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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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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.

$$u_B(t) = c_0 \int_0^t \varepsilon_B(t) \mathrm{d}t \qquad (1)$$

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

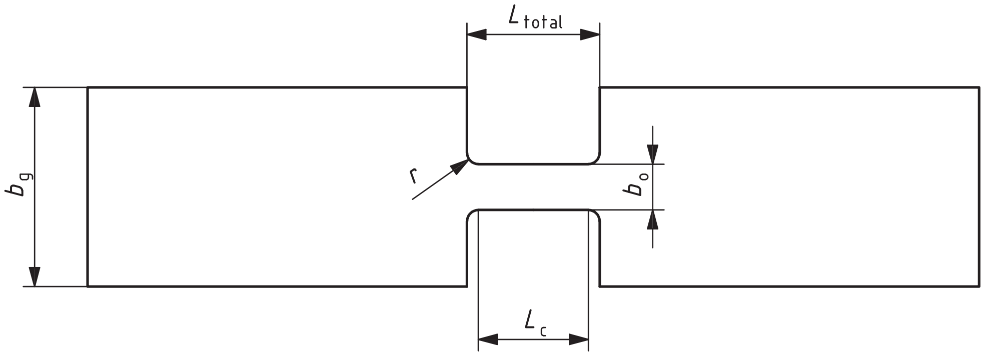
b_o is the original width of the parallel length of a flat test piece;

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.