

DEVELOPMENT OF TESTING METHOD FOR THE EVALUATION OF CYCLIC OPERATION

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FUEL-BASED ELECTRICITY
AND HEAT PRODUCTION



DEVELOPMENT OF TESTING METHOD FOR THE EVALUATION OF CYCLIC OPERATION

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Förord

Denna rapport är slutrapportering av projekt M 38160 Utveckling av provmetod för utvärdering av cyklisk drift (Energimyndighetens projektnummer P 38160) som faller under teknikområde material- och kemiteknik inom SEBRA, samverkansprogrammet för bränslebaserad el- och värmeproduktion.

Projektet har följts av en referensgrupp bestående av Jan Storesund, Inspecta Technology och Rikard Norling, Swerea KIMAB.

SEBRA, samverkansprogrammet för bränslebaserad el- och värmeproduktion, är efterföljaren till Värmeforsks Basprogram och startade som ett samarbetsprogram mellan Värmeforsk och Energimyndigheten 2013. All forskningsverksamhet som bedrevs inom Värmeforsk ingår sedan den 1 januari 2015 i Energiforsk. Därför ges denna rapport ut som en Energiforskrapport.

Programmets övergripande mål är att bidra till långsiktig utveckling av effektiva miljövänliga energisystemlösningar. Syftet är att medverka till framtagning av flexibla bränslebaserade anläggningar som kan anpassas till framtida behov och krav. Programmet är indelat i fyra teknikområden: anläggnings- och förbränningsteknik, processtyrning, material- och kemiteknik samt systemteknik.

Stockholm januari 2016

Helena Sellerholm

Områdesansvarig

Bränslebaserad el- och värmeproduktion, Energiforsk AB

Sammanfattning

Tillgänglighet är en mycket viktig parameter för kraft- och värmeproduktionsanläggningar då kostnaden för ej planerade stopp är mycket höga. Fluktuationer i elpris och ökningen av vind- och solkraft medför att allt fler nya och befintliga anläggningar tvingas köras under cykliska driftsförhållanden, vilket ökar påfrestningarna på materialen i anläggningarna. Behovet av bättre och säkrare metoder för att utvärdera riskerna med cyklisk drift är alltså stort. Dessa metoder kräver dock även att relevanta provdata finns tillgängliga för relevanta material. Traditionellt har man ofta använt sig av isoterma utmattningsprov men dessa kan vara mycket missvisande om driftstemperaturen är hög och lastcykeln i huvudsak härrör från start- och stoppcykler med stora temperaturvariationer. Det är därför av stor vikt att provning återspeglar verkliga driftsförhållanden så naturotroget som möjligt i så kallad termomekanisk utmattningsprovning (TMF) där både last och temperatur varierar cykliskt.

Standarder för TMF är relativt nya (ASTM E2368-10 och ISO 12111:2011) och täcker än så länge bara provning på släta provstavar och cykler till sprickinitiering. Två viktiga aspekter saknas således fortfarande: provning på anvisade provstavar och prov för att bestämma spricktillväxthastigheter under TMF förhållanden. Ett steg mot att även inkludera dessa två aspekter finns i det initiativ till en s.k. Code-of-practice för spänningsstyrd TMF-provning som bedrivs inom ESIS's underkommitté för högtemperaturprovning (HTMTC). Syftet är att utveckla och i förlängningen standardisera en provmetod för spänningsstyrd termomekanisk utmattningsprovning.

Round robin-provning har utförts vid Siemens Industrial Turbomachinery AB (SIT) och vid Linköpings Universitet (LiU), för att utvärdera hur effektiv ovan nämnda Code-of-practice är för att minimera spridningen i resultat mellan olika laboratorier.

Från arbetet drogs följande slutsatser:

- Provningsmetoden gör det möjligt att studera spricktillväxt under TMF förhållanden, relevanta för gasturbinkomponenter.
- Provningsmetoden är lämplig för kraftstyrd såväl som töjningsstyrd TMF spricktillväxtprovning.
- Ingen signifikant spridning mellan de två labben hittades.
- Stor spridning konstaterades mellan tester utförda i samma labb under identiska testförhållanden. Orsaken till detta är antagligen den stora kornstorleken i materialet.

Summary

Availability is a key parameter for heat and power producing plants, since the costs of unplanned outages are very high. An increasing number of existing plants are currently required to run under cyclic conditions. This trend is a result of the increase in wind and solar power, as well as fluctuations in the price of electricity. Cyclic operation increases the risk of fatigue damage to plant components. Therefore there is a great need for improved methods of life assessment and risk evaluation during cyclic operation. Such methods require relevant test data obtained under relevant testing conditions on relevant materials.

Traditionally, isothermal fatigue tests have often been used but these can be highly misleading if the operating temperature is high and the loading cycle primarily originates from the start and stop cycle with large temperature variations. It is therefore of utmost importance that the material testing as closely as possible resembles service conditions. In order to achieve this, mechanical loading and temperature must be varied cyclically in a so called Thermo-Mechanical Fatigue (TMF) test. The available standards for TMF testing are relatively new (ASTM E2368-10 and ISO 12111:2011) and cover only testing on smooth specimens for the determination of the number of cycles to crack initiation. Thus two important aspects are still missing:

1. Testing on notched specimens under TMF conditions.
2. Testing to determine crack growth rates under TMF conditions.

Within ESIS's subcommittee of high temperature testing (HTMTC) an initiative has been taken to develop, and ultimately to standardize, a test method for stress-controlled TMF. A preliminary Code of Practice (CoP) for stress-controlled TMF has been issued and this is a first step towards including the two abovementioned aspects.

In the present work, round robin testing has been performed at Siemens Industrial Turbomachinery AB (SIT) and at Linköping University (LiU), in order to evaluate the effectiveness of the abovementioned CoP in minimizing the scatter of test results obtained at different laboratories.

The following conclusions were drawn:

- The testing method makes it possible to study crack growth under TMF conditions relevant for gas turbine components.
- The testing method is suitable for both strain controlled and force controlled TMF crack growth testing.
- No significant scatter between the two labs was found.
- Significant scatter was found between tests performed under identical test conditions in the same lab. This was probably due to the coarse grain size of the tested material.

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1 Introduction

1.1 BACKGROUND

Availability is a key parameter for heat and power producing plants, since the costs of unplanned outages are very high. An increasing number of existing plants are currently required to run under cyclic conditions. This trend is a result of the increase in wind and solar power, as well as fluctuations in the price of electricity. Cyclic operation increases the risk of fatigue damage to plant components. Therefore there is a great need for improved methods of life assessment and risk evaluation during cyclic operation. Such methods require relevant test data obtained under relevant testing conditions on relevant materials.

Traditionally, isothermal fatigue tests have often been used but these can be highly misleading if the operating temperature is high and the loading cycle primarily originates from the start and stop cycle with large temperature variations. It is therefore of utmost importance that the material testing as closely as possible resembles service conditions. In order to achieve this, mechanical loading and temperature must be varied cyclically in a so called Thermo-Mechanical Fatigue (TMF) test. The available standards for TMF testing are relatively new (ASTM E2368-10 and ISO 12111:2011) and cover only testing on smooth specimens for the determination of the number of cycles to crack initiation. Thus two important aspects are still missing:

- Testing on notched specimens under TMF conditions.
- Testing to determine crack growth rates under TMF conditions.

Within the field of TMF crack growth testing, only a very limited number of studies can be found in the open literature. Attempts have been made to monitor the crack growth by optical methods [1-4] or by the potential drop method [5-8]. The most common heating method for TMF crack growth testing is induction heating [1-8], but attempts have also been made to use radiant heating [9-11] and convective heating [12].

Within ESIS's subcommittee of high temperature testing (HTMTC) an initiative has been taken to develop, and ultimately to standardize, a test method for stress-controlled TMF. A preliminary Code of Practice (CoP) for stress-controlled TMF has been issued and this is a first step towards including the two abovementioned aspects. The work will provide input to ISO's technical committee for mechanical testing within the area of fatigue (ISO/TC164/SC5).

The purpose of the present work is to support an active participation in the finalization of this code of practice and to conduct round-robin testing of the new test method. The work has been performed both by Siemens Industrial Turbomachinery AB (SIT) and Linköping University (LiU).

The test method will be generally applicable to wide range of materials used in boilers, steam turbines, and gas turbines operated under cyclic conditions.

1.2 AIMS

The project has the following aims:

1. Active participation in the finalization of a Code of Practice (CoP) for stress-controlled TMF testing, covering tests on notched and rectangular test specimen geometries.
2. Development of testing methodology and equipment enabling testing at Linköping University in accordance with the abovementioned CoP.
3. Active participation in round-robin testing in order to evaluate the effectiveness of the abovementioned CoP in minimizing the scatter of test results obtained at different European laboratories.

2 Experimental procedure

2.1 MATERIAL

The material used for testing is the cast polycrystalline nickel-based alloy Inconel 792 supplied by IHI castings. All specimens were produced from the same batch of raw material. Details can be found in the material certificate (see section 8.2 of this report).

2.2 TEST SPECIMEN

The test specimen used for testing is a single edge notched specimen with a rectangular cross-section (see drawing in section 8.1 of this report). The dimensions of the specimen were measured using a micrometer screw gauge with an accuracy of 0,01mm. On the side of the specimen, scribes were made as reference lines for optical crack length measurements during the test. The specimen geometry was chosen to obtain a stress gradient similar to that found in gas turbine blades and vanes.

2.3 TESTING PROCEDURE

The testing procedure was based on the “Preliminary version of the Code of Practice for force-controlled thermo-mechanical fatigue testing”, issued 11 July 2014 [13]. An exception from the Code of Practice was that the temperature variation within the test piece was not kept within the required limits of $\pm 7^\circ\text{C}$ or $\pm 1\%$ of T_{max} . The obtained temperature variation is reported in section 3.1.

The specimen was heated by induction heating the crack length was monitored optically during the test using a camera, which recorded images from one side of the specimen (see Figure 2).

2.4 TMF CYCLE

The same TMF cycle was used for all tests: 100-750°C, Out of Phase (OP), $R=-1,5$, with a nominal stress range of 737 MPa¹. The rate of heating and cooling was 2°C/s. See Figure 1. In the Finspong lab it was found that no significant improvement of the thermal gradient was obtained if the rate of heating and cooling was lowered to 1°C/s. Therefore 2°C/s was chosen as a compromise between cycling frequency and temperature uniformity. The TMF cycle was chosen to resemble the service conditions of a gas turbine blade or vane, which are the typical applications of the material studied.

¹ The nominal stress range $\Delta\sigma_{\text{nom}}$ is defined as $\Delta\sigma_{\text{nom}} = \Delta F/A_{\text{notch}}$, where ΔF is the applied force range and A_{notch} is the cross-sectional area in the plane of the notch.

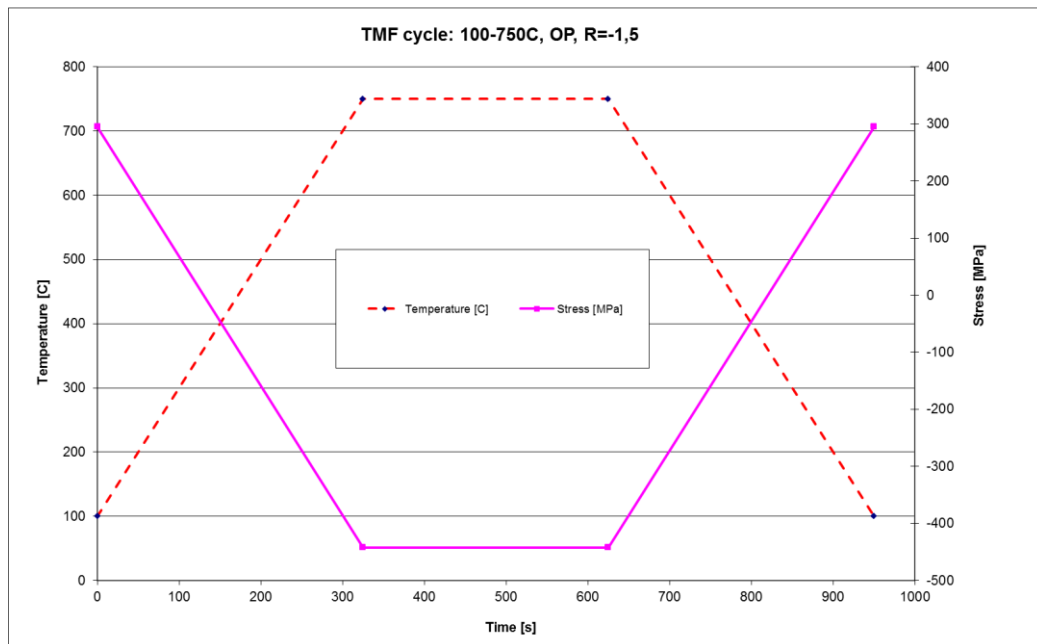


Figure 1 - TMF cycle used for all tests: 100-750°C, OP, R=-1,5 with 2°C/s heating and cooling rate and a nominal stress range of 737 MPa.

Figur 1 - TMF cykel som används för alla tester: 100-750 °C, OP, R = -1,5 med 2 °C / s värme och kylningshastighet och en nominell spänningsvidd av 737 MPa.

2.4.1 Siemens lab in Finspong

The testing in Finspång was performed on an MTS 810 servo-hydraulic machine, with a 100 kN load cell. The gauge length of the extensometer was 12 mm. The specimen was heated by a 2-1-2 "barrel-shaped" induction coil, as can be seen in Figure 2. The specimen was cooled by compressed air from two cooling nozzles.

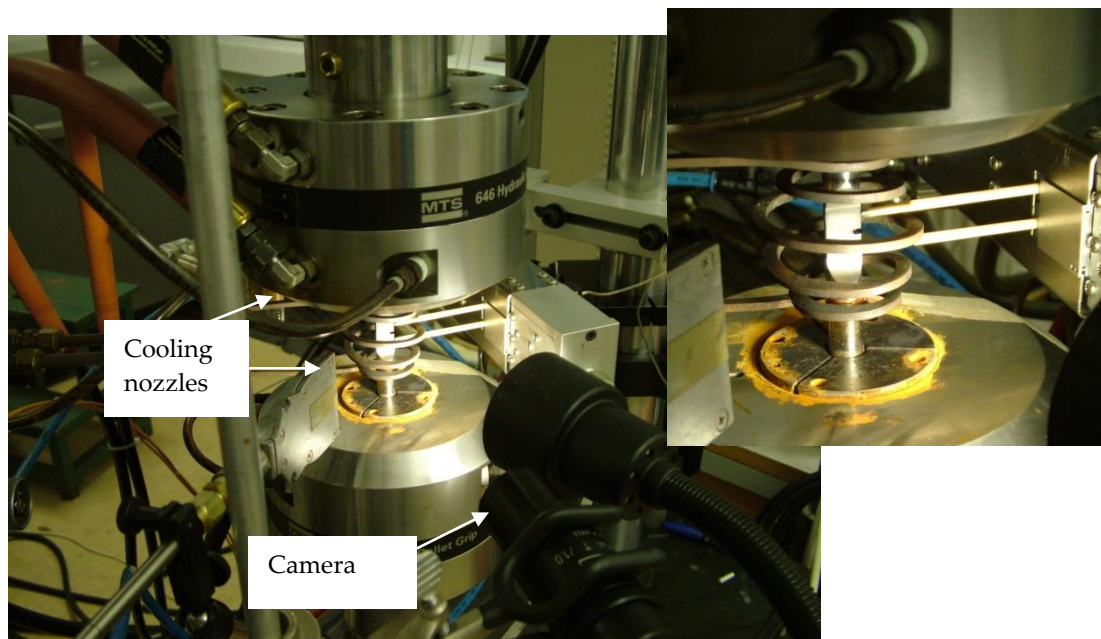


Figure 2 - Test set-up for TMF crack growth.

Figur 2 - Provuppställning för TMF spricktillväxtprovning.

Thermal Gradient Measurement

The thermal gradient in the SIT test rig was measured using an IN792 specimen instrumented with 10 thermocouples. The thermal gradient was measured at steady state at temperatures from 100°C up to 750°C and the transient thermal gradient was determined for the 100-750°C temperature cycle which was used for the TMF test (TMF cycle shown in Figure 1).

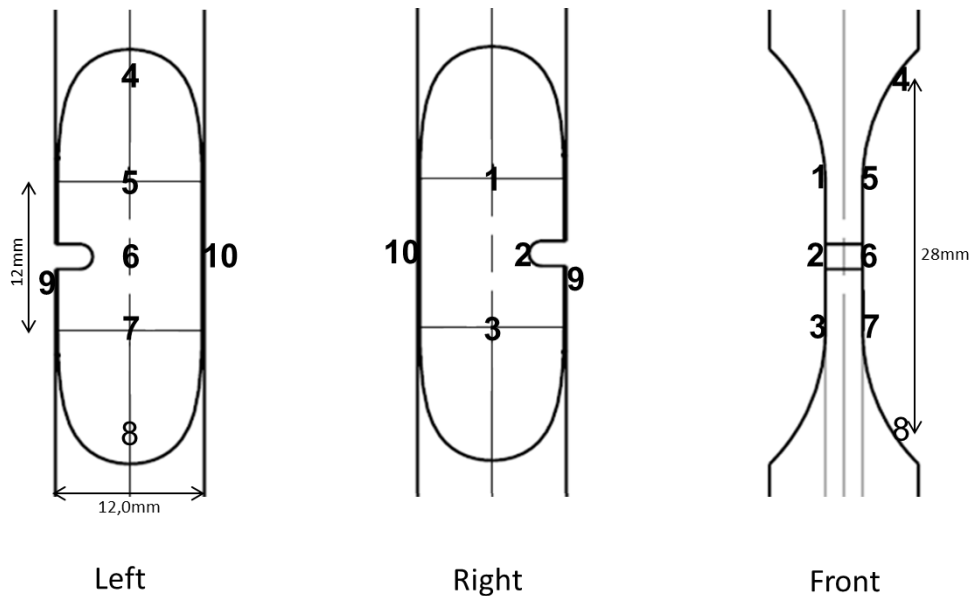


Figure 3 - Sketch of thermocouple positions on specimen for thermal gradient measurement at SIT in Finspång.

Figur 3 - Skiss av termoelementens positioner vid prov för temperaturgradientmätning på SIT i Finspång.

2.4.2 Linköping University Lab

The testing at Linköping University was performed on an Instron 8801 servo-hydraulic machine, with a 100 kN load cell. For heating an induction heater from Sigmatest was used with an induction coil with 5 parallel turns. The gauge length of the extensometer was 12.5 mm and the specimen was cooled by compressed air from two cooling nozzles. The temperature during the tests was controlled by a thermocouple spot welded in the middle of gauge length, corresponding to location 6 in Figure 3.

Crack lengths were evaluated using the compliance method; see reference 1 for more details. Optical measurements of the crack length were also performed manually (without a camera), using an inspection microscope and was found to be in very good agreement with the crack lengths determined by the compliance method. Furthermore, the final crack length of the two tests performed was also evaluated against the fracture surface and also in the case good agreement to the compliance method was found.

The tests performed at Linköping University was interrupted manually before complete rupture of the specimens. The tests were interrupted at approximately 3 mm crack length when the crack reached the location of the spot welded thermocouple.

2.5 TEST MATRIX

The test matrix and the test conditions for the tests performed at the Siemens lab in Finspång and at Linköping University can be found in the table below.

Table 1 – Test matrix and test conditions.

Tabell 1 – Provmatrix och testparametrar

Test ID	Test lab	Thermal cycle	Rate of heating and cooling [K/s]	Nominal stress range ² [MPa]	Load ratio, R	Dwell at maximum load [s]
tmf3904	SIT	100-750°C, OP	2	737	-1,5	300
tmf3905	SIT	100-750°C, OP	2	737	-1,5	300
LiU_VF2	LiU	100-750°C, OP	2	737	-1,5	300
LiU_VF3	LiU	100-750°C, OP	2	737	-1,5	300

² The nominal stress range $\Delta\sigma_{\text{nom}}$ is defined as $\Delta\sigma_{\text{nom}} = \Delta F / A_{\text{notch}}$, where ΔF is the applied force range and A_{notch} is the cross-sectional area in the plane of the notch.

3 Results

3.1 THERMAL GRADIENT

For the tests performed at Siemens Finspång the temperature distribution within the gauge length was within $\pm 15^{\circ}\text{C}$, as measured by an instrumented specimen (see Figure 3). In the plane of the notch where the crack growth takes place the temperature distribution is much smaller. In the Finspång lab the most suitable location of the controlling thermocouple was found to be position 10, indicated in Figure 3 - Sketch of thermocouple positions on specimen for thermal gradient measurement at SIT in Finspång. Figure 3.

No thermal gradient was measured for the tests performed at Linköping university. However, during visual inspection at the dwelltime at maximum temperature, no significant temperature gradients could be observed. The temperature distribution within the gauge length was estimated to be within $\pm 10^{\circ}\text{C}$.

3.2 CRACK INITIATION LIFE

The crack initiation life for the different tests are listed in Table 2. In this table, the crack initiation is defined as the cycle where the crack has reached 0.2 mm according to the camera reading.

Table 2 – Crack initiation life for all tests

Tabell 2 – Sprickinitieringslivslängd för alla prov

Test ID	Test lab	Ni, cycles to 0,2mm crack length according to camera reading
tmf3904	SIT	70
tmf3905	SIT	100
LiU_VF02	LiU	70
LiU_VF02	LiU	250*

*Base on the compliance method

3.3 FRACTURE APPEARANCE

In Figures 4-6, the fracture surfaces of the specimens and the measurements made to determine the average crack length along the final crack front are shown. The TMF fracture surface is oxidized and can thereby clearly be distinguished from the residual fracture surface which is bright. A somewhat curved crack front is expected due to the variation in triaxiality along the crack front, i.e. plane stress on the surfaces and more close to plane strain in the center of the specimen. However, in the present study it is also likely that the irregular shape of the final crack front is caused by the large grain size of the material. The grain size of the material is on the order of 1mm, which means that there are only a few grains through the thickness of the specimen. In spite of the irregular shape of the crack front, the agreement between the optical crack length measurement and the final crack length measured on the fracture surface is fairly good (see Figure 9).

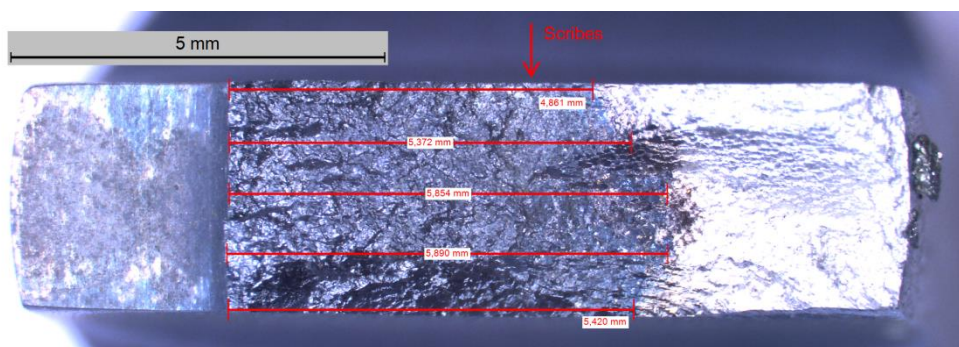


Figure 4 - Fracture surface of tmf3904

Figur 4 – Brottytan för prov tmf3904

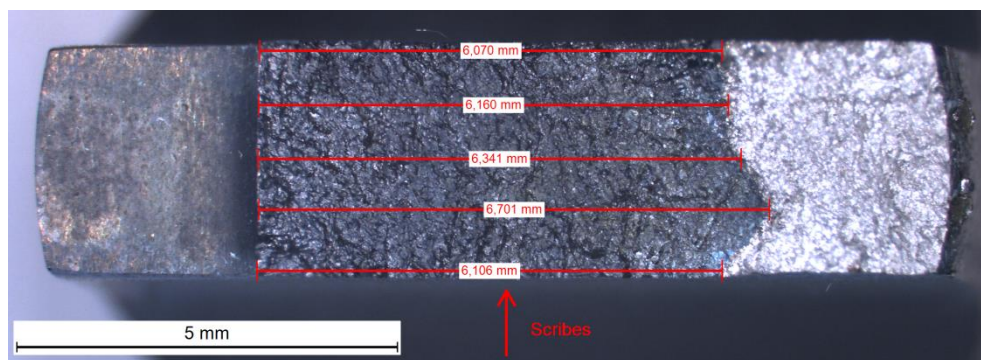


Figure 5 - Fracture surface of tmf3905

Figur 5 – Brottytan för prov tmf3905

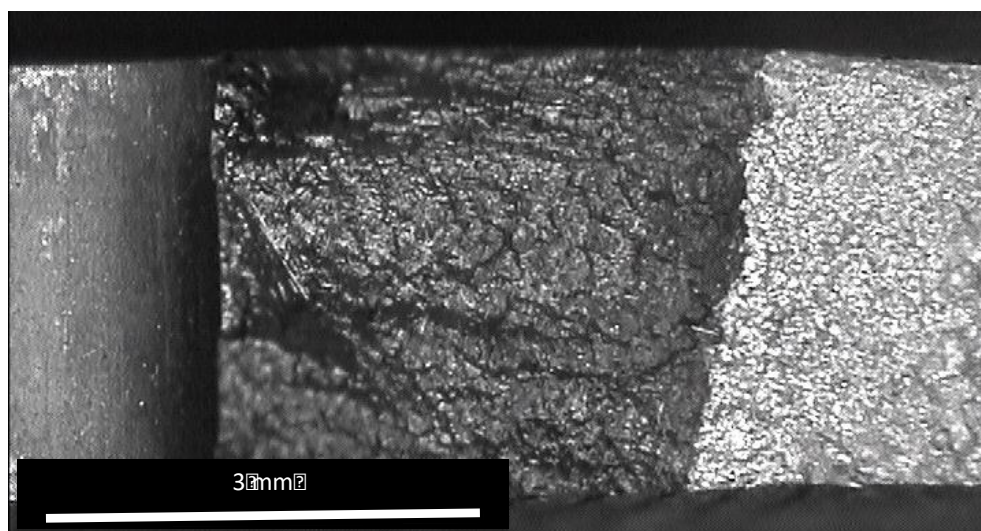


Figure 6 - Fracture surface of LiU_VF02 (Scribes on the lower side of the specimen).

Figur 5 – Brottytan för prov LiU_VF02 (Ritsar på den undre sidan av provstaven)

3.4 CRACK GROWTH

The crack growth was monitored using a camera recording images from one side of the specimen (see Figure 7). As can be seen the crack takes a meandering path and does not grow straight in the direction perpendicular to the load, as would be expected for a perfectly homogeneous and isotropic material. This is a result of the coarse, heterogeneous microstructure of the material. The dendrite structure formed during casting of the material can clearly be seen on the surface of the specimen.

For one of the tests performed at Linköping University multiple cracking were found from the notch, see Figure 8.

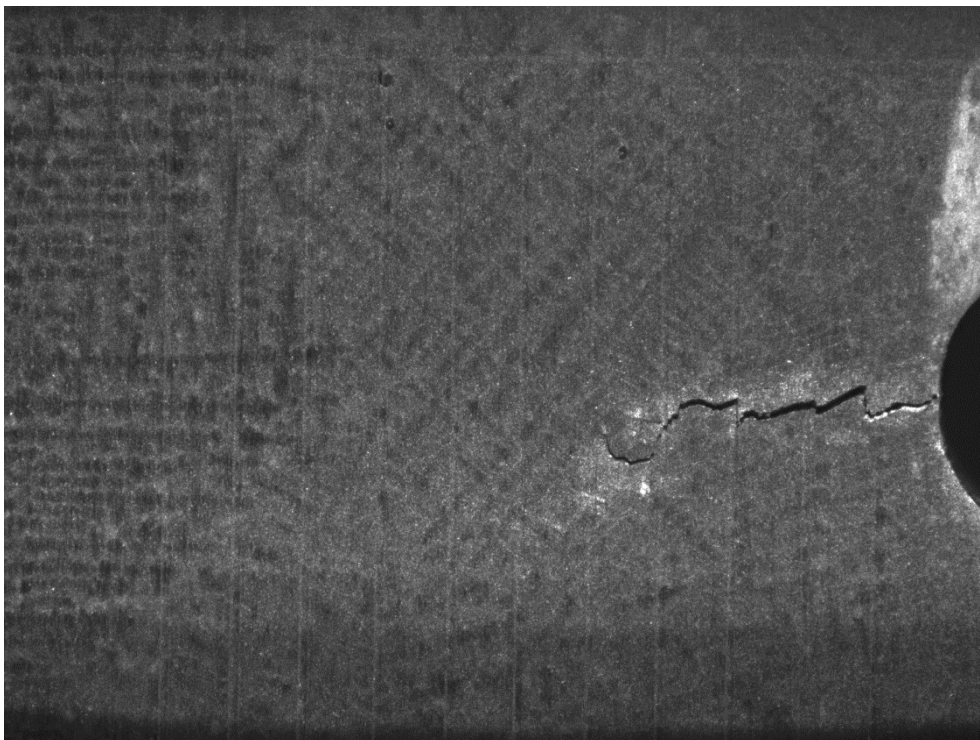


Figure 7 –Image taken during test tmf3904 in cycle 200. The crack has reached the 5th scribe, which in this case is located 2,47mm from the notch root. The nominal distance between the scribes is 0,5mm but a more precise measurement of the positions of the scribes is made in an optical microscope.

Figur 7 –Bild tagen under prov tmf3904 i cykel 200. Sprickan har nått 5:e ritsen, som i detta fall ligger 2,47mm från botten på notchen. Det nominella avståndet mellan ritsarna är 0,5mm men en mer exakt mätning av lägena för varje rits har gjorts i ett optiskt mikroskop.

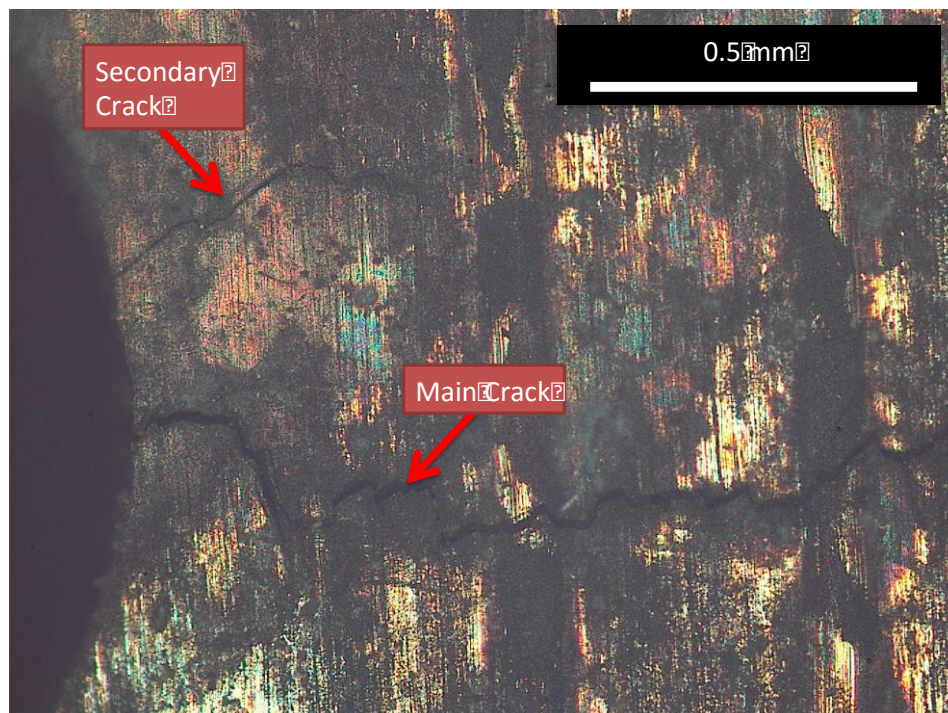


Figure 8 –Image taken after interruption of test LiU_VF3

Figur 8 – Bild tagen efter avbrott av test LiU_VF3

Figure 9 shows the crack length vs number of cycles. Even though the same TMF cycle has been used for all tests, there is quite a large variation in crack growth rates, even for specimens tested in the same test rig.

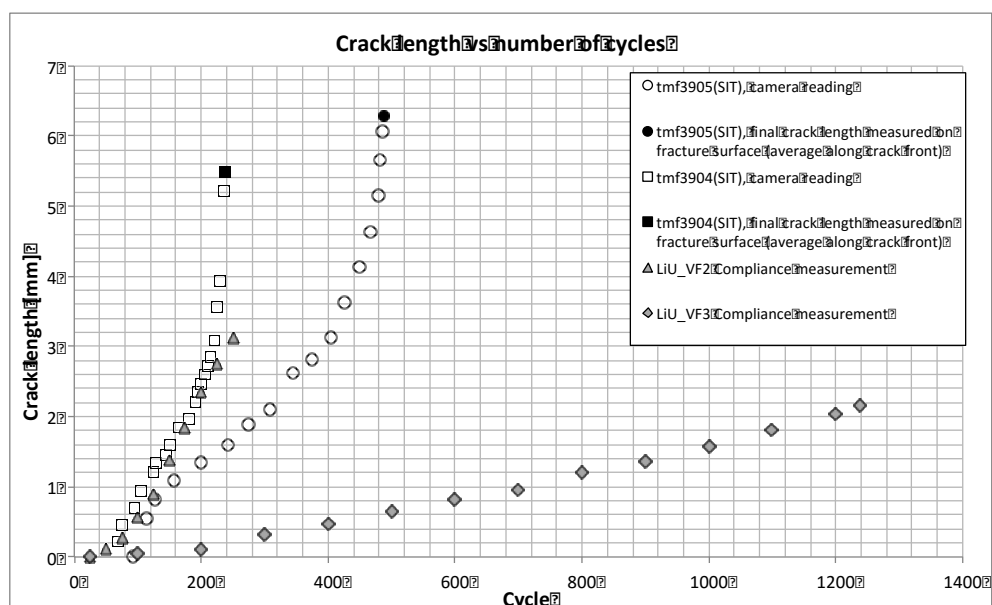


Figure 9 - Crack length vs number of cycles.

Figur 9 – Spricklängder som funktion av antal cykler

3.5 STRAIN RESPONSE

Since the testing was performed in force control, the mechanical strain range as well as the mean mechanical strain of the specimen is allowed to vary throughout the test as the specimen is inelastically deformed and cracked. The strain response is shown in Figure 10. Since the specimen is notched, the strain is not uniform throughout the specimen. The strain is measured using an extensometer centered around the notch, spanning the parallel length of the specimen (12 mm gauge length). The strain measured by the extensometer will be referred to as the “nominal strain”. No attempt was made to measure the strain field around the notch.

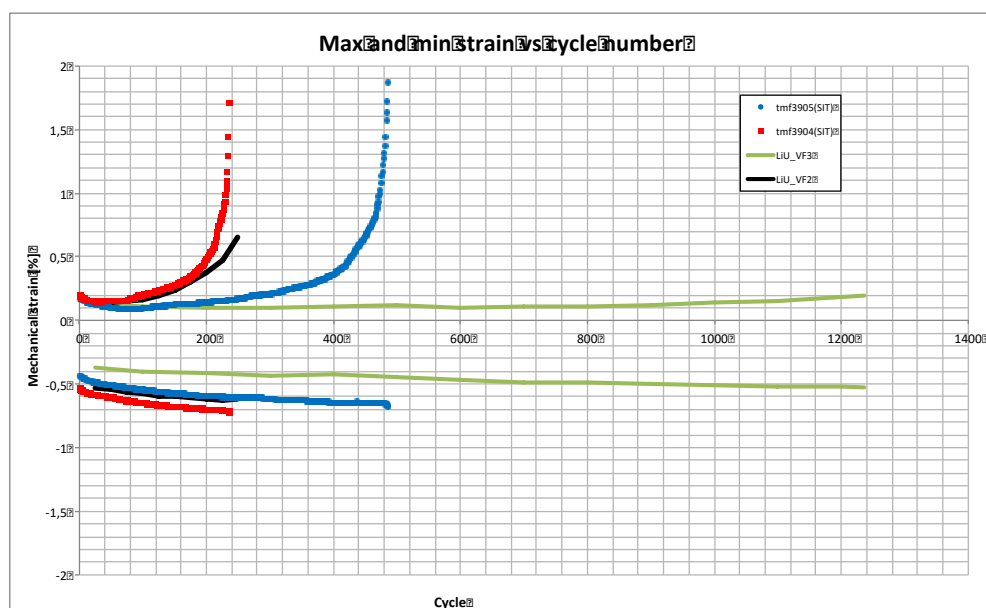


Figure 10 - Max and min nominal mechanical strain vs cycle number.

Figur 10 – Max och min nominell mekanisk töjning som funktion av antal cykler

3.6 STRESS-STRAIN LOOPS

The stress-strain loops before and after crack initiation can be seen in the figures 11-13 below.

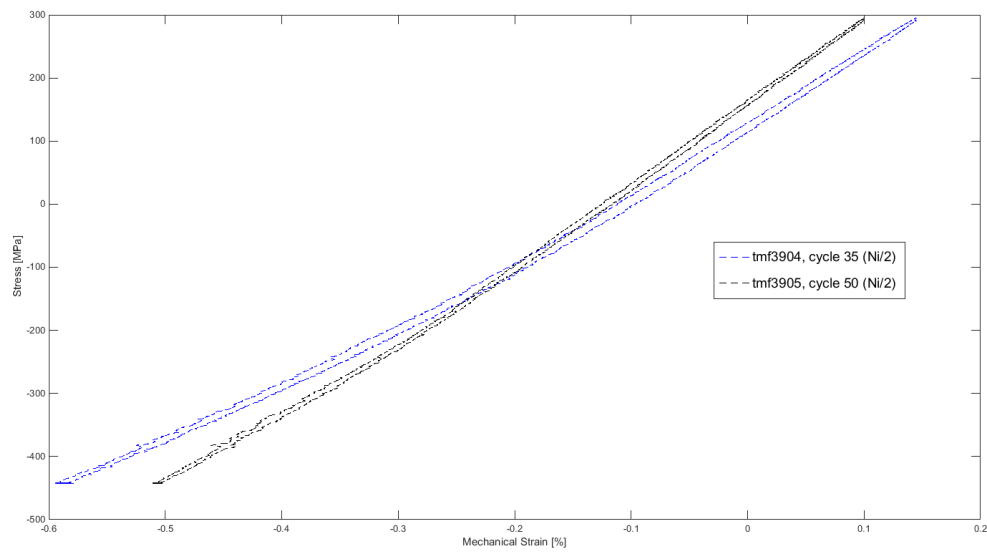


Figure 11 – Stress-strain loops at cycle Ni/2. Comparison between the Finspong tests: tmf3904 and tmf3905.

Figur 11 – Spännings-töjnings loop för cykel Ni/2. Jämförelse mellan Finspångsproven: tmf3904 och tmf3905

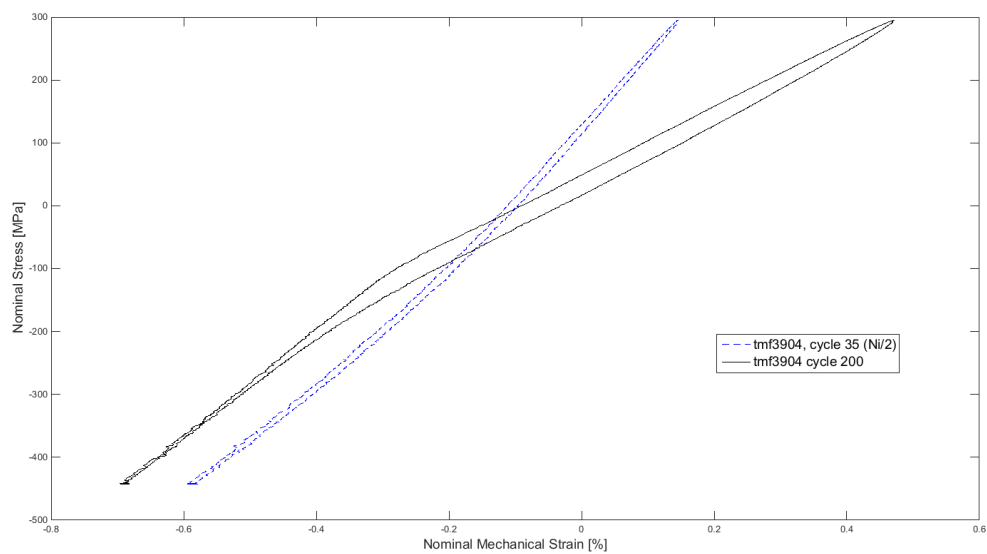


Figure 12 – Stress-strain loops from test tmf3904 at cycle 35 (without crack) and at cycle 200 (with crack).

Figur 12 – Spännings-töjnings loop för test tmf3904 vid cykel 35 (utan spricka) och cykel 200 (med spricka)

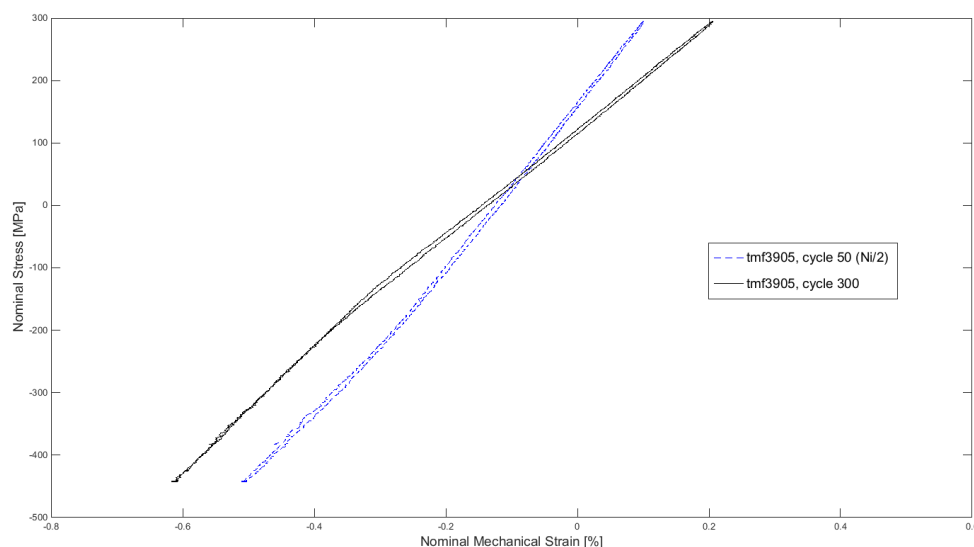


Figure 13 – Stress-strain loop from test tmf3905 at cycle 50 (without crack) and at cycle 300 (with crack).

Figur 13 – Spännings-töjnings loop för test tmf3905 vid cykel 50 (utan spricka) och cykel 300 (med spricka)

3.7 CRACK LENGTH/COMPLIANCE CORRELATION

As the crack propagates the uncracked cross-sectional area of the specimen decreases and as a consequence the stiffness of the specimen also decreases. The compliance, which is the inverse of stiffness, thus must increase when the crack length increases. The relationship between the compliance of the specimen and the crack length is shown in Figure 14. In order to obtain a relationship, which is independent of the temperature cycle and the uncracked compliance of the specific specimen, the compliance is normalized by the uncracked compliance in the TMF cycles prior to crack initiation. The dashed curve is a logarithmic expression which has been graphically fitted to the data. This logarithmic expression was used to plot crack length vs cycle number (see Figure 15). The average crack growth rates from 1 mm crack length to 2 mm crack length in the different specimens are compared in Table 3. The difference in crack growth rate between the two Finspång tests (tmf3904 and tmf3905) is approximately a factor of 2.

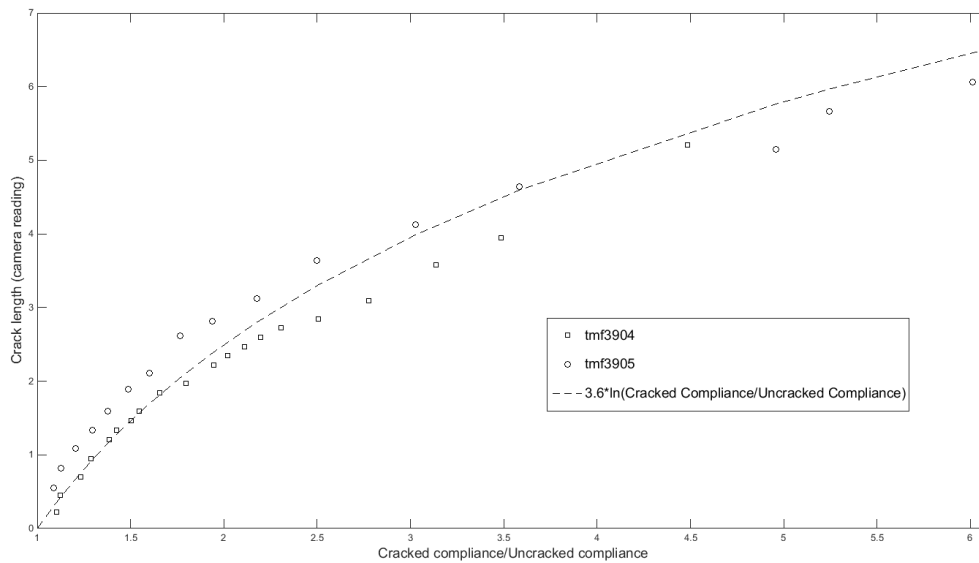


Figure 14 – Optically measured crack length vs normalized compliance and logarithmic curve fitted to the data.

Figur 14 – Optisk uppmätt spricklängd som funktion av komplians och en logaritmisk kurvanpassning till data.

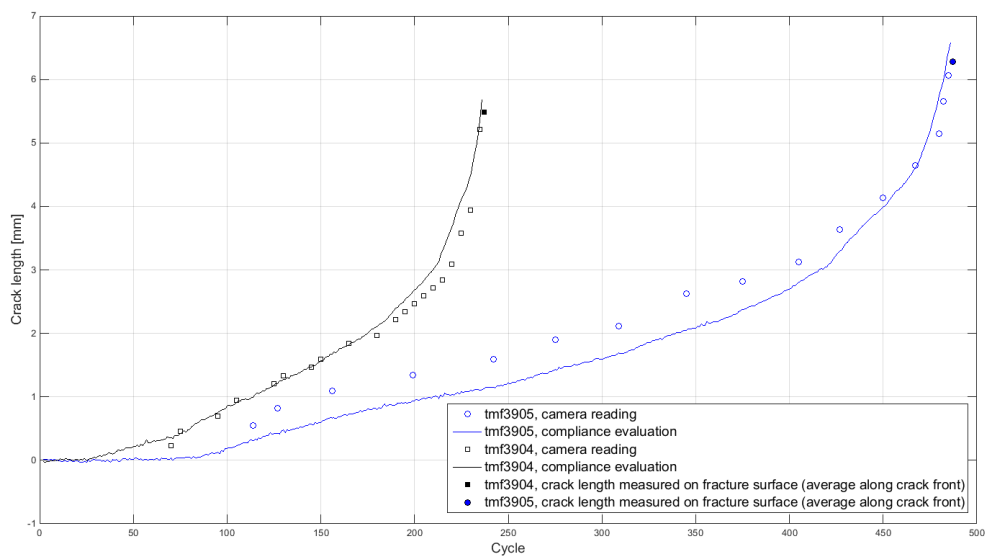


Figure 15 – Crack length vs cycle number. Camera readings compared with compliance evaluation. Also included is the final crack length measured on the fracture surface.

Figur 15 – Spricklängden som funktion av antal cykler. Optiska mätningar jämfört med kompliansutvärdering. Dessutom ingår det slutliga spricklängden mätt på brottytan.

Table 3 – Comparison of crack growth rates

Tabell 3 – Jämförelse av spricktillväxthastigheter.

	Average crack growth rate from 1mm to 2mm [mm/cycle]	
	Optical measurement	Compliance evaluation
tmf3904	0,014	0,016
tmf3905	0,0066	0,0077
LiU_VF2	0,015	0,019

LiU_VF3	0,0014	0,0021
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4 Discussion

4.1 CRACK LENGTH MEASUREMENT

In the present testing the crack length was measured optically from one side of the specimen. The fracture surface examination revealed that the final crack length varied through the thickness of the specimen. However, the difference between the final crack length measured optically on the side of the specimen and the average crack length along the final crack front was only 5% for tests tmf3904 and tmf3905. No correction for the crack front curvature was made. It is likely that the crack front curvature has a larger influence at shorter crack lengths where variation in crack length through the thickness of the specimen is larger compared to the total crack length. Changes in the crack front curvature throughout the test may also have a significant influence of the shape of the crack length vs cycles curve. The crack length is not only determined optically but also by evaluating the change in compliance of the specimen with the number of cycles (see Figure 15). The compliance increase provides an estimate of the decrease of the load bearing area of the specimen and thereby a measure of the crack area or average crack-length. In other words the crack length evaluated by the compliance method is insensitive to crack front curvature. Therefore the evaluation of crack growth rate should preferably be based on the compliance evaluation, calibrated by optical measurements and fracture surface examination. Heat tinting of the fracture surface at intermediate crack lengths could provide valuable information on the evolution of the crack front shape and improve the compliance vs crack length calibration curve. In the present work, no heat tinting was done and the compliance vs crack length calibration curve was only based on camera readings during the test and fracture surface examination (see Figure 14).

4.2 DRIVING FORCE FOR CRACK GROWTH

When choosing the specimen geometry and TMF cycle for the present testing, a strong emphasis was put on achieving testing conditions which were as representative as possible for a gas turbine component. This led to rather complex stress state in the specimen, with a crack which is growing through a residual stress field created by inelastic deformation during the crack initiation stage of the test. With an R-ratio of -1,5 the crack is closed during quite a large part of the cycle and therefore the effective stress intensity factor range is substantially lower than the nominal stress intensity factor range. In order to determine the effective stress intensity factor range, the force interval during which the crack is open would have to be determined. This has not been done in the present work and therefore the crack driving force is unknown. For a better understanding of the crack driving force it would be of interest to measure the strain field of the entire specimen gauge section throughout the test and not just the average strain across the extensometer gauge length as in the present testing. The possibility of using Digital Image Correlation (DIC) for such strain field measurements should be investigated.

4.3 INFLUENCE OF MICROSTRUCTURE

The material of the present testing had a large grain size, in the order of 1mm, which means that there are only a few grains through the thickness (3mm) of the specimen. Each grain in itself has highly anisotropic mechanical properties, which means that the orientation of the grain with regard to the loading direction will have a large influence on the crack growth rate as well as the preferred local crack growth direction (see Figure 7). This means that different specimens will display different crack initiation and growth behavior depending on the grain orientations, resulting in scatter of the test results. It should also be noted that due to this grain size effect, the difference between tests performed at the same laboratory is larger than any difference due to differences in the set-up between the two laboratories. Testing on a more fine-grained material would most likely result in smaller material-related scatter. In the present study a coarse-grained cast nickel-base alloy was chosen since this is a class of materials used in many components for which TMF crack growth data is needed. However, this study also shows that a larger amount of tests are probably needed for coarse-grained material in order to account for the large spread in fatigue life.

4.4 COMPARISON WITH STRAIN CONTROLLED TMF CRACK GROWTH

Strain-controlled TMF crack growth testing has been performed at SIT previously, using the same test setup and specimen geometry. The material of the strain controlled tests was IN792, originating from a different supplier than the material of the present round-robin testing. One of the strain-controlled tests (tmf0206) was performed under similar conditions as the round robin testing: 100-750 OP, 5 min dwell at maximum temperature, nominal mechanical strain range: 0,7%, strain ratio: $-\infty$. The crack growth behavior of this test is compared with the present round-robin testing in Figure 16. It seems that the same testing method can be successfully applied to both strain controlled TMF crack growth testing and force controlled crack TMF growth testing.

The stress intensity factor range ΔK , which is the crack driving force, depends on the nominal stress range (i.e. the force range) and the crack length. In a force-controlled test, the force range is constant and ΔK must increase as the crack becomes longer and the crack growth rate would then be expected to increase. However, in the strain-controlled tests, the force range will decrease as the crack becomes longer (as the stiffness of the specimen will decrease with increasing crack length) and as a consequence the stress intensity factor range ΔK can actually also decrease and the crack growth rate can decrease with increasing crack length. Furthermore, for a strain-controlled test, only a limited interval of stress intensity factor range is generally investigated. In the force controlled case the stress intensity factor range continues to increase with increasing crack length all the way to specimen failure. This difference actually highlights the main pro and cons with the two test methods. The strain-controlled test is probably closer to component conditions but only a limited ΔK interval can be investigated in each test. In the force controlled-test a larger ΔK interval is investigated and more data is gained but the test condition is less "component like".

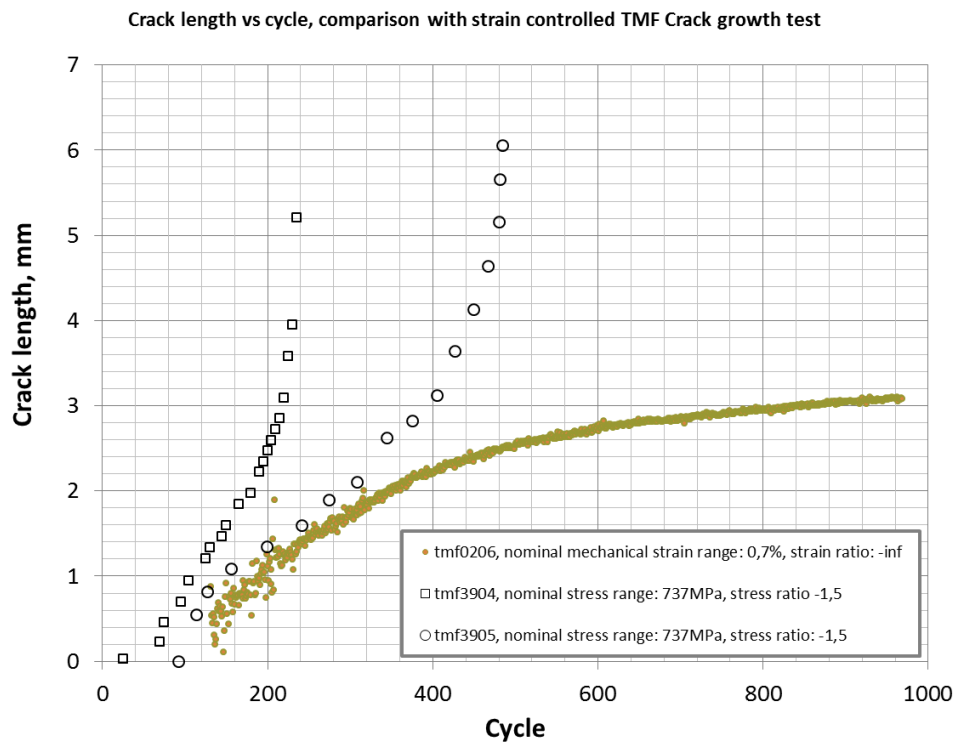


Figure 16 – Crack length vs cycle number of the present round robin tests compared with a strain controlled TMF crack growth test previously performed in the Finspång lab.

Figur 16 - Spricklängd som funktion av antal cykel. Prov från den aktuella provningen jämförts med ett töjningsstyrt TMF spricktillväxt prov som utförts i Finspång vid en tidigare undersökning.

5 Conclusions

- Round-robin TMF crack growth testing was performed in accordance with a preliminary version of the Code of Practice for force-controlled thermo-mechanical fatigue testing [13], in order to evaluate the scatter of results between two different test labs (Siemens, Finspång and Linköping University).
- The testing method makes it possible to study crack growth under TMF conditions relevant for gas turbine components.
- The testing method is suitable for both strain controlled and force controlled TMF crack growth testing.
- No significant scatter between the two labs was found.
- Significant scatter was found between tests performed under identical test conditions in the same lab. This was probably due to the coarse grain size of the tested material.

6 Recommendations and further work

- The present work has given some indication as to the scatter of TMF crack growth testing performed at different laboratories. However, the number of tests was limited and further testing is therefore necessary for a statistical evaluation. Testing should preferably be performed both on fine grained material and coarse grained material in order to evaluate the influence of grain size on the scatter of the test results.
- The possibilities of using digital image correlation (DIC) to measure the strain field in the specimen throughout the test should be explored.
- Heat tinting of the fracture surface in future tests may provide valuable information regarding the relationship between crack length and the change in compliance of the specimen. Heat tinting may also serve to improve the understanding of how the shape of the crack front changes during the test.

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8 Appendix

8.1 TEST SPECIMEN GEOMETRY

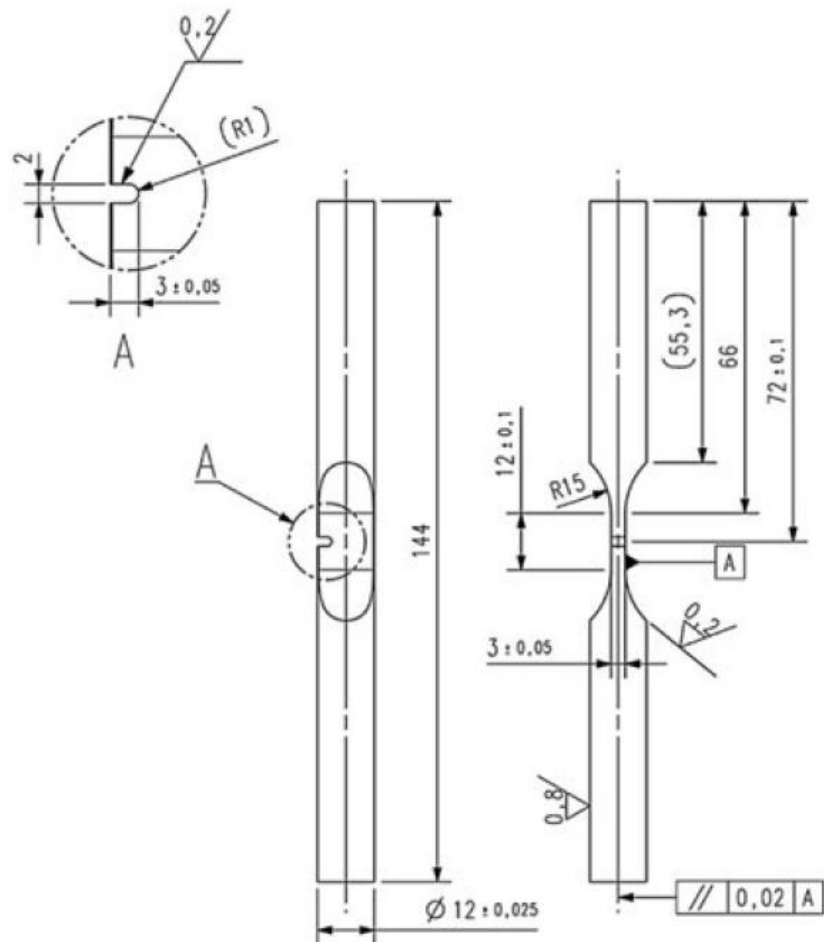
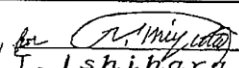


Figure 17 – Geometry of the test specimen used for TMF-CG testing.

Figur 17 – Provstavsgeometri för TMF spricktillväxtprovning.

8.2 MATERIAL CERTIFICATE

IHI Castings Co., Ltd. 1-2-1 Onodai, Soma-shi, Fukushima-ken 976-0001 JAPAN Tel: 0244-37-3785 Fax: 0244-37-3870		(1/2) CERTIFICATE No. 14-E-S044 DATE 28th Feb. 2014											
MATERIAL CERTIFICATE													
PURCHASER'S NAME	SIEMENS SWEDEN	PURCHASER'S ORDER NUMBER	7000268939-20 7000268939-50										
PART IDENT NUMBER	—	PART NAME	IN 792 Test Bar (165L × φ 25mm)										
DRAWING NUMBER	—	MATERIAL SPEC. NUMBER	638054										
CONDITION SHIPPED	Note 1)	MASTER HEAT NUMBER	133618										
MANUFACTURING LOT NUMBER	reference to page 2/2	PART SERIAL NUMBER	—										
LOT SIZE	94	QUANTITY SHIPPED	94										
CHEMICAL ANALYSIS (MASTER INGOT)													
ELEMENT	C	Si	Mn	P	S	Cr	Ni	Mo	W	Co	Hf	Ti	Al
SPEC. Max.	0.10	0.20	0.15	0.015	0.005	13.0	Bal.	2.15	4.50	9.50	0.60	4.20	3.60
RANGE Min.	0.06					12.0		1.65	3.85	8.50		3.75	3.15
CHECKED	0.08	0.01	0.01	<0.002	0.001	12.44	Bal.	1.89	3.99	8.82	0.52	4.02	3.46
ELEMENT	Ti+Al	Nb	Te	B	Zr	Fe	Pb	Bi	Ag	Se	Mg	Cu	Nv
SPEC. Max.	7.70	0.50	4.50	0.02	0.025	0.50	2ppm	0.5ppm	5ppm	3ppm	60ppm	0.05	2.36
RANGE Min.	7.20		3.85	0.01	0.010								
CHECKED	7.48	0.02	4.22	0.016	0.015	0.10	<0.5	<0.1	<1	<1	6	<0.01	2.31
MECHANICAL TESTS													
TENSILE TESTS													
CHARACTERISTICS	SPEC.	RESULTS	SPEC.	RESULTS									
TEST TEMP. (°C)	R. T.	R. T.	650	650									
Y. S. [0.2%] (MPa)	850Min.	975	750Min.	892.5									
T. S. (MPa)	1020Min.	1240	1020Min.	1288.0									
ELONG. (%)	4Min.	8.0	4Min.	15.5									
R. A. (%)	5Min.	9.5	5Min.	15.5									
THE OTHER INSPECTION													
CHARACT.	SPEC.	DECISION	REMARKS	CHARACT.	SPEC.	DECISION	REMARKS						
VISUAL INSPECTION	DL 1641-35	ACCEPT		RADIOGRAPHIC INSPECTION	DL 1641-35	ACCEPT	Note 2)						
DIMENSIONAL INSPECTION	165LX φ 25mm	ACCEPT		GRAIN SIZE INSPECTION	DL 1641-35	ACCEPT							
F. P. I.	DL 1641-35	ACCEPT		POROSITY INSPECTION	DL 1641-35	ACCEPT							
NOTE 1) HIP : 1185-1205°C (100-200MPa) × 2-4hrs → G. F. C. SOLUTION : 1121°C × 2hrs → G. F. C. AGEING : 845°C × 24hrs → G. F. C. 2) X-Ray film No. : USXE-0171~0176													
This is certify that all work done was in accordance with, and meets the requirements of specification called for in this purchase order and or referenced drawings.				by  T. Ishihara QUALITY CONTROL MANAGER									

DEVELOPMENT OF TESTING METHOD FOR THE EVALUATION OF CYCLIC OPERATION

Cykliska driftförhållanden ökar påfrestningarna på material i kraftvärmeanläggningar. Ett steg mot att standardisera en provmetod för termomekanisk utmattningsprovning (TMF) där både last och temperatur varierar cykliskt är att utvärdera hur effektiv en föreslagen metod är.

Projektet drar följande slutsatser:

- Provningsmetoden gör det möjligt att studera spricktillväxt under TMF förhållanden, relevanta för gasturbinkomponenter.
- Provningsmetoden är lämplig för kraftstyrd såväl som töjningsstyrd TMF spricktillväxtprovning.
- Ingen signifikant spridning mellan de två labben hittades.
- Stor spridning konstaterades mellan tester utförda i samma labb under identiska testförhållanden. Orsaken till detta är antagligen den stora kornstorleken i materialet.

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