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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

Reference number
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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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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 terminological 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

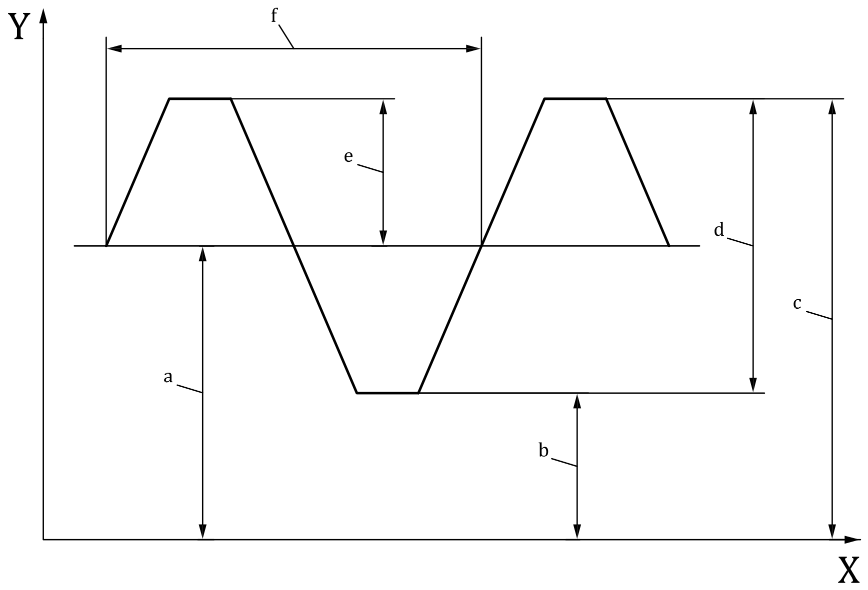
The number of cycles applied to the specimen shall be recorded such that for tests lasting less than 10 000 cycles, individual cycles can be resolved, while for longer tests the resolution should be better than 0,01 % of indicated life.

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.

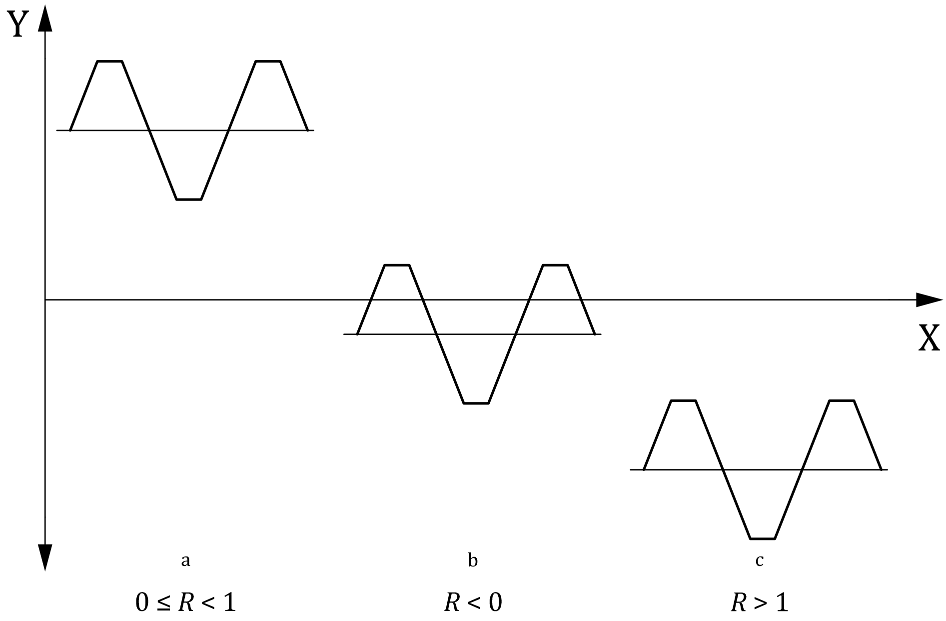
c Maximum force.

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.