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

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1. INTRODUCTION

Thermo-mechanical fatigue (TMF) test method was developed in the early 1970s to simulate, in the laboratory, loading behaviour of materials under conditions experienced in their service environment, such as turbine blades and vanes. The TMF test belongs to one of the most complex mechanical testing methods that can be performed in the laboratory. TMF is cyclic damage induced under varying thermal and mechanical loadings. When a test piece is subjected to temperature and mechanical strain phasing it is called strain controlled TMF. There are two standards for strain controlled TMF, the ASTM E2368-10 and the ISO 12111:2011. However, these standards do not allow for feature based geometries where no compensation for free thermal expansion and contraction is required, there is therefore a need for a separate procedure on force or force-controlled TMF testing.

2. SCOPE AND USE

This code of practice (CoP) applies to stress and/or force-controlled thermo-mechanical fatigue (TMF) testing. Both forms of control, force or stress, can be applied according to this CoP, but for convenience this CoP is referred to as “force-controlled thermo-mechanical fatigue”. This CoP describes the equipment, specimen preparation, and presentation of the test results in order to determine TMF properties.

This CoP covers the determination of TMF properties of materials under uniaxial loaded force-controlled conditions. A thermo-mechanical fatigue cycle is defined as specimen tests where both temperature and force amplitude waveform are simultaneously varied and independently controlled over the specimen gauge or test section. A series of such tests allows the relationship between the applied force and the number of cycles to failure to be established.

The specific aim of this document is to provide recommendations and guidance for harmonized procedures for preparing and performing stress-controlled TMF tests using various specimen geometries. The CoP serves only as a guideline for users and does not form any basis for legal liability neither of its authors nor of the TMF-Standard project partners. The purpose of this document is to ensure the compatibility and reproducibility of test results. It does not cover the evaluation or interpretation of results. Health safety issues, associated with the use of this CoP, are solely the responsibility of the user.

The following sections of this CoP are intended to provide the steps to be implemented in sequence, during the process of carrying out force-controlled TMF tests. The experimental ‘road map’ is shown in Figure 1, in the form of a flow diagram.

Force-controlled Thermo-mechanical Fatigue Test Code of Practice

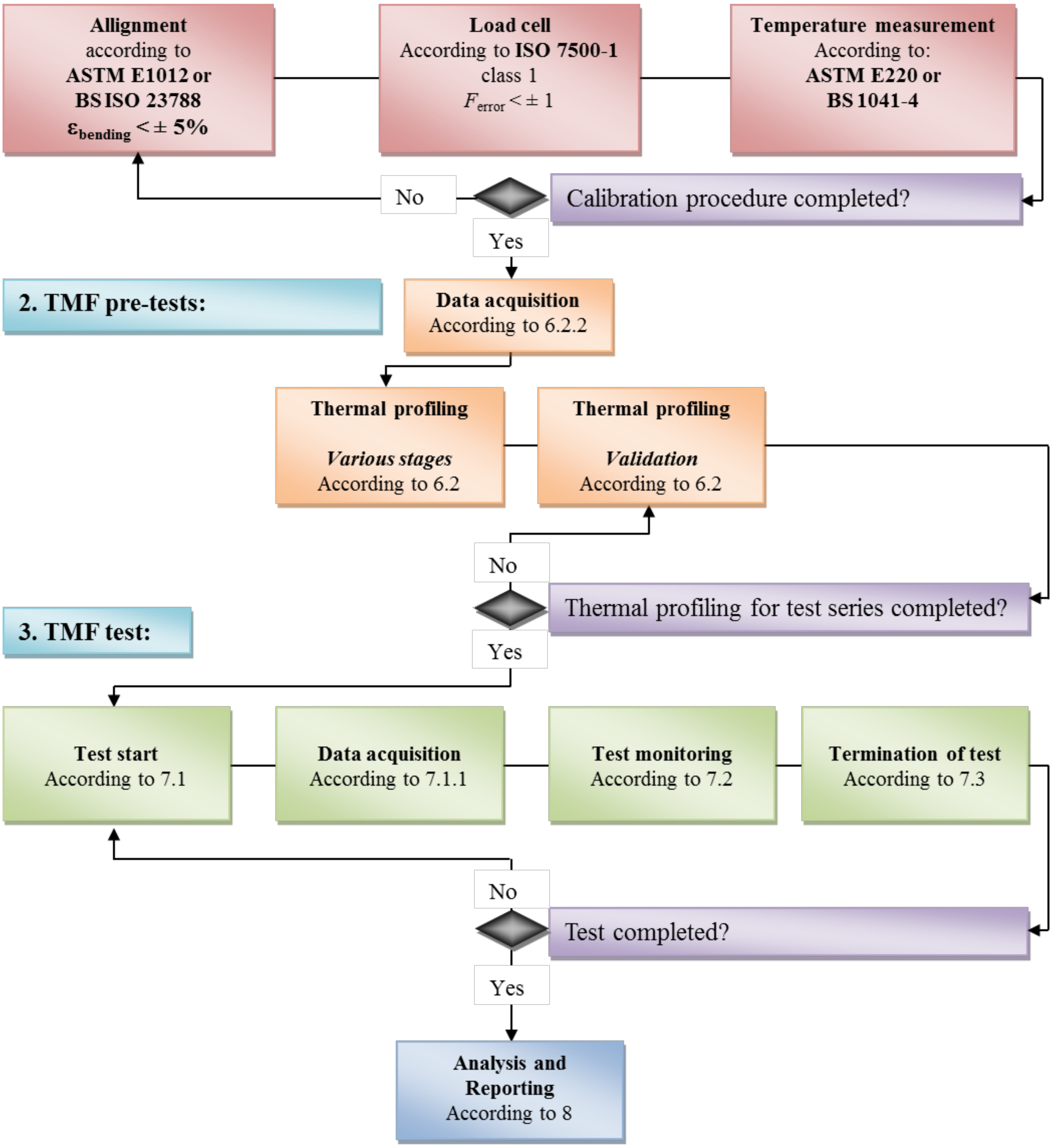


Figure 1: A flow diagram outlining the various steps in undertaking a force-controlled TMF test according to this code of practice[1].

3. NORMATIVE REFERENCES

The following referenced documents are reccommended for the application of this document.

3.1. NATIONAL AND INTERNATIONAL STANDARDS

a) BS ISO 12111:2011 Metallic materials — Fatigue testing — Strain-controlled thermomechanical fatigue testing method.
b) EN ISO 7500-1:2004 Metallic materials - Verification of static uniaxial testing machines - Part 1: Tension/compression testing machines - Verification and calibration of the force-measuring system.
c) ASTM E4 – 13 - Standard Practices for Force Verification of Testing Machines.
d) EN ISO 376:2002 - Metallic materials. Calibration of force-proving instruments used for the verification of uniaxial testing machines.
e) BS ISO 23788 Metallic materials — Verification of the alignment of fatigue testing machines
f) ASTM E1012 – 05 - Standard Practice for Verification of Test Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application.
g) ASTM E220 - 07a - Standard Test Method for Calibration of Thermocouples by Comparison Techniques.
h) BS 1041-4:1994 Temperature measurement: Guide to the selection and use of thermocouples.
i) BS EN 60584-1:1996 Thermocouples — Part 1: Reference tables for thermocouples.
j) AMS 2750D: Aerospace Material Specification. Pyrometry
k) BS EN 60584-3:2008: Thermocouples. Extension and compensating cables. Tolerances and identification system.
l) BS EN 3987:2009 Aerospace series - Test methods for metallic materials - Constant amplitude force-controlled high cycle fatigue testing.

4. DEFINITIONS AND SYMBOLS

Table 1: Definitions and symbols relating to force-controlled TMF testing

Symbol	Units	Parameter	Definition
F	kN	Force	The force applied to the test section. Tensile forces are considered to be positive and compressive forces negative.
F_{max}	kN	Maximum force	The highest algebraic value of force applied
F_{min}	kN	Minimum force	The lowest algebraic value of force applied
Delta F (ΔF)	kN	Force range	The algebraic difference between the maximum and minimum forces. $(F_{max} – F_{min})$
F_a	kN	Force amplitude	Half the algebraic difference between the maximum and minimum forces. $(F_{max} – F_{min})/2$
F_m	kN	Mean force	Half the algebraic sum of the maximum and minimum forces. $(F_{max} + F_{min})/2$
R		Force ratio	The algebraic ratio of the minimum force to the maximum force. See Figure 3 for examples of different force ratios. (F_{min} / F_{max})
R_s		Stress ratio	The ratio of minimum stress to maximum stress during a fatigue cycle. $R_s = \sigma_{min}/\sigma_{max}$, also called force ratio.
$\Delta\sigma$	MPa	Stress range	The arithmetic difference between maximum stress and minimum stress, $\Delta\sigma = \sigma_{max} - \sigma_{min}$
σ	MPa	Stress	The force divided by the nominal cross-sectional area. It is the independent variable in a stress-controlled fatigue test. The nominal cross-sectional area (engineering stress) is that calculated from measurements taken at ambient temperature and no account is taken for the change in section as a result of expansion at elevated temperatures.

σ_N	MPa	Fatigue strength at N cycles	The value of the stress amplitude at a stated stress ratio under which the specimen would have a life of at least N cycles with a stated probability.
N		Number of force cycles	The number of cycles applied.
t	seconds	Time per cycle	The time applied per cycle.
T_{max}	°C	Maximum temperature	The highest algebraic value of temperature applied
T_{min}	°C	Minimum temperature	The lowest algebraic value of temperature applied
N_f		Endurance or fatigue life	The number of cycles to failure (TMF life).
K_t		Theoretical stress concentration factor	The ratio of the notch tip stress to net section stress, calculated in accordance with defined elastic theory, to the nominal section stress. NOTE: Different methods used in determining K_t may lead to variations in reported values.
ϕ	Degrees	Phase angle	The angle between temperature and mechanical force, defined with respect to the temperature as reference variable Note. The phase angle is expressed in degrees. A positive phase angle (0< ϕ <180) means that the maximum of load lags behind the maximum temperature.

5. TEST SET UP

5.1. APPARATUS

5.1.1. Testing machine

The tests shall be carried out on a tension-compression machine designed for a smooth start-up. All test machines are used in conjunction with a computer or controller to control the test and log the data obtained. The test machine shall permit cycling to be carried out between predetermined limits of force to a specified waveform and for $R < 0$ tests there must be no discernible backlash when passing through zero. In order to minimise the risk of buckling of the specimen, the machine should have great lateral rigidity and accurate alignment between the test space support references. The machine force indicator shall be capable of displaying cyclic force maxima and minima for applied waveforms to a resolution consistent with the calibration requirement.

During elevated temperature tests the machine load cell shall be suitably shielded and/or cooled such that it remains within its temperature compensation range.

Machines employing closed loop control systems for force and temperature shall be used.

5.1.2. Testing machine calibration

Machines shall be force calibrated to class 1 (ISO 7500-1).

5.1.3. Cycle counting

The number of cycles applied to the specimen shall be recorded such that for tests lasting less than 10000 cycles, individual cycles can be resolved, while for longer tests the resolution should be better than 0.01 % of indicated life.

5.1.4. Waveform generation and control

The force cycle waveform shall be maintained consistent and is to be applied at a fixed frequency throughout the duration of a test programme. The waveform generator in use shall have repeatability such that the variation in requested force levels between successive cycles is within the calibration tolerance of the test machine as stated in 5.1.2, for the duration of the test.

Terms have been identified relative to the trapezoidal waveforms in Figures 2 and 3. Other waveform shapes may require further parameter definition although nomenclature should be retained where possible. Often, Force-controlled TMF loading waveforms do not follow standard trapezoidal patterns.

The phase angle between temperature and force is defined by the parameter Φ. Typical phase angles to characterize a TMF test are $\Phi = 0°$ which is called “in phase” and $\Phi = 180°$ which is called “out of phase”. Any other phase angle may be possible and permitted.

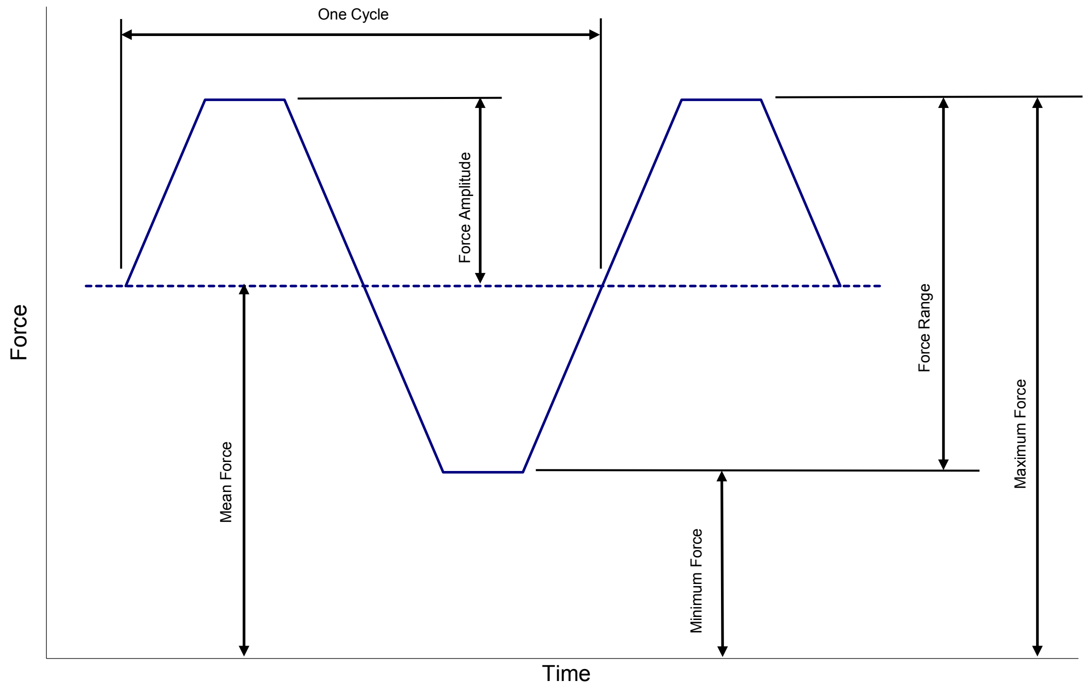


Figure 2 – Fatigue force cycle according to BS EN 2987:2009.

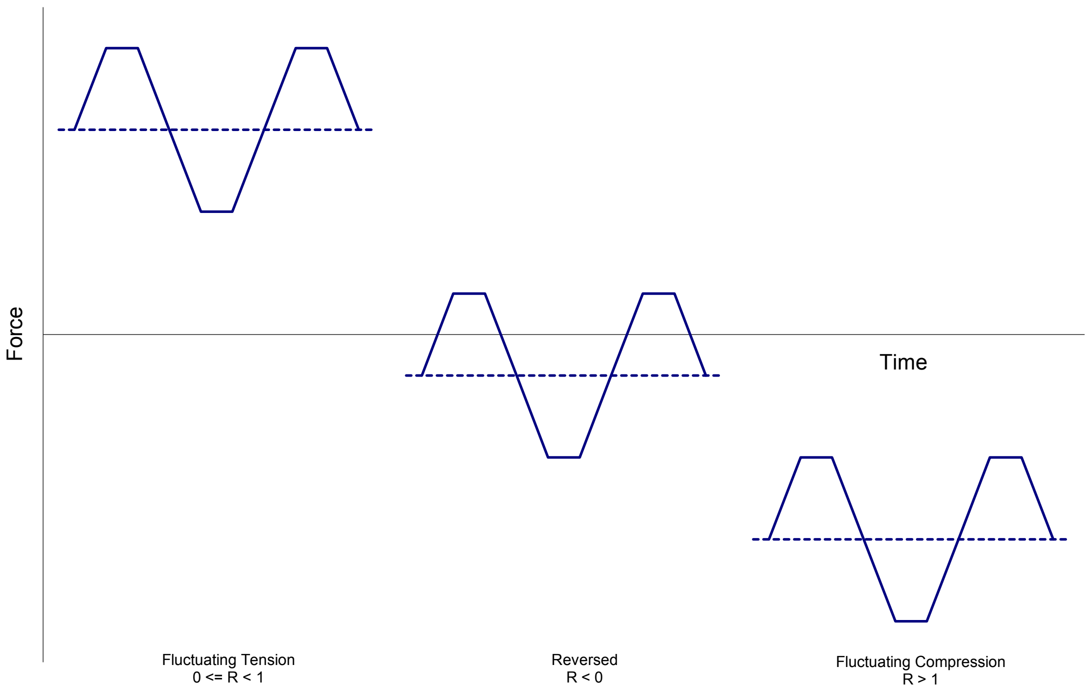


Figure 3 – Varying force ratio according to BS EN 2987:2009.

5.1.5. Force measuring system

The force measuring system, consisting of a load cell, amplifier and display, shall meet the BS EN ISO 7500-1:2004 requirements over the complete range of dynamic forces expected to occur during the TMF test series. The load cell should be rated for fully-reversed tension-compression fatigue testing. Its overload-capacity should be at least twice as high as the forces expected during the test. The load cell shall be temperature compensated and should not have a zero drift and temperature sensitivity variation greater than 0.002% (Full scale / °C). During the test duration the load cell should be maintained within the range of temperature compensation and suitably protected from the heat applied during the test.

5.1.6. Test fixtures

An important consideration for specimen grips and fixtures is that they can be brought into good alignment consistently from test to test. Good alignment is achieved from very careful attention to design details, i.e. specifying the concentricity and parallelism of critical machined parts.

In order to minimise bending strains the gripping system should be capable of alignment such that the major axis of the specimen coincides closely with the force axis throughout each stress cycle and in the case of through zero tests ($R_\varepsilon \leq 0$) must also be free from backlash effects.

NOTE: A parallelism error of less than 0.2 mm/m, and an axial error of less than 0.03 mm for a specimen of less than 300 mm in length, and of less than 0.1 mm for a test space of more than 300 mm in length, should allow the alignment requirements described in 5.1.7 to be achieved. A further benefit can be realised by minimising the number of mechanical interfaces in the load train and the distance between the machine actuator and crosshead.

5.1.7. Alignment verification

Alignment of the load train assembly shall be calibrated in accordance with ASTM E1012 or BS ISO 23788. The maximum bending strain should not exceed Class 5.

5.1.8. Heating device

Testing will generally be conducted in air at elevated temperatures, although there may be a requirement to test in vacuum or in a controlled atmosphere. Where additional apparatus is used such as vacuum chambers etc. it is essential that the full force indicated by the force indicator is being applied to the specimen and is not being diverted through the auxiliary apparatus (e.g. by friction). The heating device employed shall be such that the specimen can be uniformly heated to the specified temperature and maintained for the duration of the test. Radiant lamp furnaces are ideally suited to apply a dynamic temperature change. Induction furnaces are also suitable for rapid temperature change. However, the specimen geometry (thickness or diameter) and the temperature rate can be a limiting factor in their application.

5.1.9. Cooling device

In order to reduce the specimen temperature to the required cooling rate it is recommended to pass compressed air over the surface of the specimen. There are a number of devices which are able to satisfactorily perform this task. For induction systems a range of air jets that can be independently directed at the specimen are adequate for this task. For radiant lamp furnaces the use of an air amplifier is recommended. This is positioned at the top of the furnace and accelerates the compressed air supply through the centre of the furnace to the specimen[2].

5.2. SPECIMENS

5.2.1. Design

Subject to the objectives of the test programme, the type of specimen used will depend on the equipment capacity, the type of equipment and the form in which the material is available. Consideration should be given to the interface to the test machine i.e. the gripping system and any possible test area envelope caused by the furnacing.

The gauge portion of the specimen in a TMF test should, under ideal conditions, represent a volume element of the investigated material contained within the thermally loaded component. Therefore, the geometry of the specimen should not affect the resulting lifetime behaviour, e.g. due to stress inhomogeneities, undesired stress gradients etc. Failure must occur within the gauge section for the test to be considered valid.

5.2.2. Specimen preparation

Utmost importance should be given to the condition of the test piece and method of preparation. Inappropriate methods of preparation, which may be material specific, can greatly bias the test data generated. The effect of contaminants such as cutting fluids and degreasing agents must also be understood. Whilst it may be the purpose of some commercial tests to establish the effect of a particular representative surface finish, standard specimens must have been prepared so that no alteration of the microstructure or the introduction of residual stresses are applied to the material.

Final surface finishing processes should ensure that all machining marks or scratches on the specimen test section or end transitions, and any burrs on notches, be completely eliminated as to the prescribed surface finish of the drawing.

Throughout the test, observe any special handling requirements for the material in question.

5.2.3. Specimen measurement

The specimen dimensions for calculating the cross sectional area shall be measured prior to the test to an accuracy of 0,2% or 0,005mm, whichever is the greatest value. The surface finish must not be jeopardised by this activity.

5.2.4. Circular or rectangular sections

The width or diameter and thickness of the gauge section shall be measured at three positions on the gauge length. The cross sectional area is calculated from the average of these three values. For continuous radius gauge sections the minimum diameter shall be used.

5.2.5. Notched specimens

In the case of rectangular notched sections, the average thickness of the specimen measured at three equidistant positions in the plane of the notch root and the average value of the notch root separation measured at each side of the specimen shall be used in calculating the nominal cross-sectional area. Projection measurement equipment should be used in determining the notch separation. The average notch root radius should also be measured. The accuracy of the value of the K_t should be reported if the tolerance on machining the notch geometry affects the average K_t value by more than ± 5%. If the variability of the K_t value exceeds ± 5% then the notch geometry should be measured and reported with each test piece[2].

5.2.6. Sampling, storage and handling

Specimens must be stored in a manner that protects them from mechanical damage such as scratching, and environmental effects such as extreme humidity, chemical contamination, etc.

Before attaching thermocouples, clean and degrease non-titanium specimens thoroughly. Titanium specimens should be degreased after final finishing and from then on only be handled using cotton gloves. Throughout the testing process, any special handling requirements for the material under investigation should be adhered to. The use of clean cotton gloves is recommended. **Annex A** describes default handling and degreasing requirements.

5.2.7. Specimen insertion

Before loading ensure the load cell has been calibrated, in accordance with BS EN ISO 7500-1:2004 in compression and tension, and aligned in accordance with ASTM E1012 or BS ISO 23788:2012.

The gripping device should transmit the imposed cyclic forces without backlash. Hydraulic gripping is preferred and the number of mechanical interfaces within the load train should be minimized.

The grips should be water cooled in order to allow quick cyclic stabilisation of the longitudinal temperature distribution within the gauge length and to provide stable thermal conditions during the experiment. Therefore, the water cooled gripping device should be designed in a way that allows the heat of the specimen shaft to be carried away by the cooling water as directly as possible. Heat flow from the specimen to the load cell must be avoided.

The method employed to insert the specimen into the test fixture shall not jeopardise the alignment mechanisms, surface finish integrity or material properties. Excessive twisting should be avoided and compressive forces limited to a maximum of 500N or 10% of the intended test maximum force, whichever is smaller.

5.2.8. Threaded specimens

Select the correct type of collet for the test-temperature and ensure all components of the load train are tightened as fully as possible. For example, insert the specimen in the upper grips until finger-tight, and zero the machines load cell output. Move the lower column up until a compressive load of between -0.1 and -0.4kN then tighten the specimen in the lower column and then set the machine to hold the specimen at zero load.

5.2.9. Smooth specimens (non-threaded)

Insert the test piece in the upper grips, tighten the grips by applying hydraulic clamping, and zero the machines load cell output. Move the lower grips up until the test piece is located in the lower grips, and then tighten the grips by applying hydraulic clamping. If the testing machine does not have an 'anti-rotate' clamp then it is recommended to tighten off the lower grip before the upper grip.

5.2.10. Thermocouple attachment

The position of the thermocouples is dependent on the stage of the test programme, i.e. thermal profiling versus actual testing. Examples of the thermocouple layouts for a test programme on a feature based specimen using a radiant lamp furnace can be seen in **Annex B**.

Note: The use of other forms of thermocouples such as ribbon, beaded, etc., is permitted only when temperature control can be maintained over the period of the test within in the designated limits set out in section 6.1.1.

5.2.11. Spot welding of thermocouples

Accurate temperature monitoring is crucial in TMF testing. The best method to control the temperature can be realised by spot welding thermocouples within the gauge section. However, it must be ensured that no crack initiation can occur at the position of the spot welded thermocouple. If this cannot be ensured and alternative control method can be applied by controlling the temperature in the specimen radius. This method is described in **Annex B**. When using the method in **Annex B**, then a second temperature measurement should be applied in the gauge section, but risk of crack initiation should also be avoided. The number of thermocouples needed to control the temperature depends on the heating device used i.e., the number of heating zones of the furnace.

These thermocouples must remain attached to the surface for the entire duration of the test which can be up to approximately three months. The thickness of the thermocouple wires should not exceed 0.3mm, to reduce the effects of cold spots on the specimen. Wrapping the thermocouple wires approximately one quarter around the specimen also reduces the effects of cold spots.

Alternative methods need to be developed for either:

(1) Pyrometry: This method is non-contacting and could be used for the primary means of temperature control, to ensure the correct temperature at the centre of the specimen during the test. Pyrometry does have additional problems such as ensuring correct emissivity etc. and needs to be validated and proven over the length of a typical TMF test.

(2) Thermal imagery: Similarly to pyrometry, the emissivity is the deciding factor in the correct quantitative temperature measurement. It is feasible with the use of accurate high resolution infrared equipment with the necessary frame rate to obtain a thermal profile over the entire gauge length of the specimen. The camera should be calibrated against thermocouple readings focused at the same location. Readings should be performed over a range of temperatures to establish the accuracy of the temperature measurement obtained. Dynamic temperature measurement should be carefully controlled and verified against thermocouple readings.

5.2.12. Heating the Specimen

The specimen shall be heated to the specified temperature at the customer's prescribed heating rate. During heating, the temperature difference across the specimen should not exceed the limits recommended in Section 6.2.1 and should be held at zero force. If in doubt, advice should be sought from the customer, as to the temperature sensitivity of the particular material. Monitoring of the specimen temperature should be carried out using a calibrated temperature logger, which allows a temperature history to be saved and the parameters of the test to be recorded.

Expansion during the heating process must not result in compressive forces being applied to the specimen. The specimen shall therefore be maintained at zero force, throughout the heating process.

5.2.13. Cooling the Specimen

The specimen should be cooled using dissipated air to ensure a uniform temperature across the specimen. The cooling should be controlled to a rate which is in accordance with the test conditions. As with heating, the specimen temperature should be monitored using a calibrated temperature logger and not exceed the limits recommended in Section 6.2.1. Maintaining a constant cooling air flow across the specimen during both heating and cooling phases of the test cycle has shown to stabilise the furnace by forcing it to constantly provide power to the heating element.

6. TEST PREPARATORY ISSUES

6.1. TEMPERATURE MEASUREMENT

The temperature measuring system comprising sensors and readout equipment shall be capable of operating continuously for the duration of the test and have a resolution of at least 0.5°C and an accuracy of ± 1°C. It must be verified over the working temperature range, traceable to National Standards by a documented method. The sensors employed must not affect the surface properties of the material.

6.1.1. Temperature control

The temperature cycle shall remain constant throughout the duration of the test. The importance of maintaining constant temperature profiles through the test are discussed in Reference[3].

Throughout the duration of the test, the temperature(s) indicated by the control sensor, e.g. thermocouple, should not vary by more than the greater of: ± 5 °C or 1 % of the test temperature range from the stabilized value(s) (i.e. following the establishment of dynamic equilibrium) at any given instant in time within the cycle. Throughout the duration of the test, the temperature(s) indicated by the non-control sensor(s) should not vary.

Furthermore, the reproducibility of the position of the thermocouples and of the specimen with respect to the heat source and the specimen fixtures and cooling devices should be kept within a tolerance of ± 0.5 mm. Generally a second temperature measurement system independent of the temperature control equipment should be used to cross-check the reproducibility of the readout of the control temperature measuring device. This is applicable for the set-up phases and for the TMF test.

6.2. VERIFICATION OF TEMPERATURE UNIFORMITY - THERMAL PROFILING

The uniformity of temperature along the gauge section and at the shoulders shall be verified before every series of tests that introduces a new specimen geometry, material or test profile, or in which the cooling, fixturing or heating device mounting arrangement are adjusted.

This verification may be made by means of a dummy specimen of identical geometry and material to that to be tested, equipped with several thermocouples fixed along and around the specimen. The distance between the thermocouples should not exceed the specimen diameter and they should be suitably screened from direct radiant heat from the heating device.

The thermocouple layout will depend on the specimen geometry and any additional specific customer requirements. The profiling can consist of several stages. From the initial stage, each additional stage will contain reduced numbers of thermocouples and this is also customer specific.

Before the thermal profiling begins, temperature paths should be plotted in software which enables graphical depiction of numerical values. This will aid accurate profiling for each stage. The thermocouples at the gauge section should be considered paramount for attaining the required temperature and concentration should be given to achieving a high degree of accuracy. The control and monitor thermocouples, which are positioned on adjacent shoulders of the specimen, are used as an indirect measure to ensure the gauge section temperature is correct at all stages during profiling and during the actual test.

An alternative to profiling with thermocouples is the application of thermal imaging. The thermal imaging device should be able to obtain a thermal profile over the entire gauge length, in addition the device has to be calibrated over the temperature range and the emissivity coefficient of the surface shall be known. Commercial thermal paint (such as HE6 or HE23 Rolls-Royce Thermal Paint) can be used to assure constant emissivity during the entire profiling process (Annex C). Similarly, numerous pyrometers focused at points of interest on the specimen could also be effectively used to monitor the temperature uniformity.

6.2.1. <u>Maximum permissible temperature variation along the test piece</u>

The axial, circumferential, and radial temperature gradients shall be measured and optimized under thermal cycling conditions with the specimen at zero force prior to the commencement of TMF loading. The thermal cycle to be used during refinement of the gauge section gradient should be identical to that used for the TMF cycle.

The maximum allowable indicated temperature gradients over the gauge section at any given instant in time within the cycle shall be the greater of:

Axial (all specimen types):

± 1% T_{max}

Circumferential (rounds):
± 1% T_{max}
or ± 5°C

Transverse width (flats):
± 1% T_{max}
± 5°C

Transverse thickness
± 1 % T_{max}

NOTE *Transverse temperature profile measurement:* This is a complex procedure involving the introduction of internal sheathed thermocouples into the main body of the test piece. The temperature gradient depends on the material to be investigated its conductivity, specific heat capacity, test piece geometry and the temperature rate applied.

NOTE *Dynamic temperature calibration*. Currently, there is no standardized method for the dynamic calibration of temperature measurement devices. Therefore, for practical purposes, all temperature-related requirements specified under non-static conditions assume that the temperature-measuring system is calibrated under static conditions.

Prior to the commencement of TMF loading, the axial, circumferential and radial temperature difference shall be measured and optimized under thermal cycling conditions held at zero force. The thermal difference should be identical to that of the actual test piece geometry and the selected material.

The maximum temperature realized within the gauge section should be reported, in particular, where the nominal value was exceeded anywhere within the gauge section. In the event that these limits are not achieved the thermal values should be reported.

Forced air cooling may be necessary, in order to establish a dynamically stable temperature field across the specimen. This can be achieved by applying a constant air flow by either the use of an air amplifier and/or directly focussed onto the specimen using air nozzles.

6.2.2. Data recorders

A data recorder capable of monitoring the indicated test temperature throughout the test, within the accuracy stated in section 5 must be employed.

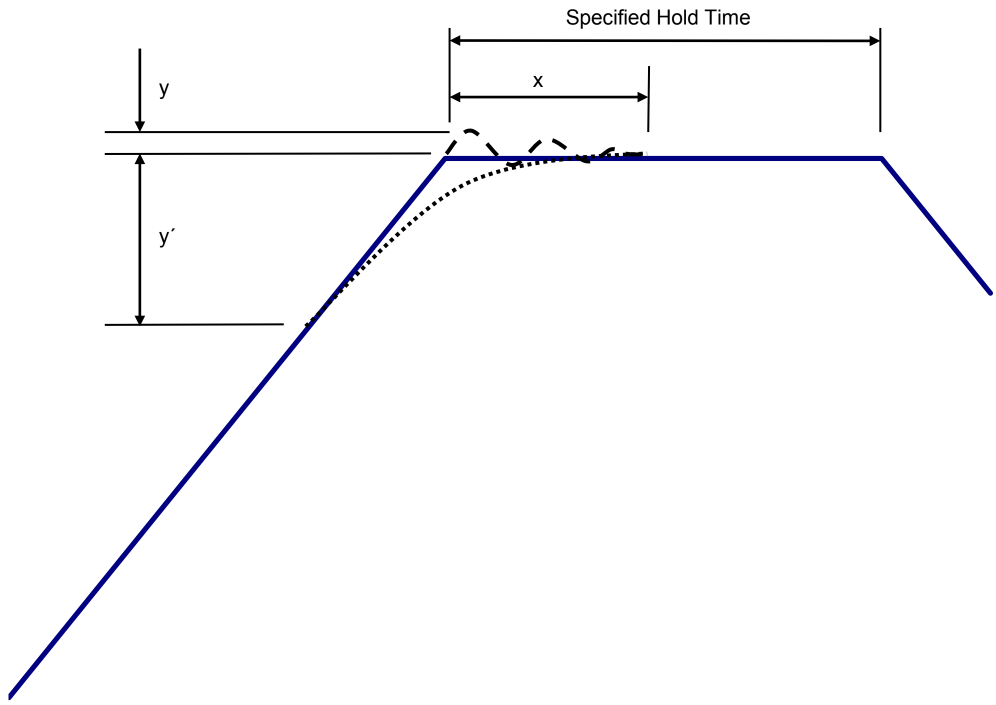
6.2.3. Furnace positioning

The furnace should be positioned concentrically around the specimen and correctly aligned with any load train. For radiant lamp furnaces, an appropriate method should be employed to ensure repeatable repositioning of the furnace chamber after each opening. One possible solution would be two column brackets which are fitted to the underside of the radiant lamp furnace to centralise the furnace with respect to the columns. These should be set against the columns so that it should not be possible to move the furnace in any horizontal direction once it is closed. Any solution must ensure that the furnace will close without fouling the thermocouples.

6.3 FORCE WAVEFORM OPTIMISATION

Any adjustment to the waveform shape should be completed within 10 cycles and must not introduce deviations from the specified waveform that exceeds the limits defined below. Thereafter it shall remain unadjusted throughout the duration of a test. The achieved frequency must be within ±10 % of the specified frequency.

In the case of trapezoidal and triangular waveforms, the discontinuities at the nodes should be well defined and angular. Oscillation at the nodes shall not exceed 1% or 20 N, whichever is greater of the intended force, and rounding features at the nodes shall not exceed 5% or 100 N, whichever is greater, of the intended force. In the case of trapezoidal waveforms, it should not constitute more than 20 % of the hold time or a maximum of 0.2 seconds, whichever is the smallest (see Figure 4). In the case of sinusoidal waveforms, the waveform shall be smooth and free from discontinuities.



y ≤ 1 % or 20 N, whichever is greater, of the intended force.
y´ ≤ 5 % or 100 N, whichever is greater, of the intended force.
x ≤ 20 % of the specified hold time (max of 0.2 s)

Figure 4: Waveform optimisation

7.3 TEMPERATURE FORCE OPTIMISATION

Generally the phase lag between mechanical loads influences the TMF test results. To reduce this effect, a minimisation of the phase lag should be performed in the pre-test. Temperature oscillation at the nodes shall not exceed ±1% T_{max} or 5°C, whichever is greater of the intended temperature, and temperature rounding features at the nodes shall not exceed ±1% T_{max} or 5°C, whichever is greater, of the intended temperature. Phase lag may have its origins in the insufficient control speed and or response time of the temperature measurement and control system.

The precise synchronisation between temperature and force is crucial for a sufficient TMF test setup. Therefore the quality of synchronisation must be checked in a pre test. To do this the common set point signal of temperature and force of the function generator must be recorded as well as the actual values of temperature and force during TMF cycling in a pre test. The synchronisation of temperature and force must be optimised in that way that the phase lag between actual temperature and actual force signal is less than 1° within the whole TMF test cycle while the recorded set point signal is the reference of the optimisation process. The TMF test cycle optimisation must be reported.

7. TEST EXECUTION

7.1. TEST START

Test forces will generally be dictated by the customer. On commencing cycling, the force requested of the machine may only be increased by a maximum of 5% of the force range in order to achieve the intended force. When performing an adaptive control mode of the testing machine, an adjustment must be completed within the first 10 cycles. The requested force must not be decreased.

NOTE: It is recommended that the requested force is not adjusted in order to achieve the precise intended force and that actual stresses and stress ratios are calculated based on measured values.

The initial loading should be on the tensile direction except for R > 1 tests, unless another option is specified.

7.1.1. Data recording

Monitoring of the indicated test temperature and recording throughout the test must be employed and the cycles recorded as advised within Section 5.1.3.

Note must be taken of achieved values and any exceptions to the profile noted.

7.1.2. Test termination

Tests should be continued without interruption until the specimen has failed or a predetermined number of cycles have been exceeded.

The criterion for failure will generally be complete separation of the specimen. The cycle count attained is the fatigue life.

It should not be assumed that tested, but unbroken specimens, have not suffered fatigue damage. Those specimens therefore should not be retested at a different stress amplitude unless requested by the customer.

7.1.3. Test validity

If the interrupted cycle has not been recorded, the TMF test should not be restarted. Any test interruption, intentional or not, must be reported.

A restarted test can be regarded as valid if the last whole cycle is re-established within 5 cycles of the restart to less than ± 1% deviation of F_{max} and force range ΔF values. In case of test interruption, which was due to a defect in the heating or cooling device, the thermal profile has again to be validated with the last accepted profile before the test is re-started.

7.1.4. During the test

Checks should be made at least daily to ensure that the test parameters, temperature and force waveforms conform to the test specification, and have remained so since the last check. If the machine software has the ability to automatically detect and log any violation of the set limits and is also able to initiate a pause in the test, then longer periods between checks are acceptable. Software that informs the operator remotely about the current status of the test improves the test quality and allows longer periods between observations. The air and water supply to the machine should also be checked at regular intervals. Ideally they should have an integrated sensor to monitor water and air flow. Any failure, of either air or water, to maintain the required rate should instigate a safe termination of the test.

7.2. TEST MONITORING

It is recommended that the time, cycle number, temperature, and force be recorded for the duration of the test with a minimum sampling rate of 200 points per cycle (in many cases it may be advantageous also to have information on the set-point signals of temperature and the stroke signal and the heating power control signal). Depending on the system limitations and the duration of the test, it may be necessary to carry out an online data reduction process. In this case it is recommended to meet the minimum data recording requirements as given below.

Force and temperature should be recorded as a function of time for representative cycles (see Table 2).

Table 2: Stress TMF data which should be reported

Plots:	Representative cycles to be recorded:	Representative cycles to be reported:
Stress vs. time	logarithmic scheme: N=1,2,3, 6,10,20,30,60,100, ...	N = 1-10, ¼ life, ½ life, ¾ life
Stress vs. temperature	logarithmic scheme: N=1,2,3, 6,10,20,30,60,100, ...	N = 1, mid-life cycle
Temperature vs. time	logarithmic scheme: N=1,2,3, 6,10,20,30,60,100, ...	N = 1, mid-life cycle
Min. and Max. of stress, stress range and peak temperatures as a function of cycles	<10000 all cycles. >10000 cycles better than 0.1% resolution of indicated life.	logarithmic scheme: N=1,2,3, 6,10,20,30,60,100, ...

The mid-life cycle to be provided in the test report should be the recorded cycle which is closest to $N_f/2$, or at least within the mid-life interval, $N = N_f \pm 5\% N_f$.

NOTE: It is recommended that cycles corresponding to any deviation from the prescribed testing tolerances should be retained.

7.3. TERMINATION OF TEST

The test shall not be terminated until a predefined criterion has been reached. The end of the test is generally the physical fracture of the specimen.
The test machine software can stop the test for a number of reasons including:

i. Pre-set number of cycles achieved
ii. Pre-set parameter limit exceeded
iii. Manual intervention
iv. Equipment failure / Power failure
v. Deviation of temperature

All tests should be tested until the specimen physically fractures. Any other failure criterion used should be detailed and explained in the subsequent report.

7.3.1. Accuracy of control parameters

In order to validate the test, the test temperature record must be consulted to ensure that there were no deviations outside the limits specified in Section 3.

NOTE: If a record of achieved force maxima and minima has been kept then this should also be consulted. This may be achieved by checking that the set force trips have not been initiated.

Data quality classifications are as follows:

- **1: Uncompromised test,** Good test with no issues.
- **2: Data integrity compromised,** Minor issues with test which might affect test life / data quality.
- **3: Scrapped test,** Major problems with test which results in no test data or data that has been significantly compromised. This classification should also be used for tests that fail before maximum force is achieved on the first cycle.

8. ANALYSIS AND REPORTING

8.1. VALIDATION OF ANALYSIS SOFTWARE

It is recommended that an ASCII data file, representative of the material under investigation and with agreed TMF test results, should be used to validate the analysis software following updating and/or modification.

8.2. TEST REPORT

Test data should be compiled and formally issued electronically in a format compatible with the customer specific data bank or in a format that can be accessed by standard office software (see section 5.1.1).

8.2.1. Essential information

The report should contain the following essential information:

- reference to this code of practice;
- description and identity of testing machine;
- test operator;
- date of test;
- failure position;
- whether the test is valid or not;
- support services material identification;
- customer cross-reference;
- specimen identity, drawing number, dimensions and reference to a documented method of preparation;
- material type and any associated code;
- temperature of the test plus any deviation from the specified limits;
- waveform, shape of loading cycle, frequency of application/hold and R ratio;
- endurance cycles, cycles to failure (N_f) and position of failure;

- any other occurrences that may affect the test result e.g. test suspensions etc.
- stress concentration factor plus method and source of its determination for notched specimens.

8.2.2. Additional information

The following information is often valuable and, when available, is recommended for inclusion in the test report:

- specimen orientation and location in original material stock from which it was taken;
- material specification/material composition, heat treatment, surface treatment;
- product size and form (e.g. casting, plate);
- minimum stress (σ_{min});
- maximum stress (σ_{max});
- stress range ($\Delta\sigma$);
- the loading curves for at least the first ten cycles, ¼ life, ½ life, ¾ life and the life cycles should also be included (or the closest cycle to the above);
- Fractographic examination of the two crack surfaces to determine any unusual causes of failure that might invalidate or qualify the test results.

NOTE: The standard presentation of data for a series of related tests is via a graphical S-N diagram. This is constructed by plotting the number of cycles to failure as the abscissa and the stress range as the ordinate. A logarithmic scale is commonly used for the number of cycles and a linear scale for the stress axis (see Figure 5).

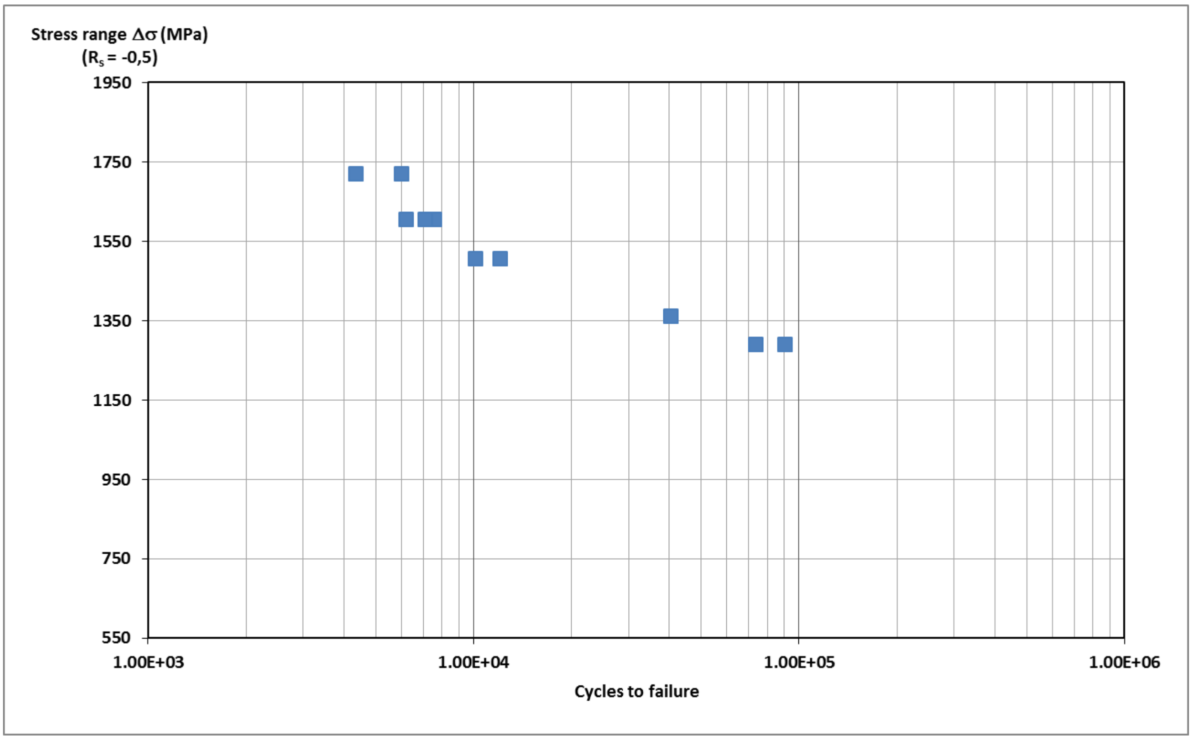


Figure 5: Typical *S-N* diagram according to BS EN 2987:2009.

Additional test data required in the report should be agreed with the customer before the test series commences.

8.2.3. Examination of fracture surface

The failure position along the length of the test section should be noted. Failure in the middle third of the gauge section is considered an 'A' fail location, failure in the outer third of the gauge section is considered a 'B' fail location and failure in the transition radius a 'C' fail location (see Figure 6). Failure of the specimen at a transition radius or outside the test section must be considered an invalid result.

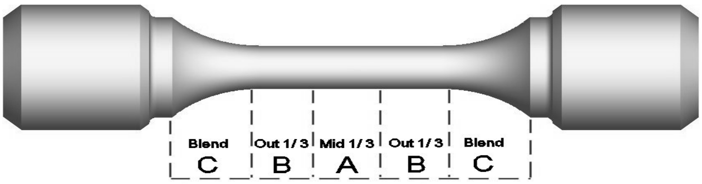


Figure 6: Failure locations along the gauge length of cylindrical or square section plain specimens.

Crack initiation from obvious surface blemishes should be noted.

NOTE: More thorough examination (e.g. with an optical and electron microscope) may be requested if microstructural effects are of interest.

NOTE: It may be possible to group a series of test results based on the failure mechanism and subsequently account for their correlation with other data.

9. ACKNOWEDGEMENTS

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NPL,	UK
HTMTC	UK
AMEC,	UK
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Raymond Lohr Consulting Engineer	UK
Linköping University,	S
Siemens Industrial Turbomachinery AB.,	S
EMPA,	CH
Derivation Research Laboratory	Ca

Annex A
(Informative)

GUIDELINES ON SPECIMEN HANDLING AND DEGREASING

For all alloys the test section must be cleaned parallel to the gauge section with an isopropyl alcohol (IPA), or IPA wipe after insertion into the machine. Once the sample has been cleaned, care must be taken to avoid physical contact with the test section. Nitrile gloves should be worn so that contact with the gauge section is avoided.

Annex B

(Informative)

Thermocouple arrangement for specimen containing a notch feature

This procedure is recommended with the use of radiant lamp furnaces.

Notch feature specimens are designed to replicate a specific feature of a component. The temperature profile should therefore be closely related to the service temperature environment of the component. The control of the temperature across the gauge section is therefore critical to replicate this as accurately as possible. The sensitivity of the material to spot welding has to be understood before the testing can commence. To avoid any possibility of crack initiation and subsequent premature failure, thermocouples are to be attached (spot welded) to the specimen surface outside of the gauge section on both adjacent shoulders of the specimen. The various stages of thermal profiling are intended to establish the relationship between these two positions and the temperature at the gauge section.

Stage 1 thermal profile layout for a feature based specimen

Dummy specimen (not used for the test) for profiling (10 TC's all are spot welded to the specimen)

TC Control	15mm above notch radius
TC Monitor	15mm below notch radius
TC1 Side 2	1 mm below notch radius
TC2 Side 1	1 mm above notch radius
TC3 Face 1	5 mm above TC6
TC4 Face 2	5 mm below TC8
TC5 Side 1	Notch centre
TC6 Face 1	Centre
TC7 Side 2	Notch centre
TC8 Face 2	Centre

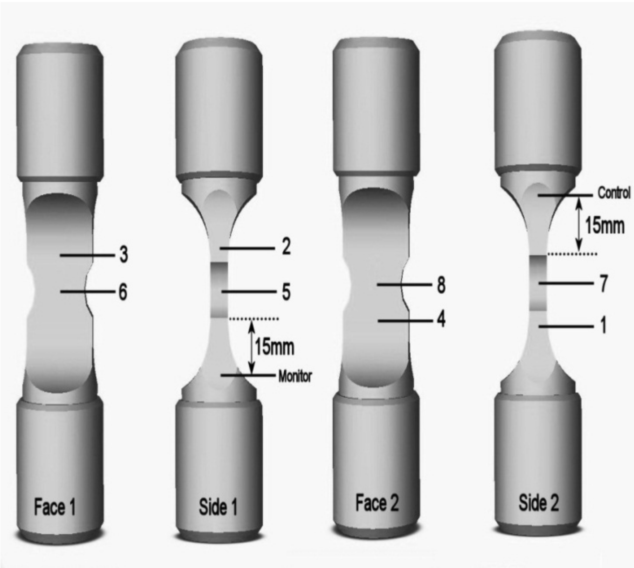

Figure 7: Schematic stage 1 TC arrangement (8 TC's).

Stage 1 can be considered complete when the temperature deviation across the specimen gauge section is within the limits set out in section 6.2.1. On completion of stage 1, a second profile (stage 2) can be performed on the same specimen, only with a total of six TC's. The four TC's within the gauge section are retained along with the control and monitor TC's the rest are removed (Figure 8). This new profile confirms another issue uniquely seen with radiant lamp furnaces, the effect of 'shadowing'. The upper TC's lay across the specimen surface and, although less than 2mm in diameter (ceramic sleeving enlarges the area of the TC), they create shadows over the specimen. Additionally they block the air cooling from reaching the specimen surface and create some turbulence. This effect will slightly affect the heating and cooling of the specimen, therefore the second profile is vital to the understanding of the temperature gradient across the specimen with fewer TC's covering the surface. To proceed to stage 2, remove the redundant TC's (see stage 2 layout) by carefully pulling them off the specimen with tweezers and then cut the wires back to the point at which they are tied by thermal string to the loading column.

Stage 2 thermal profile layout

Dummy Specimen for profiling (6 TC's)

TC Control	15mm above notch radius
TC Monitor	15mm below notch radius
TC5 Side 1	Notch centre
TC6 Face 1	Centre
TC7 Side 2	Notch centre
TC8 Face 2	Centre

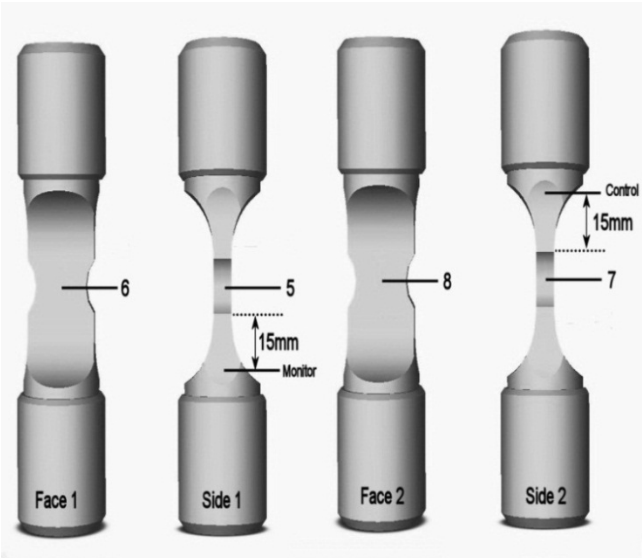

Figure 8: Schematic stage 2 TC arrangement (6 TC's).

Stage 2 can be considered complete when the temperature deviation across the specimen gauge section is within the limits set out in section 6.2.1. Stage 3 can be performed after removing the four TC's at the gauge section but retaining the control and monitor TC's (Figure 9). The temperature profile focuses only on matching the profile of the control and monitor TC's from stage 2. The furnace control and air cooling must remain unchanged. The only option is to move the furnace vertically, up or down, a few millimetres are usually sufficient. To proceed to stage 3, remove the redundant TC's (see stage 3 layout Figure 9) by carefully pulling them off the specimen with tweezers and then cut the wires back to the point at which they are tied by thermal string to the loading column.

Stage 3 thermal profile layout (Figure 9)

Dummy Specimen (2 TC's)

TC Control 15mm above notch radius
TC Monitor 15mm below notch radius

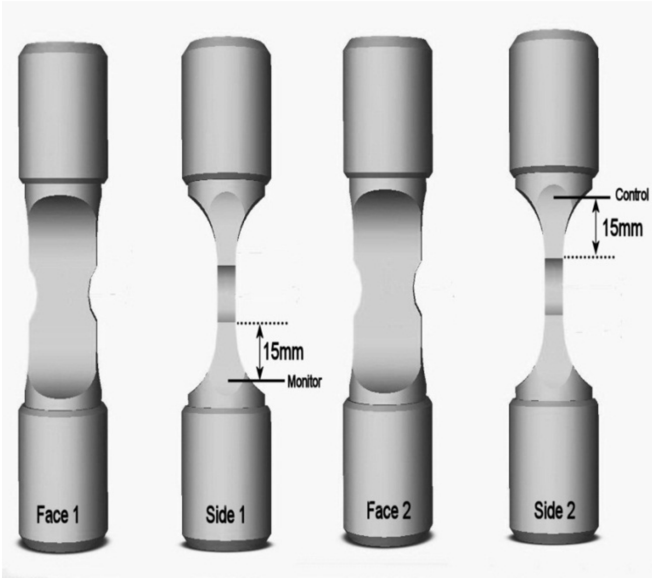

Figure 9: Schematic stage 3 TC arrangement (2 TC's).

Stage 3 can be considered complete when the temperature deviation across the specimen gauge section is within the limits set out in section 6.2.1. Stage 3 can be performed after removing the four TC's at the gauge section but retaining the control and monitor TC's (Figure 9). The temperature profile focuses only on matching the profile of the control and monitor TC's from stage 2. The furnace control and air cooling must remain unchanged. The only option is to move the furnace vertically, up or down, a few millimetres are usually sufficient. Once stage 3 has been successfully profiled, a test specimen can replace the dummy profile specimen for final validation.

Specimen – TMF Test piece (2 TC's)

TC Control 15mm above notch radius
TC Monitor 15mm below notch radius

The test specimen should be placed in the same position in relation to the depth of thread in the loading columns, its orientation in relation to the furnace, i.e. flat faces perpendicular to the front of the testing frame, etc. Attach new control and monitor TC's to the shoulders (identical to stage 3, Figure 9). After the successful thermal profile has been confirmed the testing can begin[2].

Annex C
(Informative)

Thermal Imaging for thermal profiling

Infrared thermal cameras (IRTC) have become affordable devices for measuring temperature over large temperature ranges. The advantages of using the IRTC are, they are non-contacting and they have the ability to measure from spot size to area size and over many chosen positions on the specimen. The IRTC systems can also function with dynamic temperature variation. However, the specimen surface is usually reflective and will oxidise over time, this will cause variation in the emissivity of the specimen and could lead to temperature inaccuracies. A solution to this is the application of thermal paint to the specimen surface to ensure a constant emissivity value. This variation should only be used for the profiling stages to monitor the temperature deviation on the test piece gauge length. There is insufficient data on the effects of thermal paints on the specimen properties for use in an actual test.

[1] Affeldt, E., Beck, T., Klingelhöffer, H., Loveday, M., and Rinaldi, C., Validated code of practice for strain controlled thermo-mechanical fatigue testing, EUR 22281EN DG JRC-Institute for Energy. ISBN 92-79-02216-4, 2006.

[2] Brookes, S., Nass, M., and Ward, B., The development of force-controlled thermo-mechanical fatigue testing at the Rolls-Royce Mechanical Test Operations Centre (MTOC), Dahlewitz, Germany, Deutscher Luft- und Raumfahrtkongress Berlin, 2012, http://www.dglr.de/publikationen/2012/281438.pdf

[3] Thermomechanical Fatigue Behavior of Materials, 4th Volume, ASTM STP 1428, (eds. McGaw, M.A., Kalluri, S.R., Bressers, J., Peteves, S.D.), ASTM International, West Conshohocken, PA, 2003