TECHNICAL SPECIFICATION

ISO/TS 21913

First edition
2022-06

Temperature verification method applied to dynamic fatigue testing

Méthode de vérification de la température appliquée aux essais de fatigue dynamique

Reference number
ISO/TS 21913:2022(E)

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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).

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This document was prepared by Technical Committee ISO/TC 164, *Mechanical Testing of Metals*, Subcommittee SC 05, *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

It is the aim of this document to provide methodologies to verify the error in indicated measurement relative to the actual temperature of the specimen test piece. Therefore, it is essential to account for all factors, inclusive of environmental effects; not limiting the assessment to, for example, the performance of a recording system and the thermoelectric coefficient of a batch of thermocouple wire.

Certain types of test and advanced simulation rely on accurately controlled and rapidly changing temperature during the test, usually synchronised with control of mechanical loading. Within the scope of this document, that would usually be a thermo-mechanical fatigue test.

Where temperature varies deliberately and rapidly during the test, it is appropriate to verify the degree of time lag in system temperature reading. Without this evaluation (and implicitly a correction) then either the apparent temperature accuracy or the phase accuracy may need to be unnecessarily reduced.

This document has been written with the intention of using congruent language and approach to that used for calibration of extensometers[1] and verification of force measurement[2][3].

Temperature verification method applied to dynamic fatigue testing

1 Scope

This document establishes verification procedures to determine the accuracy, speed of response, and stability of temperature measurement for materials testing equipment. These procedures are specified for the expected use in fatigue tests on metals where these characteristics are important to the fidelity of tests at high or varying temperature.

The principles set out include sufficient provision for both contacting and non-contacting methods of temperature measurement.

This document is for the end-to-end verification of registered value compared with "true" specimen temperature at the point of measurement. It cannot be used to specify the correct method or location of measurement.

NOTE The methodologies could be found applicable to test types beyond mechanical fatigue of metals, but that is outside the remit of this document.

2 Normative references

There are no normative references in this document.

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
test system
equipment used to perform the (fatigue) test during which this temperature measurement is to be utilised.

Note 1 to entry: This includes the gripping or fixtures, a representative specimen, the heating system (all parts which influence the measurement), measurement conditioning device (e.g. thermocouple conditioning system), data recording device and software.

Note 2 to entry: This verification is expected to take place on a complete test system, but it does not strictly require the presence of the load frame provided that all parts influencing the specimen environment are held in a representative configuration.

Note 3 to entry: The operating environment of the test system should be considered as part of the verification, because changes in temperature of conditioning electronics can affect the measurement, especially if the cold junction of a thermocouple or the detector array of a thermo-optical device is not at constant temperature.

Note 4 to entry: to entry:: Good laboratory conditions would typically be maintained by some form of climate control, but that is not always possible and it does not guarantee to prevent local problems for specific instruments.

3.2
representative specimen
test piece to be used in the verification process

Note 1 to entry: It should be of the same dimensions and material as the specimen(s) to be tested. In certain cases this may be unfeasible so a very similar geometry to that expected in the final test schedule, with comparable conductivity and emissivity should be used. Ideally, this would be an actual test specimen, but some deviation is acceptable, provided it does not significantly affect the heat transfer characteristics of the system.

3.3
reference system
independent measurement system to be used to verify the *test system* (3.1)

Note 1 to entry: This should have a resolution at least 3 times smaller than that which will be published for the verification (preferably more than 5 times) and should be traceable to a certified constant reference.

3.4
resolution
resolution of the temperature measurement system
fluctuation amplitude (half of the difference between maximum and minimum indicated values) of the noise on the indicated temperature, over a period of 30 s or 30 consecutive readings at the intended rate of data acquisition (whichever is larger)

Note 1 to entry: expressed in K or °C.

Note 2 to entry: Stated for specific temperature test point(s),or may be described as a function of indicated temperature.

3.5
bias error
bias error of the temperature measurement system
difference between indicated temperature and reference measurement, for the mean average of values measured over 30 s or 30 consecutive readings at the intended rate of data acquisition (whichever is larger) at constant temperature

Note 1 to entry: expressed in K or °C.

Note 2 to entry: Alternatively, the average of values during one complete loading cycle may be used for slower isothermal cycles, whose duration exceeds 30 s.

Note 3 to entry: Stated for specific temperature test point(s), or may be described as a function of indicated temperature.

3.6
measurement drift
maximum variation between indicated temperature and reference measurement, during a representative test period

Note 1 to entry: expressed in K or °C.

Note 2 to entry: Stated for specific temperature test point(s), or may be described as a function of indicated temperature.

3.7
time lag
delay, between a known change in specimen temperature and the resultant change in indicated temperature

Note 1 to entry: expressed in seconds.

Note 2 to entry: This determination is made on the basis of delay in rate of temperature change, thus requires a method of heating capable of significant changes in specimen heating rate within a few seconds.

3.8
stabilisation time
amount of time after a change in temperature ramp rate, during which the combination of heating system and measurement device leads to an additional level of error in reading

Note 1 to entry: This is pertinent to variable temperature tests (typically thermo-mechanical fatigue) where certain combinations of temperature control system and measurement device can lead to a temporarily unstable or significantly inaccurate measurement, at points when there is a significant change in heat flow into or out of the specimen. It will generally not be relevant to isothermal test scenarios.

3.9
in situ verification
verification performed with the complete *test system* (3.1) in a fully assembled state, with all system components which will be present in the test

Note 1 to entry: including (but not limited to):

— Mechanical grips or other fixtures used to introduce loads to the specimen

— Furnace or temperature chamber or other environmental enclosure

— Transparent or open ports used to allow access to for other monitoring or measurement devices

— Baffles or wadding used to prevent unintended convective heat loss

— Shields or sheathing or other materials used to protect transducers

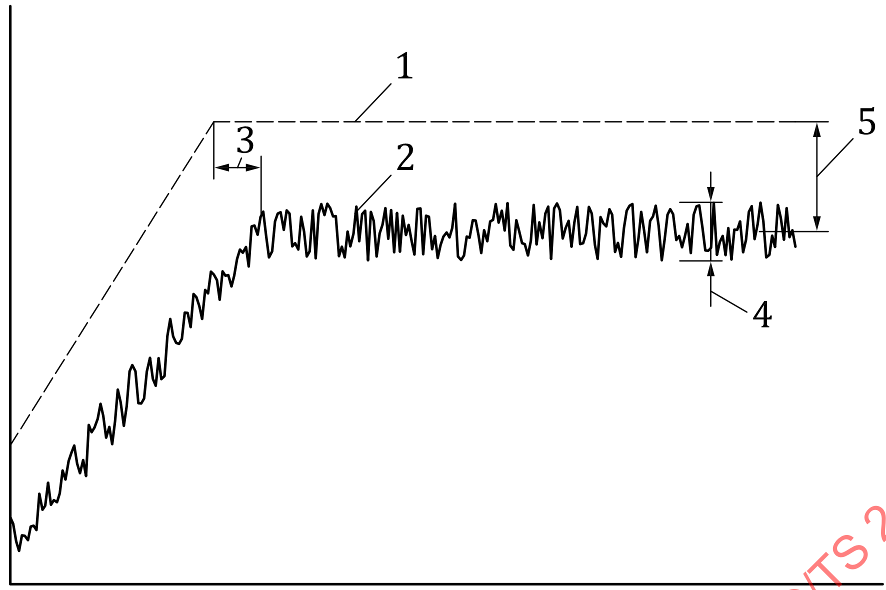
— Cooling systems such as fans or water circulators

— Transducer extension cables

Note 2 to entry: The purpose of using a fully representative verification is to capture errors which may be introduced by “parasitic” heating or cooling effects on the measurement device.

4 Measurement behaviour

Figure 1 provides a schematic representation summarising the characteristic behaviours of interest in this document, as described by the terms defined in 3.4 to 3.9, in the context of how they would be observed during a ramp-dwell test.



Key

Vertical axis: temperature
Horizontal axis: time
1 model specimen temperature
2 indicated specimen temperature corresponding to model
3 time lag
4 resolution (of the temperature measurement system)
5 isothermal bias error

Figure 1 — illustration of temperature measurement characteristics

Note 1 to entry a separate time lag will also be present between the command signal of the temperature control system and the specimen temperature. This is not the same as the time lag to be measured by the methods in this document, although a similar quantification method is possible.

Annex A provides general information on common temperature measurement techniques for specimens in fatigue test systems. These are intended to assist in consideration of techniques for both the test system and the reference system,

5 Representative verification equipment

5.1 Reference measurements

The reference system should be capable of providing a measurement whose centre can be localised within < 2 mm from the central measurement point to be verified and should be < 1 mm where possible. Where possible, any aspect of area-averaging should be comparable between the reference and the test system.

The verified accuracy and resolution of the test system cannot exceed that of the reference system. (That is to say, an isothermal accuracy of 0,1 °C could not be verified using a reference system whose resolution is only 0,5 °C).

The reference system should be stable (or have a proven, repeatable, drift correction) to better than 1 % of reading in °C, over the duration of the verification process at the selected temperature(s). For thermocouple-based references, the cold junction temperature should be appropriately controlled, for example using a “triple point” bath or similar device.

NOTE Detailed discussion of laboratory equipment, resolution and uncertainties in the context of thermocouple verification can be found in ASTM E2846[7].

5.2 Direct physically connected thermocouples (welded to specimen)

At the time of writing, an unsheathed thermocouple, with thin wires (<0,25 mm), welded to the surface of a specimen is generally considered the most reliable, practical method of measuring the skin temperature of a metallic specimen[6] and there is a published European code of practice for use in fatigue testing[7].

For that reason, it should be acceptable to verify this type of measurement on the basis of a summation of errors, which should include (but not be limited to) errors generated by:

— thermocouple conductor composition

— use of thermocouple compensating cables

— conditioning electronics calibration

— cold junction temperature stability

ASTM E2846[7] provides some guidance on use of this approach and developing an expanded uncertainty. ASTM E220[10] provides a normative calibration method for an individual thermocouple before integration into the test system.

This method of determination is not infallible and great care should be taken in ensuring correct placement of wires and good, clean, conductive weld points. It is necessary to eliminate sources of stray EMF, by ensuring close interlinking of earth between specimen and test system (note that a mechanical test frame does not always have an earth link to the temperature measurement electronics in use), and avoiding unbalanced induced current effects from passing thermocouple conductors near to strong electromagnetic fields.

If at all possible, the system should be subject to a full in situ verification, even if frequent partial verifications are performed on system components off-line.

5.3 Contacting thermocouples and other contacting devices not welded to specimen

A full in situ verification should be performed if a contacting device is used (as opposed to a welded thermocouple).

Many fatigue tests are performed using temperature “probes” contacting the specimen, but not welded to the surface (see Annex A). This can take the form of:

— a sheathed thermocouple, whose tip is gently spring-loaded against the surface

— an unsheathed thermocouple, bead welded and tied onto the specimen

— an unsheathed thermocouple, with its junction point held against the specimen by tensioning the wires

— other devices and placement methods

This can be a more practical solution than welding, due to the fact that it allows the measurement location to be placed within the parallel length or gauge length, without, in theory, interfering with the surface condition of the specimen (which the normative references mentioned in this document require to be tightly controlled). Furthermore, performing a good, clean thermocouple weld demands considerable skill on the part of the operator. However, in this case, environmental effects could add significantly to the total error. For example, the insulating effect may be measurable if a binding of ceramic cord is used to hold the probe in place.

5.4 Non-contacting thermo-optical devices

A full in situ verification should be performed if a non-contacting device is used. If not, then the verification should be performed with an optically equivalent path (i.e. apertures and lenses) between source or target and detector.

Calibration methods and guidance on use of this type of equipment may be found in ISO 10880[11] and ISO 18251-1[12]. ASTM E1933[13] defines a normative method for measuring emissivity.

5.4.1 Constant emissivity coatings

In the case that an infrared camera or pyrometer system is in use with a constant emissivity coating, a similar methodology to that given in 5.2 for welded thermocouple systems is acceptable. In this case a summation of errors should be used, which should include (but not be limited to) errors identifiable from:

— variability in coating emissivity and thickness

— black body transducer calibration

— transducer element temperature stability

— viewing angle of surface

— reflected radiation from other sources

Nonetheless, care should be taken, since problems can occur with coatings due to disbonding from the surface and flaking under high strains or prolonged exposure to very high temperature. When this happens, the coating will no longer retain the same relationship to the bulk temperature of the specimen.

NOTE Use of a coating over the entire specimen surface will affect the result of a mechanical test and the practitioner needs to consider whether it affects how representative or comparable the data generated will be.

5.4.2 Native surfaces

For some tests, a native surface may be usable, typically oxidised prior to mechanical testing by pre-conditioning at test temperature under an oxidising atmosphere. This can provide a stable oxide layer, resulting in constant emissivity needed for reliable readings. However, this is not always reliable for reasons including: change in chemical composition; change in layer thickness; roughening or spalling due to high strains or prolonged exposure to very high temperature. Pre-oxidised surfaces may be beneficial for some tests, but in general, it cannot be assumed that it provides guaranteed stability during a test.

For a pre-oxidised or otherwise native specimen surface, a full in situ verification is required.

6 Basic isothermal verification methods

6.1 Equipment set up

For isothermal verification in situ, the test system should be set up with a representative specimen, in the intended test configuration. This should include any data acquisition features in hardware or software, which could affect the measurement performance, such as expected signal range, data acquisition rate, or signal filtering.

The temperature control system should be set to maintain the temperature at the required target, the specimen heated to that set point and a suitable soak period allowed before commencing the measurement procedure.

6.2 Measurement of system resolution

At a stable temperature, data should be collected from the test system for not less than 30 s or 30 consecutive readings (whichever provides the larger sample).

System resolution should be declared as the amplitude [(maximum – minimum)/2] of this data set.

6.3 Summation of component bias errors

Identify the measurement system components or blocks which can be measured and attribute a component bias error to each and a component resolution for the digital signal conditioning and data acquisition. These may be measured directly off-line, or in situ, or it is acceptable to use a documented manufacturer's specification. Data acquisition system error may be assessed by use of a high precision voltage source to simulate the designated thermocouple output at the temperature(s) of interest, then following the procedures in 6.2 and 6.4 of this document.

The estimated system resolution and system bias error should be the summation of all the identified component values at the temperature(s) of interest.

For thermocouple-based measurement systems, it is acceptable to use the procedures for verification in a calibration laboratory that are laid out in ASTM E2846,[7] but note that this does not mandate the use of the same signal conditioning and data acquisition electronics. These should be accounted for, as should the influence of thermocouple attachment to the specimen.

6.4 Single point measurement of system bias error

At a stable temperature, data should be collected concurrently from the test system and the reference system for not less than 30 s or 30 consecutive readings (whichever provides the larger sample) on both systems.

System bias error should be declared as the difference between the mean of the test system data from the mean of the reference system data.

6.5 Multiple point assessment of resolution and bias error

For some measurement systems, both resolution and bias error vary as a continuous function of specimen temperature. Therefore, for verification of systems intended to run at varying temperatures, a series of no fewer than 3 single-point readings may be taken, as detailed above, and a curve fitted to the relationship with temperature.

If more than 5 single point readings are collected and a function can be identified with a correlation coefficient better than 0,98 then this relationship may be declared. If fewer than 5 points are available or if a good correlation cannot be identified, then a simple straight line should be applied such that all data points fall below it (i.e. the resolution or bias deduced from this line for any given temperature will ensure a conservative value in an uncertainty budget).

This pair of functions may be used to estimate the system resolution and bias error at intermediate temperatures. They should not be used to extrapolate to temperatures lying outside the range of single-point data available.

This clause should not be used where measurement drift (as per 6.2) exceeding 2 °C or 2 % of reading in °C (whichever is greater) is expected to take place during the time required to conduct the full series of verifications.

7 Evaluation of long term measurement drift

7.1 Single point method (Post-test measurement)

For the best confidence in the achieved accuracy of measurement during a test (single or series) of any significant duration, the isothermal bias error verification (Clause 5) should be performed immediately before and after the test.

Note 1 In the context of isothermal fatigue testing, the consideration of a significant duration typically would be exceeding 100 h. However, some combinations of test piece and measurement device might only cause readings to drift significantly with a much longer or a much a shorter time span.

The isothermal temperature achieved for the post-test verification should be within ±5 °C of that used in the original verification, according to the reference measurement system. This provides some latitude for the effectiveness of the temperature control system, while retaining a comparable measurement point. The measurement drift should then be determined as the difference between the measurement accuracy determinations before and after test.

The single point drift value should be used only as a contribution to the total measurement uncertainty for test conditions. It should not be used to make corrections to recorded data.

Note 2 This evaluation would not generally be feasible for every test. It has advantages in terms of certainty of what has happened during the specific test of interest, and using a simpler assessment, only when needed. The key disadvantage is that it provides no information on the time distribution of the drift; that is to say that 90 % of the measurement drift might have occurred during the first 10 % of the test time.

7.2 Time profile method (System assessment)

For a general assessment of drift, a representative specimen and measurement system may be subjected to a series of verification measurements during one continuous period held at temperature (or cycled for thermo-mechanical fatigue systems).

The temperature verification point used should be maintained within ±5 °C for all data included within the profile. Each measurement drift point should be determined as the difference in measurement accuracy determinations relative to the initial accuracy at test start.

The drift profile may be used to make corrections to the data record of a test conducted under comparable conditions.

8 Verification of dynamic temperature measurement

8.1 Time lag

8.1.1 Continuous ramp method

This method requires a multiple point assessment of bias error (5.3) to have been conducted.

The temperature control system should be set to a moderate ramp rate, such that both test system and reference system are capable of recording at least 10 readings per 5 °C of temperature increase or decrease. Data should be collected continuously by the test system and the reference system.

The bias error vs temperature relationship determined as per 5.2 should be used to correct the test system data. The data from the reference system should be used to identify a section of the data where temperature changes linearly with time over a range of at least 20 °C; time lag can be determined as the time difference between the when the reference system data and the corrected test system data crossed the midpoint of this temperature range.

8.1.2 Turning point method

This method requires a temperature control apparatus which is capable of significantly variable ramp rates in temperature.

The temperature control system should be set to a suitable ramp sequence, consisting of at least two consecutive ramp rates at whose temperature time gradient differs by at least a factor of 2 (this may be in the same direction, or ramp then dwell, or reversing). The rate and duration should be such that both test system and reference system are capable of recording at least 30 consecutive readings during each ramp stage. Data should be collected continuously by the test system and the reference system. The turning point can be determined as the intersection of two linear fit lines for the two heating rates, (using the same fitting method for each data set).

The time lag should be declared as the time difference between the turning point observed by the reference system and that observed by the measurement system (a schematic representation of this is shown in Clause 4, Figure 1).

NOTE This approach to time lag determination could also be applied to the lag between the control command and the resulting change in surface temperature, but that is outside the scope of this document and other complications can be generated by the control and heating devices.

8.2 Stabilisation time

Certain combinations of temperature control system and measurement device can lead to a temporarily unstable or significantly inaccurate measurement, at points when there is a significant change in heat flow into or out of the specimen.

The stabilisation time should be determined as the time between the identified turning point in temperature command signal and the re-establishment of a constant time lag or bias error.

NOTE In the present version, this document does not mandate a quantification of the magnitude of over- or under-reading. The reader is advised that use of an alternative measurement method is likely to be the simplest solution. However, if this is not feasible then it can sometimes be possible to introduce corrections to the temperature control waveform, if the behaviour is sufficiently repeatable.

9 Reporting

The report should include the following information as appropriate to the verification:

- Test system bias error, at specified temperature(s)
- Test system resolution, at specified temperature(s)
- Test system drift, at specified temperature(s)
- Test system details
- Reference system details
- Heating system details
- Specimen geometry and clamping method details
- Specimen material(s)

Additionally, a report for dynamic temperature measurement should include:

- Test system time lag
- Lag time determination conditions and method used
- Test system stabilisation time, at specified temperature(s)

Annex A
(informative)

Specific considerations for specimen temperature measurement during fatigue tests

A.1 Thermocouple attachment methods

A.1.1 Directly welded to specimen

This has been shown to be a highly reliable method of taking specimen temperature measurements using thermocouples. Equipment manufacturers recommend this, especially for feedback measurements for temperature control systems.

The key risk is that welding will lead to unacceptable surface damage to the specimen. Additionally, spot welding of thermocouples is a moderately skilled task, which is still more challenging for small specimens.

Guidance is provided on appropriate placement and wire separation in the European Code of Practice for TMF[9].

A.1.2 Sheathed thermocouples

In a significant number of cases, laboratories performing high volumes of isothermal tests on small specimens, prefer to use thin, sheathed thermocouples. They can be self-supporting and malleable, so operators perceive them to be robust and easy to re-use and to put in contact with the specimen surface. Typically, the tip is held against the specimen by the elastic flexure of the sheath, or in some cases a stiffer device is used with a spring-loading system.

This approach could perform poorly in verification according to this document . In broad terms this would tend to be caused by the thermocouple sheath experiencing more effective heating as well as lower conductive losses compared with the specimen. The user should anticipate that these effects will vary significantly with both target temperature and with specimen size.

A.1.3 Welded bead tied to specimen

This approach is a compromise between welding to the specimen and using a self-supporting design. It permits the user to benefit from the low thermal mass and lesser susceptibility to parasitic effects which are available by direct spot-weld, but with minimal risk of introducing damage to the specimen surface. However, the efficacy of contact with the specimen can be quite variable and dependent upon operator skill, with consequent effects on repeatability.

A.2 Parasitic effects on reading

Protruding thermocouple wires can cause over-reading during heating, especially if large diameter conductors or metallic sheaths are used, due to the effects of additional heat absorption and conduction into the thermocouple junction. Additionally, the thermocouple wires can shield the specimen from cooling air blast resulting in the measurement not being representative of the entire specimen. This effect is of particular concern when using radiant lamp heating systems and air blast cooling for cyclic temperature control, such as for thermomechanical fatigue[14].