
Metallic materials — High strain rate torsion test at room temperature

*Matériaux métalliques — Essai de torsion à haute vitesse de
déformation à température ambiante*

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Published in Switzerland

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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 2, *Ductility testing*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

In many dynamic events, such as punch forming, metal cutting, and vehicle collision, the metallic components are susceptible to dynamic impact loading, in which case the maximum strain rate of the order of 10^4 s^{-1} can be achieved. During this extreme loading condition, the strength of the material can be significantly higher than that under quasi-static loading conditions. The shear mechanical properties of metallic materials, such as yield strength, flow stress and failure strain are essential information for analysis of shear failure of components, and are also the basic data for construction of constitutive relations. The shear mechanical properties of many metallic materials depend also on strain rate as properties under uniaxial load. Therefore, to determine the shear mechanical properties of metallic materials at high strain rates by torsion test is also of great importance for engineering design, structural optimization, processing and evaluation of metallic structures. For additional information see

- ISO 26203-1, and
- ISO 26203-2.

The split Hopkinson (Kolsky) bar is one of the major test methods for measurement of mechanical properties of materials at high strain rates ($\geq 10^2 \text{ s}^{-1}$). It is designed on the base of two assumptions, namely

- a) one-dimensional elastic wave propagation in elastic bars, and
- b) uniform distribution of stress-strain along the length of the short test piece.

The fundamental principle is as follows: a small test piece is sandwiched between two long elastic bars, which are used as loading and measuring devices by means of elastic stress wave propagation. On the one hand, the propagating waves on elastic bars load dynamically the test piece; on the other hand the force and displacement measurements of test piece can be calculated by measuring the elastic strain of the bars through gauges attached to the bars. The torsional split Hopkinson bar apparatus, one kind of split Hopkinson bar techniques, can provide solutions for dynamic torsional testing problems and is widely used to obtain accurate stress-strain curves at around 10^3 s^{-1} .

This document provides test method for the torsional split Hopkinson bar apparatus.

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Metallic materials — High strain rate torsion test at room temperature

1 Scope

This document specifies terms and definitions, symbols and designations, principle, apparatus, test piece, procedure, data processing, evaluation of test result, test report and other contents for the torsion test at high strain rates for metallic materials by using torsional split Hopkinson bar (TSHB).

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

stress wave

strain wave

propagation of disturbance of stress (or strain) in a medium

Note 1 to entry: When a localized mechanical disturbance is applied suddenly into a deformable solid medium, the disturbance results in the variations of particle velocity, and also the variations of stress and strain states. The variations or disturbances of the stress and strain states propagate to the other parts of the medium in the form of waves. The resulting waves in the medium are due to mechanical stress (or strain) effects and, thus, these waves are called stress wave (or strain) wave.

3.2

elastic stress wave

elastic strain wave

stress wave or strain wave (3.1) propagating in an elastic medium

Note 1 to entry: When loading conditions result in stresses below the yield point of solid medium, the medium behaves elastically, and consequently the *stress wave or strain wave* (3.1) is elastic.

3.3

elastic torsional wave

type of propagation of rotation disturbance inducing shear deformation in elastic medium

Note 1 to entry: The direction of particle movement is perpendicular to the wave propagation direction.

3.4

wave front

moving surface which separates the disturbed from the undisturbed part in a medium

3.5

elastic torsional wave velocity

propagation velocity of *wave front* (3.4) of *elastic torsional wave* (3.3)

3.6**split Hopkinson bar**

experimental apparatus that utilizes the split-bar system to determine the dynamic stress-strain curves of materials from the information of *stress wave or strain wave* (3.1) propagation in bars

Note 1 to entry: In a split Hopkinson bar apparatus a short test piece is sandwiched between the two long elastic bars, called incident and transmitter bars, by which the test piece is loaded, and force and displacement are measured.

3.7**TSHB****torsional split Hopkinson bar**

kind of *split Hopkinson bar* (3.6) used for testing materials in torsion

Note 1 to entry: in a torsional split Hopkinson bar (TSHB) apparatus the *elastic torsional wave* (3.3) propagation is utilized to measure the shear mechanical properties of materials at high strain rates.

3.8**incident wave**

elastic stress wave or elastic strain wave (3.2) generated in the incident bar, propagating towards the test piece

3.9**reflected wave**

elastic stress wave or elastic strain wave (3.2) reflected to the incident bar from the incident bar-test piece interface

Note 1 to entry: When the *incident wave* (3.8) propagates till the bar-test piece interface, a part of the *incident wave* (3.8) is reflected back into the incident bar.

3.10**transmitted wave**

elastic stress wave or elastic strain wave (3.2) transmitted through the transmitter bar-test piece interface and into the transmitter bar

Note 1 to entry: When the *incident wave* (3.8) propagates till the bar-test piece interface, a part of the *incident wave* (3.8) is reflected back into the incident bar, and a second part of the wave is transmitted through the test piece to the transmitter bar.

3.11**average engineering plastic strain rate**

arithmetic average of the engineering plastic shear strain rate function of time

Note 1 to entry: The arithmetic average value of the engineering plastic shear strain rate function can be found by calculating the definite integral of the function and dividing the integral value by the time interval for plastic deformation.

3.12**gauge length**

length of thin-wall section of the test piece

4 Symbols and designations

Table 1 — Symbols and designations

Symbol	Designation	Unit
a_1	Distance from the strain gauge location on the incident bar to the bar-test piece interface	mm
NOTE During the data processing, the unit of shear strain rate and average engineering plastic strain rate is (ms) ⁻¹ ; the resulting expression should be converted to s ⁻¹ .		

Table 1 (continued)

Symbol	Designation	Unit
a_2	Distance from the strain gauge location on the transmitter bar to the bar-test piece interface	mm
C_b	Velocity of the torsional wave propagation of the elastic bar	mm/ms
ρ_b	Density of the elastic bar	g/mm ³
D_b	Diameter of the elastic bar	mm
L_b	Length of the elastic bar	mm
G_b	Shear modulus of the elastic bar	MPa
L_E	Length of the energy storage section	mm
L_I	Length of the incident bar	mm
L_T	Length of the transmitter bar	mm
M	Applied torque in the bar at gauge station	N·mm
M_s	Torque in the test piece	N·mm
M_R	Torque of the reflected wave	N·mm
$M_{\max}$	Maximum torque applied on the energy storage section	N·mm
r_b	Radius of the elastic bar	mm
J_b	Polar moment of inertia of the elastic bar	mm ⁴
τ_Y	Shear yield strength of the elastic bar material	MPa
ρ_s	Density of the test piece	g/mm ³
G_s	Shear modulus of the test piece	MPa
D	Diameter of cylindrical flange	mm
D_1	Diameter of the circumcircle of regular hexagonal flange	mm
d_1	Inner diameter of thin-wall section	mm
d_2	Outer diameter of thin-wall section	mm
L	Total length of the test piece	mm
L_1	Flange length of the test piece	mm
L_s	Gauge length of the test piece	mm
r_s	Mean radius of the thin-wall of the test piece	mm
δ_s	Thickness of the thin-wall section of the test piece	mm
r	Radius at the shoulder of the test piece	mm
$\dot{\theta}_1, \dot{\theta}_2$	Angular velocities of the ends of the test piece	(ms) ⁻¹
$\dot{\gamma}_s$	Engineering plastic shear strain rate in the test piece	(ms) ⁻¹
$\dot{\gamma}$	Engineering shear strain rate	(ms) ⁻¹
C_s	Velocity of the torsional wave propagation of the test piece	mm/ms
γ_s	Engineering plastic shear strain in the test piece	-
$\bar{\dot{\gamma}}_s$	Average engineering plastic shear strain rate in the test piece	(ms) ⁻¹
τ_s	Engineering shear stress of the test piece	MPa
γ	Engineering shear strain	-
τ	Engineering shear stress	MPa
U	Voltage of channel signal	V

NOTE During the data processing, the unit of shear strain rate and average engineering plastic strain rate is (ms)⁻¹; the resulting expression should be converted to s⁻¹.

Table 1 (continued)

Symbol	Designation	Unit
U_{0j}	Voltage of the j^{th} channel signal at the strain calibration, $j = 1, 2, \dots, n$	V
U_j	Output voltage of the j^{th} channel signal, $j = 1, 2, \dots, n$	V
U_B	Bridge voltage	V
T_1	Starting point of the incident wave	ms
T_2	Starting point of the reflected wave	ms
T_3	Starting point of the transmitted wave	ms
λ	Length of the incident wave	ms
t	Time	ms
T	Load duration of stress wave	ms
T_0	Time corresponding to the yield strength in engineering shear stress-time curve	ms
ΔT	Sampling interval	ms
Δt	Rise time of the incident wave	ms
Δt_i	Time interval between the incident and reflected waves	ms
ξ	Dummy variable	ms
e	Engineering elastic strain	10^{-6}
e_j	Measured strain value of the j^{th} channel, $j = 1, 2, \dots, n$	-
e_I	Strain of incident wave recorded by gauge on the incident bar	-
e_R	Strain of reflected wave recorded by gauge on the incident bar	-
e_T	Strain of transmitted wave recorded by gauge on the transmitter bar	-
γ_R	Measured shear strain of reflected wave on incident bar	-
γ_b	Shear strain on the surface of the bar	-

NOTE During the data processing, the unit of shear strain rate and average engineering plastic strain rate is $(\text{ms})^{-1}$; the resulting expression should be converted to s^{-1} .

5 Principle

The shear stress-strain characteristics of metallic materials at high strain rates are evaluated by torsional split Hopkinson bar (TSHB) method, which utilizes two long elastic bars for applying the load to the test pieces sandwiched between bars, and also for measuring the displacements and loads as transducers at the test piece ends. The bars remain elastic throughout the test and are long enough so that the strain signals are recorded before the elastic wave is reflected back from the other end. The histories of load and deformation in test piece are calculated by one dimensional wave propagation theory from strain signals obtained by strain gauges mounted on two bars by use of [Formulae \(1\) to \(3\)](#)^[4]:

$$\dot{\gamma}_s(t) = \frac{2r_s \cdot C_b}{r_b \cdot L_s} [e_I(t) - e_R(t) - e_T(t)] \quad (1)$$

$$\gamma_s(t) = \frac{2r_s \cdot C_b}{r_b \cdot L_s} \int_0^t [e_I(\xi) - e_R(\xi) - e_T(\xi)] d\xi \quad (2)$$

$$\tau_s(t) = \frac{G_b \cdot r_b^3}{4r_s^2 \cdot \delta_s} [e_I(t) + e_R(t) + e_T(t)] \quad (3)$$

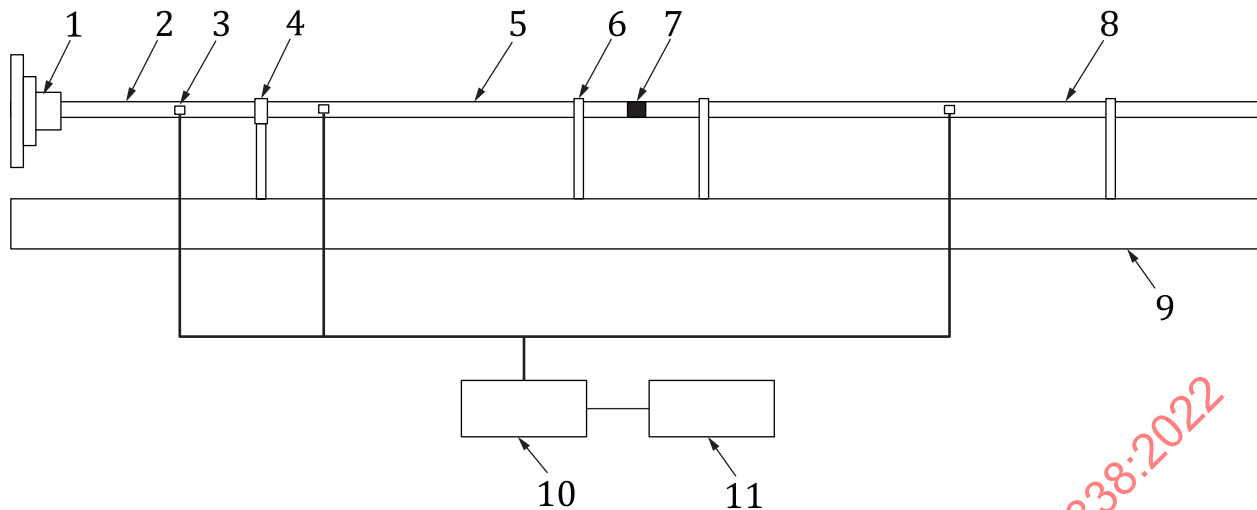
where

- γ_s is the engineering plastic shear strain in the test piece;
- τ_s is the engineering shear stress of the test piece;
- e_I is the strain of incident wave recorded by gauge on the incident bar;
- e_R is the strain of reflected wave recorded by gauge on the incident bar;
- e_T is the strain of transmitted wave recorded by gauge on the transmitter bar;
- r_s is the mean radius of the thin-wall of the test piece;
- r_b is the radius of the elastic bar;
- L_s is the gauge length of the test piece;
- δ_s is the thickness of the thin-wall section of the test piece;
- C_b is the velocity of the torsional wave propagation of the elastic bar;
- G_b is the shear modulus of the elastic bar;
- t is time;
- ξ is dummy variable.

6 Apparatus

6.1 Apparatus components

The TSHB apparatus consists of three major components: loading device (rotary actuator, energy storage section and clamp), bar components (incident bar and transmitter bar), and data acquisition and recording system (strain gauge, amplifier and data recorder) (see [Figure 1](#), the stored-torque TSHB for example).



Key

- 1 rotary actuator
- 2 energy storage section
- 3 strain gauge
- 4 clamp
- 5 incident bar
- 6 bearing
- 7 test piece
- 8 transmitter bar
- 9 supporting frame
- 10 amplifier
- 11 data recorder

Figure 1 — Schematic of torsional split Hopkinson bar apparatus

6.2 Loading device

The loading device is used for generating the incident wave by means of explosives, or sudden release of a stored torque, or impact, etc. In stored-torque TSHB, the incident wave is initiated by the instantaneous release of a torque, which is elastically stored previously in a section of the incident bar between the clamp and the turning end. The loading device in stored-torque TSHB apparatus consists of three major components:

- a) a rotary actuator fastened to free end of the incident bar, by which the external torque is applied;
- b) an energy storage section, the segment of the incident bar for storing torsional elastic strain energy;
- c) a clamp with a quick releasing mechanism.

6.3 Bar components

The bar components in TSHB consist of an incident bar, a transmitter bar and some bearings. By using long elastic bars, the incident strain signal should be recorded before the elastic wave is reflected back from bar-test piece interface, i.e. the incident and the reflected waves are recorded separately. The reflected strain should be recorded before the wave is reflected back again from the other end of incident bar, and transmitted strain should be recorded before the wave is reflected back from the other end of transmitter bar (see [Annex A](#)). Consequently, the strain signals on the bars can be measured without being disturbed by the wave interaction.

6.4 Data acquisition and recording system

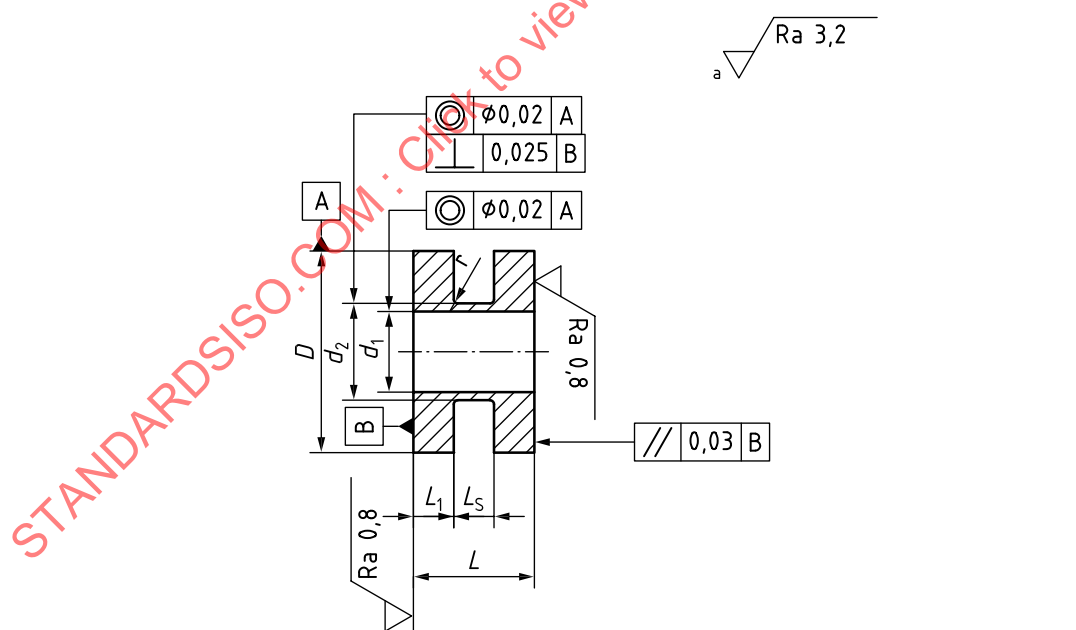
The data acquisition and recording system consists of strain gauge, amplifier and data recorder such as oscilloscopes (see [Annex B](#)). The testing data is acquired with the use of strain gauges mounted on the incident and transmitter bars in conjunction with an oscilloscope. The frequency response of all instruments in the system shall be selected to ensure that all recorded data are not negatively influenced by the frequency response of any individual components. Signal conditioning amplifiers are usually employed to maximize precision in the obtained strain measurements. The minimum frequency response for amplifier shall be not lower than 100 kHz, the minimum resolution of measured data for digital data recorders shall be not less than 10 bits, and the sampling frequency of data recorder should be not lower than 1 MHz. It is recommended that frequency response for amplifier is on the order of 500 kHz conforming to ISO 26203-1[2].

7 Test piece

7.1 Dimensions of test piece

- a) The test pieces used in the torsional testing are short and thin-wall tubes with integral flanges. Two types of geometric configurations are recommended:
- 1) type-A, tubular test piece with cylindrical flanges (see [Figure 2](#)), and
 - 2) type-B, tubular test piece with hexagonal flanges (see [Figure 3](#)).

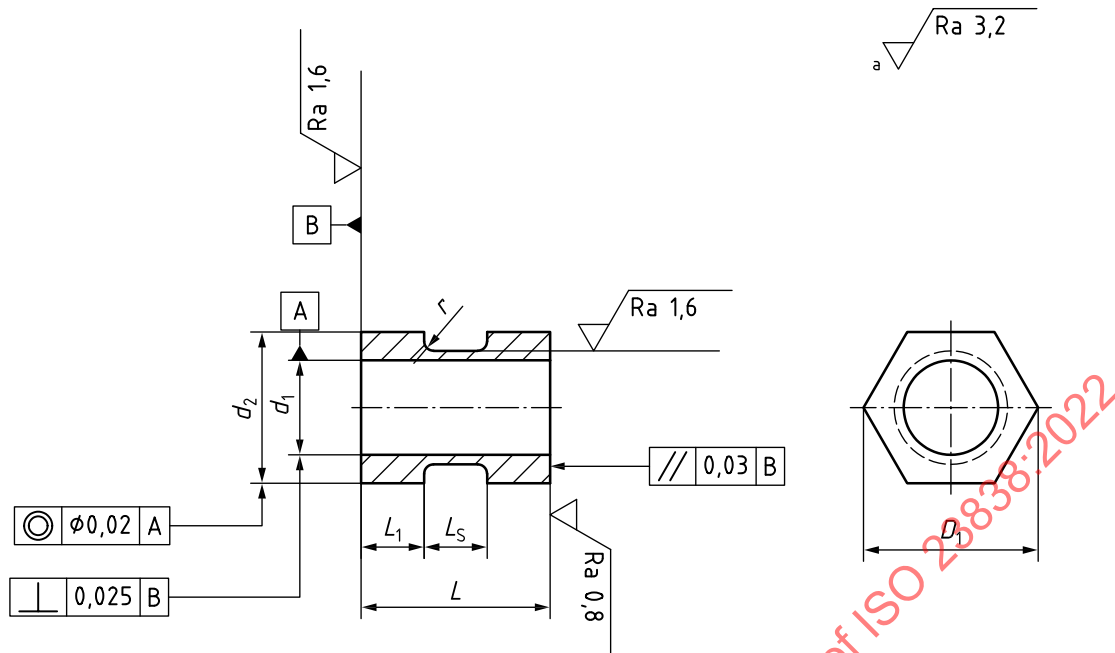
The type-A test piece is glued to the ends of bars with high strength adhesive, for example with epoxy adhesive. The type-B test piece is connected to the ends of bars by mechanical means using hexagonal flanges with matching sockets at the ends of bars.



Key

L	total length of the test piece	d_2	outer diameter of thin-wall section
L_1	flange length of the test piece	D	diameter of cylindrical flange
L_s	gauge length of the test piece	r	radius at the shoulder of the test piece
d_1	inner diameter of thin-wall section	a	Others.

Figure 2 — Type-A test piece



Key

L	total length of the test piece	d_2	outer diameter of thin-wall section
L_1	flange length of the test piece	D_1	diameter of the circumcircle of regular hexagonal flange
L_s	gauge length of the test piece	r	radius at the shoulder of the test piece
d_1	inner diameter of thin-wall section	a	Others.

Figure 3 — Type-B test piece

b) The dimensions of test piece are determined by the following requirements:

- 1) Diameter-to-thickness ratio of test piece in the thin-wall section shall comply with the following rule shown in [Formula \(4\)](#):

$$\frac{d_1}{\delta_s} \geq 10 \quad (4)$$

where

d_1 is the inner diameter of thin-wall section;

$\delta_s = \frac{d_2 - d_1}{2}$ is the thickness of the thin-wall section of the test piece;

d_2 is the outer diameter of thin-wall section.

- 2) The gauge length of the test piece, L_s , shall comply with the following rule in [Formula \(5\)](#)^{[8][9]} and shall not be less than 2,5 mm.

$$L_s < \frac{C_s \cdot \Delta t}{5} \quad (5)$$

where

L_s is the gauge length of the test piece;

- $c_s = \sqrt{\frac{G_s}{\rho_s}}$ is the velocity of the torsional wave propagation of the test piece;
- G_s is shear modulus of the test piece;
- ρ_s is the density of the test piece;
- Δt is the rise time of the incident wave.

The rise time of incident wave can be determined from difference between time points corresponding to the maximum strain and the starting point of incident wave (See [Annex C](#)).

- 3) The radius at the shoulder of test piece shall be small enough so that the total length of thin-wall section could be considered as the original gauge length. The radius of the shoulder of test piece should be equal or less than 0,5 mm.

7.2 Measurement of test piece dimensions

The test piece dimensions shall be measured and recorded before tests. Selection of the measuring equipment shall meet the following requirements for resolution, and the equipment shall be periodically calibrated.

- For the measurement of inner diameter and outer diameter of thin-wall section, the resolution of measuring equipment shall be superior to 0,002 mm.
- For the measurement of length of thin-wall section, the resolution of measuring equipment shall be superior to 0,02 mm.
- For the measurement of thickness of thin-wall section, the resolution of measuring equipment shall be superior to 0,002 mm.

Measure the inner diameter of the test piece, d_1 , and outer diameter of thin-wall section, d_2 , and calculate the mean radius of the thin-wall of the test piece, r_s , using [Formula \(6\)](#).

$$r_s = \frac{d_1 + d_2}{4} \quad (6)$$

where

- r_s is the mean radius of the thin-wall of the test piece;
- d_1 is the inner diameter of thin-wall section;
- d_2 is the outer diameter of thin-wall section.

8 Procedure

8.1 Calibration of the apparatus

The output of the strain gauge should be calibrated by applying a known static torsional force to the strain gauged elastic bar. The strain gauge can be calibrated through checking if the following relationship is satisfied.

$$\gamma_b = \frac{M \cdot r_b}{G_b \cdot J_b} \quad (7)$$

where

- γ_b is the shear strain on the surface of the bar;
- M is the applied static torque in the bar at gauge station;
- r_b is the radius of the elastic bar;
- G_b is the shear modulus of the elastic bar;
- J_b is the polar moment of inertia of the elastic bar.

The velocity of the torsional wave propagation of the elastic bar can be calculated by applying the theoretical equation with the density and shear modulus of the elastic bar, given as [Formula \(8\)](#).

$$c_b = \sqrt{\frac{G_b}{\rho_b}} \quad (8)$$

where

- G_b is the shear modulus of the elastic bar;
- ρ_b is the density of the elastic bar.

The velocity of the torsional wave propagation of the elastic bar can be also determined using [Formula \(9\)](#) by measuring the transmission time of the elastic torsional wave in the incident bar alone, where the incident wave will be reflected into the bar at the free end,

$$c_b = \frac{2a_1}{\Delta t_i} \quad (9)$$

where

- a_1 is the distance from the strain gauge location on the incident bar to the bar-test piece interface;
- Δt_i is the time interval between the incident and reflected waves.

The physical properties of bars can be calibrated through checking if the elastic torsional wave velocities measured from the test computed with [Formula \(9\)](#) and theoretically calculated with [Formula \(8\)](#) are in consistency.

8.2 Recording the temperature of the test environment

The test is carried out at room temperature between 10 °C and 35 °C, unless otherwise specified. The test temperature may be recorded if needed. Tests carried out under controlled conditions should be conducted at a temperature of (23 ± 5) °C conforming to ISO 26203-1^[2].

8.3 Checking the bar alignment

Check the alignment of bars with the method specified in [A.5.4](#).

8.4 Mounting test piece

Connect coaxially test piece between the incident and transmitter bars, prevent any relative movement between the test piece flange and the bars during the loading.

When a type-A test piece is selected, the test piece should be glued to the ends of bars, for example with epoxy adhesive, ensure high bonding strength to apply torsional force on the test piece in order to prevent any relative movement between the test piece flange and the bars during the loading.

8.5 Loading

Firstly, install an unbroken, notched bolt into the jaws of the vise to ready the clamping mechanism. Secondly, apply clamping pressure to the incident bar, and employ the rotary actuator to apply a predetermined rotation to the free end of the incident bar in order to elastically store a torque in the energy storage section. Then, instantaneously release the torque, causing the notched bolt to fracture and the clamping jaws to release the incident bar. A torsional stress wave then initiates from clamping point, and propagates towards the test piece, dynamically loading the test piece in torsion.

8.6 Measuring and recording

Measure and record the following information:

- dimensions, elastic torsional wave velocity and shear modulus of the elastic bars;
- strain gauge parameters such as dimensions, sensitivity ratio, resistance value and the position of strain gauge on the bars;
- status of the apparatus, including test circuit and strain calibration values;
- preloaded shear strain of the energy storage section;
- original waveform from bars.

9 Data processing

9.1 Strain on bars

Strain on bars shall be calculated according to [Formula \(10\)](#):

$$e_j(t) = U_j(t) / U_{0j} \quad (10)$$

where

e_j is the measured strain value of the j^{th} channel, $j = 1, 2, \dots, n$;

U_j is the output voltage of the j^{th} channel signal, $j = 1, 2, \dots, n$;

U_{0j} is the voltage of the j^{th} channel signal at the strain calibration, $j = 1, 2, \dots, n$;

t is time.

9.2 Waveform processing

9.2.1 Determination of waveform baseline

Attach two strain gauges symmetrically on the bar surface across from each other, take the average value of the two strain signals for the data processing.

Take the average value of data in the straight section before the rising of the wave as the waveform baseline. During the data processing, reset waveform baselines of waves to zero.

9.2.2 Determination of starting points of waves

Recommended method is specified in [Annex C](#) for the determination of the starting points of incident, reflected and transmitted waves. The determined starting points shall be on corresponding waveform baseline and near the rising stage.

9.2.3 Synchronization of waves

Shift the incident wave, reflected wave and transmitted wave calculated from [Formula \(10\)](#) at the three locations to the same starting point (e.g. T_0 or zero time), so that the calculations of strain functions with synchronized time can be conveniently operated as [Formulae \(1\), \(2\) and \(3\)](#). Check the dynamic equilibrium of the test piece using the shifted waves. The test piece is regarded as being in dynamic equilibrium if the waves satisfy [Formula \(11\)](#):

$$0,9|e_T| \leq |e_I + e_R| \leq 1,1|e_T| \quad (11)$$

where

- e_I is the strain of incident wave recorded by gauge on the incident bar;
- e_R is the strain of reflected wave recorded by gauge on the incident bar;
- e_T is the strain of transmitted wave recorded by gauge on the transmitter bar.

9.2.4 Determination of loading duration of stress wave

After shifting the incident, reflected and transmitted signals to the starting point (see [Annex C](#) for specifications), determine the intersection of platform and falling edge of incident signal, take a time point corresponding to the intersection as the ending time of loading duration of stress wave.

When the fracture of a test piece occurs, determine the intersecting point of flat portion after rise time and steep dropping edge of transmitted signal. Take the corresponding time point to the intersection as the ending time of loading duration of stress wave.

9.3 Engineering plastic shear strain rate

Calculate the engineering plastic shear strain rate according to the formulae in the [Annex A](#).

9.4 Engineering plastic shear strain

Calculate the engineering plastic shear strain according to the formulae in the [Annex A](#).

9.5 Engineering plastic shear stress

Calculate the engineering plastic shear stress according to the formulae in the [Annex A](#).

9.6 Engineering plastic shear stress-shear strain curve

Use the engineering shear stress obtained in [9.5](#) and engineering shear strain obtained in [9.4](#) to obtain the engineering shear stress-shear strain curve.

9.7 Average engineering plastic shear strain rate

The average engineering plastic shear strain rate is obtained by calculating the arithmetic average of the engineering strain rate function of time from [9.3](#) by [Formula \(12\)](#):

$$\bar{\gamma}_s = \frac{1}{T - T_0} \int_{T_0}^T \dot{\gamma}_s(\xi) d\xi \quad (12)$$

where

- $\bar{\gamma}_s$ is the average engineering plastic shear strain rate in the test piece;

- $\dot{\gamma}$ is the engineering plastic shear strain rate in the test piece;
- T_0 is the time corresponding to the yield strength in engineering shear stress-time curve;
- T is the load duration of stress wave;
- ξ is dummy variable.

9.8 Test example

[Annex D](#) shows an example of testing the engineering shear stress-shear strain curve of metallic materials at high strain rates by using the torsional split Hopkinson bar at room temperature.

10 Evaluation of test result

The following cases may influence the evaluation of material properties, and interface slippage or test piece buckling means an invalid test, and a retest or a suitable interpretation of the test data should be considered:

- a) there is any relative slip at the bar-test piece interface;
- b) the buckling of the test piece occurs at gauge section of test piece;

Meanwhile, it is recommended to compare the deformation of the test piece calculated by the TSHB method with the deformation of the test piece measured by the optical techniques to confirm test result.

11 Test report

The test report should contain items selected from the following:

- a) a reference to this document, i.e. ISO 23838:2022;
- b) specified materials, if known (names of tested materials and sources);
- c) test method used (strain-measuring method, and type of load cell, etc.);
- d) identification of the test piece;
- e) geometry and dimensions of the test piece;
- f) environmental conditions of the test;
- g) instruments (amplifier, oscilloscope, etc.);
- h) confirmation of dynamic equilibrium;
- i) measured properties and results (i.e. engineering stress-strain curve with average strain rate);
- j) personnel performing the test, the review and the approval.

Annex A (informative)

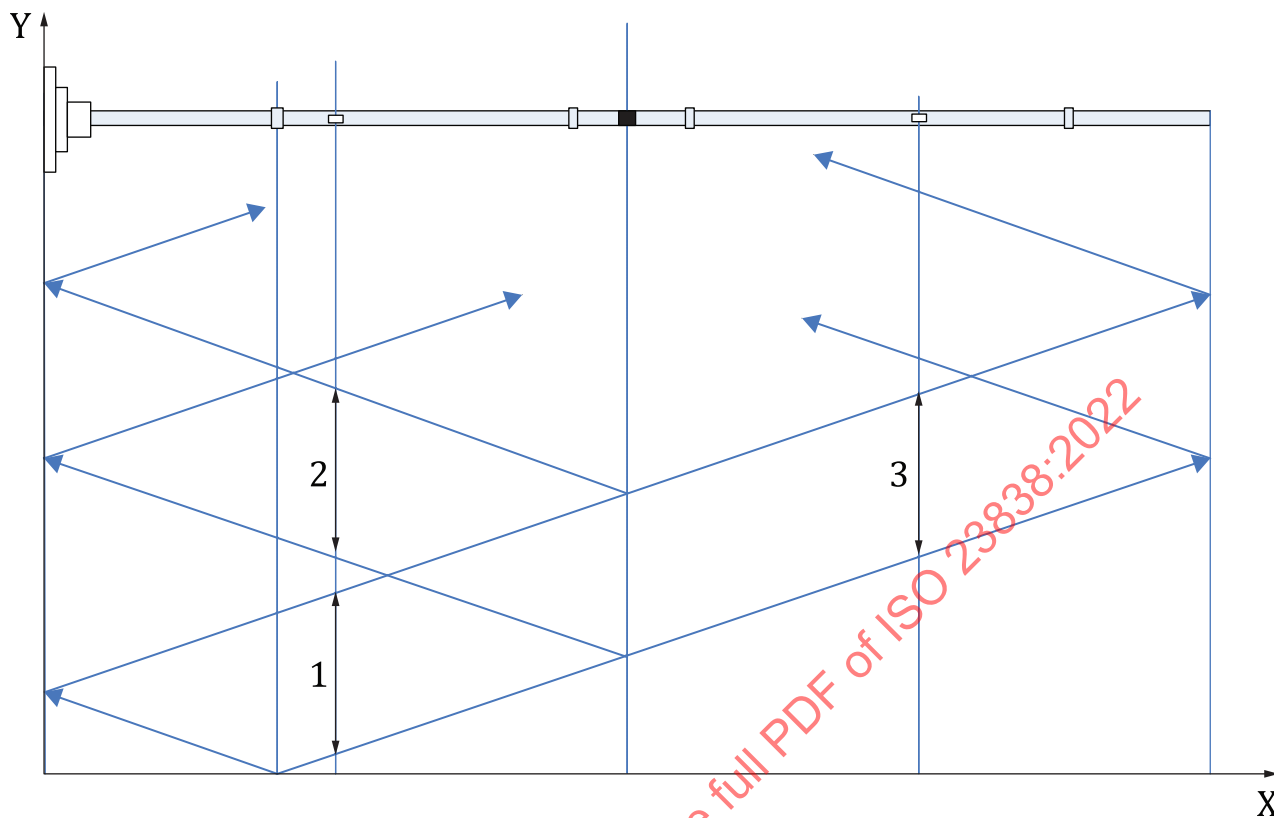
Torsional split Hopkinson bar

A.1 Principle of TSHB method

The original split Hopkinson bar testing method was proposed to measure the compressive mechanical behaviour of materials at high strain rates^[5]. Because of its simplicity, some modified Hopkinson bar apparatuses were developed by many investigators for measuring tensile or torsional properties by loading test pieces in uniaxial tension or torsion^{[2][6][7]}.

The TSHB apparatus is made up of two collinear bars that are made of the same material and having the same diameter. The bars are applied as wave-guides and the dynamic loading unit, and also as the measuring unit. To conduct a test, a torsional wave has to be generated in the incident bar. There are several ways to initiate the torsional wave in the incident bar, for instance the way of a sudden release of a stored torque and the way by explosives. In the stored-torque TSHB, the torque is generated by first tightening the clamp and then turning the end of the bar, and the loading wave in the incident bar is produced by the release of the stored torque. Once upon release of the clamp, the torsional pulse front propagates down the bar toward the test piece, and simultaneously a torsional pulse of equal magnitude propagates from the clamp toward the loading pulley and is reflected back in the incident bar, forming an entire incident wave with wave front and unloading stage^[4].

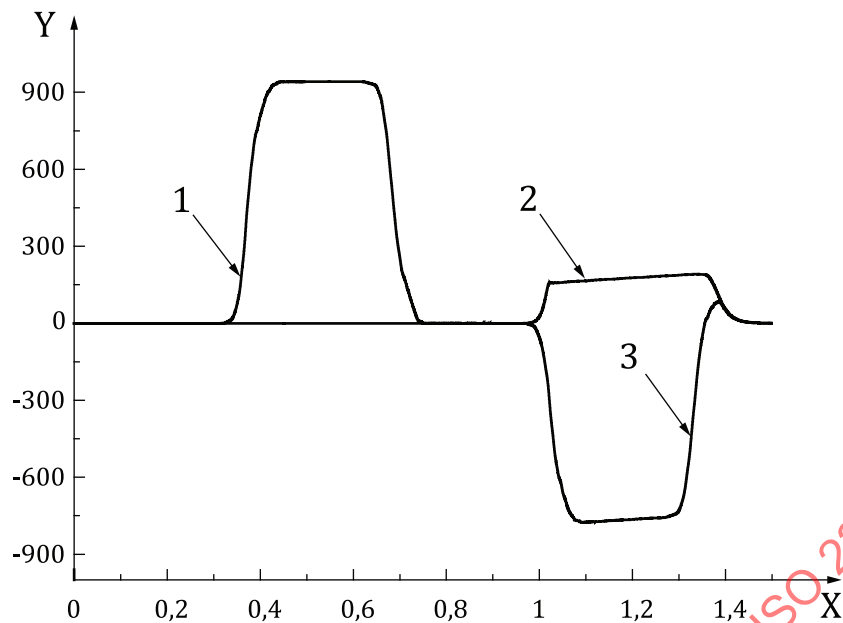
The incident wave propagates down the incident bar towards the test piece, dynamically loading the test piece in torsion. Once the incident wave reaches the test piece, some portion of the wave is transmitted through the test piece and into the transmitter bar, while the remainder of the wave is reflected back to the incident bar, as shown in [Figure A.1](#) (for example the stored-torque TSHB). The stress waves can be recorded as incident, transmitted and reflected pulses using strain gauges mounted on the bars. The typical incident, transmitted and reflected signals obtained by strain gauges are shown in [Figure A.2](#).



Key

- X distance
- Y time
- 1 incident wave
- 2 reflected wave
- 3 transmitted wave

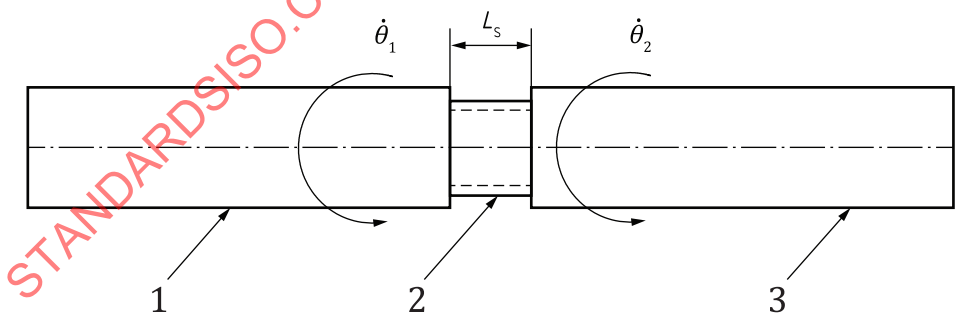
Figure A.1 — Schematic of a stored-torque TSHB and its wave characteristic diagram



- Key**
- X time (ms)
 - Y engineering elastic strain (10^{-6})
 - 1 incident wave
 - 2 transmitted wave
 - 3 reflected wave

Figure A.2 — Typical incident, transmitted and reflected signals obtained by strain gauges

Under stress wave loading, the end of the incident bar where the test piece is attached rotates with an angular velocity $\dot{\theta}_1$ that is much larger than the angular velocity $\dot{\theta}_2$ of the other end of the test piece that is connected to the transmitter bar, as shown in [Figure A.3](#). The difference in the angular velocity between the test piece ends causes the test piece to deform in shear at a high strain rate.



- Key**
- 1 incident bar
 - 2 test piece
 - 3 transmitter bar
 - $\dot{\theta}_1$ angular velocities of the end of the test piece
 - $\dot{\theta}_2$ angular velocities of the end of the test piece
 - L_s gauge length of the test piece

Figure A.3 — Angular velocities of the ends of the test piece

The shear strain rate in the test piece as a function of time, $\dot{\gamma}_s(t)$, is determined from the difference in the angular velocity between the ends of the test piece as given by [Formula \(A.1\)](#):

$$\dot{\gamma}_s(t) = \frac{r_s}{L_s} [\dot{\theta}_1(t) - \dot{\theta}_2(t)] \quad (\text{A.1})$$

where

- $\dot{\gamma}_s$ is the engineering plastic shear strain rate in the test piece;
- $\dot{\theta}_1$ is angular velocities of the end of the test piece;
- $\dot{\theta}_2$ is angular velocities of the end of the test piece;
- r_s is the mean radius of the thin-wall of the test piece;
- L_s is the gauge length of the test piece.

If the test piece is designed as outlined in this standard, the deformation of the test piece will be uniform since it is short and the time it takes for the wave to propagate through is very short^[5]. If the deformation is uniform, the torque at both ends is equal and the test piece is in force equilibrium. The difference in the angular velocity $[\dot{\theta}_1(t) - \dot{\theta}_2(t)]$ can be determined from the torque of the reflected wave given by [Formula \(A.2\)](#):

$$\dot{\theta}_1(t) - \dot{\theta}_2(t) = \frac{2[-M_R(t)]}{\rho_s \cdot J_b} \quad (\text{A.2})$$

where

- $\dot{\theta}_1$ is angular velocities of the end of the test piece;
- $\dot{\theta}_2$ is angular velocities of the end of the test piece;
- M_R is the torque of the reflected wave;
- ρ_s is the density of the test piece;
- J_b is the polar moment of inertia of the elastic bar;
- t is time.

The torque, M , at a gauge station is related to the measured shear strain on the surface of the bar, γ_b , by [Formula \(A.3\)](#):

$$M = \frac{G_b \cdot J_b}{r_b} \gamma_b \quad (\text{A.3})$$

where

- M is the torque at a gauge station of the bar;
- γ_b is the shear strain on the surface of the bar;
- r_b is the radius of the elastic bar;
- G_b is the shear modulus of the elastic bar;
- J_b is the polar moment of inertia of the elastic bar.

Further, the engineering plastic shear strain rate in the test piece as a function of strain of reflected pulse can be calculated by [Formula \(A.4\)](#):

$$\dot{\gamma}_s(t) = \frac{r_s}{L_s} \frac{2C_b}{r_b} [-\gamma_R(t)] \quad (\text{A.4})$$

where

$\dot{\gamma}_s$ is the engineering plastic shear strain rate in the test piece;

r_s is the mean radius of the thin-wall of the test piece;

r_b is the radius of the elastic bar;

L_s is the gauge length of the test piece;

C_b is the velocity of the torsional wave propagation of the elastic bar;

γ_R is the measured shear strain of reflected wave on incident bar;

t is time.

The shear strain γ_R in [Formula \(A.4\)](#) is calculated by $\gamma_R = 2e_R$ from the recorded strain of the gauge oriented at a 45° angle to the bar, i.e. the principal strain e_R . Hence the engineering plastic shear strain rate in the test piece $\dot{\gamma}_s(t)$ in [Formula \(A.4\)](#) can be obtained from the recorded reflected wave $e_R(t)$, as given by [Formula \(A.5\)](#):

$$\dot{\gamma}_s(t) = -\frac{4r_s \cdot C_b}{r_b \cdot L_s} e_R(t) \quad (\text{A.5})$$

where

$\dot{\gamma}_s$ is the engineering plastic shear strain rate in the test piece;

r_s is the mean radius of the thin-wall of the test piece;

r_b is the radius of the elastic bar;

L_s is the gauge length of the test piece;

C_b is the velocity of the torsional wave propagation of the elastic bar;

e_R is the strain of reflected wave recorded by gauge on the incident bar;

t is time.

Further, the engineering plastic shear strain in the test piece $\gamma_s(t)$ is obtained by integrating the strain rate $\dot{\gamma}_s(t)$ as given by [Formula \(A.6\)](#):

$$\gamma_s(t) = \int_0^t \dot{\gamma}_s(\xi) d\xi = -\int_0^t \frac{4r_s \cdot C_b}{r_b \cdot L_s} e_R(\xi) d\xi \quad (\text{A.6})$$

where

γ_s is the engineering plastic shear strain in the test piece;

$\dot{\gamma}_s$ is the engineering plastic shear strain rate in the test piece;

- r_s is the mean radius of the thin-wall of the test piece;
 r_b is the radius of the elastic bar;
 L_s is the gauge length of the test piece;
 C_b is the velocity of the torsional wave propagation of the elastic bar;
 e_R is the strain of reflected wave recorded by gauge on the incident bar;
 t is time;
 ξ is dummy variable.

The engineering shear stress in the test piece, τ_s , is determined from the torque in the test piece, M_s . For a thin-wall tube the shear stress is given by [Formula \(A.7\)](#):

$$\tau_s = \frac{M_s}{2\pi r_s^2 \cdot \delta_s} \quad (\text{A.7})$$

where

- τ_s is the engineering shear stress of the test piece;
 r_s is the mean radius of the thin-wall of the test piece;
 M_s is the torque in the test piece;
 δ_s is the thickness of the thin-wall section of the test piece.

Because the stress in the test piece is assumed to be uniform, the torque at each end of the test piece is the same, and the torque of the wave transmitted to the transmitter bar is the torque in the test piece. In terms of the strain measured by the strain gauge station on the transmitter bar, e_T , the engineering shear stress in the test piece is given by [Formula \(A.8\)](#):

$$\tau_s(t) = \frac{G_b \cdot r_b^3}{2r_s^2 \cdot \delta_s} e_T(t) \quad (\text{A.8})$$

where

- τ_s is the engineering shear stress of the test piece;
 G_b is the shear modulus of the elastic bar;
 r_b is the radius of the elastic bar;
 r_s is the mean radius of the thin-wall of the test piece;
 δ_s is the thickness of the thin-wall section of the test piece;
 e_T is the strain of transmitted wave recorded by gauge on the transmitter bar;
 t is time.

If three waves are used to calculate the difference in the angular velocity $\dot{\theta}_1(t) - \dot{\theta}_2(t)$, the engineering plastic shear strain rate, engineering plastic shear strain and stress in the test piece can be obtained from the three waves as^{[10][11]}:

$$\dot{\gamma}_s(t) = -\frac{2r_s \cdot C_b}{r_b \cdot L_s} [e_I(t) - e_R(t) - e_T(t)] \quad (A.9)$$

$$\gamma_s(t) = \frac{2r_s \cdot C_b}{r_b \cdot L_s} \int_0^t [e_I(\xi) - e_R(\xi) - e_T(\xi)] d\xi \quad (A.10)$$

$$\tau_s(t) = \frac{G_b \cdot r_b^3}{4r_s^2 \cdot \delta_s} [e_I(t) + e_R(t) + e_T(t)] \quad (A.11)$$

where

- $\dot{\gamma}_s$ is the engineering plastic shear strain rate in the test piece;
- γ_s is the engineering plastic shear strain in the test piece;
- τ_s is the engineering shear stress of the test piece;
- e_I is the strain of incident wave recorded by gauge on the incident bar;
- e_R is the strain of reflected wave recorded by gauge on the incident bar;
- e_T is the strain of transmitted wave recorded by gauge on the transmitter bar;
- r_s is the mean radius of the thin-wall of the test piece;
- r_b is the radius of the elastic bar;
- L_s is the gauge length of the test piece;
- δ_s is the thickness of the thin-wall section of the test piece;
- C_b is the velocity of the torsional wave propagation of the elastic bar;
- G_b is the shear modulus of the elastic bar;
- t is time;
- ξ is dummy variable.

A.2 Rotary actuator

The rotary actuator is used to apply a predetermined rotation to the free end of the incident bar in order to elastically store a torque in the portion of the incident bar between the rotary actuator and clamping mechanism. During loading process the bar shall remain elastic. The maximum torque applied on free end of the bar is limited by the shear yield strength of the bar material. Hence the maximum torque shall satisfy [Formula \(A.12\)](#):

$$M_{\max} \leq \frac{\tau_Y \cdot J_b}{r_b} \quad (A.12)$$

where

- $M_{\max}$ is the maximum torque applied on the energy storage section;

τ_Y is the shear yield strength of the elastic bar material;

J_b is the polar moment of inertia of the bar;

r_b is the radius of the bar.

EXAMPLE For a bar with a diameter of 25 mm and made of Ti6Al4V ($\tau_Y = 600$ MPa) the applied torque $M_{\max}$ according to [Formula \(A.12\)](#) is $1,84 \cdot 10^6$ N·mm.

A.3 Energy storage section

The section is the segment for storing torsional elastic strain energy, which is a part of the incident bar between the rotary actuator and clamping mechanism, and its length, L_E , governs the length of the incident wave, λ in [Formula \(A.13\)](#):

$$\lambda = \frac{2L_E}{C_b} \quad (\text{A.13})$$

where

λ is the length of the incident wave;

L_E is the length of energy storage section of the incident bar;

C_b is the velocity of the torsional wave propagation of the elastic bar.

A.4 Clamp

The clamping mechanism controls the torque storage and release, and clamp shall maintain rather strong rigidity during the energy storage and release.

A.5 Bars

A.5.1 Materials of bars

The incident and transmitter bars shall be made of the identical material, generally the metallic materials, for example, aluminium alloy, titanium alloy and steel.

A.5.2 Dimensions of bars

The incident and transmitter bars shall have the identical diameter, while their lengths can be different. The incident and transmitter bars can be designed according to [Formula \(A.14\)](#) and [Formula \(A.15\)](#), respectively. The length-diameter ratio of the bars shall be larger than 40.

$$L_I \geq 10D_b + 2L_E \quad (\text{A.14})$$

$$L_T \geq 10D_b + 1,2L_E \quad (\text{A.15})$$

where

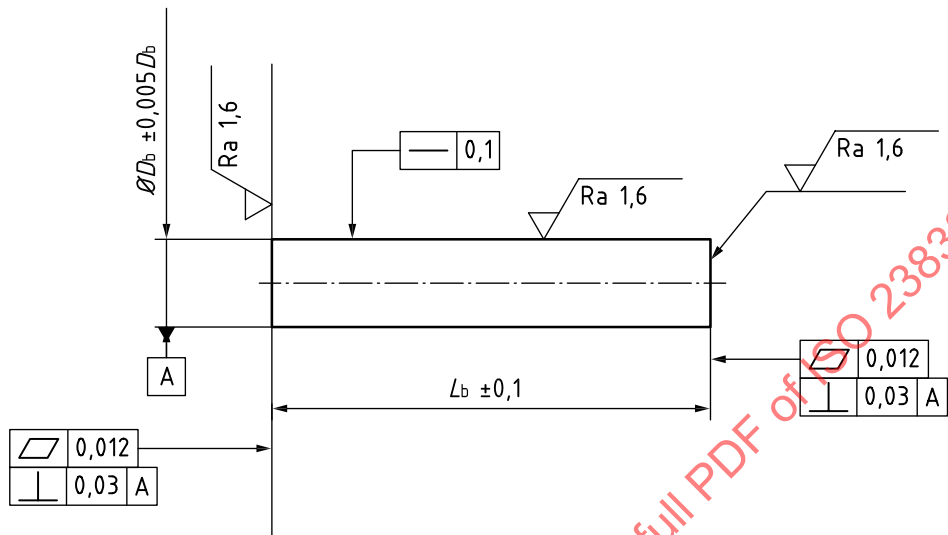
L_I is the length of the incident bar;

L_E is the length of energy storage section;

L_T is the length of the transmitter bar;
 D_b is the diameter of the elastic bar.

A.5.3 Machining precision of bars

The bars shall have the machining precision specified in [Figure A.4](#).

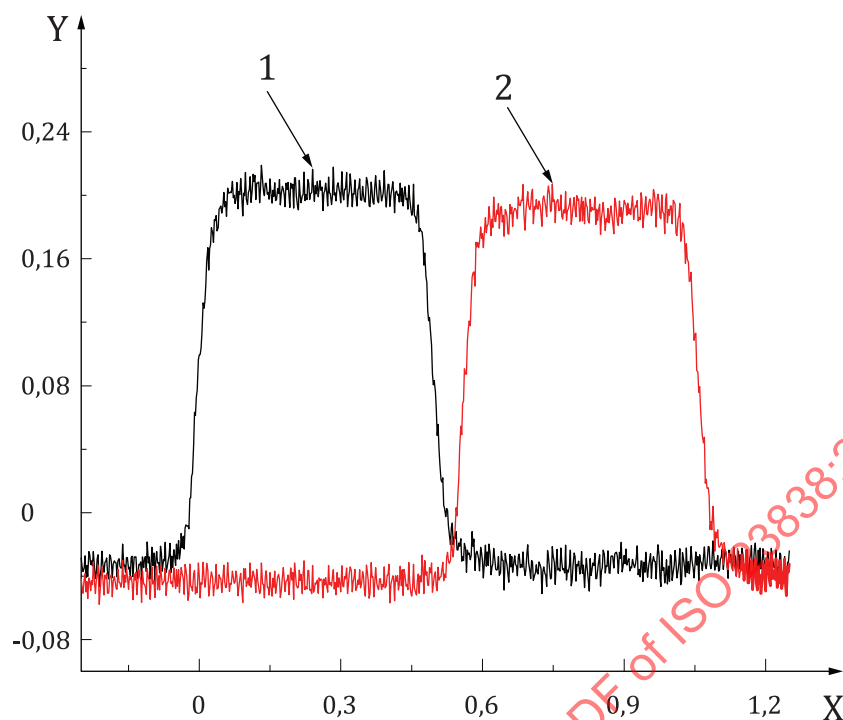


Key
 L_b length of the elastic bar
 D_b diameter of the elastic bar

Figure A.4 — Shape and dimensions of bar

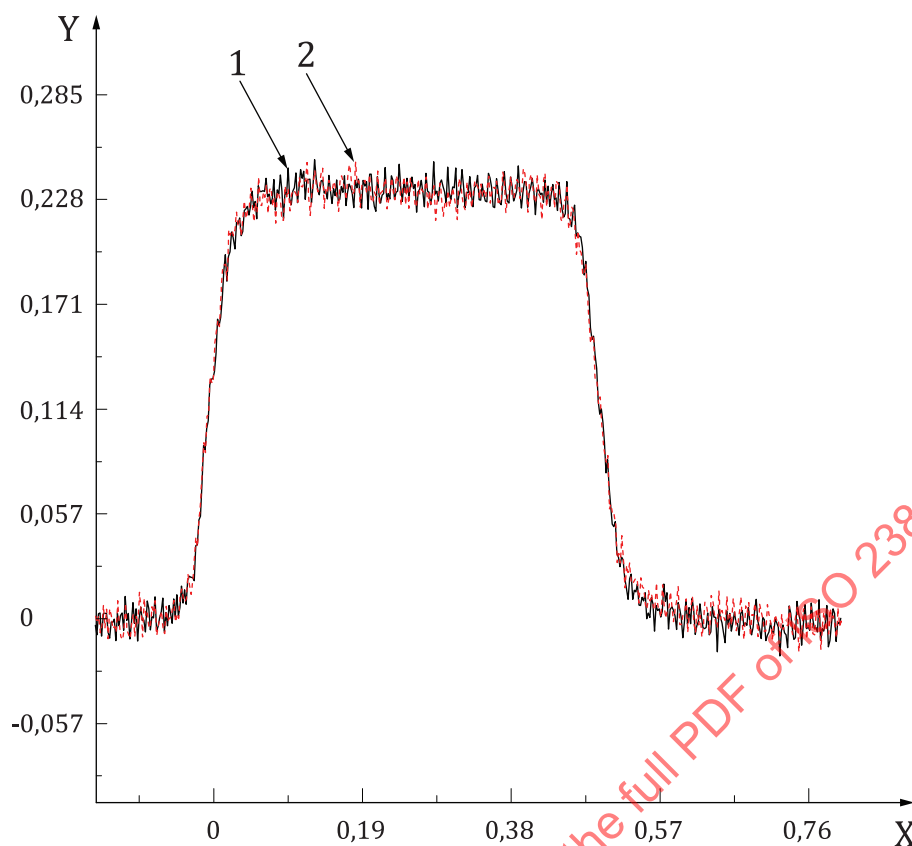
A.5.4 Alignment check for bars

The bars shall keep good alignment. The alignment can be checked by the method of torsion test without test piece. The specific method is as follows: affix the incident bar and the transmitter bar firmly, apply the load, and measure the incident and transmitted waves (see [Figure A.5](#)). If the two signals are the same (see [Figure A.6](#)) or the difference between two waves is less than 5 %, the alignment of bars meets the test requirement.

**Key**

- X time (ms)
Y voltage of channel signal (V)
1 incident wave
2 transmitted wave

Figure A.5 — Incident and transmitted waves without test piece between bars

**Key**

- X time (ms)
 Y voltage of channel signal (V)
 1 incident wave
 2 transmitted wave

Figure A.6 — Shifted waves**A.6 Bearing**

The bearings are used to suspend and adjust the bars, but they shall not restrain the axial movement and rotation of bars.

A.7 Data processing using two-wave formulae**A.7.1 Reflected wave and transmitted wave**

The engineering plastic shear strain rate, engineering plastic shear strain and engineering shear stress can be obtained from reflected and transmitted waves.

- a) Engineering plastic shear strain rate:

$$\dot{\gamma}_s(t) = -\frac{4r_s \cdot C_b}{r_b \cdot L_s} e_R(t) \quad (\text{A.16})$$

- b) Engineering plastic shear strain:

$$\dot{\gamma}_s(t) = -\frac{4r_s \cdot C_b}{r_b \cdot L_s} \int_0^t e_R(\xi) d\xi \quad (A.17)$$

c) Engineering shear stress:

$$\tau_s(t) = \frac{G_b \cdot r_b^3}{2r_s^2 \cdot \delta_s} e_T(t) \quad (A.18)$$

where

$\dot{\gamma}_s$ is the engineering plastic shear strain rate in the test piece;

γ_s is the engineering plastic shear strain in the test piece;

τ_s is the engineering shear stress of the test piece;

e_R is the strain of reflected wave recorded by gauge on the incident bar;

e_T is the strain of transmitted wave recorded by gauge on the transmitter bar;

r_s is the mean radius of the thin-wall of the test piece;

r_b is the radius of the elastic bar;

L_s is the gauge length of the test piece;

δ_s is the thickness of the thin-wall section of the test piece;

C_b is the velocity of the torsional wave propagation of the elastic bar;

G_b is the shear modulus of the elastic bar;

t is time;

ξ is dummy variable.

A.7.2 Incident wave and transmitted wave

The engineering plastic shear strain rate, plastic shear strain and shear stress can be obtained from incident and transmitted waves.

a) Engineering plastic shear strain rate:

$$\dot{\gamma}_s(t) = \frac{4r_s \cdot C_b}{r_b \cdot L_s} [e_I(t) - e_T(t)] \quad (A.19)$$

b) Engineering plastic shear strain:

$$\gamma_s(t) = \frac{4r_s \cdot C_b}{r_b \cdot L_s} \int_0^t [e_I(\xi) - e_T(\xi)] d\xi \quad (A.20)$$

c) Engineering shear stress:

$$\tau_s(t) = \frac{G_b \cdot r_b^3}{2r_s^2 \cdot \delta_s} e_T(t) \quad (A.21)$$

where

- $\dot{\gamma}_s$ is the engineering plastic shear strain rate in the test piece;
- γ_s is the engineering plastic shear strain in the test piece;
- τ_s is the engineering shear stress of the test piece;
- e_I is the strain of incident wave recorded by gauge on the incident bar;
- e_T is the strain of transmitted wave recorded by gauge on the transmitter bar;
- r_s is the mean radius of the thin-wall of the test piece;
- r_b is the radius of the elastic bar;
- L_s is the gauge length of the test piece;
- δ_s is the thickness of the thin-wall section of the test piece;
- C_b is the velocity of the torsional wave propagation of the elastic bar;
- G_b is the shear modulus of the elastic bar;
- t is time;
- ξ is dummy variable.

A.8 Data processing using three-wave formulae

The engineering shear strain rate, shear strain and shear stress can be obtained from incident, reflected and transmitted waves.

a) Engineering shear strain rate:

$$\dot{\gamma}_s(t) = \frac{2r_s \cdot C_b}{r_b \cdot L_s} [e_I(t) - e_R(t) - e_T(t)] \quad (\text{A.22})$$

b) Engineering shear strain:

$$\gamma_s(t) = \frac{2r_s \cdot C_b}{r_b \cdot L_s} \int_0^t [e_I(\xi) - e_R(\xi) - e_T(\xi)] d\xi \quad (\text{A.23})$$

c) Engineering shear stress:

$$\tau_s(t) = \frac{G_b \cdot r_b^3}{4r_s^2 \cdot \delta_s} [e_I(t) + e_R(t) + e_T(t)] \quad (\text{A.24})$$

where

- $\dot{\gamma}_s$ is the engineering plastic shear strain rate in the test piece;
- γ_s is the engineering plastic shear strain in the test piece;
- τ_s is the engineering shear stress of the test piece;
- e_I is the strain of incident wave recorded by gauge on the incident bar;
- e_R is the strain of reflected wave recorded by gauge on the incident bar;

- e_T is the strain of transmitted wave recorded by gauge on the transmitter bar;
 r_s is the mean radius of the thin-wall of the test piece;
 r_b is the radius of the elastic bar;
 L_s is the gauge length of the test piece;
 δ_s is the thickness of the thin-wall section of the test piece;
 C_b is the velocity of the torsional wave propagation of the elastic bar;
 G_b is the shear modulus of the elastic bar;
 t is time;
 ξ is dummy variable.

A.9 Recommended calculation formulae

The two-wave formulae from incident and transmitted waves, [Formulae\(A.19\)](#), [\(A.20\)](#) and [\(A.21\)](#), in [A.7.2](#) are recommended when the measured strains satisfy dynamic equilibrium [Formula \(11\)](#). The three-wave formulae in [A.8](#) are recommended when the measured strains don't satisfy dynamic equilibrium [Formula \(11\)](#).

Annex B (informative)

Data acquisition and recording system

B.1 General

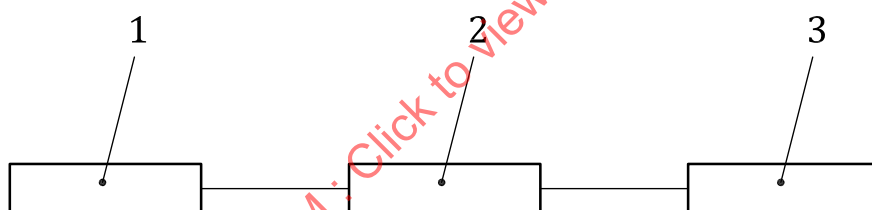
Refer to [Figure 1](#) for the composition of data acquisition and recording system.

This Annex specifies the data acquisition method and the technical requirements of data acquisition system.

B.2 Components of the system

The data acquisition and recording system consists of three major components: strain gauge, amplifier and data recorder.

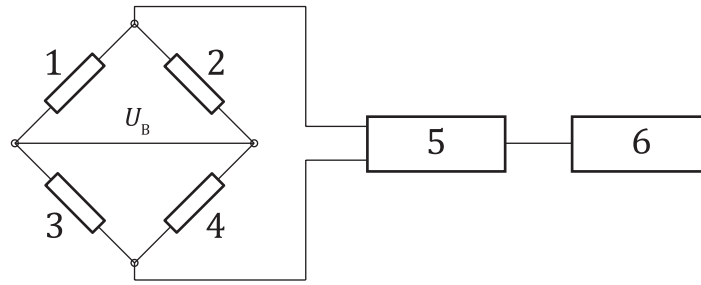
According to the connection modes of strain gauge, there are non-bridge data acquisition system (see [Figure B.1](#)) or bridge data acquisition system (see [Figure B.2](#)). It is recommended to use the Wheatstone circuits to form a bridge data acquisition system. When the bridge circuit is used, it is recommended to affix a same type of strain gauge on the metal block made of the identical material with bars for the temperature compensation.



Key

- 1 strain gauge
- 2 amplifier
- 3 data recorder

Figure B.1 — Non-bridge data acquisition system

**Key**

- 1 strain gauge
- 2 temperature compensated strain gauge
- 3,4 standard resistance
- 5 amplifier
- 6 data recorder
- U_B bridge voltage

Figure B.2 — Bridge data acquisition system**B.3 Strain gauge**

The strain gauge shall be chosen and used according to the following requirements:

- a) The grid length of strain gauge, which is determined according to the diameter of bar, shall not be larger than 5 mm, with 2 mm recommended;
- b) Two strain gauges shall be mounted on each bar, diametrically across from each other;
- c) The sensitive grid of strain gauge shall have an angle of 45° to the longitudinal direction of the bar, with a deviation not larger than 5°;
- d) The mounted positions of strain gauges on incident bar shall meet [Formulae \(B.1\)](#) and [\(B.2\)](#). The mounted positions of strain gauges on transmitter bar shall meet [Formulae \(B.3\)](#) and [\(B.4\)](#):

$$a_1 \geq 10D_b \quad (\text{B.1})$$

$$a_1 > 1,2L_E \quad (\text{B.2})$$

$$a_2 \geq 10D_b \quad (\text{B.3})$$

$$L_T - a_2 > 1,2L_E \quad (\text{B.4})$$

where

- a_1 is the distance from the strain gauge location on the incident bar to the bar-test piece interface;
- D_b is the diameter of the elastic bar;
- L_E is the length of the energy storage section;
- a_2 is the distance from the strain gauge location on the transmitter to the bar-test piece interface;
- L_T is the length of the transmitter bar.