ASSESSMENT OF OPTICAL BASED CONTROL METHODS FOR THERMO-MECHANICAL FATIGUE

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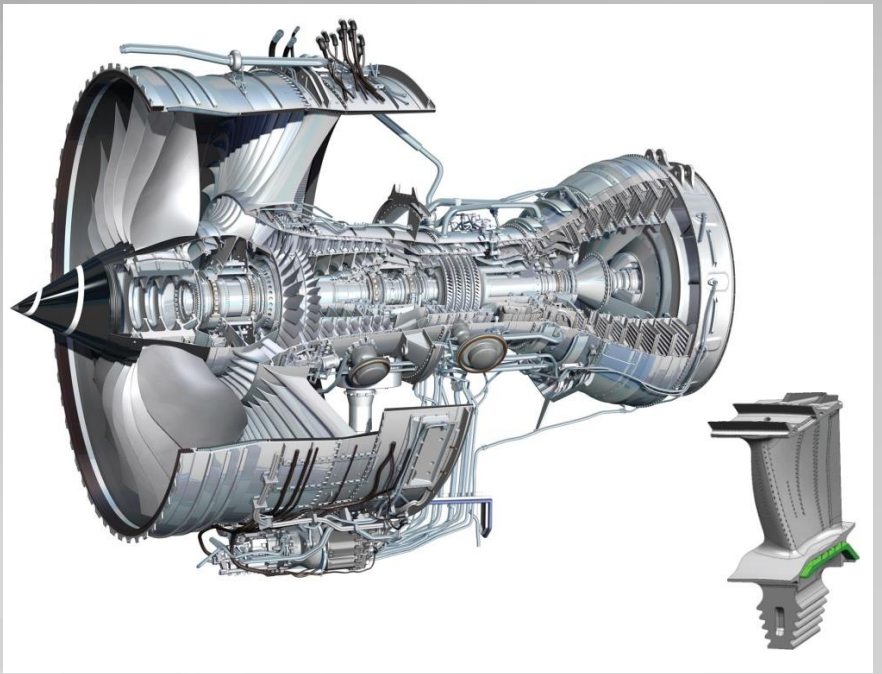
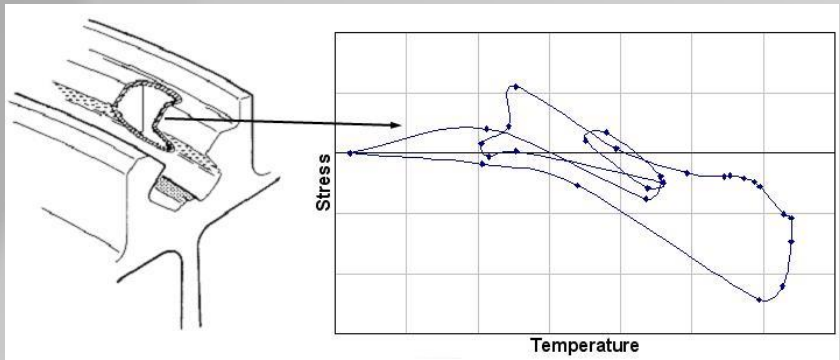
Industrial Motivation

- 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





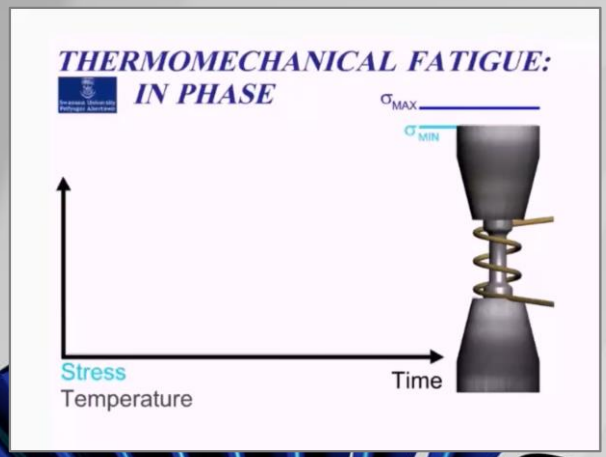
- Extrapolation of isothermal fatigue (IF) results to incorporate these effects show limited success
- Generation of TMF data is required to allow the development of lifing methodologies under TMF loading

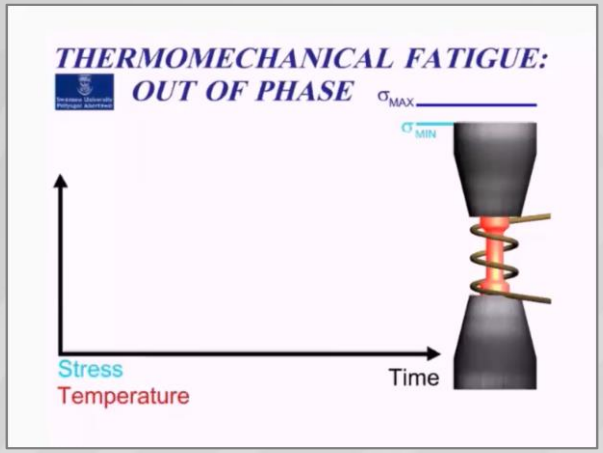
Thermo-Mechanical Fatigue (TMF)

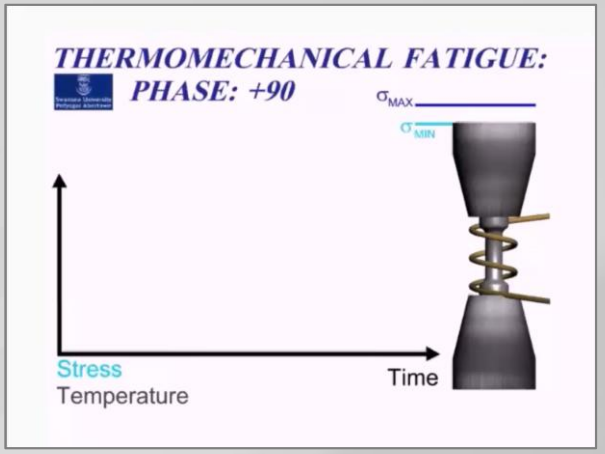
- Diverse mechanisms are involved, Primarily . . .

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.



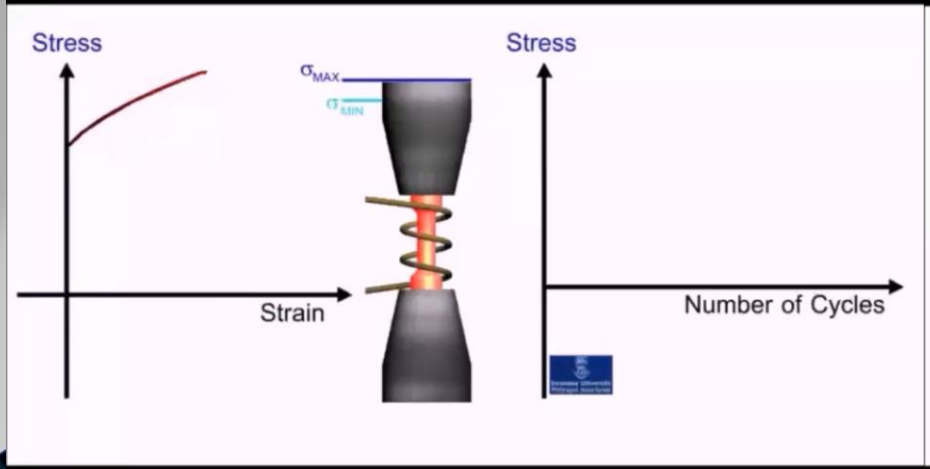




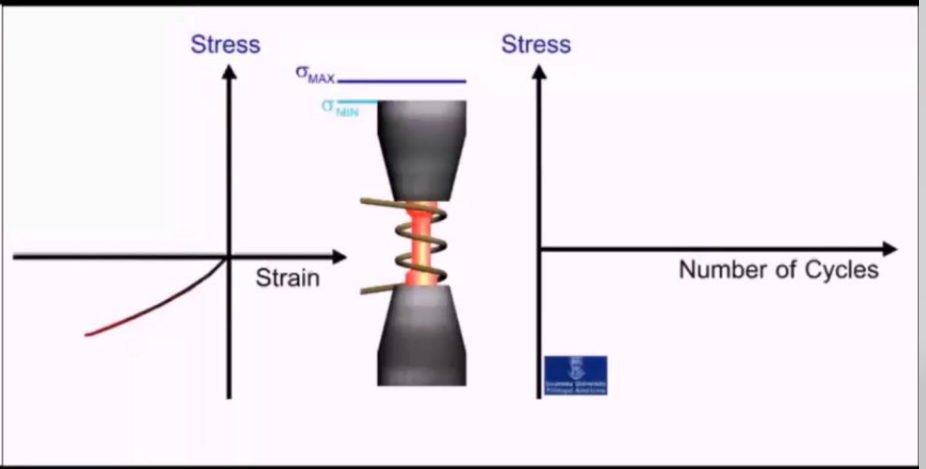
Typical TMF Hysteresis Behaviour

- Initial material behaviour may change significantly during the test.
- Understanding the stress/strain evolution throughout the test is often critical in order to be able to predict life.
- Cycle may evolve to very different stress conditions due to the interaction of plasticity and creep which often makes TMF tests differ significantly from isothermal fatigue.
- However without accurate temperature control, reliable test data for component lifing cannot be achieved.

In-Phase (ϕ = 0°)

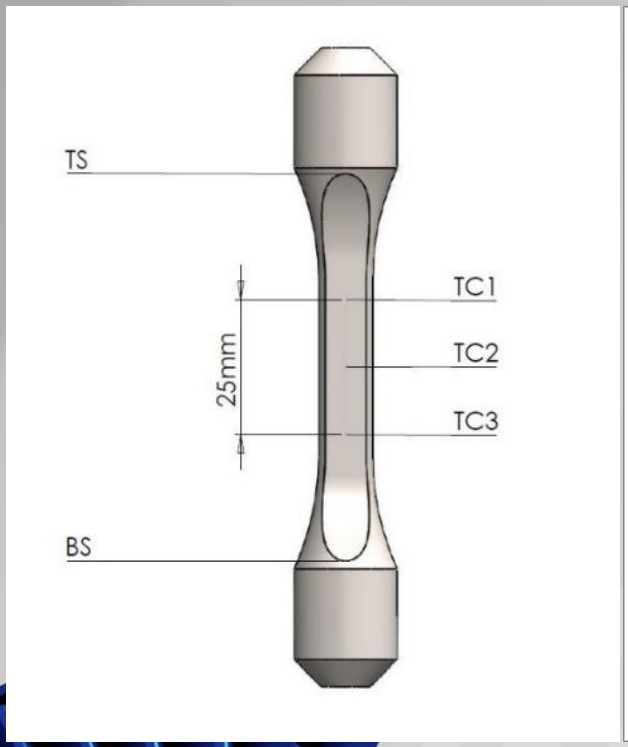


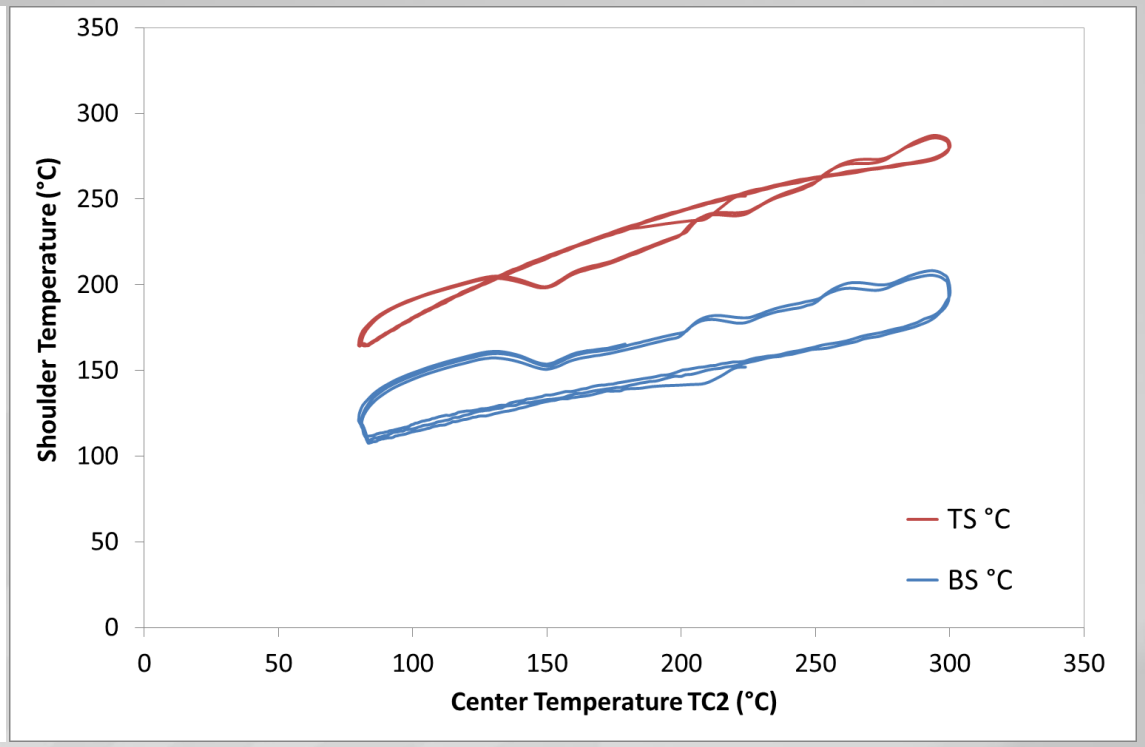
Out-Phase (ϕ = -180°)



Thermocouple Shoulder Control

- Unfavourable to weld on the specimen gauge length – Nucleation of cracks
- Contact temperature measurement can be achieved at the specimen shoulder.
- Complex setup and often temperatures at either shoulder are not stable with loops overlapping and drifting, unacceptable for temperature control purposes.



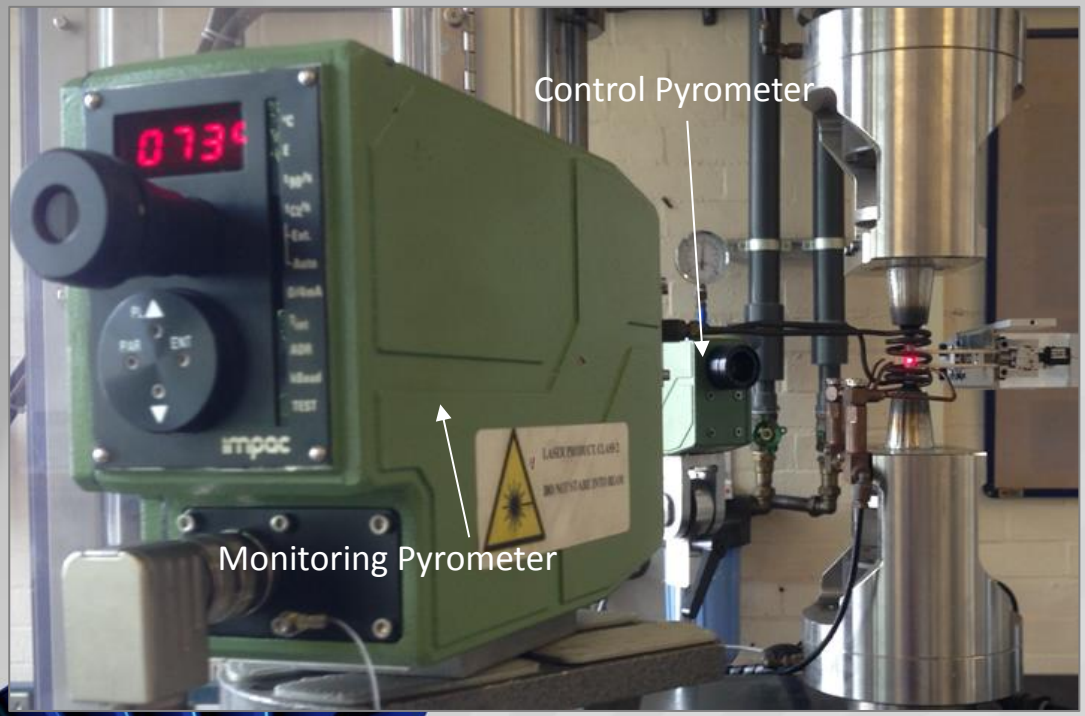


TMF Standards:

- **ASTM E2368-10**: Standard Practice for Strain Controlled Thermo-mechanical Fatigue Testing *(Released in 2004, updated in 2010)*
- **ISO 12111:2011**: Metallic materials – Fatigue Testing – Strain Controlled Thermo-mechanical Fatigue Testing Method *(Released 2011)*

Pyrometer Control

- Non-invasive temperature control can be acheived using pyrometry
- High temperature pre-exposure to produce a constant surface emissivity, ε.



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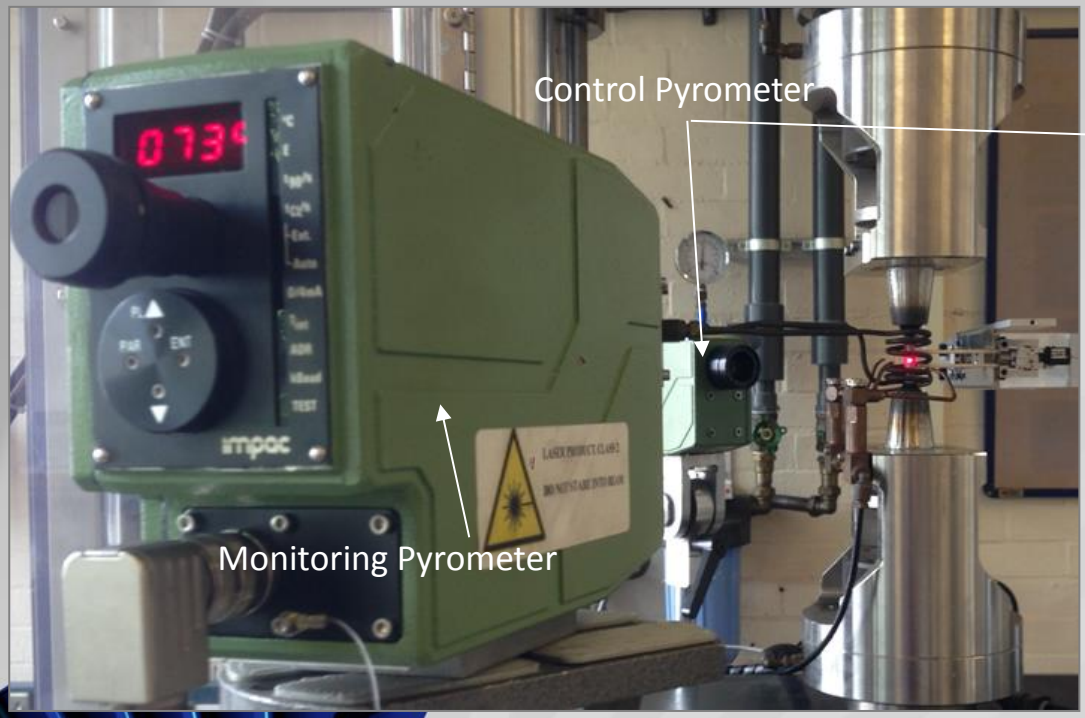
Pyrometer Control

- High temperature pre-exposure can reduce Fatigue life

  Encinas-Oropesa, A., Drew, G. L., Hardy, M. C., Leggett, A. J., Nicholls, J. R., and Simms N. J., Proceedings of the Eleventh TMS International Symposium, Superalloys, pp. 609-618, 2008

- Thermal Profiling still achieved using thermocouples



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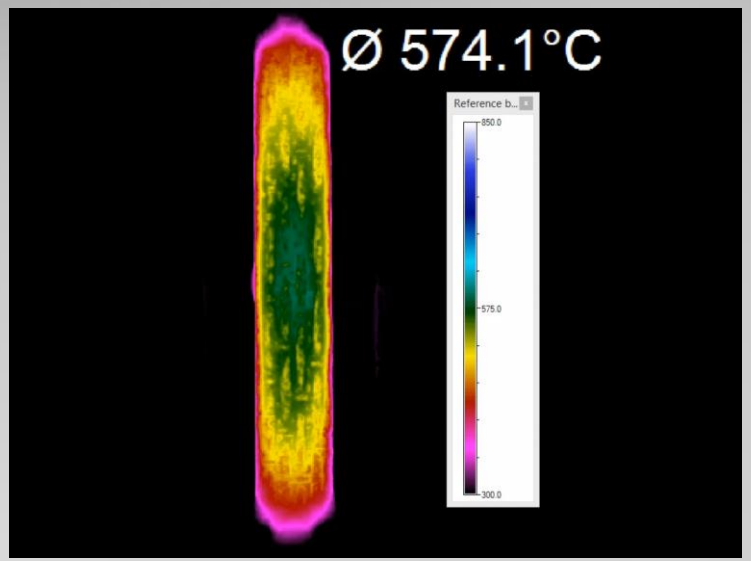
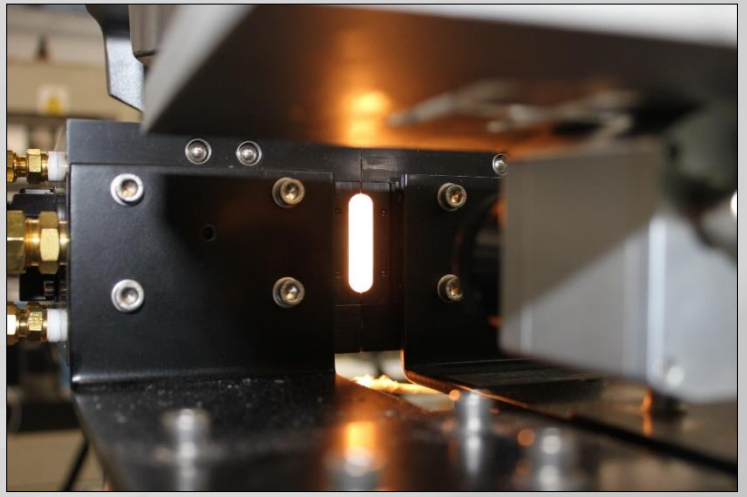
Introduction - Thermography

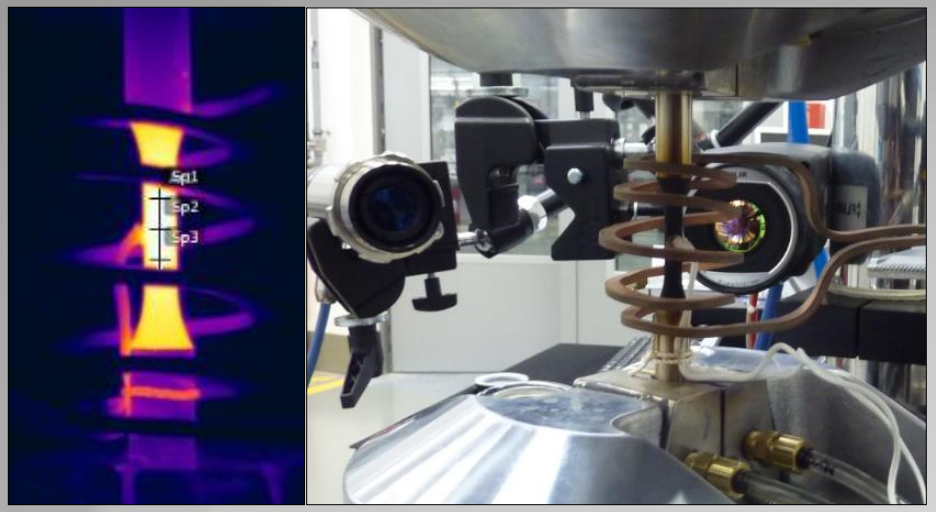
- Technique that can deliver….
  - Accurate Temperature control
  - Incorporates Thermal Profiling
  - Not influenced by Surface emissivity
  - Completely Non-Invasive
  - Metallic and non-metallic materials
  - Robust and repeatable
- Infra-red, Thermography?



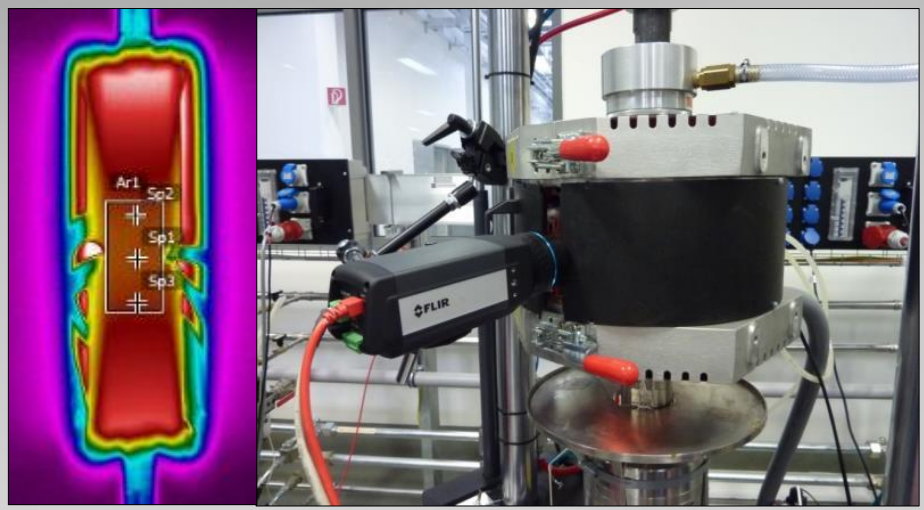


Previous Work – Rolls-Royce plc, MTOC, Germany

Induction Heating

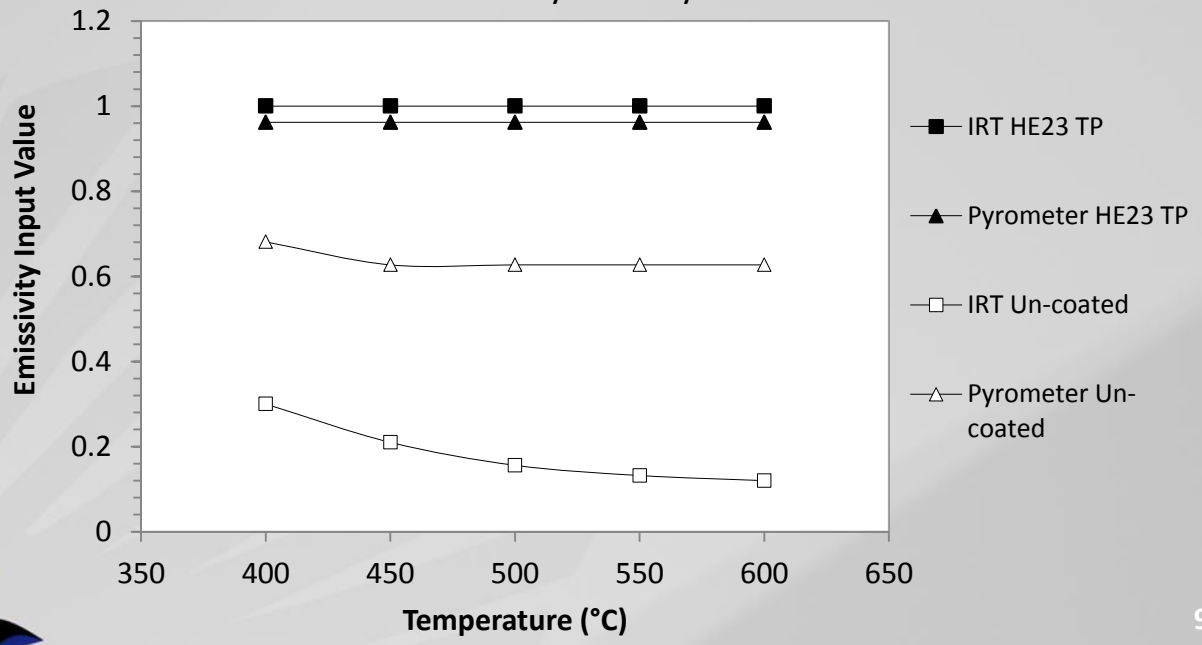


Radiant Lamp Furnace Heating

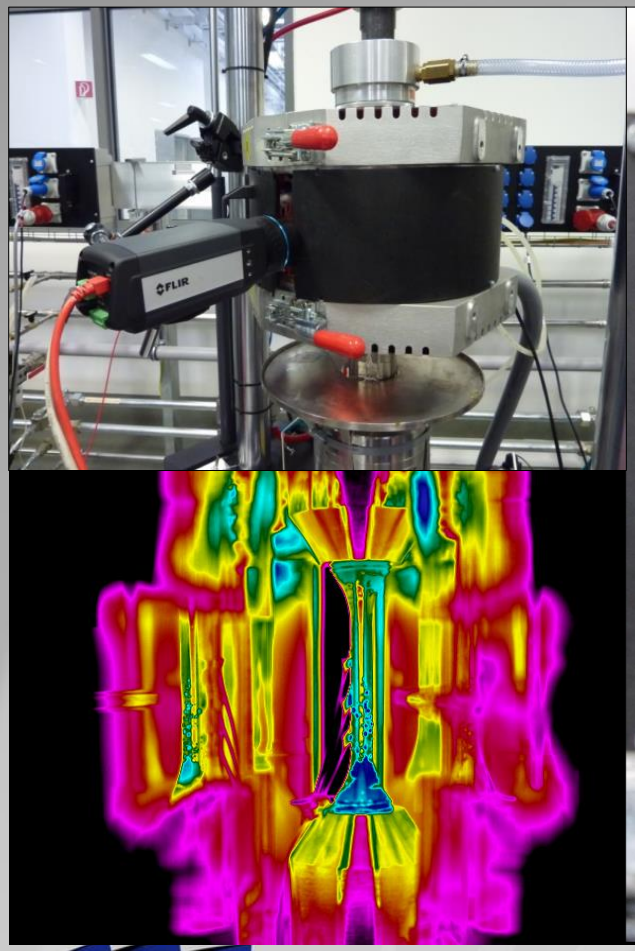


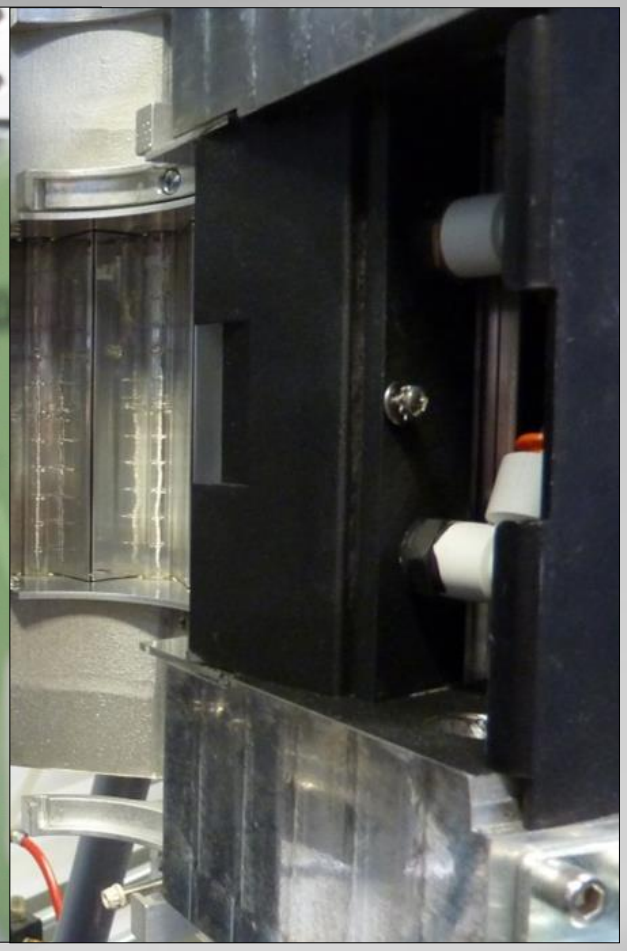
HE23 Thermal Paint

Surface Emissivity Stability



Previous Work – Radiation Reflections

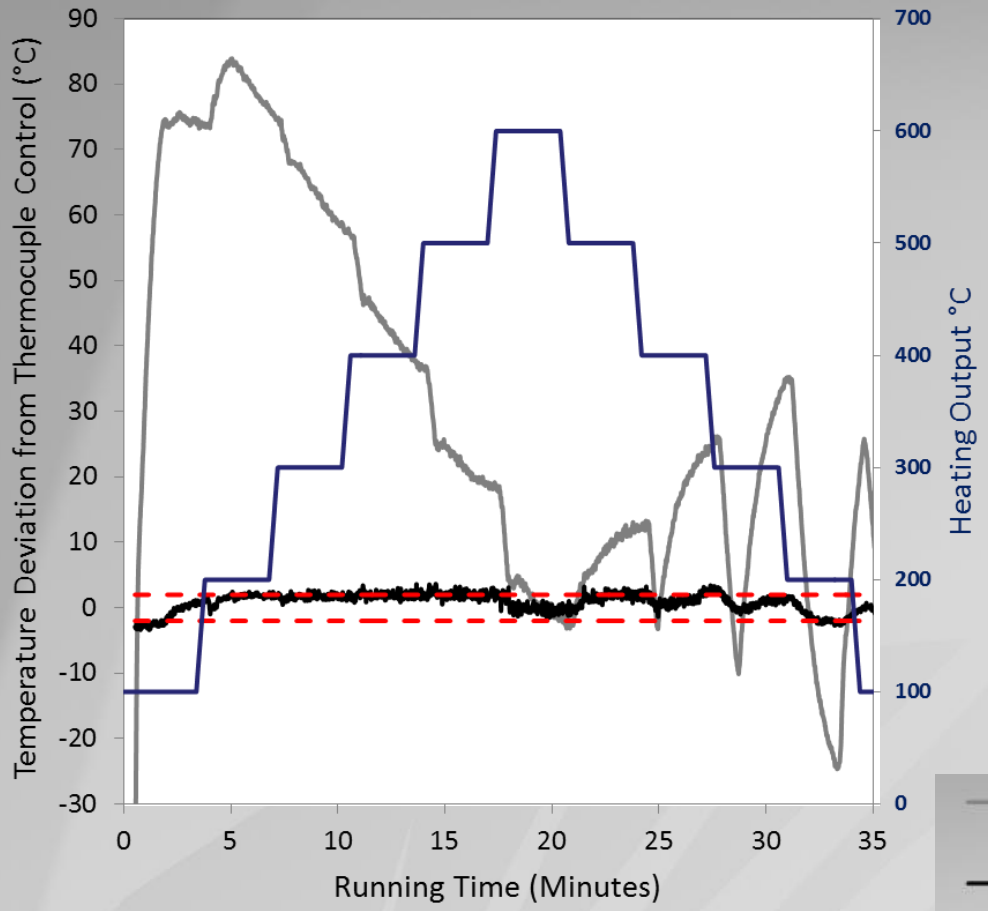




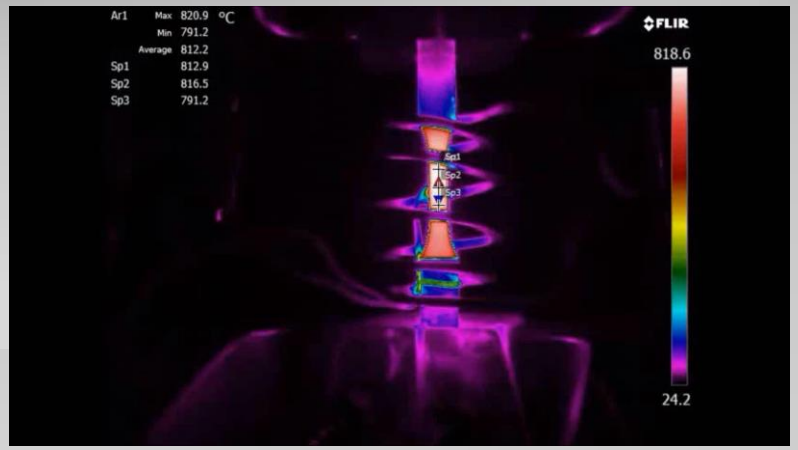
Jones, J.P., et al., Non-invasive temperature measurement and control techniques under thermomechanical fatigue loading. Materials Science and Technology **2014**. 30(15): p. 1862-1876

Jones, J.P., et al. Assessment of Infrared Thermography for Cyclic High-Temperature Measurement and Control. in 4th Evaluation of Existing and New Sensor Technologies for Fatigue, Fracture and Mechanical Testing. **2015**. Toronto: ASTM International.

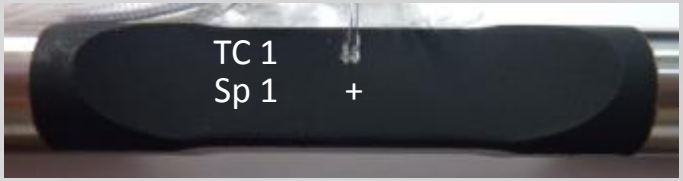
Previous Work – HE23 Stability



Thermography View



HE23 Coated Test Piece



IR Thermography Monitor

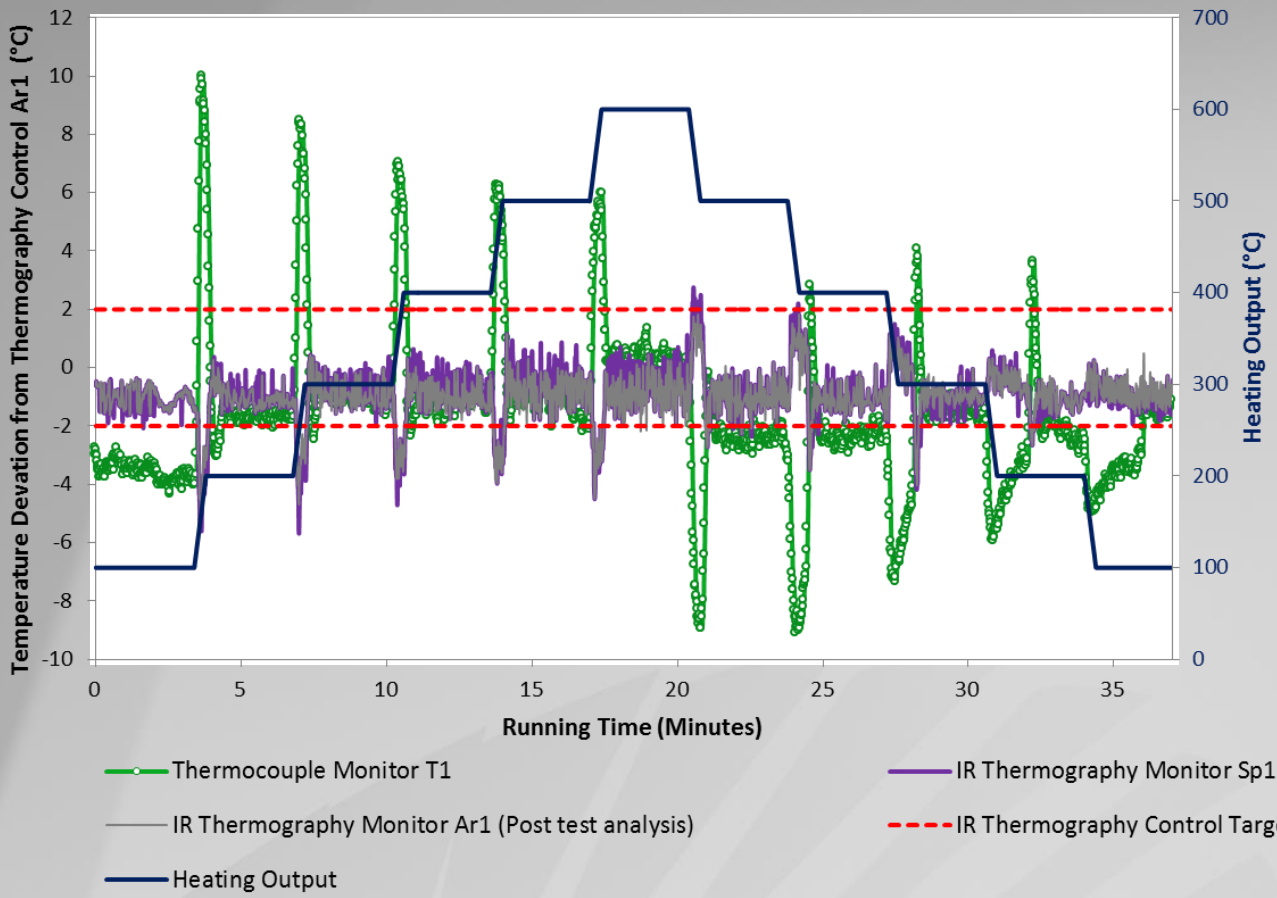
IR Thermography Monitor HE23

Thermocouple Control Target Temperautre ±2°C

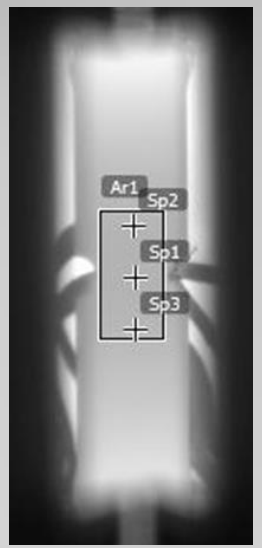
Heating Output

- Brandt, R., C. Bird, and G. Neuer, Emissivity reference paints for high temperature applications. Meas. (IMEKO), 2008. 41(7): p. 731-736

Previous Work – Thermography vs Thermocouples



Thermography View



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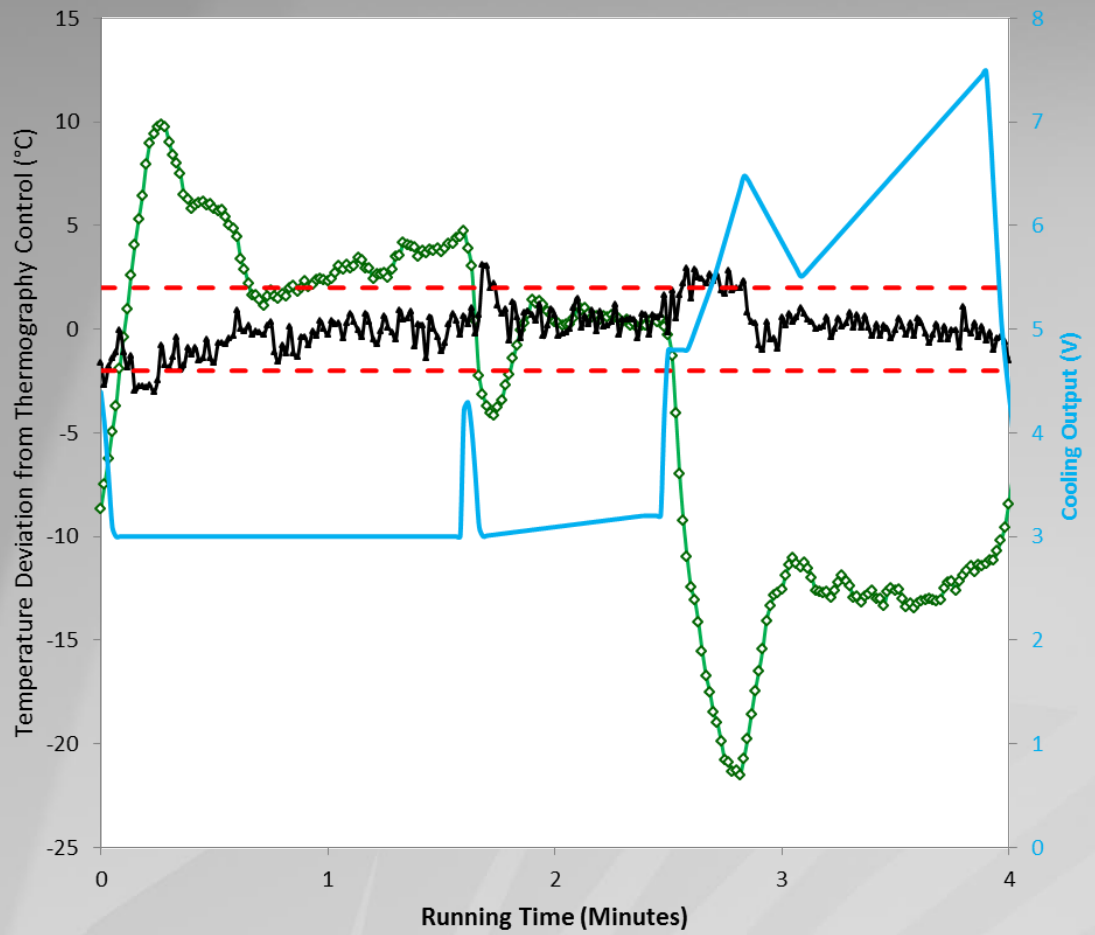

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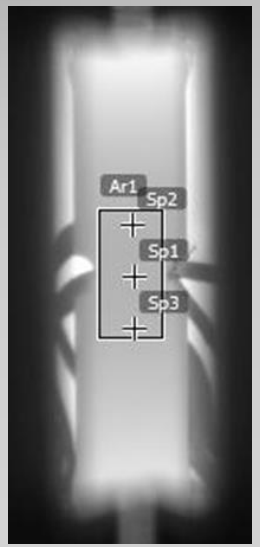

Thermocouple Monitor TC1

IR Thermography Monitor Sp1 (Post test analysis)

IR Thermography Control Ar1 Target Temperature ± 2°C

Cooling Output

- Jones, J.P., et al., Non-invasive temperature measurement and control techniques under thermomechanical fatigue loading. Materials Science and Technology **2014**. 30(15): p. 1862-1876
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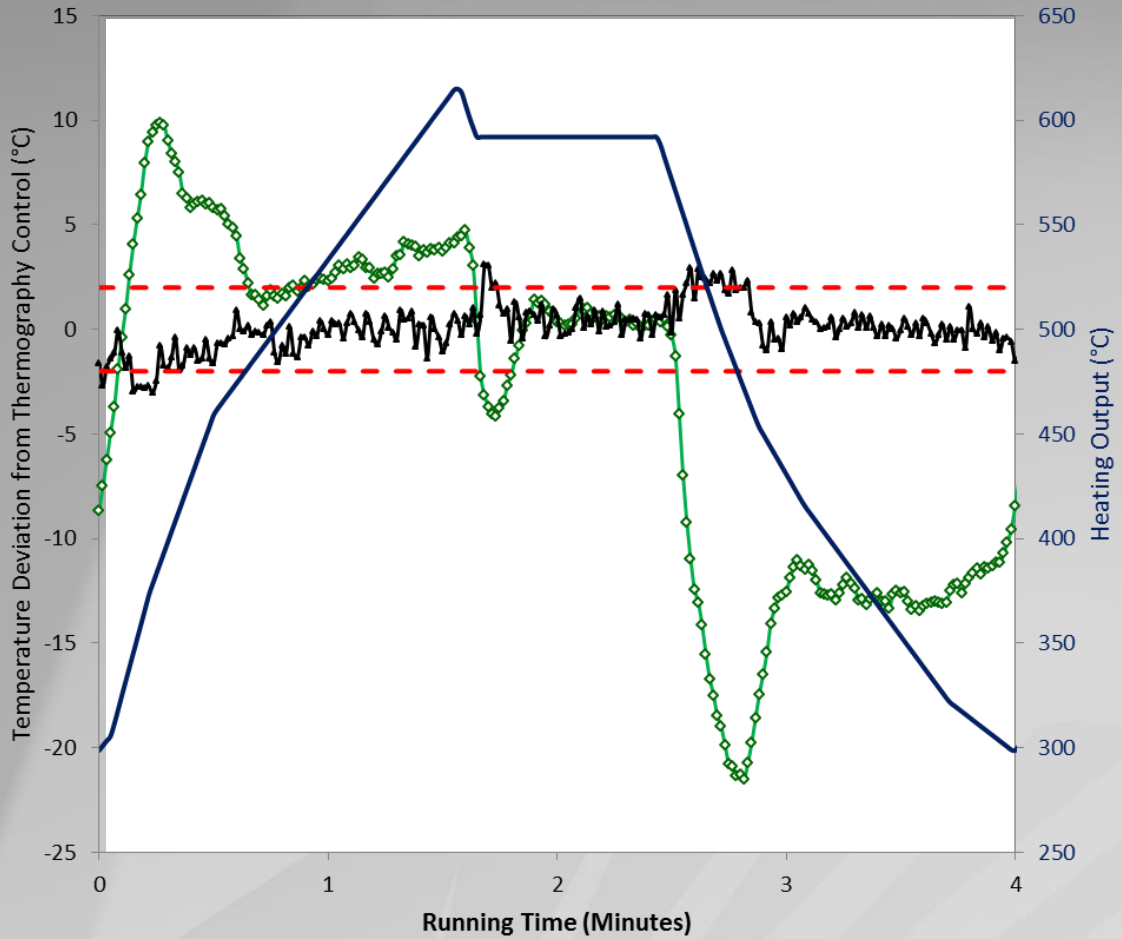
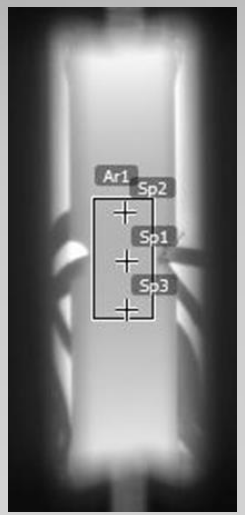


Thermography View



Thermocouple Monitor TC1

IR Thermography Monitor Sp1 (Post test analysis)

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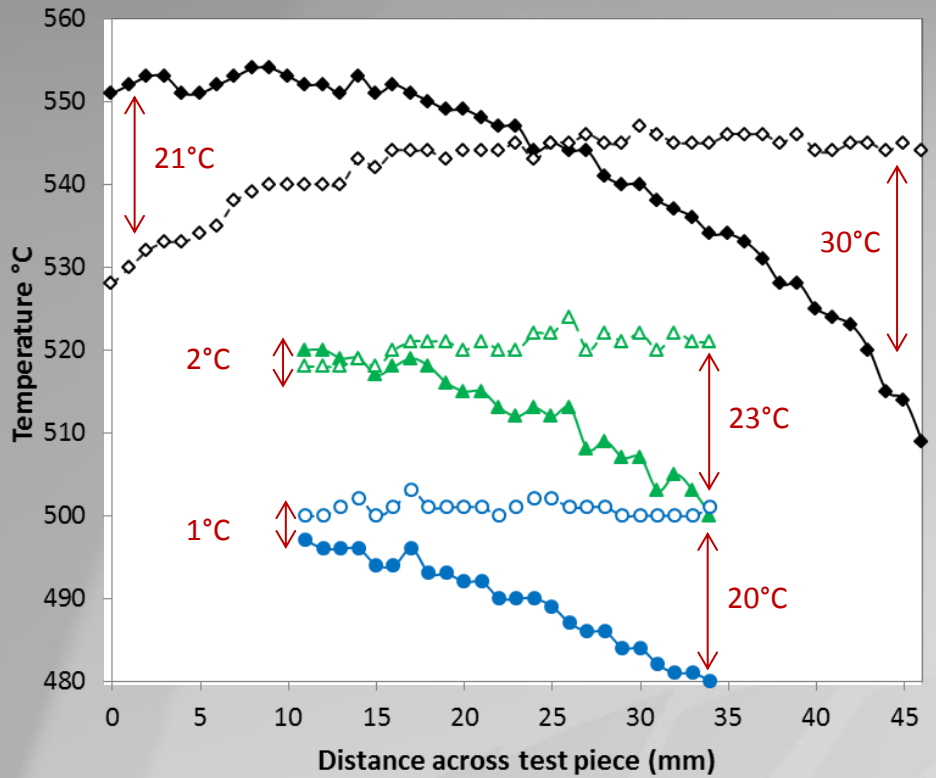
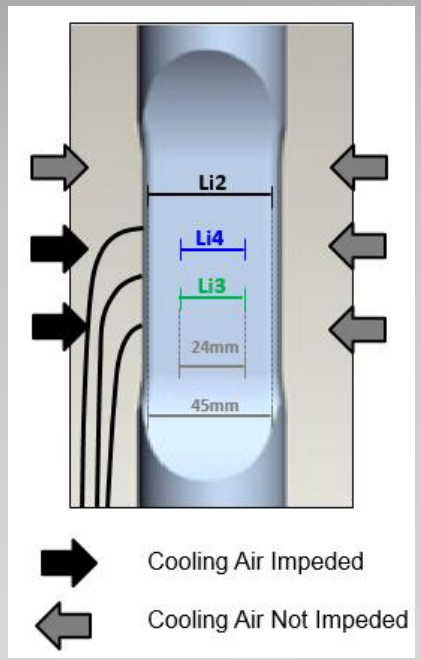
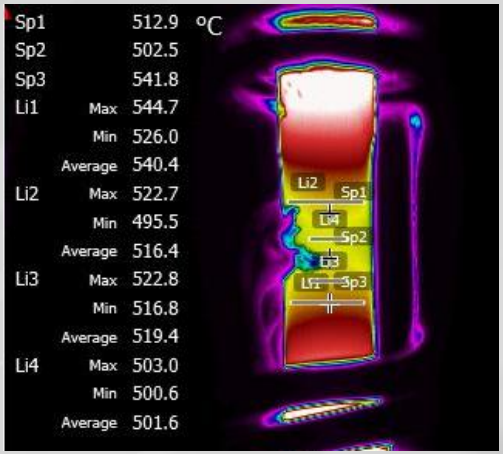
Previous Work – Thermocouple Shadowing





Cooling Direction



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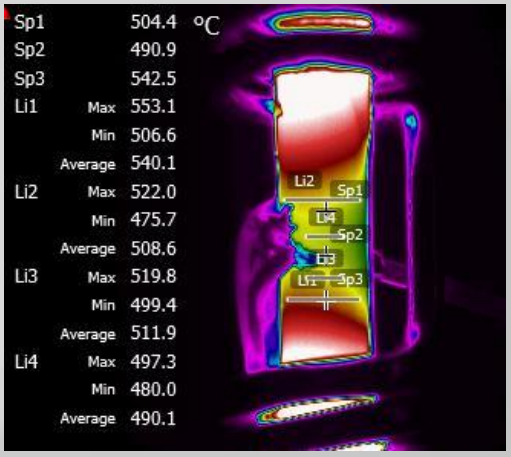
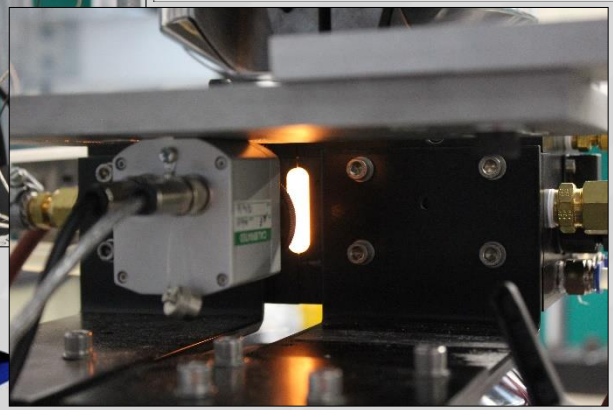
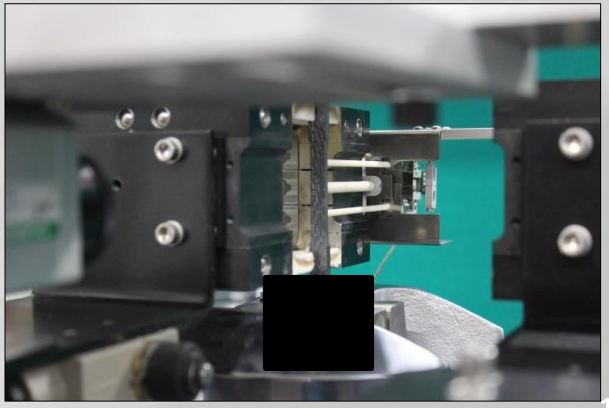


Bespoke TMF Setup – Non Metallic Materials





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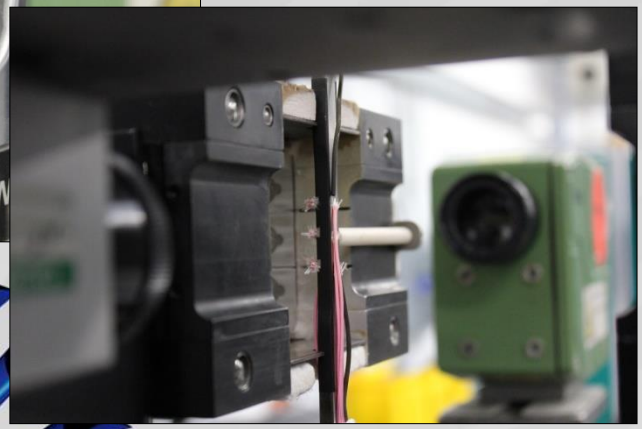
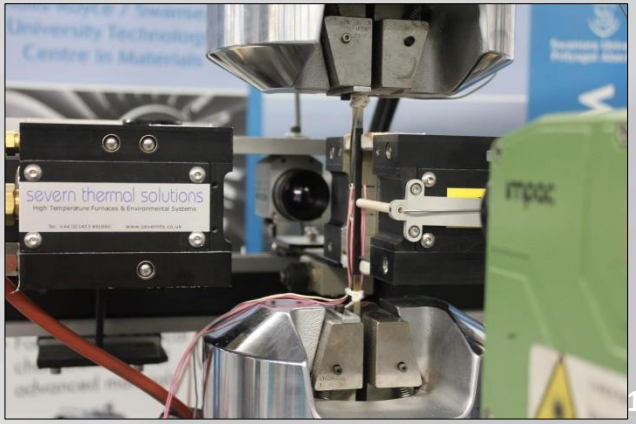
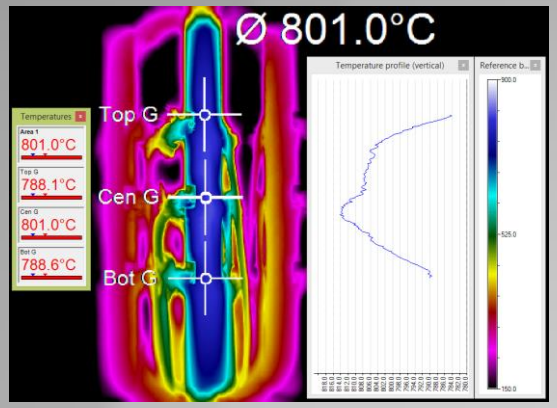


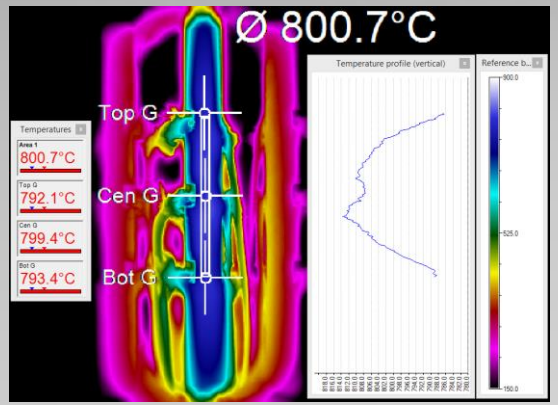


Control Method Comparison

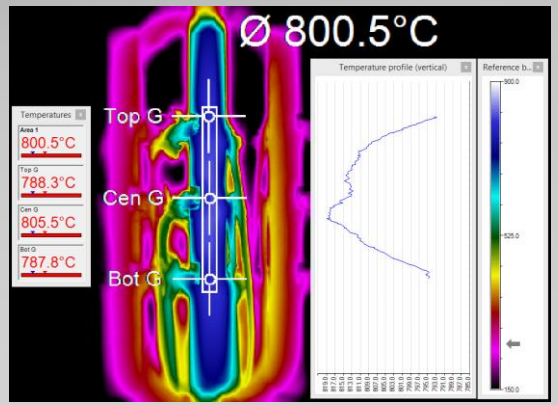
Single Point Control

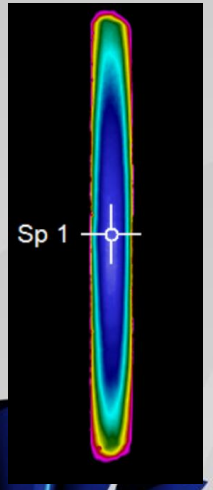


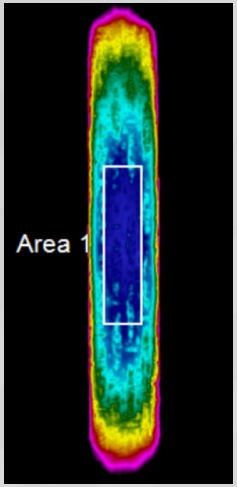
Small Area Control (2 x 25mm)

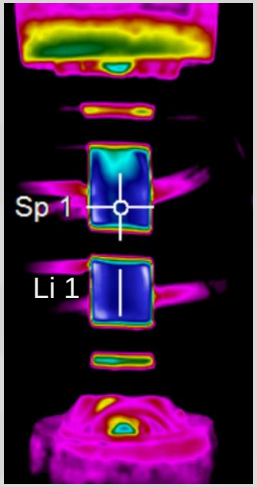


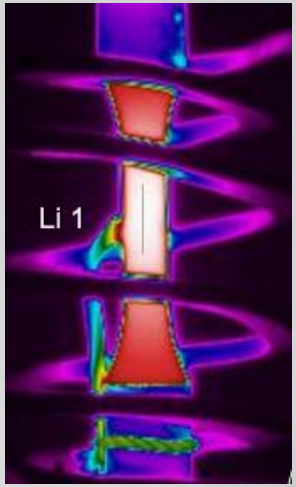
Large Area Control (3 x 30mm)



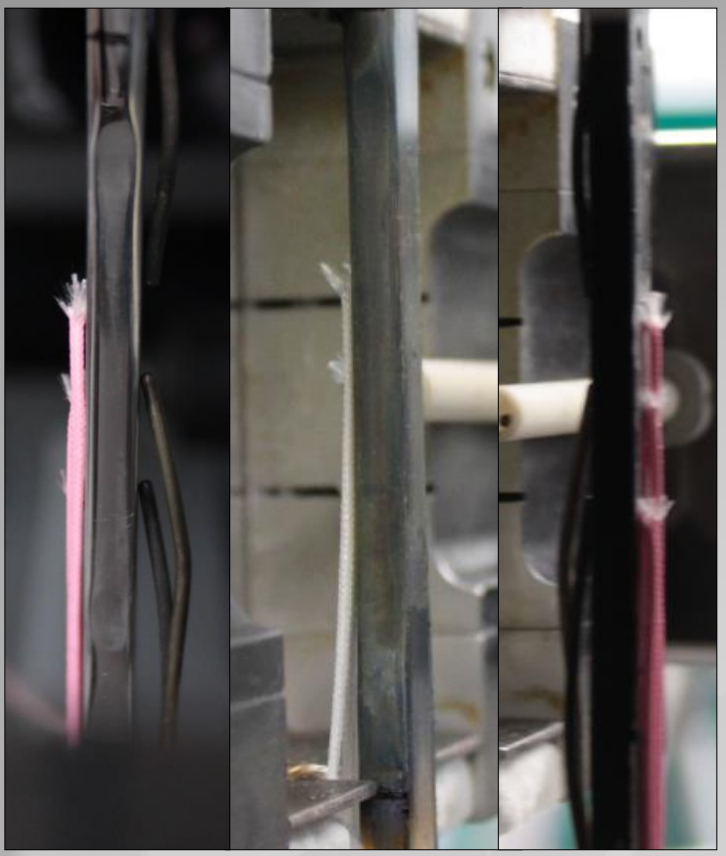


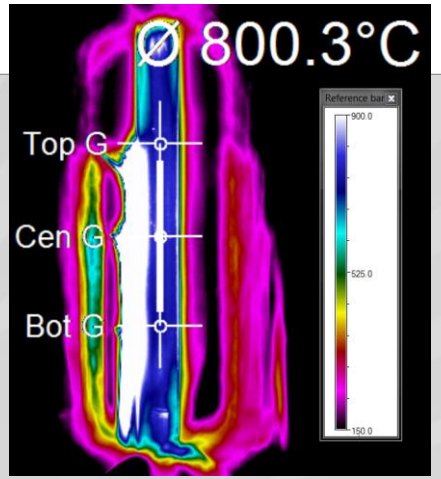


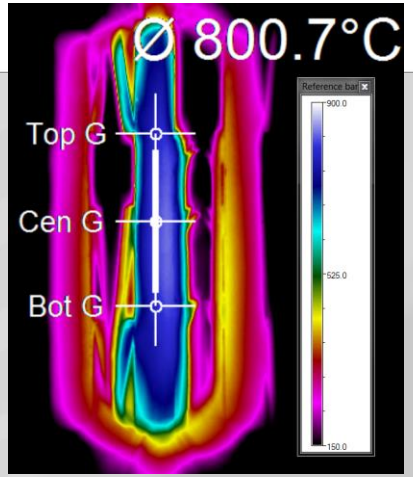




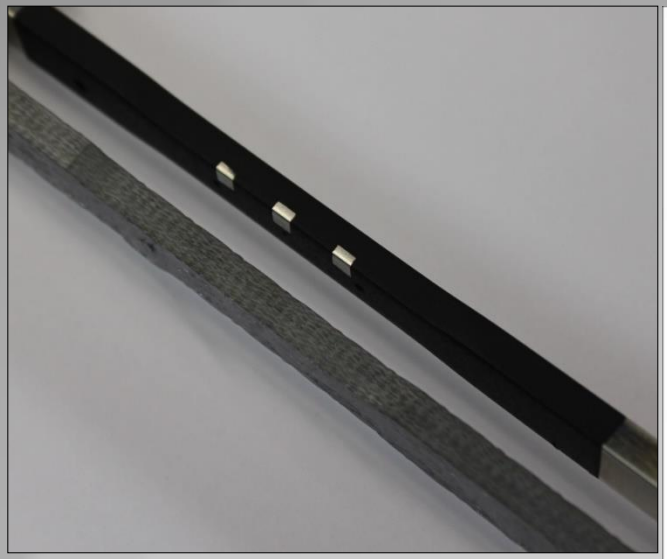
Diverse Surface Conditions

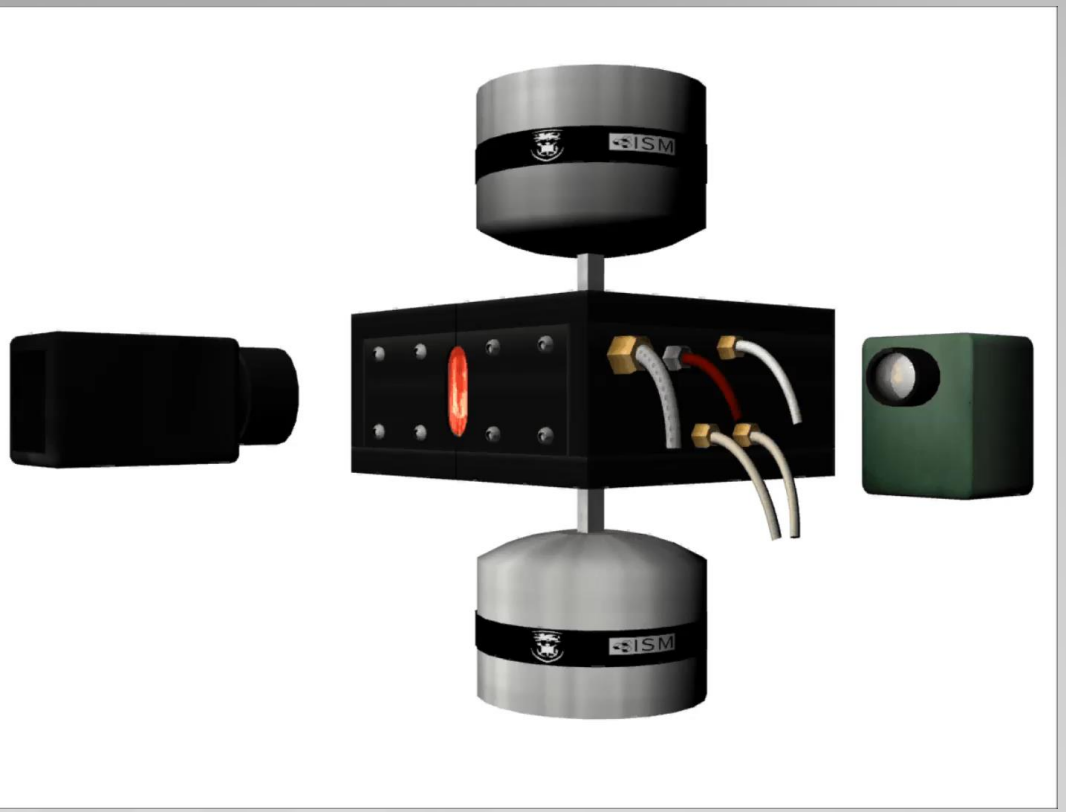


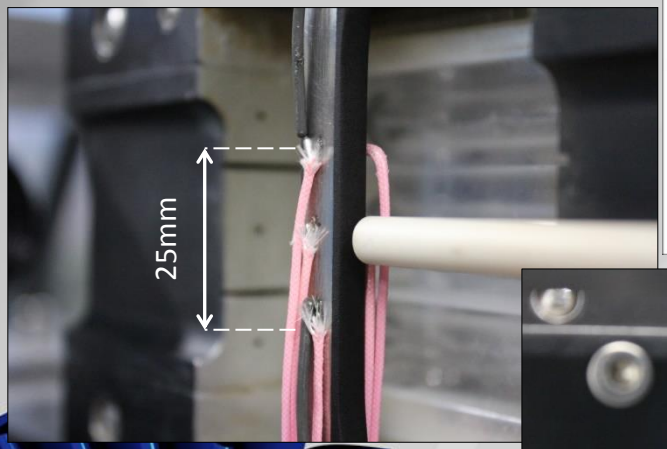


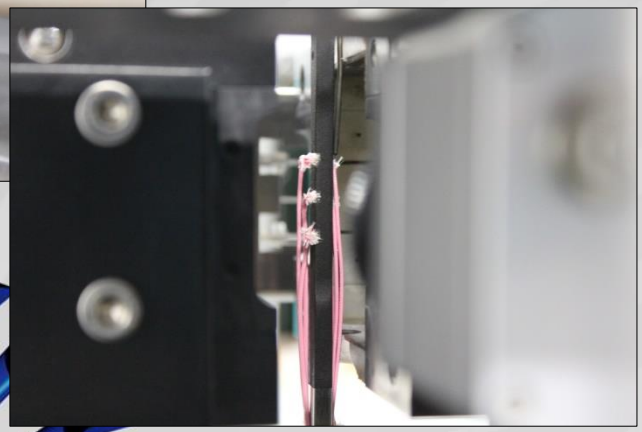


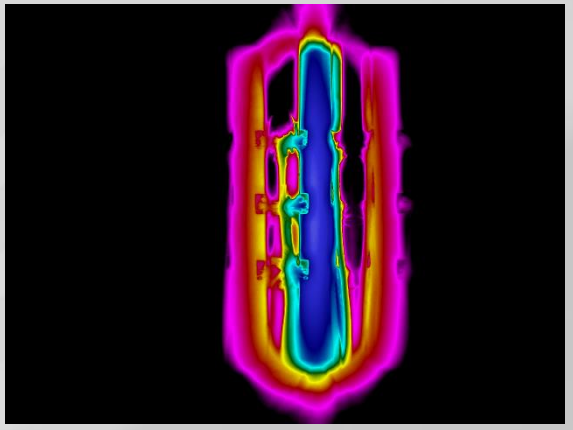
Temperature Measurement Comparisons



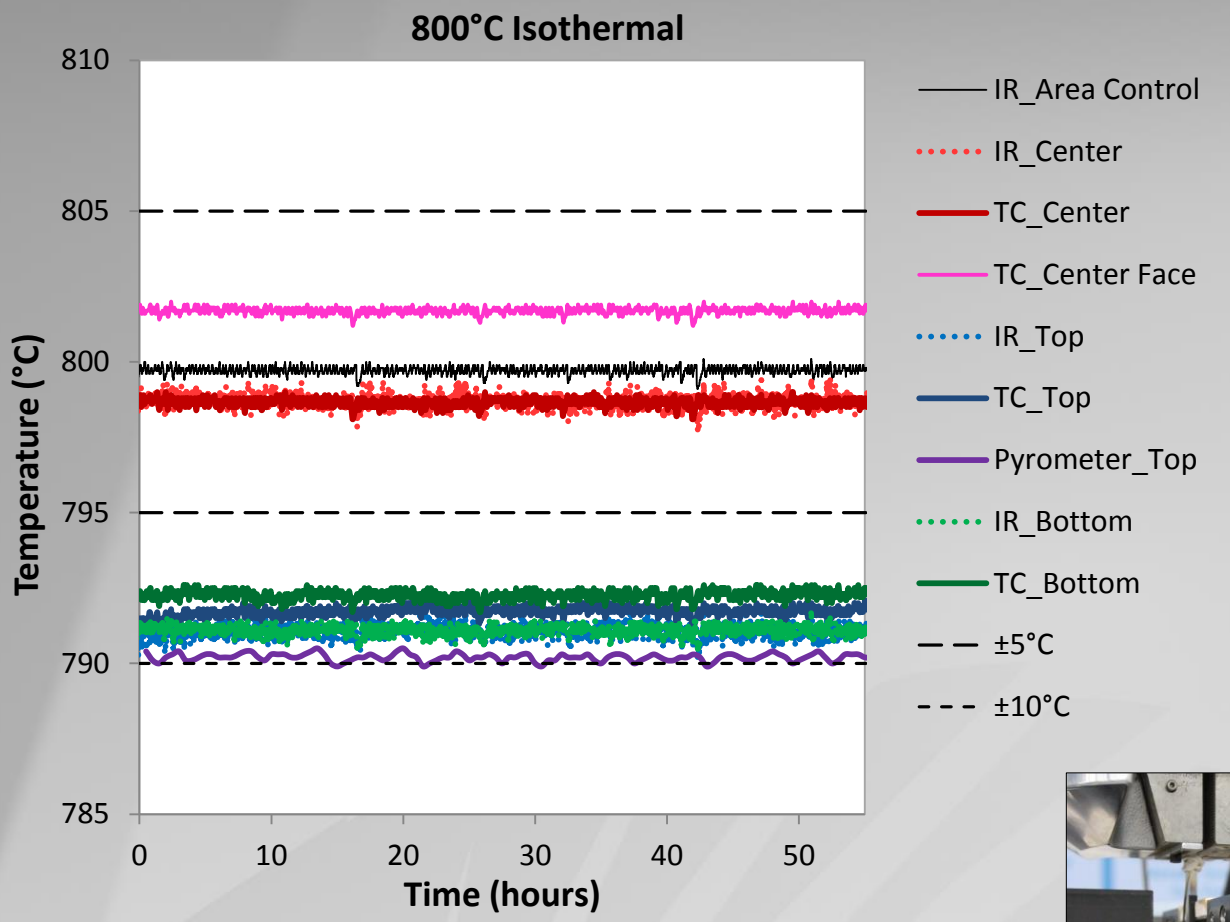


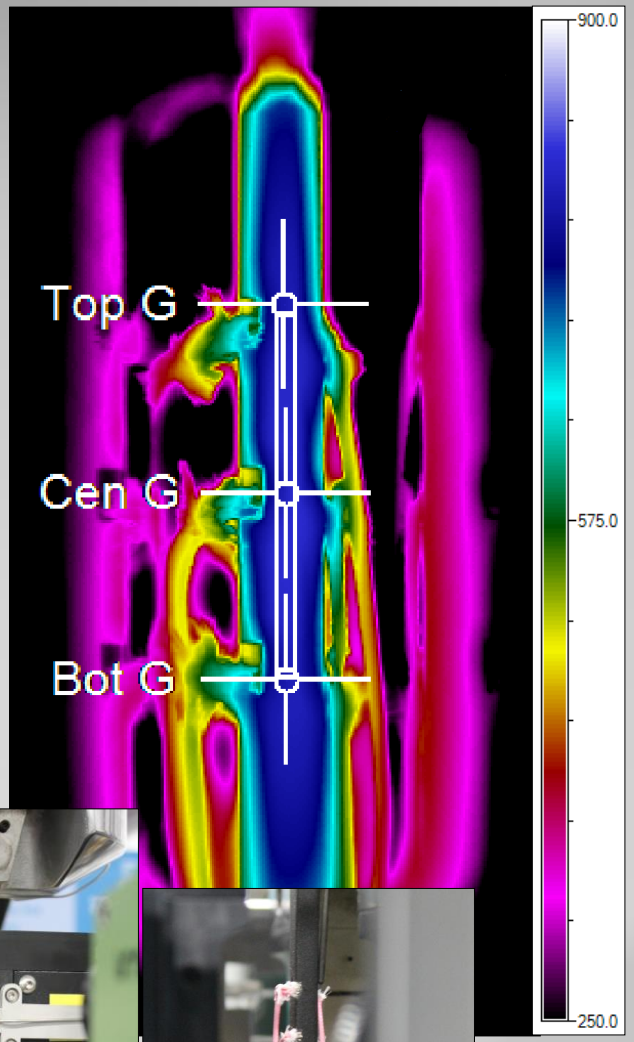




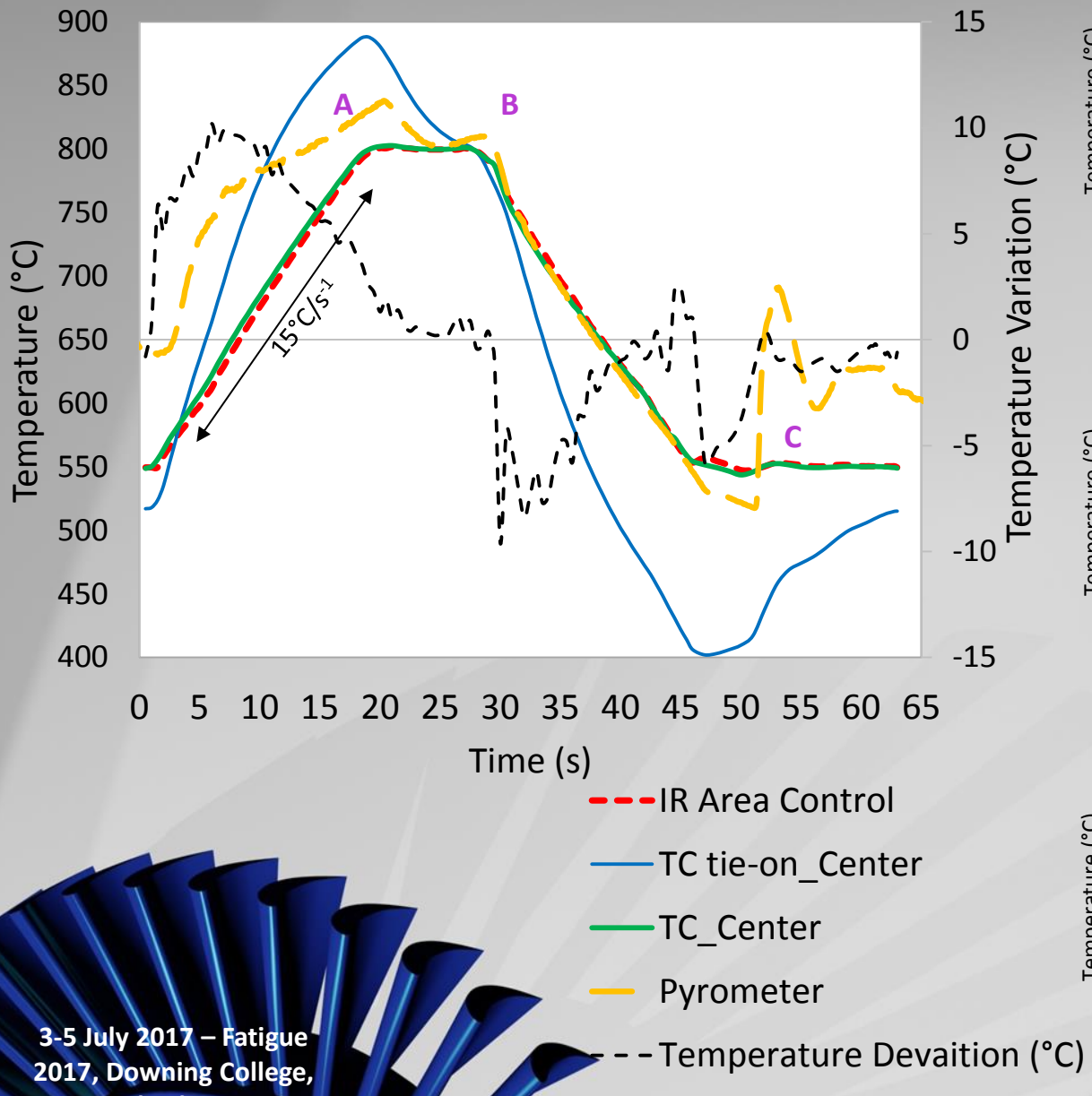


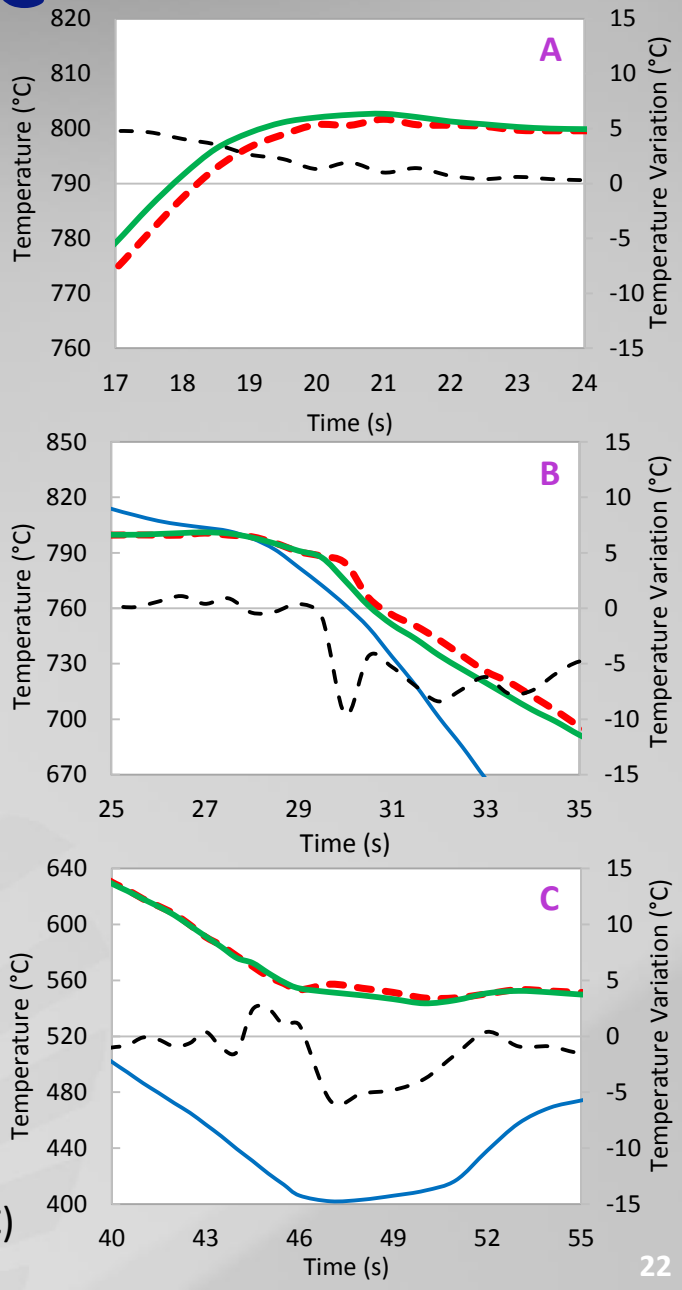
Isothermal Accuracy, IR vs TC



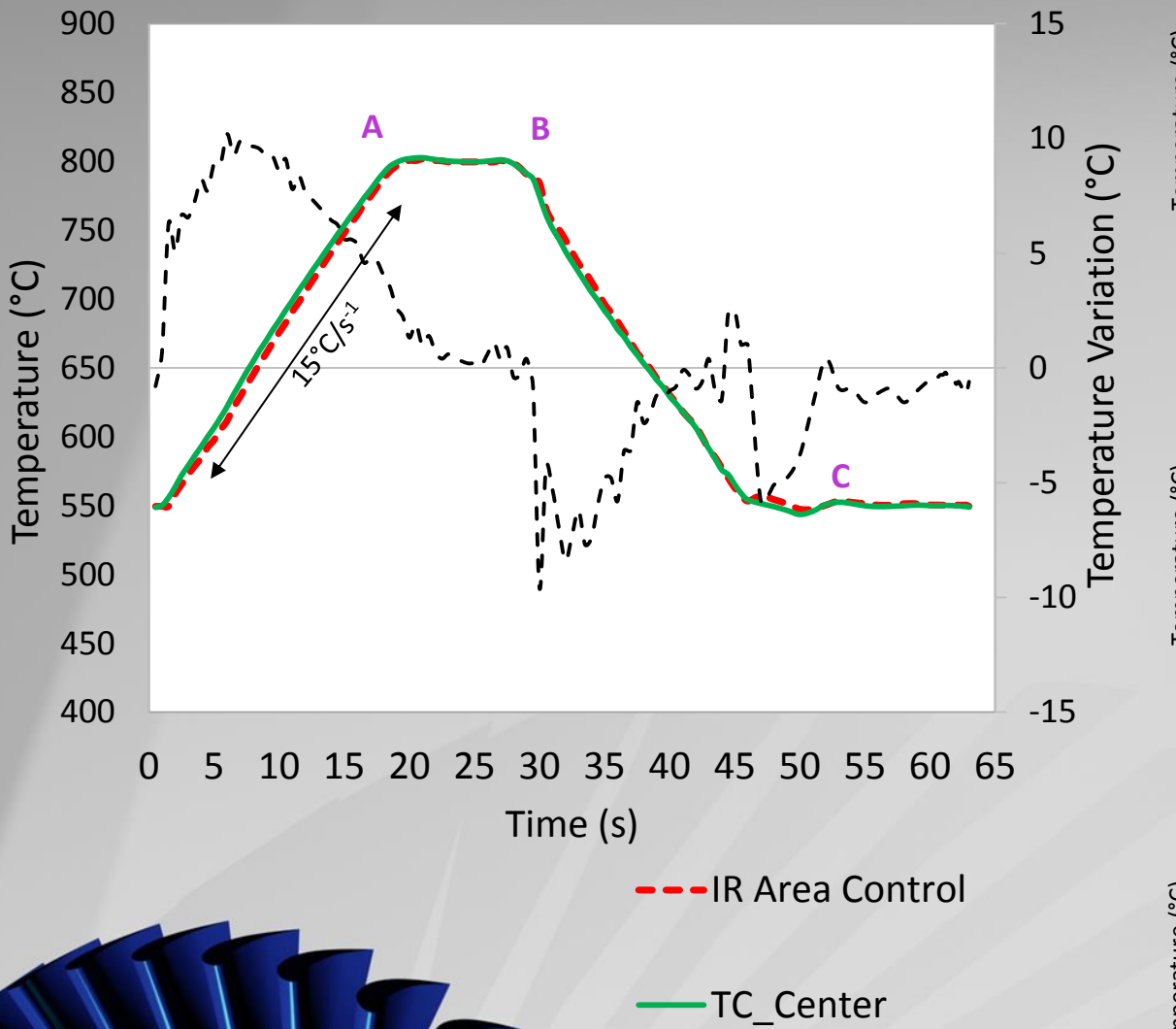


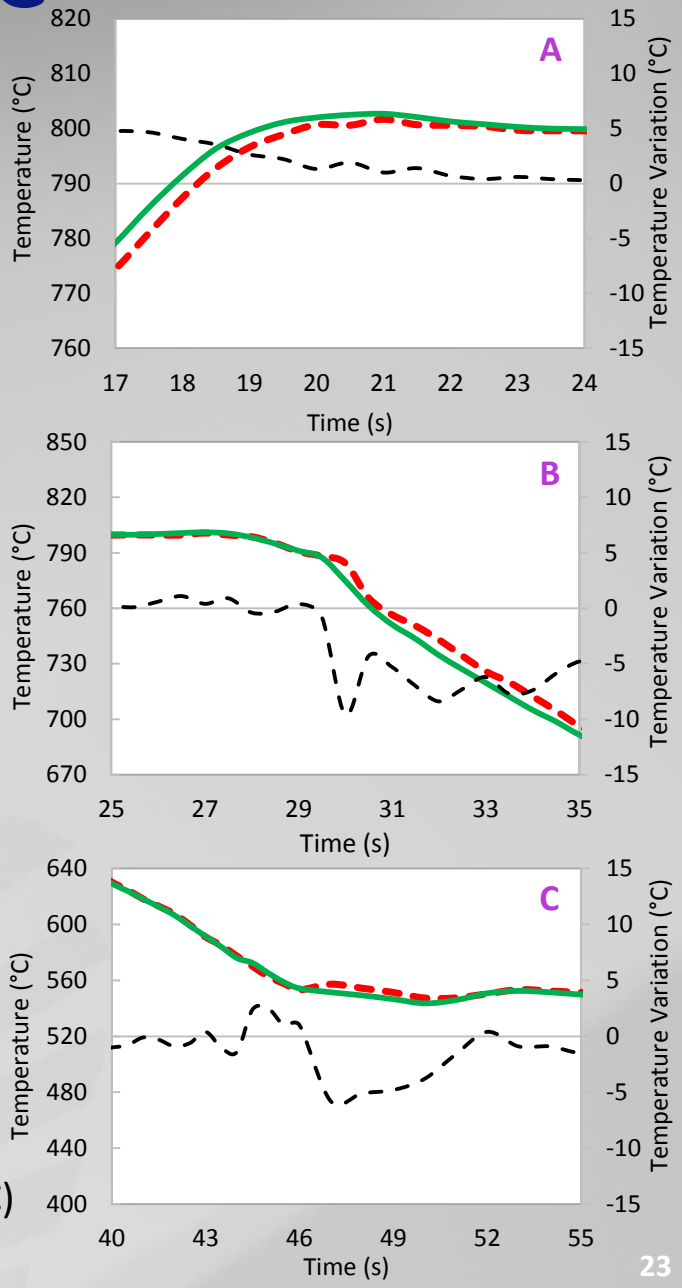
Dynamic Accuracy, IR vs TC



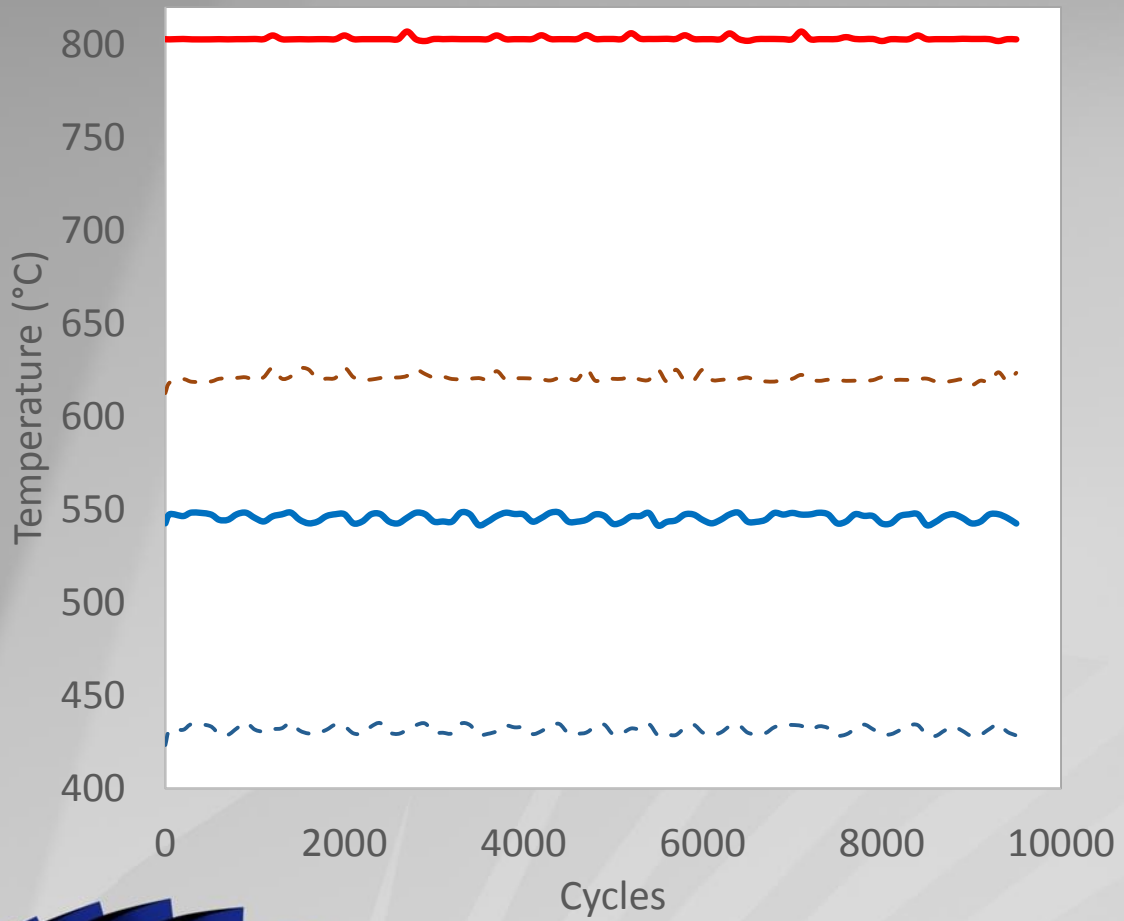


Dynamic Accuracy, IR vs TC





Dynamic Temperature Stability, Max/Min Cycle Peaks

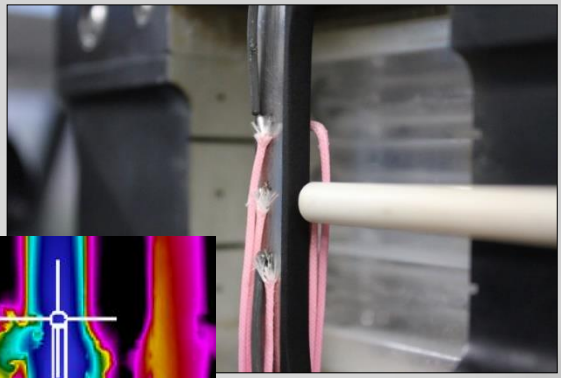


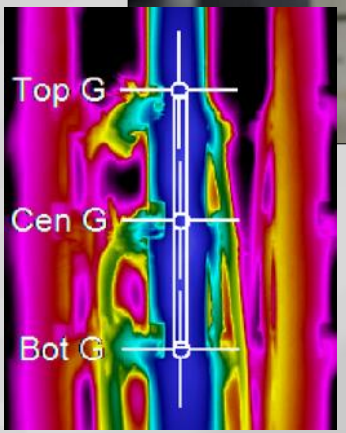
Max_IR Control

Min_IR Control

Max_TC Non Contact

Min_TC Non Contact

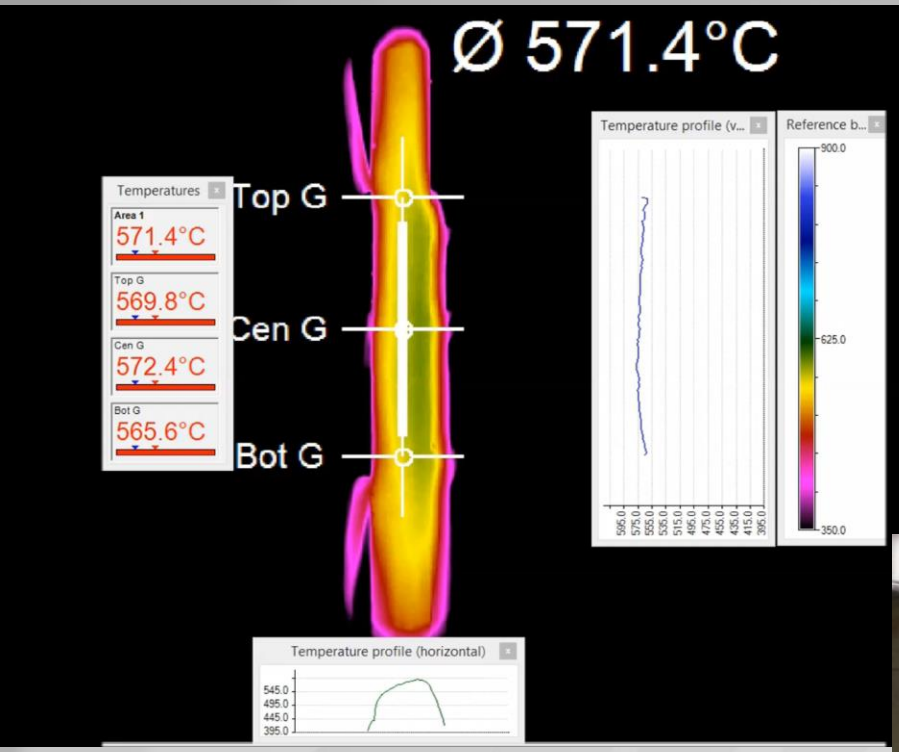


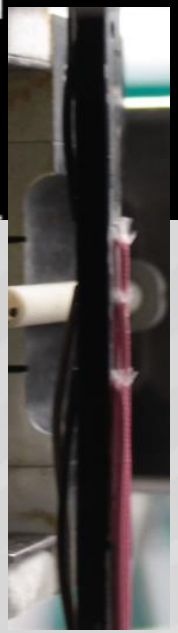


10,000 cycles = 270 hours

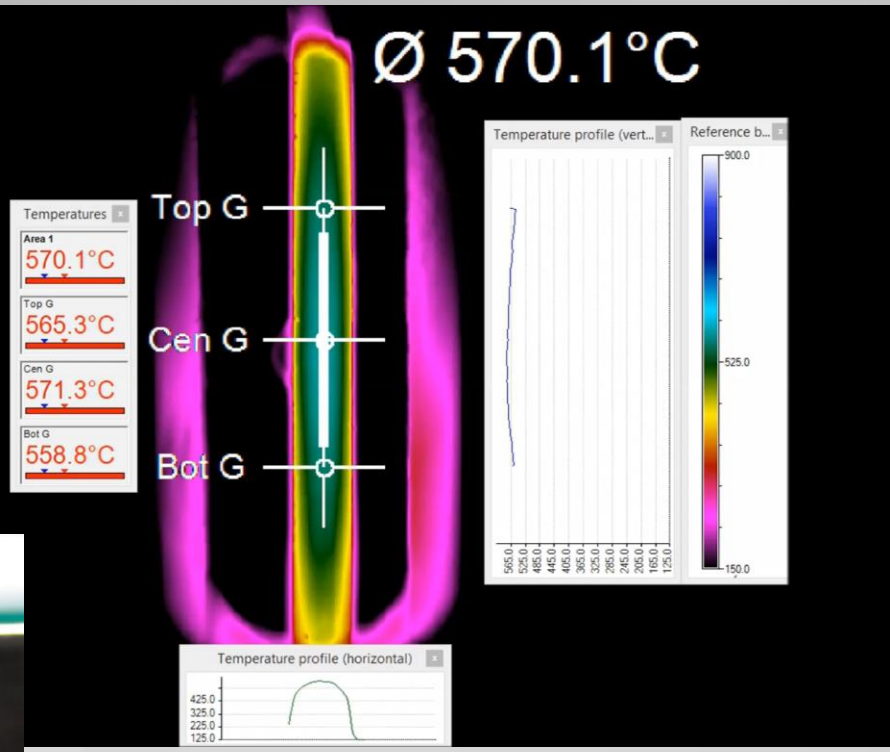
Thermocouple Complications

Thermocouples



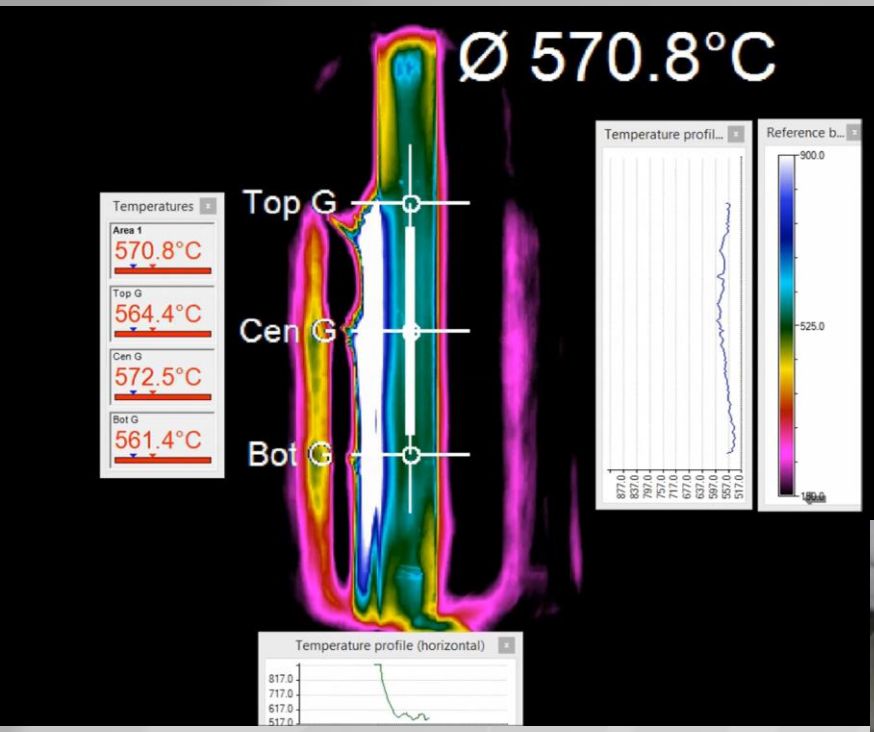


No Thermocouples

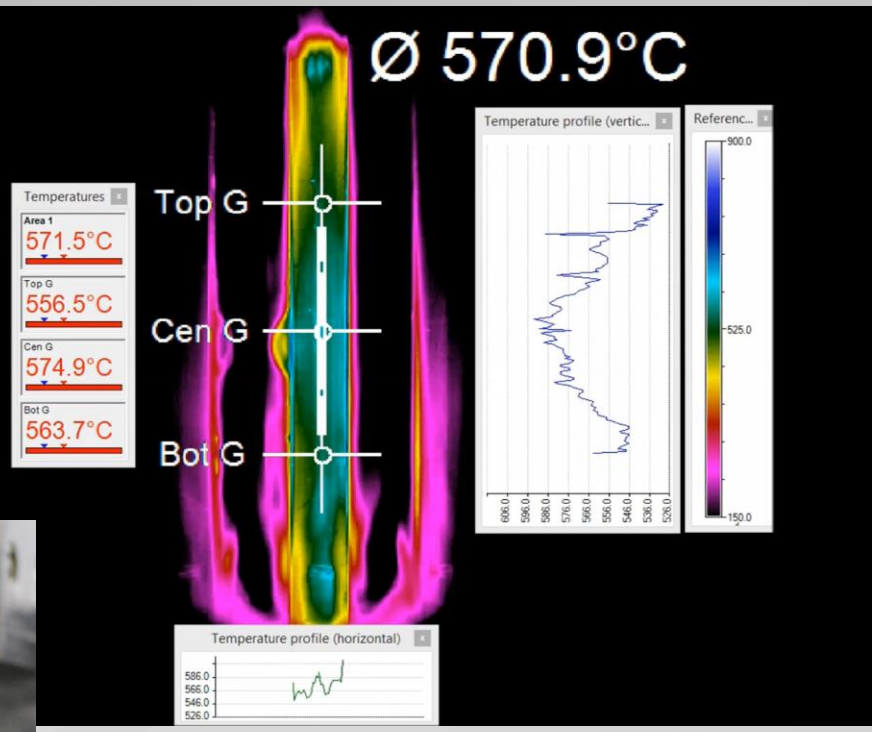


Evolving Surface Complications

Thermocouples



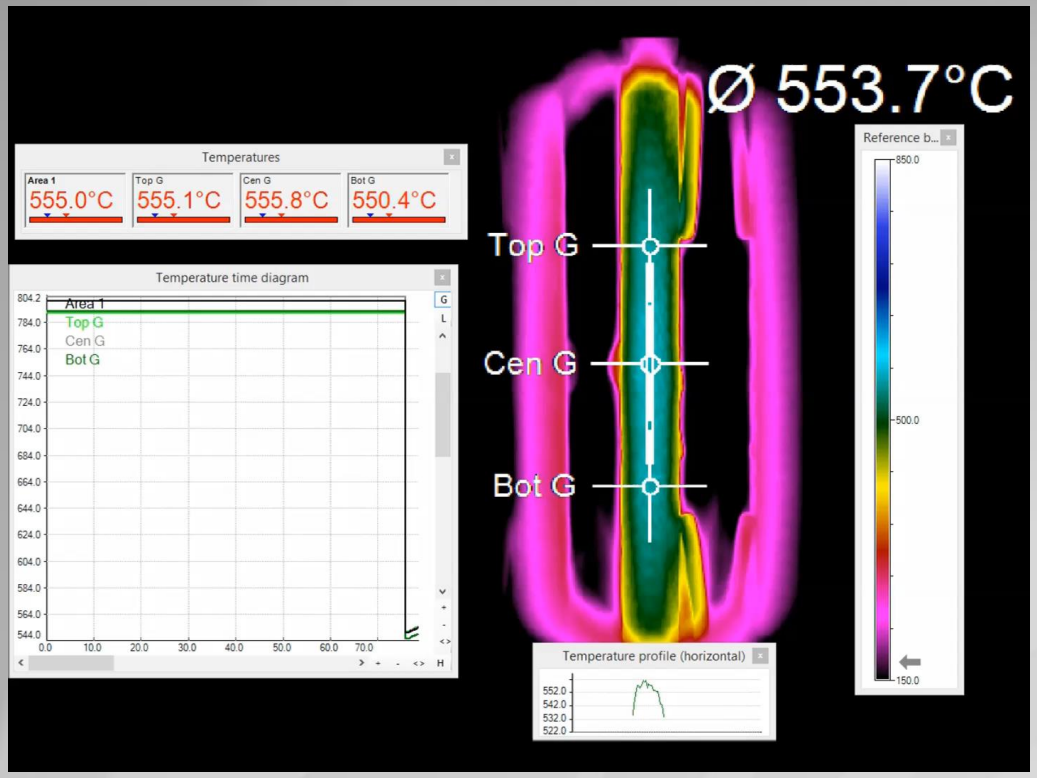
No Thermocouples



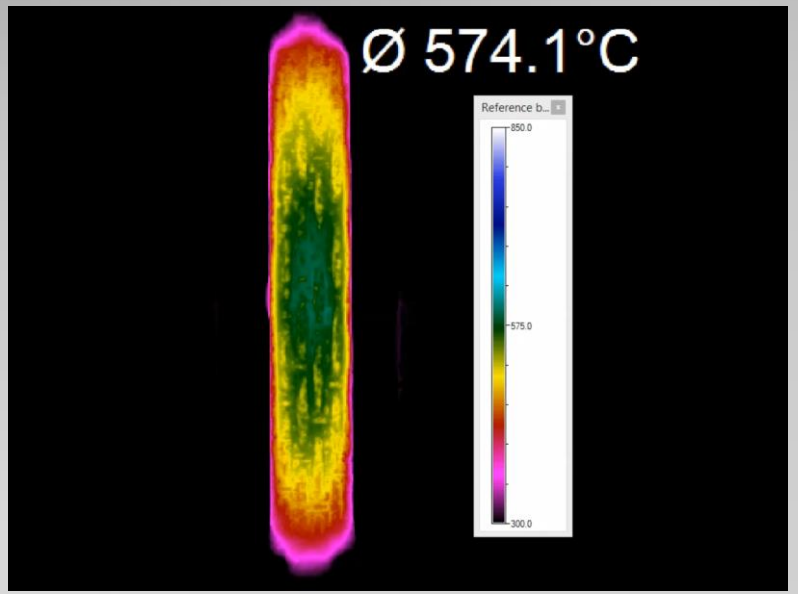
Pre-Exposed Surface
800°C for 50 hours.
ε used = 0.57

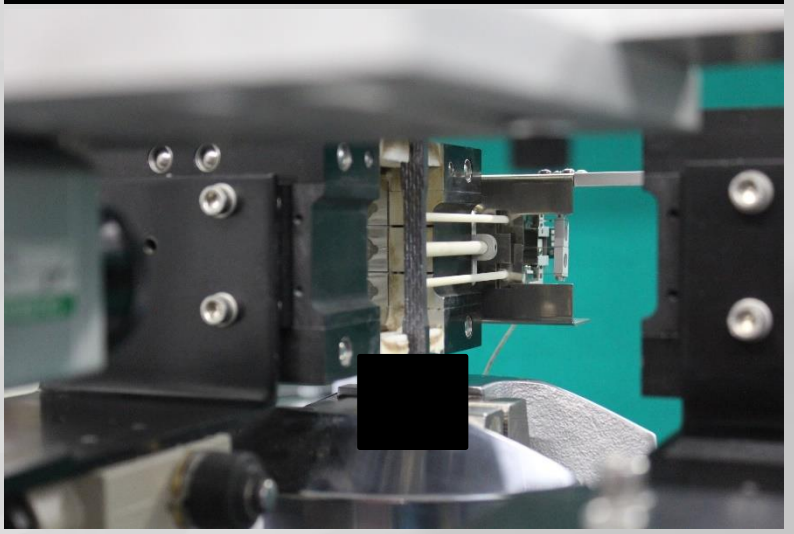
Non Metallic High-Temperature Control

Specimen Side View



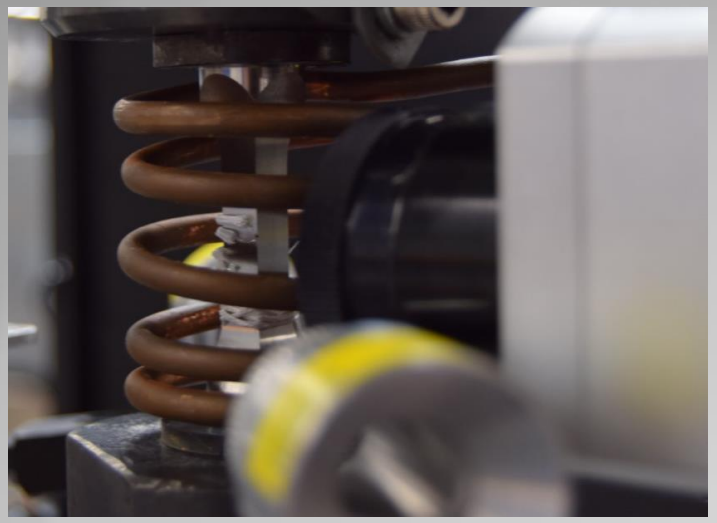
Specimen Face View





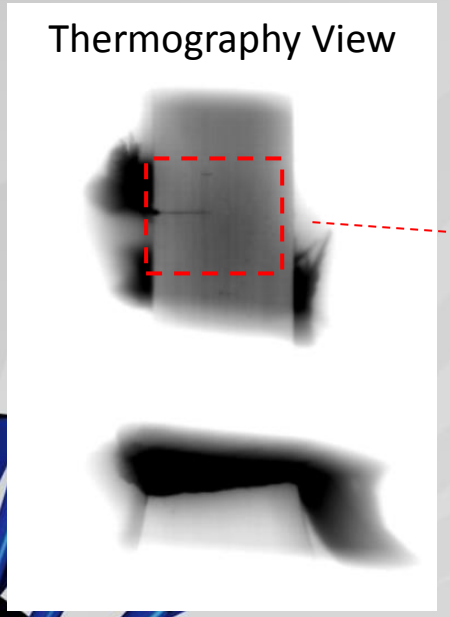
Crack Length Measurements

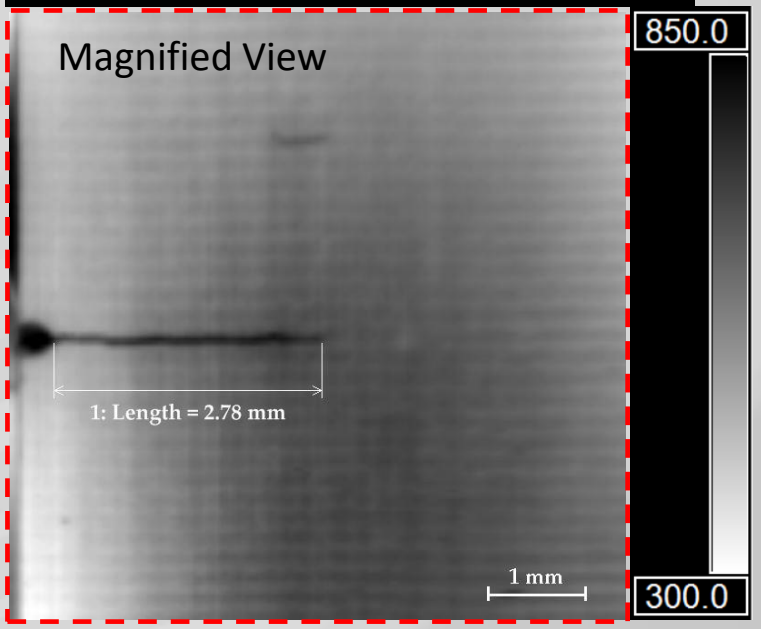
TMF Crack Growth Setup



Keyence Microscope Image

Thermography View





Conclusions: Advantages / Disadvantages

Measurement	Thermocouple	Pyrometer	Thermography
Mode	Invasive	Non Invasive	Non Invasive
Area	≈ 2mm²	≈ 2mm²	Entire Gauge Section
Dynamic Accuracy	Externally Influenced	Good	Good
Set up Time	Slow	Fast	Fast
Profiling	Thermocouple Based	Thermocouple Based	Thermography Based
Repeatability	Externally Influenced	Good	Good
Emissivity Influenced	No	Yes	Yes
Post Test Analysis	No	No	Yes
Shadowing Effects	Yes	No	No
Cold Spot Identification	No	No	Yes
In-Situ Adjustments	No	No	Yes
Initial Cost	Low	Ok	High
Calibration Cost	High	Low	Low

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Any Questions?