INTERNATIONAL STANDARD

ISO 12106

First edition
2003-03-15

Metallic materials — Fatigue testing — Axial-strain-controlled method

Matériaux métalliques — Essais de fatigue — Méthode par déformation axiale contrôlée

Reference number
ISO 12106:2003(E)

PDF disclaimer

This PDF file may contain embedded typefaces. In accordance with Adobe's licensing policy, this file may be printed or viewed but shall not be edited unless the typefaces which are embedded are licensed to and installed on the computer performing the editing. In downloading this file, parties accept therein the responsibility of not infringing Adobe's licensing policy. The ISO Central Secretariat accepts no liability in this area.

Adobe is a trademark of Adobe Systems Incorporated.

Details of the software products used to create this PDF file can be found in the General Info relative to the file; the PDF-creation parameters were optimized for printing. Every care has been taken to ensure that the file is suitable for use by ISO member bodies. In the unlikely event that a problem relating to it is found, please inform the Central Secretariat at the address given below.

STANDARDSISO.COM : Click to view the full PDF of ISO 12106:2003

© ISO 2003

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

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 12106 was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 5, *Fatigue testing*.

Introduction

The design of mechanical components subjected to fatigue loadings requires, in a number of industrial sectors (nuclear, aeronautical, mechanical engineering), the knowledge of the behaviour of the materials under reversed strain control conditions (referred to as low-cycle fatigue) when cyclic plasticity is present.

In order to ensure reliability and consistency of results from different laboratories, it is necessary to collect all data using test methodologies that comply with a number of key points.

This International Standard concerns both the generation and the presentation of results for fatigue properties of metallic materials.

Metallic materials — Fatigue testing — Axial-strain-controlled method

1 Scope

This International Standard specifies a method of testing uniaxially loaded specimens under strain control at constant amplitude, uniform temperature and strain ratio $R_\varepsilon = -1$.

It can also be used as a guide for testing under other conditions.

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 9513:1999, *Metallic materials — Calibration of extensometers used in axial testing*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.[3 to 9]

3.1
stress
instantaneous force divided by the instantaneous cross-sectional area of the gauge length

$$\sigma = F/A$$

NOTE At strain values less than 10 %, the true stress is approximated by the engineering stress, $F_\mathrm{F}/A_\mathrm{o}$.

3.2
gauge length
length between extensometer measurement points

3.3
strain
true total strain

$$\varepsilon = \int_{L_\mathrm{o}}^{L} \frac{\mathrm{d}L}{L}$$

where L is the instantaneous length of the gauge section

NOTE At true strain values less than 10 %, ε is approximated by the engineering strain $\Delta L/L_\mathrm{o}$.

3.4
cycle
smallest segment of the strain-time function that is repeated periodically

3.5
maximum
greatest algebraic value of a variable within one cycle

3.6
minimum
least algebraic value of a variable within one cycle

3.7
mean
one-half of the algebraic sum of the maximum and minimum values of a variable

3.8
range
algebraic difference between the maximum and minimum values of a variable

3.9
amplitude
half the range of a variable

3.10
fatigue life
N_f
number N of cycles that have to be applied to achieve a failure

NOTE Failure criteria are defined, for example, in 7.8. The failure criterion used shall be reported with the results.

3.11
hysteresis loop
closed curve of the stress-strain response during one cycle

4 Symbols

For the purposes of this document, the symbols defined in 4.1 to 4.3 apply.

4.1 Specimens

See Table 1.

Table 1 — Symbols and designations concerning specimens

Specimen	Symbol	Designation	Unit
	L_o	Initial gauge length	mm
	L	Instantaneous gauge length	mm
	A_o	Initial gauge section	mm^2
	A	Instantaneous section with $AL = A_\mathrm{o}L_\mathrm{o}$	mm^2
	A_f	Minimum area at failure	mm^2
	r	Transition radius (from parallel length into the grip end of the test specimen)	mm
	L_t	Total length of specimen	mm
Cylindrical			
	d	Diameter of cylindrical gauge section	mm
	D	External diameter of specimen	mm
	L_r	Length of reduced section	mm
Flat-sheet			
	B	Width of gauge section	mm
	t	Thickness	mm
	W	Width of grip end	mm

4.2 Fatigue testing

4.2.1 Symbols

E	modulus of elasticity, in gigapascals (GPa);
E_T	modulus for unloading following a peak tensile stress (see Figure 1), in gigapascals (GPa);
E_C	modulus for unloading following a peak compression stress (see Figure 1), in gigapascals (GPa);
N_f	number of cycles to failure;
t_f	time to failure (= N_f cycles), in seconds (s);
σ	true stress, in megapascals (MPa);
ε	true strain;
Δ	range of a parameter;
$R_{\mathrm{p}0,2}$	0,2 % proof stress;
Rz	mean surface roughness, in micrometres (µm);
R_σ	stress ratio $\left(= \sigma_\mathrm{min}/\sigma_\mathrm{max}\right)$;
R_ε	strain ratio $\left(= \varepsilon_\mathrm{min}/\varepsilon_\mathrm{max}\right)$;
$\dot{\varepsilon}$	strain rate, in seconds to the power of minus one (s^{-1}).

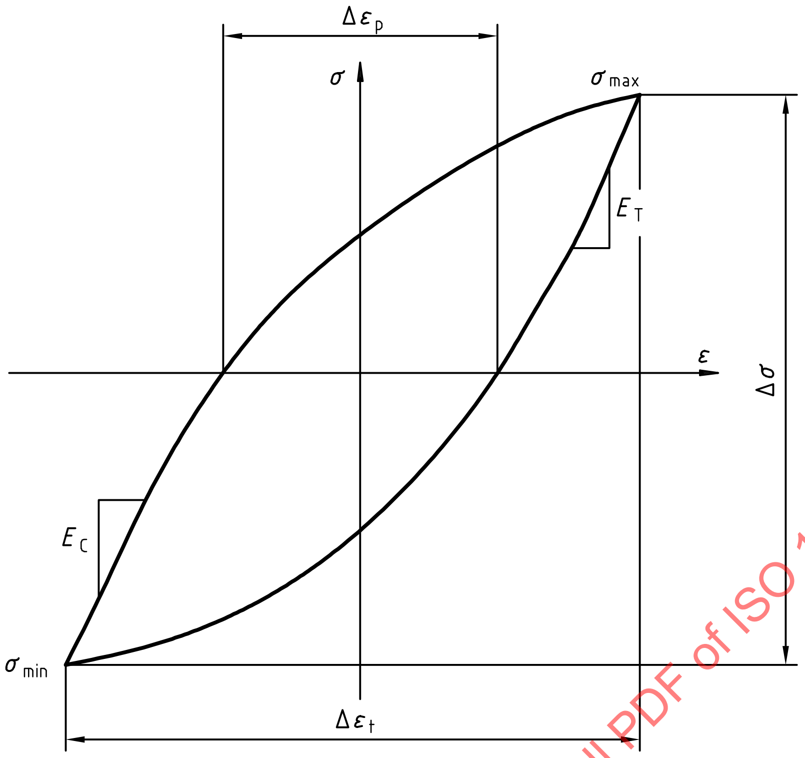


Figure 1 — Stress-strain hysteresis loop

4.2.2 Subscripts

t	total;
p	plastic;
e	elastic;
a	amplitude;
m	mean;
1/4	related to first 1/4-cycle;
min	minimum;
max	maximum.

4.3 Expression of results

See Table 2.

Table 2 — Symbols and designations concerning the expression of results

Symbol	Designation	Unit
$\sigma_{y'}$	Cyclic yield strength [a]	MPa
n	Monotonic strain hardening exponent	—
n'	Cyclic strain hardening exponent	—
K	Monotonic strength coefficient	MPa
K'	Cyclic strength coefficient	MPa
$\sigma_{f'}$	Fatigue strength coefficient	MPa
b	Fatigue strength exponent	—
$\varepsilon_{f'}$	Fatigue ductility coefficient	—
c	Fatigue ductility exponent	—

[a] 0,2 % offset is typically used.

5 Apparatus

5.1 Test machine

5.1.1 General

The tests shall be carried out on a tension-compression machine designed for a smooth start-up with no backlash when passing through zero. The machine shall have great lateral rigidity when the crosshead is in the operating position and accurate alignment between the test space support references.

The complete machine-loading system (including load cell, grips and specimen) shall have great lateral rigidity and be capable of controlling strain and measuring force when applying the recommended wave cycle. It may be hydraulic or electromechanical.

5.1.2 Load cell

The load cell shall be designed for tensile-compressive fatigue tests and shall have great axial and lateral rigidity. Its capacity shall be suitable for the forces applied during the test.

The indicated force as recorded at the output from the computer in an automated system or from the final output recording device in any non-automated system shall be within the specified permissible variation from the actual force. The load cell capacity shall be sufficient to cover the range of forces measured during a test to an accuracy better than 1 % of the reading.

The load cell shall be temperature-compensated and shall not have zero drift or sensitivity variation greater than 0,002 % of full scale per degree Celsius.

During high-temperature or cryogenic testing, suitable shielding/compensation may be provided for the cell so it is maintained within its compensation range.

5.1.3 Gripping of specimen

The gripping device shall transmit the cyclic forces to the specimen without backlash along its longitudinal axis. The distance between the grips shall be small to avoid any tendency of the specimen to buckle. The geometric qualities of the device shall ensure correct alignment in order to meet the requirements specified in 5.1.4; it is therefore necessary to limit the number of components of which these gripping devices are composed and reduce the number of mechanical interfaces to a minimum.

The gripping device shall ensure that the way in which the specimen is mounted is reproducible. It shall have surfaces ensuring the alignment of the specimen and surfaces allowing transmission of tensile and compressive forces without backlash throughout the duration of the test. Materials shall be selected so as to ensure correct functioning across the test temperature range.

5.1.4 Alignment check

Bending due to misalignment in rigid-grip systems is generally caused by one or more of the following (see Figure 2): angular offset of the grips, lateral offset of the loading bars (or grips) in an ideally rigid system, an offset in the load-train assembly in a non-rigid system or (in the case of servo-hydraulic machines) an actuator rod with side-play in the bearings.

The alignment shall be checked before each series of tests and any time a change is made to the load train. The bending strains shall be < 5 % of the axial strain at both the maximum and minimum applied strain. Figure 3 shows a recommended strain gauge configuration for checking alignment. There are other techniques for measuring alignment that are adequate for this purpose.[17 to 20] See Annex A for details of methodology. For an example of an alignment check that includes an elastic-plastic method, see [19].

5.2 Strain measurement

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

The extensometer used shall be suitable for measuring dynamic strain over long periods during which there shall be minimal drift, slippage and instrument hysteresis. It shall measure directly the axial strain on the gauge section of the specimen.

The strain-measuring system, including the extensometer and its associated electronics, shall be accurate to within 1 % of the range of strain applied. The extensometer shall conform to ISO 9513:1999, Class 1.

The geometry of the contact zones and the pressure exerted by the extensometer on the specimen shall be such that they prevent slippage of the extensometer but do not damage the specimen.

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

5.3 Heating device and temperature measurement [10, 14 to 16]

A uniform rise in temperature shall be ensured without the test temperature being exceeded.

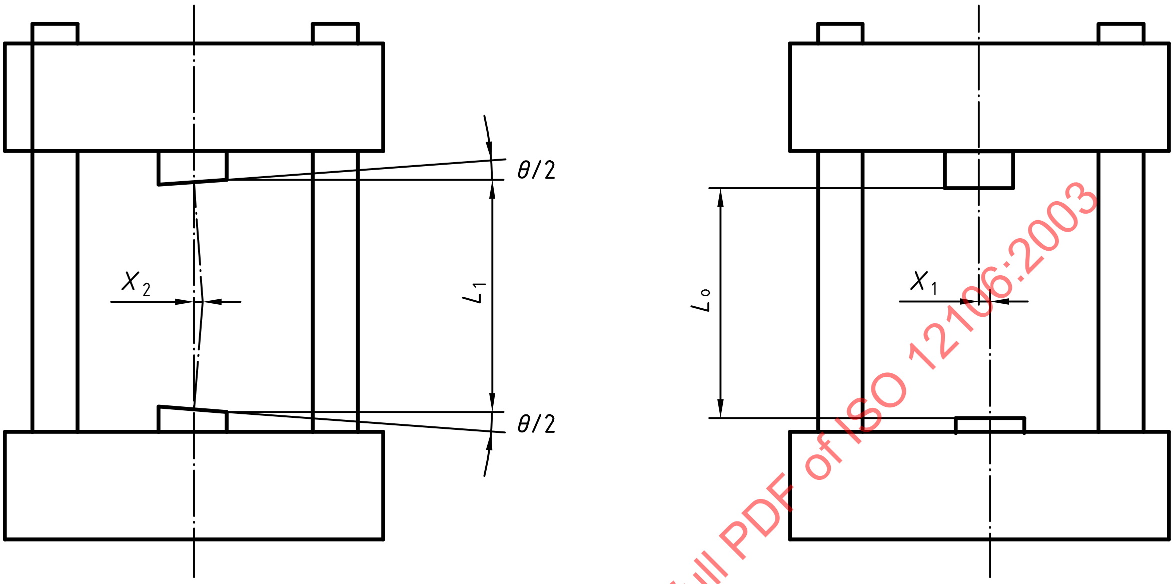
If a direct induction heating system is used, it is advisable to select a generator with a frequency sufficiently low to prevent “skin effects” on heating.

The heating device shall produce a temperature gradient not exceeding 3 °C over the gauge length of the specimen and shall ensure, throughout the test, and with due consideration to all combined sources of error, that deviations between the test temperature and that of the specimen are within 5 °C.

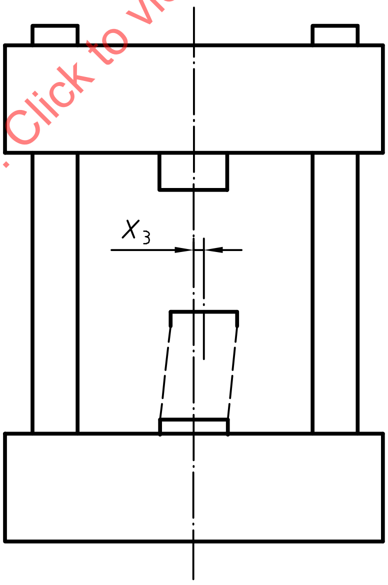
These deviations shall be checked using three thermocouples or other appropriate devices, one at each end and one in the middle of the gauge length of the specimen.

In a test, the specimen temperature may be measured using thermocouples in contact with the specimen surface. Direct contact between the thermocouple and the specimen is necessary and shall be achieved without affecting the test results (e.g. crack initiation at the point of contact of the thermocouple shall be avoided). Commonly used methods of attaching the thermocouples are by binding in place, by pressure or by resistance spot welding.

The temperature shall be measured by at least one sensor independently of the one used for control purposes.

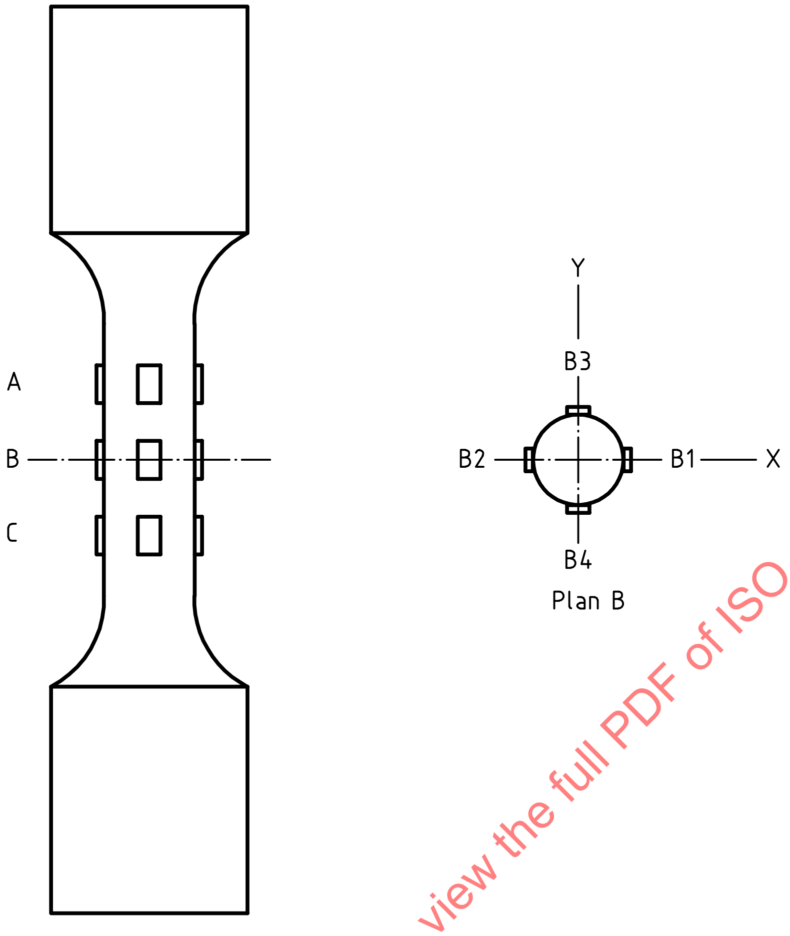


a) Angular offset **b) Lateral offset**



c) Load-train offset in a non-rigid system

Figure 2 — Bending mechanisms due to misalignment in fatigue test systems



Bending X-X: $\dfrac{\varepsilon_{\mathrm{A2}} - \varepsilon_{\mathrm{A1}}}{\varepsilon_{\mathrm{A2}} + \varepsilon_{\mathrm{A1}}} \times 100 = \%\ A_{\text{X-X}}$

Bending Y-Y: $\dfrac{\varepsilon_{\mathrm{A3}} - \varepsilon_{\mathrm{A4}}}{\varepsilon_{\mathrm{A3}} + \varepsilon_{\mathrm{A4}}} \times 100 = \%\ A_{\text{Y-Y}}$

Bending in plane A: $\sqrt{\left(\%\ A_{\text{X-X}}\right)^2 + \left(\%\ A_{\text{Y-Y}}\right)^2} < 5\ \%$

Shall be repeated for plane C with plane B optional.

No plane is allowed to have bending greater than 5 %.

Figure 3 — Alignment scheme

5.4 Instrumentation for test monitoring

5.4.1 Recording systems

The following systems shall be considered a minimum requirement for the analog recording of data:

- an X-Y recorder used to record stress-strain hysteresis loops;
- a recorder for several time-dependent parameters: force, strain and temperature;
- a peak-to-peak detector.

Variant 1:

The X-Y recorder may be replaced by an oscilloscope or digital storage device capable of reproducing the recorded signal either in photographic or analog form. These devices are necessary when the rate of recording of signals higher than the maximum rate of the recorder. They allow permanent records to be reproduced subsequently at a lower rate.

Variant 2:

The systems described above may be replaced by a computerized system capable of carrying out the task of collecting and processing data digitally. The sampling frequency of stress-strain data points shall be sufficient to ensure correct definition of the hysteresis loop, especially in the regions of strain reversal. Different data collection strategies will affect the number of data points per loop needed, however. Typically, 200 points per loop are required.

5.4.2 Cycle counter

A cycle counter is essential for knowing the number of straining cycles. For the majority of the strain rates used, counters without multiplication factors should suffice.

5.5 Checking and verification

The test machine and its control and measurement systems shall be checked regularly.

Specifically:

Each transducer and its associated electronics shall always be checked as a unit:

- the force-measuring system(s) shall be verified in accordance with the relevant ISO or national standard;
- the strain-measuring system(s) shall be verified in accordance with the relevant ISO or national standard;
- the temperature-measuring system(s) shall be verified in accordance with the relevant ISO or national standard.

It is good practice before each series of tests to check the gauge length of the extensometer, the load cell and the extensometer calibration using a shunt resistor or another suitable method, and also to check the thermocouple or pyrometer calibration.

6 Specimens

6.1 Geometry

6.1.1 Products (bars and flat sheets over 5 mm thick)

The gauge portion of the specimen in a low-cycle fatigue 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 shall 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 the whole gauge portion;
- allow the extensometer to measure the strain without interference or slippage.

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

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 [21] to [30] in Bibliography), the following geometric dimensions (see Figure 4) are recommended:

— diameter of cylindrical gauge length:	$d = 5$ mm
— gauge length:	$L_o = 2d$
— transition radius (from parallel-sided section to grip end):	$r = 2d$
— external diameter (grip end):	$D = 2d$
— length of reduced section:	$L_r < 8d$

Other geometric cross-sections and gauge lengths may be used for specimens provided that uniform distribution of stress and strain in the gauge length is ensured.

It is important that general tolerances for the specimens respect the three following properties:

— parallelism:	//	$= 0{,}005D$;
— concentricity:	◎	$= 0{,}005D$;
— perpendicularity:	⊥	$= 0{,}005D$;

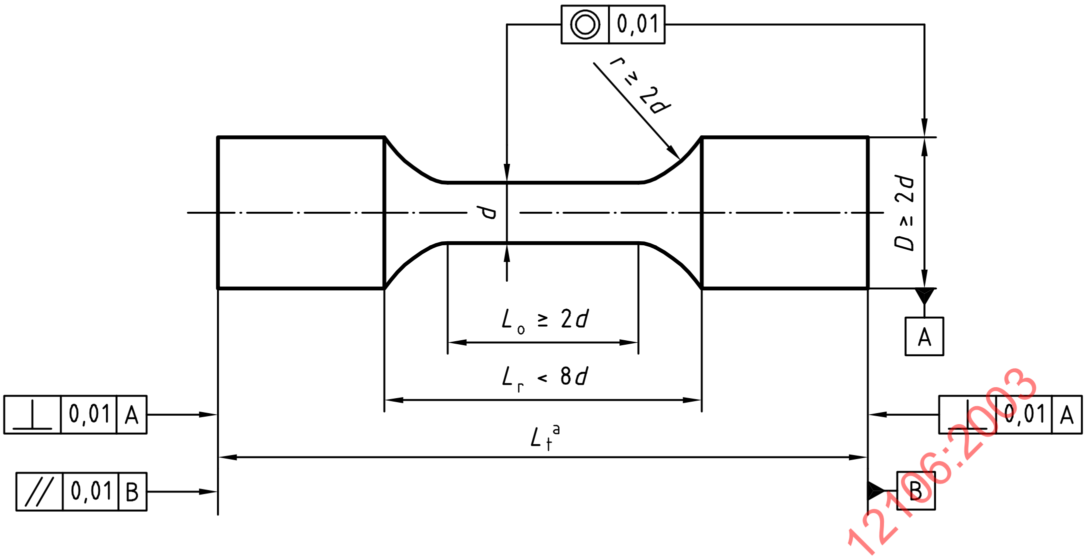
(these values are expressed in relation to the axis or reference plane).

The dimensions of end connections shall be defined as a function of the test machine. Recommended end connections are as follows:

- threaded connection;
- smooth cylindrical connection (with hydraulic jaws);
- button-end connection.

The test fixture shall locate the specimen and provide axial alignment. It shall not permit backlash. Design of the test fixture will depend on the specimen end details. A number of examples are given in Figure 5.

In general, designs in which specimen alignment depends entirely on screw threads are not recommended.



[a] Function of gripping system

Figure 4 — Recommended geometry of cylindrical specimen

6.1.2 Flat products of thickness less than 5 mm

6.1.2.1 General

In general, the considerations discussed in the preceding paragraphs also apply to tests on the above products. However, these tests require specific geometries and fixtures in order to avoid problems of buckling.

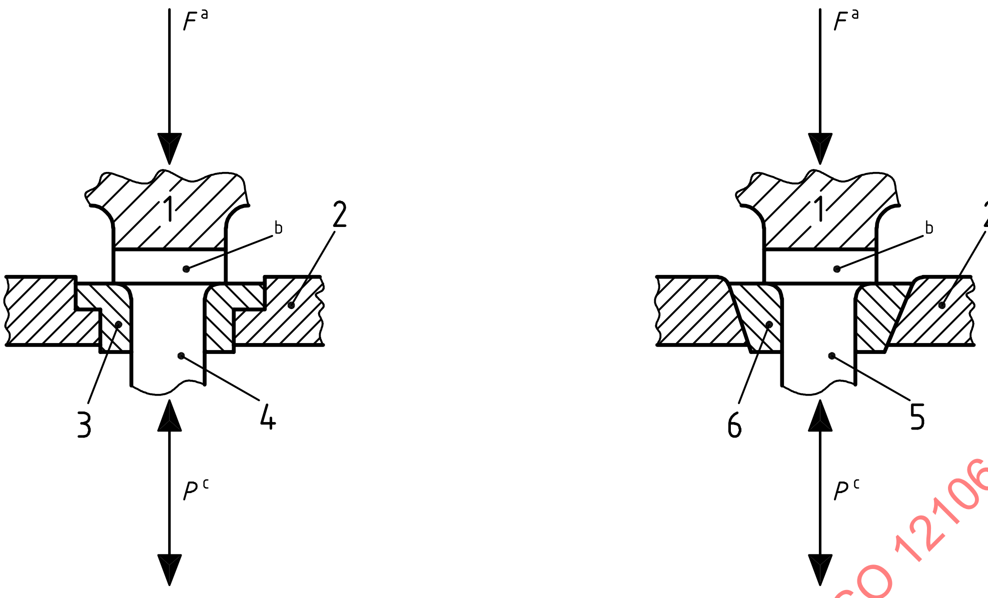
Due to the fact that low loads are generally applied, more sensitive force transducers than usual may be required. The gripping system may necessitate the use of flat mechanical or hydraulic jaws. However, with the latter type of assembly it is difficult to ensure correct alignment.

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 (see Figure 6).

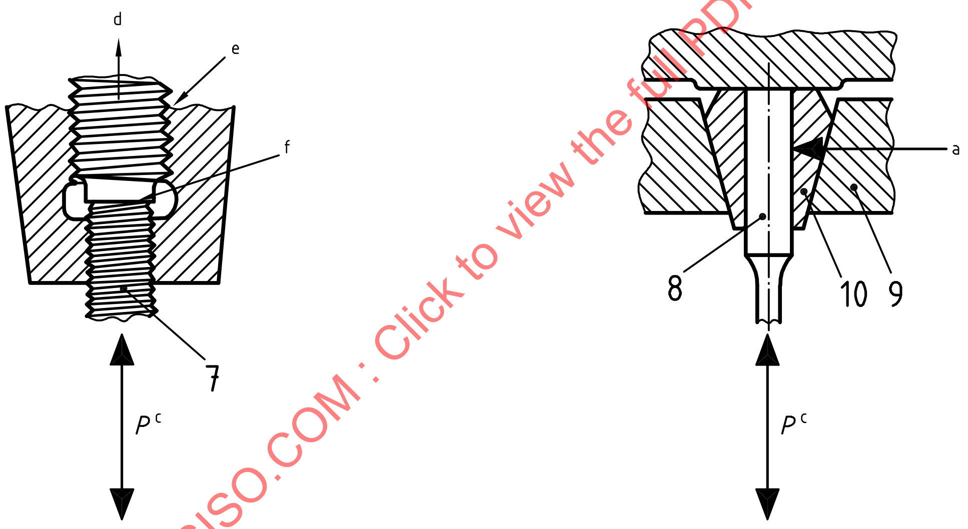
The correct alignment of the specimen shall be carefully checked with a trial specimen for:

- parallelism and alignment of the grips;
- alignment of specimen with the loading axis.

This verification shall be carried out using a specimen, with a geometry as similar as possible to that of the test specimen, instrumented with strain gauges on the two faces.



a) Button-head fixture **b) Button-head or efficiency button-head fixture**



c) Threaded-specimen fixture **d) Straight-sided (cylindrical) specimen fixture**

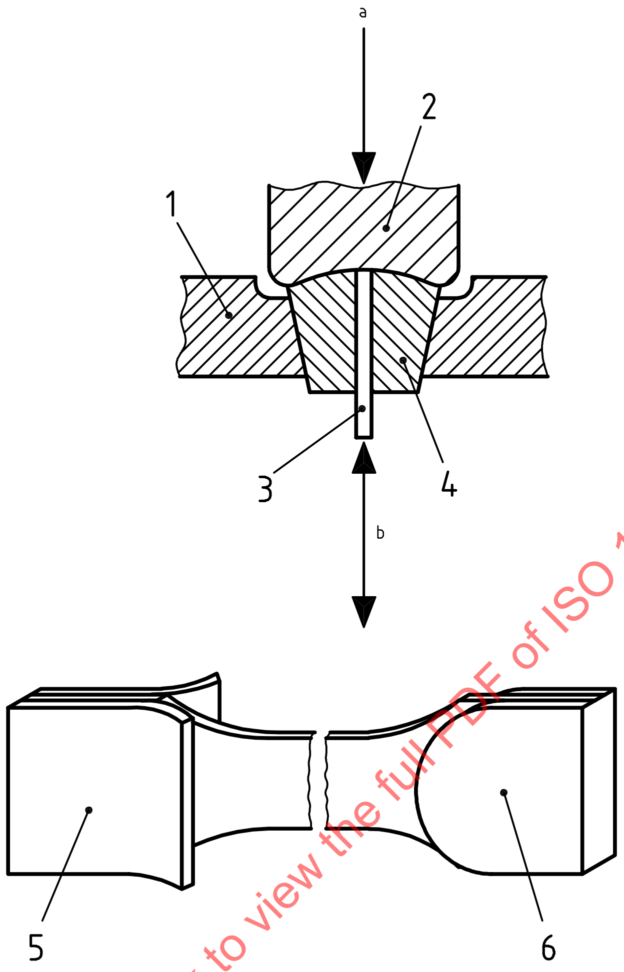
Key

1	clamp	6	conical split collar
2	body of fixture	7	threaded specimen
3	cylindrical split collar	8	cylindrical specimen
4	button-head specimen	9	body of fixture
5	button-head or efficiency button-head specimen	10	conical chuck

The clamping force shall be greater than the cyclic load to avoid backlash within the specimen fixture.

a	Clamping force	d	To load train
b	Flat anvil for specimen alignment	e	Specimen clamping
c	Cyclic load	f	Flat anvil and specimen end for alignment

Figure 5 — Schematic examples of fixing techniques for various specimen designs



Key

1 body of fixture
2 conical clamp
3 sheet specimen
4 conical chuck
5 bent end tabs to prevent grip indentation in gripping area (may be held in place by epoxy)
6 rounded end tabs

[a] Clamping force
[b] Cyclic load

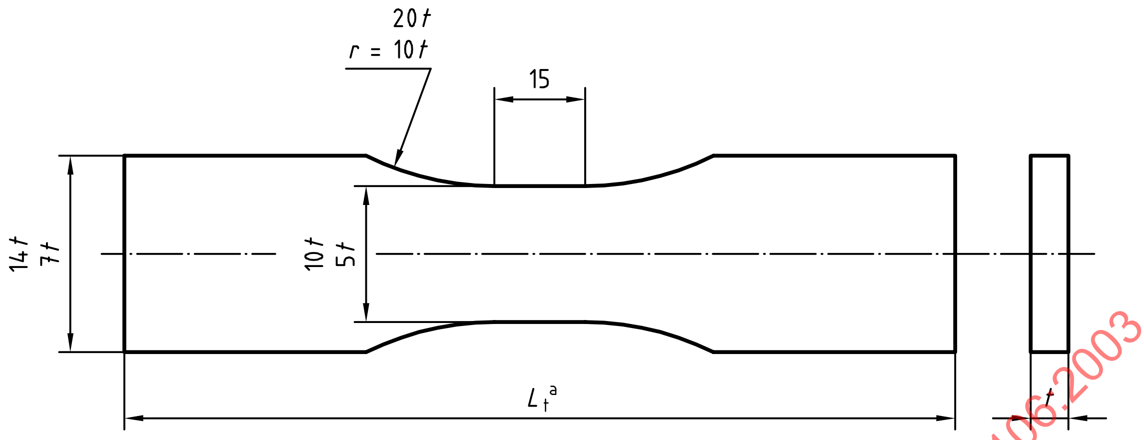
Figure 6 — Gripping scheme for flat-sheet specimen

6.1.2.2 Thicknesses between 2,5 mm and 5 mm

It is possible to conduct these tests without anti-buckling restraints.

A possible geometry for a flat specimen is shown in Figure 7. In this case, it is preferable to use an extensometer positioned on one face of the specimen rather than on the edge.

Dimensions in millimetres



[a] Function of gripping system

Figure 7 — Possible geometry of flat-sheet specimen

6.1.2.3 Thicknesses below 2,5 mm

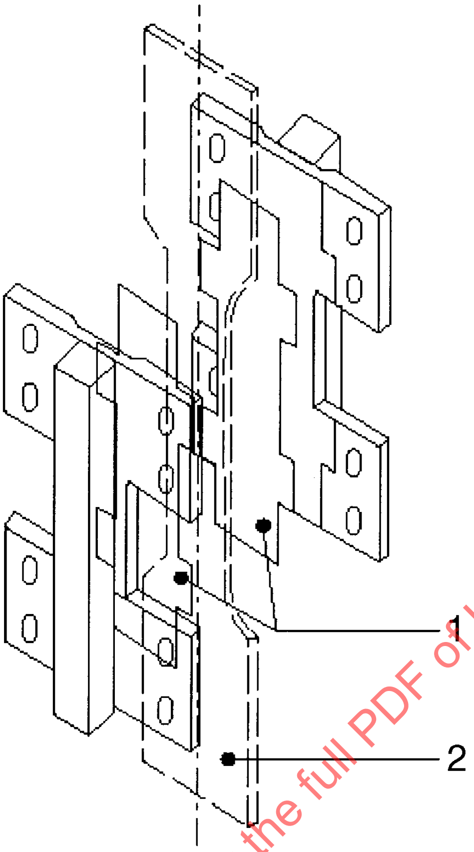
The use of anti-buckling restraints may be necessary. Their geometries shall be matched to those of the specimens and shall allow strains to be measured along their edges.

A number of precautions are required to limit the increase in load induced by friction between the restraint and specimen. This friction shall not at any time create a load increase greater than 2 %. The use of a polytetrafluoroethylene film approximately 1 mm thick, for example, offers a partial solution to this problem, as does boron nitride powder as a dry lubricant. Hydrocarbon-based lubricants are not recommended as they will affect the test results.

The frictional forces may vary from one specimen to another. They shall be measured before each test from the load-displacement curves recorded in the elasticity range of the material in tension with and without anti-buckling restraints.

The use of anti-buckling restraints may require strain measurement on the edge of the specimen. In this case, it is advisable to use two identical extensometers positioned on both sides of the specimen and use the average signal to control the test.

An example of an anti-buckling restraint is shown in Figure 8.



Key

1 polytetrafluoroethylene film

2 specimen

Figure 8 — Anti-buckling restraints for flat-sheet specimen

6.2 Preparation of specimens

6.2.1 General

In any low-cycle fatigue test programme designed to characterize the intrinsic properties of a material, it is important to observe the following recommendations 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, any deviation shall be noted in the test report.

6.2.2 Machining procedure

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 or they may be associated with deformation of the material or microstructural alterations. Their influence is less marked in tests at elevated temperatures because they are partially or totally relaxed once the temperature is maintained. However, they should 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 diameter 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 axis.

NOTE 1 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.

NOTE 2 Introduction of contaminants.

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

6.2.3 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, shall 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.

The specimens shall carry a mark at each stage of 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.

6.2.4 Surface condition of specimen

The surface condition of specimens has an effect on the test results. This effect 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;
- the introduction of contaminants.

The recommendations below allow the influence of these factors to be reduced to a minimum.

The surface condition is commonly quantified by the mean roughness or equivalent (e.g. 10 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 plastic deformation.

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

Another important parameter not covered by mean roughness is the presence of localized machining scratches. Finishing operations on round specimens will normally eliminate all circumferential scratches produced during turning. Final grinding followed by longitudinal mechanical polishing is particularly recommended. A low-magnification check (at approximately × 20) shall not show any circumferential 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 shall 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.

6.2.5 Dimensional check

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

6.2.6 Storage and handling

After preparation, the specimens shall be stored so as to prevent any risk of 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 shall 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 a specimen, each half may still be identified.

7 Procedure

7.1 Laboratory environment

The low-cycle fatigue test is reasonably complex and the quality of the results obtained depends on the methods employed as well as on the environment.

The tests shall be carried out under suitable environmental conditions:

- uniform ambient temperature and relative humidity;
- minimum atmospheric pollution (dust, chemical vapours, etc.);
- no extraneous electrical signals that will affect machine control and data acquisition;
- minimum extraneous mechanical vibrations.

7.2 Test machine control

The stability of the servo-control shall be such that the peak values of the applied strain are maintained throughout the test to within ± 1 % of the desired values.

7.3 Mounting of the specimen

Place the specimen in position in such a way that any preliminary strain during mounting is avoided.

7.4 Cycle shape — Strain rate or frequency of cycling

The same cycle shape for the controlled parameter (strain) shall be retained throughout the whole test programme unless the aim of this programme is to study the effect of the cycle shape on the behaviour of the material. A triangular cycle shape is normally used for continuous cycling tests.

NOTE For tests conducted at high temperatures, a sinusoidal cycle shape is generally to be avoided because it represents a variable strain rate.

Low-cycle fatigue tests are generally carried out with an imposed constant total strain rate.

The range of frequencies for low-cycle fatigue tests is most often between 0,01 Hz and 1 Hz. In terms of the total strain rate, the majority of tests are carried out within the interval ranging from 5×10^{-4} s^{-1} to 5×10^{-2} s^{-1} (0,05 % s^{-1} to 5 % s^{-1}).

7.5 Start of test

7.5.1 Preliminary measurements

It is recommended that testing begin by cycling within the elastic range of the material at ambient temperature in order to measure the modulus of elasticity of the material and ensure the correct functioning of the measuring system (force and strain). The value of this modulus shall not deviate by more than ± 5 % from the expected value.

In the same context (verification of the strain and temperature measuring chain), it is recommended where possible that the coefficient of mean expansion of the material be determined by monitoring the thermal strain recorded by the extensometer as the temperature changes from ambient temperature to test temperature (machine under load control and zero force). This coefficient shall not deviate by more than ± 5 % from the expected value.

Usually, the extensometer is mounted on the specimen at ambient temperature and will not be readjusted to the original gauge length after transition to the test temperature. In this case, the strain measurement at elevated temperature shall correct for the gauge length extension due to thermal expansion. Therefore, the gauge length extension shall at least be recorded for post-test correction. Automated systems shall use the corrected gauge length for on-line control and data acquisition.

In some systems, especially at temperatures $> 1\,000$ °C, the extensometer may be mounted while the specimen is “hot”. In this case, it will not be possible to determine the expansion coefficient. However, the gauge length shall be known with good confidence.

7.5.2 Determination of the modulus of elasticity $E_{1/4}$

Measure the modulus of elasticity $E_{1/4}$ in the same way as in 7.5.1 within the regime where no inelastic strain is apparent for each specimen at the test temperature.

7.5.3 Test commencement

For a specific test programme, it is necessary to select the direction of the first quarter of the cycle. It is usual to select tension-going; however in actual, thermally induced, low-cycle fatigue situations, the first quarter-cycle is invariably compression.

For tests carried out under strain control, it will normally be required to change to strain from force control following modulus checks and specimen heat-up. The test machine shall accomplish this transfer without “overshoots” that could prejudice the rest of the test.

The amplitude of the strain limits shall not exceed that selected as the test control parameter by more than 5 %. Adjustment of the strain, in order to attain the desired strain level under the requirements specified in 7.2, shall be completed within 10 cycles or 1 % of the time to failure, whichever is less.

In the event of an inadvertent or accidental stop, before restarting ensure that:

- the specimen has not been damaged by the stop;
- the extensometer has not slipped.

These two points may be verified by analysing the recordings. In these conditions, a restart without overshoot is permissible.

7.6 Number of specimens

A minimum of eight specimens is recommended to generate a fatigue strain-life curve covering at least three decades in numbers of cycles.

7.7 Data recording

7.7.1 Stress-strain hysteresis loops

At the start of the test, a continuous recording shall be made of the initial hysteresis loops — stress response as a function of the controlled strain. Then, during the course of the test, a periodic recording is sufficient. The frequency of these recordings shall be chosen as a function of the intended overall duration of the test. The option generally used consists of recording the first ten cycles and then applying a logarithmic increase (20, 50, 100, 200, 500, etc.).

In the case of automated data acquisition, the recording of loops may be programmed either with a predefined interval or as a function of the progression of each of the two parameters (stress and strain). In all cases, the sampling frequency shall be sufficient to allow clear definition of the hysteresis loop (see 5.4.1).

7.7.2 Data acquisition

If test equipment permits, record stress, strain and temperature as functions of time. If this is not possible, at least record peak values of stress, strain and temperature so that the definition of failure given in 7.8 may be invoked.

7.8 Failure criteria

There are various ways of defining a failure, with total separation of the specimen being only one of these. It may depend on the interpretation of the fatigue test result and on the nature of the material being tested. The failure criteria under consideration are generally based on the appearance, presence or intensification of a phenomenon that has been observed or recorded that indicates severe damage or imminent failure of the specimen.

The number of cycles to failure, N_f, may be defined as the number of cycles corresponding to the following failure criteria:

a) total separation of the specimen into two distinct parts;

b) a certain percentage change in the maximum tensile stress in relation to the level determined during the test;

c) a certain change in the ratio of the moduli of elasticity in the tensile and compressive part of the hysteresis loops; typically, E_T/E_C = 0,5 is employed for defining failure (see Figure 9);

d) a certain percentage change in the maximum tensile stress in relation to the maximum compressive stress.

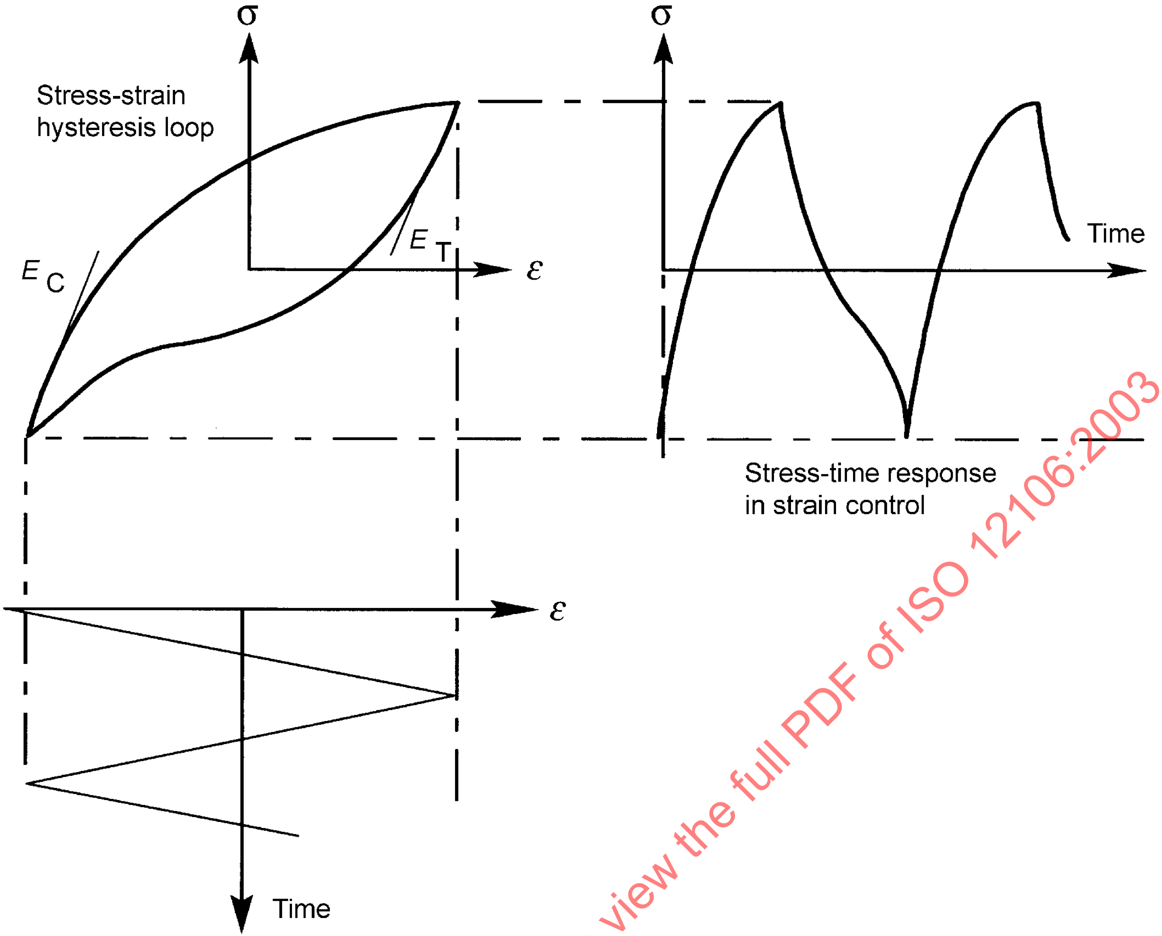


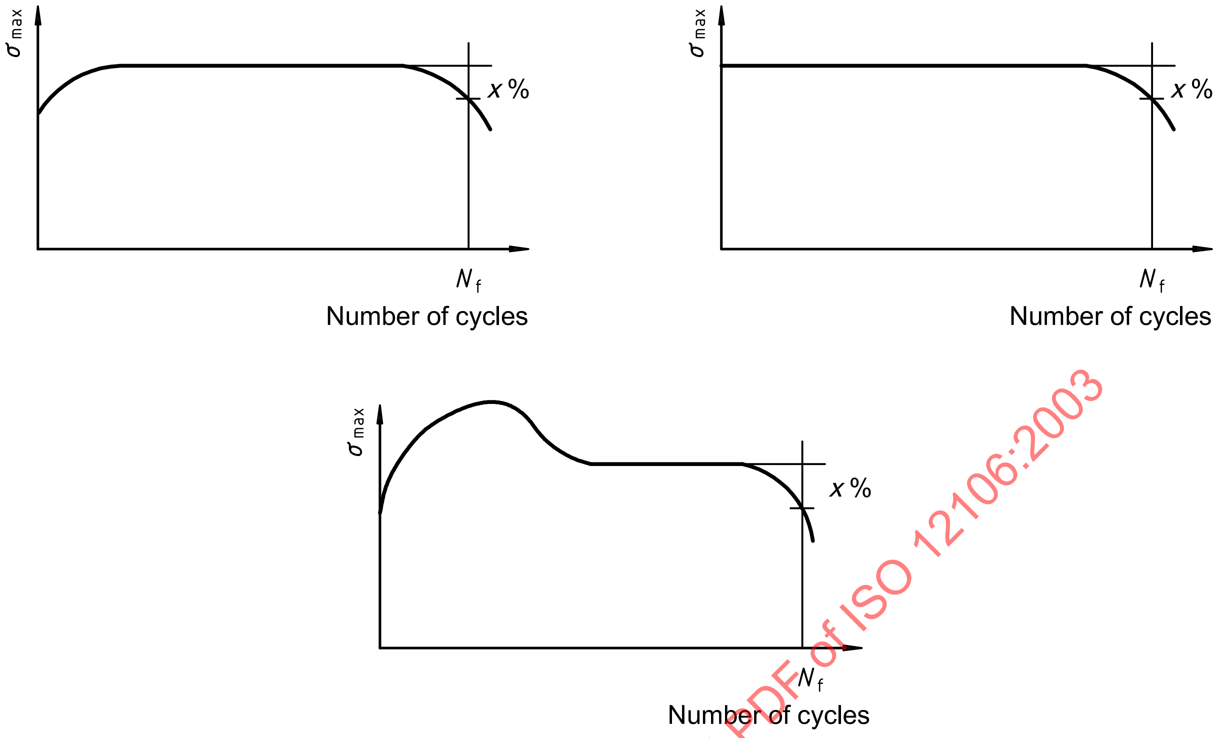
Figure 9 — Definitions of tension and compression modulus for determination of failure

The use of criteria a) and b) is the most common. However, any of the above criteria can be used for failure. The specific failure criteria used for the test series shall be reported. Figure 10 shows examples of the stress-decrease criterion. In this case, the number of cycles to failure, N_f, is defined as the number of cycles corresponding to a decrease of x % in the stress value extrapolated over the tensile stress-number of cycles curve when the stress falls sharply. A recommended value of x is 25.

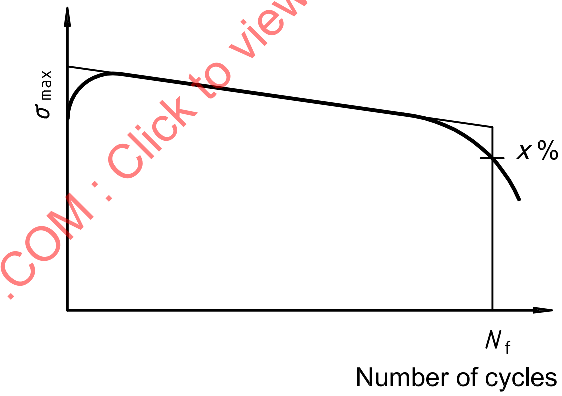
This criterion relates to the presence of one (or more) macroscopic crack(s) in the specimen. In general, the ratio of cracked surface area to the original cross-sectional area of the specimen is of the same magnitude as the ratio of stress decrease.

In all cases, the location of the failure in relation to the gauge length shall be identified and shall appear in the test results.

A post-test examination of the specimen shall be conducted in order to ensure the validity of the test. This means checking on the one hand for the correct location of the failure or main cracks and, on the other, ensuring the absence of faults or anomalies which could lead to incipient and premature failure (surface faults, porosity, inclusions, excessively large imprints left by the extensometer or bending of the specimen related to an alignment problem).



a) **For materials with stable or steady-state behaviour after initial hardening then softening**



b) **For materials with continuous softening**

Figure 10 — End-of-test criterion based on stress

7.9 End of test

The test is terminated when the conditions for the selected end-of-test criterion are fulfilled where the test machine is equipped with facilities allowing this criterion to be applied. If this is not the case, there shall be other possibilities for stopping the machine, either when a force threshold value is no longer reached (generally, a low fraction of full scale depending on the range) or, using the control signal, when the deviation between the command signal and the feedback signal reaches a certain value.

It is desirable that a test should not be automatically terminated by inappropriate preselection of stress limits, for example in the case of continuous cyclic softening illustrated in Figure 10. It is recommended in such cases that material response be observed prior to selection of stress limits and, in fact, a *post facto* determination of the number of cycles to failure may be necessary.

If the test terminates automatically prior to total failure of the specimen, the data shall be reviewed prior to specimen removal to ensure that the failure criterion has been achieved. If premature termination has occurred, then the test can be restarted. If the failure criterion has been met, then force control shall be re-established and zero force set for cool-down and specimen removal. If the specimen failure was “complete separation”, then the normal procedure would be to switch to “position control” for cool-down and specimen removal.

For high-temperature tests, the furnace shall be switched off as soon as the test terminates in order to limit the oxidation of the specimen and cracked surfaces with a view to carrying out subsequent fractographic examinations. If a test terminates prior to total failure of the specimen, every effort shall be made to ensure that the specimen will not be over-forced during cool-down of the heating device.

8 Expression of results

8.1 Data necessary

The data necessary for analysis of results is specified in 8.2.1 and 8.2.2.

8.2 Basic data

8.2.1 Determination of the modulus of elasticity $E_{1/4}$

Determine $E_{1/4}$ by cycling in the elasticity range of the material at the test temperature (see 7.5.2).

8.2.2 Recorded data (see 7.7)

Peak stress and strain range values as a function of the number of cycles, stress-strain hysteresis loops at the rate of three loops per decade (cycles 1, 2, 5, 10, 20, 50, etc.) plus those representative of failure, and the number of cycles corresponding to the first of the two following events to occur:

- total separation;
- drop of the tensile stress to below the value selected in 7.8.

8.3 Analysis of results

8.3.1 Distinction between different types of strain value

The different types of strain value are as follows:

the values of $\varepsilon_{\max}$ and $\varepsilon_{\min}$ imposed during the test are measured;

$\varepsilon_{\max}$ and $\varepsilon_{\min}$ are also computed from $\varepsilon \approx \ln(1 + e)$, where e is the engineering strain, and $\Delta\varepsilon_t$ is estimated;

$\Delta\varepsilon_e$ is calculated from $\frac{\Delta\sigma}{E}$ (where E is the average of the $E_{1/4}$ values measured over a series of specimens);

$\Delta\varepsilon_p$ is obtained from the difference $\Delta\varepsilon_t - \Delta\varepsilon_e$ for a continuous cycling test with no dwell periods.

8.3.2 Determination of fatigue life (see 7.8)

The number of cycles to failure N_f is defined in 7.8, a) to d).

8.3.3 Stress-strain and strain-fatigue life relationships

Tables 3 to 5 show the properties determined in a monotonic tensile test (reference material data) and in a low-cycle fatigue test [monotonic stress-strain curve (first quarter of cycle), cyclic stress-strain curve at $N_f/2$, and fatigue life N_f].

Table 3 — Monotonic test — Monotonic stress-strain values (first 1/4-cycle)

Property	Determination	Relation
$E_{1/4}$	Modulus of elasticity measured for a given specimen	
E	Average value of $E_{1/4}$ measured over a series of test specimens	
$R_{P0,2}$	Yield strength (0,2 % proof stress)	
n	Monotonic strain hardening exponent	Slope of lg σ_a – lg ε_{pa} plot
K	Monotonic strength coefficient. Stress intercept at ε_{pa} = 1 on lg σ_a – lg ε_{pa} plot.	$\sigma_a = K(\varepsilon_{pa})^n$

Table 4 — Cyclic test — Cyclic stress-strain values (stabilized cycle)

Property	Determination	Relation
$\sigma_{y'}$, cyclic yield strength (0,2 % offset)		
n', cyclic strain hardening exponent	Slope of lg σ_a = lg ε_{pa} plot	
K', cyclic strength coefficient	Stress intercept at ε_{pa} = 1 on lg σ_a – lg ε_{pa} plot	$\sigma_a = K'(\varepsilon_{pa})^{n'}$
Constitutive equation		$\frac{\Delta\varepsilon}{2} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'}$

Table 5 — Low-cycle fatigue test — Fatigue life

Property	Determination	Relation
σ_f', fatigue ductility coefficient	Stress intercept at $2N_f$ = 1 on lg σ_a – lg $2N_f$ plot	$\sigma_a = \sigma_f'(2N_f)^b$ (Basquin equation)
b, fatigue strength exponent	Slope of lg ($\Delta\varepsilon_e/2$) – lg $2N_f$ plot (Specify $2N_f$ range)	
ε_f', fatigue ductility coefficient	Plastic-strain intercept at $2N_f$ = 1 on lg ($\Delta\varepsilon_p/2$) – lg $2N_f$ plot	$\Delta\varepsilon_p/2 = \varepsilon_f'(2N_f)^c$ (Coffin-Manson equation)
c, fatigue ductility exponent	Slope of lg ($\Delta\varepsilon_p/2$) – lg $2N_f$ plot (Specify $2N_f$ range)	
Total strain amplitude	$\Delta\varepsilon_t/2 = \Delta\varepsilon_e/2 + \Delta\varepsilon_p/2$ $\Delta\varepsilon_t/2 = (\sigma_f'/E)(2N_f)^b + \varepsilon_f'(2N_f)^c$	

9 Test report

9.1 General

The test report shall include full information on the aim of the study and the material. It shall also include the details of the test methods and conditions, the analysis and presentation of the results, and descriptions of any anomalies or interruptions which may have arisen during each test.

This information is indicated in 9.2 to 9.8 below.

9.2 Purpose of the test

State the aim of the study.

9.3 Material

- Standardized designation;
- composition in mass percent;
- product;
- heat treatment;
- microstructure/hardness;
- mechanical properties at test temperature.

9.4 Specimen

Provide a drawing of the specimen indicating:

- the direction and location of sampling from the product;
- the final machining phase and mean longitudinal roughness value Ra.

9.5 Test methods

- Test machine:
  - frame capacity: ± ..... kN, calibration: ..... kN (10 V, X bit resolution);
  - type of actuator (hydraulic, electro-mechanical, etc.);
  - force capacity of actuator: ± ..... kN;
  - controller type (analog, digital, hybrid).

NOTE A hybrid controller has an analog servo-loop plus a digital operator interface.

- Load train:
  - type of grip (manually or hydraulically preloaded + description or photo);
  - method of ensuring axiality and level of bending at typical test force(s).

- Heating system:
  - type of furnace (resistive, radiant, inductive, etc.);
  - estimate of axial temperature gradient in gauge length of specimen: ..... °C;
  - temperature and variation in temperature during test: ..... °C ± ..... °C;
  - type of thermocouple;
  - heat-up time, time at test temperature prior to test commencing, and time at test temperature during test.
- Extensometer:
  - description of extensometer used (diagram or photo);
  - gauge length: ..... mm;
  - operating range: ± ..... mm (10 V, X bit resolution);
  - calibration procedure and results;
  - date of last calibration: ....;

9.6 Test conditions

- Axial-strain range: ....;
- strain ratio R_ε (= $\varepsilon_{\text{min}}/\varepsilon_{\text{max}}$): ....;
- waveform: ....;
- strain rate or frequency: ....;
- first quarter-cycle (tensile or compressive).

9.7 Presentation of results

9.7.1 Presentation of single test results (see 8.2.2)

For each test prepare:

- a table giving the total strain values (max., min., range), true stress (max., min., range) and plastic-strain variation as a function of number of cycles in accordance with Table 6;
- two curves giving the variation in the tensile and compressive stresses as a function of the number of cycles in semi-logarithmic coordinates and in linear coordinates;
- hysteresis loops representative of test start-up and near mid-life, and those representative of failure.

NOTE Log-linear coordinates are normally preferred.

Table 6 — Variation in strain and stress as a function of number of cycles during a low-cycle fatigue test

Material: ....

Specimen reference: ....

Amplitude of total strain applied: ....

Test temperature: ....

Modulus of elasticity $E_{1/4}$: ....

Strain rate: ....

Cycle	**Total strain** %			**Stress** MPa			**Plastic strain** %
	max.	min.	range	max.	min.	range	range

9.7.2 Presentation of results of test series

For a series of tests prepare:

- a table, Table 7, summarizing the results in order of decreasing strain amplitudes,
- the curves representing the variation in:
  - the total-strain amplitude ε_{ta} as a function of the number of cycles (log-log coordinates),
  - the stress amplitude σ_a at mid fatigue life as a function of the number of cycles (log-log coordinates),
  - the stress amplitudes σ_a and $\sigma_{a1/4}$ as a function of ε_{ta} and $\varepsilon_{ta1/4}$ (log-log coordinates), indicating the values for K, n, K' and n',
  - the total-, elastic- and plastic-strain amplitudes as a function of the number of cycles (log-log coordinates), indicating the values of the coefficients $\sigma_{f'}$, b, $\varepsilon_{f'}$ and c.

For parametric relationships, the number of tests for which the coefficients have been determined shall be stated in addition to the domain of the fit.

Examples of graphical representations are shown in Figures B.1 to B.4. [7, 12]

Table 7 — Summary of results of a test series

Strain amplitude	Number of cycles to failure	Stress amplitude at mid-life
ε_{10}	$N_{f,10}$	σ_{10}
ε_9	$N_{f,9}$	σ_9
ε_8	$N_{f,8}$	σ_8
ε_7	$N_{f,7}$	σ_7
ε_6	$N_{f,6}$	σ_6
ε_5	$N_{f,5}$	σ_5
ε_4	$N_{f,4}$	σ_4
ε_3	$N_{f,3}$	σ_3
ε_2	$N_{f,2}$	σ_2
ε_1	$N_{f,1}$	σ_1

9.8 Values to be stored in a low-cycle fatigue database

It is good practice to store data essential for the use of results of low-cycle fatigue tests in an easily accessible and user-friendly form.

These data include but are not limited to:

a) the table summarizing individual test results (Table 6)

b) the table summarizing the test results for the series (Table 7)

c) a table summarizing the analysis of the results in accordance with Table 8.

Tables 6, 7 and 8, prepared using a computer and spreadsheet-type software, may serve as a basis for preparing a database which is exportable by means of a communication network or disk (data files generally being in ASCII format).