Comparing Crack Growth Testing and Simulation Results Under Thermo-Mechanical Fatigue Conditions

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Abstract As the need for improved prediction of component life and development of new materials for use at high temperatures becomes more demanding, there is increasing requirement for a detailed understanding of thermo-mechanical fatigue (TMF) behaviour including the combined effects of fatigue and dwell on the overall crack growth rates under such conditions.
To generate experimental TMF crack growth test data, a conventional servo-electric load frame, used in combination with a radiant lamp furnace, has been employed. The method for the measurement of crack growth under the TMF load cycle is also described. The performance of the experimental method is demonstrated with trials on an advanced nickel-based superalloy, RR1000.
To reduce future testing requirements, simulation via the finite element method provides a means for crack growth prediction. This clearly requires validation with real test data at the outset. A method is described whereby separate fatigue and time dependent growth data can be combined and applied to TMF load cycles ranging from simple test cycles to full flight cycles. Results of this method used in conjunction with finite element based crack growth simulation are compared with experimental data, using the test method described above, from several TMF load cycles for RR1000 specimens.

Keywords thermo-mechanical fatigue, crack growth rates, finite element analysis, crack growth simulation

1. Introduction

The ultimate objective of simulating thermo-mechanical testing by analysis is to develop a method which can be applied to crack growth prediction during complex loading cycles. One particular application is for aerospace engine flight cycles. Such flight cycles consist of out-of-phase stress and temperature time histories having duration of order of several hours. An example is shown in Figure 1.

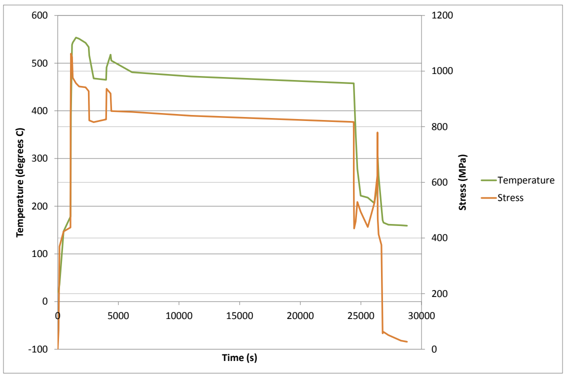

Figure 1. Typical stress and temperature time histories

For a crack located within a component experiencing such flight cycles, each point along the crack front will experience a slightly different stress and temperature time history. The salient features are:

- Peak temperature and stress occur at the end of the climb phase with the temperature

reaching a maximum at a different time to the stress.
- The cruise condition has a relatively uniform stress and temperature.
- Additional local fluctuations in stress and temperature may occur depending upon manoeuvres carried out during the flight

2. Development of the Test Facility

In the work presented here a new fatigue crack growth test facility has been developed and this is briefly described. There are three essential elements in the provision of thermo-mechanical fatigue crack growth testing:

1. an adaptable and stable mechanical load application system
2. a responsive heating system
3. a suitable crack monitoring system

A standard servo-electric test frame was used for the load application system, because of the long term load stability and previous experience with this equipment. Appropriate calibration of the load cell [1] was undertaken, along with checking the load-train alignment [2].

Figure 2. The general test piece arrangement within the radiant lamp furnace

A radiant lamp furnace was decided to be the most appropriate heating system for this application (rather than induction/RF heating) because of the need to obtain a uniform temperature profile around the cracked test piece. Thus a 12kW furnace, with 12 lamps (~250 mm long) vertically aligned around the test piece (Figure 2), was installed on the test frame.

A reasonably conventional crack length monitoring approach was used - applying electrical DC potential difference measurements and then cross-calibrated against the physical crack length. The relatively simple thermal cycles required initially (Figure 3) were consistent with this method. A constant current (DC – 20A) source was used.

3. Test Technique Development

There is currently no standard methodology for the measurement of fatigue crack growth rates under TMF conditions. However, a proprietary test method [3], based upon an ASTM standard [4], but using a square section corner crack test piece; has formed the basis of the new test technique. The second part of the test technique that is required here is the application of the desired thermal cycle (and mechanical load). A related code-of-practice [5] for strain controlled TMF testing has been used to standardise the method of calibrating the thermal cycle applied to the test piece.

Bespoke control software was also developed to perform and record these tests.

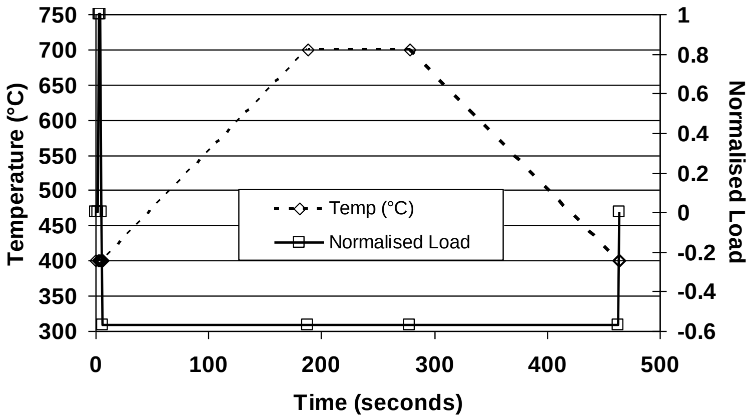

Figure 3. The desired load (normalised) and temperature cycle for the measurement of crack growth rate

3.1 Temperature Measurement

Dynamic temperature measurement during TMF, when using radiant lamp furnaces, requires a reliable experimental method and standard mineral insulated N type thermocouples have been used but these require careful control of shielding from direct radiant light on the thermocouple tip.

Spot-welded N type thermocouples (i.e. thermocouple wires spot-welded onto the specimen surface ~1 mm apart, as recommended in [5] and location shown in Figure 4) have been used to calibrate the thermal behaviour of the test. These are thought to provide the most accurate test piece temperature but cannot be used during the test because of the risk of inducing cracks.

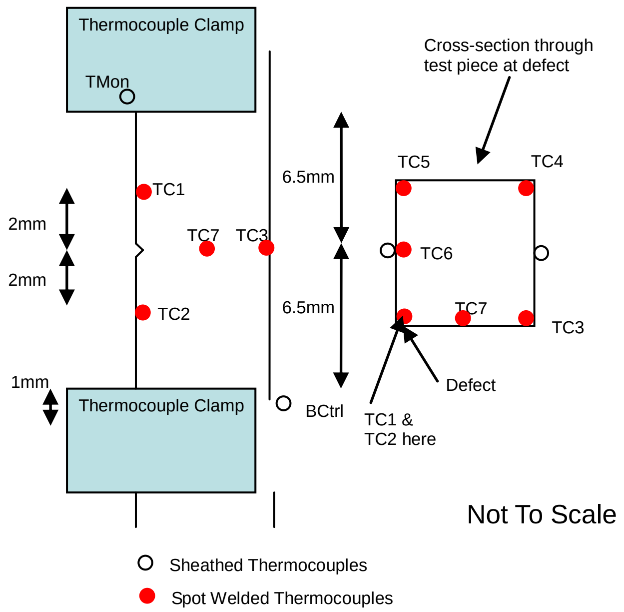

Figure 4. Schematic of the placement of the thermocouples for the TMF thermal trials

3.2 Thermal Cycle Calibration

Prior to TMF testing, there were two calibration trials required:

- to demonstrate that the temperature variation (gradient) was less than 10^{o}C throughout the desired thermal cycle, using the spot welded thermocouples located as shown in Figure 4.

- to cross-correlate the test piece temperature, measured by a spot-welded thermocouple (e.g. TC7 in Figure 4) with the controlling sheathed thermocouples and ensure that the thermal and load cycles were correctly applied and synchronised.

3.3 Test Set-Up

The test piece had a square section (7 x 7 mm), with a corner notch introduced into the centre of a 20 mm parallel gauge length. The sheathed thermocouples were attached as shown before and ~63µm diameter Pt wires were then spot-welded to the test piece surface to monitor the PD across the crack. The sample was pre-cracked with load shedding to reduce the stress intensity factor below that of the desired starting stress intensity factor. Once the thermal performance on the two sheathed thermocouples matched that previously observed during the calibration, then it was possible to commence the test.

4. Crack Growth Rate Measurements and Facility Demonstration

To calculate the crack lengths and growth rates it was found that fitting a polynomial to the PD measurements provided the best way to generate reasonable data. A simple linear relationship between the crack length and the PD measurement is assumed for this procedure. The stress intensity factors were calculated using proprietary fits for the “geometry dependent compliance factor” (Y_n) within the basic equation:

$$\Delta K = \Delta\sigma . Y_n . (\pi . a)^{1/2} \quad (1)$$

- where ΔK = change in stress intensity factor, $\Delta\sigma$ = the change in applied stress, Y_n= a geometry dependent compliance factor and a = crack length. Only the tensile portion of the loading was used in the stress intensity factor calculation and hence a maximum stress intensity factor is shown in the plot against the normalised da/dN (Figure 5).

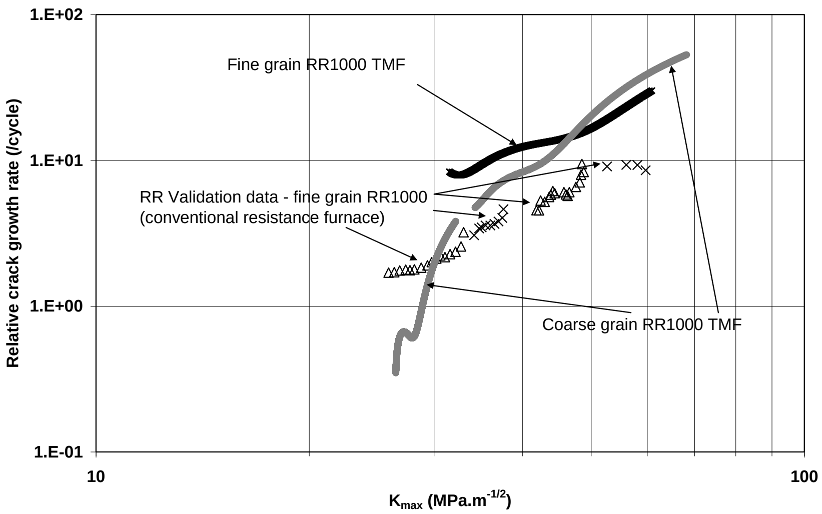

Figure 5. Plot of relative crack growth rate again the maximum stress intensity factor for two microstructural variants of RR1000

The final stage of the facility development was to demonstrate its operation and compare it with existing data obtained using a conventional resistance furnace. This demonstration was undertaken using an advanced nickel base superalloy known as RR1000, used for gas turbine disc applications and manufactured using a powder metallurgy and forging process. These initial trial tests showed reasonable agreement with existing data, although somewhat higher rates were measured with the new facility. Following the initial demonstration, the RR10000 material in a coarse grained condition was also tested and this data is also shown on Figure 5, highlighting the potential benefit from this material, compared with the fine grained variant. All of the crack growth modelling was based upon the coarse grained variant of RR1000 and a range of additional thermal/load cycles were evaluated experimentally and compared with the modelled behaviour below.

5. TMF Crack Growth Simulation Procedure

The approach often used for calculating the combined effect of fatigue and time dependent crack growth is a linear summation through the load cycle of the separate fatigue and time contributions to the overall growth [6-8] to give the effective overall growth rate for a single load cycle:

$$\left(\frac{da}{dN}\right)_{total} = \left(\frac{da}{dN}\right)_{fatigue} + \left(\frac{da}{dN}\right)_{time} \tag{2}$$

The way in which this expression is used in the literature often relates to simple repeated loading waveforms with a single cyclic event e.g. ramp-up, hold time, and ramp-down. [9] presents a summary of approaches used by several authors. However, for a general and complex loading cycle such as the one in Figure 1, the load history and resulting stress intensity factors are defined by a series of data points which do not conform to a simple waveform. It is then necessary to generalize Eq. (2) to account for major and minor fatigue cycle effects within the overall load cycle as well as the time history of load variation. This generalization can be written as:

$$\left(\frac{da}{dN}\right)_{total} = \sum_{1}^{fatigue cycles} \left(\frac{da}{dn}\right) + \int_{load\,cycle} \left(\frac{da}{dt}\right) dt \tag{3}$$

where *da/dn* is the growth rate due to an individual fatigue cycle within the total load cycle and *da/dt* is the instantaneous time dependent growth rate at some time t within the total load cycle. Summation of Eq. (3) over multiple load cycles provides the accumulated crack growth history:

$$da = \sum_{1}^{load\,cycles} \left[\left(\frac{da}{dN}\right)_{total} \right] \tag{4}$$

In order to carry out this summation, two sets of data must be provided to an appropriate integration scheme: (1) the time history of stress intensity factor and temperature for points on the crack front; (2) the crack growth laws for calculating instantaneous da/dn and da/dt values.

5.1 Integration scheme

For simple 2D geometries where a handbook K solution is available, it is possible to obtain K vs t with a combination of a spreadsheet and results from finite element analyses of an uncracked component. This procedure is used in-house at Rolls-Royce and has been used to validate the finite element based implementation described below [10]. For general cases with an arbitrary 3D crack front, the finite element method can be used to provide the K solution as a function of time. In using this approach, a finite element model containing a particular crack size is analysed through a full load cycle. The results of the analysis can be used to provide a K vs time history for each crack front node. The time histories can then be cycle counted to extract discrete cyclic events. A typical (normalized) K time history and the cyclic events associated with it are shown in Figure 6.

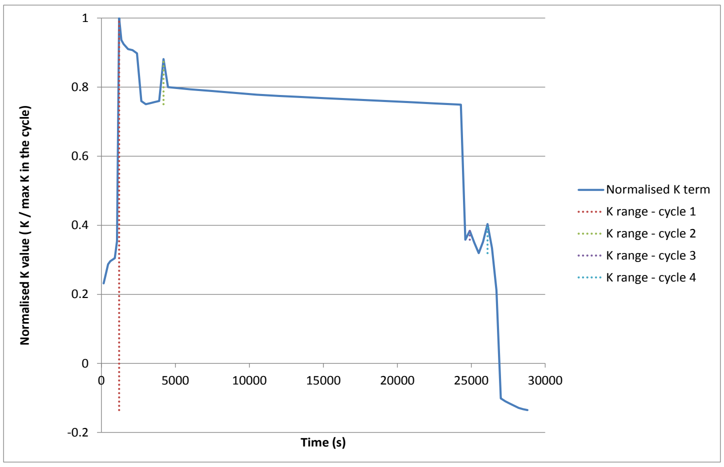

Figure 6. Normalised K time history and cyclic events

The calculation of crack growth for a single crack front position through one load cycles using Eqn. 2 and Eqn. 3 then proceeds by integrating the sequence of K vs t segments with discrete da/dn effects added as the fatigue cycles occur. The procedure of extracting a full K vs t time history from a finite element analysis and carrying out a combined fatigue and time integration has been implemented for a general 3D crack in version 7.8 of Zencrack [11]. A number of aspects of the integration process cannot be described fully here but are mentioned briefly:

- The finite element analysis provides K vs t data for one crack size and one load cycle. The integration scheme modifies the basic K vs t history to account for changes due to the increased crack size as the crack grows. When the mesh is updated to a new crack position and submitted for a new finite element analysis, a new baseline K vs t solution is generated.
- The definition of cyclic events as a result of the cycle counting process will, in general, lead to different temperatures at minimum and maximum conditions for a fatigue cycle. When calculating da/dn for the cycle, an appropriate temperature assumption must be made.
- Mode mixity and local changes of growth direction through the load cycle are possible.

Two examples of integration output from this process are shown in Figure 7. The da/dt contributions are only non-zero when the temperature is above the threshold temperature defined for the da/dt growth law. The first (and largest) cyclic event produces a visible instantaneous (vertical segment) on the da plot. Cyclic events 2, 3 and 4 have much lower da/dn values and the vertical segment da contributions from them are too small to be seen on the scale of this figure.

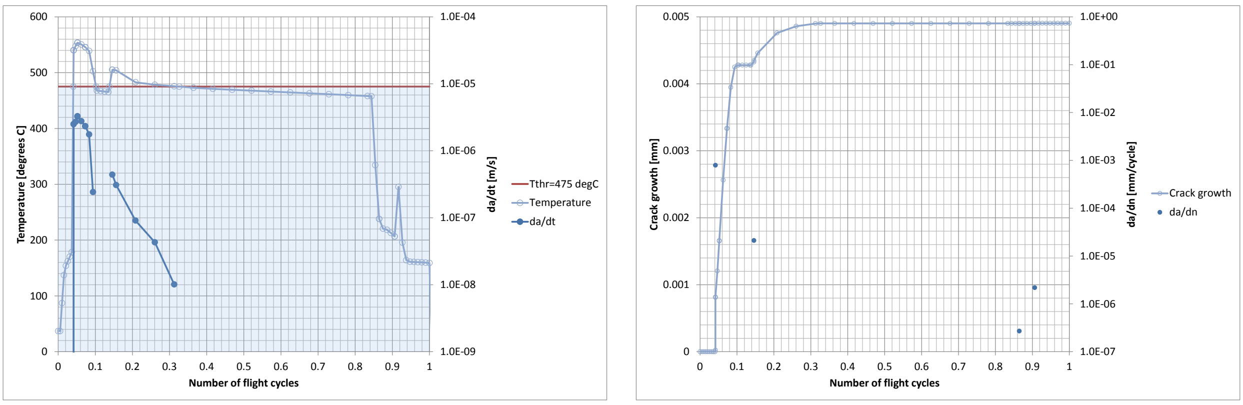

Figure 7. T, da/dt, da/dn and da through integration of a load cycle

5.2 Crack Growth Laws

The practical implementation of a combined fatigue and time dependent crack growth integration scheme using a linear summation model requires use of meaningful crack growth data. Baseline fatigue crack growth data is available in many forms but the combined use with time dependent data is more challenging. The approach used here is the use of isothermal testing to derive temperature dependent growth laws which can be applied for non-isothermal cases. Results for the simulation of the non-isothermal tests using this isothermally derived data can then be compared to the actual non-isothermal TMF test results.

A number of authors have reported the use of a rate dependent Arrhenius law for addressing temperature dependency in time dependent crack growth data [12,13]. This type of law has been implemented in Zencrack as a “COMET” crack growth law [10]. This equation (Eq. (5)) takes account of the synergetic interaction of **C**reep, **O**xidation, **M**icrostructure, **E**nvironment and **T**emperature through the definition of the D coefficient. A and B are temperature independent material constants, n is a temperature dependent material parameter and T_C is the temperature in °C. A full description of the law and a process for determining A and B is given in [10].

$$\frac{da}{dt} = D\left(K\right)^n \quad , \quad D = Ae^{\left(\frac{-B}{Tc+273.15}\right)} \tag{5}$$

6. Application of Simulation Procedure to TMF Test Specimens

The geometry for the test specimen is shown in Figure 8. This figure also shows an initial cracked mesh and a typical mesh with an advanced crack position. The specimen contains a central 7mm square cross-section into which the starter crack is located (at the mid-length position). The finite element model is a half symmetry model with the crack introduced at the symmetry plane. An uncracked Abaqus model containing C3D20 elements is created and the crack is introduced by Zencrack. The crack tip is modelled with collapsed crack front elements having quarter point nodes. The load is applied at a single point and distributed onto the cylindrical outer surface of the end of the model using a distributed coupling constraint. The load and temperature time histories are defined using *AMPLITUDE definitions. For these analyses the temperature changes are deemed to be instantaneous throughout the body (i.e. the temperature is uniform through the model at any time instant). The Abaqus *CONTOUR INTEGRAL option is used to calculate energy release rates along the crack front through the time history. The analysis uses temperature dependent Young’s modulus and Poisson ratio for coarse grained RR1000. Temperature dependent Walker coefficients are used for the fatigue law and a COMET law is used for the time dependent growth law. The cracked model is analysed using Abaqus and the full time history results are extracted and processed by Zencrack using the procedure described in section 5. The crack growth is calculated and the mesh updated. This process repeats to simulate crack growth in the specimen.

Several TMF load cycles were defined for testing and simulation. The temperature and normalized load variations for the cycles designated 1, 3, 4a, 4b, 4c and 4d are shown in Figure 9. Due to project time constraints not all tests were completed. Simulation results in section 7 are presented for all load cycles with test results available for cycle 1, 3 and 4d. A 400°C isothermal load cycle using the load variation of cycle 3 is also presented in the results.

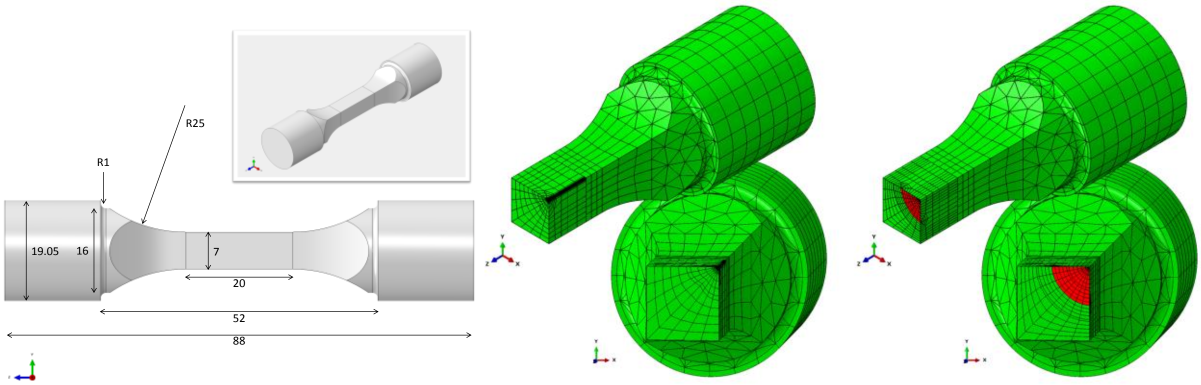

Figure 8. Geometry and typical meshes for initial (left) and advanced (right) crack positions

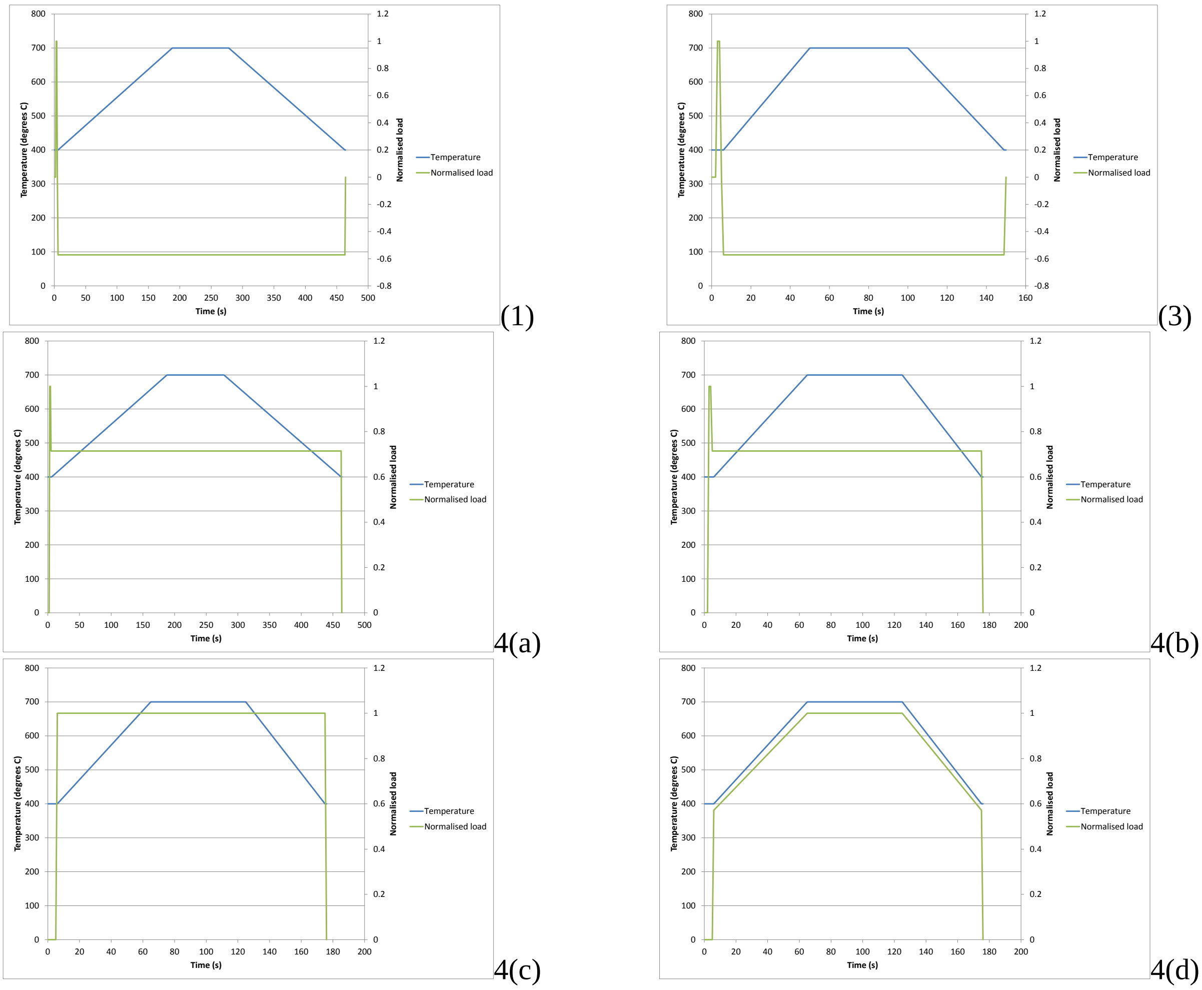

Figure 9. Definition of TMF cycle 1, 3, 4a, 4b, 4c and 4d

7. Simulation Results Compared With Test Results

The test and simulation results are presented as relative da/dN against K_{max} in Figure 10 and Figure 11. The da/dN value is total effective da/dN per TMF cycle. The K_{max} value is the maximum K for the TMF load cycle.

The load and temperature variations in cycles 1 and 3 are the same – the difference being that cycle 1 has duration of 464s compared to 300s for cycle 3. For both these load cycles, the applied load is compressive when the temperature is above the threshold for time dependent crack growth to become active i.e. the value of da/dt is always zero in the simulation. Therefore, simulation results for cycles 1 and 3 are effectively dependent only upon the fatigue cycle which occurs during the load cycle. This fatigue cycle is the same for cycles 1 and 3 and so the simulation results for cycles 1 and 3 are identical in Figure 10. The test results for these two cycles are also similar and show good agreement with the simulation. Cycle 4d presents a more interesting case as the temperature is above the threshold for time dependent growth for about 80% of the cycle duration and during this time the load is either increasing, at maximum hold value or decreasing. Therefore time dependent growth can be expected.

Simulation results for all cycles are shown in Figure 11. On this scale, cycle 4c appears to have the same result as cycle 4d. However, the cycle 4c result is slightly higher. This is the expected outcome since, although the temperature histories for the cycles are the same, cycle 4c has a longer period at maximum load than cycle 4d and hence more time dependent growth is expected. The additional time dependent growth is however relatively small as the extra time at maximum load is in the region close to the temperature threshold for time dependent growth (i.e. da/dt will be small even if K is high). The result for cycle 4a falls above cycle 4b. Again this is not an unexpected result: cycle 4a has a longer period than 4b with extra time spent accruing time dependent growth at high temperature. Cycle 4a falls below 4c. The maximum load level for 4a is lower than for cycle 4c but the period is greater. The trade-off between high load and longer duration in this case has the result that the high load short duration of cycle 4c produces a higher overall growth rate (i.e. higher da/dt values).

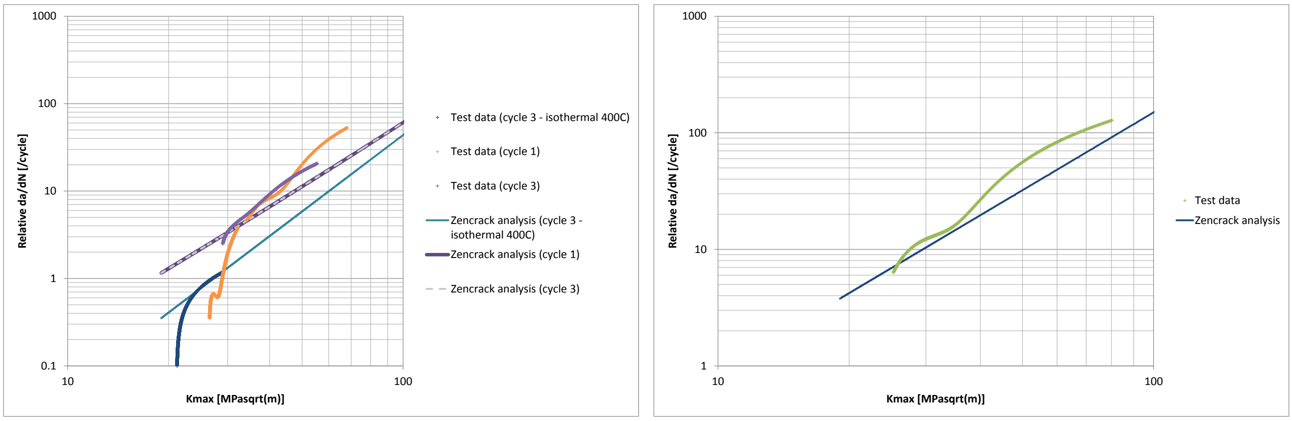

Figure 10. Test and simulation results for cycles 1 and 3 (left) and 4d (right)

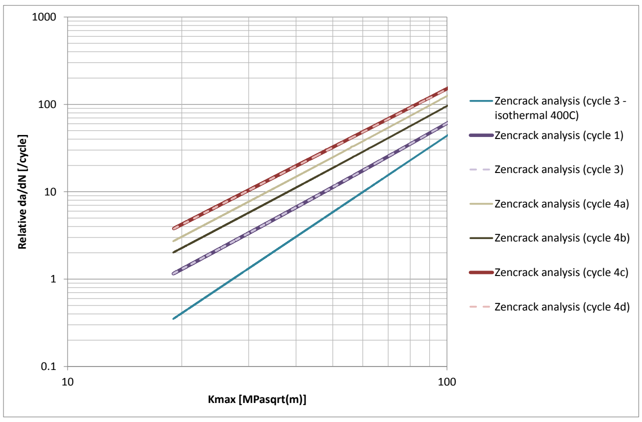

Figure 11. Simulation results for cycles 1, 3, 4a, 4b, 4c and 4d

8. Summary

Development of a TMF test facility has been demonstrated and a simulation technique has been developed to predict TMF crack growth in test specimens based on growth laws determined from isothermal tests. The simulation technique is a general one which can be applied to complex loading scenarios applied to real components. Only a small number of TMF test results are so far available but initial comparisons between test and simulation are encouraging. Additional test results and simulation comparisons are required to further verify the simulation approach.

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