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Metallic materials — Fatigue testing — Strain-controlled thermomechanical fatigue testing method

Matériaux métalliques — Essais de fatigue — Méthode d'essai de fatigue thermo-mécanique avec déformation contrôlée

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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.

ISO 12111 was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 5, *Fatigue testing*.

Introduction

The fatigue lives of structural components subjected to simultaneously occurring thermal and mechanical loadings are often of critical interest and concern to design engineers. A common approach to investigating the behaviours of materials subjected to combined thermal and mechanical loadings is to idealize the conditions of a critical material element on a uniaxial laboratory test specimen. The test condition is one where cyclic, theoretically uniform, within the test section, temperature and strain fields are externally imposed, simultaneously varied and controlled. Such a test is designated as "thermomechanical fatigue", commonly abbreviated as TMF.

In order to ensure reliability and consistency of results from different laboratories, it is necessary to generate and collect all data using test methodologies that comply with an established standard.

This International Standard addresses both the generation and presentation of TMF data.

Metallic materials — Fatigue testing — Strain-controlled thermomechanical fatigue testing method

1 Scope

This International Standard is applicable to the TMF testing of uniaxially loaded metallic specimens under strain control. Specifications allow for any constant cyclic amplitude of mechanical strain and temperature with any constant cyclic mechanical strain ratio and any constant cyclic temperature-mechanical strain phasing.

NOTE A list and sketch of the most common cyclic types is shown in Annex A.

The range of cycles considered corresponds to that which is generally considered as the low-cycle fatigue domain, that is, $N_f \leq 10^5$.

2 Normative references

The following referenced documents are indispensable for the application 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 7500-1:2004, *Metallic materials — Verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Verification and calibration of the force-measuring system*

ISO 9513, *Metallic materials — Calibration of extensometer systems used in uniaxial testing*

ISO 12106, *Metallic materials — Fatigue testing — Axial-strain-controlled method*

ISO 23718, *Metallic materials — Mechanical testing — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 23718 and ISO 12106 and the following apply.

3.1
stress
σ
F_i/A_o, where F_i is the instantaneous force and A_o is the original cross-sectional area at room temperature

3.2
original gauge length
L_o
length on the specimen between extensometer measurement points at room temperature and zero strain

NOTE This definition avoids the complexity of a continually varying gauge length due to thermal expansion and contraction.

3.3
gauge length
L
instantaneous length on the specimen between extensometer measurement points

3.4
strain
ε
$\Delta L/L_o$, where ΔL is the change in length and L_o is the gauge length measured at room temperature

3.5
total strain
ε_{tot}
algebraic sum of the mechanical and thermal strains:

$$\varepsilon_{tot} = \varepsilon_m + \varepsilon_{th}$$

3.6
thermal strain
ε_{th}
strain corresponding to the free expansion induced by a change in temperature

3.7
mechanical strain
ε_m
strain that is independent of temperature and is associated with the applied force on the specimen

3.8
elastic strain
strain component resulting when the stress is divided by the temperature-dependent Young's modulus

3.9
inelastic strain
strain component resulting when the elastic strain is subtracted from the mechanical strain

3.10
cycle
smallest segment of the strain-temperature-time pattern that is repeated periodically

3.11
maximum
greatest algebraic value of a variable within one cycle

3.12
minimum
least algebraic value of a variable within one cycle

3.13
mean
one-half of the algebraic sum of the maximum and minimum values of a variable

3.14
range
algebraic difference between the maximum and minimum values of a variable

3.15
amplitude
half the range of a variable

3.16
fatigue life
number of applied cycles, N_f, to achieve a defined failure criterion

EXAMPLE An example of this is found in 7.11.

3.17
hysteresis loop
closed curve of the stress-mechanical strain response during one cycle

3.18
mechanical strain ratio
R_ε
minimum mechanical strain divided by the maximum mechanical strain

3.19
phase angle
Φ
angle between temperature and mechanical strain, defined with respect to the temperature as reference variable

NOTE The phase angle is expressed in degrees. A positive phase angle ($0 < \Phi < 180$) means that the maximum of the mechanical strain lags behind the maximum temperature.

4 Symbols

D	diameter of grip end of specimen, mm
d	diameter of cylindrical gauge section, mm
E	modulus of elasticity, Young's modulus
L_o	original gauge length, mm
N_f	cycles to failure, cycles
n	cycle number
R_ε	mechanical strain ratio = $\varepsilon_{min}/\varepsilon_{max}$
T	temperature, °C
Δ	range of a parameter
ε	strain, unit in % or dimensionless
σ	stress, MPa
Φ	phase angle, degrees

Subscripts (if used):

m	mechanical
max	maximum
min	minimum
th	thermal
tot	total

5 Apparatus

5.1 Testing machine

5.1.1 General

The tests shall be conducted on a tension-compression machine designed for smooth start-up with no backlash when passing through zero force. The machine shall be capable of controlling strain and measuring force when applying the recommended waveform. It may be hydraulic or electromechanical.

The load frame shall have high lateral stiffness when the crosshead is in the operating position and accurate alignment (both parallelism and concentricity) between the load train support references.

The complete load train (including force transducer, pullrods/grips, and specimen) shall also have high lateral stiffness to minimize specimen bending.

5.1.2 Force measuring system

The force measuring system, comprising force transducer, conditioner and readout. This system shall meet the requirements of ISO 7500-1, Class 1 over the range of forces expected during the test series.

NOTE Class 1 requires that force indication errors should not exceed ± 1 % of reading over the verified range.

The force transducer shall be suitable for the forces applied during the test.

The force transducer shall be temperature compensated and not have a zero drift or sensitivity variation greater than 0,002 % of full scale per one degree Celsius. During the test, it shall be maintained within its temperature compensated range.

5.1.3 Specimen gripping device

The gripping device shall transmit the cyclic forces to the specimen without backlash for the duration of the test. The geometric qualities of the device shall ensure correct alignment in order to meet the requirements specified in 5.1.4.

NOTE It is good design practice to reduce the number of mechanical interfaces to a minimum.

The gripping device shall ensure that the alignment is reproducible over successive specimens.

The gripping device materials shall be selected so as to ensure correct functioning across the range of test conditions.

5.1.4 Load train alignment

Load frame, including grips, shall be aligned using a specimen, with a geometry as similar as possible to that of the test specimen, instrumented with strain gauges. The permitted maximum bending strain due to the machine shall be no more than 50 microstrain at zero force or 5 % of the applied axial mechanical strain, whichever is the greater. This shall be carried out at 12-month intervals and in the following events:

a) as part of the commissioning procedure of a newly acquired testing machine;

b) after an accidental buckling of a specimen, unless it can be demonstrated that the alignment has not changed; and

c) if any adjustment has been made to the load train.

NOTE A relevant procedure is given in VAMAS Report No. 42[13].

5.2 Strain measuring system

The strain measuring system (optical, mechanical, etc.) including the extensometer and its associated electronics shall conform to ISO 9513, Class 1.

For gauge lengths less than 15 mm, a Class 0.5 system is recommended.

The strain shall be measured on the specimen using an axial extensometer.

The extensometer shall be suitable for measuring dynamic strain over long periods during which there should be minimal drift, slippage or instrument hysteresis. It shall measure axial extension directly over the gauge length of the specimen.

The transducer section of the extensometer should be protected from thermal fluctuations that give rise to drift.

Given the transient nature of the temperature in a TMF test, it is recommended that the extensometer is actively cooled, so that the transducer section of the extensometer remains isothermal during the course of the test.

The kinematic design of contacting extensometry should be such that lateral or angular motions of the specimen contact zone do not cause the extensometer contact points or knife edges to slip.

The contact pressure and operating force of the extensometer should be low enough to avoid damaging the specimen surface and giving rise to crack initiation at the extensometer contact points or knife edges.

5.3 Heating system

The heating system shall be capable of applying the maximum heating and cooling rates required by the TMF test series.

To minimize radial temperature gradients with a direct induction heating system, it is advisable to select a generator with a sufficiently low frequency (typically in the several hundred kHz range and lower). This will help to minimize “skin effects” during heating.

During a test, the specimen temperature shall be measured using thermocouples, pyrometers, RTDs, or other such temperature-measurement devices.

For thermocouples, direct contact between the thermocouple and the specimen shall be achieved without causing incipient failure at the point of contact.

NOTE Commonly used methods of attachment are: resistance spot welding (outside the gauge length) and fixing by binding or by pressing a sheathed thermocouple against the specimen surface.

If the temperature within the gauge section is measured with an optical pyrometer, steps shall be taken during calibration to address possible variation in the specimen's thermal emissivity over the duration of the test. Potential solutions may include two-colour pyrometers and pre-oxidizing the specimen surface.

5.4 Instrumentation for test monitoring

A computerized system capable of carrying out the task of collecting and processing force, extension, temperature, and cycle count data digitally is recommended. Sampling frequency of data points shall be sufficient to ensure correct definition of the hysteresis loop especially in the regions of reversals. Different data collection strategies will affect the number of data points per loop needed, however, typically 200 points per loop are required.

Alternatively, an analog system capable of measuring the same data may be used and would include:

— an X-Y-Y recorder used to record force, extension, and temperature hysteresis loops;

— a strip-chart recorder for several time-dependent parameters: force, extension and temperature;

— a peak detector per signal;

— a cycle counter.

The recorders may be replaced with storage devices capable of reproducing the recorded signals either in photographic or analog form. These devices are necessary when the rate of recorded signals is greater than the maximum slew-rate of the recorder. They allow permanent records to be reproduced subsequently at a lower rate.

5.5 Checking and verification of the apparatus

The testing machine and its control and measurement systems should be checked regularly.

Specifically, each transducer and associated electronics shall always be checked as a unit.

— The force measuring system(s) shall be verified according to ISO 7500-1.

— The strain measuring system(s) shall be verified according to ISO 9513.

— The temperature measuring system(s) shall be traceable to the relevant national standard.

It is good practice before each series of tests to check the base length of the extensometer, the force cell and extensometer calibrations using a shunt resistor or other suitable method and the thermocouple or pyrometer calibrations.

6 Specimens

6.1 Geometry

6.1.1 General

The total specimen bending is comprised of bending from load frame misalignment and specimen bending from test specimen asymmetry. To minimize the bending contribution due to the test specimen, it is important to carefully control deviations from the intended test specimen geometry.

6.1.2 Solid round specimens

6.1.2.1 The gauge portion of the specimen in a TMF test 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.

This geometry should fulfil the following conditions:

— provide a uniform cylindrical gauge portion;

— minimize the risk of buckling in compression to avoid failure initiation at the transition radius;

— provide a uniform strain distribution over its whole gauge portion;

— allow the extensometer to measure the strain without interference or slippage.