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Metallic materials — Tensile testing at high strain rates —

Part 1: Elastic-bar-type systems

Matériaux métalliques — Essai de traction à vitesses de déformation élevées —

Partie 1: Systèmes de type à barre élastique

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva, Switzerland
Tel. +41 22 749 01 11
Fax +41 22 749 09 47
copyright@iso.org
www.iso.org

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Foreword

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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 on 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 the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 1, *Uniaxial testing.*

This second edition cancels and replaces the first edition (ISO 26203-1:2010), of which it constitutes a minor revision.

The main changes compared to the previous edition are as follows:

— a note above 7.1 d) has been added.

A list of all parts in the ISO 26203 series can be found on the ISO website.

Introduction

Tensile testing of metallic sheet materials at high strain rates is important to achieve a reliable analysis of vehicle crashworthiness. During a crash event, the maximum strain rate often reaches 10^3 s^{-1}, at which the strength of the material can be significantly higher than that under quasi-static loading conditions. Thus, the reliability of crash simulation depends on the accuracy of the input data specifying the strain-rate sensitivity of the materials.

Although there are several methods for high-strain rate testing, solutions for three significant problems are required.

The first problem is the noise in the force measurement signal.

— The test force is generally detected at a measurement point on the force measurement device that is located some distance away from the test piece.

— Furthermore, the elastic wave which has already passed the measurement point returns there by reflection at the end of the force measurement device. If the testing time is comparable to the time for wave propagation through the force measurement device, the stress-strain curve may have large oscillations as a result of the superposition of the direct and indirect waves. In quasi-static testing, contrarily, the testing time is sufficiently long to have multiple round-trips of the elastic wave. Thus, the force reaches a saturated state and equilibrates at any point of the force measurement device.

— There are two opposing solutions for this problem.

  — The first solution is to use a short force measurement device which will reach the saturated state quickly. This approach is often adopted in the servo-hydraulic type system.

  — The second solution is to use a very long force measurement device which allows the completion of a test before the reflected wave returns to the measurement point. The elastic-bar-type system is based on the latter approach.

The second problem is the need for rapid and accurate measurements of displacement or test piece elongation.

— Conventional extensometers are unsuitable because of their large inertia. Non-contact type methods such as optical and laser devices should be adopted. It is also acceptable to measure displacements using the theory of elastic wave propagation in a suitably-designed apparatus, examples of which are discussed in this document.

— The displacement of the bar end can be simply calculated from the same data as force measurement, i.e. the strain history at a known position on the bar. Thus, no assessment of machine stiffness is required in the elastic-bar-type system.

The last problem is the inhomogeneous section force distributed along the test piece.

— In quasi-static testing, a test piece with a long parallel section and large fillets is recommended to achieve a homogeneous uniaxial-stress state in the gauge section. In order to achieve a valid test with force equilibrium during the dynamic test, the test piece is to be designed differently from the typically designed quasi-static test piece. Dynamic test pieces are intended to be generally smaller in the dimension parallel to the loading axis than the test pieces typically used for quasi-static testing.

The elastic-bar-type system can thus provide solutions for dynamic testing problems and is widely used to obtain accurate stress-strain curves at around 10^3 s^{-1}. The International Iron and Steel Institute developed the “Recommendations for Dynamic Tensile Testing of Sheet Steel” based on the interlaboratory test conducted by various laboratories. The interlaboratory test results show the high data quality obtained by the elastic-bar-type system. The developed knowledge on the elastic-bar-type system is summarized in this document; ISO 26203-2 covers servo-hydraulic and other test systems used for high-strain-rate tensile testing.

Metallic materials — Tensile testing at high strain rates —

Part 1:
Elastic-bar-type systems

1 Scope

This document specifies methods for testing metallic sheet materials to determine the stress-strain characteristics at high strain rates. This document covers the use of elastic-bar-type systems.

The strain-rate range between 10^{-3} and 10^{3} s^{-1} is considered to be the most relevant to vehicle crash events based on experimental and numerical calculations such as the finite element analysis (FEA) work for crashworthiness.

In order to evaluate the crashworthiness of a vehicle with accuracy, reliable stress-strain characterization of metallic materials at strain rates higher than 10^{-3} s^{-1} is essential.

This test method covers the strain-rate range above 10^{2} s^{-1}.

NOTE 1 At strain rates lower than 10^{-1} s^{-1}, a quasi-static tensile testing machine that is specified in ISO 7500-1 and ISO 6892-1 can be applied.

NOTE 2 This testing method is also applicable to tensile test-piece geometries other than the flat test pieces considered here.

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 http://www.electropedia.org/

3.1
elastic-bar-type system
measuring system in which the force-measuring device is lengthened in the axial direction to prevent force measurement from being affected by waves reflected from the ends of the apparatus

Note 1 to entry: The designation “elastic-bar-type system” comes from the fact that this type of system normally employs a long elastic bar as force-measuring device.

4 Principles

The stress-strain characteristics of metallic materials at high strain rates are evaluated.

At a strain rate higher than 10 s^{-1}, the signal of the loading force is greatly perturbed by multiple passages of waves reflected within the load cell that is used in the quasi-static test. Thus, special techniques are required for force measurement. This may be accomplished in two opposite ways:

— one is to lengthen the force measurement device in the loading direction, in order to finish the measurement before the elastic wave is reflected back from the other end (elastic-bar-type systems);

— another way is to shorten the force measurement device, thus reducing the time needed to attain dynamic equilibrium within the force measurement device and realizing its higher natural frequency (servo-hydraulic type systems).

Tests at low strain rates (under 10^{-1} s^{-1}) can be carried out using a quasi-static tensile testing machine. However, special considerations are required when this machine is used for tests at strain rates higher than conventional ones. It is necessary to use a test piece specified for high-strain-rate testing methods. Annex A provides details of the test procedure for this practice.

5 Symbols and designations

Symbols and their corresponding designations are given in Table 1.

Table 1 — Symbols and designations

Symbol	Unit	Designation
		Test piece
a_o	mm	original thickness of a flat test piece
b_o	mm	original width of the parallel length of a flat test piece
b_g	mm	width(s) of the grip section of a test piece
L_o	mm	original gauge length [see 7.1 e)]
L_c	mm	parallel length
L_{total}	mm	total length that includes the parallel length and the shoulders
L_u	mm	final gauge length after fracture
r	mm	radius of the shoulder
S_o	mm^2	original cross-sectional area of the parallel length
S_b	mm^2	cross-sectional area of the elastic bar
		Time
t	s	time
		Elongation
A	%	percentage elongation after fracture NOTE With non-proportional test pieces, the symbol A is supplemented with an index which shows the basic initial measured length in millimetres, e.g. A_{20mm} = Percentage elongation after fracture with an original gauge length L_o = 20 mm.
A_u	%	specified upper limit of percentage elongation for mean strain rate
		Displacement
u	mm	displacement by the elastic wave
u_1	mm	displacement at the end of the original gauge length
u_2	mm	displacement at the end of the original gauge length
$u_B(t)$	mm	displacement of the end of the elastic bar at time t
		Strain
e	—	engineering strain
e_s	—	desired engineering strain before achieving equilibrium
ε	—	elastic strain

Table 1 *(continued)*

Symbol	Unit	Designation
ε_B	—	elastic strain at the end of the elastic bar (see Annex B)
ε_g	—	elastic strain at section C (see Annex B)
Strain rate		
$\dot{e}$	s^{-1}	engineering strain rate
$\bar{\dot{e}}$	s^{-1}	mean engineering strain rate
Force		
F	N	force
F_m	N	maximum force
Stress		
R	MPa	engineering stress
R_m	MPa	tensile strength
R_t	MPa	proof strength, total extension
Modulus of elasticity		
E	MPa	modulus of elasticity
E_b	MPa	modulus of elasticity of the bar
Wave velocity		
c_0	mm s^{-1}	velocity of the wave propagation in the elastic bar
c	mm s^{-1}	elastic wave propagation velocity in the test piece
Velocity		
$v_A(t)$	mm s^{-1}	velocity of the impact block (see Annex B)
v	mm s^{-1}	particle velocity at any point in the bar (see Annex C)
v_i	mm s^{-1}	incident particle velocity (see Annex C)
v_r	mm s^{-1}	reflected particle velocity (see Annex C)
v_t	mm s^{-1}	transmitted particle velocity (see Annex C)

6 Apparatus

6.1 Elastic bar. By using a long elastic bar, the test should be finished before the elastic wave is reflected back from the other end of the bar that is on the opposite side of the test piece. Consequently, the force can be measured without being perturbed by the reflected waves. For this method, the one-bar testing machine and the split Hopkinson bar (SHB) testing machine are normally used (see Annex B and Annex C).

6.2 Input device. For the input method, open-loop-type loading is normally applied. The upper limit of the input speed is approximately 20 m s^{-1}. For the SHB testing machine, a striker tube or striker bar is used. For the one-bar testing machine, a hammer is normally used.

6.3 Clamping mechanism. A proper clamping mechanism (a method for connecting a test piece and an elastic bar) is critical to data quality (see Annex B and Annex C).

The clamping fixtures for the SHB or one-bar testing machines are mounted directly on the elastic bars. The clamping fixtures should be of the same material and diameter as the elastic bars to ensure minimal impedance change when the stress wave propagates through the loading train. If a different material or size is used, proper consideration should be made in the evaluation of stress and strain.

6.4 Force measurement device. Force should be measured by strain gauges of a suitably short gauge length, typically 2 mm, attached to elastic bars that are directly connected with the test piece.

The location of the strain gauges should be in an area where the elastic wave is not influenced by end effects. In order to measure a one-dimensional elastic wave, the strain gauges shall be attached at a distance at least five times the diameter of the bars from the ends of the bars (see Annex B and Annex C).

NOTE The measurable strain-rate range by this method is 10^2 s^{-1} or higher. It is impractical to construct a testing machine for strain rates below 10^2 s^{-1} because bar lengths of several tens of metres in length would be required.

To ensure the validity of stress-strain curves, the straightness of the elastic bars is crucial. Proper supports or guides for the elastic bars are essential in achieving this.

6.5 Displacement measurement device. Strain in the tensile test is represented by the ratio between the relative displacement between two points in the gauge section, e.g. the initial and final gauge lengths of the test piece.

Generally, in quasi-static testing, an extensometer attached to the gauge section of the test piece is used and the measurement is accurate. However, at high strain rates, it is impossible to use this method due to the inertia effects of the extensometer. Thus, displacement or test piece elongation measurement at high strain rates shall use the non-contact type devices or strain gauges on elastic bars.

Measuring devices that can be utilized for measuring displacement in elastic-bar-type systems are described in 6.5.1 to 6.5.3. These devices are recommended for strain rates up to 10^3 s^{-1} and measured displacements should be recorded for the duration of the test. These devices may be used in combination. For example, when devices 6.5.1 and 6.5.3 are used in combination, the displacement at one end of the original gauge length (L_o) is measured by the non-contact type displacement gauge (6.5.1) and the other end is measured by the strain gauge (6.5.3) that is attached on the surface of the bar.

6.5.1 Non-contact type displacement gauge. The displacement at one end of the original gauge length (L_o) is measured and recorded by laser, optical or similar devices.

By using two 6.5.1 type devices or one 6.5.1 type device and one 6.5.3 type device, the variation of L_{total} in Figure 1 (type-A test piece in Clause 7) with time can be measured and the elongation can be calculated.

6.5.2 Non-contact type extensometer. High-speed cameras, Doppler or laser extensometers, or other non-contact systems can be applied for measuring the variation of L_c in Figure 2 (type-B test piece in Clause 7).

6.5.3 Strain gauge. The variation of displacement of the end of the elastic bar with time should be calculated using Formula (1) which is based on the strain history measured by the strain gauge attached to the elastic bar.

$$u_B(t) = c_0 \int_0^t \varepsilon_B(t) dt \quad (1)$$

where

$u_B(t)$ is the displacement of the end of the elastic bar at time t;

ε_B is the elastic strain at the end of the elastic bar (see Annex B);

c_0 is the velocity of the wave propagation in the elastic bar.

6.6 Data acquisition instruments. Amplifiers and data recorders such as oscilloscopes are used to assess stress-strain curves from raw signals. Each instrument should have a sufficiently high frequency response. The frequency response of all elements in the electronic measurement system shall be selected to ensure that all recorded data are not negatively influenced by the frequency response of any individual component; typically, this requires minimum frequency response on the order of 500 kHz. For digital data recorders, the minimum resolution of measured data should be 10 bits.

7 Test piece

7.1 Test-piece shape, size and preparation

Test-piece geometry is determined by the following requirements.

a) The required maximum strain rate determines the parallel length. A test piece of shorter length can achieve higher strain rates. In order to achieve force equilibrium in the test piece, the parallel length should be short enough at a given strain-rate range.

b) In order to assure equilibrium of forces at the strain rates up to 10^3 s^{-1}, the preferred parallel length is less than 20 mm.

Uniform deformation over the parallel length of the test piece requires that the force should be equilibrated at both ends of the test piece. Force propagates as an elastic wave. To achieve equilibrium, at least the following inequality [see Formula (2)] should be satisfied:

$$\frac{L_c}{c} \leq \frac{e_s}{\dot{e}} \tag{2}$$

where

L_c is the parallel length of the test piece;

c is the elastic wave propagation velocity in the test piece;

e_s is the desired engineering strain before achieving equilibrium;

$\dot{e}$ is the testing strain rate.

c) The width of the test piece should be determined to obtain uniaxial stress during the test. The following rule, shown in Formulae (3) and (4), should be applied:

$$\frac{L_o}{b_o} \geq 2 \tag{3}$$

$$\frac{b_o}{a_o} \geq 2 \tag{4}$$

where

a_o is the original thickness of a flat test piece;

b_o is the original width of the parallel length of a flat test piece;

L_o is the original gauge length.

NOTE Lower limit value of Formula (3), $L_o/b_o = 2$, can result in a highly non-uniform strain distribution when testing very high strength, low work-hardening materials such as Ti-6Al-4V and high strength steel.

d) Generally, unless impractical or unnecessary, the thickness of the test piece should be the full thickness of the material as far as testing capacity permits.

e) The radius at the shoulder of the type-A test piece (see Figure 1) should be small enough that L_{total} is considered as the original gauge length (L_o). The radius at the shoulder of the type-B test piece (see Figure 2) should be large enough that L_c is considered as the original gauge length (L_o).

For type-A and type-B test pieces, uncertainties exist in uniaxial tensile data calculated from bar displacement. These uncertainties result from the non-uniformity of axial strain within the original gauge length, used here as the reference gauge length for strain calculations. To assess the potential effects of strain non-uniformity, it is recommended that two sets of quasi-static true-stress versus true-strain data be compared, i.e.

1) one obtained from strain measurements based on bar displacements (i.e. the displacements at the bar-end positions on the test piece) and referenced to L_{total} or L_o for the selected high strain-rate test piece geometry, and

2) the other obtained from strain measurements with an extensometer mounted to the central part of the parallel reduced section of a conventional tensile test piece conforming to ISO 6892-1.

The result of this comparison should be incorporated in the test report to provide an assessment to potential users of high-strain-rate tensile data obtained with this document. If the difference is outside of a value agreed by the user and the tester, then strain measurements based on local strain measurements within the gauge length should be used.

f) The grip should have a much larger cross-section than that of the parallel length of the test piece to ensure negligible deformation and definitely no plastic deformation at the grip zone. Usually, because the thicknesses of the grip and gauge length of the test piece are the same, the ratio of the grip and the gauge length width shall comply with the following rule shown in Formula (5):

$$\frac{b_o}{b_g} < \frac{R_t}{R_m} \tag{5}$$

where

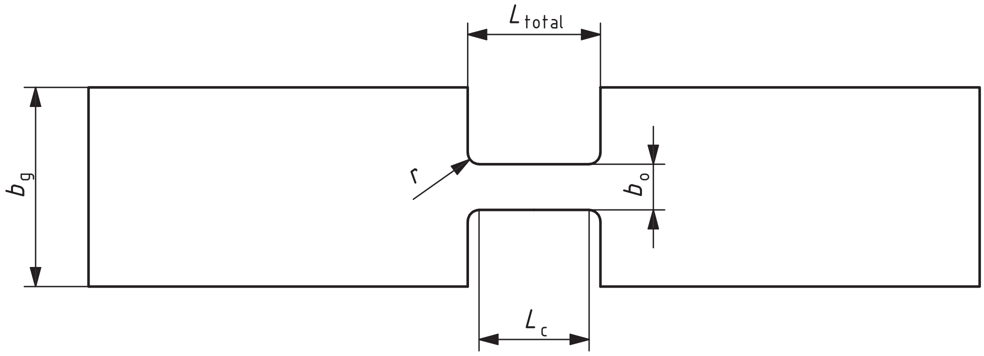
b_o is the original width of the parallel length of a flat test piece;

b_g is the width of the grip section of a test piece;

R_m is the tensile strength;

R_t is the proof strength, total extension.

g) Machined surface should be free of cold work, cracks, notches and other surface defects, which can cause stress concentration.



Key

b_o original width of the parallel length

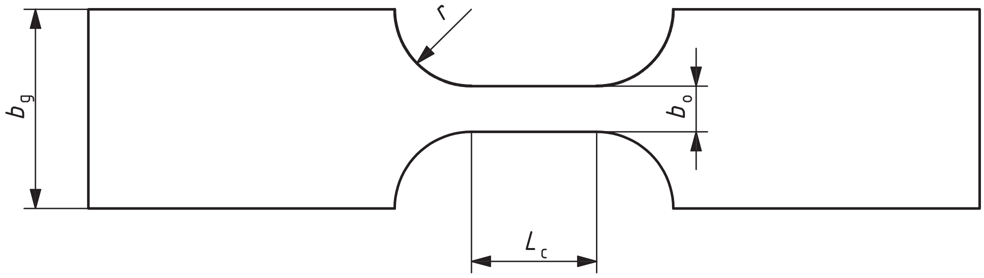
b_g width of the grip section

L_c parallel length

L_{total} total length that includes the parallel length and the shoulders

r radius of the shoulder

Figure 1 — Type-A test piece



Key

b_o original width of the parallel length

b_g width of the grip section

L_c parallel length

r radius of the shoulder

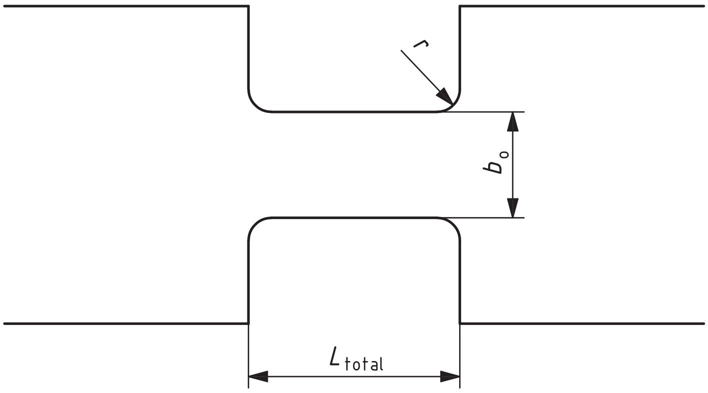
Figure 2 — Type-B test piece

7.2 Typical test piece

Recommended dimensions of test pieces are shown in Figures 3 and 4. The ratio between the widths of the grip and gauge section is normally above 2.

Based on the test methods and/or test purposes, other test piece configurations can be used.

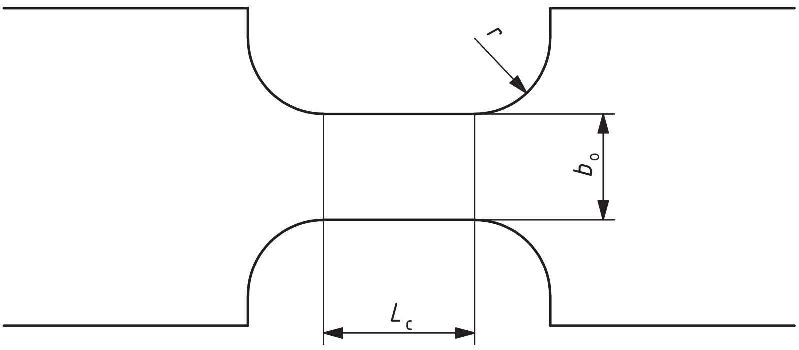
The typical test pieces in Figures 3 and 4 are appropriate when the maximum measured strain rate is up to 10^3 s^{-1} and when the comparison of test results obtained at several strain rates is required. During uniform elongation, the size effect of a test piece would be small. However, because after uniform elongation, measured properties depend on the test-piece size, it is recommended that all test pieces used to obtain a single data set should have the same geometry and dimensions, even for the low-strain-rate tests.



Dimensions in millimetres

b_o	Maximum 5
L_{total}	10
r	1,5

Figure 3 — Typical dimensions of a type-A test piece



Dimensions in millimetres

b_o	Maximum 5
L_c	10
r	5,0

Figure 4 — Typical dimensions of a type-B test piece

8 Calibration of the apparatus

8.1 General

The output of the strain gauge should be calibrated by applying a known static force to the strain gauged elastic bar. Figure B.1 shows an example of the one-bar testing machine.

In the case of the SHB testing machine, stress and strain can be calculated by applying the theoretical equation with the density, modulus of elasticity and the transmission speed of the longitudinal wave in the elastic bar. In this case, it is necessary to carry out tests after precisely measuring each physical property and ensuring its consistency. Details are given in Annex C.

8.2 Displacement measuring device

For the displacement measuring devices, the appropriate calibration shall be carried out in the static condition.

9 Procedure

9.1 General

Using the input device (6.2), high speed strain is applied on the test piece along the axial direction of the test piece. The force applied to the test piece is measured by the force measurement device (6.4). At the same instance, the variation of L_{total}, L_c or L_o of the test piece is measured by the displacement measurement device (6.5).

The configuration of the test piece should be determined based on the designated strain-rate range, the input device (6.2), the force measurement device (6.4), and the displacement measurement device (6.5).

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.

9.2 Mounting the test piece

When the test piece is mounted in the clamp, ensure good alignment to apply only axial force. Also, the test piece and the elastic bar should be connected carefully to ensure a good alignment.

When a type-A test piece is selected, the test piece should be mounted such that the spacing between grip ends is L_{total} (see Figure 1) and the test-piece reduced-gauge section should be centred within this space (see Figure C.3).

9.3 Applying force

Force is applied by the methods described in 6.2. To obtain the targeted strain rate, the velocity of the striker tube, striker bar or hammer should be determined in advance.

NOTE Guidelines on the velocity of the hammer for the one-bar method and the velocity of the striker for the split Hopkinson bar method are provided in B.2 and C.2, respectively.

9.4 Measuring and recording

The force measurement devices (6.4) measure the time variation of elastic strain, and the displacement measuring devices (6.5) measure the time variation of the displacement of the interfaces between the elastic bars and the test piece or of both end points of L_0. These measured data shall be recorded.

a) Engineering strain and engineering strain rate ($e, \dot{e}$)

Engineering strain (e) and engineering strain rate ($\dot{e}$) should be calculated from displacement data obtained following the technique outlined in 6.5. Engineering strain and engineering strain rate should be calculated using Formulae (6) and (7).

$$e = (u_1 - u_2) / L_0 \tag{6}$$

$$\dot{e} = \frac{e_{n+1} - e_n}{\Delta t} \tag{7}$$

where

u_1, u_2 are displacements at the ends of the original gauge length;

e_{n+1} is the engineering strain at step n+1;

e_n is the engineering strain at step n;

Δt is time increment between steps n and n+1.

b) Engineering stress (R)

Using the force measured according to 6.4, the engineering stress is calculated using Formula (8).

$$R = F/S_o \tag{8}$$

where

R is the engineering stress;

F is the force;

S_o is the original cross-sectional area of the parallel length.

c) Percentage elongation after fracture (A)

Percentage elongation after fracture should be determined using Formulae (9) and (10) as appropriate.

For a type-A test piece,

$$A = \frac{L_u - L_{total}}{L_{total}} \tag{9}$$

where

A is the percentage elongation after fracture;

L_u is the gauge length after fracture;

L_{total} is the original gauge length of a type-A test piece.

For a type-B test piece,

$$A = \frac{L_u - L_c}{L_c} \tag{10}$$

where

A is the percentage elongation after fracture;

L_u is the gauge length after fracture;

L_c is the original gauge length of a type-B test piece.

d) Mean strain rate ($\bar{\dot{e}}$)

The mean value of the strain rate is obtained by averaging between strains of 1 % (0,01) and 10 % (0,1) as shown in Formula (11):

$$\bar{\dot{e}} = \frac{(0{,}1 - 0{,}01)}{t_{10} - t_1} \tag{11}$$

where

$\bar{\dot{e}}$ is mean strain rate (s^{-1});

t_1 is the time at a strain of 1 %;

t_{10} is the time at a strain of 10 %.

When the fracture strain is less than 10 %, calculate the mean strain rate between a strain of 1 % and the measured fracture strain.

By agreement, the upper limit of strain range can be changed from 10 % to another specified value such as the strain at the peak force.

When another specified value is applied as the upper limit of percentage elongation, the symbol should be as follows:

$$\bar{\dot{e}}_{1-A_u}$$

where A_u is the specified upper limit of percentage elongation for mean strain rate.

10 Evaluation of the test result

Due to problems in evaluation of material characteristics, a retest or a suitable interpretation of the test data should be considered for the following cases:

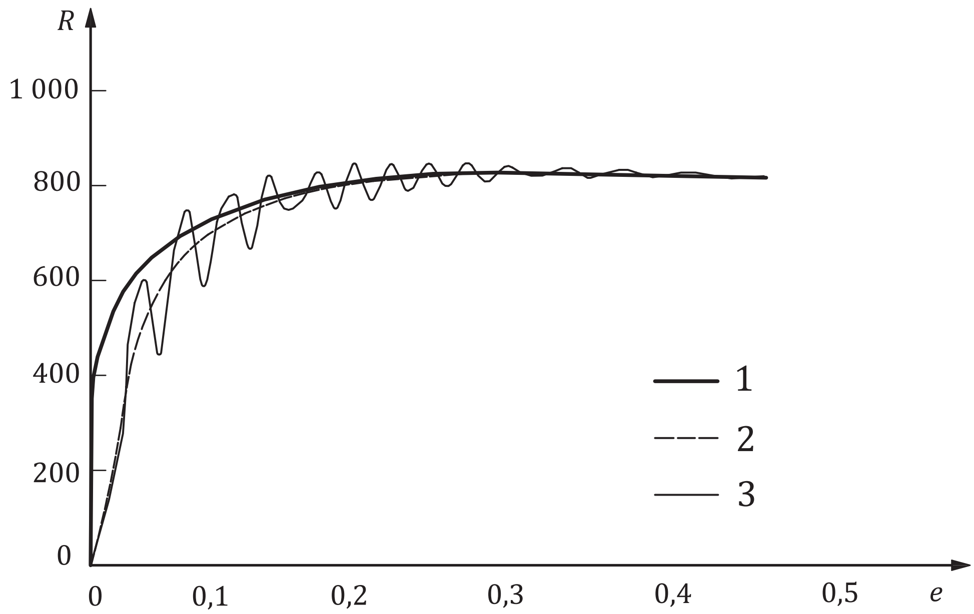
a) the fracture of a test piece does not occur within a quarter distance of the gauge length from the centre of the test piece;

b) the signal of stress has large oscillations (see Figure 5);

c) the mean strain rate is significantly different from the target strain rate and the initial rise in the strain rate is not within the agreed strain range (e.g. 5 % of strain);

d) within the agreed strain range, the variation of strain rate exceeds ±30 % of the mean strain rate;

e) the slope of the stress-strain curve in the elastic region in the dynamic condition is significantly different from expected slope (irregular slope, Figure 5).



Key

1 data without measurement problems

2 irregular slope

3 irregular slope + oscillation

R engineering stress (MPa)

e engineering strain

Figure 5 — Example of a measurement problem in a high-strain-rate test

There are two major quality issues for high-strain-rate tensile testing: 1) load oscillation and 2) irregular slope of the stress-strain curve in the elastic region.

The first issue is due to a problem in the force measurement system. Load oscillations appear when the test machine, or elements in the load train, are not properly aligned (e.g. non-straight or misaligned elastic bar). This can be remedied through a careful readjustment of the machine configuration and/or alignment of the support or guides for the elastic bar.

The second issue concerns an irregular slope in the elastic region of the stress-strain curve. This can be due to the addition of deformation in elements of the load train outside the gauge section of the test piece. This problem is seldom seen in bar-type systems because the displacement of the bar end can be obtained using the theory of elastic wave propagation. However, an irregular slope can appear when the mounting or clamping strength between the test piece and the attachment (see Figures B.2 and B.3) is insufficient and/or when the edge of the test piece (i.e. the edge of L_{total}) is located at a position significantly different from the bar end.

In such cases, the testing configuration should be adjusted.

11 Test report

By agreement between interested parties, the test report should contain items selected from the following:

a) a reference to this document, i.e. ISO 26203-1:2018;

b) specified materials, if known;

c) the test method (force-measuring method, displacement-measuring method, and type of load cell, etc.);

d) the identification of the test piece;

e) the geometry and dimensions of sampling of the test piece;

f) the location and direction of the test piece;

g) measured properties and results, i.e. stress-strain curve with strain rate, mean strain rate, maximum tensile stress-strain, per cent elongation after fracture, etc.

Annex A
(informative)

Quasi-static tensile testing method

A.1 General

This annex explains the method to be used for determination of tensile properties of metallic materials using strain-control within an approximate strain-rate range between 10^{-3} s^{-1} and 10^{-1} s^{-1}.

A.2 Input method/machine types

The testing machine used for causing strain shall be in conformity with ISO 7500-1. The grade of the testing machine shall be subject to agreement between the parties concerned. For this test, a testing machine of the electro-mechanical or servo-hydraulic type is usually used.

A.3 Clamping method

The testing machine shall be equipped with a clamp suitable for the test piece. The clamp shall be capable of securely holding the test piece over the operation centreline of the tester throughout the test and shall have a construction that does not apply force other than tensile force.

A.4 Force measurement method

The force during the test is measured with a load cell usually comprising an electrical-resistance strain gauge attached to an elastic body.

A.5 Displacement measurement

Depending on the shape of the test piece, L_o, L_c or L_{total} is measured.

Displacement during the test is measured by the travel of the crosshead or, preferably, with an extensometer attached to the test piece.

In cases where the crosshead travel is measured, the resulting strain rate at the test piece may be lower than strain rate determined from the crosshead travel because the compliance of the testing machine is not considered. An explanation is given in ISO 6892-1:2016, Annex F.

NOTE An extensometer of a type that uses a differential transformer, an optical extensometer or a strain gauge can be used.

A.6 Test piece

Using same configurations of test pieces for high-strain-rate testing and quasi-static testing is recommended. Depending on agreement between the parties concerned, however, a test piece of a different size may be used.

NOTE In the evaluation of automotive crash properties, material properties at different strain rates are required. For consistent evaluation at all strain rates in the strain range, the use of identical test pieces is desirable.

A.7 Procedure

A.7.1 Test piece setup

Using a clamp suitable for the test piece with a particular geometry, it should be ensured that axial force only is applied to the test piece throughout the test.

A.7.2 Straining

By feedback control from an extensometer, strain shall be applied to the test piece at the required strain rate. For the displacement measurement by the cross-head displacement, the cross-head velocity shall be controlled to ensure that the estimated strain rate over the parallel length coincides with the required strain rate.

If necessary, an approach zone in which the test piece cannot be strained until the strain rate reaches the required strain rate may be provided.

A.7.3 Measurement and recording

During the test, force and test piece displacement changes in time shall be measured and recorded using force and displacement measuring apparatus. Strain rate, engineering stress, and mean strain rate can be calculated from data measured, using Formulae (A.1) and (A.2).

a) Strain rate ($\dot{e}$)

$$\dot{e} = \frac{e_{n+1} - e_n}{\Delta t} \tag{A.1}$$

where

e_{n+1} is the amount of strain at step n+1;

e_n is the amount of strain at n step;

Δt is the time increment between steps n and n+1.

b) Engineering stress (R)

$$R = \frac{F}{S_o} \tag{A.2}$$

where

F is the force;

S_o is the original cross-sectional area of the parallel length.

c) Mean engineering strain rate ($\bar{\dot{e}}$)

The mean value of the engineering strain is obtained in accordance with 9.4 d).

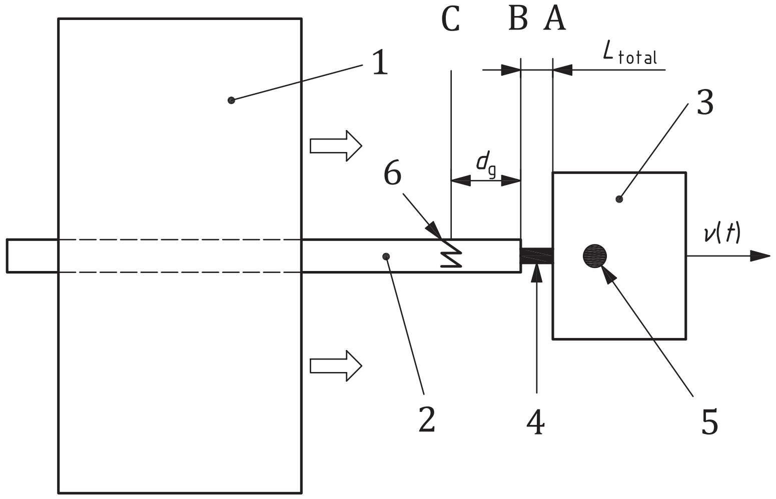
Annex B
(informative)

Example of one-bar method

B.1 Principle of the one-bar method

Force is measured by a long elastic bar known as the output bar. The measurement has to be completed before the return of the elastic wave reflected at the other end of the output bar. An input of deformation is made by an impact block that is directly hit by a hammer and the impact block causes deformation of the test piece. In principle, there is no limitation to the duration of the testing time using this configuration.

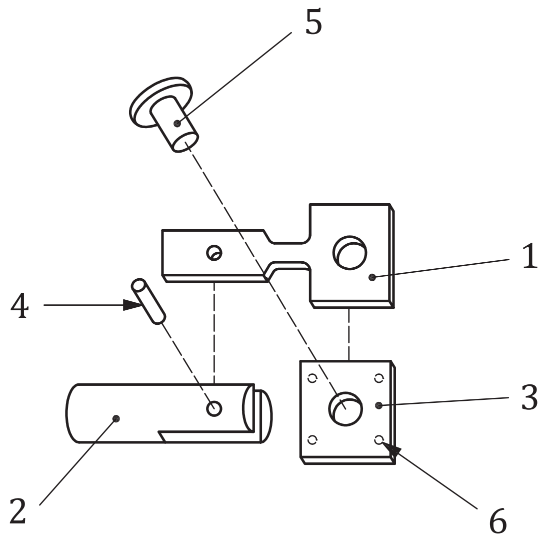
In principle, there is no upper bound of the applicable range of strain rate in the one-bar method. However, taking into account that the test piece has a finite length, the upper limit is practically from 2×10^3 s^{-1} to 3×10^3 s^{-1}. The lower bound is limited by the return of the stress waves to the position of the strain gauge from the other end of the bar and is normally about 10^2 s^{-1}. The lower limit depends on the length of the output bar[1][2][3][4][5].



Key

1	hammer
2	output bar
3	impact block
4	test piece
5	fastening rod
6	strain gauges
d_g	distance between sections B and C
L_{total}	total length that includes the parallel length and the shoulders
$v(t)$	velocity of the impact block
A	end of the impact block
B	end of the output bar
C	position of strain gauge

Figure B.1 — Scheme of the one-bar method high-strain-rate tensile testing machine



Key

1 test piece
2 attachment
3 reinforcement
4 positioning pin
5 fastening rod
6 spot weld

Figure B.2 — Test piece for the one-bar method

B.2 Input method/machine types

Deformation input is controlled by the velocity of the hammer in an open-loop manner. The hammer hits the impact block, which then causes deformation of the test piece. The maximum velocities of the hammer and the impact block are about 10 m s^{-1} and (15 to 20) m s^{-1}, respectively. The velocity of the impact block depends not only on the velocity of the hammer but also on the properties of the test piece. The velocity of the hammer should be chosen based on these factors in order to obtain the desired strain rate.

B.3 Clamping methods

An attachment and a fastening rod are used to clamp the test piece. The diameter of the attachment is selected so as to be equal to that of the output bar. As shown in Figure B.2, a slit is formed in the attachment and the test piece is firmly attached using adhesive such that the attachment can be considered as an integral part of the test piece. The attachment is installed on the output bar using a screw thread. Precise alignment and intimate contact are required in order to minimize the acoustic impedance mismatch. Therefore, the end of the attachment can be considered as the end of the output bar after the clamping. The other end of the test piece is clamped to the impact block using the fastening rod. The tensile force is applied through the fastening rod that penetrates a hole in the test piece. A reinforcement plate is spot-welded onto the test piece in order to strengthen the hole region.

B.4 Force measurement

Force is measured by the output bar to which the test piece is directly clamped. The output bar should be long enough that the measurement is complete before the return of the elastic waves reflected at the other end of the output bar. The bar diameter is selected depending on the maximum force of the test piece. For instance, several experiments have been performed on the condition that the length of the output bar is 5 m and the diameter is in the range of 12 mm to 20 mm.

The axial force $F(t)$ at section B in Figure B.1 can be determined from the amplitude of the elastic strain at section B, ε_B, as shown in Formula (B.1):

$$F(t) = E_b S_b \varepsilon_B(t) \tag{B.1}$$

where

E_b is the modulus of elasticity of the bar;

S_b is the cross-sectional area of the bar;

ε_B is the elastic strain at section B.

Considering the propagation of the elastic waves in the bar, ε_B, can be expressed in terms of the elastic strain at section C, ε_g, as shown in Formula (B.2):

$$\varepsilon_B(t) = \varepsilon_g(t + d_g/c_0) \tag{B.2}$$

where

c_0 is the velocity of the wave propagation;

d_g is the distance between sections B and C;

ε_g is the elastic strain at section C.

When the length of the test piece L_o is short enough and the stress distribution is homogeneous throughout the length L_o of the test piece, the engineering stress of the test piece becomes as given in Formula (B.3):

$$R(t) = \frac{F(t)}{S_o} = \left(\frac{S_b}{S_o}\right) E_b \varepsilon_g (t + d_g / c_0) \tag{B.3}$$

B.5 Displacement measurement

Both end displacements of the test piece are measured using two different techniques. The displacement in the output bar side, u_B, is measured by the strain gauge attached to the output bar at the distance d_g from the bar end, as is usually performed in the bar system. The displacement in the impact block side, u_A, is measured by a non-contact type electro-optical-displacement transducer.

Displacement calculations from strain gauge output assume that wave propagation in a bar is one-dimensional. The displacement by the elastic wave that propagates in the negative direction of x is given as shown in Formula (B.4):

$$u = f(x + c_0 t) \tag{B.4}$$

Thus, the relation between time derivative of the displacement ($\partial u/\partial t$) and the strain ($\varepsilon = \partial u/\partial x$) becomes Formula (B.5):

$$\frac{\partial u}{\partial t} = c_0 \frac{\partial u}{\partial x} \tag{B.5}$$

The displacement at section B is as given in Formula (B.6):

$$u_B = \int_0^t \frac{\partial u_B}{\partial t} dt = c_0 \int_0^t \varepsilon_B dt \tag{B.6}$$

Considering the delay of the wave propagation [$\varepsilon_B(t) = \varepsilon_g(t + d_g/c_0)$], the displacement at section B can be rewritten as shown in Formula (B.7):

$$u_B = \int_0^t \frac{\partial u_B}{\partial t} dt = c_0 \int_0^t \varepsilon_g (t + d_g / c_0) dt \tag{B.7}$$

Displacement in the impact block side, u_A, is recorded as the velocity $v_A(t)$ of the impact block using an analogue differentiating device. Then, the displacement of section A is as shown in Formula (B.8):

$$u_A = \int_0^t v_A(t) dt \tag{B.8}$$

When the length of the test piece L_o is short enough and the strain distribution is homogeneous throughout the length L_o of the test piece, the engineering strain of the test piece is as shown in Formula (B.9):

$$e(t) = \frac{u_A - u_B}{L_o} = \frac{1}{L_o} \int_0^t \left[v_A(t) - c_0 \varepsilon_g (t + d_g / c_0) \right] dt \tag{B.9}$$

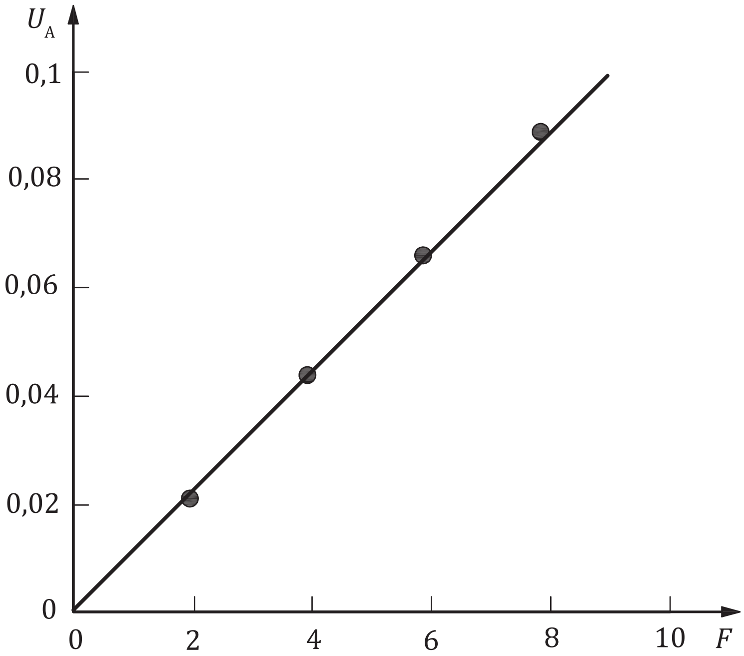
The engineering strain rate is derived by the time derivative of the engineering strain as shown in Formula (B.10):

$$\dot{e}(t) = \frac{1}{L_o} \left[v_A(t) - c_0 \varepsilon_g (t + d_g / c_0) \right] \tag{B.10}$$

B.6 Test procedure

B.6.1 Calibration and verification of the force measurement

Before the execution of tests, calibration and verification of the force measurement device should be performed. The output of ε_g is recorded during static loading of the output bar, which should be kept straight during calibration. An example is shown in Figure B.3. Here, ε_g is expressed as its amplified signal (U_A). It should be verified that the output (ε_g) shows a linear relation with the force.



Key

F force (kN)

U_A amplified signal (V)

Figure B.3 — Example of the force measurement calibration in the one-bar method

B.6.2 Clamping of the test piece

The attachment, which is actually a part of the test piece, is installed on the output bar using a screw. On this occasion, the alignment of the output bar and the test piece should be strictly maintained along the tensile direction. A proper support or guide might be effective to achieve this. However, it should be noted that excessive contact between the support/guide and the bar decays the quality of the bar's strain gauge signal. The other end of the test piece is clamped by the fastening rod with the impact block.

B.6.3 Input of deformation

The hammer directly hits the impact block at a given velocity and the impact block generates the tensile deformation in the test piece through the fastening rod.

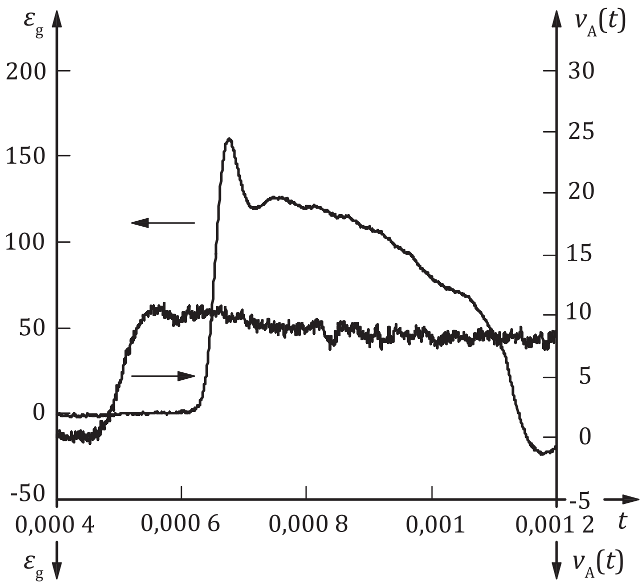
B.6.4 Measurement and record

The output of the strain gauge attached to the output bar, ε_g, is measured and recorded as a function of time. At the same time, the velocity of the impact block, $v_A(t)$, which is the time derivative of the displacement, is also measured and recorded as a function of time.

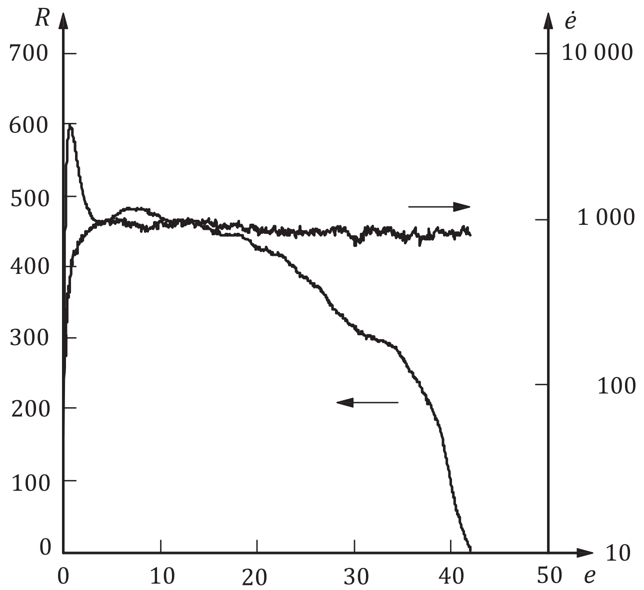
B.7 Example of a high-strain-rate tensile test using the one-bar method

An example of a high-strain-rate tensile test for mild steel is shown in Figure B.4. Figure B.4 a) shows the output signals recorded by a digital oscilloscope. One is the output signal of the strain gauge, ε_g, and the other is the velocity of the impact block, $v_A(t)$. The engineering stress, the engineering strain and the engineering strain rate are evaluated using these data and the formulae above and shown in Figure B.4 b).

Another example for high strength steel is shown in Figure B.5.



a) Raw output signals from the strain gauge and the electro-optical displacement transducer



b) Engineering stress, engineering strain and engineering strain rate obtained by analysis of raw data

Key

t time (s)

ε_g elastic strain at section C (10^{-6})

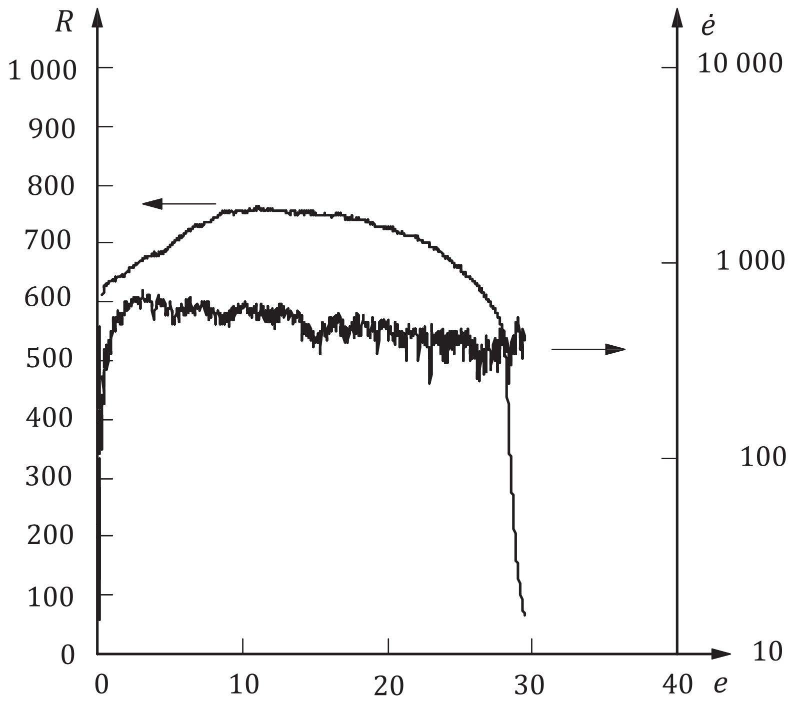
$v_A(t)$ velocity of impact block (10^3 mm·s^{-1})

e engineering strain (%)

R engineering stress (MPa)

$\dot{e}$ engineering strain rate (s^{-1})

Figure B.4 — Example of a high-strain-rate tensile test using the one-bar method (mild steel)



Key

e engineering strain (%)

R engineering stress (MPa)

$\dot{e}$ strain rate (s^{-1})

Figure B.5 — Example of a high-strain-rate tensile test using the one-bar method (high strength steel)

Annex C
(informative)

Example of split Hopkinson bar (SHB) method

C.1 Principle of the SHB method

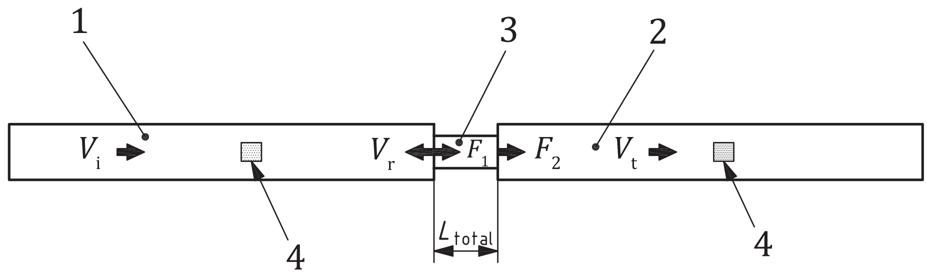
The original SHB testing machine was developed to measure the compressive mechanical behaviour of materials at high strain rates. Because of its simplicity, modified Hopkinson bar schemes were designed by many investigators for loading test pieces in uniaxial tension and torsion[6][7].

The SHB testing machine comprises two elastic bars (an input bar and an output bar), made of the same material and having the same diameter, and a mechanism to generate an incident wave in the input bar. When waves of constant amplitude are applied to the input bar, and the incident, reflected, and transmitted waves are depicted at the input bar/test piece interface and the test piece/output bar interface, respectively, as shown in Figure C.1, the engineering strain rate in the test piece is given by Formula (C.1)[8]:

$$\dot{e}(t)=\frac{1}{L_{\text{total}}}\left\{v_{\text{t}}(t)-\left[v_{\text{i}}(t)-v_{\text{r}}(t)\right]\right\} \quad (C.1)$$

where

$\dot{e}$	is the engineering strain rate;
v_{i}	is the incident particle velocity;
v_{r}	is the reflected particle velocity;
v_{t}	is the transmitted particle velocity;
L_{total}	is the total length that includes the parallel length and the shoulders.



Key

1 input bar
2 output bar
3 test piece
4 strain gauge
F_1 force at the end of the input bar
F_2 force at the end of the output bar

Figure C.1 — Incident, reflection and transmission of the strain waves in the input and output bar

The velocity can be related to strain by Formula (C.2).

$$\sigma = -\rho c_0 v, \quad c_0 = \sqrt{\frac{E}{\rho}} \tag{C.2}$$

$$v = -\frac{\sigma}{\rho c_0} = -\frac{E\varepsilon}{\rho c_0} = -\frac{\rho {c_0}^2 \varepsilon}{\rho c_0} = -c_0 \varepsilon \tag{C.3}$$

where

σ is the propagating stress;

c_0 is the propagation velocity of the elastic wave in the bar;

ρ is the density of the bar;

E is the modulus of elasticity;

ε is the elastic strain in the bar;

v is the particle velocity at any point in the bar.

By substituting Formula (C.3) in Formula (C.1), the engineering strain rate is as shown in Formula (C.4):

$$\dot{e}(t) = \frac{1}{L_{total}} \left\{ v_t(t) - \left[v_i(t) - v_r(t) \right] \right\} = -\frac{c_0}{L_{total}} \left\{ \varepsilon_t(t) - \left[\varepsilon_i(t) - \varepsilon_r(t) \right] \right\} \tag{C.4}$$

where

ε_i is the elastic strain generated by the incident wave;

ε_r is the elastic strain generated by the reflected wave;

ε_t is the elastic strain generated by the transmitted wave.

On the other hand, force at each end of the test piece is as given in Formulae (C.5) and (C.6):

$$F_1(t)=ES_b\left[\varepsilon_i(t)+\varepsilon_r(t)\right] \tag{C.5}$$

$$F_2(t)=ES_b\varepsilon_t(t) \tag{C.6}$$

where

F_1 is the force at the end of input bar;

F_2 is the force at the end of output bar;

S_b is the cross-sectional area of the elastic bar.

The engineering stress is given in Formula (C.7):

$$R(t)=\frac{F_1+F_2}{2S_o}=\frac{ES_b}{2S_o}\left[\varepsilon_i(t)+\varepsilon_r(t)+\varepsilon_t(t)\right] \tag{C.7}$$

where

R is the engineering stress in the test piece;

S_o is the original cross-sectional area of the test piece.

If the forces at both ends of the test piece are equal, Formula (C.8) applies[6]:

$$\varepsilon_i(t)+\varepsilon_r(t)=\varepsilon_t(t) \tag{C.8}$$

From Formula (C.8), engineering strain rate $\left(\dot{e}\right)$, engineering strain (e), and engineering stress (R) are generally given by Formulae (C.9), (C.10) and (C.11)[9].

$$\dot{e}(t)=\frac{2c_0}{L_{\text{total}}}\left[\varepsilon_i(t)-\varepsilon_t(t)\right] \tag{C.9}$$

$$e(t)=\int_0^t\dot{e}(t)\mathrm{d}t \tag{C.10}$$

$$R(t)=\frac{ES_b}{S_o}\varepsilon_t(t) \tag{C.11}$$

The SHB method is a high-strain-rate tensile testing method for a strain-rate range generally between 10^2 s^{-1} and 10^3 s^{-1}. The strain-rate range can reach up to 10^4 s^{-1} by shortening the gauge length; however, it may induce impact deformation. The maximum strain induced in the test piece is determined by the product of the strain rate and the loading time (duration of the incident wave). Therefore, if the strain rate is too low, only the initial plastic deformation of the test piece can be evaluated.

C.2 Input method

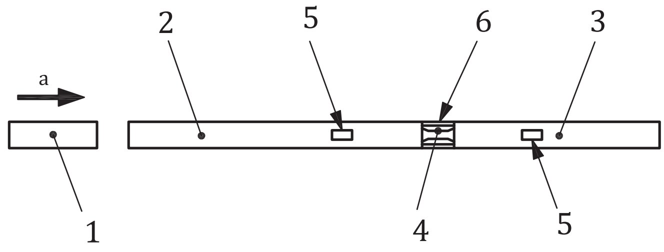
Figure C.2 shows three typical models of loading mechanisms which use the SHB method. All three are of the open-loop type. They are used in practical applications in systems where

— compressive waves are generated by a striker and reflected waves from the opposite side of the loading end are utilized in a high-strain-rate tensile test [Figure C.2 a)],

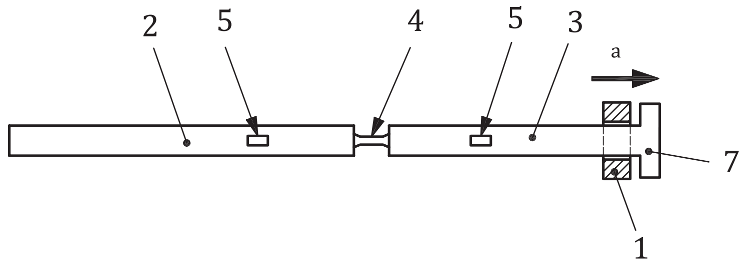
— tensile waves are directly applied by a striker [Figure C.2 b)], or

— tensile waves accumulated by clamping the input bar are released into the input bar [Figure C.2 c)][10][11].

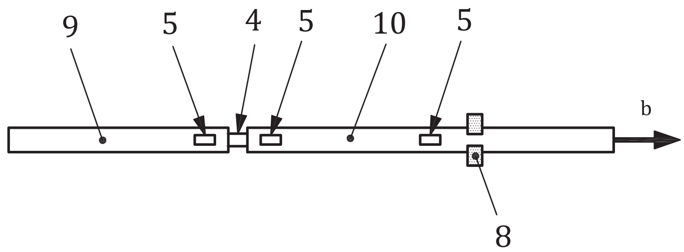
When designing an SHB testing machine, Reference [12] may be useful.



a) Rod impact type



b) Tube impact type



c) Clamp type

Key

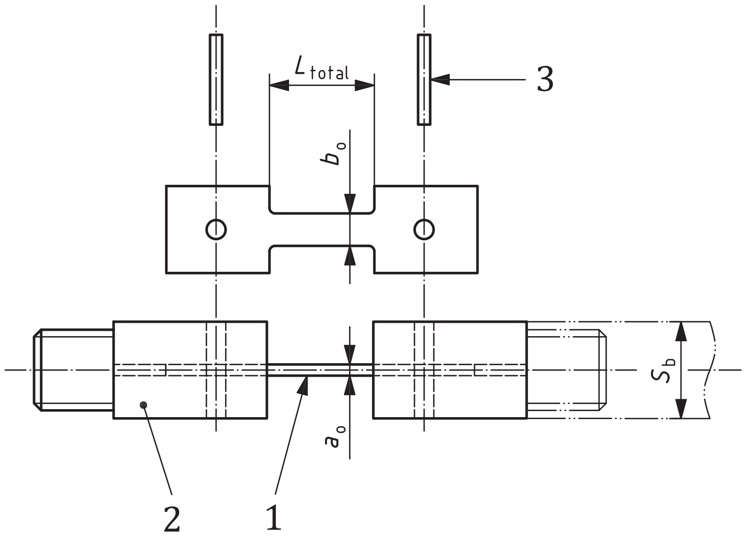
1 striker bar
2 bar no. 1
3 bar no. 2
4 test piece
5 strain gauge
6 split collar
7 yoke
8 clamp
9 transmitter bar
10 incident bar
a Applying force.
b Static applying force.

Figure C.2 — Input methods with SHB

C.3 Clamping method

The attachments shown in Figure C.3 are generally used for clamping the test piece. The attachments have the same diameter as the input and output bars to prevent elastic wave reflection at the attachments. Also, the attachments have a slit, as illustrated, and are firmly fixed to the test piece with adhesive. This means that the attachments act as integral parts of the test piece. The attachments are connected with screws to the input bar in perfect alignment to minimize changes in acoustic impedance. When the test piece is thus fixed, the ends of the attachments can be regarded as the ends of the input and output bars.

NOTE Other clamping methods can be applied.



Key

1 test piece

2 attachment

3 positioning pin

Figure C.3 — Clamping method of the test piece with SHB

C.4 Stress measurement method

For the measurement of strain and calculation of stress, strain gauges are attached to the input and output bars (elastic bars) to which a test piece is directly connected. The engineering stress of the test piece is given by Formula (C.11).

C.5 Strain measurement method

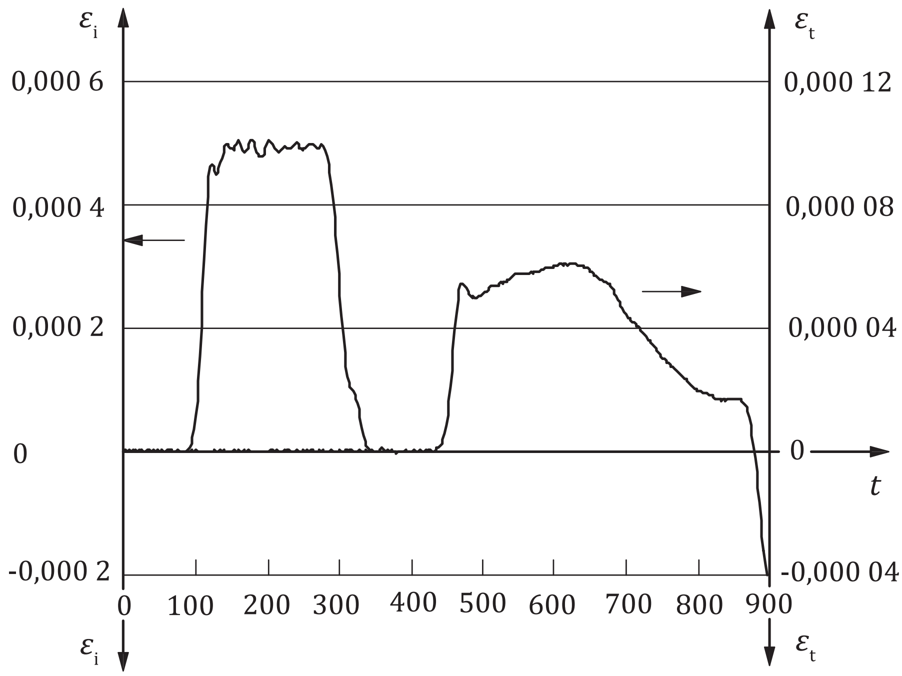
In the SHB method, the engineering strain of the test piece is calculated by measuring the elastic strain of the strain gauge attached to the input and output bars in accordance with Formula (C.10).

C.6 Example of a high-strain-rate tensile test using the SHB method

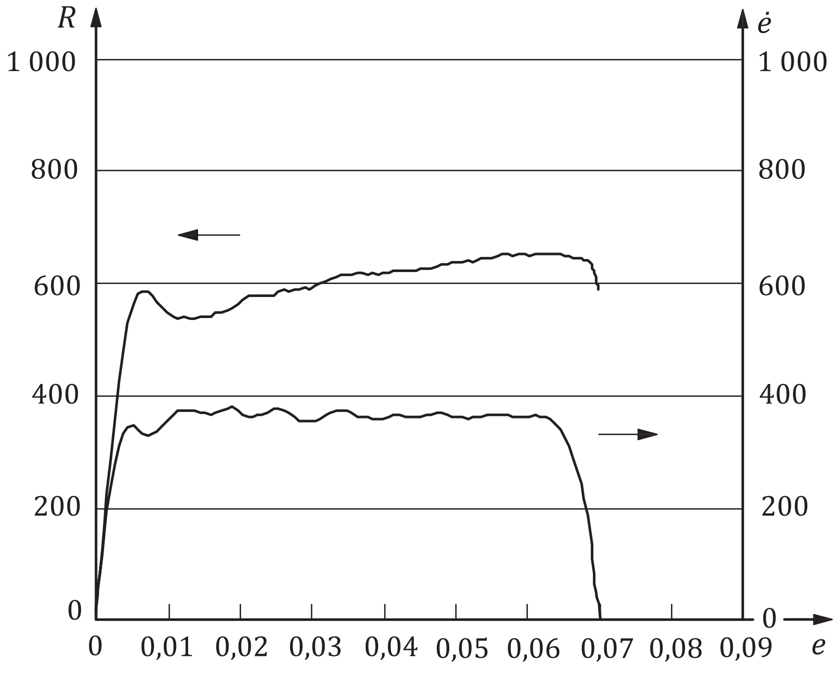
Figure C.4 presents an example of a measurement using the SHB method.

Figure C.4 a) shows output signals taken with a digital oscilloscope. These signals were output from strain gauges attached to the input and output bars. They provide a record in time of the elastic strain of the elastic bars at a point where the strain gauge is attached. There is a slight time lag between the reflected and transmitted waves and the theoretical values, partly due to wave transmission through the intermediate test piece. Therefore, the starting points of the waveforms need to be decided appropriately.

Based on the data shown in Figure C.4 a), the engineering strain rate, engineering strain and engineering stress were calculated using Formulae (C.9), (C.10) and (C.11), respectively. The results are shown in Figure C.4 b)[13].



a) Output signals from the strain gauges on the input and output bars



b) Stress-strain and strain rate–strain curves based on the output signals

Key

t time (10^{-6} s)

ε_i elastic strain in input bar

ε_t elastic strain in output bar

e engineering strain

R engineering stress (MPa)

$\dot{e}$ engineering strain rate (s^{-1})

Figure C.4 — Example of a test result from an SHB machine

C.7 Methods for deciding constants

C.7.1 General

Since the calculations for stress, strain and strain rate using the SHB method are based on theoretical formulae, it is essential that the ρ, E and c_0 values of the input and output bars, used in these calculations, are accurate.

C.7.2 Density

A test piece for measuring the density (ρ) of the input and output bars should be prepared using the same material as that used for the input and output bars. Measure its density with an accuracy of at least three significant digits, using, for instance, a method for measuring the specific gravity of a solid material (see Reference [14]).

C.7.3 Modulus of elasticity

Measure the modulus of elasticity (E) of the input and output bars with an accuracy of at least three significant digits, using, for instance, a method described in the testing method for the modulus of the elasticity of metal (see References [15] and [16]).

C.7.4 Propagation velocity of longitudinal waves

The propagation velocity of longitudinal waves through the input and output bars (c_0) can be measured by attaching strain gauges to several places of the elastic bar and providing the input wave.

Check the validity of the above measurement by substituting the density (ρ), the modulus of elasticity (E) and the obtained propagation velocity of longitudinal waves (c_0) in Formula (C.12).

$$c_0 = \sqrt{\frac{E}{\rho}} \tag{C.12}$$

Then apply the propagation velocity of longitudinal waves to the calculation of the stress and strain. The difference between the measured and calculated velocities should be within 2 %.

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[16] ASTM E1875, *Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Sonic Resonance*

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