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Metallic materials – Fatigue testing – Force controlled thermo-mechanical fatigue testing method

Matériaux métalliques – Essai de fatigue – Méthode d'essai de fatigue thermomécanique à force contrôlée

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 4, *Fatigue, fracture and toughness testing*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Thermo-mechanical fatigue (TMF) test method was developed in the early 1970's 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 specimen is subjected to temperature and mechanical strain phasing it is called strain controlled TMF. ASTM E2368 and ISO 12111 concern strain controlled TMF. However, these do not allow for specimens where no compensation for free thermal expansion and contraction is required. Therefore, this document addresses the need for a separate procedure for force controlled TMF testing.

This document 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 force controlled TMF tests using various specimen geometries. The document 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 Standard, are solely the responsibility of the user.

The following clauses of this document are intended to provide the steps to be implemented in sequence, during the process of carrying out force controlled TMF tests.

Metallic materials – Fatigue testing – Force controlled thermo-mechanical fatigue testing method

1 Scope

This document 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 document. This document describes the equipment, specimen preparation, and presentation of the test results in order to determine TMF properties.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7500-1, *Metallic materials — Calibration and verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Calibration and verification of the force-measuring system*

ISO 12111, *Metallic materials — Fatigue testing — Strain-controlled thermomechanical fatigue testing method*

ISO 23788, *Metallic materials — Verification of the alignment of fatigue testing machines*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
force
F
force applied to the test section, in kN

Note 1 to entry: Tensile forces are considered to be positive and compressive forces negative.

3.2
maximum force
F_{max}
highest algebraic value of force applied, in kN

3.3
minimum force
F_{min}
lowest algebraic value of force applied, in kN

3.4
force range
ΔF
algebraic difference between the maximum and minimum forces, in kN

Note 1 to entry: $\Delta F = F_{max} - F_{min}$

3.5
force amplitude
F_a
half the algebraic difference between the maximum and minimum forces, in kN

Note 1 to entry: $F_a = (F_{max} - F_{min})/2$

3.6
mean force
F_m
half the algebraic sum of the maximum and minimum forces, in kN

Note 1 to entry: $F_m = (F_{max} + F_{min})/2$

3.7
force ratio
R
algebraic ratio of the minimum force to the maximum force

Note 1 to entry: $R = F_{min}/F_{max}$

Note 2 to entry: See Figure 2 for examples of different force ratios.

3.8
stress ratio
R_s
ratio of minimum stress to maximum stress during a fatigue cycle

Note 1 to entry: $R_s = \sigma_{min}/\sigma_{max}$

3.9
stress range
$\Delta\sigma$
arithmetic difference between maximum stress and minimum stress, in MPa

Note 1 to entry: $\Delta\sigma = \sigma_{max} - \sigma_{min}$

3.10
stress
σ
force divided by the nominal cross-sectional area, in MPa

Note 1 to entry: It is the independent variable in a stress-controlled fatigue test.

Note 2 to entry: 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.

3.11
fatigue strength at *N* cycles
σ_N
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, in MPa

3.12
maximum stress
σ_{max}
highest algebraic value of stress applied, in MPa

3.13
minimum stress
σ_{min}
lowest algebraic value of stress applied, in MPa

3.14
number of force cycles
N
number of loading and unloading sequences applied

3.15
time per cycle
t
time applied per loading and unloading sequence

3.16
maximum temperature
T_{max}
highest algebraic value of temperature applied, in °C

3.17
minimum temperature
T_{min}
lowest algebraic value of temperature applied, in °C

3.18
fatigue life
N_f
number of cycles to failure

3.19
theoretical stress concentration factor
K_t
ratio of the notch tip stress to net section stress, calculated in accordance with defined elastic theory, to the nominal section stress

Note 1 to entry: Different methods used in determining K_t may lead to variations in reported values.

3.20
phase angle
Φ
angle between temperature and mechanical force, defined with respect to the temperature as reference variable

Note 1 to entry: 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.

4 Test methods

4.1 Apparatus

4.1.1 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 shall 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.

4.1.2 Testing machine calibration

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

4.1.3 Cycle counting

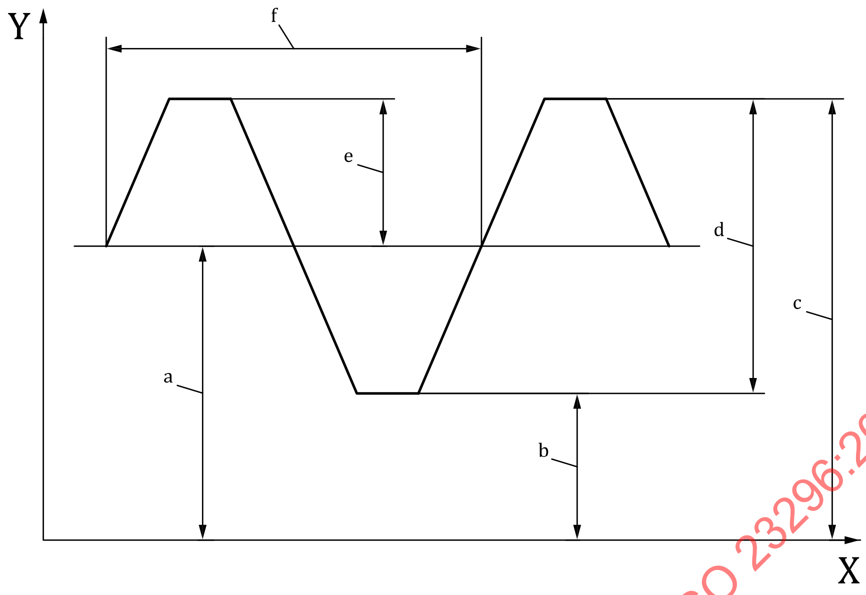
The number of cycles applied to the specimen shall be recorded such that for tests lasting less than 10 000 cycles, individual cycles can be resolved, while for longer tests the resolution should be better than 0,01 % of indicated life.

4.1.4 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 ISO 7500-1, for the duration of the test.

Terms have been identified relative to the trapezoidal waveforms in Figure 1 and Figure 2. 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.



Key

X time

Y force

a Mean force.

b Minimum force.

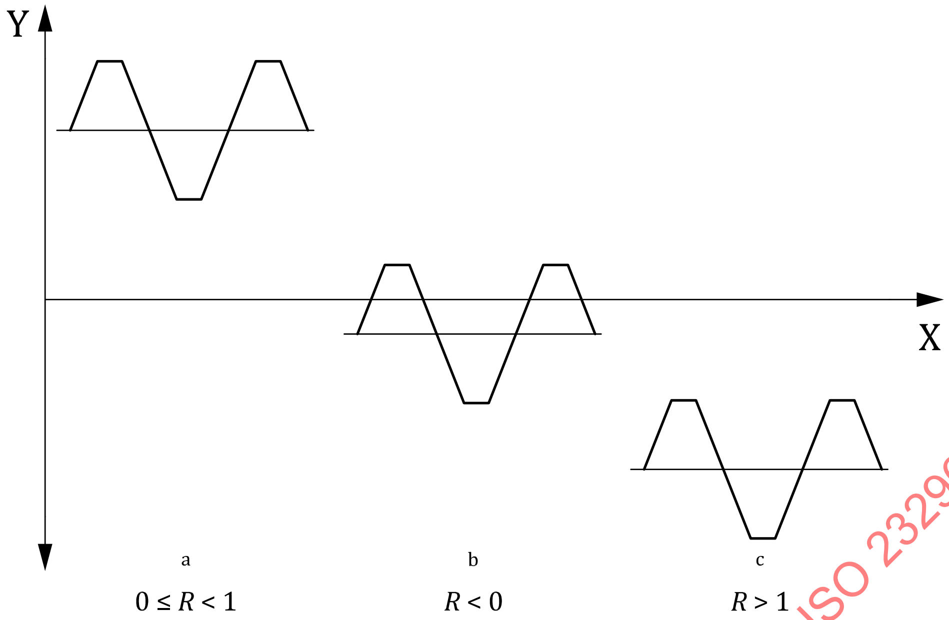
c Maximum force.

d Force range.

e Force amplitude.

f One cycle.

Figure 1 — Trapezoidal fatigue force cycle



Key

X time

Y force

[a] Cyclic tension.

[b] Reversed.

[c] Cyclic compression.

Figure 2 — Varying force ratio

4.1.5 Force measuring system

The force measuring system, consisting of a load cell, amplifier and display, shall meet the requirements of ISO 7500-1 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.

4.1.6 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 ($R\varepsilon \leq 0$) shall also be free from backlash effects.

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 4.1.7 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.

4.1.7 Alignment verification

Alignment of the load train assembly shall be conducted and verified in accordance with ISO 23788 to a minimum of class 10.

4.1.8 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.

4.1.9 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 best positioned at the top of the furnace. Coupled to a compressed air supply the air amplifier accelerates a curtain of air through the centre of the furnace.

4.2 Specimens

4.2.1 Geometry

Subject to the objectives of the test programme, the type of specimen geometry 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 deviations etc. Failure shall occur within the gauge section for the test to be considered valid.

Generally, a specimen having a fully machined test section is of the type shown in Figure 3 for a smooth cylindrical-type gauge section. The specimens may be of the following:

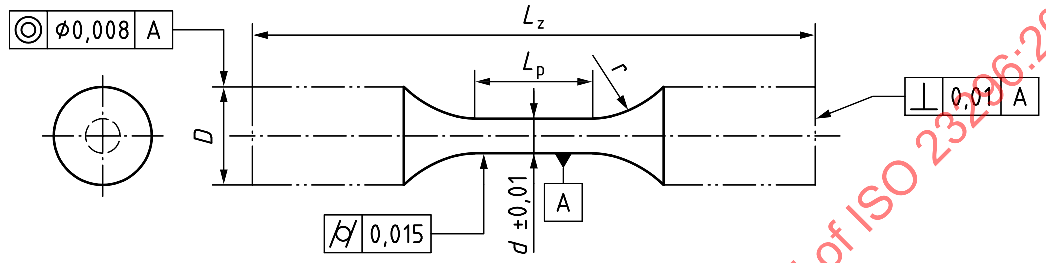
— circular cross-section with tangentially blending fillets between the test section and the ends, or with a continuous radius between the ends (i.e. "hourglass" specimen);

— rectangular cross-section of uniform thickness over the test section with tangentially blending fillets between the test section and the gripped ends (see Figure 4).

Specimens commonly known as "hourglass" specimens may be employed for testing with caution. In such specimens, there is a continuous radius between grip ends with a minimum diameter or width of the test section centrally located between these ends for cylindrical and flat specimens respectively. Unlike a smooth, constant diameter or width, gauge section where a volume of material is equally under stress, the hourglass specimen permits sampling only of a thin planar element of material at the minimum cross section. Thus, the fatigue results produced may not represent the response of the bulk material where, particularly in the long-life fatigue regime, inclusions govern behaviour in high hardness metals and there is a duality in crack initiation from surface to subsurface. In fact, such results may be non-conservative particularly in the longer life regime where the largest micro discontinuity may not lie in the planar section of greatest stress.

It is important to note that for specimens of rectangular cross-section, it may be necessary to reduce the test section in both width and thickness. If this is necessary, then blending fillets will be required in both the width and thickness directions. Also, for a rectangular-section specimen, where it is desired to take account of the surface condition in which the metal will be used in actual application, then at least one surface of the test section of the test piece should remain unmachined. It is often the case, for fatigue tests conducted using a rectangular-section piece, that the results are not always comparable to those determined on cylindrical specimens because of the difficulty in obtaining an adequate surface finish or because fatigue cracks initiate preferentially at the corner(s) of the rectangular test piece.

Dimensions in millimetres

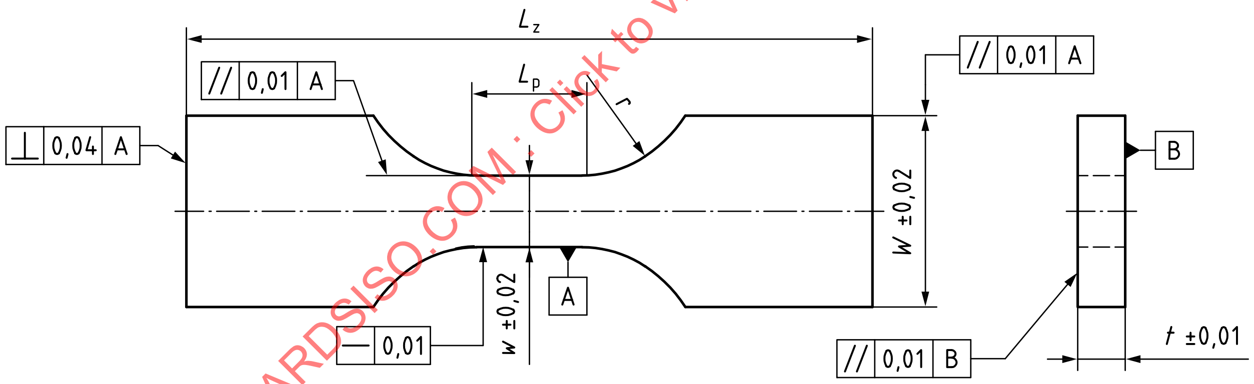


NOTE 1 For definitions of symbols for geometrical tolerances, see ISO 5459.

NOTE 2 The perpendicularity requirement applies to any gripping parts used for alignment.

Figure 3 — Recommended geometry of cylindrical specimen

Dimensions in millimetres



NOTE 1 For definitions of symbols for geometrical tolerances, see ISO 5459.

NOTE 2 The perpendicularity requirement applies to any gripping parts used for alignment.

Figure 4 — Possible geometry of flat-sheet specimen

The gauge portion of the specimen represents a volume element of the material under study, which implies that the geometry of the specimen shall not affect the use of the results. The width of the specimen is reduced in the gauge length to avoid failures in the grips. In some applications it might be necessary to add end-tabs to increase the grip and thickness, as well as to avoid failure in the grips.

Geometric dimensions in Table 1 are recommended.

Table 1 — Geometric dimensions

Parameter	Dimensions
Diameter of cylindrical gauge length	$d \geq 3$ mm
Transition radius (from parallel section to grip end)	$r \geq 2d$
External diameter	$D \geq 2d$
Length of reduced section	$L_p \leq 8d$

Other geometric cross-sections and gauge lengths may be used. It is important that general tolerances of the specimens respect the three following properties:

— Parallelism // ≤0,005*d*

— Concentricity ◎ ≤0,005*d*

— Perpendicularity ⊥ ≤0,005*d*

These values are expressed in relation to the axis or reference plane.

4.2.2 Specimen preparation

Utmost importance should be given to the condition of the specimen 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 shall 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 shall 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.

4.2.3 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 0,005 mm, whichever is the greatest value. The surface finish shall not be jeopardised by this activity.

4.2.4 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.

4.2.5 Sampling, storage and handling

Specimens shall 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.

4.2.6 Specimen insertion

Before loading ensure the load cell has been calibrated, in accordance with ISO 7500-1 in compression and tension, and aligned in accordance to ISO 23788.

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 shall 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 500 N or 10% of the intended test maximum force, whichever is smaller.

Insert the specimen 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 specimen 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.

4.2.7 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 found 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 the section on temperature control 5.1.2. For more information regarding the appropriate choice of thermocouples it is advisable to consult ASTM E220, BS 1041-4, BS 60584-1 and EN 60584-3.

4.2.8 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 shall 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 shall remain attached to the specimen surface for the entire duration of the test which can be as much as three months. The thickness of the thermocouple wires should be kept as small as possible, to reduce the effects of cold spots on the specimen (the thermocouple effectively absorbs heat from the specimen surface causing localised cooling). 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:

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.

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.

4.2.9 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 5.2.1 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 shall not result in compressive forces being applied to the specimen. The specimen shall therefore be maintained at zero force, throughout the heating process.

4.2.10 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 5.2.2. 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.

5 Test preparatory issues

5.1 Temperature measurement

5.1.1 General

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 shall be verified over the working temperature range. The sensors employed shall not affect the surface properties of the material.

5.1.2 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 [14].

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.

5.2 Verification of temperature uniformity - Thermal profiling

5.2.1 General

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 high temperature thermal paint (such as HE6 or HE23 Rolls-Royce high temperature paint) can be used to assure constant emissivity during the entire profiling process (see Annex C). Similarly, numerous pyrometers focused at points of interest on the specimen could also be effectively used to monitor the temperature uniformity.

5.2.2 Maximum permissible temperature variation along the specimen

The axial, circumferential, and radial temperature deviation 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 deviation should be identical to that used for the TMF cycle.

The maximum allowable indicated temperature deviation 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} or ±5 °C whichever is greater;

— circumferential (rounds): ±1 % T_{max} or ±5 °C whichever is greater;

— transverse width (flats): ±1 % T_{max} or ±5 °C whichever is greater;

— transverse thickness ±1 % T_{max} or ±5 °C whichever is greater.

NOTE 1 Transverse temperature profile measurement: This is a complex procedure involving the introduction of internal sheathed thermocouples into the main body of the specimen. The temperature deviation depends on the material to be investigated its conductivity, specific heat capacity, specimen geometry and the temperature rate applied.

NOTE 2 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 specimen 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 (a curtain of accelerated air) and/or directly focussed around or onto the specimen using air nozzles.

5.2.3 Data recorders

A data recorder capable of monitoring the indicated test temperature throughout the test, within the accuracy stated in 5.1 shall be employed.

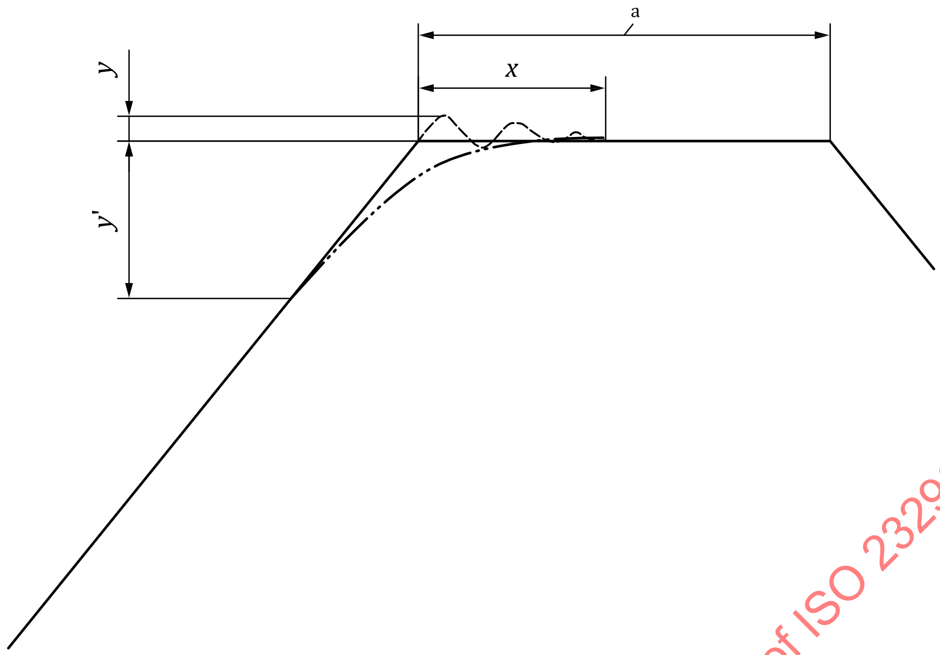
5.2.4 Furnace positioning

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 shall ensure that the furnace will close without fouling the thermocouples.

5.3 Force waveform optimisation

Any adjustment to the waveform shape should be completed within 10 cycles and shall 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 shall be within ±10 % of the specified frequency.

In the case of trapezoidal and triangular waveforms, the discontinuities at the nodes (caused by the change of force mode) should be well defined and angular. Oscillation at the nodes shall not exceed 1 % of the intended force amplitude and rounding features at the nodes shall not exceed 5 %, of the intended force amplitude. 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 5). In the case of sinusoidal waveforms, the waveform shall be smooth and free from discontinuities.



Key

x ≤20 % of the specified hold time (max of 0.2 s)

y ≤1 %, of the intended force amplitude.

y' ≤5 %, of the intended force amplitude.

a Specified hold time.

Figure 5 — Force waveform optimisation

5.4 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 shall be checked in a pre-test. To do this the common set point signal of temperature and force of the function generator shall 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 shall 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 shall be reported.

5.5 The application of an extensometer to measure maximum and minimum mechanical strain to observe the effects of ratcheting

In force-controlled TMF testing, the specimens can sometimes fail in a manner which is associating with ratcheting. Under such conditions, there are significant differences in fatigue lives and fracture modes between the load- and the strain-controlled tests. This effect can cause misleading test results which in turn can lead to ambiguity in material behaviour. Annex D describes the requirements for measuring strain in a uniaxial force-controlled TMF test.

6 Test execution

6.1 Test start

6.1.1 General

Engineering stress or force values 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 shall be completed within the first 10 cycles. The requested force shall not be decreased.

The requested force should not be 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.

6.1.2 Data recording

Monitoring of the indicated test temperature and recording throughout the test shall be employed and the cycles recorded as advised within 4.1.3.

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

6.1.3 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 different stress amplitudes unless requested by the customer.

6.1.4 Test validity

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

6.1.5 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.

6.2 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 — Force TMF data which should be reported

Plots	Representative cycles	Representative cycles
Force vs. time	logarithmic scheme: N = 1,2,3,6,10,20,30,60,100, ...	N = 1 to 10, ¼ life, ½ life, ¾ life
Force 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 ($\Delta\sigma$) and peak temperatures as a function of cycles	<10 000 all cycles. >10 000 cycles better than 0,1 % resolution of indicated life.	logarithmic scheme: N=1,2,3,6,10,20,30,60,100, ...

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

6.3 Termination of test

6.3.1 General

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:

— pre-set number of cycles achieved;

— pre-set parameter limit exceeded;

— manual intervention;

— equipment failure/power failure;

— 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.

6.3.2 Accuracy of control parameters

In order to validate the test, the test temperature record shall be consulted to ensure that there were no deviations outside the limits specified in Clause 5.

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:

a) Uncompromised test: Good test with no issues.

b) Data integrity compromised: Minor issues with test which might affect test life/data quality.

c) 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.

The measurement uncertainty of test results should be calculated according to Annex E.

7 Analysis and reporting

7.1 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.

7.2 Test report

7.2.1 General

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 4.1.1).

7.2.2 Essential information

The report should contain the following essential information:

a) a reference to this document, i.e. ISO 23296:2022;

b) description and identity of testing machine;

c) test operator;

d) date of test;

e) failure position;

f) whether the test is valid or not;

g) support services material identification;

h) customer cross-reference;

i) specimen identity, drawing number, dimensions and reference to a documented method of preparation;

j) material type and any associated code;

k) temperature of the test plus any deviation from the specified limits;

l) waveform, shape of loading cycle, frequency of application/hold and *R* ratio;

m) cycles to failure, N_f, and position of failure;

n) any other occurrences that may affect the test result e.g. test suspensions etc.

o) stress concentration factor plus method and source of its determination for notched specimens.

7.2.3 Additional information

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

a) specimen orientation and location in original material stock from which it was taken;

b) material specification/material composition, heat treatment, surface treatment;

c) product size and form (e.g. casting, plate);

d) minimum stress, σ_{min};

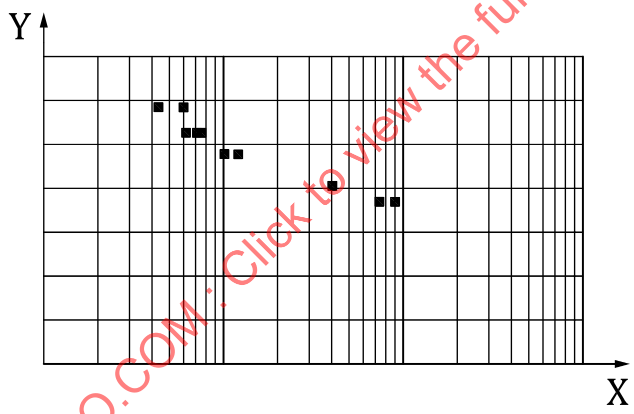
e) maximum stress, σ_{max};

f) stress range, $\Delta\sigma$;

g) 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);

h) 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 6).



Key

X number of cycles to failure, N_f

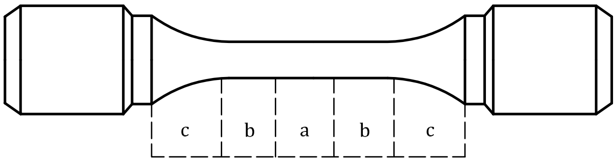
Y stress range, $\Delta\sigma$ (MPa)

Figure 6 — Typical S-N diagram

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

7.2.4 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 7). Failure of the specimen at a transition radius or outside the test section shall be considered an invalid result.



Key

a Middle third of the gauge section.

b Outer third of the gauge section.

c Transition radius.

Figure 7 — Failure locations along the gauge length of cylindrical or square section plain specimens

Crack initiation from obvious surface blemishes should be noted.

Annex A
(informative)

Guidelines on specimen handling and degreasing

For all alloys the test section should 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 should 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 a specimen containing a notch feature

B.1 General

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

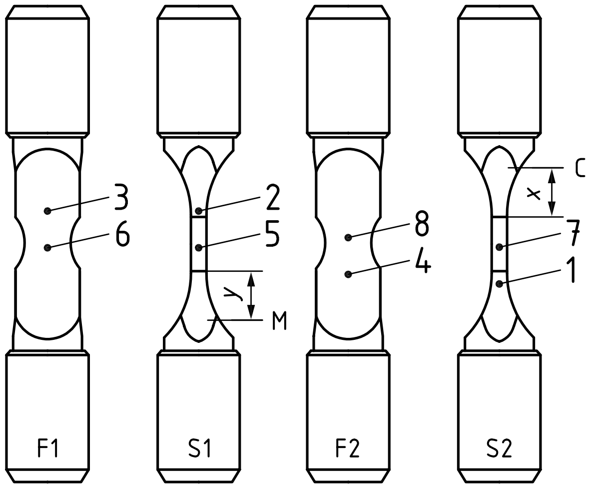
Notch feature specimens are designed to replicate a specific feature of a component. The temperature profile should therefore be closely related to the service temperature environment of the component. The control of the temperature across the gauge section is therefore critical to replicate this as 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, during the test thermocouples are to be attached (spot welded) to the specimen surface outside of the gauge section on both adjacent shoulders of the specimen (control and monitor TCs). The various stages of thermal profiling are intended to establish the relationship between these two positions and the temperature at the gauge section. The following thermocouple layouts are examples for one type of geometry, which may not be suitable for other geometry types. Omission of intermediate thermal profile stages, with the exception of stage 3 which relates to the actual test, can be considered.

B.2 Stage 1 thermal profile layout for a feature-based specimen

A dummy specimen which is not used for the test and only used for profiling should be configured according to Table B.1. Ten thermocouples (TC) are spot welded to the specimen, see Figure B.1.

Table B.1 — Thermocouple positions for stage 1

TC control	15 mm above notch radius
TC monitor	15 mm 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



Key

C TC control
M TC monitor
F1 face 1
F2 face 2
S1 side 1
S2 side 2
x distance from top of the feature where a TC can be spot welded which will not compromise the test
y distance from bottom of the feature where a TC can be spot welded which will not compromise the test
Numbers refer to individual positions of the TCs.

Figure B.1 — Schematic stage 1 TC arrangement (10 TCs)

Stage 1 can be considered complete when the temperature deviation across the specimen gauge section is within the limits set out in 5.2.1. On completion of stage 1, a second profile (stage 2) can be performed on the same specimen, only with a total of six TCs. The four TCs within the gauge section are retained along with the control and monitor TCs the rest are removed (see Figure B.2). This new profile confirms another issue uniquely seen with radiant lamp furnaces, the effect of 'shadowing'. The upper TCs lay across the specimen surface and, although less than 2 mm 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 deviation across the specimen with fewer TCs covering the surface. To proceed to stage 2, remove the redundant TCs (see Table B.2 and Figure B.2 for the 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.

B.3 Stage 2 thermal profile layout

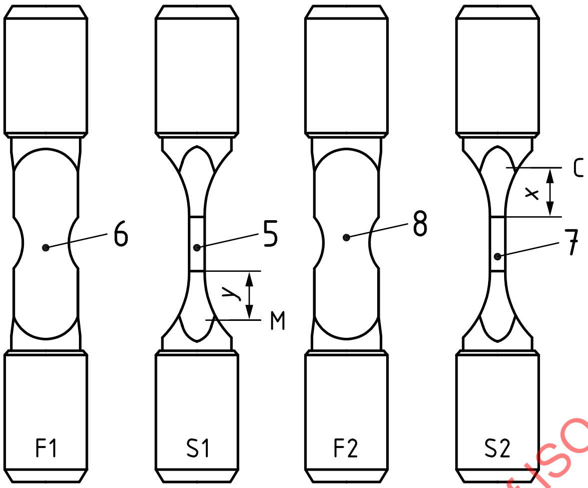
A dummy specimen which is not used for the test and only used for profiling should be configured according to Table B.2. (6 TCs, see Figure B.2)

Table B.2 — Thermocouple positions for stage 2

TC control	15 mm above notch radius
TC monitor	15 mm below notch radius
TC5 side 1	Notch centre
TC6 face 1	Centre

Table B.2 *(continued)*

TC7 side 2	Notch centre
TC8 face 2	Centre



Key

C TC control

M TC monitor

F1 face 1

F2 face 2

S1 side 1

S2 side 2

x distance from top of the feature where a TC can be spot welded which will not compromise the test

y distance from bottom of the feature where a TC can be spot welded which will not compromise the test

Numbers refer to individual positions of the TCs.

Figure B.2 — Schematic stage 2 TC arrangement (6 TCs)

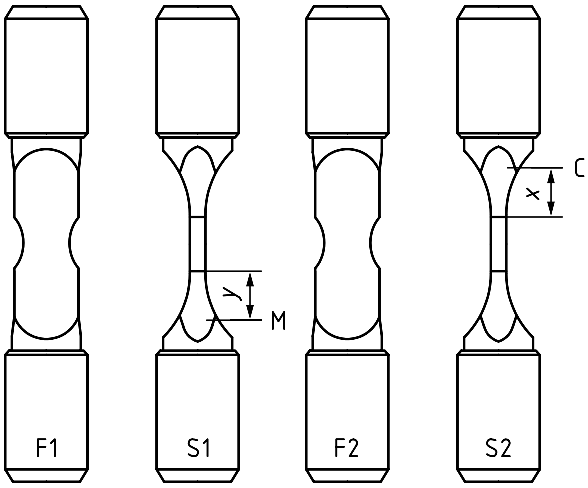
Stage 2 can be considered complete when the temperature deviation across the specimen gauge section is within the limits set out in 5.2.1. Stage 3 can be performed after removing the four TCs at the gauge section but retaining the control and monitor TCs (see Figure B.3). The temperature profile focuses on matching the profile of the monitor TC from stage 2. The furnace heating control and air cooling can be adjusted to allow for the imbalance caused by the TC removal. To proceed to stage 3, remove the redundant TCs (see stage 3 layout Table B.3 and Figure B.3) 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.

B.4 Stage 3 thermal profile layout

A dummy specimen which is not used for the test and only used for profiling should be configured according to Table B.3. (2 TCs, see Figure B.3)

Table B.3 — Thermocouple positions for stage 3

TC control	15 mm above notch radius
TC monitor	15 mm below notch radius



Key

C TC control

M TC monitor

F1 face 1

F2 face 2

S1 side 1

S2 side 2

x distance from top of the feature where a TC can be spot welded which will not compromise the test

y distance from bottom of the feature where a TC can be spot welded which will not compromise the test

Figure B.3 — Schematic stage 3 TC arrangement (2 TCs)

Stage 3 can be considered complete when the temperature deviation across the specimen gauge section is within the limits set out in 5.2.1. Stage 3 can be performed after removing the four TCs at the gauge section but retaining the control and monitor TCs (Table B.3 and Figure B.3). The temperature profile focuses only on matching the profile of the control and monitor TCs from stage 2. The furnace heating control and air cooling can be adjusted to allow for the imbalance caused by the TC removal. Once stage 3 has been successfully profiled, a test specimen can replace the dummy profile specimen for final validation.

B.5 Test specimen – (2 TCs)

The test specimen should be placed in the same position in relation to the depth 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 TCs to the shoulders (identical to stage 3, Table B.3 and Figure B.3). After the successful thermal profile has been confirmed the testing can begin.

In the case of rectangular specimens with 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 should 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 specimen.

NOTE Positioning of the control and monitor thermocouples can be varied according to the stress concentrations expected with the particular specimen geometry. Moving these two thermocouples closer to the notch radius has been found to improve accuracy of profiling and provide better temperature control. Refer to geometry stress models for the best positioning of these two thermocouples.

