INTERNATIONAL STANDARD

ISO 1352

Second edition
2011-04-15

Metallic materials — Torque-controlled fatigue testing

Matériaux métalliques — Essais de fatigue par couple de torsion commandé

Reference number
ISO 1352:2011(E)

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Published in Switzerland

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Foreword

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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 1352 was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 5, *Fatigue testing*.

This second edition cancels and replaces the first edition (ISO 1352:1977), which has been technically revised.

Metallic materials — Torque-controlled fatigue testing

1 Scope

This International Standard specifies the conditions for performing torsional, constant-amplitude, nominally elastic stress fatigue tests on metallic specimens without deliberately introducing stress concentrations. The tests are typically carried out at ambient temperature in air (ideally at between 10 °C and 35 °C) by applying a pure couple to the specimen about its longitudinal axis.

While the form, preparation and testing of specimens of circular cross-section and tubular cross-section are described in this International Standard, component and other specialized types of testing are not included. Similarly, low-cycle torsional fatigue tests carried out under constant-amplitude angular displacement control, which lead to failure in a few thousand cycles, are also excluded.

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 554:1976, *Standard atmospheres for conditioning and/or testing — Specifications*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
maximum stress
τ_{max}
highest algebraic value of shear stress in the stress cycle

3.2
minimum stress
τ_{min}
lowest algebraic value of shear stress in the stress cycle

3.3
mean stress
τ_m
static component of the shear stress

NOTE It is one half of the algebraic sum of the maximum shear stress and the minimum shear stress:

$$\tau_m = \frac{\tau_{max} + \tau_{min}}{2}$$

3.4
stress amplitude
τ_a
variable component of stress

NOTE It is one half of the algebraic difference between the maximum shear stress and the minimum shear stress:

$$\tau_a = \frac{\tau_{max} - \tau_{min}}{2}$$

3.5
number of cycles
N
number of cycles applied at any stage during the test

3.6
stress ratio
R
algebraic ratio of the minimum shear stress to the maximum shear stress in one cycle

NOTE It is expressed as

$$R = \frac{\tau_{min}}{\tau_{max}}$$

3.7
stress range
$\Delta\tau$
range between the maximum and minimum shear stresses

NOTE It is expressed as

$$\Delta\tau = \tau_{max} - \tau_{min}$$

3.8
fatigue life at failure
N_f
number of stress cycles to failure in a specified condition

3.9
fatigue strength at N cycles
τ_N
value of the shear stress amplitude at a stated stress ratio under which the specimen would have a life of N cycles

3.10
torque
T
twisting force producing shear stress or twisting deformation about the axis of the specimen

4 Symbols and abbreviated terms

D diameter or width across flats of the gripped ends of the specimen

NOTE The value of D may be different for each end of the specimen.

d diameter of specimen of circular cross-section, where stress is maximum

d_o outer diameter of test section of specimen of tubular cross-section, where stress is maximum

d_i inner diameter of test section of specimen of tubular cross-section

L_c length of test section

L_p parallel length of specimen's test section

L_g gauge length of the specimen's test section

r transition blending radius at ends of test section which starts the transition from d to D (see Figures 3 and 4)

NOTE This curve need not be a true arc of a circle over the whole of the distance between the end of the test section and the start of the enlarged end for specimens of the types shown in Figure 3.

5 Principle of test

Nominally identical specimens are mounted on a torsional fatigue testing machine and subjected to the loading condition required to introduce cycles of torsional stress. Any one of the types of cyclic stress illustrated in Figure 1 may be used. The test waveform shall be constant-amplitude sinusoidal, unless otherwise specified.

In an axially symmetrical specimen, change of mean torque does not introduce a different type of stress system and mean stress in torsion may always be regarded as positive in sign.

The torque is applied to the specimen about the longitudinal axis passing through the centroid of the cross-section.

The test is continued until the specimen fails or until a predetermined number of stress cycles has been exceeded.

Cracks produced from torsional fatigue testing may be parallel to the longitudinal axis of the specimen, perpendicular to the longitudinal axis or at any angle between these two.

Tests shall be conducted at ambient temperature (ideally between 10 °C and 35 °C) unless otherwise agreed with the customer.

The results of fatigue testing can be affected by atmospheric conditions, and where controlled conditions are required, ISO 554:1976, 2.1, applies.

6 Test plan

Before commencing testing, the following shall be agreed by the parties concerned and any modifications shall be mutually agreed upon:

a) the form of specimen to be used (see Clause 7);

b) the stress ratio(s) to be used;

c) the objective of the tests, i.e. which of the following is to be determined:

— the fatigue life at a specified stress amplitude;

— the fatigue strength at a specified number of cycles;

— a full Wöhler or S–N curve;

d) the number of specimens to be tested and the test sequence;

e) the number of cycles a specimen is subjected to before the test is terminated.

NOTE 1 Some methods of data presentation are given in Annex A. See ISO 12107 for details, including data analysis procedure and statistical presentation.

NOTE 2 Commonly employed numbers of cycles for test termination are

— 10^7 cycles for structural steels, and

— 10^8 cycles for other steels and non-ferrous alloys.

7 Shape and size of specimen

7.1 Form

Generally, a specimen having a fully machined test section of one of the types shown in Figures 3 and 4 should be used.

The specimen may be of

— circular cross-section, with tangentially blending fillets between the test section and the ends (see Figure 3), or

— tubular cross-section, with tangentially blending fillets between the test section and the ends in the outer surface (see Figure 4).

For tubular specimens, the diameter of the inner surface at the ends may be greater than or equal to that at the test section. For a specimen having a inner diameter at the ends greater than that at the test section, crack initiation or failure outside the test section invalidates the test, which should be counted as a discontinued (stopped) test at the number of cycles completed.

Fatigue test results determined using the specimen of tubular cross-section are not always comparable to those obtained from the specimen of circular cross-section. Therefore, caution should be exercised when comparing fatigue lives obtained on the same material from specimens having different cross-sections.

Typical specimen ends are shown in Figure 5. It is recommended that ends suitable for meeting the alignment criterion be chosen.

7.2 Dimensions

7.2.1 Specimens of circular cross-section

It is recommended that the geometric dimensions given in Table 1 be used (see also Figure 3).

Table 1 — Dimensions for specimens of circular cross-section

Diameter of cylindrical gauge length, in millimetres	$5 \leqslant d \leqslant 12$
Length of test section	$L_c \leqslant 5d$
Transition radius (from parallel section to grip end)	$r \geqslant 3d$
External diameter (grip end)	$D \geqslant 2d$
The tolerance on d shall be ±0,05 mm.	

To calculate the applied torque loading, the actual diameter of each specimen shall be measured to an accuracy of 0,01 mm. Care should be taken not to damage the surface when measuring the specimen prior to testing.

It is important that general tolerances of the specimen respect the two following properties:

— parallelism: 0,005d or better

— concentricity: 0,005d or better

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

7.2.2 Specimens with tubular cross-section

In general, the considerations applicable to specimens of circular cross-section also apply to tests on tubular specimens.

The specimen wall thickness shall be large enough to avoid instabilities during cyclic loading without violating the thin-walled tube criterion, i.e. a mean diameter-to-wall thickness ratio of 10:1 or greater is required.

It is recommended that the geometric dimensions given in Table 2 be used (see also Figure 4).

Table 2 — Dimensions for specimens of tubular cross-section

Wall thickness in test section, t	$0{,}05d_o$ to $0{,}1d_o$
Outer diameter of test section	d_o
Transition radius (from parallel section to grip end), r	$\geqslant 3d_o$
Length of test section, L_c	$1d_o$ to $3d_o$
External diameter (grip end)	$D \geqslant 1{,}5d_o$
Concentricity between the outer diameter, d_o, and the inner diameter, d_i, should be maintained within $0{,}01t$.	

8 Preparation of specimens

8.1 General

In any 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. Deviation from these recommendations is permitted if the test program aims to determine the influence of a specific factor (surface treatment, oxidation, etc.). In all cases, any deviations shall be noted in the test report. Specimens should be machined from normally stress-free material unless otherwise agreed with the customer.

8.2 Machining procedure

Machining the specimens can induce residual stress on the specimen surface that could affect the test results. These stresses can be induced by heat gradients at the machining stage — stresses associated with deformation of the material or microstructural alterations. However, they can 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 preferable.

— 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.

— For tubular specimens the bore should be fine-honed.

Failure to observe the above can result in alteration in the microstructure of the material. This phenomenon can be caused by an increase in temperature and by the strain-hardening induced by machining; it can be a matter of a change in phase or, more frequently, of surface recrystallization. This invalidates the test as the material mechanical properties are changed.

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

8.3 Sampling and marking

The sampling of test materials from a semi-finished product or component can have a major influence on the results obtained during the test. It is therefore necessary to clearly identify the location and orientation of each specimen.

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), and

— the marking of each of the specimens.

Specimens shall 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 to adversely affect the quality of the test.

Identification shall be applied to each end of the specimen before testing.

8.4 Surface conditions of specimen

The surface conditions of the specimens can affect the test results. This is generally associated with one or more of the following factors:

— specimen surface roughness;

— presence of residual stresses;

— alteration in the microstructure of the material;

— introduction of contaminants.

To minimize the impact of these factors, the following is recommended.

The impact of surface roughness on the results obtained depends largely on the test conditions and its effect 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 Ra (or equivalent) within the parallel section.

Another important parameter not covered by mean roughness is the presence of localized machining scratches. Finishing operations should eliminate all circumferential scratches produced during turning. Final grinding followed by mechanical polishing is highly recommended. A visual inspection at low magnification (approximately ×20) should only show polishing marks appropriate to the grade of the final polishing medium.

It is preferable to carry out a final polishing operation after 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 surface. This treatment should not alter the microstructural characteristics of the material under study. The details of the heat treatment and machining procedure shall be reported with the test results.

8.5 Dimensional checks

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

8.6 Storage and handling

After preparation, the specimens should be stored so as to prevent any risk of damage (scratching by contact, oxidation, etc.). If there is any damage on the surface of the specimen during storage, it should be removed by repolishing the specimen. The use of individual boxes or tubes with end caps is recommended. In certain cases, storage in a vacuum or in a desiccator is necessary.

Handling should be reduced to the minimum necessary. Particular attention shall be given to marking of the specimen. Identification shall be applied to each end of the specimen before testing.

9 Apparatus

9.1 Testing machine

9.1.1 General

The tests shall be carried out on a testing machine having a clockwise/anticlockwise (counter-clockwise) torsional loading capability, with smooth start and no backlash when passing through zero. The test start settings shall allow the required level to be reached without any overload. The time frame for reaching the required level should be as short as reasonably possible.

The machine should have adequate lateral and torsional stiffness and alignment.

The complete machine loading system (including torque cell, grips, and specimen) shall be capable of controlling and measuring torque when the recommended wave cycle is applied. The specimen shall be unconstrained in the axial direction to prevent extraneous forces being introduced.

The testing machine torque measuring system shall be verified statically using a suitable method of calibration and shall be traceable to national standards.

It is important to recognize the potential effect of dynamic errors introduced by the inertial mass between the torque cell and the specimen. Inertia torque errors, expressed as a percentage of torque range, can be expected to vary with frequency and are strongly influenced by specimen compliance. For details, see ISO 4965, which, although intended for axial fatigue testing, gives principles that also apply to torsional fatigue testing.

The machine shall be equipped with a cycle-counting system accurate to 1 % and shall be able to shut down automatically when the specimen fails.

9.1.2 Torque cell

The torque cell shall be fatigue rated. The indicated torque, as recorded at the output from the computer in an automated system, or from the final output recording device in a non-automated system, shall be within specified limits. The torque cell capacity shall be sufficient to cover the range of torque measured during a test to an accuracy of 1 % of the reading or better. The torque cell shall be temperature-compensated and should have a zero drift no greater than 0,002 % of full scale per degree Celsius. Sensitivity variation should not be greater than 0,002 % of full scale per degree Celsius.

9.1.3 Gripping of specimen

The gripping device shall transmit the cyclic torques to the specimen without backlash along its circumferential direction for the duration of the test. The geometric qualities of the device shall ensure correct alignment so that it is in accordance with 9.1.4.

The gripping device shall enable repeatable assembly and have surfaces that ensure alignment of the specimen. It shall also allow transmission of reversed torque without backlash throughout the duration of the test.

9.1.4 Alignment check

It is important that the best uniform stress distribution be obtained for every fatigue test. Axial alignment of the test machine for both axial fatigue machines and torsional fatigue machines is measured using an alignment check methodology[3].

NOTE 1 Annex B briefly describes the alignment check methodology.

In addition, it is important to document the applied stress distribution in the test section of the fatigue specimen. This applied stress uniformity is controlled by both the test machine and the specimen.

NOTE 2 Annex C describes a procedure for measuring and documenting the applied stress uniformity for torsional tests.

The stress uniformity may be checked before each series of tests or whenever a change is made to the load train.

9.1.5 Axial force

For torsional testing, the axial force shall be zero.

9.2 Instrumentation for test monitoring

9.2.1 Recording system

A device for measuring applied torque against time with an accuracy of 1% of full scale of the torque cell shall be considered as a minimum requirement for the recording of data.

Computerized data collection systems shall have collection rates fast enough to meet this requirement; non-computerized data collection systems may need a high-speed recorder or storage device, which can then be played back at a slower rate to determine the peak and valley torque magnitude for each cycle.

9.2.2 Cycle counter

A cycle counter is essential for recording the number of cycles applied; it shall stop automatically on specimen failure.

9.2.3 Checking and verification

The proper operation of the testing machine and its control and measurement systems should be checked annually or more frequently if required. The time interval between verifications shall not exceed 13 months, except for testing machines being used in long-term tests that exceed this period, in which case the test machine shall be verified upon completion of the test.

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

The torque measuring system(s) shall be traceable to a national standard.

10 Test procedure

10.1 Mounting of specimen

Care should be taken to ensure that each specimen is located in the driven and stationary (top and bottom, left and right) grips so that the axis of the specimen lies along the axis of torsion of the testing machine and the intended stress pattern is imposed. Care should also be taken to ensure that no (or minimal) axial stress is applied to the specimen during the mounting of the specimen on the testing machine.

10.2 Speed of testing

The frequency of the torque cycle will depend upon the type of testing machine employed and the test programme requirements. The frequency chosen shall be that suitable for the particular combination of material, specimen and testing machine.

At high frequencies, substantial heating of the specimen can occur, which could affect the test fatigue life and strength results. In such cases, it is advisable to record the increase in temperature and to include it in the test report. If the test programme allows, the test frequency should be reduced if the specimen temperature increase is excessive for the material.

NOTE If the influence of the environment is significant, the test result is likely to be frequency-dependent.

10.3 Application of torque

The general procedure for attaining full-torque running conditions shall be the same for each specimen. The mean torque and torque range shall be maintained within ±1 % of the torque range.

10.4 Calculation of nominal torsional stress

Torsional (shear) stress, τ, results from the torque, T, applied to the specimens of circular and tubular cross-sections. The torsional stress is always largest at the outer diameter of the test section. Under elastic loading conditions, the nominal torsional stress varies linearly from zero at the axis of twist to a maximum at the outer diameter, and the following calculation of torsional stress, τ, is recommended:

$$\tau = \frac{16T}{\pi d^3}$$ at the outer diameter for solid specimens of circular cross-section;

$$\tau = \frac{16Td_\mathrm{o}}{\pi\left(d_\mathrm{o}^4 - d_\mathrm{i}^4\right)}$$ at the outer diameter for specimens of tubular cross-section.

10.5 Recording of temperature and humidity

The maximum and minimum air temperatures and the humidity shall be recorded daily for the duration of the test.

If specimen self-heating is of concern, the temperature of the specimen shall be monitored and recorded.

10.6 Failure and termination criteria

10.6.1 Failure

Unless otherwise agreed, the criterion for specimen failure shall be specimen separation.

In particular applications, other criteria (for example, the occurrence of a visible fatigue crack, plastic deformation of the specimen or the rate of crack propagation) may be adopted.

10.6.2 Termination

The test shall be terminated when either the specimen fails or a predetermined number of cycles is completed, as agreed by the concerned parties.

11 Test report

The test report shall include reference to this International Standard as well as the following information for the test series, if available:

— material tested, its metallurgical characteristics, mechanical properties, and any heat treatment given to the specimen(s);

— location of the specimen(s) in the parent material;

— form and nominal dimensions of the specimen(s);

— surface condition of the specimen(s).

The test report shall include the following for each individual specimen:

a) cross-sectional dimensions;

b) minimum and maximum peak torque applied;

c) applied stress conditions;

d) frequency and fatigue life;

e) a description of the testing machine used, its type and serial number, the torque cell and serial number, number and load train description;

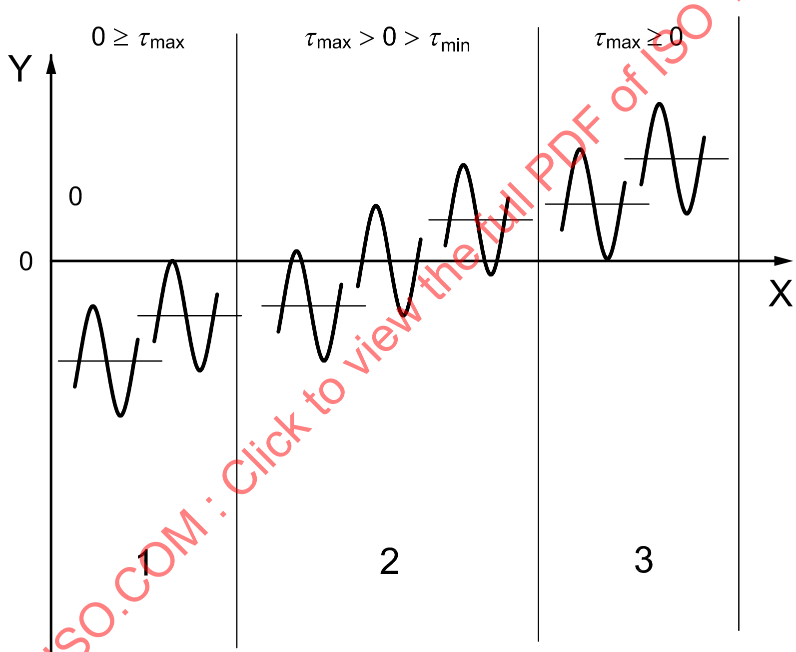
f) temperature of the specimen if self-heating occurs (i.e. greater than 35 °C);

g) maximum and minimum air temperatures and relative humidity;

h) criterion for ending the test, i.e. its duration (e.g. 10^7 cycles), or complete failure of the specimen, or any other criterion;

i) any special observations or deviations from the required test conditions.

Additionally, test results may be presented graphically.



Key

X time

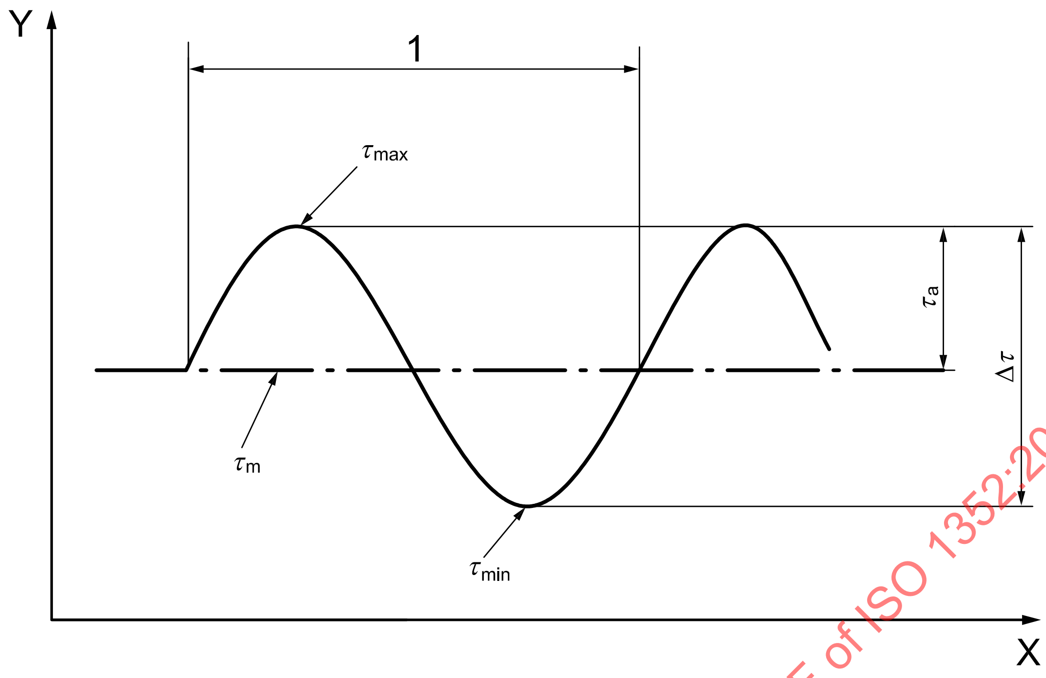
Y stress

1 fluctuating compression

2 reversed

3 fluctuating tension

Figure 1 — Types of cyclic stress



Key

X time

Y stress

1 one stress cycle

Figure 2 — Fatigue stress cycle

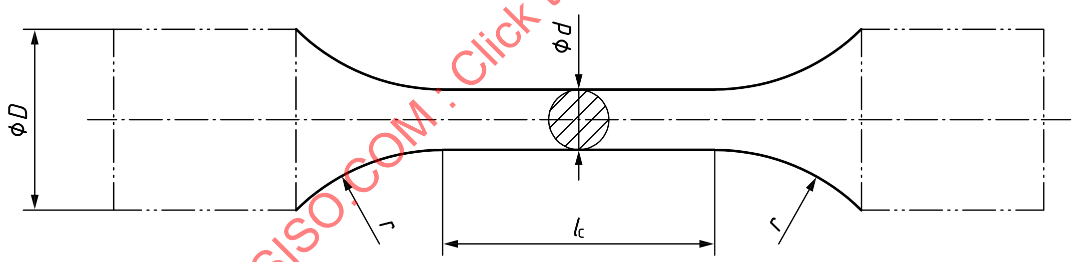


Figure 3 — Test pieces with circular cross-section

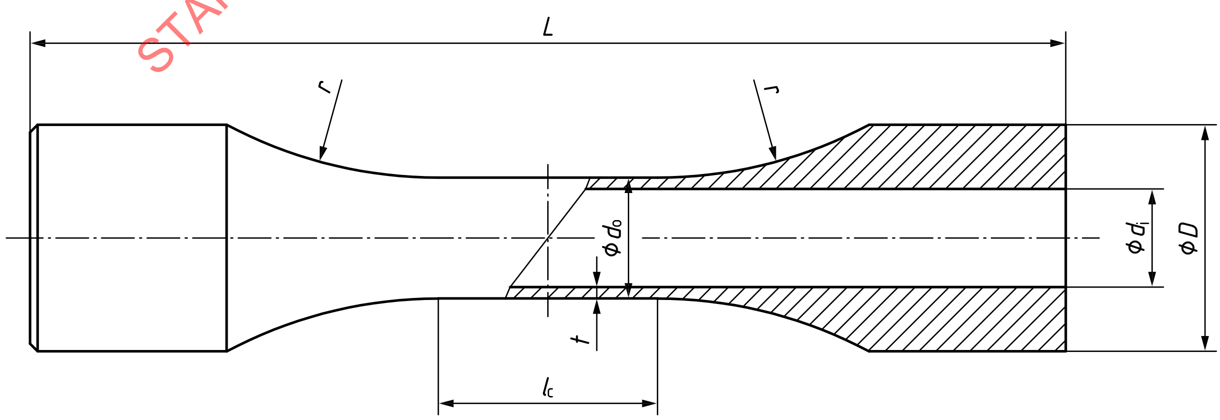


Figure 4 — Test piece with tubular cross-section

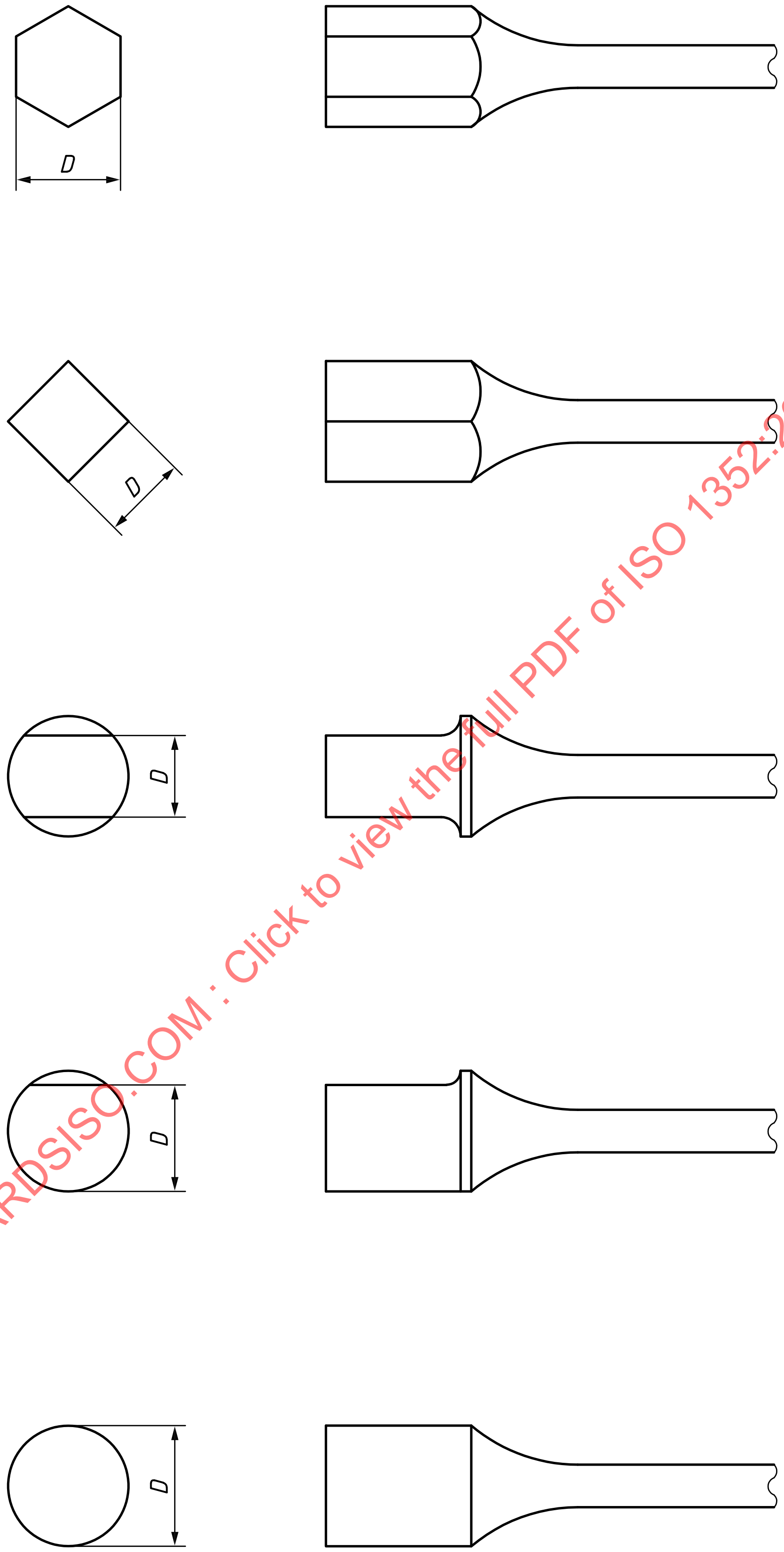


Figure 5 — Typical specimen ends

Annex A
(informative)

Presentation of results

A.1 General

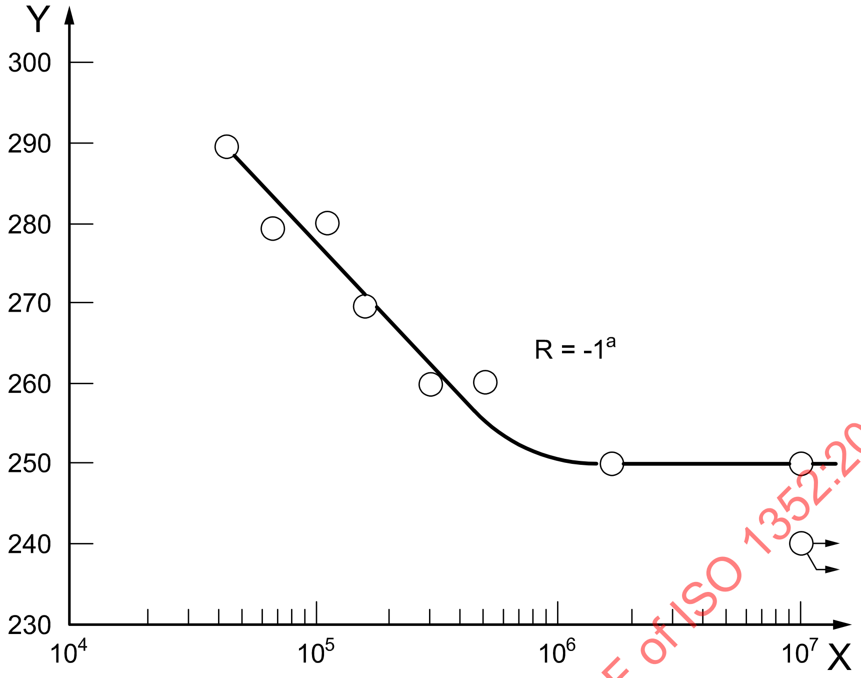
The design of the investigation and the use to be made of the results govern the choice of the most suitable method for presenting the results, graphically or otherwise, from the many available methods. The results of fatigue tests are usually presented graphically. In reporting fatigue data, the test conditions should be clearly defined.

A.2 Wöhler or S–N curve

The most general method of graphically presenting the results is to plot the number of cycles to failure as the abscissa and the values of stress amplitude or (depending on the type of stress cycle) those of any other stress as the ordinate. The curve drawn smoothly as an approximate middle line through the experimental points is called a Wöhler or S–N curve. A logarithmic scale is used for the number of cycles and the choice of using either a linear or logarithmic scale for the stress axis lies with the experimenter. Individual curves are plotted for each set of tests for each R ratio. Experimental results are usually plotted on the same figure. An example is shown in Figure A.1, where a linear stress scale is used.

A.3 Mean stress diagrams

The fatigue strengths derived from the Wöhler or S–N curve are plotted as fatigue strength diagrams. The results can be represented by a graph giving directly, for particular endurances, the stress amplitude against the mean stress, as shown in Figure A.2 (Haigh diagram), or by plotting the maximum and minimum stresses against the mean stress, as shown in Figure A.3 (Smith diagram). Experimental results may be plotted on the same figure.



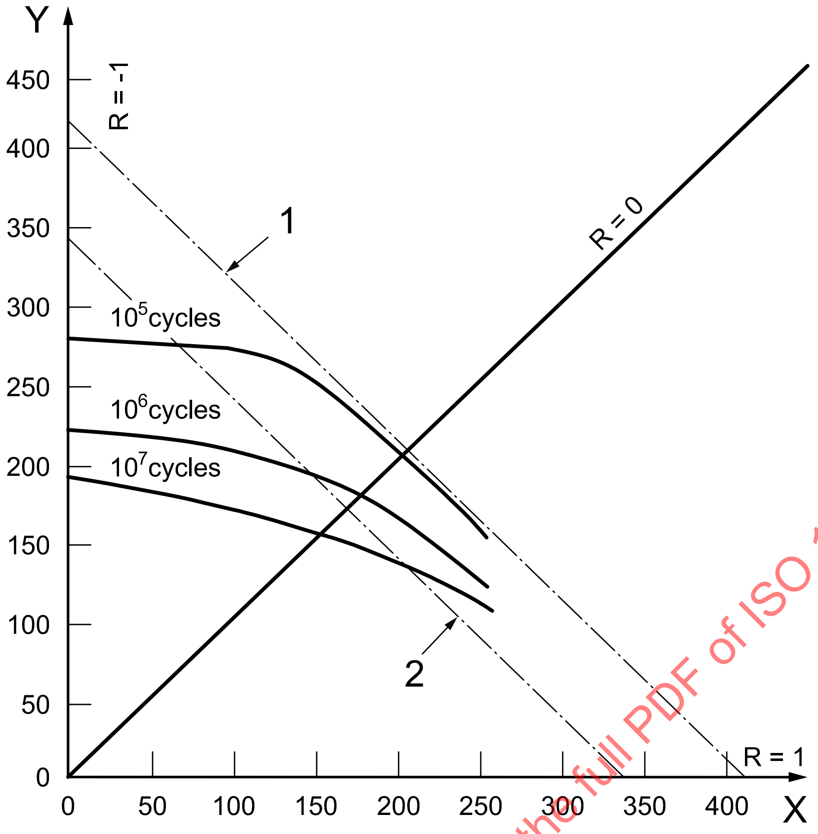
Key

X number of cycles to failure, N

Y stress amplitude, τ_a, N/mm^2

[a] Ambient temperature.

Figure A.1 — Wöhler or S-N curve



Key

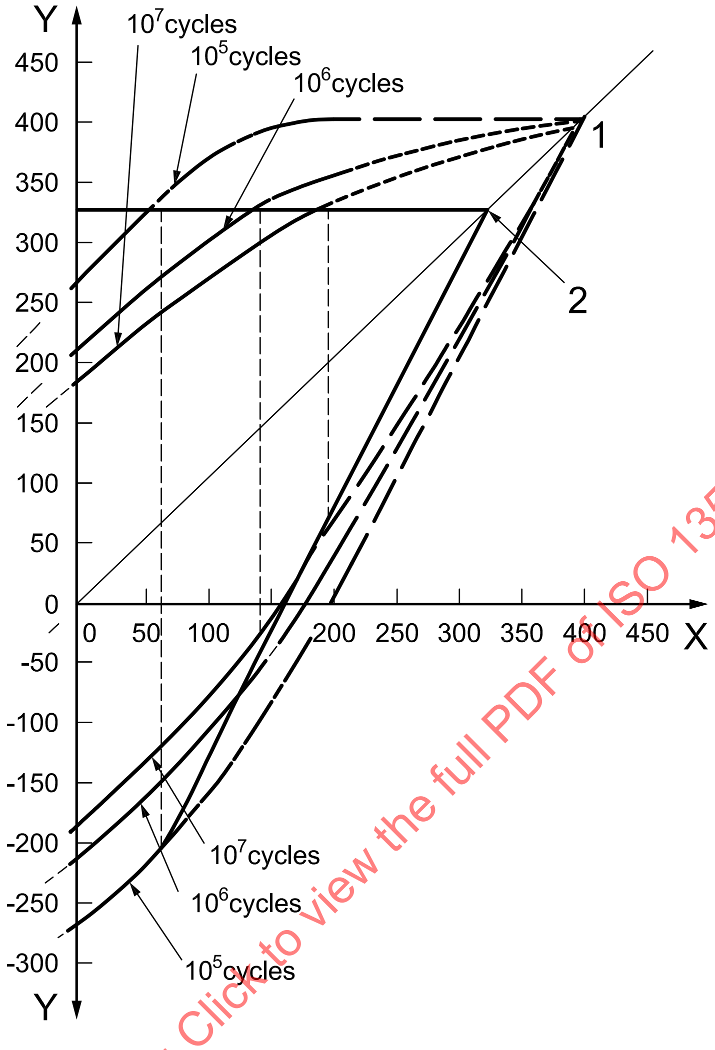
X mean stress, τ_m, N/mm^2

Y stress amplitude, τ_a, N/mm^2

1 sheer stress

2 0,2 % proof stress

Figure A.2 — Stress amplitude against mean stress — Haigh diagram



Key

X mean stress, τ_m, N/mm^2

Y maximum and minimum stresses, τ_{max} and τ_{min}, N/mm^2

1 sheer stress

2 0,2 % proof stress

Figure A.3 — Maximum and minimum stresses against mean stress — Smith diagram

Annex B
(informative)

Verification of alignment of torsional fatigue testing machines

B.1 The alignment check shall be carried out using a standard axial alignment specimen or bar alignment device. The bar alignment device is illustrated in Figure B.1, and the axial alignment specimen, shown in Figure B.2, should be of a geometry similar to the specimens being tested. It is recommended that the alignment specimen be made from a hardened heat-treated steel.

B.2 The bar alignment device, as a non-strain-gauged device, may be useful for checking the alignment in the test system both qualitatively and relatively quickly. The device, as illustrated in Figure B.1, should consist of a split bar and a sleeve, both made to precise tolerances. It is recommended that the sleeve and bar be made of the same materials.

B.3 In order to check the misalignment due to angular offset, lateral offset and/or load train offset, the axial strain-gauged alignment specimen should have resistance strain gauges secured at the locations illustrated in Figure B.2. With the top or bottom (not both) of the strain-gauged specimen secured in the gripping arrangement, the temperature should be allowed to equilibrate and the zero reference adjustments to the bridge amplifiers be made. At this time, the alignment specimen should be gripped in both the upper and lower grips.

B.4 The gauged specimen should be loaded in torsion to a maximum tensile strain of 0,4 %, or to a torque corresponding to the maximum torsional strain to be imposed on specimens in the test series if this value does not exceed 0,4 % strain of the gauge specimen. The maximum bending strains are calculated according to the scheme described in Reference [3], in which the bending strains are separated into the machine contribution and the specimen contribution. If the maximum bending strain for the machine contribution exceeds 50 microstrains in one or more of the two instrumented planes, adjustments should be made in the test frame actuator or fixtures and/or force transducer, followed by a repetition of the procedure until 50 microstrains is achieved.

It is recommended that the general procedure for preparation of the alignment specimen and checking of the alignment follow that described in Reference [3].

Care should be taken when applying a series of torsional loads or torsional strains to the specimen because the axial strain gauges cannot sense the torsional strain or deformation imposed on the specimen. Therefore, it is recommended that the torsional loads to be imposed on the specimen be pre-determined using another specimen with the same dimension and material as the gauged specimen.

B.5 The procedure should be repeated in reversed torsion to ascertain that the alignment is within that specified (i.e. $< 5,0$ %).

B.6 If the check is not satisfactory,

— the reproducibility of the measurements shall be verified by carrying out the process several times,

— it shall be established that the results are attributable to the test assembly and not to the specimen, and

— the elements making up the gripping train (instruments, cell, machine) shall be checked for geometric accuracy.

