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Metallic materials — Sheet and strip — Biaxial tensile testing method using a cruciform test piece

Matériaux métalliques — Tôles et bandes — Méthode d'essai de traction biaxiale sur éprouvette cruciforme

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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

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

This second edition cancels and replaces the first edition (ISO 16842:2014), of which it constitutes a minor revision. The changes compared to the previous edition are as follows:

— the font of "a" Figure 1 has been modified to "*a*";

— the description in 6.1 h) has been modified for clarity;

— the title of Figure 2 b) has been modified for clarity;

— ISO 10275 has been moved from Clause 2 (Normative references) to the Bibliography;

— ISO 7500-1 has been added to Clause 2 (Normative references);

— the font of "C" Figure C.2 has been modified to "*C*";

— general editorial corrections have been made.

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

Introduction

This document specifies the testing method for measuring the biaxial stress-strain curves of sheet metals subject to biaxial tension at an arbitrary stress ratio using a cruciform test piece made of flat sheet metals. The document applies to the shape and strain measurement position for the cruciform test piece. The biaxial tensile testing machine is described in Annex C, only in terms of the typical example of the machine and the requirements with which the machine ought to conform.

The cruciform test piece recommended in this document has the following features:

a) the gauge area of the test piece ensures superior homogeneity of stress, enabling measurement of biaxial stress with satisfactory accuracy;

b) capability of measuring the elasto-plastic deformation behaviour of sheet metals at arbitrary stress or strain rate ratios;

c) free from the out-of-plane deformation as is encountered in the hydrostatic bulge testing method;

d) easy to fabricate from a flat metal sheet by laser cutting, water jet cutting, or other alternative manufacturing methods.

Metallic materials — Sheet and strip — Biaxial tensile testing method using a cruciform test piece

1 Scope

This document specifies the method for measuring the stress-strain curves of sheet metals subject to biaxial tension using a cruciform test piece fabricated from a sheet metal sample. The applicable thickness of the sheet is 0,1 mm or more and 0,08 times or less of the arm width of the cruciform test piece (see Figure 1). The test temperature ranges from 10 °C to 35 °C. The amount of plastic strain applicable to the gauge area of the cruciform test piece depends on the force ratio, slit width of the arms, work hardening exponent (n-value) (see Annex B) and anisotropy of a test material.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 80000-1, *Quantities and units — Part 1: General*

ISO 7500-1, *Metallic materials — Calibration and verification of static uniaxial testing machines — Part 1: Tension/compression testing machines —Calibration and verification of the force-measuring system*

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
cruciform test piece
test piece which is recommended in the biaxial tensile test and whose geometry is specified in this document

Note 1 to entry: See Figure 1.

3.2
gauge area
square area which is located in the middle of the cruciform test piece and is enclosed by the four arms of the cruciform test piece

Note 1 to entry: See Figure 1.

3.3
arm
generic name for all areas other than the gauge area in the cruciform test piece

Note 1 to entry: The arms play a role of transmitting tensile forces in two orthogonal directions to the gauge area of the cruciform test piece (see Figure 1).

3.4
biaxial tensile testing machine
testing machine for applying biaxial tensile forces to a cruciform test piece in the orthogonal directions parallel to the arms of the test piece

Note 1 to entry: See Annex C.

3.5
yield surface
group of stress determined in a stress space, at which a metal starts plastic deformation when probing from the elastic region into the plastic range

Note 1 to entry: See Annex A and Reference [1].

3.6
yield function
mathematical function used to generate the conditional equation (yield criterion) to which the stress components ought to conform when the material subject to the stress is in the plastic deformation state

Note 1 to entry: See Annex A.

3.7
contour of plastic work
graphic figure derived by subjecting the material to plastic deformation along various linear stress paths and plotting the stress points in stress space at the instance when the plastic work consumed per unit volume along each stress path becomes identical and the plotted stress points are approximated into either a smooth curve or curved surface

Note 1 to entry: See Annex A.

4   Principle

Measurement is made at room temperature on the yield stress and the stress-strain curves of sheet metals under biaxial tensile stresses by measuring simultaneously and continuously the biaxial tensile forces and strain components applied to the gauge area of a cruciform test piece while applying biaxial tensile forces in the orthogonal directions parallel to the arms of the test piece. The test piece is made of a flat sheet metal and has a uniform thickness. The measured biaxial stress-strain curves are used to determine contours of plastic work of the sheet samples (see Annex A). According to the finite element analyses of the cruciform test piece (as recommended in Clause 5) and the strain measurement position (as specified in 6.2.4), the stress calculation error is estimated to be less than 2,0 %[2][3].

5   Test piece

5.1   Shape and dimensions

Figure 1 shows the shape and dimensions of the cruciform test piece recommended in document. The test piece shall be as described as follows:

a)   In principle, the thickness of a test piece, a, shall be the same as that of the as-received sheet sample, without any work done in the thickness direction. See 5.1 b) for an exception to the rule.

b)   The arm width, B, should be 30 mm or more, except where it is determined according to the agreement between parties involved in transaction. It shall satisfy $a \leq 0,08B$ and should be accurate to within ±0,1 mm for all four arms. The sheet thickness can be reduced to satisfy $a \leq 0,08B$ according to the agreement between the parties involved in transaction.

c)   Seven slits per one arm shall be made. Specifically, one slit shall be made on the centreline (x-axis or y-axis) of the test piece with a positional accuracy of ±0,1 mm, and three slits shall be made at an interval of $B/8$ with a positional accuracy of ±0,1 mm on each side of the centreline. All slits shall

have the same length, L, and should be accurate to within $\pm 0{,}1$ mm. The relationship of $B \leq L \leq 2B$ should be established. The opposing slit ends shall be made at an equal distance, $B_{Sx}/2$ and $B_{Sy}/2$, from the centreline with a positional accuracy of $B/2 \pm 0{,}1$ mm.

d) The slit width, w_S, should be made as small as possible (see Figure B.2), preferably less than $0{,}3$ mm.

e) The grip length, C, is considered to be sufficient if it can secure the test piece to the grips of the biaxial tensile testing machine and can transmit the necessary tensile force to the test piece. The standard grip length would be $B/2 \leq C \leq B$, but it can be determined arbitrarily according to the agreement between the parties involved in the transaction.

f) An alternative test piece geometry can be used. In the use of the alternative cruciform test pieces, the evidence of the stress measurement accuracy shall be clarified between the contractual partners.

5.2 Preparation of the test pieces

a) The permitted variations in thickness and the permitted variations from a flat surface of the sheet metal sample from which the cruciform test pieces are taken shall be in accordance with relevant product standards or national standards.

b) The standard sampling direction of the test piece shall be such that the directions of arms are parallel to the rolling (x) and transverse (y) directions of the sheet sample, respectively. The test piece sampling direction can be determined according to the agreement between parties involved in transaction.

c) For the fabrication of the test piece (including making of slits), any method, e.g. laser cutting, water jet cutting, or other alternative manufacturing methods, demonstrated to work satisfactorily can be used if agreed upon by the parties.

d) Unless otherwise specified and except for the sampling work, unnecessary deformation or heating to the test piece shall be avoided.
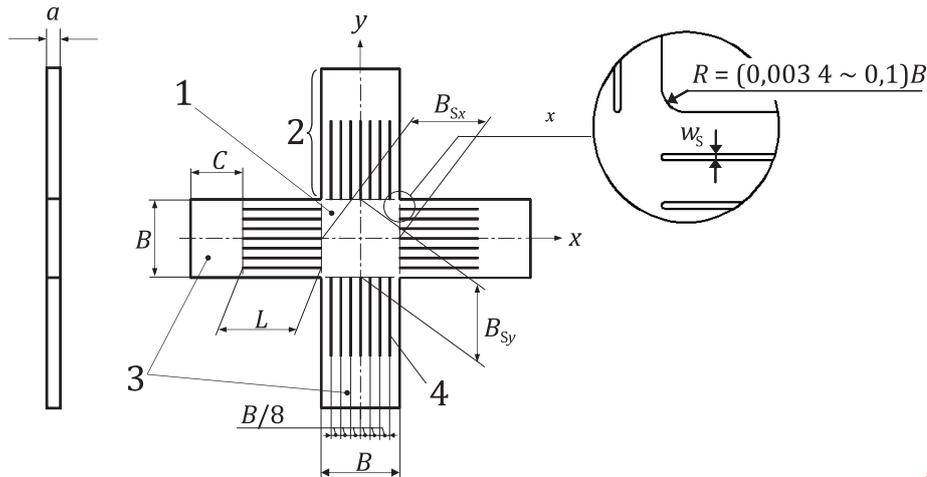
Key

1   gauge area

2   arm

3   grip

4   slit

a thickness of a test piece

B arm width

B_{Sx} distance between opposing slit ends in the x direction

B_{Sy} distance between opposing slit ends in the y direction

C grip length

L slit length

R corner radius at the junctions of arms to the gauge area

w_S slit width

Figure 1 — Standard shape and dimensions of the recommended cruciform test piece[2][3]

6 Testing method

6.1 Testing machine

The specifications required for the biaxial tensile testing machine (hereinafter referred to as testing machine) are as follows (for examples of typical testing machines, see Annex C):

a) It shall have sufficient functions and durability to hold four grips of a cruciform test piece (hereinafter referred to as test piece) in one single plane with a tolerance of ±0,1 mm during testing.

b) Two opposing grips shall move along a single straight line (hereinafter referred to as x-axis and y-axis), and the x- and y-axes shall intersect at an angle of 90° ± 0,1° (The plane that contains the x- and y-axes is referred to as the reference plane, while the intersection of x- and y-axes is referred to as the centre of testing machine).

c) It shall have a function for adjusting the two opposing grips to the position at an equal distance from the centre of the testing machine with a tolerance of ±0,1 mm before the installation of a test piece to the grips.

d) It shall have a function for enabling the installation of a test piece to the grips while aligning the centre of the test piece to the centre of the testing machine.

e) It shall have a function for enabling equal displacement of two opposing grips or the maintenance of the centre of the test piece always on the centre of the testing machine with a tolerance of ±0,1 mm during biaxial tensile test (for example, the testing machines shown in Figures C.1 and C.2 use a link mechanism to ensure equivalent displacement of two opposing grips).

f) It shall have a capability of servo-controlled biaxial tensile testing to perform a test with a constant nominal stress ratio (constant force ratio) and/or a test with a constant true stress ratio, and/or a test with a constant strain-rate ratio, according to the purpose of the test (see C.2). For a link type biaxial tensile testing machine, it shall ensure equal displacement of two opposing grips (see C.3).

g) Modern control electronics allow independent and combined control of each actuator. This is called modal control (see C.4).

h) It shall have a function for measuring and storing the values of the tensile forces (two channels, one for each of the two axes, x and y) and strain components (two channels, one for each of the two axes, x and y) during biaxial tensile test with the specified accuracy and time interval agreed by the parties concerned.

6.2 Measurement method of force and strain

6.2.1 General

This subclause specifies the method for measuring the tensile forces (F_x, F_y) and nominal strain components (e_x, e_y) applied to the x and y directions of a cruciform test piece.

6.2.2 Measurement method of force

For measurement of F_x and F_y, load cells shall be used in the x and y directions. The force-measuring system of the testing machine shall be calibrated in accordance with ISO 7500-1, class 1, or better.

6.2.3 Measurement method of strain

For measurement of e_x and e_y, strain gauges or other methods (e.g. an optical measurement system) shall be used. Measure e_x and e_y to the nearest 0,000 1 or better.

6.2.4 Strain measurement positions

Figure 2 shows the position(s) of a strain gauge (or strain gauges) for measuring e_x and e_y. e_x and e_y shall be measured at a position, with a distance of $(0,35 \pm 0,05)B$ from the centre of test piece, on the centreline parallel to the maximum tensile force. The strain measurement position can also be determined according to the agreement between parties involved in transaction.

NOTE   According to the finite element analyses of the cruciform test piece as recommended in Clause 5 and the strain measurement position as specified in Figure 2, the stress calculation error is estimated to be less than 2,0 %[2][3].

a1) $F_x \geq F_y$

a2) $F_x \leq F_y$

a) A case of measuring e_x and e_y, using a biaxial strain gauge

b1) $F_x \geq F_y$

b2) $F_x \leq F_y$

b) A case of measuring e_x and e_y, using two uniaxial strain gauges
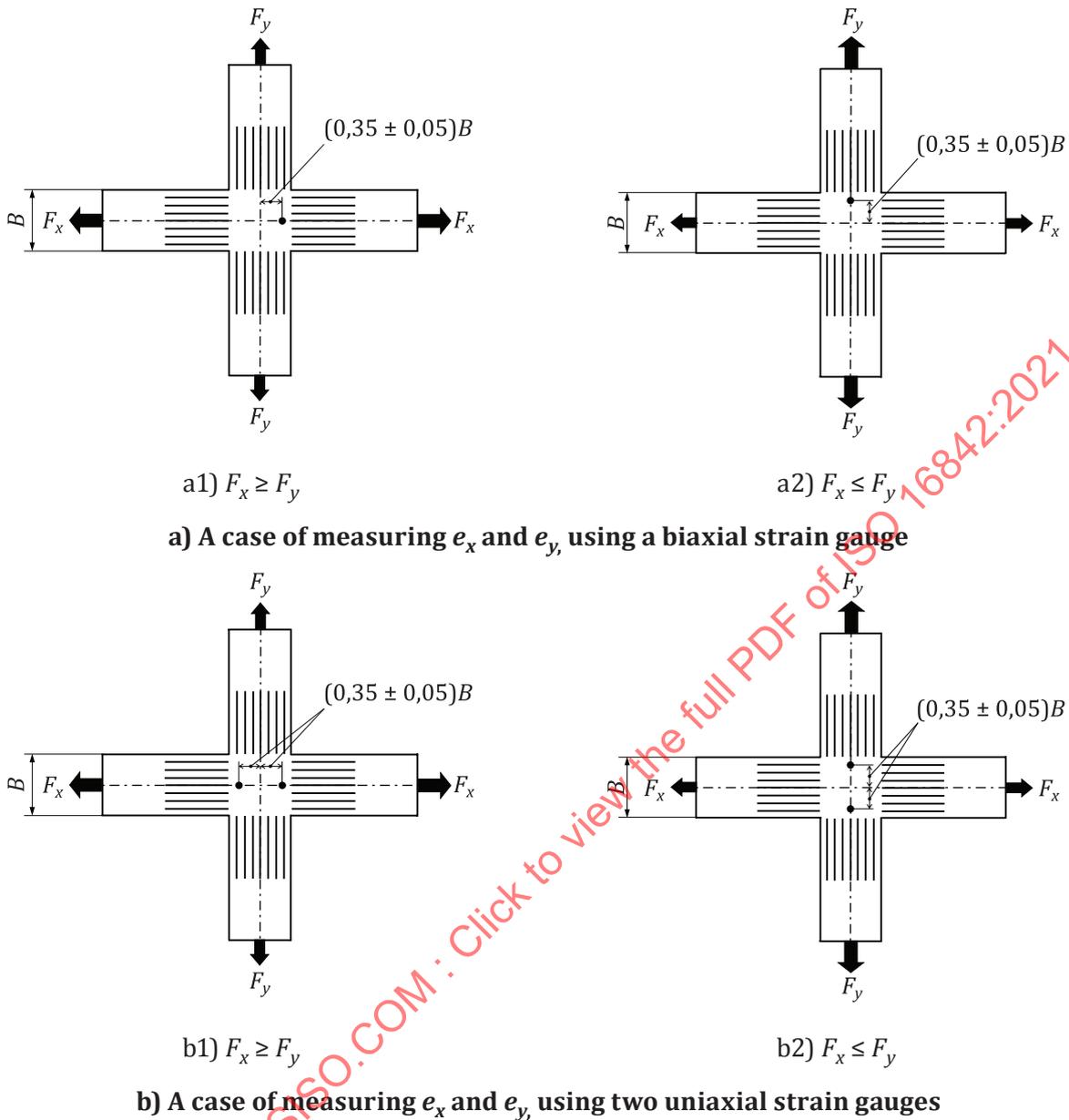
Key

B arm width

e_x nominal strain in the x direction

e_y nominal strain in the y direction

F_x tensile force in the x direction

F_y tensile force in the y direction

Figure 2 — Strain measurement position[2][3]

6.3   Installation of the test piece to a biaxial tensile testing machine

The test piece shall be fixed by four grips of a biaxial tensile testing machine. Care shall be taken to ensure alignment of the centre of the test piece with the centre of the testing machine.

6.4 Testing methods

While keeping the force ratio, true stress ratio, strain-rate ratio, or the grip displacement-rate ratio constant, biaxial tensile forces shall be applied to the test piece. F_x, F_y and e_x, e_y shall be measured with constant time intervals and the data shall be recorded on appropriate equipment. The test ends when the desired strain or stress level is achieved, or should be ended when fracture or localized necking occurs in the arm or gauge area. The recommended strain-rate is $0,1$ s^{-1} to $0,0001$ s^{-1}.

NOTE   A similar testing method has been used for abrupt strain path changes (see Annex A.3).

7   Determination of biaxial stress-strain curves

7.1   General

Using the measured values of F_x, F_y and e_x, e_y, the stress-strain curves in the x and y directions of the cruciform test piece shall be determined. These curves are used to determine contours of plastic work for the test material (see A.2).

7.2   Determination of the original cross-sectional area of the test piece

Calculate the original cross-sectional areas of the gauge area perpendicular to the x- and y-axes, A_{Sx} and A_{Sy}, from Formulae (1) and (2):

$$A_{S\,x} = a \times B_{Sy} \tag{1}$$

$$A_{S\,y} = a \times B_{Sx} \tag{2}$$

where

   a is the thickness of the test piece, expressed in mm;

   B_{Sx} is the distance between opposing slit ends on the x axis, expressed in mm;

   B_{Sy} is the distance between opposing slit ends on the y axis, expressed in mm.

Measure a to the nearest $0,01$ mm or better using a micrometer with sufficient resolution. B_{Sx} and B_{Sy} shall be determined to the nearest $0,1$ mm or better using a measuring device with sufficient resolution. The calculated values of A_{Sx} and A_{Sy} shall be rounded to $0,1$ mm^2 according to ISO 80000-1.

7.3   Determination of true stress

Calculate the true stress components in the x and y directions, σ_x and σ_y, from Formulae (3) and (4):

$$\sigma_x = \frac{F_x}{A_{S\,x}}(1 + e_x) \tag{3}$$

$$\sigma_y = \frac{F_y}{A_{S\,y}}(1 + e_y) \tag{4}$$

where

A_{Sx} is the original cross-sectional areas of the gauge area perpendicular to the *x*-axes, expressed in mm^2;

A_{Sy} is the original cross-sectional areas of the gauge area perpendicular to the *y*-axes, expressed in mm^2;

e_x is the nominal strain in the *x* direction measured by the method described in 6.2;

e_y is the nominal strain in the *y* direction measured by the method described in 6.2;

F_x is the tensile force in the *x* direction, expressed in N;

F_y is the tensile force in the *y* direction, expressed in N.

7.4 Determination of true strain

Calculate the true strain components in the *x* and *y* directions, ε_x and ε_y, from Formulae (5) and (6):

$$\varepsilon_x = \ln(1 + e_x) \tag{5}$$

$$\varepsilon_y = \ln(1 + e_y) \tag{6}$$

where

e_x is the nominal strain in the *x* direction measured by the method, as described in 6.2;

e_y is the nominal strain in the *y* direction measured by the method, as described in 6.2.

ε_x and ε_y shall be calculated to the digit of 10^{-5} from Formulae (5) and (6), and the result shall be rounded to the digit of 10^{-4} according to ISO 80000-1.

Examples of the measured biaxial true stress-true strain curves for a cold rolled ultralow carbon steel sheet are shown in Figure 3.

a) A case of $F_x:F_y = 1:1$ b) A case of $F_x:F_y = 2:1$

Key

X $\varepsilon_x, \varepsilon_y$
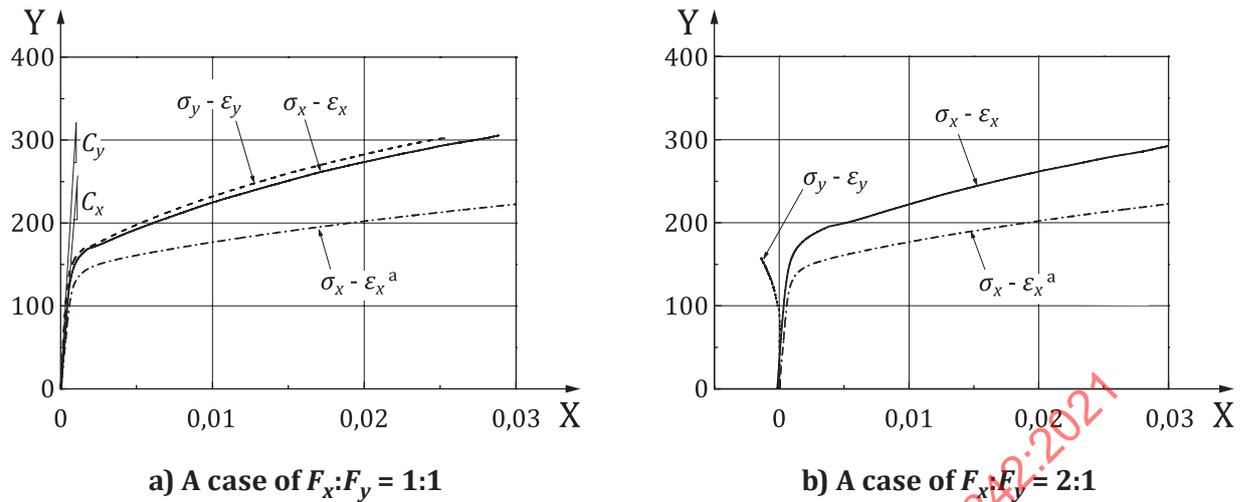
Y σ_x, σ_y / MPa

C_x slope of the elastic part of the $\sigma_x - \varepsilon_x$ curve measured in the biaxial tensile test, in MPa

C_y slope of the elastic part of the $\sigma_y - \varepsilon_y$ curve measured in the biaxial tensile test, in MPa

F_x tensile force in the x direction, in N

F_y tensile force in the y direction, in N

ε_x true strain in the x direction

ε_y true strain in the y direction

σ_x true stress in the x direction, in MPa

σ_y true stress in the y direction, in MPa

a Uniaxial tensile true stress-true strain curve.

NOTE   The uniaxial tensile true stress-true strain curve in the rolling direction (RD) of the same material is also shown for comparison.

Figure 3 — Examples of true stress-true strain curves measured in the biaxial tensile test of cold rolled ultralow carbon steel sheet

7.5 Determination of true plastic strain

Calculate the true plastic strain components in the x and y directions, ε_x^p and ε_y^p, from Formulae (7) and (8):

$$\varepsilon_x^p = \varepsilon_x - \frac{\sigma_x}{C_x} \tag{7}$$

$$\varepsilon_y^p = \varepsilon_y - \frac{\sigma_y}{C_y} \tag{8}$$

where

C_x is the slope of the elastic part of the $\sigma_x - \varepsilon_x$ curve measured in the biaxial tensile test, expressed in MPa;

C_y is the slope of the elastic part of the $\sigma_y - \varepsilon_y$ curve measured in the biaxial tensile test, expressed in MPa;
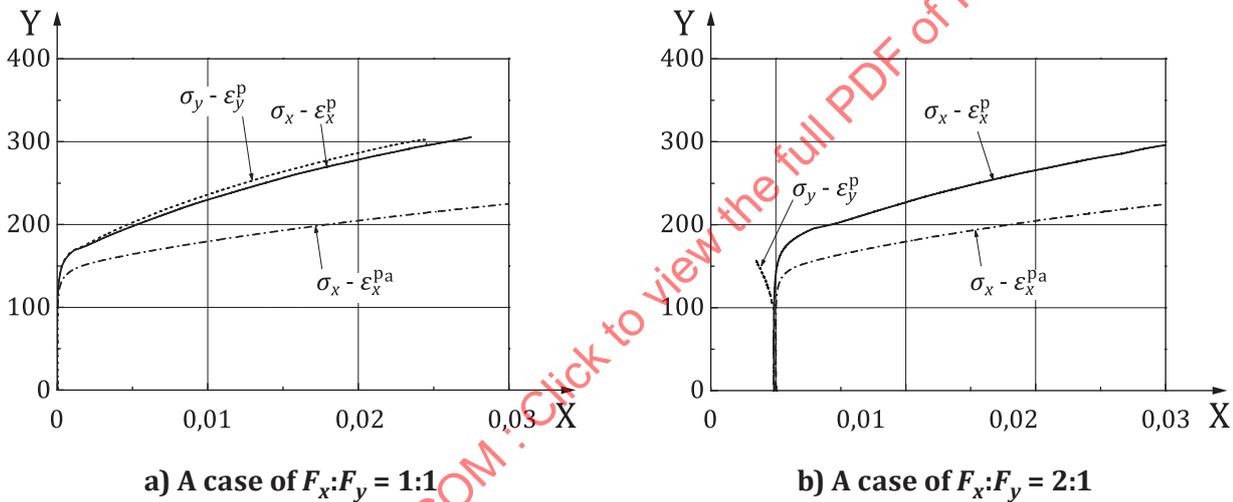
ε_x is the true strain in the x direction;

ε_y is the true strain in the y direction;

σ_x is the true stress in the x direction, expressed in MPa;

σ_y is the true stress in the y direction, expressed in MPa.

ε_x^p and ε_y^p shall be calculated to the digit of 10^{-5} from Formulae (7) and (8), and the result shall be rounded to the digit of 10^{-4} according to ISO 80000-1.

Examples of measured true stress-true plastic strain curves corresponding to Figure 3 are shown in Figure 4.

a) A case of F_x:F_y = 1:1

b) A case of F_x:F_y = 2:1

Key

X ε_x^p, ε_y^p

Y σ_x, σ_y / MPa

F_x tensile force in the x direction, in N

F_y tensile force in the y direction, in N

ε_x^p true plastic strain in the x direction

ε_y^p true plastic strain in the y direction

σ_x true stress in the x direction, in MPa

σ_y true stress in the y direction, in MPa

[a]   Uniaxial tensile true stress-true plastic strain curve.

NOTE   The uniaxial tensile true stress-true plastic strain curve in the rolling direction (RD) of the same material is also shown for comparison.

Figure 4 — Examples of true stress-true plastic strain curves measured in the biaxial tensile test of cold rolled ultralow carbon steel sheet

8   Test report

8.1   Information in the report

The test report shall contain at least the following information unless otherwise agreed by the parties concerned:

a)   identification of the test piece;

b)   specified material, if known;

c)   thickness of the original sheet sample;

d)   dimensions of the test piece: arm width, B; grip length, C; slit length, L; corner radius at the junctions of arms to the gauge area, R; slit width, w_S; thickness of the test piece, a (see Figure 1);

e)   location and direction of sampling of the test pieces, if known, and the fabrication method of the test pieces;

f)   strain measurement method;

g)   test temperature;

h)   testing machine;

i)   loading conditions (force ratio, true stress ratio, strain-rate ratio, or grip displacement ratio for the link type biaxial tensile testing mechanism shown in Figure C.2, strain-rate, etc.);

j)   test results: data specified according to the agreement between the parties involved in transaction (force-time diagram, strain-time diagram, contour of plastic work, stress path in stress space, strain path in strain space, etc.).

8.2   Additional note

It is recommended that the record of the following items is added in the test report:

a)   sample mill sheet;

b)   photo of overall appearance of the test piece after test.

Annex A
(informative)

Method for measuring a yield surface

A.1 General

This annex specifies methods for measuring a yield surface of a sheet metal. A yield surface is effective when the plastic deformation characteristics of sheet metals are to be evaluated quantitatively and when an optimum yield function is to be identified for the metals under biaxial stress. The determination of an appropriate yield function based on the biaxial tensile tests is useful for improving the predictive accuracy of FEA for sheet metal forming processes[4][5][6][7].

A.2 Method for measuring contours of plastic work

Figure A.1 shows a method for measuring a contour of plastic work for sheet metals. A uniaxial tensile test in the rolling direction of the material is conducted first, and the uniaxial true stress, σ_0, and plastic work, W_0, dissipated per unit volume are determined for a predetermined value of the uniaxial true plastic strain, ε_0^p. In this case, W_0 is determined as an area below the measured true stress-true plastic strain curve. Then, the biaxial tensile tests with the force ratios, $F_x{:}F_y$, or the true stress ratio, $\sigma_x{:}\sigma_y$, held at specific proportions and the uniaxial tensile test in the transverse direction are also carried out. Finally, groups of true stress points, $(\sigma_0, 0)$, (σ_x, σ_y), and $(0, \sigma_{90})$, for which the same amount of plastic work as W_0 is required, are plotted in the principal stress space to form a contour of plastic work associated with ε_0^p. When ε_0^p is sufficiently small, the associated work contour can be practically viewed as an initial yield surface for the material.
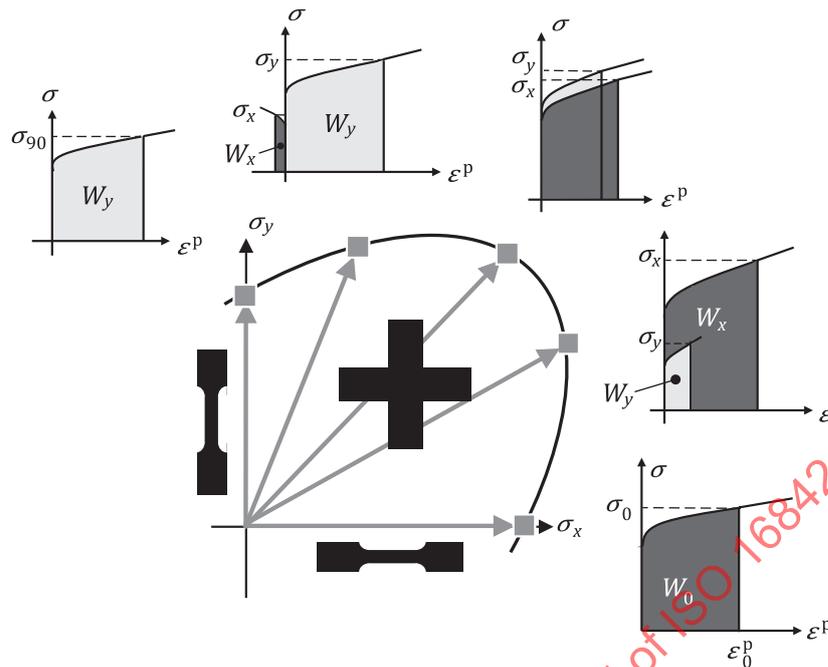
Key

W_x plastic work per unit volume dissipated by the tensile force in the x direction

W_y plastic work per unit volume dissipated by the tensile force in the y direction

W_0 plastic work per unit volume dissipated in the uniaxial tensile test to a strain of ε_0^p in the x direction; $W_0 = W_x + W_y$

ε_0^p uniaxial true plastic strain reached in the uniaxial tensile test in the x direction

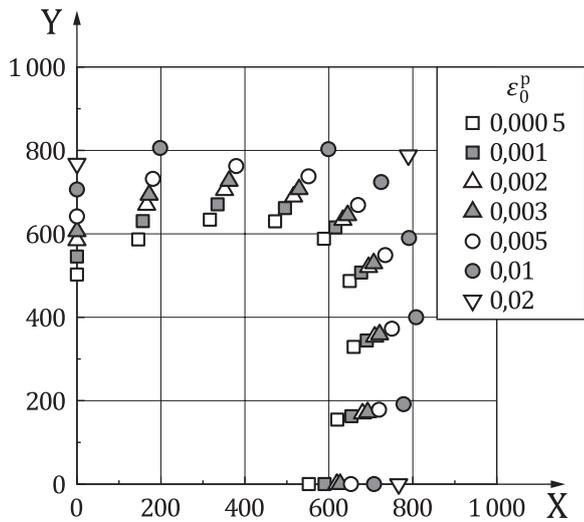σ_x true stress in the x direction

σ_y true stress in the y direction

σ_0 tensile true stress reached in the uniaxial tensile test in the x direction and associated with W_0
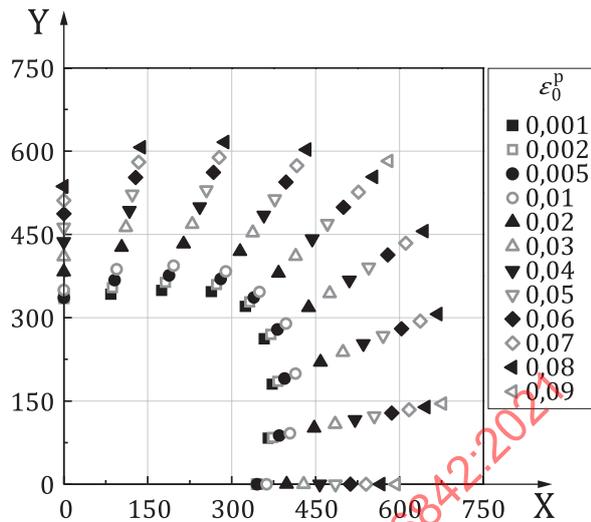
σ_{90} tensile true stress reached in the uniaxial tensile test in the y direction and associated with W_0

**Figure A.1 — A schematic diagram for the determination of a contour of plastic work**

Figure A.2 shows examples of contours of plastic work measured for different sheet metals using cruciform test pieces as shown in Figure 1. The force ratio, $F_x:F_y$, was set to 1:0, 4:1, 2:1, 4:3, 1:1, 3:4, 1:2, 1:4 and 0:1. For the force ratios of 1:0 and 0:1, a standard uniaxial tensile test piece was used.
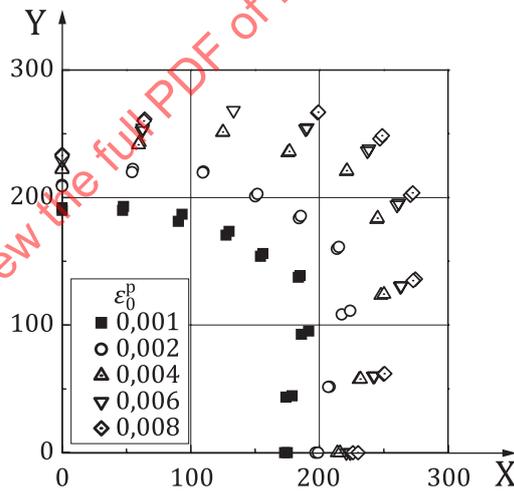
a) High-strength steel sheet with a tensile strength of 780 MPa

b) SUS304 stainless steel sheet
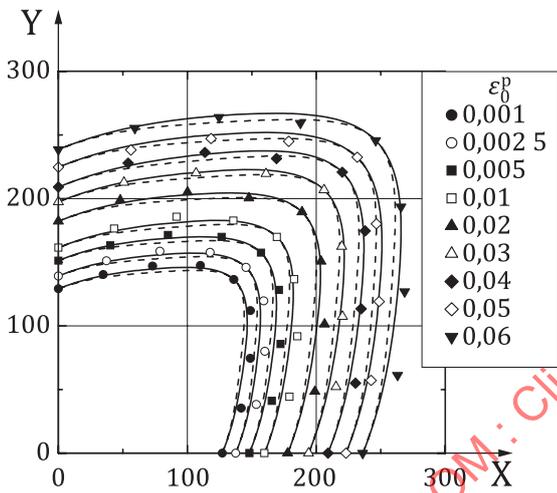
c) 5 000 series aluminium alloy sheet

d) AZ31 magnesium sheet

Key

X σ_x / MPa

Y σ_y / MPa

ε_0^p uniaxial true plastic strain reached in the uniaxial tensile test in the x direction

σ_x true stress in the x direction, in MPa

σ_y true stress in the y direction, in MPa

Figure A.2 — Examples of contours of plastic work measured using cruciform test pieces
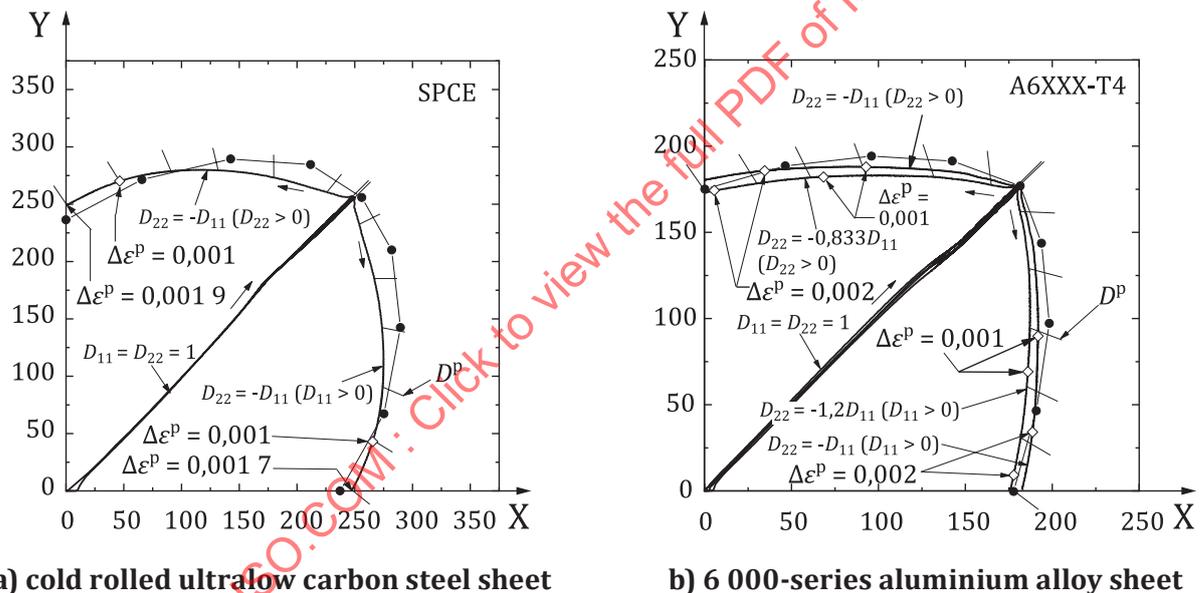
A.3 Use of abrupt strain path change for detecting a yield vertex and subsequent yield surface

Conventionally, a yield surface is determined by probing in many different stress directions from the elastic region into the plastic range. In considering the possibility that a corner exists on the subsequent yield surface at the point of loading, as predicted by crystal plasticity, Reference [1] has argued that any such corner will be erased by the unloading needed to probe the yield surface.

Reference [8] proposed a new method for determining the shape of the subsequent yield surface in the vicinity of a current loading point. A proportional strain path is prescribed until the loading point of interest has been reached, and an abrupt strain path is prescribed that will cause the stress point to move quickly along the yield surface. This determination can be achieved without any unloading, which would be required if the subsequent yield surface was to be determined by probing from the elastic region. This method is therefore capable of detecting a yield vertex formed at the point of loading.

Reference [9] applied the abrupt strain path change method to a cruciform test piece, and successfully measured a yield vertex and non-normality behaviour of the plastic strain-rate. Figure A.3 shows the observed stress paths for an aluminium alloy and an IF steel, using the cruciform test piece shown in Figure 1, in a closed-loop, servo-controlled biaxial tensile testing machine. In the first step of straining, equibiaxial stretching, $D_{11} = D_{22} > 0$, was prescribed. At a nominal strain, $e_{11} = e_{22} = 0,01$, the prescribed strain-rates were abruptly changed to $D_{11} = -D_{22} > 0$, or alternatively, $D_{22} = -D_{11} > 0$. It is apparent that the stress paths for the abrupt strain path change with $D_{22} = -D_{11}$ cannot be non-yielding stress paths in the elastic region. It is therefore inferred that a yield surface vertex exists at the point of loading in the figure.

Similar tests were performed for a metastable austenitic stainless cast steel[10], although the geometry of the test piece used is different from that shown in Figure 1.

a) cold rolled ultralow carbon steel sheet

b) 6 000-series aluminium alloy sheet

Key

X	σ_{11}/ MPa
Y	σ_{22}/ MPa
σ_{11}	true stress in the *x* direction, in MPa
σ_{22}	true stress in the *y* direction, in MPa
D_{11}	stretching in the *x* direction
D_{22}	stretching in the *y* direction
D^p	plastic strain-rate
$\Delta\varepsilon^p$	accumulated equivalent (von Mises) plastic strain measured from the strain path change point

NOTE   The curve marked with · is a work contour measured for the as-received material subjected to linear stress paths.

Figure A.3 — Subsequent yield surfaces observed with abrupt strain path changes following equibiaxial tension[9]

Annex B
(informative)

Factors affecting the maximum equivalent plastic strain applicable to the gauge area of the test piece

B.1 General

For the cruciform test piece covered by this document, the arms are subjected to uniaxial tension, so that the test is over at a time when the nominal stress of the arm reaches the material tensile strength. Accordingly, the maximum equivalent plastic strain, $\varepsilon^{\mathrm{p}}_{\max}$, applicable to the gauge area can be estimated using the Considère condition for maximum load in a strip in tension[11]. $\varepsilon^{\mathrm{p}}_{\max}$ depends mainly on the force ratio, $F_x:F_y$, the work hardening exponent, n (n-value, see ISO 10275), of the test material, the slit width of the cruciform test piece, w_{S}, and the anisotropy of the test material. This annex shows the effects of the work hardening exponent and the slit width on $\varepsilon^{\mathrm{p}}_{\max}$.

B.2 Effect of work hardening exponent (*n*-value)

Figure B.1 shows the effect of *n*-value on $\varepsilon^{\mathrm{p}}_{\max}$ when the slit width of the cruciform test piece is 1 % of the arm width and the number of slits is seven. For materials having larger *n*-value, $\varepsilon^{\mathrm{p}}_{\max}$ becomes larger. This is because the material with larger *n*-value has the higher stress increase-rate along with increase in the arm's plastic deformation, which in turn causes increase in the stress acting on the gauge area. Note here that the values of $\varepsilon^{\mathrm{p}}_{\max}$ in Figure B.1 should be viewed only for reference, because these are numerical analysis solutions based on the simple mechanics of plasticity, the maximum load condition for the arm[11], by assuming the isotropy of the material.

Key
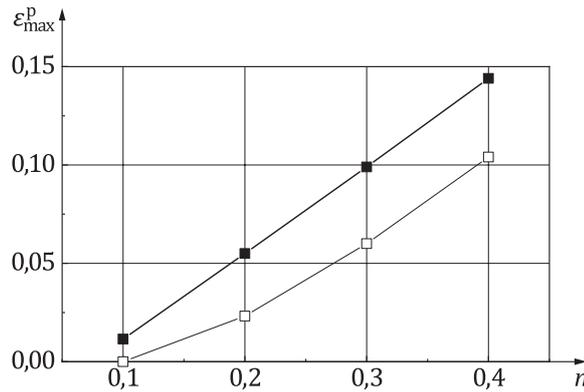
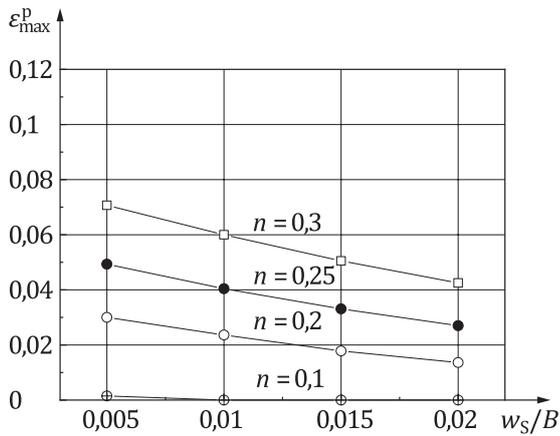|	
F_x	tensile force in the x direction, in N
F_y	tensile force in the y direction, in N
w_S	slit width, in mm
B	arm width, in mm
n	work hardening exponent (n-value)
ε_{max}^p	maximum equivalent plastic strain applicable to the gauge area

—■— $F_x:F_y$ = 1:1

—□— $F_x:F_y$ = 2:1

NOTE 1   Material model: Von Mises yield criterion[2].
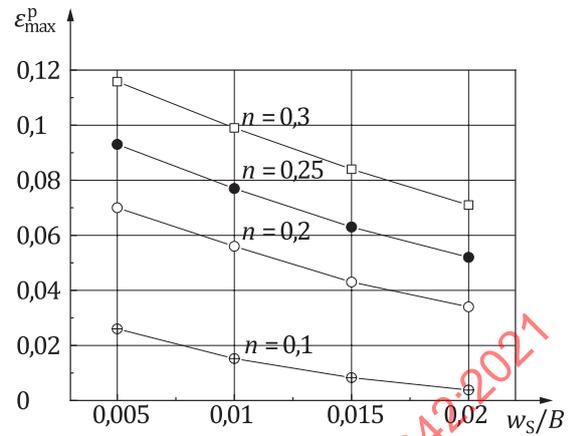
NOTE 2 w_S/B = 0,01.

Figure B.1 — Effects of n-value on the maximum equivalent plastic strain applicable to the gauge area of a cruciform test piece

B.3   Effect of slit width

Figure B.2 shows the effects of the slit width on ε_{max}^p when the force ratios, $F_x:F_y$, are 2:1 and 1:1 and the number of slits is seven. As the effective sectional area of the arm decreases with increasing w_S, the force transmitted to the gauge area decreases, resulting in the decrease of ε_{max}^p. Note that the results shown in Figure B.2 should be viewed only for reference because they are numerical analysis solutions based on the simple mechanics of plasticity, the maximum load condition for the arm[11], by assuming the isotropy of the material.

a) $F_x{:}F_y = 2{:}1$　　　　　　　　**b) $F_x{:}F_y = 1{:}1$**

Key

F_x　　tensile force in the x direction, in N

F_y　　tensile force in the y direction, in N

w_S　　slit width, in mm

B　　arm width, in mm

n　　work hardening exponent (n-value)

ε_{max}^{p}　maximum equivalent plastic strain applicable to the gauge area

NOTE　　Material model: Von Mises yield criterion[2].

Figure B.2 — Effects of the slit width on the maximum equivalent plastic strain applicable to the gauge area of a cruciform test piece

Annex C
(informative)

Biaxial tensile testing machine

C.1   General

This annex shows examples of the testing machine applicable to the biaxial tensile testing method.

C.2   Servo controlled biaxial tensile testing machine

Figure C.1 shows the structural example of a servo-controlled biaxial tensile testing machine[12][13]. The main body consists of the frame, four actuators (hydraulic cylinder or servo motor) arranged in two orthogonal directions, grip connected to each actuator and one load cell installed in each axis. Opposing hydraulic cylinders are connected to common hydraulic lines so that they are subjected to the same hydraulic pressure. The hydraulic pressure of each pair of opposing hydraulic cylinders is servo-controlled independently. Displacements of opposing hydraulic cylinders are equalized using the pantograph-type link mechanism proposed by Reference [14], so that the centre of the cruciform test piece is always kept at the centre of the testing machine during biaxial tensile tests. A load cell is included in each loading direction. This testing machine can control the stress ratio[12][13] or strain-rate ratio[9] by means of the servo actuators.