The Deformation Behaviour of Thermo-Mechanical Fatigue Crack Growth: *Captured through advanced non-invasive methodologies*

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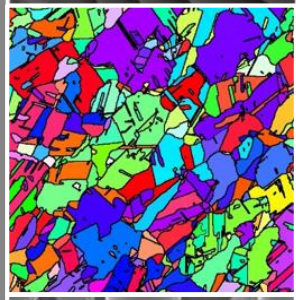
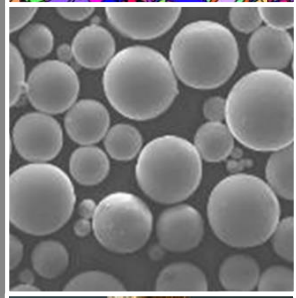
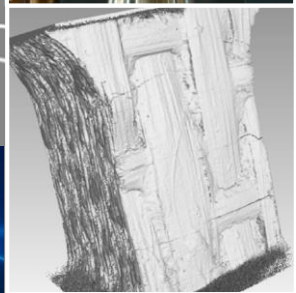





Introduction

DevTMF Partners

1. **Swansea University**, Wales. *Testing and analysis*
2. **Nottingham University**, England. *Modelling and round robin testing*
3. **Linkoping University**, Sweden. *Modelling and round robin testing*
4. **Rolls-Royce plc**, UK. *Material and technical support*

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.

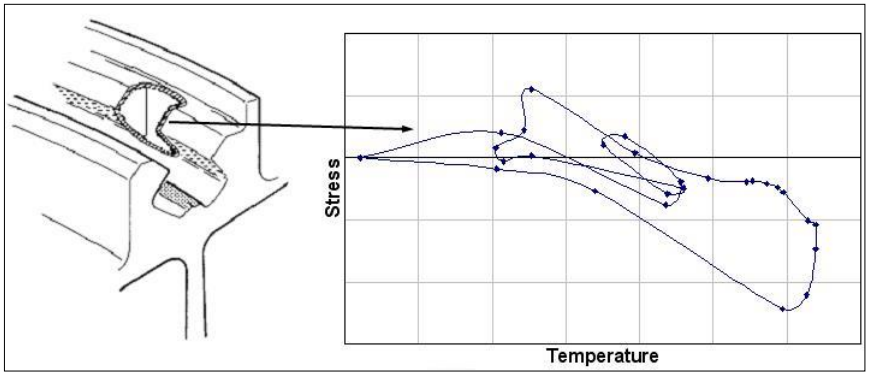
Content

1. Introduction and background
2. TMFCG Test Development
3. Non-invasive TMF Crack Growth Analysis.

Introduction - Industrial Motivation

TMF tests are designed to bridge the gap between loading regimes simulated in test laboratories and those found in arduous real life loading environments such as those found within a modern day gas turbine.

- 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

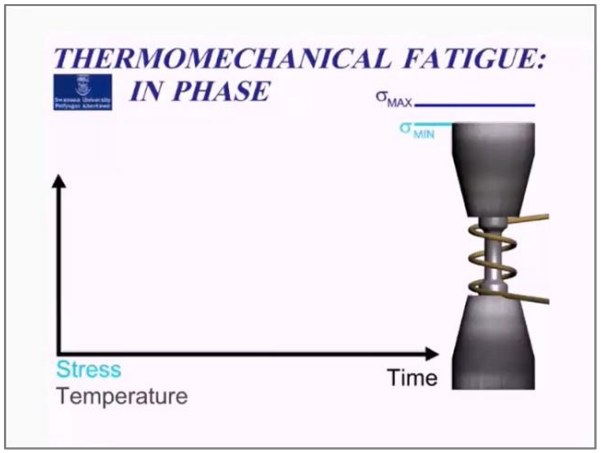


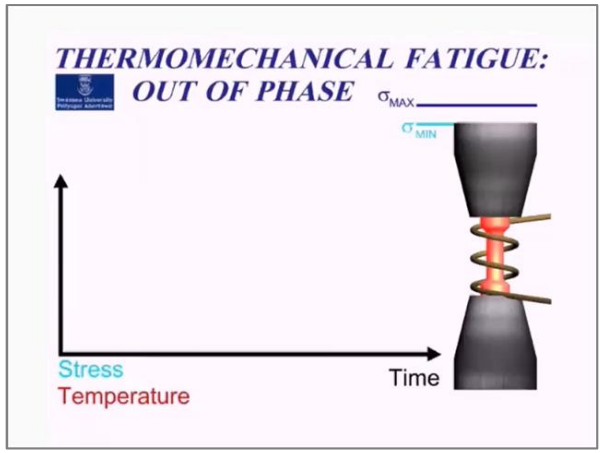
Introduction - TMF

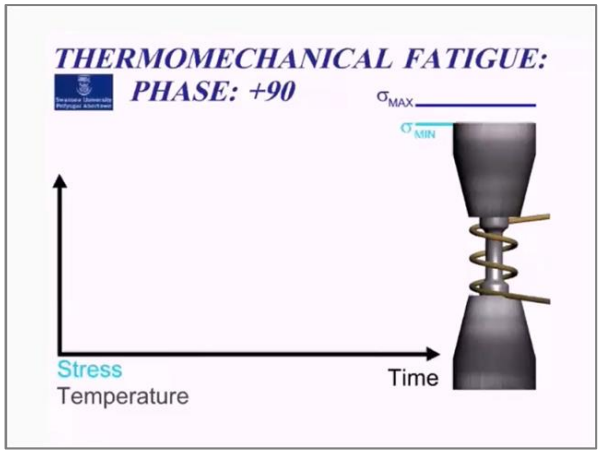
- Diverse mechanisms are involved, Primarily . . .

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

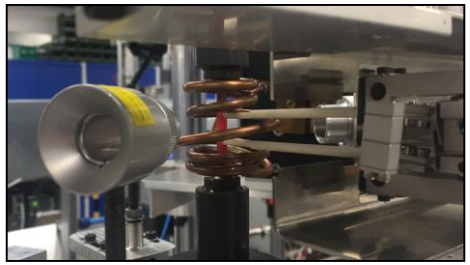




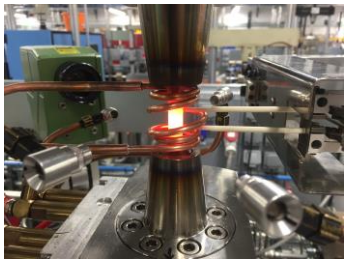


SU_Background in TMF

Strain Control (Solid)

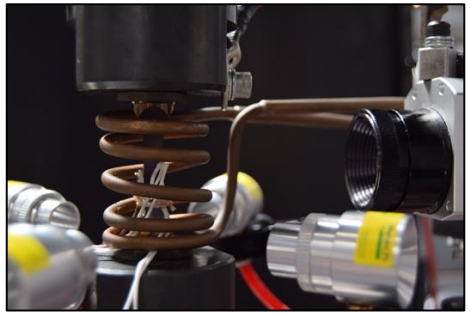


Strain Control (Hollow)

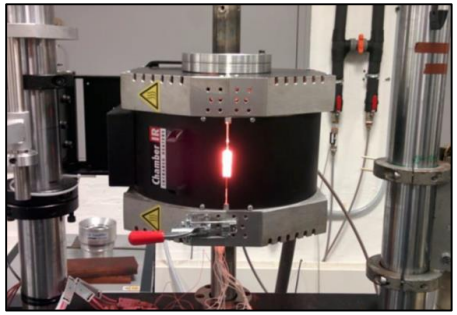


SMaRT Swansea Materials Research & Testing Ltd / ISM laboratory

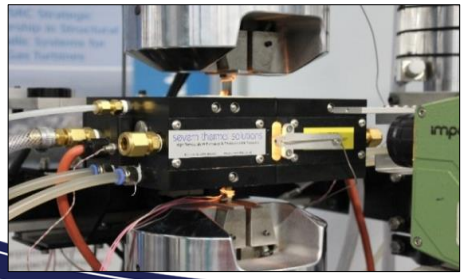
Crack Growth



Stress Control



Non Metallic Testing

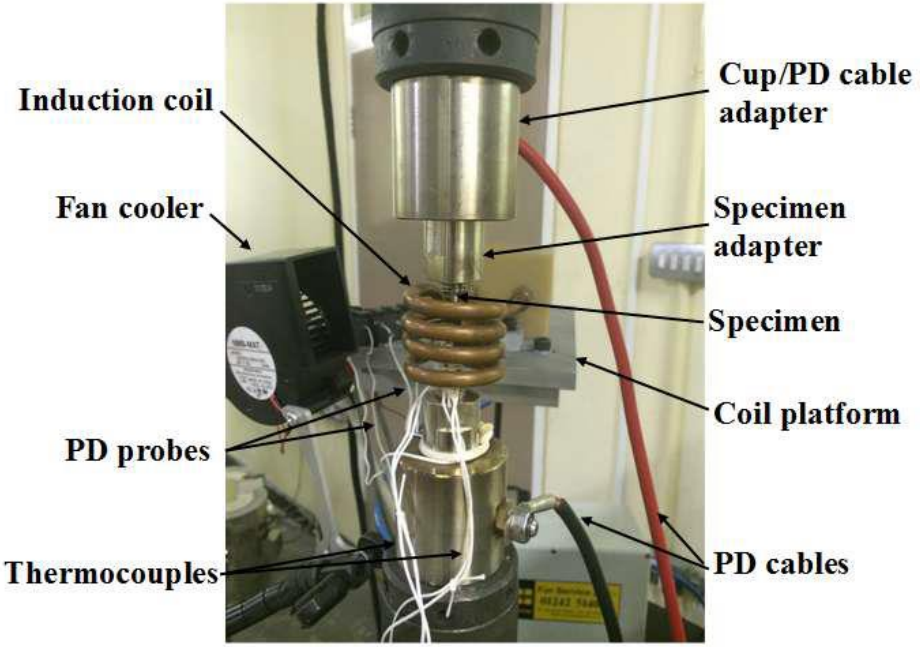


Thermo-mechanical fatigue and fracture of INCO718 Walter J. Evans, J. E. Screech, S. Williams. DOI:10.1016/j.ijfatigue.2007.01.041. **2007**

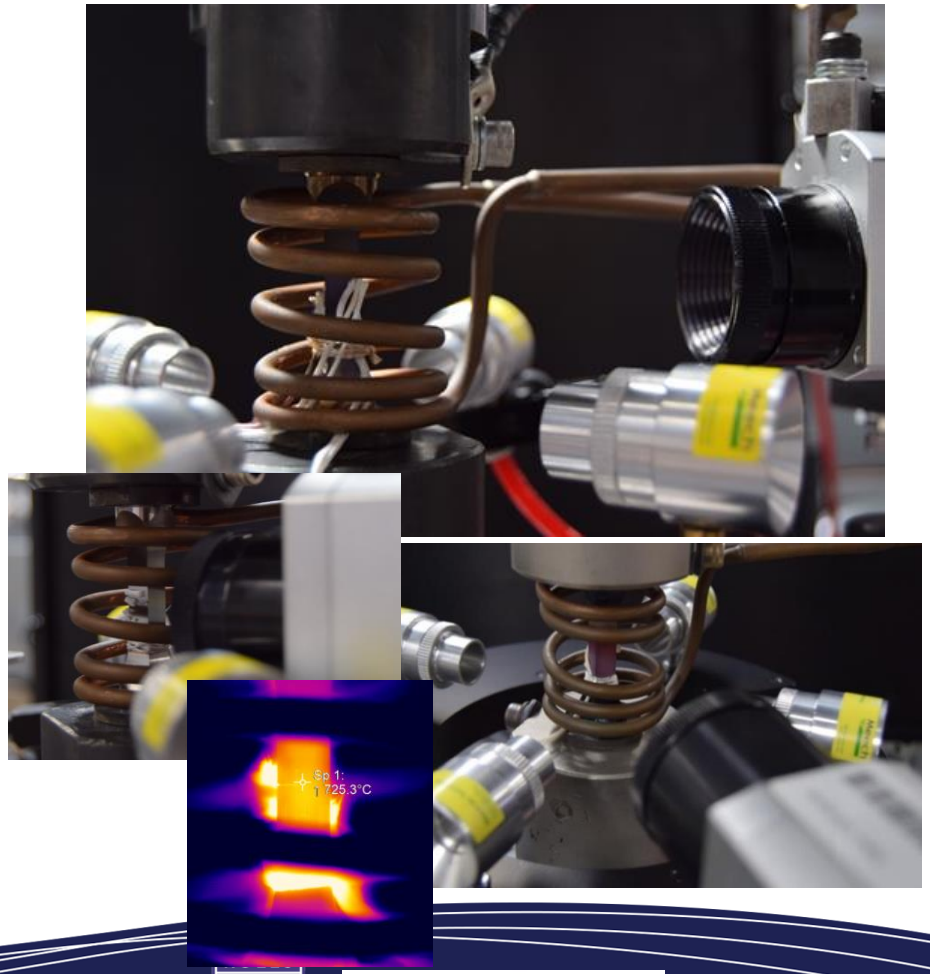
Development of test facilities for thermo-mechanical fatigue testing. J.Palmer, J.Jones, A.Dyer, R.Smith, R.Lancaster, M.Whittaker. https://doi.org/10.1016/j.ijfatigue.2018.12.015. **2018**

DevTMF Rig Development

DevTMF Strain Control

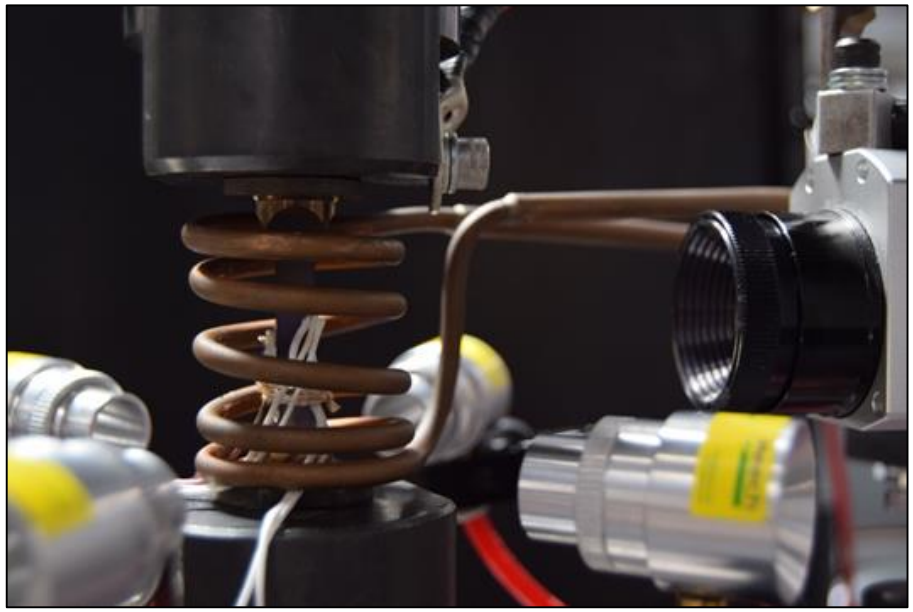


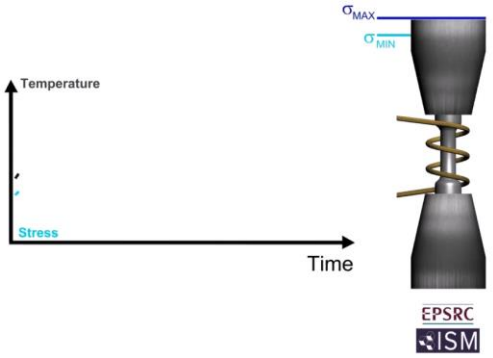
DevTMF Crack Growth



TMFCG Testing

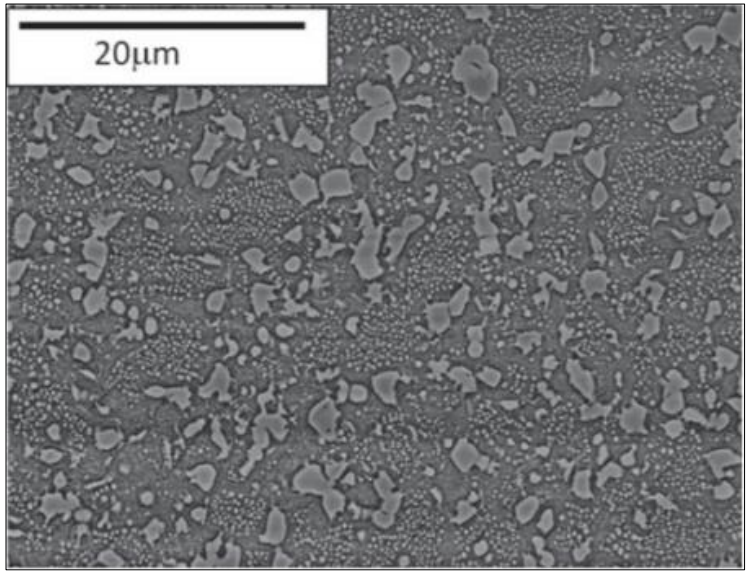
Direct Current Potential Drop technique (DC PD)





Material

Fine grained RR1000



Coarse grained RR1000

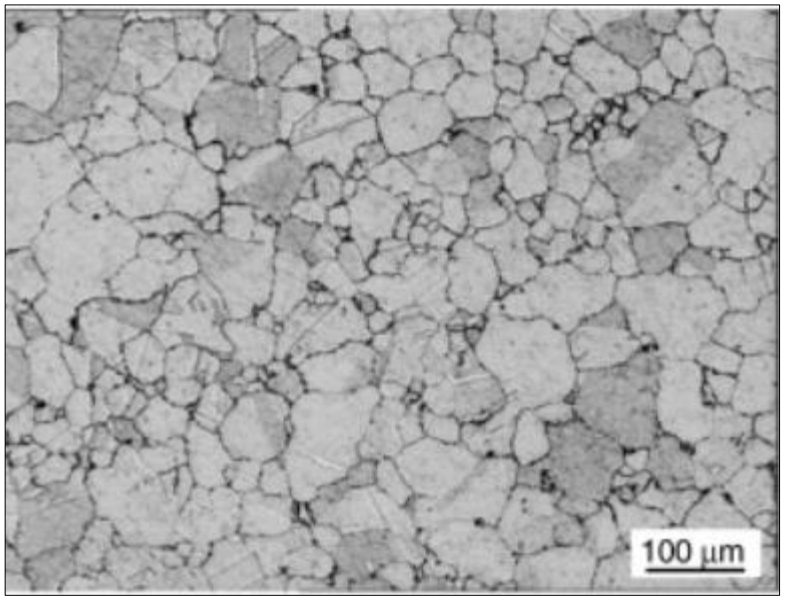
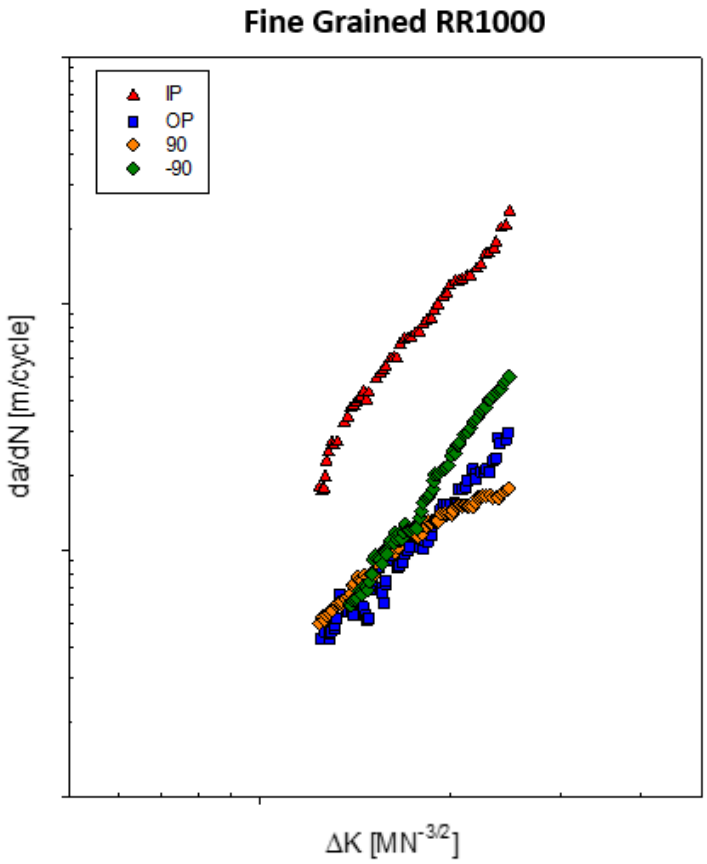
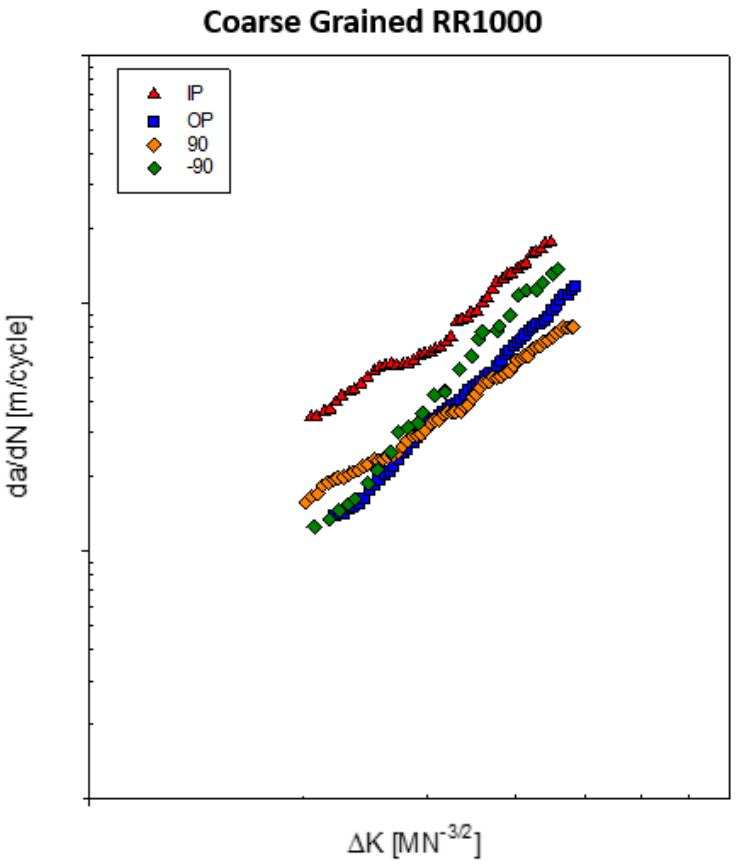


Image courtesy of Li et al, Effects of microstructure on high temperature dwell fatigue crack growth in a coarse grain PM nickel based superalloy, Acta Materialia, Volume 90, 15 May 2015, Pages 355-369

TMFCG – Phase Angle Effects

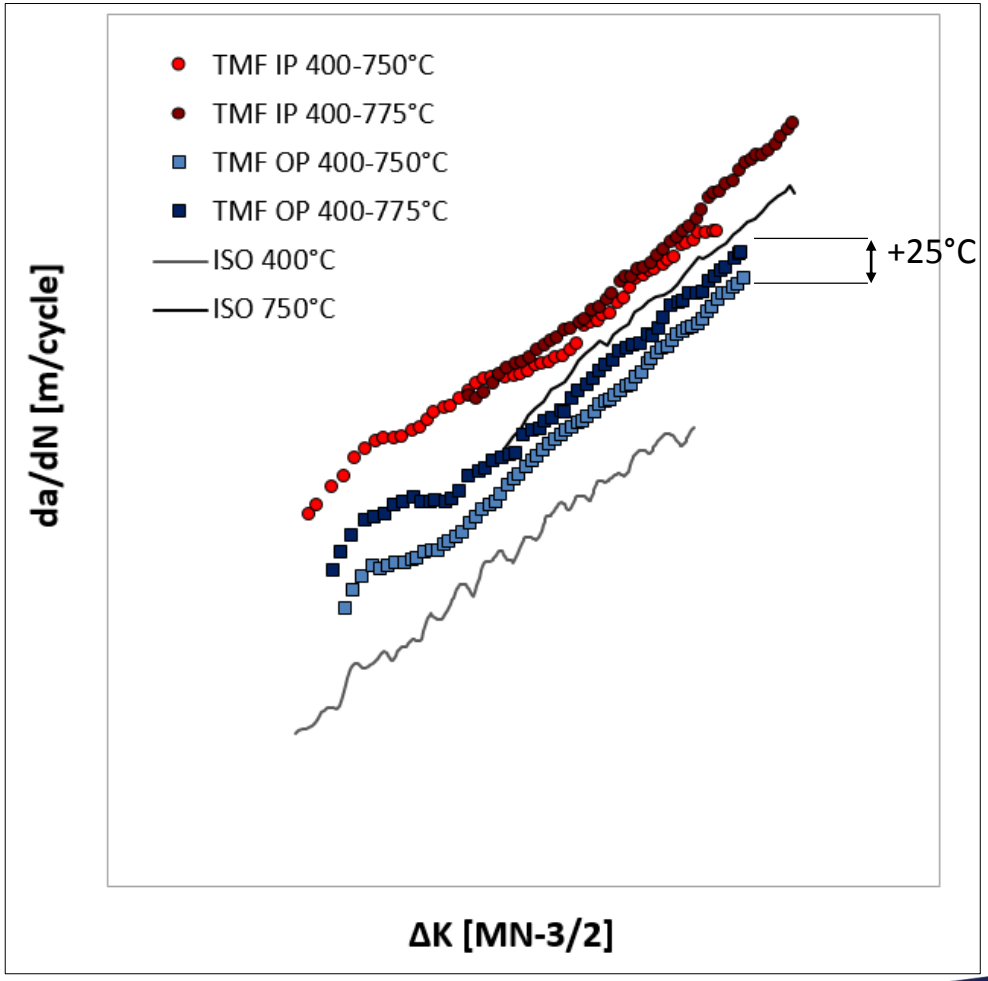




- Strong dependence on phase angle

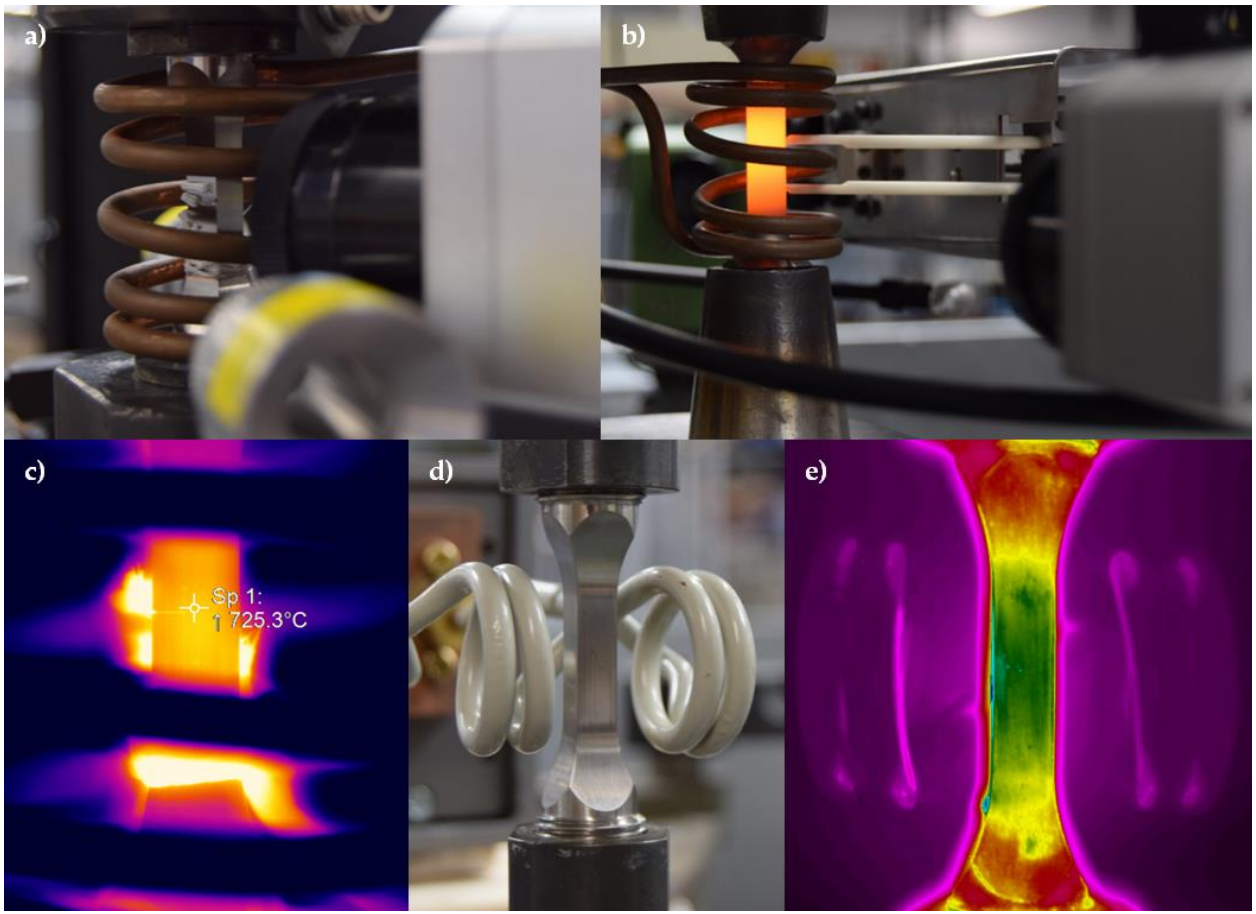
Effects of Peak Temperature

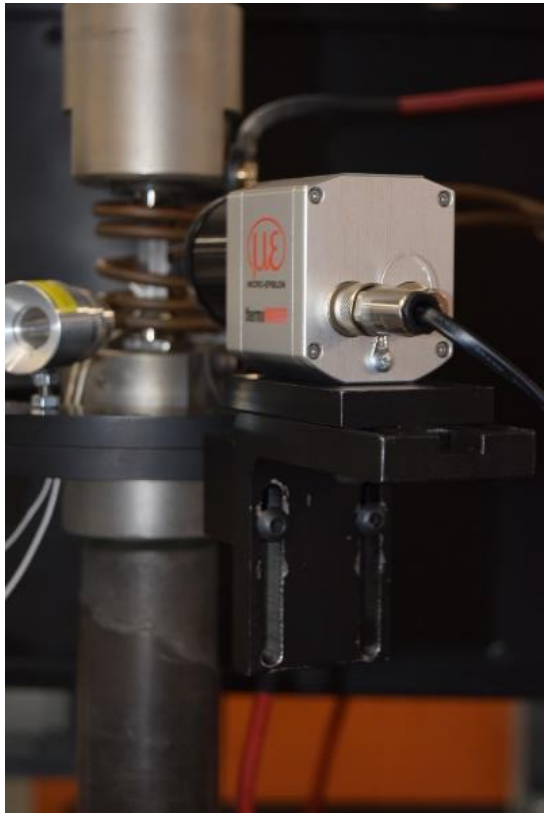
Coarse Grain RR1000



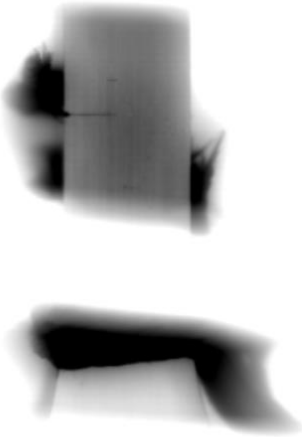
- TMF CG RR1000
- In phase tests show faster rates than equivalent isothermal tests
- Dependent on cycle time
- In Out of Phase tests increased Tmax influencing TMF CP rates

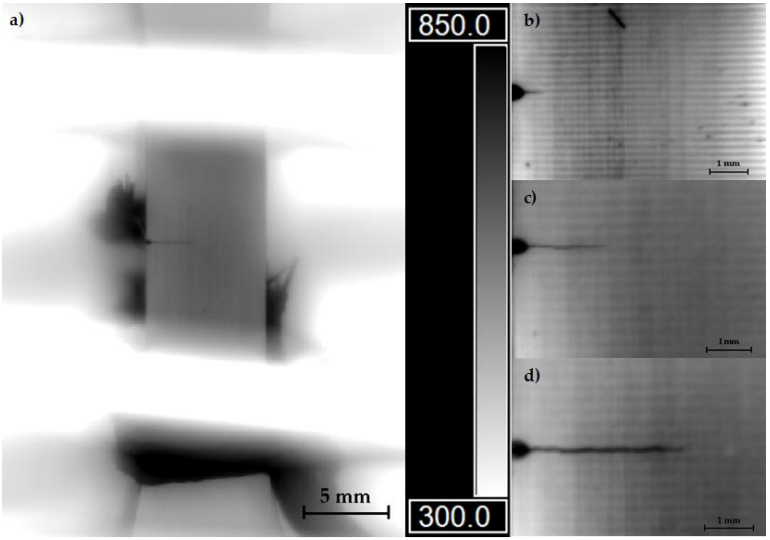
TMFCG with Thermography

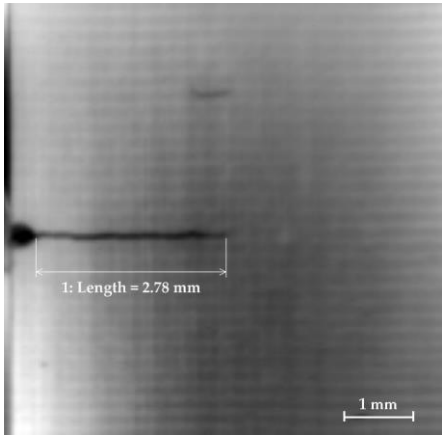




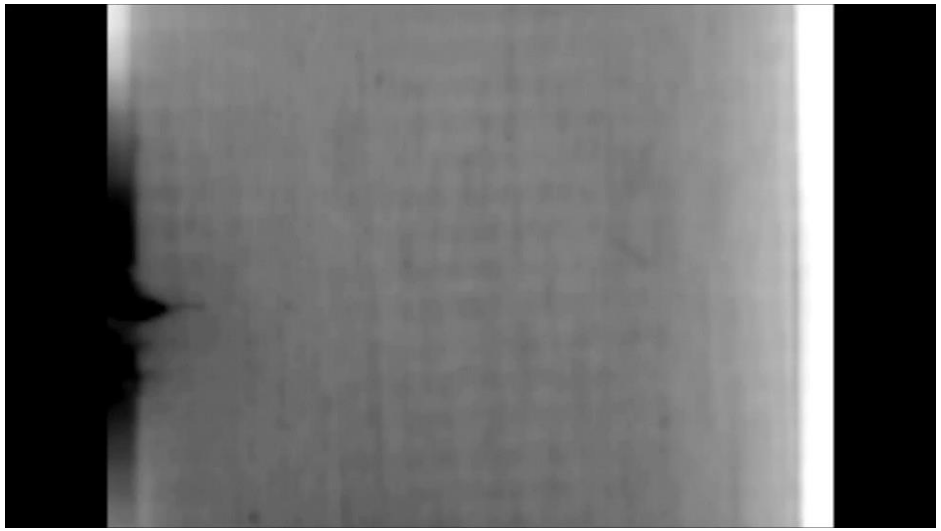
IR Crack Growth Measurements

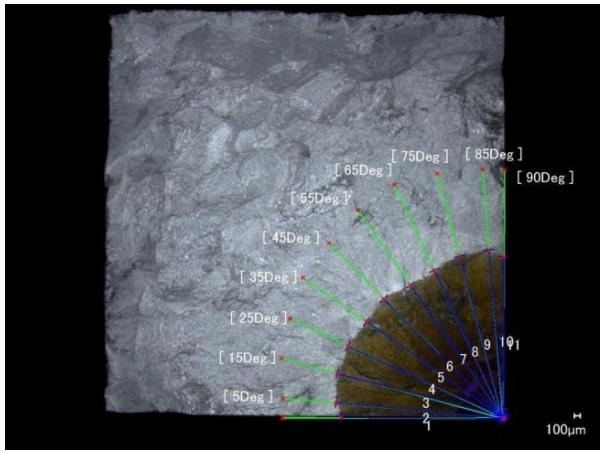


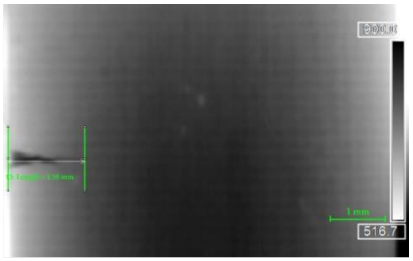


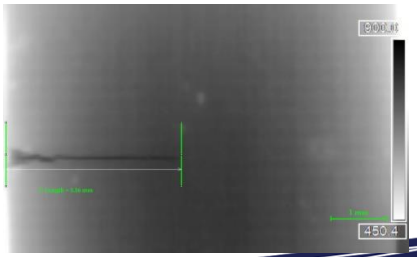


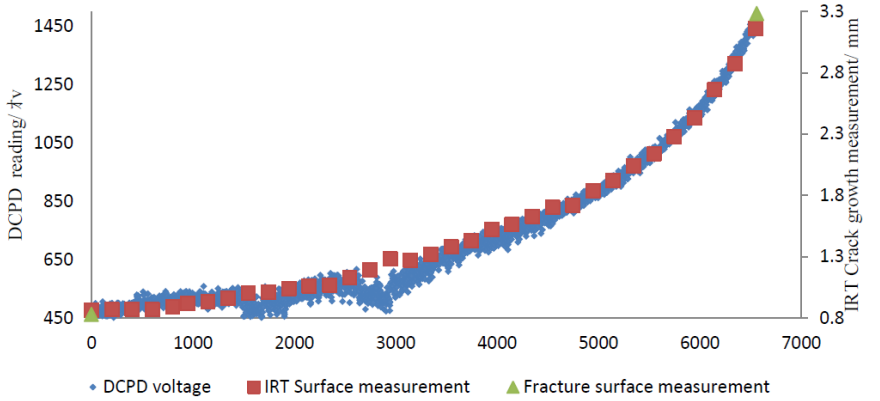
IR Crack Growth Measurements











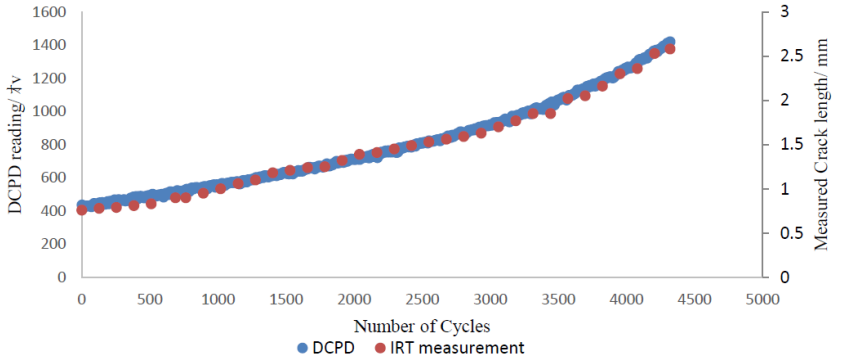
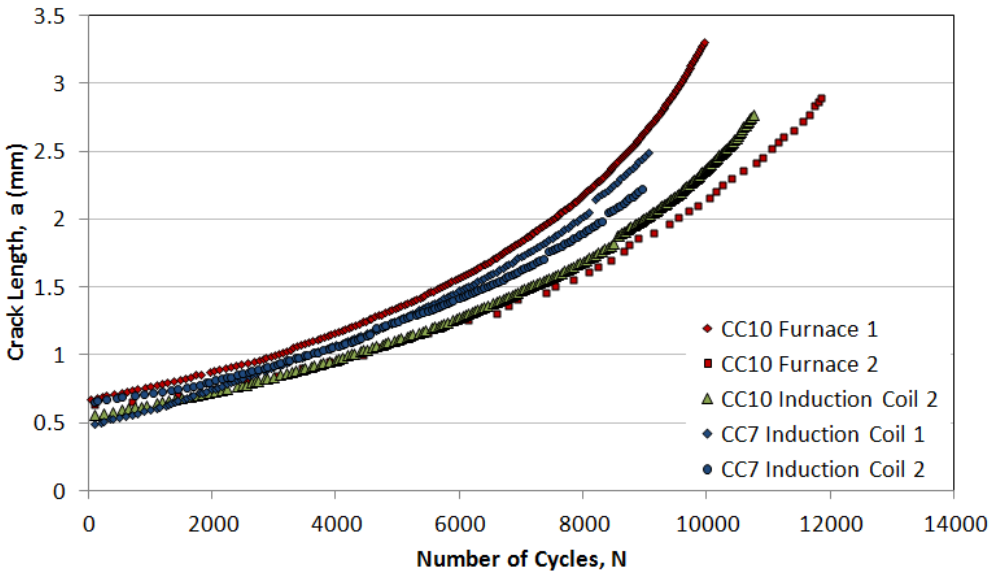


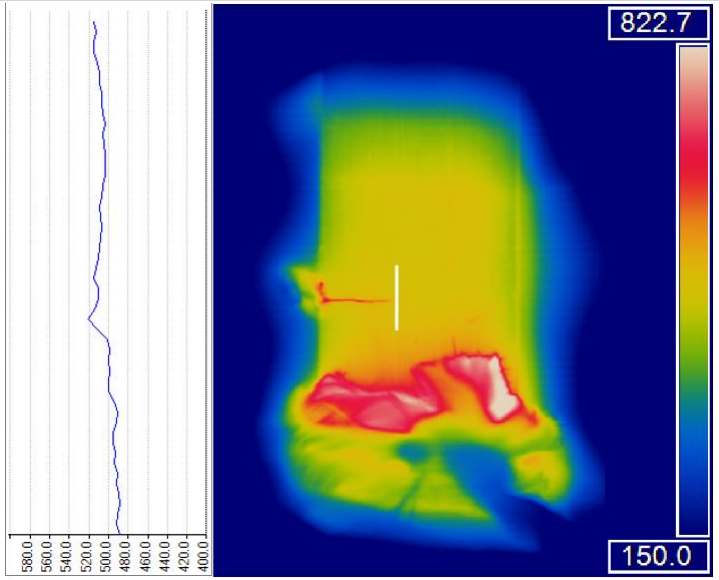
Image of surface crack length 3549 cycles

Image of surface crack length after 6549 cycles

Crack Tip Heating Investigations

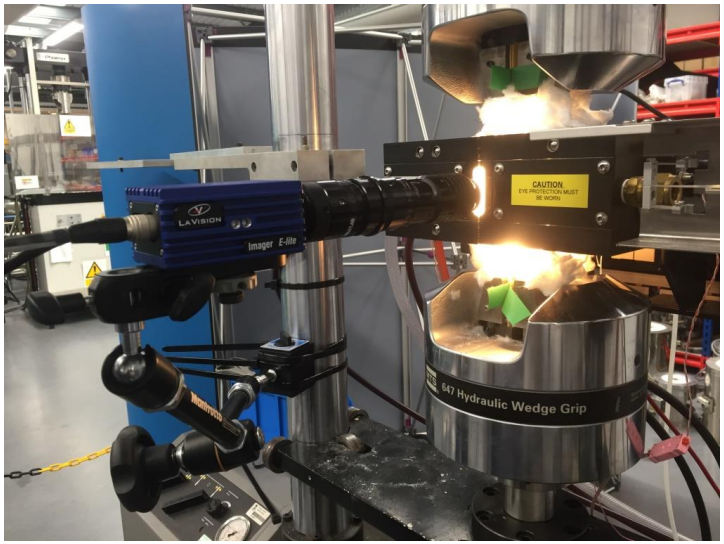


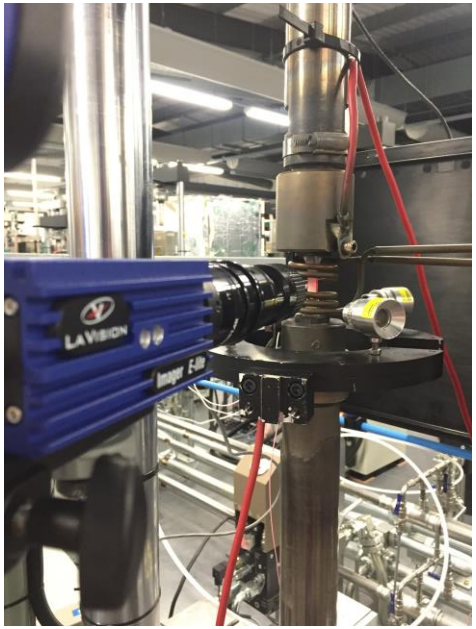
Waspaloy crack length vs. number of cycles: furnace and induction coil comparisons at 650°C, 450MPa and R=0.1.



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

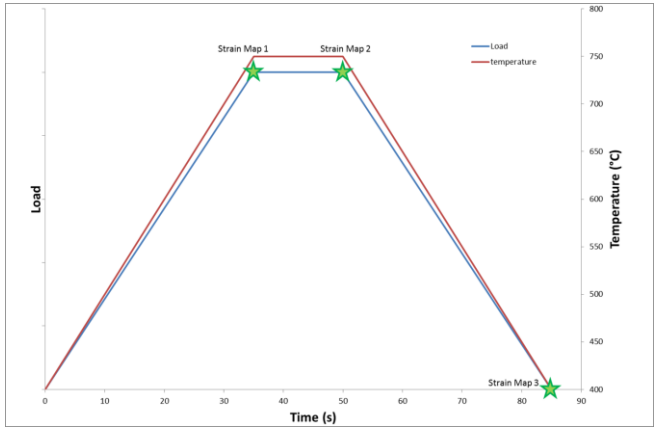
TMFCG with DIC

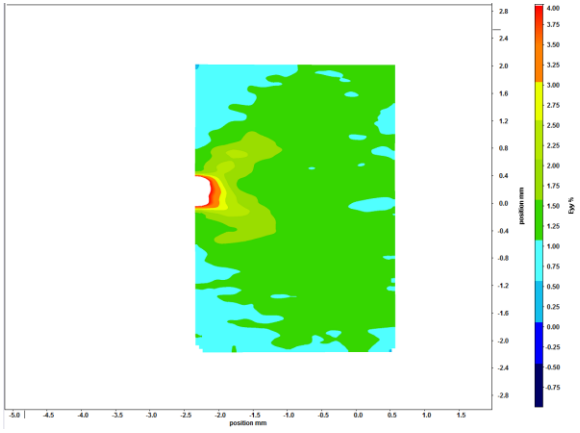


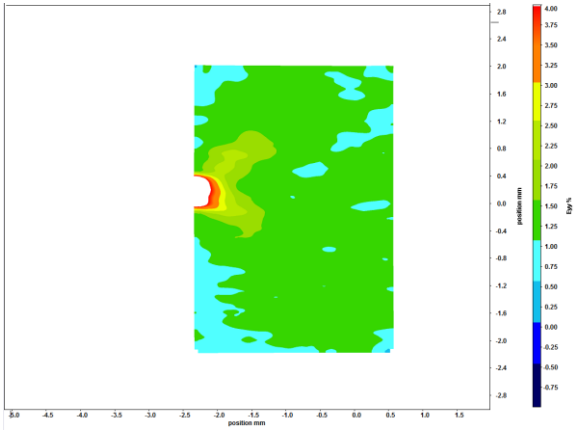


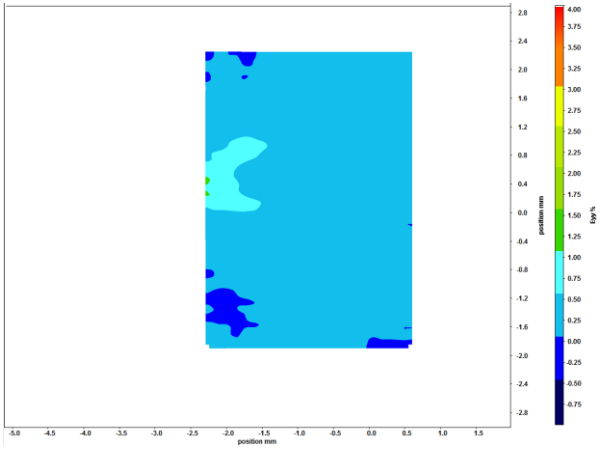
TMFCG with DIC

In Phase

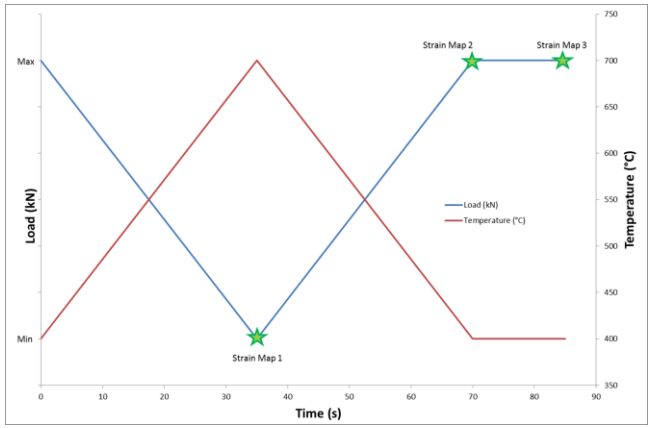


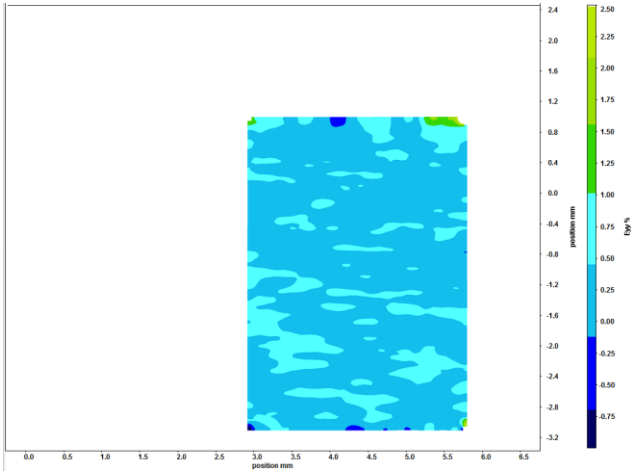


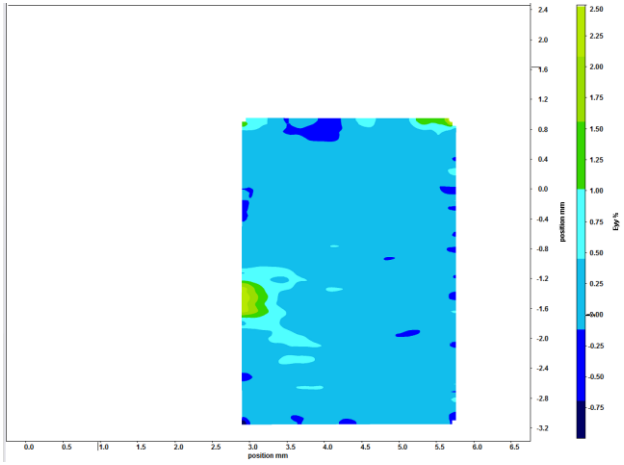


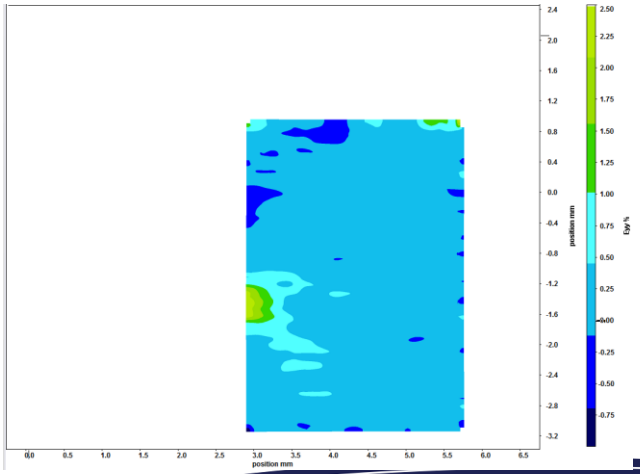


Out Of Phase – On load









Non-Invasive TMFCG

A completely Non-Invasive TMF CP test method

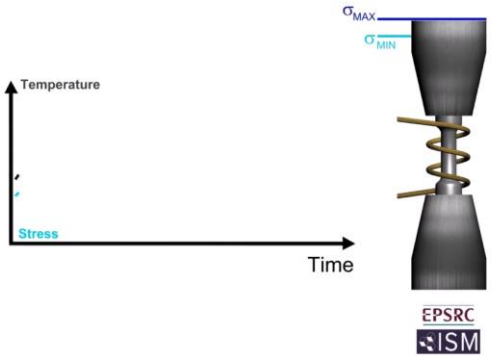
Advantages * Avoid complications with thermocouple control

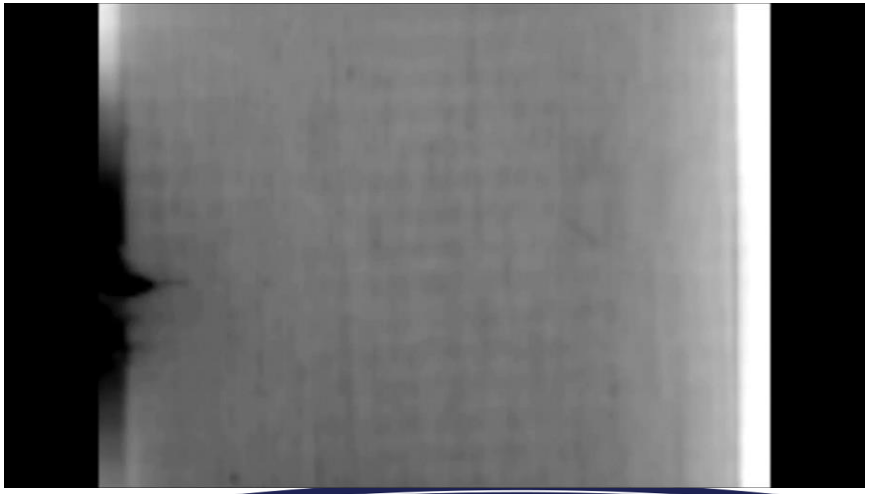
- Crack initiations at welds.
- Thermocouple shadowing and or over/undershooting

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.





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.

The provision of materials and technical support from Rolls-Royce plc is gratefully acknowledged. A special mention must be paid to Turan Dirlik, Steve Brookes, Veronica Gray and the ISM/SMaRT staff.

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Any Questions?

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Software for Materials and Component Testing