# INTERNATIONAL STANDARD

# ISO
# 12111

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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.

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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**
$\sigma$
$F_i/A_o$, 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**
$\varepsilon$
$\Delta L/L_o$, where $\Delta L$ is the change in length and $L_o$ is the gauge length measured at room temperature

**3.5**
**total strain**
$\varepsilon_{tot}$
algebraic sum of the mechanical and thermal strains:

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

**3.6**
**thermal strain**
$\varepsilon_{th}$
strain corresponding to the free expansion induced by a change in temperature

**3.7**
**mechanical strain**
$\varepsilon_m$
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**
$R_\varepsilon$
minimum mechanical strain divided by the maximum mechanical strain

**3.19**
**phase angle**
$\Phi$
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

$R_\varepsilon$               mechanical strain ratio = $\varepsilon_{min}/\varepsilon_{max}$

$T$               temperature, °C

$\Delta$               range of a parameter

$\varepsilon$               strain, unit in % or dimensionless

$\sigma$               stress, MPa

$\Phi$               phase angle, degrees

Subscripts (if used):

m               mechanical

max               maximum

min               minimum

th               thermal

tot               total

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# 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.

The parallel length of the specimen shall be longer than the extensometer gauge length. However, it shall not exceed $L_o + (d/2)$ to reduce risk of failure outside the extensometer gauge length.

**6.1.2.2**    Taking into account these requirements, the experience gained by a large number of laboratories and the results of calculations taken from different types of specimens (see References [1], [2], [3], [10] and [11]), the following geometric dimensions [see Figures 1 to 4 in which $(L_o/d) > 2$] are specified:

—  diameter of cylindrical gauge length: $d \geq 5$ mm;

—  gauge length: $L_o \geq d$;

—  transition radius (from parallel section to grip end): $r \geq 2d$;

—  diameter of grip end: $D \geq d$;

—  length of reduced section or distance between grips for a constant cross section specimen: $L_c < 8d$.

Other geometric cross sections and gauge lengths may be used for specimens provided that the uniform distribution of stresses, strains and temperatures in the gauge length are ensured.

**6.1.2.3**    It is important that general tolerances of the specimens respect the three following properties:

—  parallelism            $= 0{,}005D$ or better;

—  concentricity          $= 0{,}005D$ or better;

—  perpendicularity      $= 0{,}005D$ or better.

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

**6.1.2.4**    The dimensions of end connections shall be defined as a function of the testing machine. The recommended end connections are as follows:

—  smooth cylindrical connection (hydraulic collets);

—  button-end connection.

The gripping device shall locate the specimen and provide axial alignment. It should not permit backlash. The design of the gripping device will depend on the specimen end details. A number of examples are given in Figures 1 to 4.

In general, designs in which specimen alignment depends on screw threads are <u>not</u> recommended.
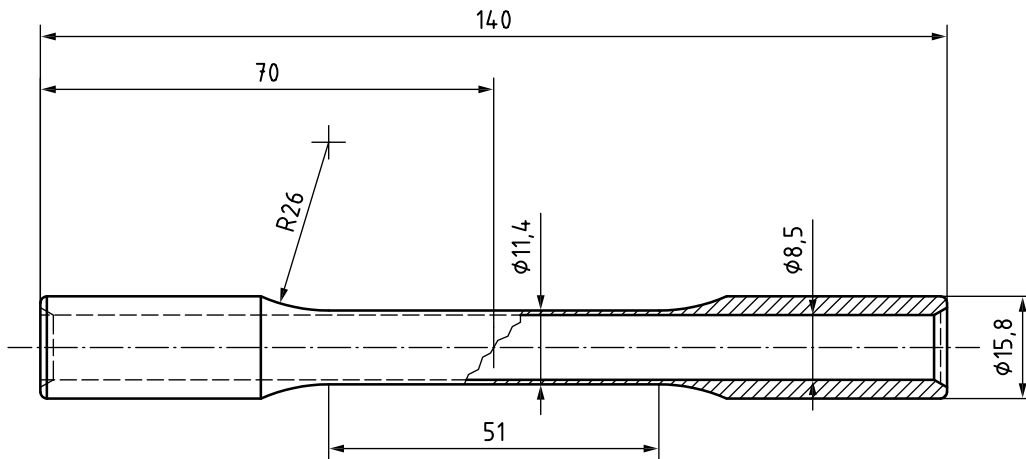
Dimensions in millimetres

**Figure 1 — Cylindrical smooth shank TMF tube** (see Reference [1] in the Bibliography)
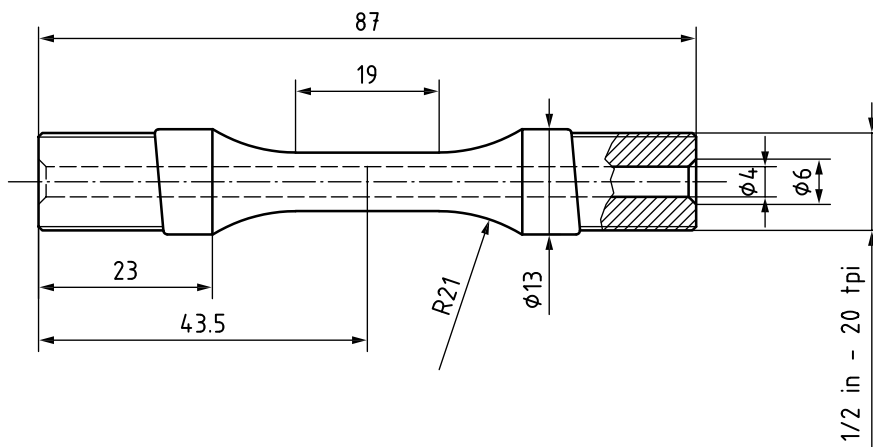
Dimensions in millimetres

**Figure 2 — Cylindrical threaded shank TMF tube** (see Reference [2] in the Bibliography)
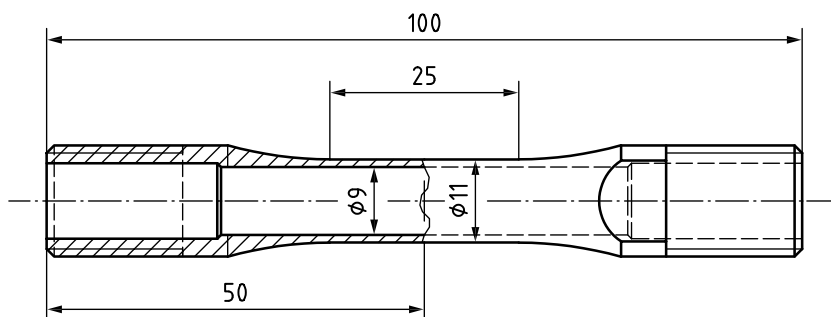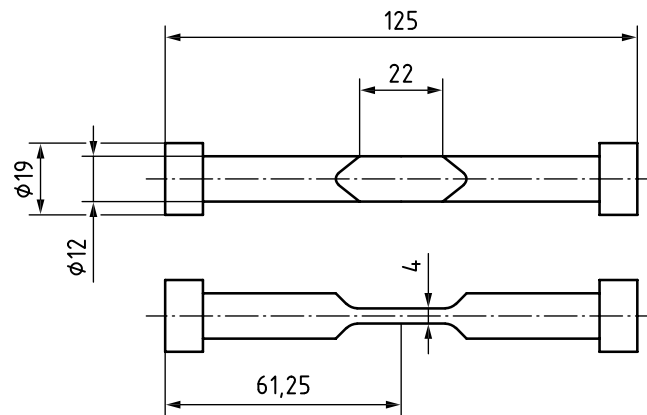
Dimensions in millimetres

**Figure 3 — Cylindrical smooth shank TMF tube** (see Reference [3] in the Bibliography)

Dimensions in millimetres



**Figure 4 — Rectangular solid sample** (see Reference [10] in the Bibliography)

### 6.1.3  Round tubular specimens

In general, the considerations discussed in 6.1.2 also apply to tests on tube specimens. In addition, tolerances should be maintained such that wall thickness variation is maintained within 1 % of the nominal wall thickness around the circumference.

Tubular specimens have the advantage over solid specimens of minimizing the radial temperature gradient.

The specimen wall should be sufficiently thick in order to be representative of the material microstructure.

As a general rule, the ratio of mean diameter to wall thickness should be in the range 5 to 30, in order to satisfy thin-wall specimen criteria. Buckling tendencies at high axial strain ranges will tend to push specimen design to the lower end of this range.

### 6.1.4  Solid rectangular specimens

In general, the considerations discussed in 6.1.2 also apply to tests on rectangular specimens. However, these tests require specific geometries and fixtures in order to avoid problems of buckling.

The gripping system may necessitate the use of flat mechanical or hydraulic jaws. However, flat parallel jaw faces require additional measures to ensure alignment in the two unconstrained degrees of freedom.

In general, 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 end thickness as well as to avoid failure in the grips.

## 6.2  Preparation of specimens

In any TMF test programme designed to characterize the intrinsic properties of a material, it is important to observe the recommendations given in 6.3 to 6.7 in the preparation of specimens. A deviation from these recommendations is possible if the test programme aims to determine the influence of a specific factor (surface treatment, oxidation, etc.) that is incompatible with these recommendations. In all cases, this deviation shall be noted in the test report.

## 6.3 Machining procedure

### 6.3.1 General

The machining procedure selected may produce residual stresses on the specimen surface likely to affect the test results. These stresses may be induced by heat gradients at the machining stage, stresses associated with deformation of the material or microstructural alterations. Their influence is less marked in tests involving relatively high temperatures because they are partially or totally relaxed upon preliminary thermal cycling. However, they are to be reduced by using an appropriate final machining procedure, especially prior to a final polishing stage. For harder materials, grinding rather than tool operation (turning or milling) may be preferred.

— Grinding: from 0,1 mm of the final dimension at a rate of no more than 0,005 mm/pass.

— Polishing: remove the final 0,025 mm with papers of decreasing grit size; it is recommended that the final direction of polishing be along the specimen axial direction.

— Tubular test pieces: the bore should be fine-honed.

### 6.3.2 Alteration in the microstructure of the material

This phenomenon may be caused by the increase in temperature and by the strain-hardening induced by machining. It may be a matter of a change in phase or more frequently of surface recrystallization. The immediate effect of this is to make the test invalid as the material tested is no longer the initial material. Every precaution should therefore be taken to avoid this risk.

### 6.3.3 Introduction of contaminants

The mechanical properties of some materials deteriorate when in the presence of certain elements or compounds. An example of this is the effect of chlorine on steels and titanium alloys. These elements shall therefore be avoided in the products used (cutting fluids, etc.). Rinsing and degreasing of specimens prior to storage is also recommended.

## 6.4 Sampling and marking

The sampling of test materials from a semi-finished product or a component may have a major influence on the results obtained during the test. It is therefore necessary for this sampling to be carried out with full knowledge of the situation.

A sampling drawing, attached to the test report, should, when available, indicate clearly

— the position of each of the specimens,

— the characteristic directions in which the semi-finished product has been worked (direction of rolling, extrusion, etc., as appropriate),

— the marking of each of the specimens.

It is recommended that specimens carry a unique identifying mark throughout their preparation. This may be applied using any reliable method in an area not likely to disappear during machining or likely to adversely affect the quality of the test.

## 6.5 Surface condition of the specimen

The surface conditions of the specimens may have an effect on the test results. This is generally associated with one or more of the following factors:

— the specimen surface roughness;

— the presence of residual stresses;

— alteration in the microstructure of the material;

— introduction of contaminants.

The recommendations below allow the influence of these factors to be minimized.

The surface condition is commonly quantified by the mean roughness or equivalent (e.g. ten point roughness or maximum height of irregularities). The importance of this variable on the results obtained depends largely on the test conditions, and its influence is reduced by surface corrosion of the specimen or inelastic deformation.

It is preferable, whatever the test conditions, to achieve a mean surface roughness of less than 0,2 µm $R_z$ (or equivalent).

Another important parameter not covered by mean roughness is the presence of localized machining scratches. Finishing operations should eliminate all scratches transverse to the loading direction. Final grinding followed by longitudinal mechanical polishing is particularly recommended. A low magnification check (approximately $\times 20$) should not show any transverse scratches.

If heat treatment is to be carried out after rough finishing of the specimens, it is preferable to carry out the final polishing after the heat treatment. If this is not possible, the heat treatment should be carried out in a vacuum or in inert gas to prevent oxidation of the specimen. Stress relief is recommended in this case.

This treatment should not alter the microstructural characteristics of the material under study. The specifics of the heat treatment and machining procedure shall be reported with the test results.

## 6.6 Dimensional check

The dimensions should be measured on completion of the final machining stage using a method of metrology that does not alter the surface condition.

## 6.7 Storage and handling of specimens

After preparation, the specimens shall be stored so as to prevent any damage (scratching by contact, oxidation, etc.). The use of individual boxes or tubes with end caps is recommended. In certain cases, storage in a vacuum or in a desiccator filled with silica gel is necessary.

Handling should be reduced to the minimum necessary.

Particular attention shall be given to marking the specimens. It is desirable for both ends of the specimens to be marked so that after failure each specimen half may still be identified.

# 7 Procedure

## 7.1 Laboratory environment

A TMF experiment is complex in nature, and the quality of results obtained depends upon the methods employed as well as the environment.

The tests should be carried out under suitable environmental conditions:

— uniform ambient temperature;

— minimal atmospheric pollution (dust, chemical vapours, etc.);

— no extraneous electrical signals that will affect machine control and data acquisition;

— minimal extraneous mechanical vibrations.

## 7.2 Specimen mounting

The specimen shall be placed in position and gripped with minimal extraneous forces. Care shall be taken to not scratch the external (and internal, in the case of a tube) gauge section surface while mounting contact-type extensometers.

## 7.3 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 [5].

Any hysteresis existing at any given temperature point in the temperature, $T$ versus thermal strain, $\varepsilon_{th}$ cycle under zero force conditions should be no greater than 5 % of the $\Delta\varepsilon_{th}$ induced.

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: $\pm 5$ °C or 1 % of the test temperature range from the stabilized (i.e. following the establishment of dynamic equilibrium) value(s) 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 from the stabilized value(s) at any given instant in time within the cycle by more than $\pm 3$ °C.

## 7.4 Temperature gradients

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

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

Axial (all specimen types):

$\pm 2$ % $\Delta T$

or   $\pm 10$ °C

Circumferential (rounds):

$\pm 1 \% \, \Delta T$

or $\pm 5 \, °C$

Transverse (flats):

$\pm 7 \, °C$

where $\Delta T$ is the cyclic temperature range in the cycle, given in °C and measured under dynamic conditions.

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

It is advisable to examine and restrict the dynamic temperature gradients existing through the thickness of the specimen (i.e. radial gradients) within the axial gauge section. Such gradients are of particular concern when rapid temperature rates are used.

This gradient may be measured by attaching thermocouples to the inside and outside surfaces for tubular specimens at the same axial location. When using solid specimens, a hole may be drilled out, removing as little material as possible, to enable a thermocouple to be mounted internally.

An optical pyrometer may be used to ascertain surface temperature gradients during cycling.

## 7.5   Mechanical strain control

The mechanical strain cycle shape shall remain constant throughout the duration of the test.

The mechanical strain ($\varepsilon_m$), as calculated by:

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

shall not deviate from the desired value by more than 2 % of the mechanical strain range, at any given instant in time within the cycle. The desired value is established by the difference between the total strain and the compensating thermal strain. Both the mechanical strain and the temperature should remain cyclically constant and synchronized throughout the duration of the test. No cumulative error is permitted.

## 7.6   Thermal strain compensation

### 7.6.1   General

To achieve a desired mechanical strain, the temperature induced thermal strain should be actively compensated during the test.

### 7.6.2   Compensation methods

#### 7.6.2.1   Overview

Several methods can be employed to compensate for the induced thermal strains. These methods may vary depending upon specific testing equipment, control hardware and control software. However, the overriding objective is to provide sufficiently accurate thermal strain compensation at any given point within the cycle, so as to facilitate accurate control of the mechanical strain component. Two commonly employed methods are given in 7.6.2.2 and 7.6.2.3.

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#### 7.6.2.2 Method 1

The thermal strain is compensated by recording the free expansion thermal strains (specimen at zero force) as a function of specimen temperature prior to test initiation. The temperature cycle used must be identical to that used for the subsequent thermomechanical fatigue test. These values can be fitted to an appropriate algebraic function or functions (typically, one for the heating portion of the cycle and one for the cooling) where temperature is the independent variable. The function(s) can then be used to calculate the instantaneous compensating strains for the thermomechanical fatigue test in real time.

This approach can be incrementally expressed by:

$$\varepsilon_{tot} = \varepsilon_m(t) + \varepsilon_{th}(T)$$

where $T$ is the temperature at time, $t$.

#### 7.6.2.3 Method 2

The thermal strain is compensated by recording the free expansion thermal strains (specimen at zero force) as a function of cycle time prior to test initiation. The temperature cycle used must be identical to that used for the subsequent thermomechanical fatigue test. These recorded values can be recalled at the appropriate corresponding times within the cycle to provide the strain compensation values. This approach can be incrementally expressed by the following:

$$\varepsilon_{tot} = \varepsilon_m(t) + \varepsilon_{th}(t)$$

where $\varepsilon_{th}(t) \neq$ constant.

#### 7.6.2.4 Summary

Method 2 does not provide closed-loop control of mechanical strain and can result in a significant overstrain to the specimen if the desired specimen temperature is not consistently achieved.

It is generally not sufficiently accurate to take the free thermal strain range, divide it into equal time or temperature-based increments, and use this constant increment for subsequent compensation calculations. This approach does not account for the normal nonlinear thermal expansion ($\alpha$) nor does it account for potential temperature lags experienced during reversals. Method 1 will minimize damage to the specimen if a temperature problem develops during the test.

### 7.6.3 Compensation accuracy

The accuracy of the thermal strain compensation routine shall be checked prior to the initiation of the thermomechanical fatigue test by subjecting the specimen to thermal cycling in mechanical strain control, at zero mechanical strain. Here, the thermal strain compensation method shall be used to actively compensate for the induced thermal strain of the specimen.

During this cycle, the maximum acceptable resulting stress shall be calculated from the peak mechanical strains from the specific test being considered, along with the corresponding moduli for the two temperatures at which the maximum and minimum mechanical strains occur:

$$\sigma_{max} = 2\ \% \times \varepsilon_{max,m} \times E(T \text{ at } \varepsilon_{max,m})$$

$$\sigma_{min} = 2\ \% \times \varepsilon_{min,m} \times E(T \text{ at } \varepsilon_{min,m})$$

Allowable stress $\leq (\sigma_{max} - \sigma_{min})/2$.

The absolute values of the measured stresses during the thermal cycling at zero mechanical strain shall not exceed the allowable stress range as computed above, ensuring that the mechanical strain range controlled during the actual test is within 2 % of the mechanical strain range.

## 7.7 Temperature/mechanical strain phasing

Temperature/mechanical strain phasing is typically not a problem if a common control clock is employed for both temperature and mechanical strain.

The temperature value used in assessing the temperature/mechanical strain phasing shall be the response (feedback) value measured on the specimen during thermal cycling, and not the command values.

However, if two independent clocks are used, the following apply.

— The mechanical strain value used in assessing the temperature/mechanical strain phasing shall be that calculated from the instantaneous total strain and the compensating thermal strain component in time within the cycle:

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

— Throughout the duration of the test, the temperature/mechanical strain phase difference shall not exceed a 5°phase shift from that desired at any given instant in time within the cycle.

Typically, the temperature phasing is the response variable needing special attention. It is suggested that in determining the phase shift, one may measure the temperature and strain at the same instant in time, compare with the initial cycle, and thereby determine the phase shift. This phase shift should be monitored throughout the test.

Examples of typical strain/temperature phase relationships are given in Figure 5.
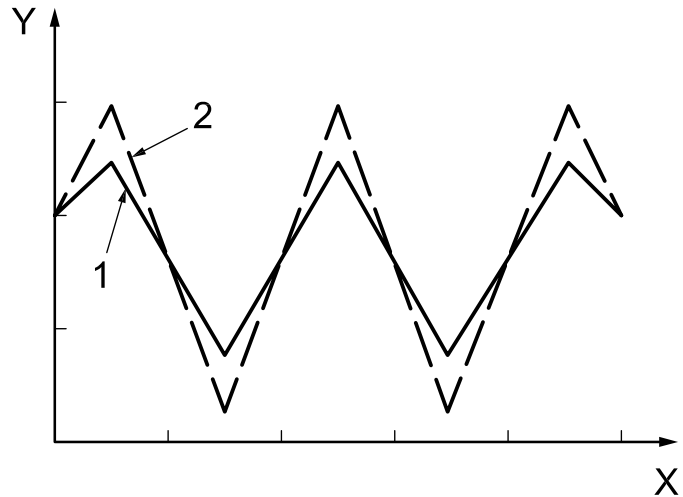
a) **In-phase TMF test** ($\Phi = 0$)



**Key**

X  time, $t$

Y  $\varepsilon_m$, $T$

1  $\varepsilon_m$

2  $T$
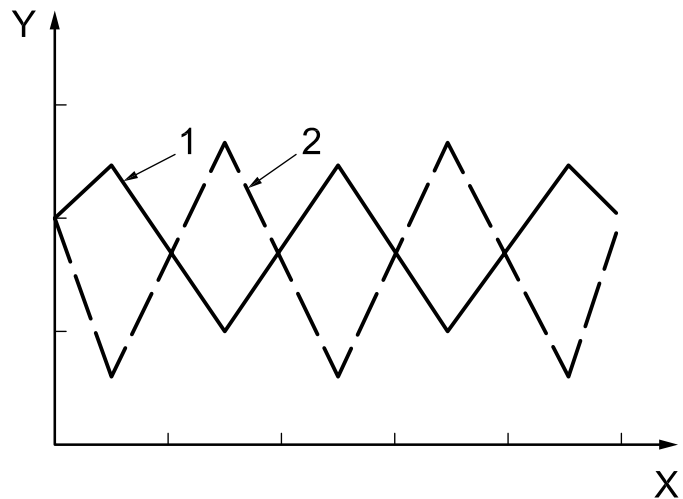
b) **Out-of-phase TMF test** ($\Phi = 180$)

**Figure 5 — Schematics of mechanical strain and temperature for in- and out-of-phase TMF tests**

## 7.8   Command waveforms

The waveforms for mechanical strain and temperature shall remain repeatable throughout the test program.

It is often desired to maintain a constant cyclic period for the series of tests within a single test and test program. In so doing, changes in the imposed mechanical strain range will necessarily cause a change in mechanical strain rate. However, it is recommended that the test-to-test mechanical strain rates vary by no more than a factor of 5.

## 7.9   Start of test

All tests within a series shall begin in the same direction of initial mechanical straining, tensile or compressive, unless the purpose of the study is to examine initial loading effects.

### 7.9.1 Preliminary measurements

#### 7.9.1.1 Modulus check

The tension and compression modulus values shall be checked, at a minimum, at both room temperature and at the maximum temperature (see Annex B) in the cycle to be run in order to verify (by comparison) that the extensometer is not slipping and is working properly. The modulus value so determined should not vary by more than 5 % from the known value. If the modulus varies by more than 10 % from the known modulus, the test shall not be continued.

#### 7.9.1.2 Thermal expansion

The thermal expansion shall be measured and recorded over the full temperature range of the TMF cycle. This measurement shall be made once for each specimen after dynamic temperature equilibrium is achieved under force control at zero force during thermal cycling conditions identical to those used for the TMF test.

### 7.9.2 Commencement of TMF mechanical straining

The mechanically induced strain of the TMF loading should then be started, with minimal time pause, at the temperature/time point in the cycle when $\varepsilon_m = 0$.

In the case where the TMF cycle does not have a point of $\varepsilon_m = 0$ (e.g. cycles with $R_\varepsilon > 0$), the mechanical strain may be gradually ramped to its minimum absolute value such that this value is reached at the appropriate temperature in the thermal cycle. At this point, the properly phased TMF cycle is immediately commenced. For large total strain amplitude tests, the mechanical strain may be increased to its final amplitude over multiple cycles to prevent overshoot. Such a gradual increase may also be required for materials that exhibit a serrated yielding phenomenon.

## 7.10 Monitoring the test

The control variables of specimen temperature and total strain must be monitored during the course of the test. The mechanical strain shall be maintained to the criteria set forth in 7.5, and the specimen temperature condition shall be maintained to the criteria set forth in 7.3.

## 7.11 Failure criteria

### 7.11.1 Specimen separation

The specimen is considered to have failed when there is total separation or fracture of the specimen into two parts at some location within the uniform gauge section. All failure locations should be recorded.

### 7.11.2 Tensile force drop

With this method, the specimen is considered to have failed when there is a specified (typically between 5 and 50 %) force drop from the stabilized peak tensile force or from the projected straight line locus of peak tensile stress versus cycles in the case of continuously softening materials.

### 7.11.3 Specimen cracking

A surface replication technique can be used for determining failure of the specimen. In this method, the fatigue test must be interrupted (see 7.13) at predetermined cyclic intervals to replicate the surface of the specimen, e.g. with acetyl cellulose film. The film is subsequently examined for surface connected cracks and failure is defined when the largest crack observed has grown to a specified length (typically between 0,1 mm and 1,0 mm).

## 7.12 Failure

The test is terminated when the conditions for the selected end of test criterion are fulfilled. The specimen-heating device should be switched off as soon as the test terminates in order to limit the corrosion/oxidation of the specimen and cracked surfaces with a view to carrying out post mortem examinations. If the failure criterion is other than specimen separation, every effort should be taken to ensure that the specimen is not over-loaded during test termination.

It is recommended that post mortem examinations (metallographic and fractographic analysis) be conducted on the failed specimens. These will provide insight into various failure mechanics and also serve to make known any unusual phenomena that might stand to invalidate the test results.

## 7.13 Test interruption sequence

If a test is interrupted, then care shall be taken to ensure that upon restart there is no significant overshoot in temperature, axial force or mechanical strain. An example of a suitable technique is given below.

Prior to interrupting a strain-controlled TMF test, record the maximum and minimum forces of the final 3 cycles. After the test has been discontinued, record several free thermal cycles (at zero force control) prior to cooling the specimen to room temperature and note the maximum and minimum strain values. The thermal strain range should not have changed but may have shifted due to gauge section changes. Prior to removing the extensometer, a room temperature strain value should be recorded and the extensometer's position marked on the specimen. After specimen replication and its careful re-mounting, the extensometer should be placed at the markings and manually adjusted to the same strain value as when removed. Thermal cycling should then be initiated and the thermal strains should match the post shutdown strains previously recorded. Adjust the extensometer until the thermal strains are matched. Upon restart, the forces recorded prior to shut down shall be matched. Some small amount of extensometer tare may be used to aid in matching the previous force level.

# 8   Expression of results

## 8.1   Preliminary data

The elastic modulus, measured as a function of temperature, $E(T)$ (see Annex B), may be plotted for each specimen.

The thermal strain as a function of temperature, shall be plotted and tabulated for each specimen.

## 8.2   Reduction of recorded data

As a minimum, plots of stress, mechanical strain, and temperature as a function of time, mechanical strain as a function of stress and temperature shall be generated for representative cycles.

## 8.3   Analysis of results

### 8.3.1   Determination of TMF life

The failure criterion shall be defined in detail and maintained constant for the test series.

### 8.3.2   Strain-life relationship

As a minimum, a plot of the cyclic life as a function of applied mechanical strain range shall be generated.

## 9 Test report

### 9.1 Aim of the study

The test report should include full information on the aim of the study, indicating the specific objectives.

### 9.2 Material

All relevant available material details should be reported. This should include the standardized product designation, the material composition in weight percent, material state at test initiation (e.g. processing, heat-treatments, etc.) microstructures/grain sizes and hardness, and the sampling information.

### 9.3 Specimen

A drawing of the specimen design shall be provided together with details of the preparation procedures.

### 9.4 Test equipment details

The following information shall be provided on request:

a) load train, including force transducer type, capacity and class, and specimen gripping fixtures;

b) testing machine, including frame capacity and serial number, actuator type and capacity, and controller type;

c) test control and data collection, including all digital and analog controllers, recorders and data recording equipment;

d) heating and cooling systems, including where appropriate, type and model;

e) temperature measurement thermocouple and/or pyrometer types and specific configurations;

f) extensometer, type, gauge length, operating range and class.

### 9.5 Description of test methodology

The following information shall be provided on request, which may be subject to normal intellectual property considerations:

a) specimen alignment method and results;

b) thermal strain compensation technique and results, i.e. Method 1 or Method 2, see 7.6.2.;

c) test commencement technique;

d) test interruption technique.

### 9.6 Test termination technique including definition of failure

The test termination technique, including definition of failure, shall be reported.

### 9.7 Deviations from specified test tolerances or recommended procedures

Any deviations from the specified test tolerances or recommended procedures shall be reported.

## 9.8   Test conditions

All of the test variables including: mechanical strain limits, rates and waveform, temperature limits, rates and waveform, and temperature/mechanical strain phasing relationship shall be reported.

## 9.9   Presentation of results

### 9.9.1   Presentation of single test results

Presentation of single test results shall include graphical plots of stress, total extensometer output, temperature and thermal strain, all as a function of time, together with hysteresis loops, for representative cycles, of mechanical strain versus stress and temperature. See Annex A for representative diagrams.

A list of the following quantities shall also be included for every recorded cycle up to failure: maximum and minimum of stress, total extensometer output, and temperature.

### 9.9.2   Presentation of results of test series

Presentation of a test series will depend on the aim of the study. It would normally include, for each temperature range and cycle type (e.g. in-phase, out-of-phase), plots as a function of life (or life fraction $n/N_f$) of maximum and minimum stress, and of inelastic mechanical strain range.

In addition a graph of elastic modulus versus temperature may be included for each batch of material tested and a graph of thermal strain versus temperature for each specimen.

Table 1 lists representative data to be reported for a test series:

**Table 1 — Representative data for test series**[11]

| Plots | Representative cycles to be recorded | Representative cycles to be reported |
|---|---|---|
| Stress versus time | logarithmic scheme: $N = 1, 2, 3, 6, 10, 20, 30, 60, 100, ...$ | $N = 1$, mid-life cycle |
| Mechanical strain versus time | logarithmic scheme: $N = 1, 2, 3, 6, 10, 20, 30, 60, 100, ...$ | $N = 1$, mid-life cycle |
| Temperature versus time | logarithmic scheme: $N = 1, 2, 3, 6, 10, 20, 30, 60, 100, ...$ | $N = 1$, mid-life cycle |
| Stress versus mechanical strain (hysteresis loop) | logarithmic scheme: $N = 1, 2, 3, 6, 10, 20, 30, 60, 100, ...$ | $N = 1$, mid-ife cycle |
| Mechanical strain versus temperature | logarithmic scheme: $N = 1, 2, 3, 6, 10, 20, 30, 60, 100, ...$ | $N = 1$, mid-life cycle |
| Min. and max. of stress, stress range, and peak temperatures as a function of cycle number | All cycles | logarithmic scheme: $N = 1, 2, 3, 6, 10, 20, 30, 60, 100, ...$ |

# Annex A
(informative)

# Representative diagrams

A "strain-temperature" diagram is shown in Figure A.1 for a typical mechanical strain range of 0,6 %. In deciding the temperature-strain path, the proposed convention is to plot ± total strain (mechanical strain) on the horizontal axis and temperature on the vertical axis.

Thus, an IP (in-phase) test (maximum temperature at maximum strain) appears as the line EF of positive slope in Figure A.1 whereas the converse OP (out-of-phase) test is given as the line of negative slope GH.

In Figure A.1, a symmetrical diamond cycle starting at $T_{min}$ and zero strain and taken in the prescribed order PQRS would be classed as a special case of the "clockwise diamond cycle". If performed in the reverse order PSRQ, it becomes a "anti-clockwise diamond cycle".

There is no clockwise or anticlockwise sense in the OP and IP extremes since the paths are superimposed.

A definition is required for phase lag. The origin of 0° is taken as the IP line (tension-going strain coinciding with rise in temperature) so in the example of Figure A.1 the OP line is 180° out of phase and the symmetrical diamond PQRS is 90° out of phase.

Two other asymmetrical diamond paths have been shown in Figure A.1. It is clear that JKLM is 135° out of phase while WXYZ is 45° out of phase. It is also evident (in the way that the parallelogram shapes have been constructed), that WXYZ is nearer the IP path while JKLM approaches the OP path for increasing phase lag.

The definitions have been chosen in such a way that as the phase angle increases, so do the respective intercepts on the strain axes, J and L, approach the maximum and minimum values of 0,3 % and −0,3 %, so in the present case the strain values are ± 0,15 %.

It would be possible, for example, to anchor the intercepts at zero strain points P and R in Figure A.1 but such "skewed diamonds" would not approach the OP and IP cycles in the limit, and moreover the leg PS for example would be performed isothermally in the limit. In a practical cycle, the strain limits at the extremes of $T_{max}$ and $T_{min}$ can vary independently.

Typical hysteresis loops for OP and IP cycles are shown in Figure A.2. Such loops often display inverse symmetry.

A typical strain-temperature diagram based on zero strain intercepts is shown in Figure A.3. The corresponding hysteresis loop is shown in Figure A.3. It is clear that this loop is highly asymmetrical.

**Key**
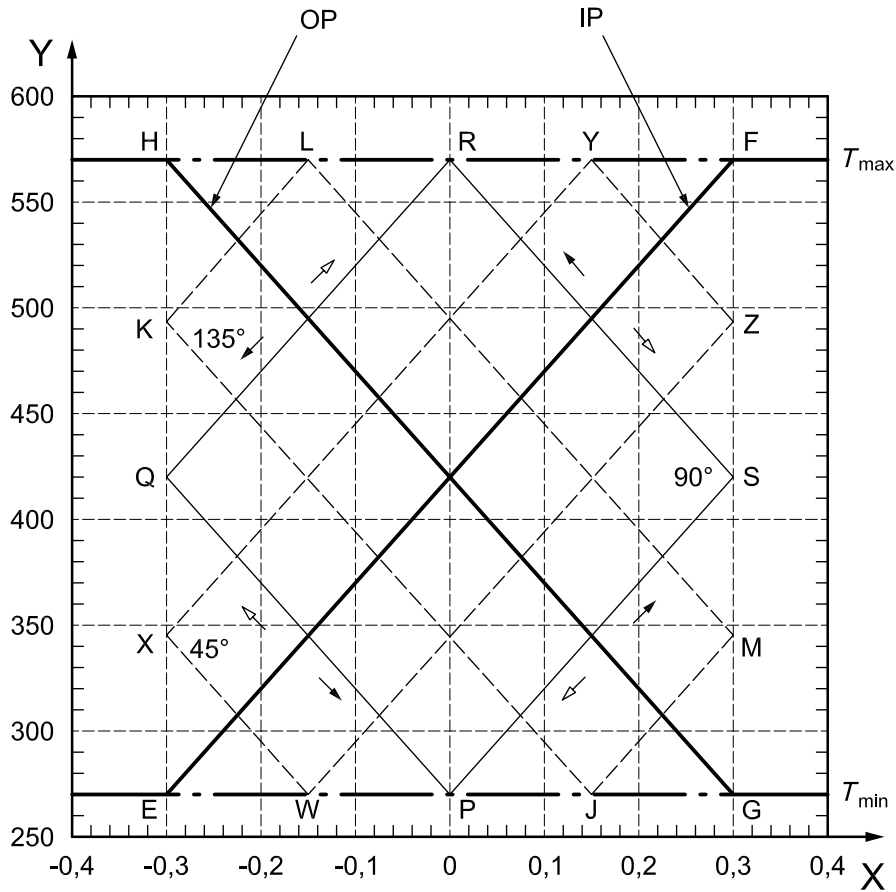
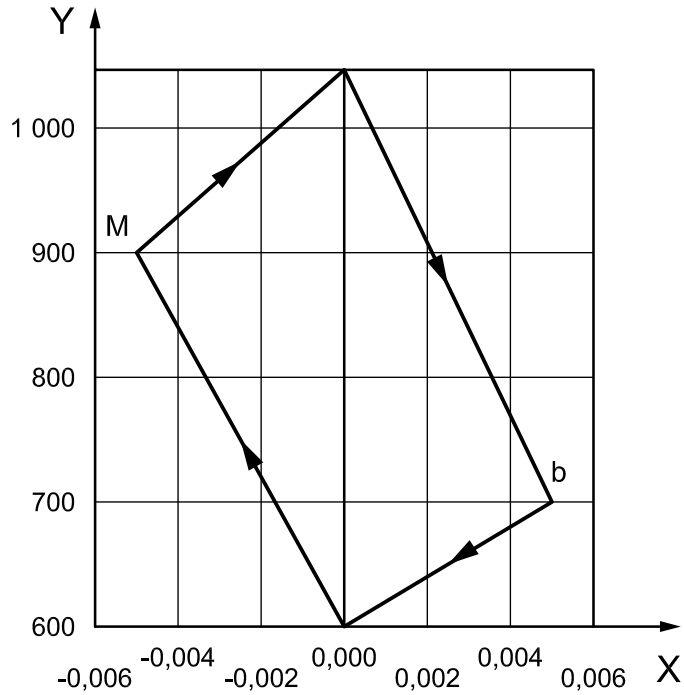| | | | |
|---|---|---|---|
| X | mechanical strain, in percent | OP | out-of-phase |
| Y | temperature, in °C | →▷ | clockwise |
| IP | in-phase | → | anticlockwise |

**Figure A.1 — Definition of TMF cycle types** (derived from Reference [6])



**Key**
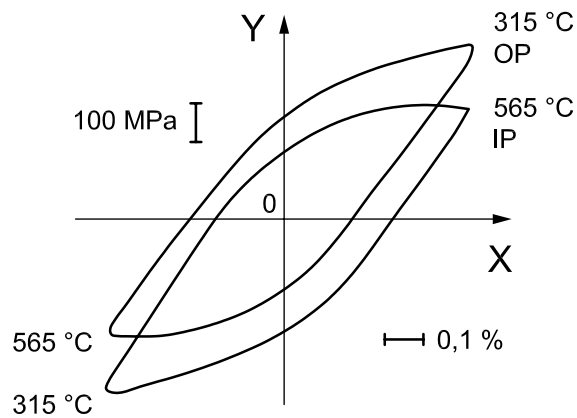
X  mechanical strain, in percent

Y  stress, in MPa

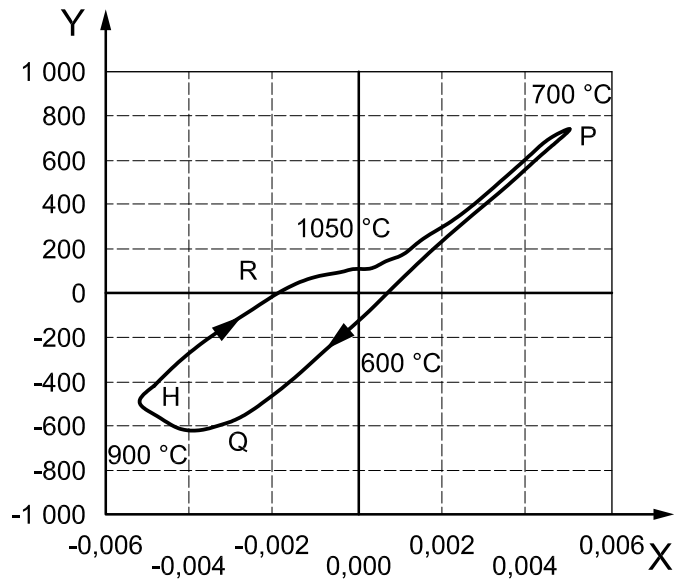**Figure A.2 — Typical OP and IP loops** (after Reference [7])

**Key**

X   mechanical strain

Y   temperature, in °C

See References [8] and [9] for the use of b, M.

**a) Mechanical strain vs. temperature**



**Key**

X   mechanical strain

Y   stress, in MPa

See References [8] and [9] for the use of P, Q, H, R.

**b) Mechanical strain vs. stress**

**Figure A.3 — Typical clockwise loop following mechanical strain-temperature path indicated**

# Annex B
(informative)

# Modulus of elasticity determination

The $E$ modulus may be determined by using the following procedure.

The evaluation of $E$ modulus at each temperature has to be made after a suitable temperature stabilization and cycling in tension and compression load control with triangular (or sinusoidal) wave form, applying forces which do not exceed an equivalent stress of 20 % of the yield stress at the maximum temperature, and using a force cycling frequency of 0,1 Hz or higher. At least 5 cycles at each temperature are required.

The number of measurements needed is related to the magnitude of the temperature range and the strain or stress magnitude at the temperatures of interest. As a guideline, modulus values should be measured at minimum, mean and maximum temperatures of the thermal cycle or at $\Delta T$ intervals where the modulus change over the $\Delta T$ is no more than 5 %, whichever provides better resolution.

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