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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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Foreword

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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 ($\geq 10^2\ s^{-1}$). 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.

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)$^{-1}$
$\dot{\gamma}_\mathrm{s}$	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	-
$\bar{\dot{\gamma}}_\mathrm{s}$	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
$U_{0\,j}$	Voltage of the j^{th} channel signal at the strain calibration, $j = 1, 2, \ldots, n$	V
U_j	Output voltage of the j^{th} channel signal, $j = 1, 2, \ldots, n$	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, $j = 1, 2, \ldots, n$	-
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 $(\mathrm{ms})^{-1}$; 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]:

$$\dot{\gamma}_\mathrm{s}(t) = \frac{2r_\mathrm{s} \cdot C_\mathrm{b}}{r_\mathrm{b} \cdot L_\mathrm{s}} \left[e_\mathrm{I}(t) - e_\mathrm{R}(t) - e_\mathrm{T}(t) \right] \tag{1}$$

$$\gamma_\mathrm{s}(t) = \frac{2r_\mathrm{s} \cdot C_\mathrm{b}}{r_\mathrm{b} \cdot L_\mathrm{s}} \int_0^t \left[e_\mathrm{I}(\xi) - e_\mathrm{R}(\xi) - e_\mathrm{T}(\xi) \right] \mathrm{d}\xi \tag{2}$$

$$\tau_\mathrm{s}(t) = \frac{G_\mathrm{b} \cdot r_\mathrm{b}^3}{4r_\mathrm{s}^2 \cdot \delta_\mathrm{s}} \left[e_\mathrm{I}(t) + e_\mathrm{R}(t) + e_\mathrm{T}(t) \right] \tag{3}$$

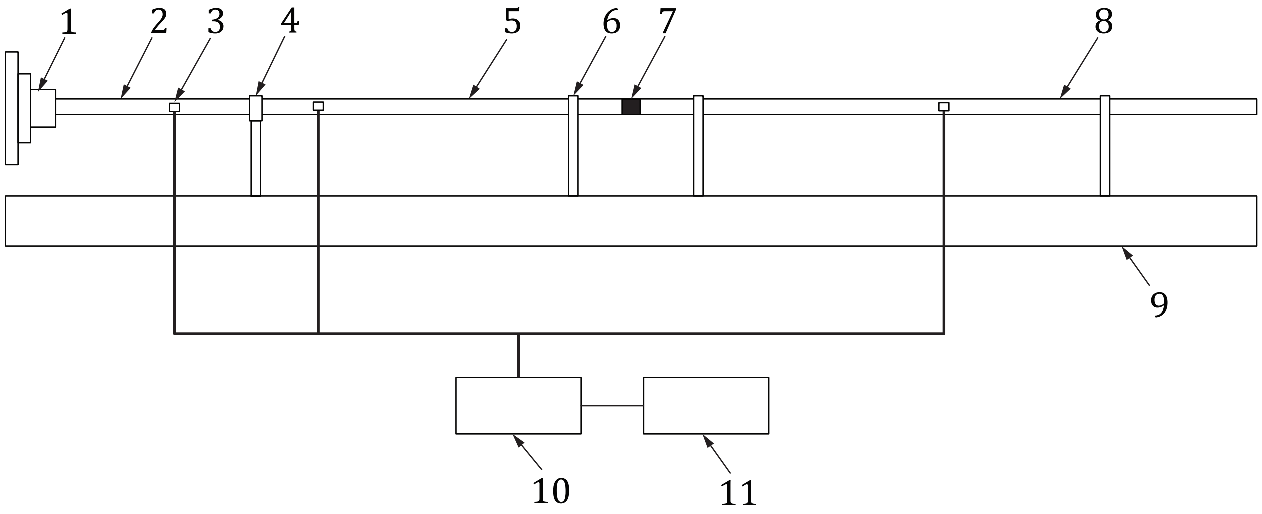
where

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 than10 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

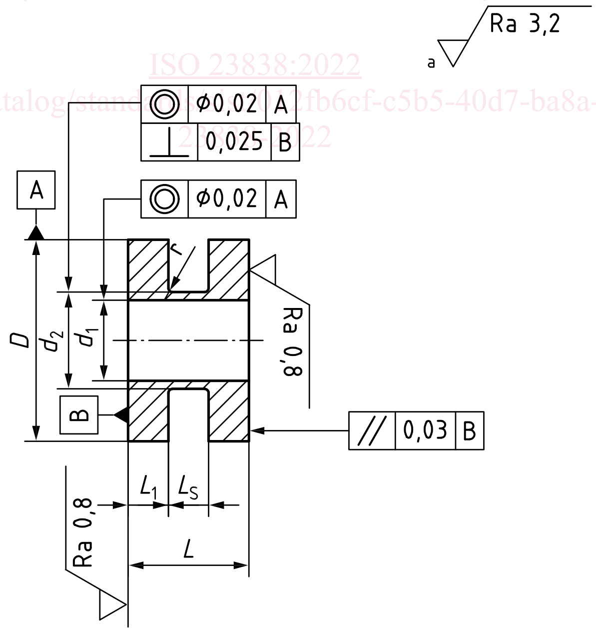
7.1 Dimensions of test piece

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