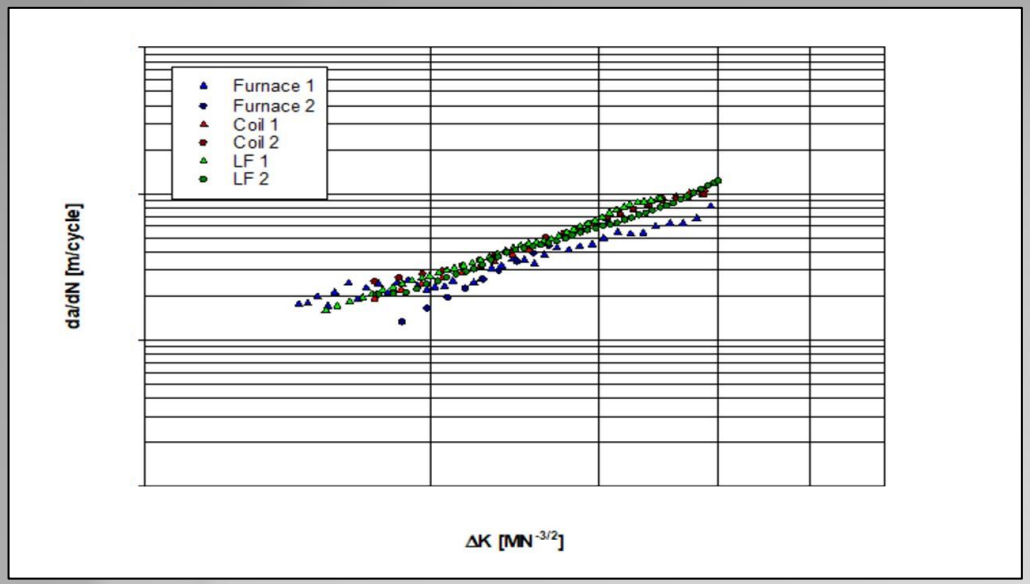
Alternative heating - Lamp furnace





Effect of Lamp Furnace vs Induction Coil

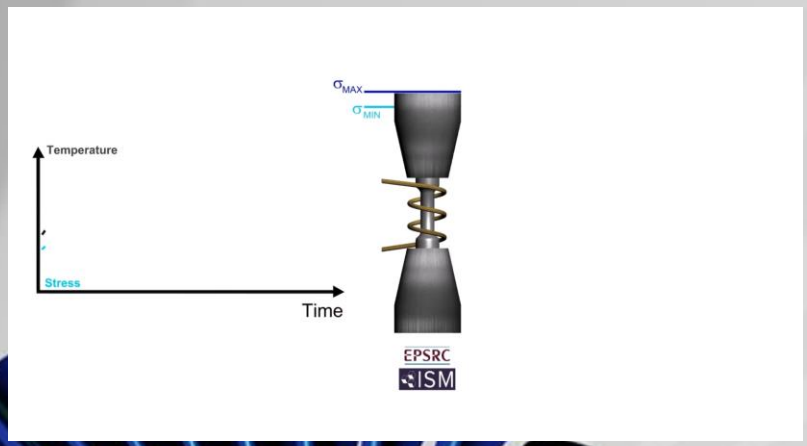
Isothermal fatigue crack growth



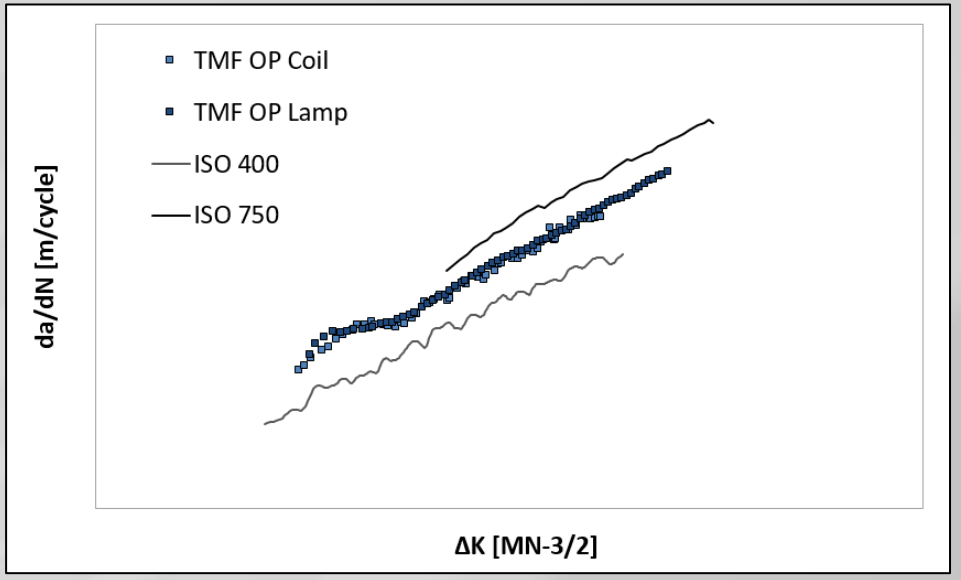
- Ti-6246 corner crack specimens tested at the same isothermal conditions, using three different heating methods
- Crack growth rates are consistent across heating methods

- 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

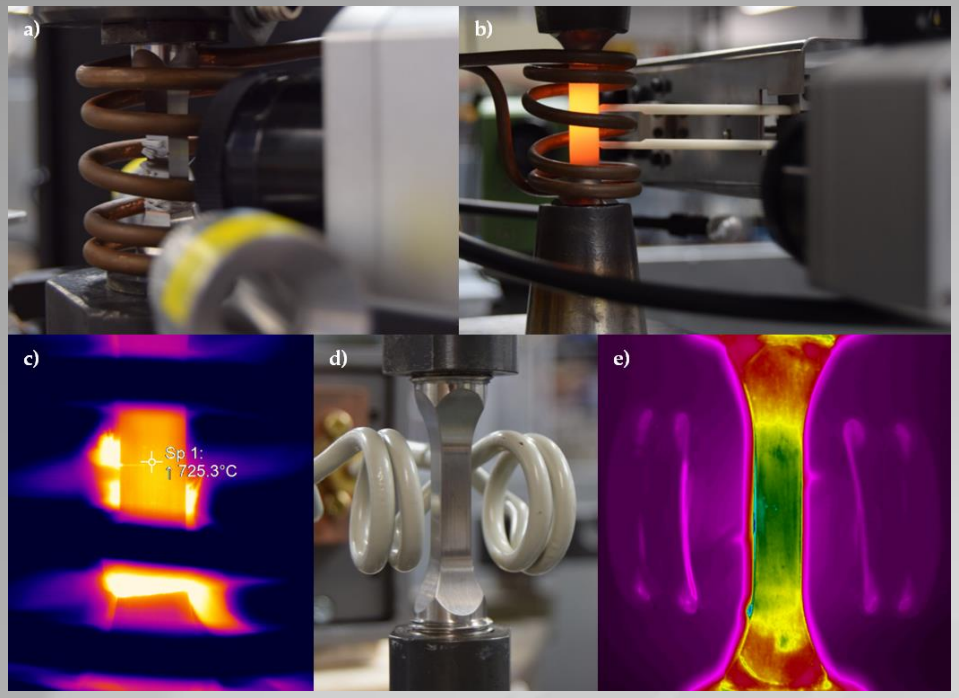
In phase TMF crack growth

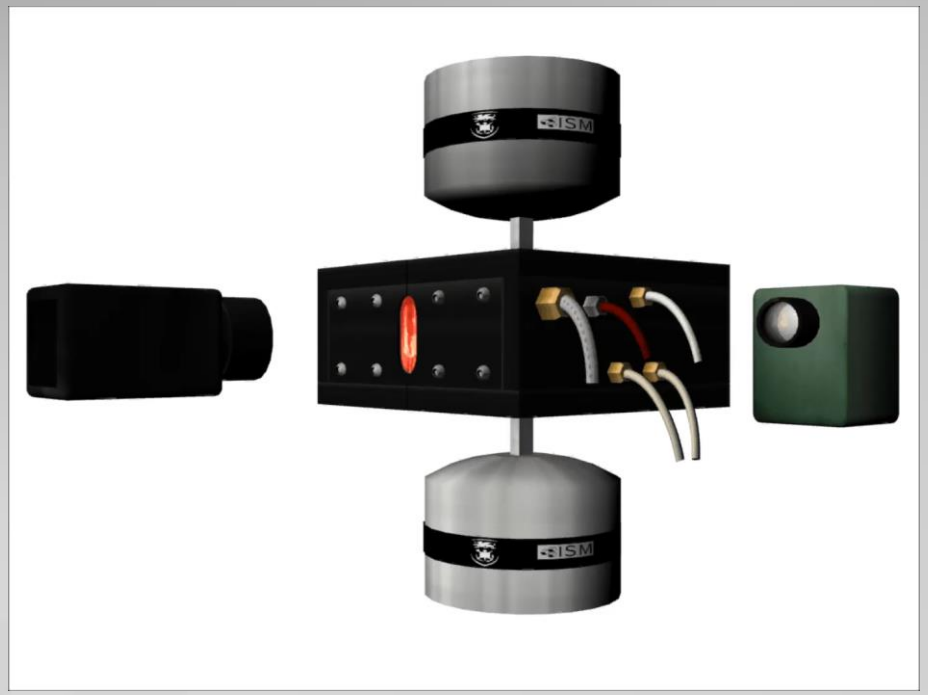


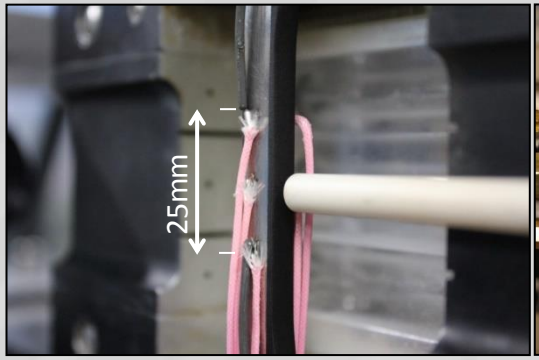
Out of phase TMF crack growth

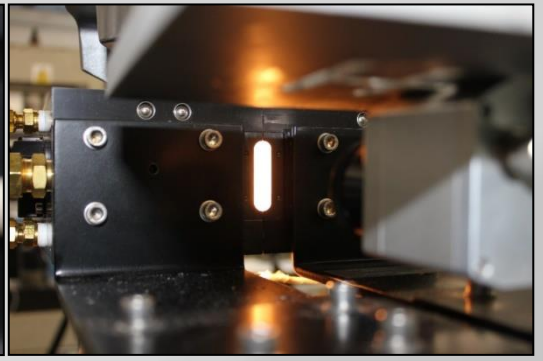


Thermography Control





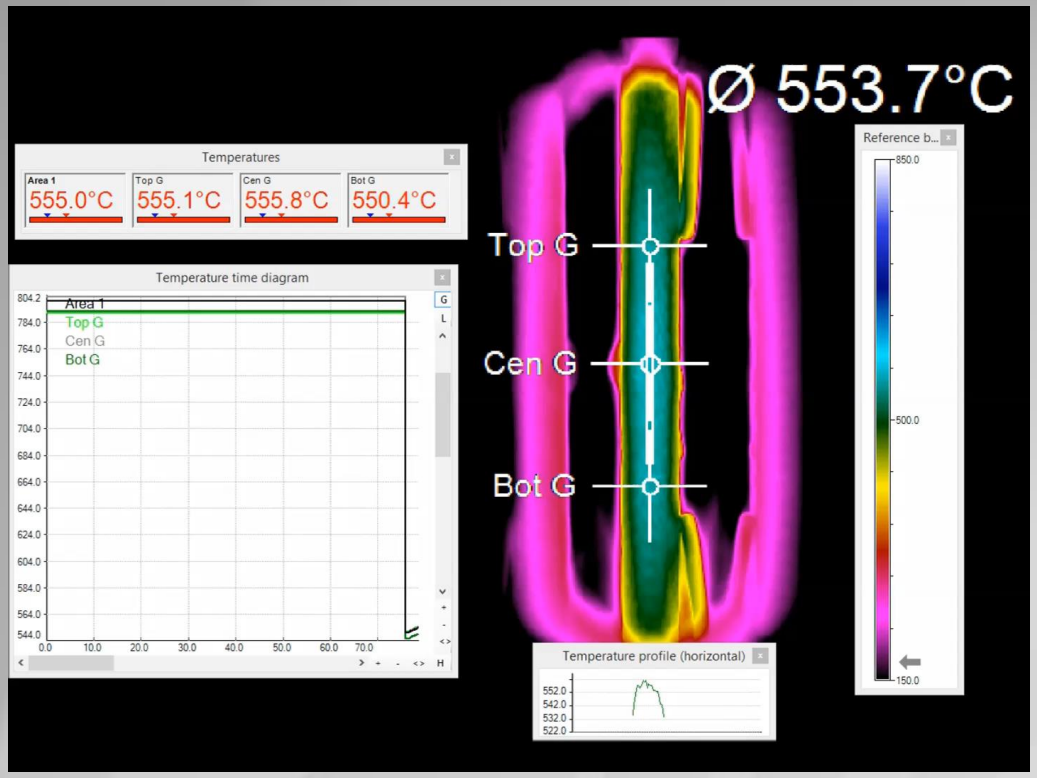




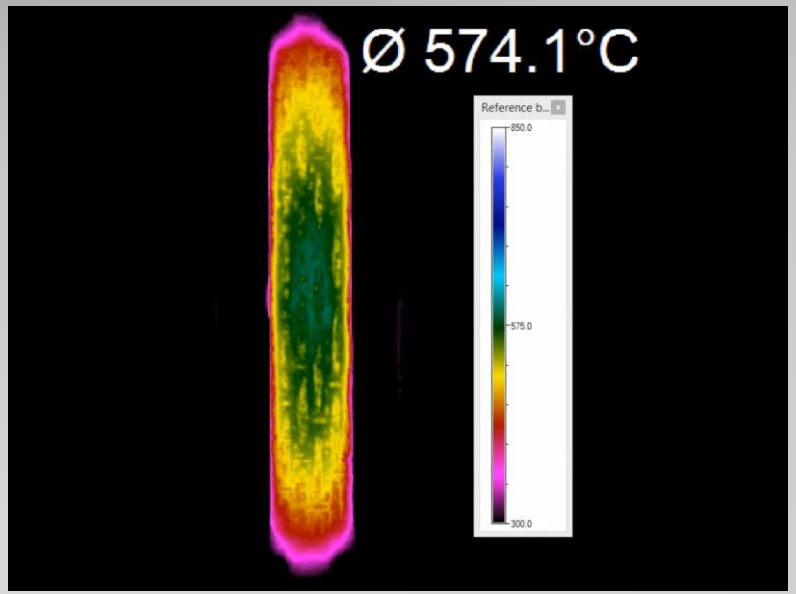
IN-LINE MEASUREMENT AND CONTROL FOR METALS PROCESSING. IOM3 WARWICK

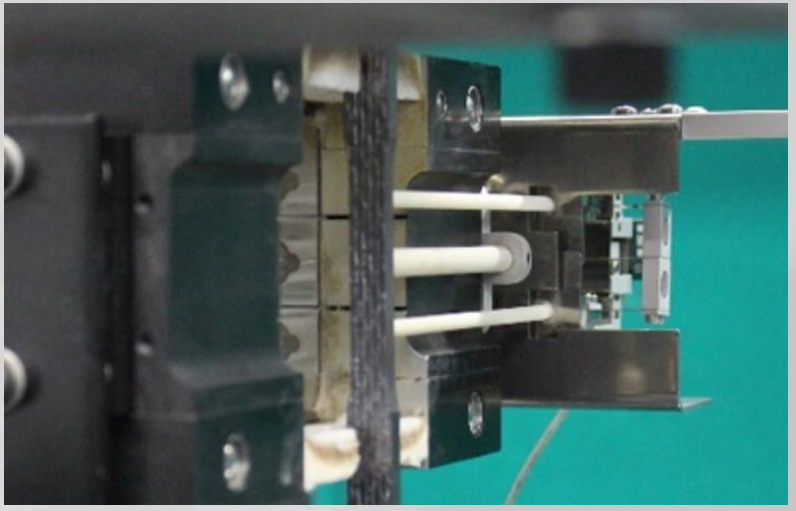
Thermography control

Ceramic Specimen Side



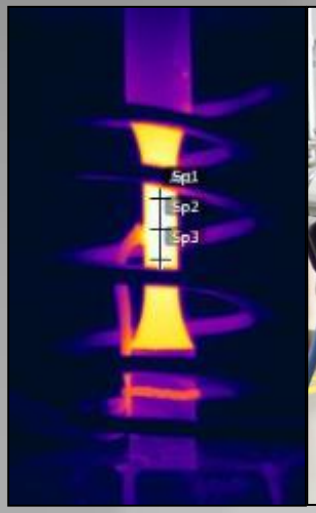
Ceramic Specimen Face

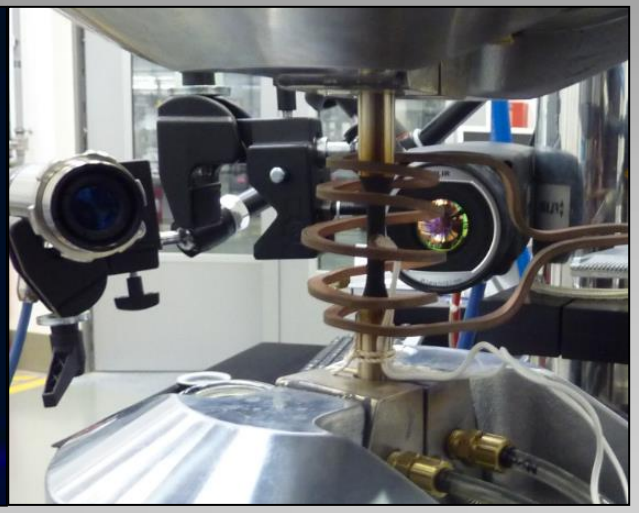


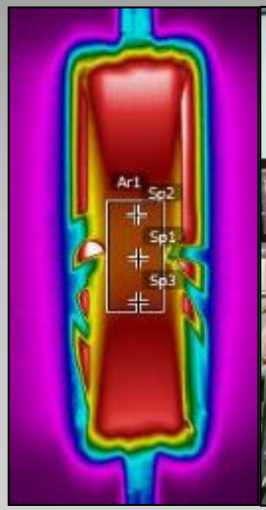


Non-invasive control complications

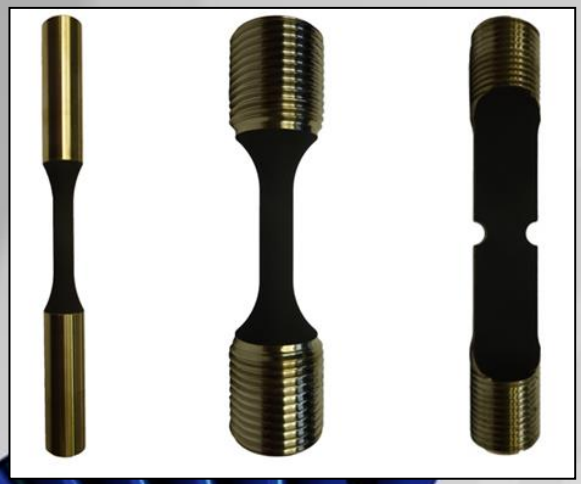
Emissivity

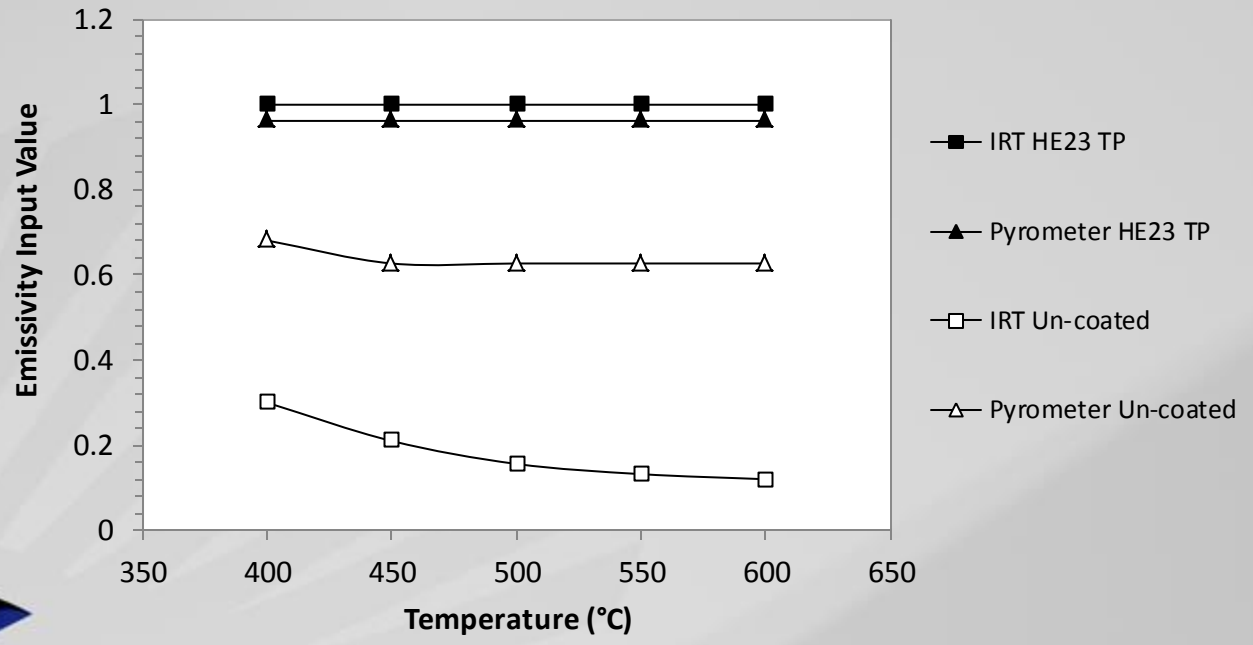






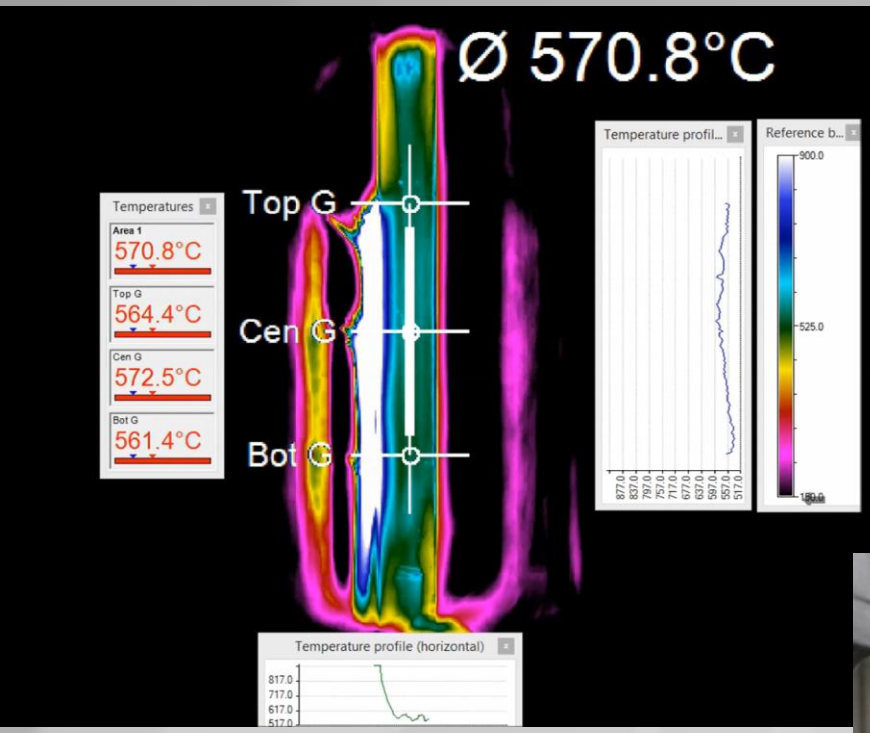
HE23 Thermal Paint



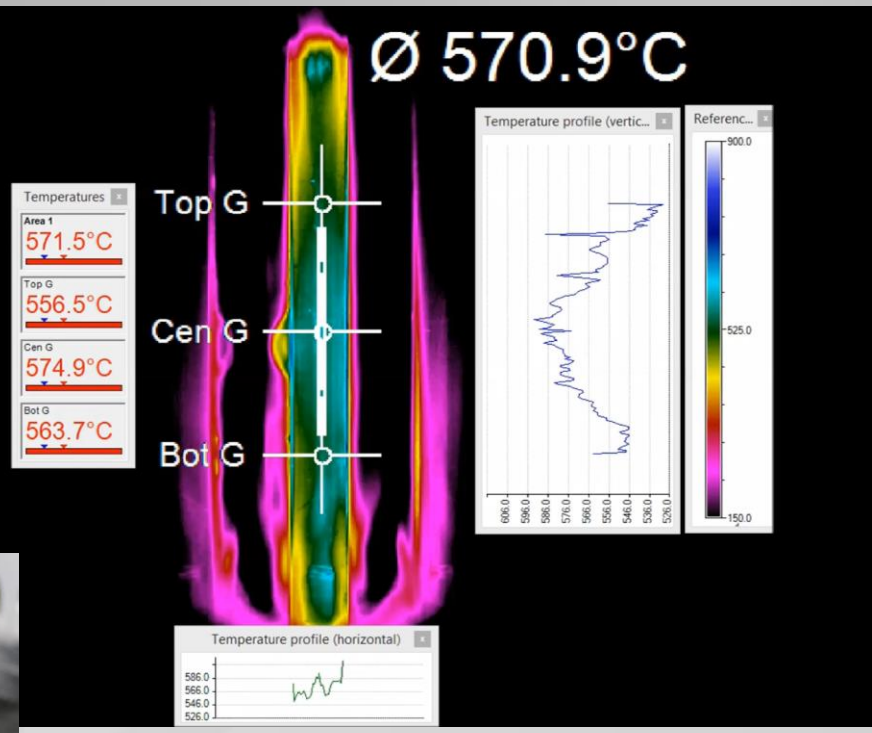


Non-invasive control complications

Thermocouples



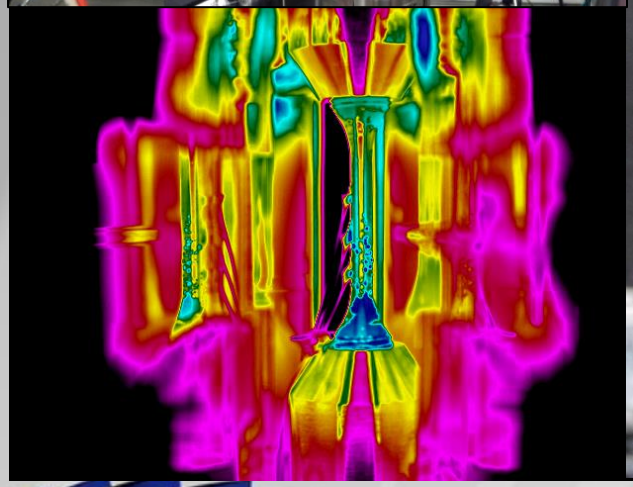
No Thermocouples

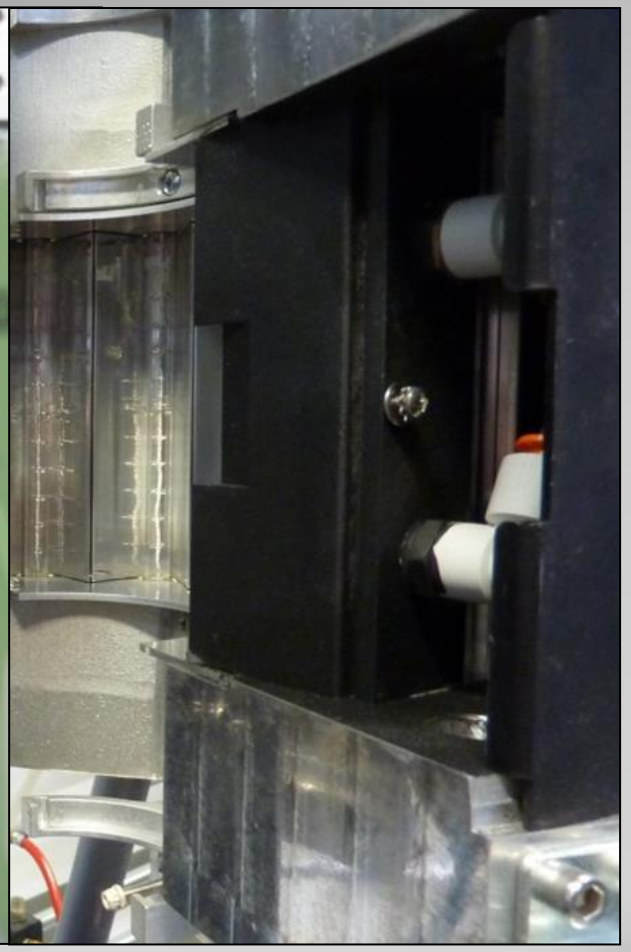


Pre-oxidised Surface
800°C for 50 hours.
ε used = 0.57

Non-invasive control complications

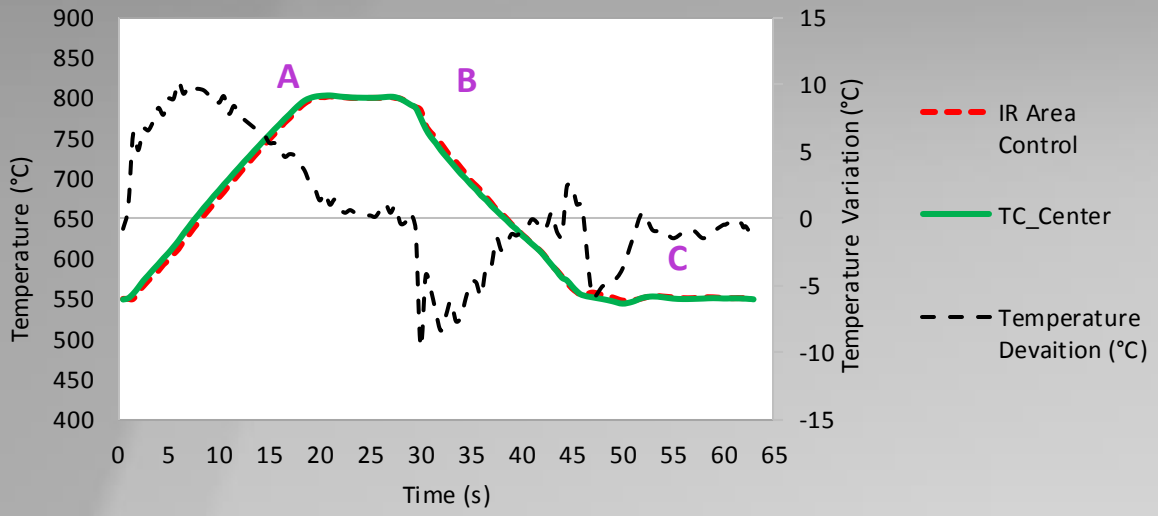
Reflective surfaces

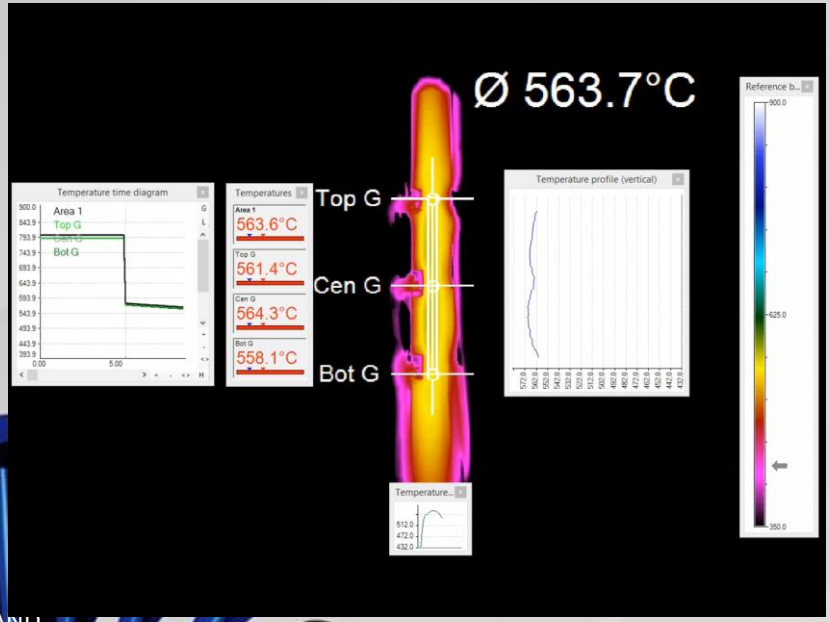


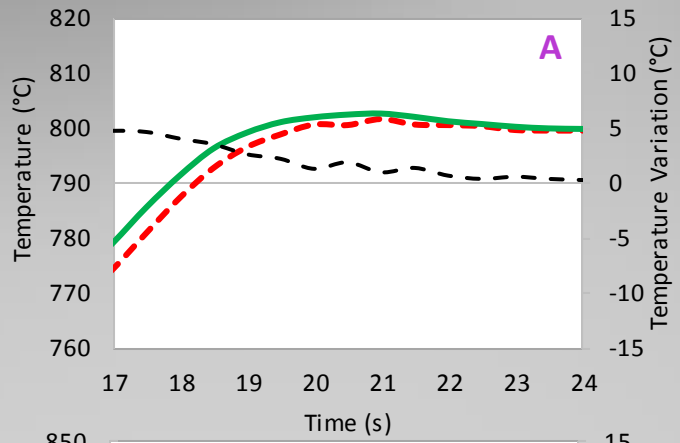


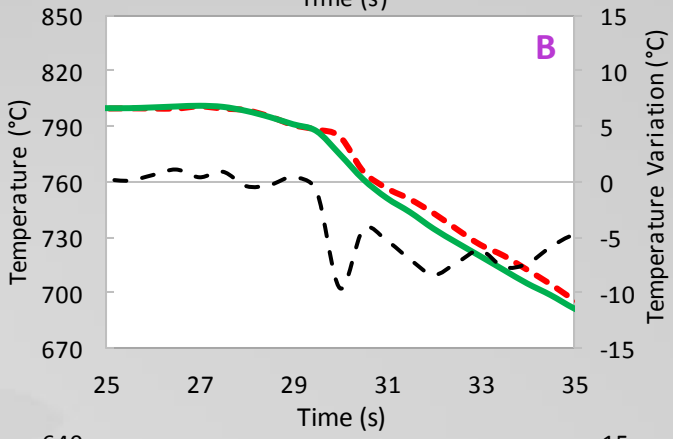
Advantages of thermography control

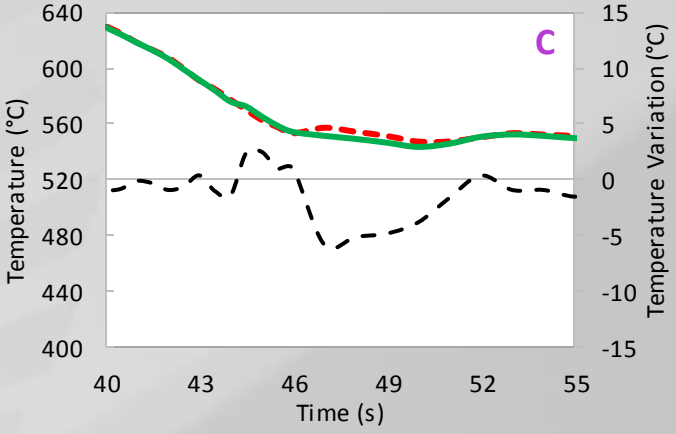
Thermal profiling and multiple zone control





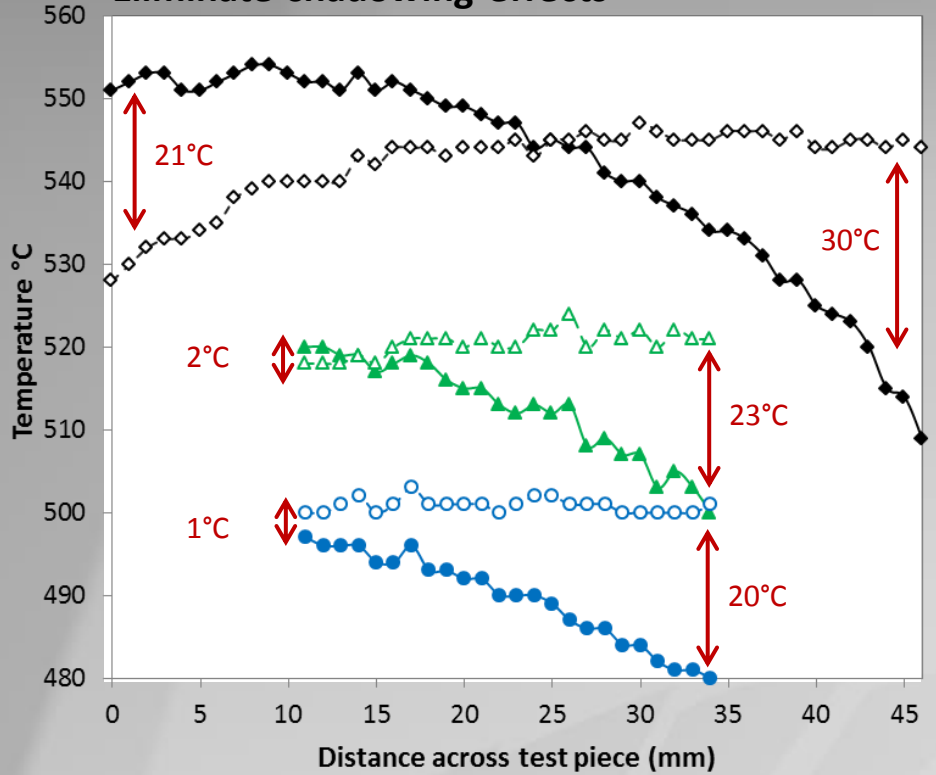


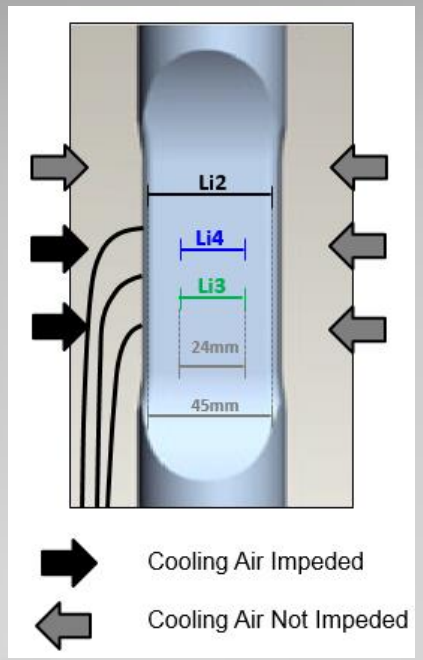


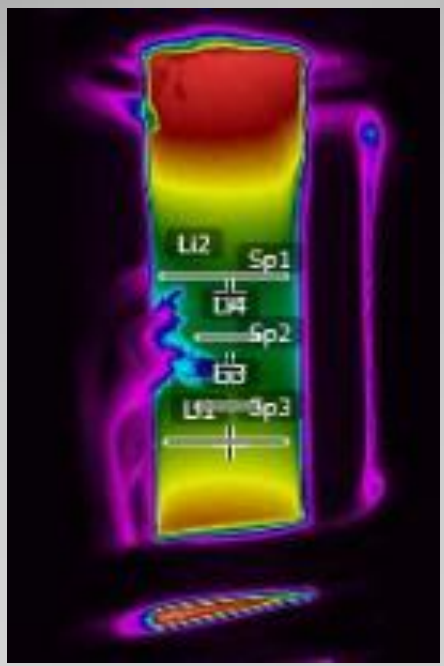


Advantages of thermography control

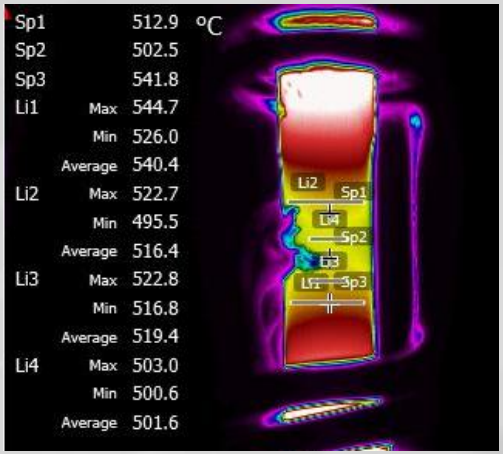
Eliminate shadowing effects



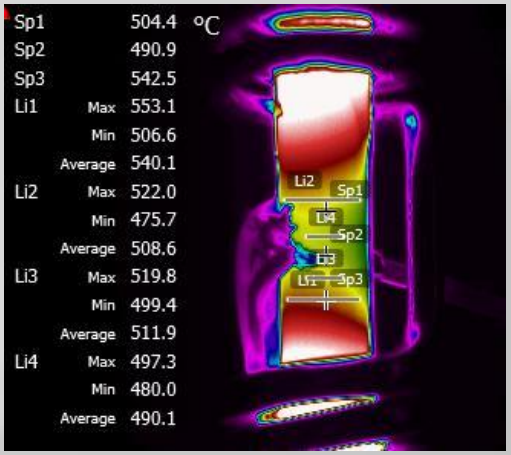




Cooling Direction

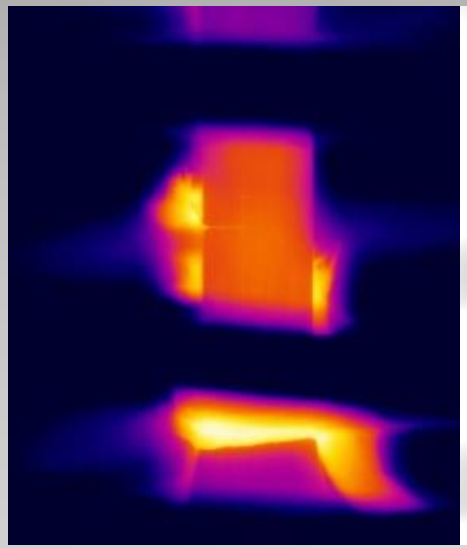


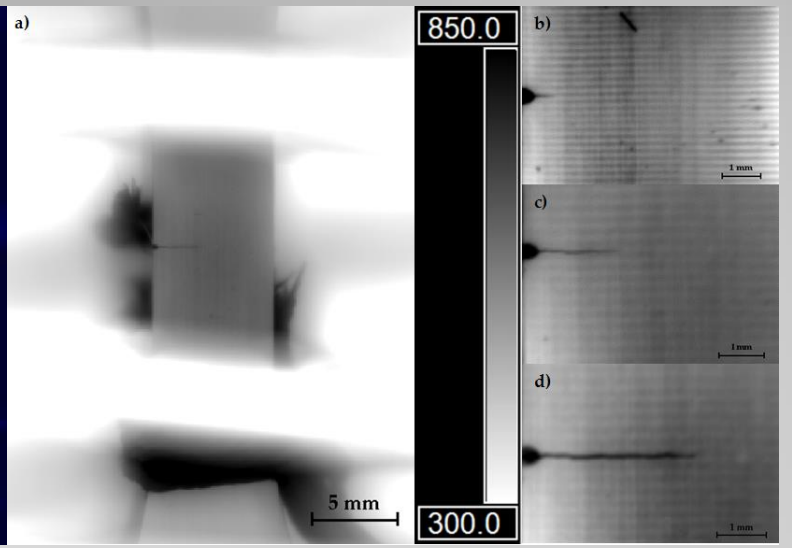
Cooling Direction

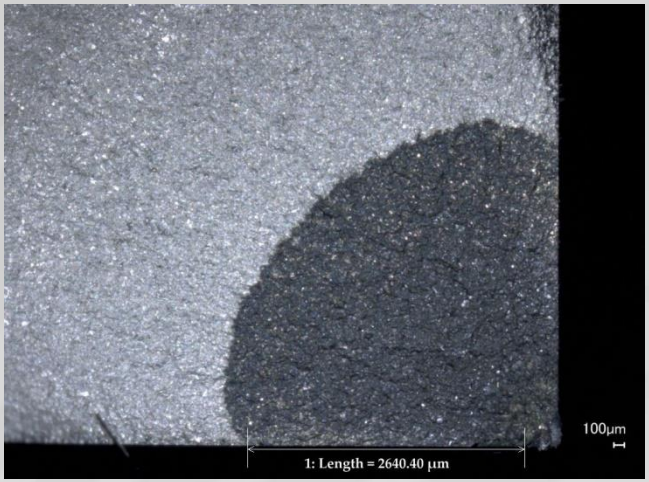


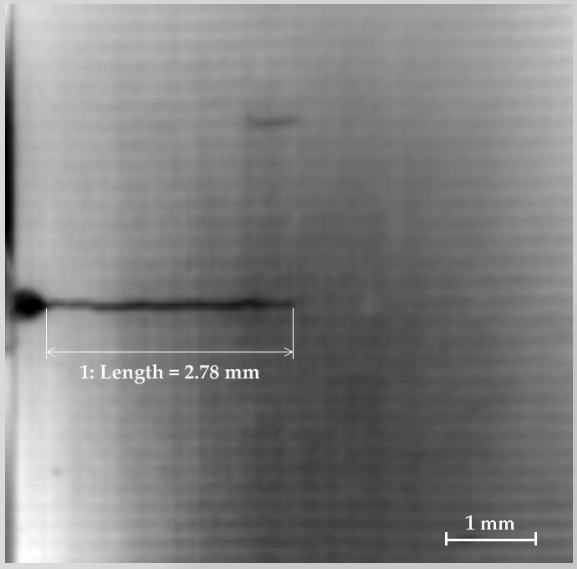
Advantages of thermography control

Non invasive crack growth measurements



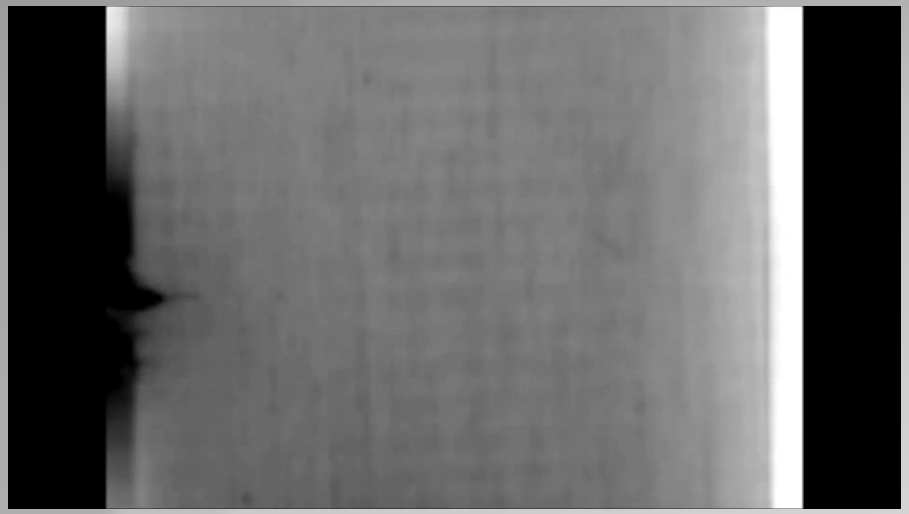


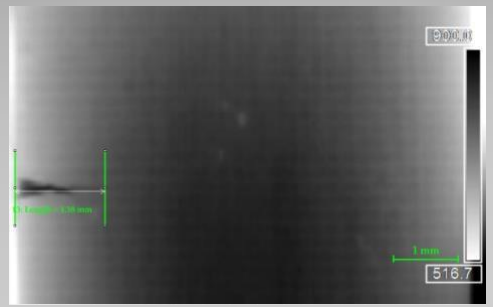




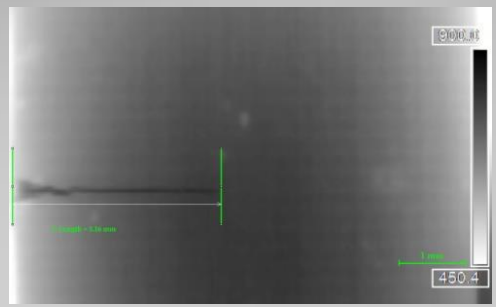
Advantages of thermography control

Non invasive crack growth measurements

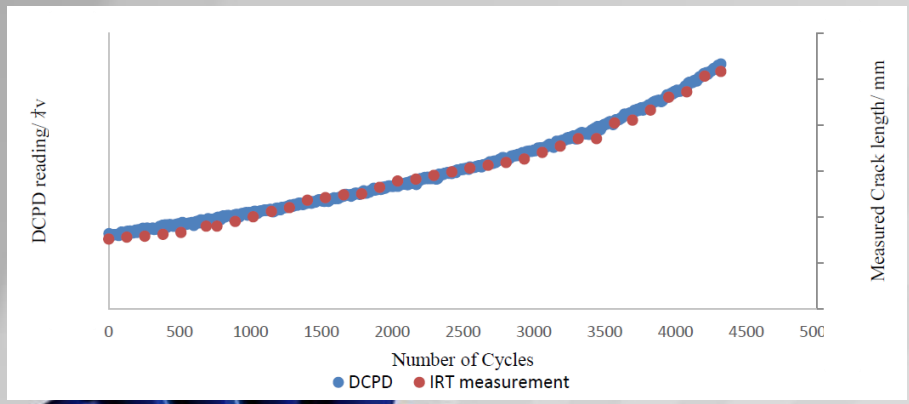


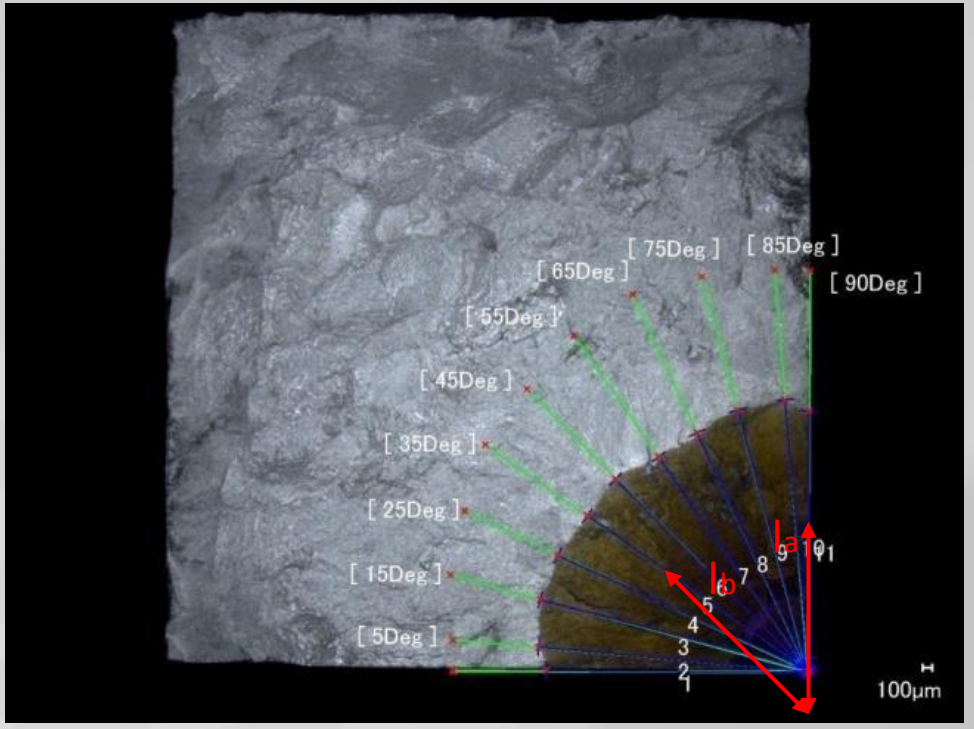


Surface crack length 3549 cycles



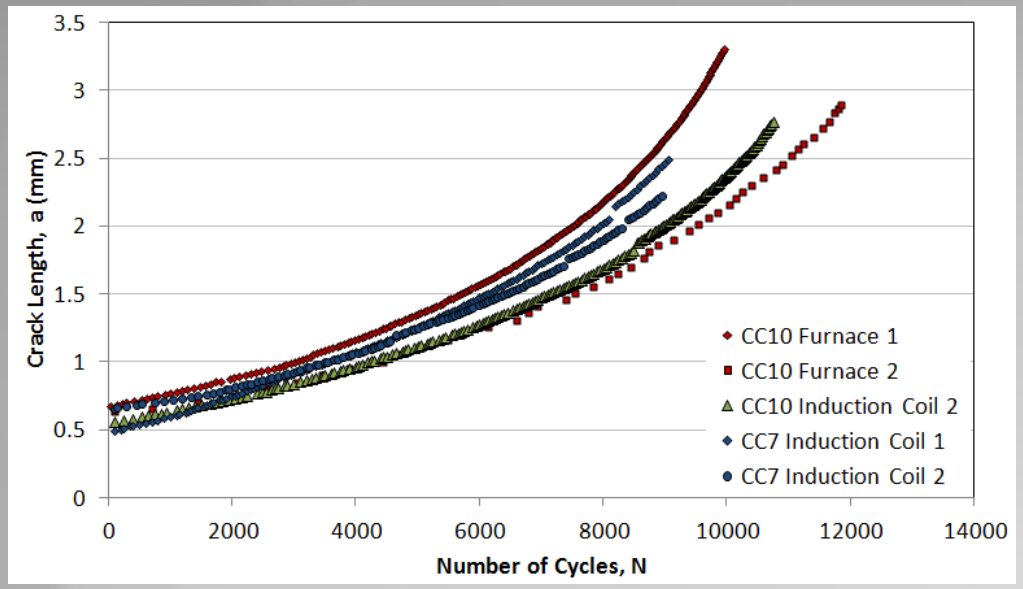
Surface crack length after 6549 cycles



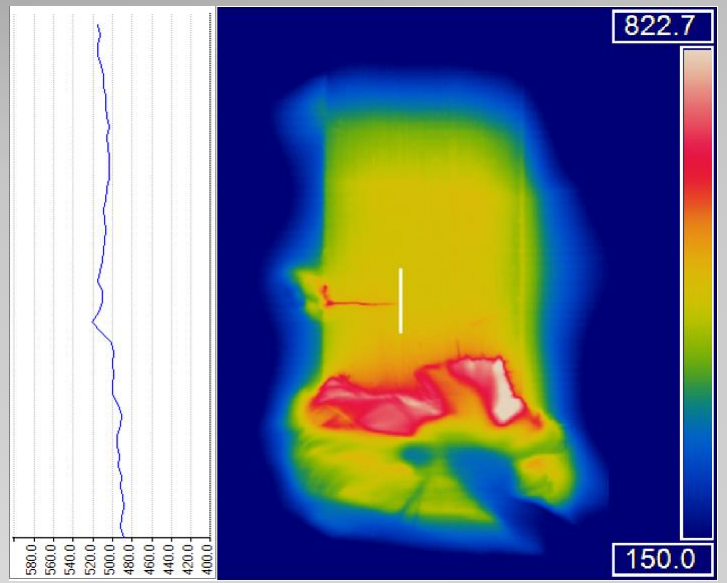


Advantages of thermography control

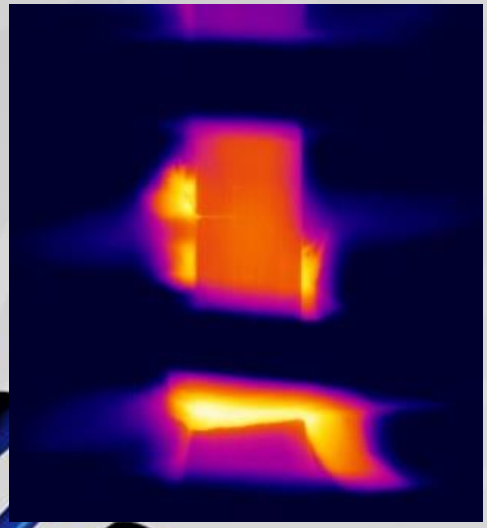
Crack tip heating investigations

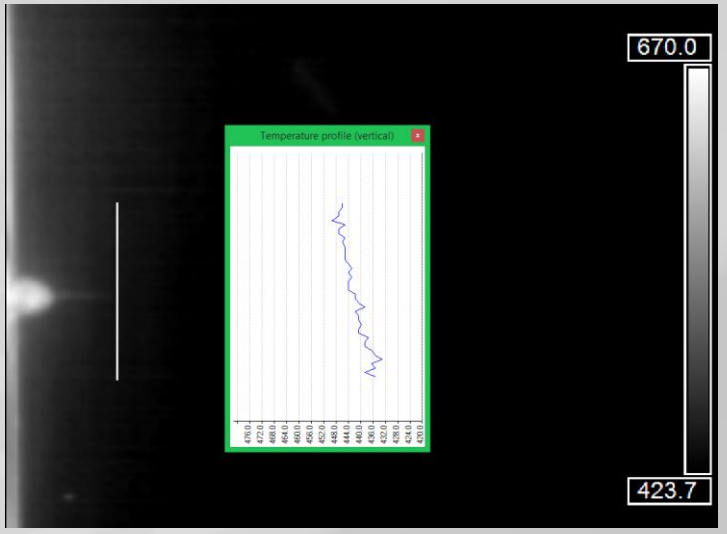


Waspaloy crack length vs. number of cycles: furnace and induction coil comparisons at 650°C, 450MPa and R=0.1.



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





Advantages of thermography control

- Enables a completely non-Invasive control method for high temperature testing, primary advantages with non-metallic materials.
- Removes complications with PD probe attachments and coil interferences in DCPD FCG testing.
- Avoids complications with thermocouple control
  - Crack initiations at welds.
  - Thermocouple shadowing and or over/undershooting
- Excellent thermal profiling advantages prior to testing with any control method.
- Enables aggressive environmental testing to be carried out
- Allows multiple zone temperature control allowing possible thermal gradient testing
- Can be combined with strain analysis equipment such as digital image correlation (DIC)

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Any Questions?