TMF Crack Growth: Research and Development Performed Towards a European Interlaboratory Code of Practice

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High Temperature Testing

Webinars organised by ZwickRoell Testing Systems

22nd of June 2020

https://www.zwickroell.com/de-de/virtual-testing-forum/key-topics/high-temperature-testing

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.

Presentation outline

- Introduction
- Experimental methods
- Results
- Conclusions
- Questions

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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.

Clean Sky 2

DevTMF

Introduction

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Clean Sky 2

DevTMF

Introduction

Vision 2020 and Flightpath 2050

Europe's Vision for Aviation targets for new aircraft technology relative to 2000 performance

- Reduce perceived external noise by 50% by 2020 and 65% by 2050
- Reduce fuel consumption and CO_2 emissions by 50% by 2020 and 75% by 2050
- Reduce No_x emissions by 80% by 2020 and 90% by 2050

https://www.acare4europe.org/

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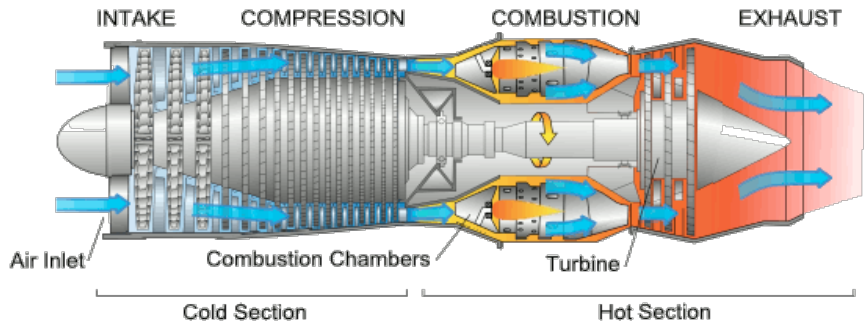
DevTMF

Introduction



Higher turbine temperature

Dennis G, 'Principles of Turbo machinery', McMillan (1956). ISBN 0-471-85546-4. LCCN 56002849.

Increase of operation and service life

Optimised performance and efficiency

Reduced overhaul and replacement costs

Lower fuel consumption/environmental impact

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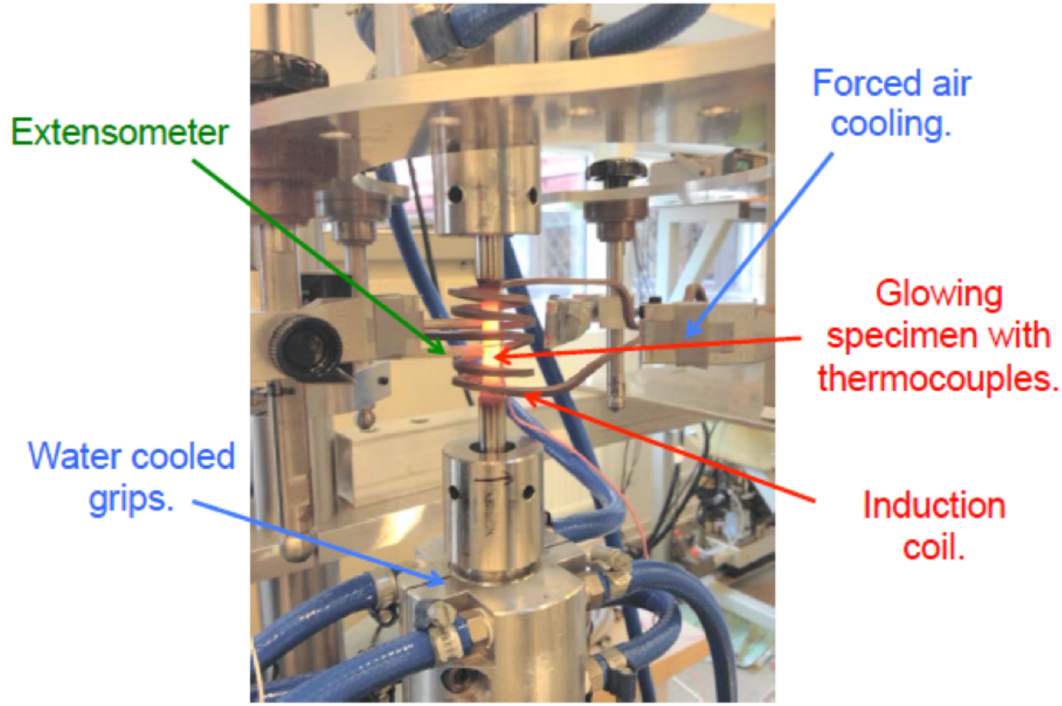
Introduction



Existing standards

Strain controlled TMF:
EU CoP
ASTM E2368 – 10
ISO 12111:2012

Force controlled TMF:
A CoP developed by Rolls-Royce
MTOC

TMF crack growth:
Not covered by CoP or standard
Investigated in isolation and with limited conditions

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Introduction

- P. Häfner, E. Affeldt, T. Beck, H. Klingelhöffer, M. Loveday, C. Rinaldi, Code of Practice for strain controlled TMF testing, EU FP5 project TMF STANDARD
- S. Brookes, A. Scholz, H. Klingelhöffer, M. Whittaker, M. Loveday, A.Scholz, A. Wisby, N. Ryder, R. Lohr, S. Stekovic, J. Moverare, S. Holdsworth, D. Dudzinski, Code of Practice for force-controlled TMF testing, Rolls-Royce MTOC

Joint Research Centre

Validated Code-of-Practice for Strain-Controlled Thermo-Mechanical Fatigue Testing

Peter Hähner, Ernst Affeldt, Tilmann Beck, Hellmuth Klingelhöffer, Malcolm Loveday, Claudia Rinaldi

June 2006

EUROPEAN COMMISSION
Joint Research Centre
EUR 22281 EN

TMF-STANDARD Project

Workpackage 6: Drafting of refined protocol for TMF test method, input in ISO/TC164/SC5/WG TMF

Deliverable D12

Final version of the Validated Code of Practice for Strain-Controlled THERMO-MECHANICAL FATIGUE TESTING

CONTRACT N° : G6RD-CT-2001-00526 PROJECT N° : GRD2-2000-30014

Project title : **THERMO-MECHANICAL FATIGUE – THE ROUTE TO STANDARDISATION**
ACRONYM : TMF STANDARD

PROJECT CO-ORDINATORS : MTU Aero Engines, D, and JRC-Institute for Energy, NL

PARTNERS: IWK University of Karlsruhe, BAM (Federal Institute for Materials Research and Testing), ARMINES, National Physical Laboratory, Cambridge University, CNR-IENI, CESI, KIMAB (former Swedish Inst. of Mat. Research), FZJ Jülich, IFW-Technical University of Darmstadt, University of Siegen, CEAT, Imperial College, Silesian University of Technology, ONERA, FZK Karlsruhe, SNECMA, Ecole National des Mines de Paris, ALSTOM Baden

PROJECT START DATE : 01 Oct. 2001 DURATION : 48 months

Date of issue of this report: 15.12.2005

Project funded by the European Community under the 'Competitive and Sustainable Growth' Programme (1998-2002)

TMF-STANDARD 2 Project

Drafting of refined protocol for force-controlled TMF test method, input in ISO/TC164/SC5

Code of Practice for FORCE-CONTROLLED THERMO-MECHANICAL FATIGUE TESTING

Project title: **FORCE-CONTROLLED THERMO-MECHANICAL FATIGUE – THE ROUTE TO STANDARDISATION**

PROJECT CO-ORDINATOR: Rolls-Royce Mechanical Test Operations Centre

AUTHORS:
S. Brookes, A. Scholz, H. Klingelhöffer, M. Whittaker, M. Loveday, A.Scholz, A. Wisby, N. Ryder, R. Lohr, S. Stekovic, J. Moverare, S. Holdsworth, D. Dudzinski.

PARTNERS:
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NPL, National Physical Laboratory, Teddington, UK
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AMEC, Warrington, UK
Severn Thermal Solutions, Bristol, UK
Raymond Lohr Consulting Engineer, UK
Linköping University, Linköping, S
Siemens Industrial Turbomachinery AB, Finspong, S
EMPA, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, CH
Derivation Research Laboratory, Ottawa, Ca

PROJECT START DATE: 01 June 2012 CURRENT DURATION: 36 months

Date of issue of this version: COP Stress TMF (Version7).docx 06 August 2015

Page 1 of 32

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Introduction

Title:	**Dev**elopment of Experimental Techniques and Predictive Tools to Characterise **T**hermo-**M**echanical **F**atigue Behaviour and Damage Mechanisms (**DevTMF**)
Funded:	EU's Horizon 2020 and Clean Sky 2
Start date:	1st of Feb 2016
Duration:	60 months
Consortium:	3 partners (Linköping University, Swansea University and the University of Nottingham) and 1 topic manager (Rolls – Royce plc)
No of tests:	≈100 including 15 for the round robin exercise

https://ec.europa.eu/programmes/horizon2020/what-horizon-2020

https://www.cleansky.eu/discover

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Clean Sky 2

DevTMF

Introduction

Objectives of DevTMF

- Validate TMF test methods (both strain TMF and TMF CG)
- Generate accurate and high quality TMF test data
- Develop material models for both crack initiation and propagation during TMF
- Validate with component relevant cycles

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Introduction

Objectives of TMF CG activities

- To harmonise TMF CG experimental method between partners with respect to appropriate heating/cooling methods, crack monitoring techniques and specimen design
- To establish guidelines and procedures for local Code of Practice for the tests at the consortium level
- To draft a Code of Practice with support from the HTMTC organisation
- To promote further collaboration towards standardisation of TMF CG experimental method

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.

Experimental methods

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.

Experimental methods

TMF CG back-to-back testing:

- 3 laboratories
- 2 different specimen designs
- 3 different crack growth measurement methods
- 2 different heating methods
- 3 different coil designs for induction heating

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Experimental methods

TMF CG back-to-back testing:

- Validation of coil designs
- Validation of heating methods
- Validation of temperature measurement and control
- Pre-cracking procedures
- Effect of heating zone at crack tip

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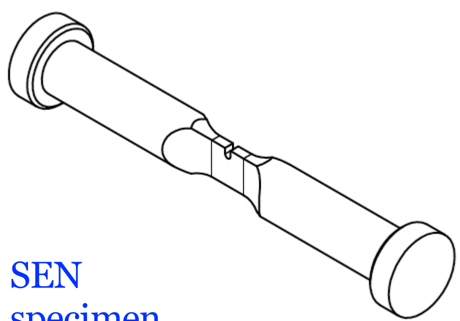
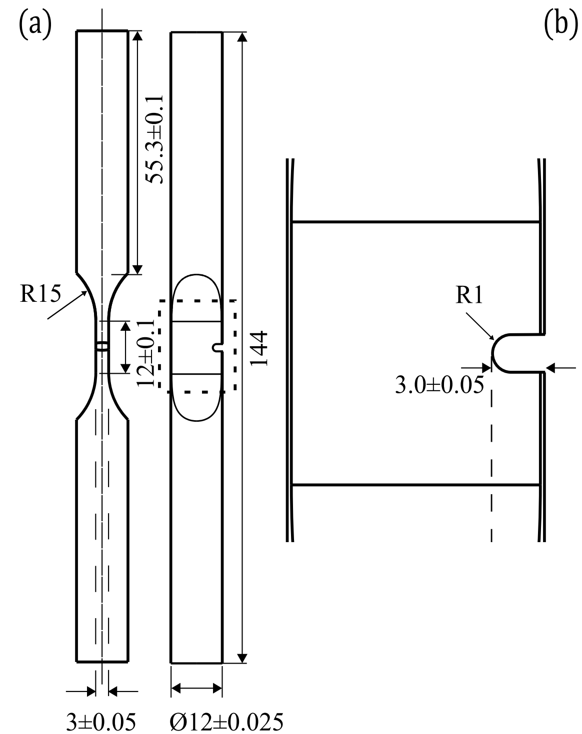
Experimental methods

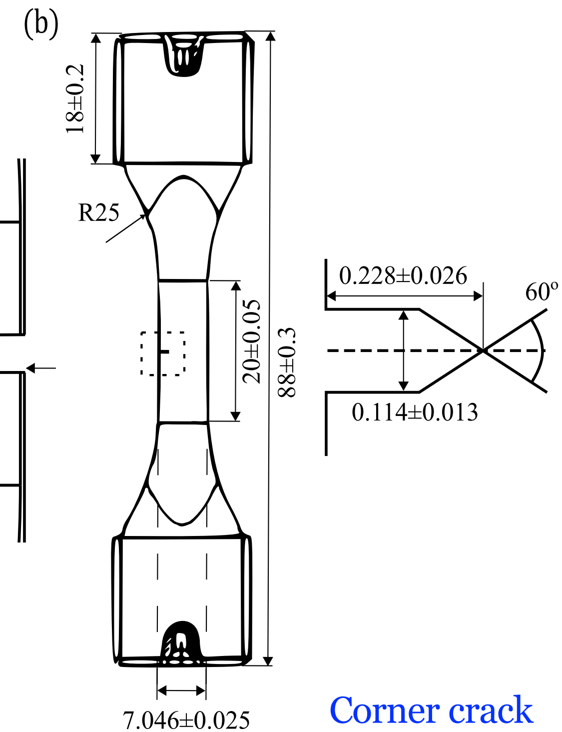
TMF CG back-to-back testing: specimen designs



SEN specimen used at Nottingham



SEN specimen used at Linköping



Corner crack specimens at Swansea

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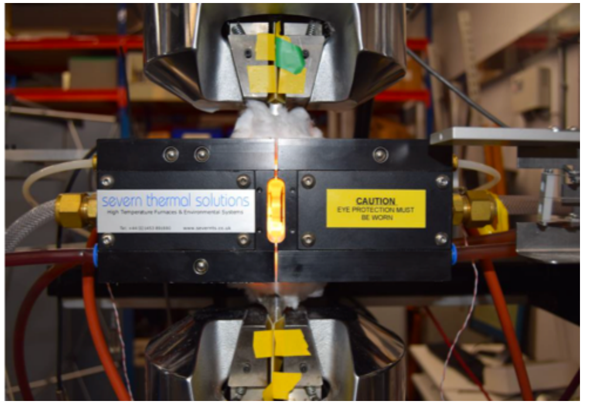
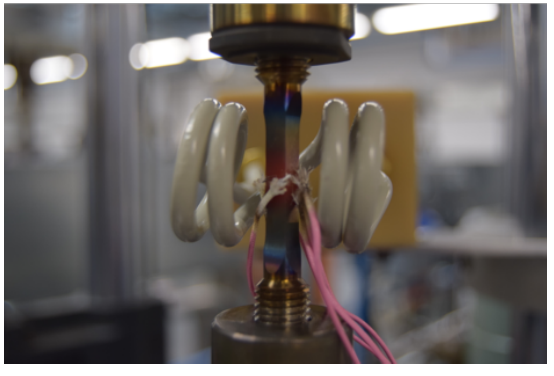
DevTMF

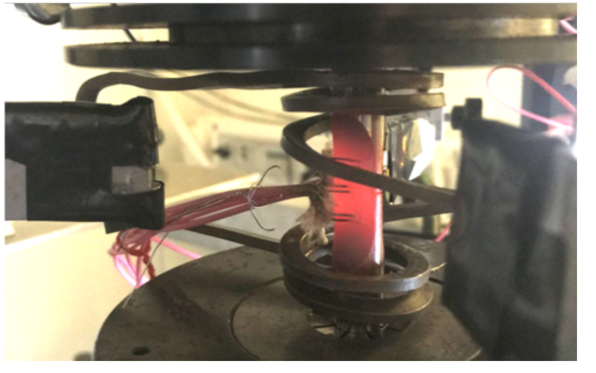
Experimental methods

TMF CG back-to-back testing: heating methods

- Induction with different coil set-ups
- Infra-red lamp furnace







Different coil designs

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Experimental methods

TMF CG back-to-back testing: TMF cycles

- 70s triangular cycle
- 400-750°C
- Stress controlled
- R=0
- In-phase (IP) and out-of-phase (OP)
- Variations in the pre-crack procedure

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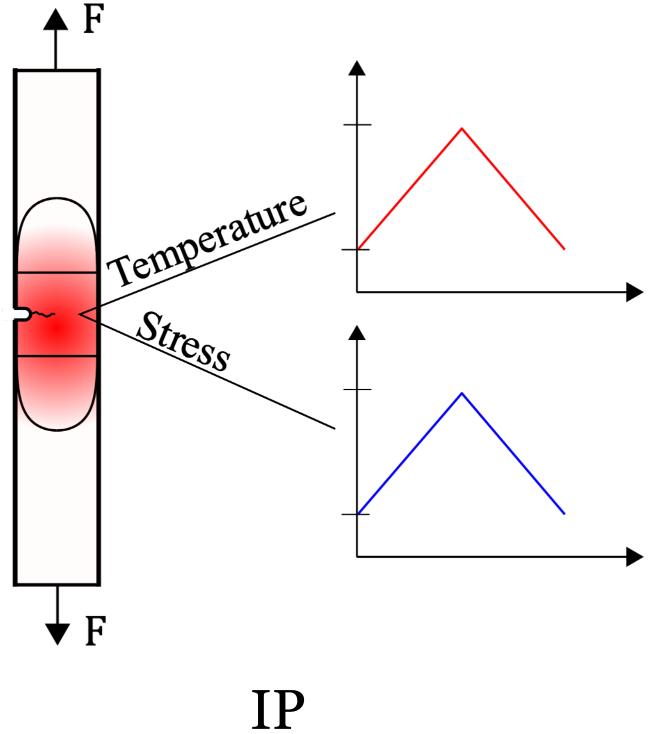
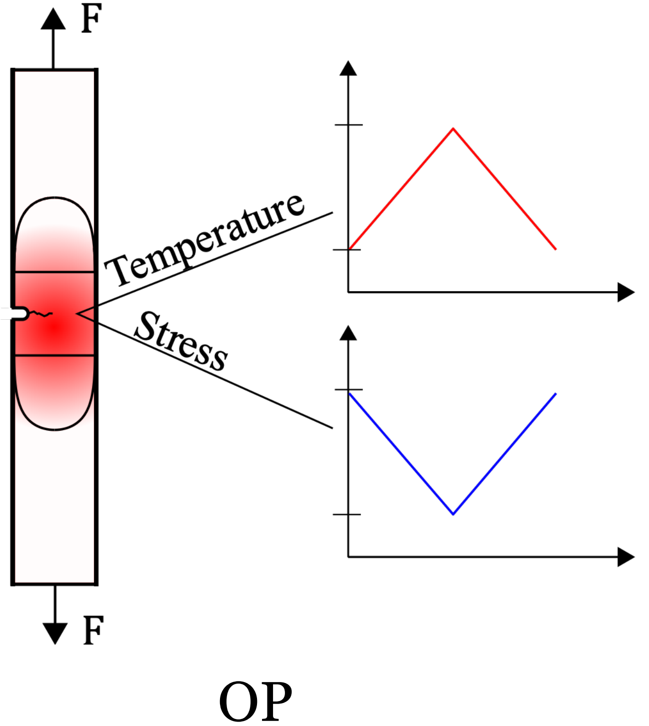
Experimental methods

TMF CG back-to-back testing: TMF cycles





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Experimental methods

TMF CG back-to-back testing: temperature measurements

Measurement	Thermocouple	Pyrometer	Thermography
Mode	Invasive	Non Invasive	Non Invasive
Area	≈ 2mm^2	≈ 2mm^2	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

Conclusions

- Pyrometer and thermography offer non-invasive measurements
- Accurate temperature control with thermography
- TCs unfavourable to weld
- TCs are complex set up
- Temperature at shoulder not stable
- Surface emissivity and pre-exposure can cause shorter fatigue life with pyrometer but not with thermography

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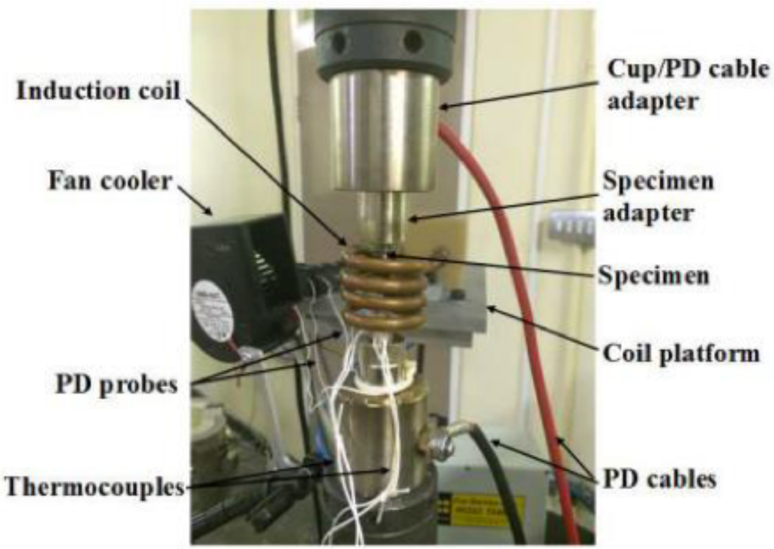
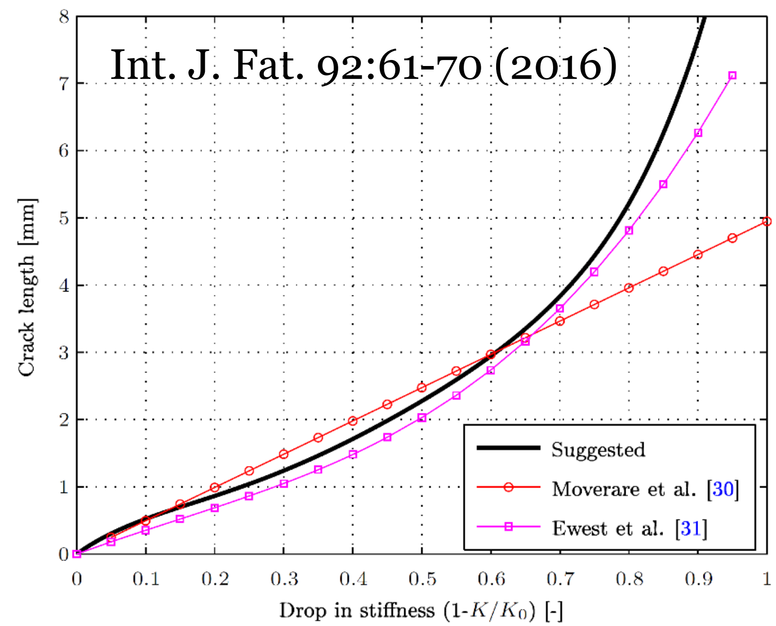
Experimental methods

TMF CG back-to-back testing: crack growth measurement methods

- Direct Current Potential Drop (DCPD)
- Compliance method
- Alternating Current Potential Drop





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Clean Sky 2
DevTMF

Results

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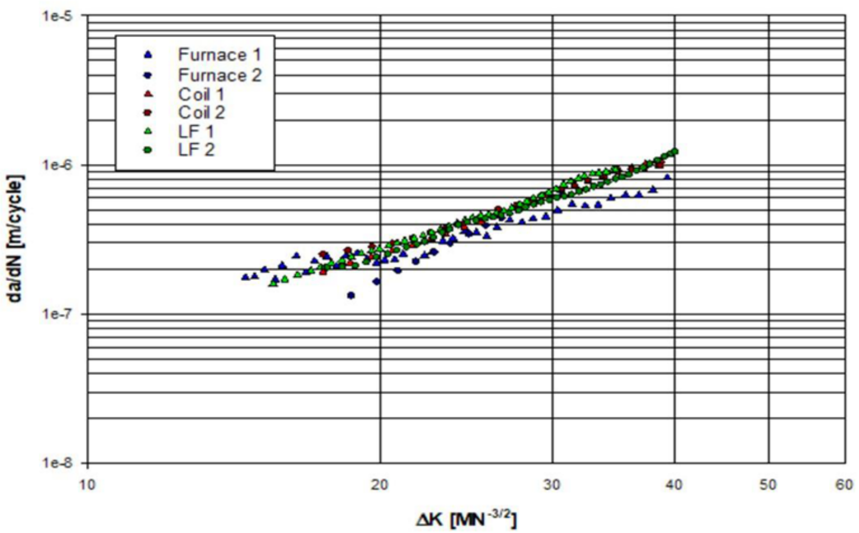
Results

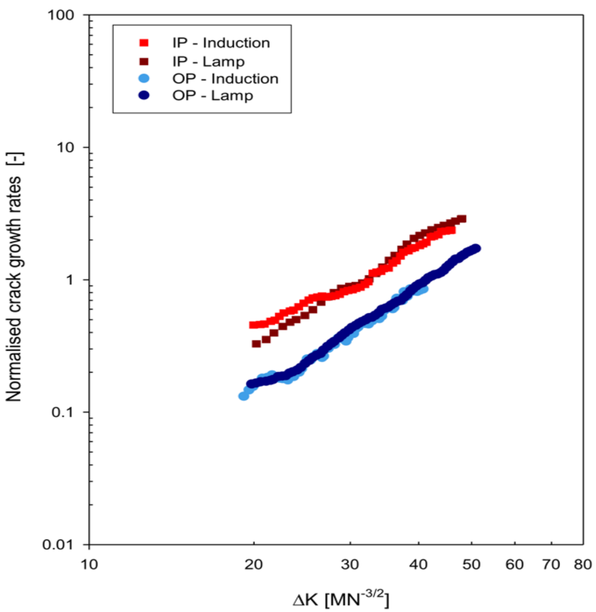
TMF CG back-to-back testing: effect of lamp furnace vs induction coil, Swansea

Ti-6246 CC tested at the same isothermal conditions



J. Palmer et al., Development of test facilities for thermo-mechanical fatigue testing. *International Journal of Fatigue 121 (2019) 208-218*

CG rates are consistent across different heating methods



S. Stekovic et al., DevTMF – Towards code of practice for thermo-mechanical fatigue crack growth. *International Journal of Fatigue (2020) 105675.*

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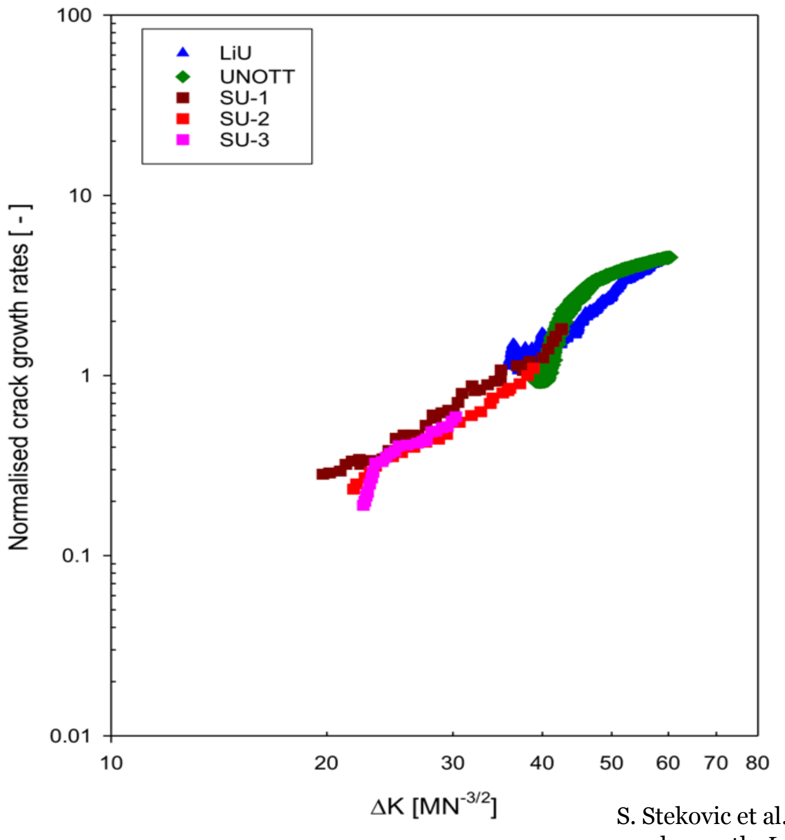
Results

TMF CG back-to-back testing: OP crack growth rates



OP CG rates are consistent between the laboratories

S. Stekovic et al., DevTMF – Towards code of practice for thermo-mechanical fatigue crack growth. *International Journal of Fatigue (2020) 105675.*

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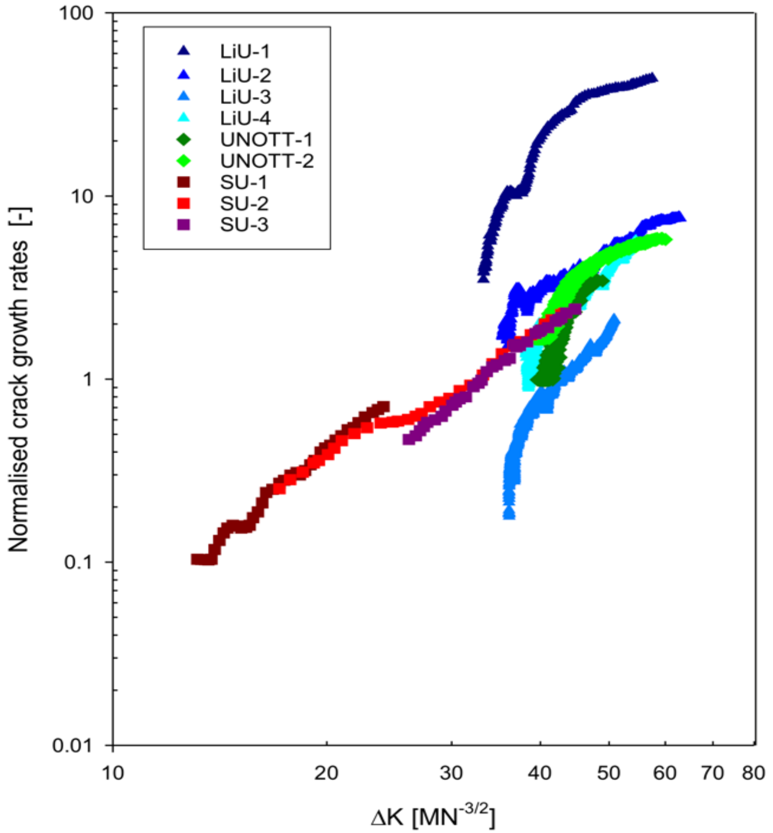
Results

TMF CG back-to-back testing: IP crack growth rates



IP CG rates are mostly consistent between the laboratories

Faster crack growth rates in one specimen from LiU (dominated by microstructure effect)

S. Stekovic et al., DevTMF – Towards code of practice for thermo-mechanical fatigue crack growth. *International Journal of Fatigue (2020) 105675*.

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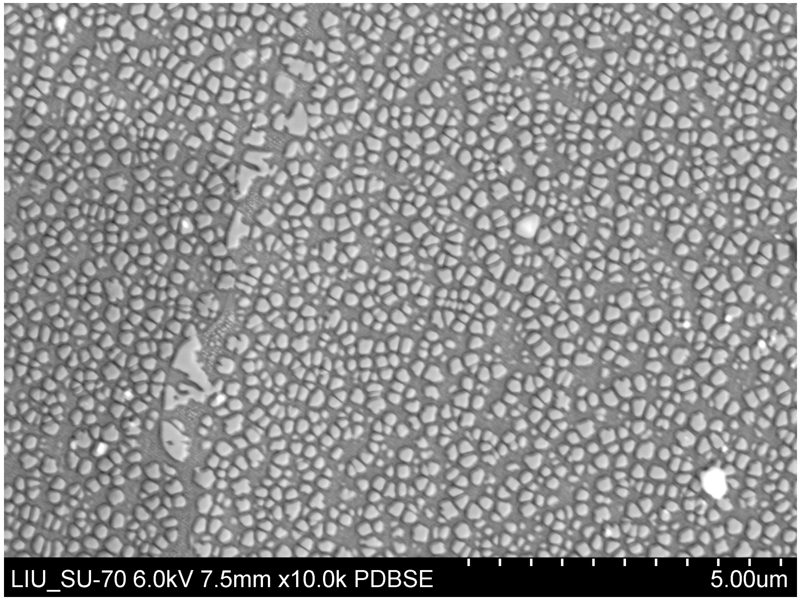
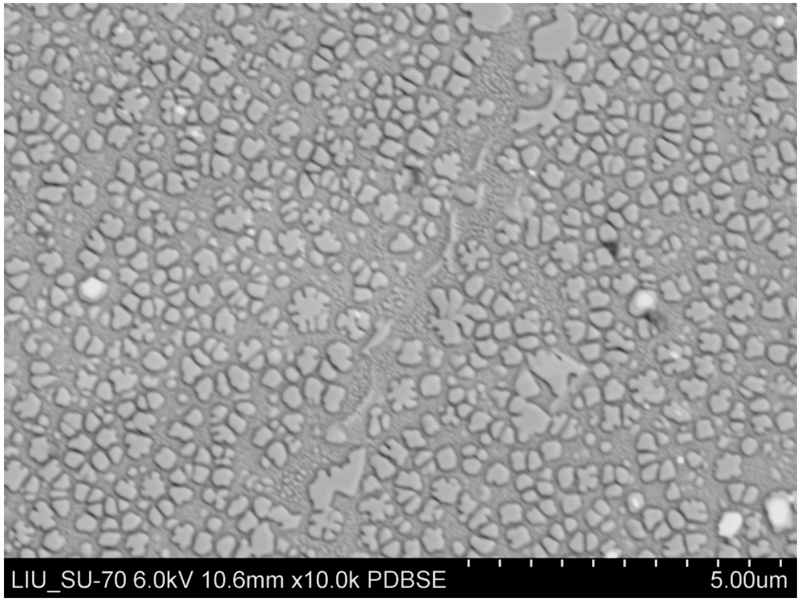
Results

TMF CG back-to-back testing: IP crack growth rates

Faster TMF CG IP rate



Slower TMF CG IP rate



Secondary γ´: Max 210nm, average 155nm

Secondary γ´: Max 335nm, average 280nm

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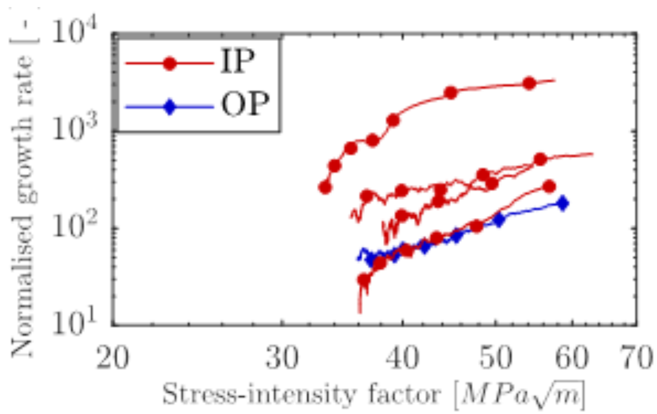
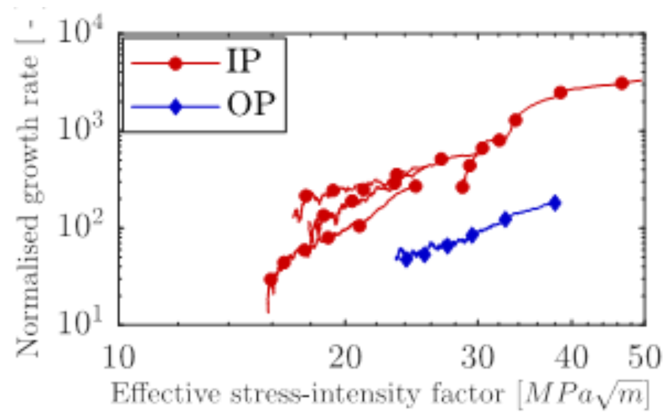
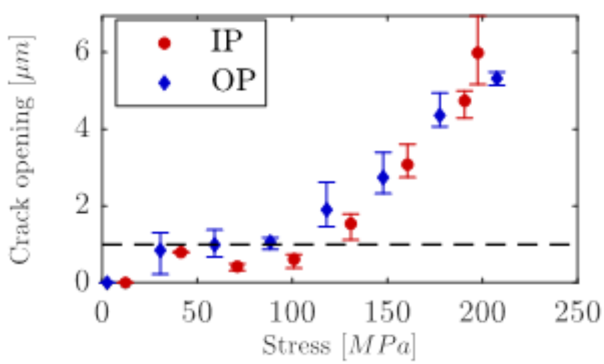
Results

TMF CG back-to-back testing: crack closure effect, different pre-cracking procedure







V. Norman et al., On the mechanistic difference between in-phase and out-of-phase thermo-mechanical fatigue crack growth. *International Journal of Fatigue (2020) 105528.*

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DevTMF

Results

Recommendations:

- Heating methods – effect of induction on DCPD negligible
- Coil design – non-uniform multi-turn longitudinal field helical coil
- Temperature measurements – use of thermocouples, pyrometry and thermography
- Crack tip heating – no significant effect
- Specimen design – similar results obtained
- Accurate readings from both DCPD, compliance method and ACPD
- Pre-cracking procedure – different stages

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DevTMF

TMF CG Code of Practice

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HT MT
High Temperature Mechanical Testing Committee

Welcome

The High Temperature Mechanical Testing Committee (HTMTC) was established in 1982 following a conference held at NPL on 'Measurement of High Temperature Mechanical Properties of Materials'. The membership of the committee includes experts in the field of high temperature testing drawn from industry, research institutions and universities. The HTMTC operates as Technical Committee 11 (TC11) of the European Structural Integrity Society (ESIS).

The HTMTC is a non-profit company limited by guarantee (Reg. No. 2149907) and is also a Registered Charity (Reg. No. 800892).

The HTMTC aims to improve the techniques and procedures used for the high temperature testing of materials, and to disseminate this information to the materials community as a whole.

It achieves these aims by:

- Providing a Forum for Discussion
- Organizing Conferences and Laboratory Visits
- Publishing Conference Proceedings and Codes of Practice
- Initiating Research Activities

Membership of the HTMTC is open to all interested parties particularly engineers, scientists and technical personnel from industry, laboratories and research institutes who have an interest in high temperature mechanical testing. Further information on becoming a member can be obtained via the contacts shown below.

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Conclusions

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Conclusions

- Internal comparison of the TMF CG data between three laboratories
- Reproducibility and repeatability of the TMF CG results
- Robustness of the TMF CG testing and dependency on test laboratory
- Towards standardisation of TMF CG test method

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Questions?

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