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

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National foreword

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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

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The committee responsible for this document is ISO/TC 164, *Mechanical testing of metals*, Subcommittee 2, *Ductility testing*.

Introduction

This International Standard 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 International Standard 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 that the machine should comply with.

The cruciform test piece recommended in this International Standard 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 International Standard 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 shall be 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 shall range 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, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10275, *Metallic materials — Sheet and strip — Determination of tensile strain hardening exponent*

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

3 Terms and definitions

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

3.1
cruciform test piece
test piece which is recommended in the biaxial tensile test and whose geometry is specified in this International Standard (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 (see Figure 1)

3.3
arm
generic name for all areas other than the gauge area in the cruciform test piece. 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 (see Annex C)

3.5
yield surface
a 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[1] (see Annex A)

3.6
yield function
mathematical function used to generate the conditional equation (yield criterion) which the stress components should comply with when the material subject to the stress is in the plastic deformation state (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 (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 Clause 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 this International Standard. The test piece shall be as described below.

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 that it can be 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 parties involved in transaction.

c) Seven slits per one arm shall be made. Specifically, one slit shall be made on the centerline (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 an positional accuracy of ± 0,1 mm on each side of the centerline. All slits shall have the same length, L, and should be accurate to within ±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, $B_{\mathrm{Sx}}/2$ and $B_{\mathrm{Sy}}/2$, from the centerline 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 enough 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 can be determined arbitrarily according to the agreement between parties involved in 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 has to be clarified between the contractual partners.

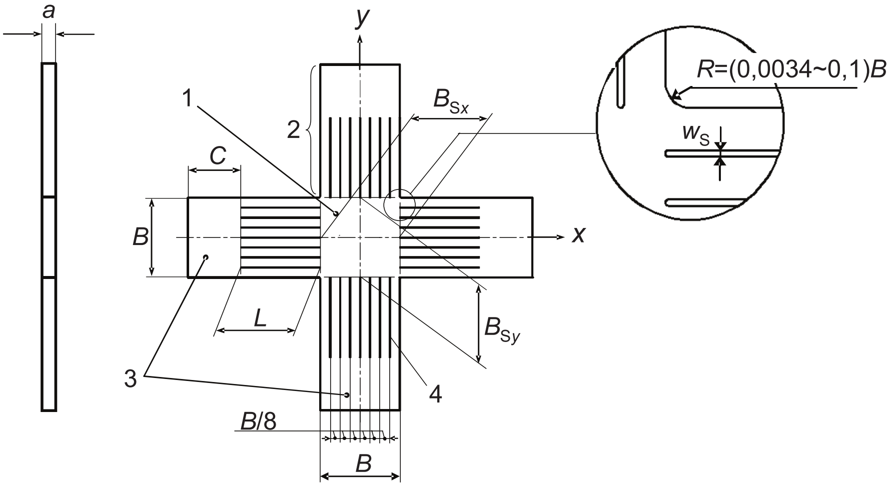
5.2 Preparation of the test pieces

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 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 Annex C.2). For a link type biaxial tensile testing machine, it shall ensure equal displacement of two opposing grips (see Annex C.3).

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

h) It shall have a function for measuring and storing the values of the tensile forces (two channels for the *x*- and *y*-axes) and strain components (two channels for the *x*- and *y*-axes) 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, 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.

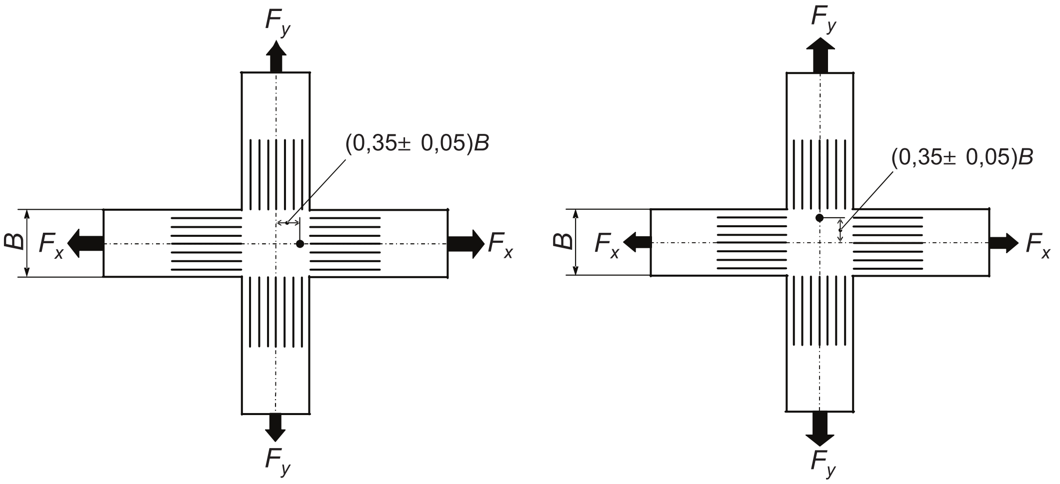
6.2.3 Measurement method of strain

For measurement of (e_x, 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, e_y). (e_x, e_y) shall be measured at a position, with a distance of (0,35 ± 0,05)B from the centre of test piece, on the centerline parallel to the maximum tensile force. The strain measurement position can also be determined according to the agreement between parties involved in transaction.

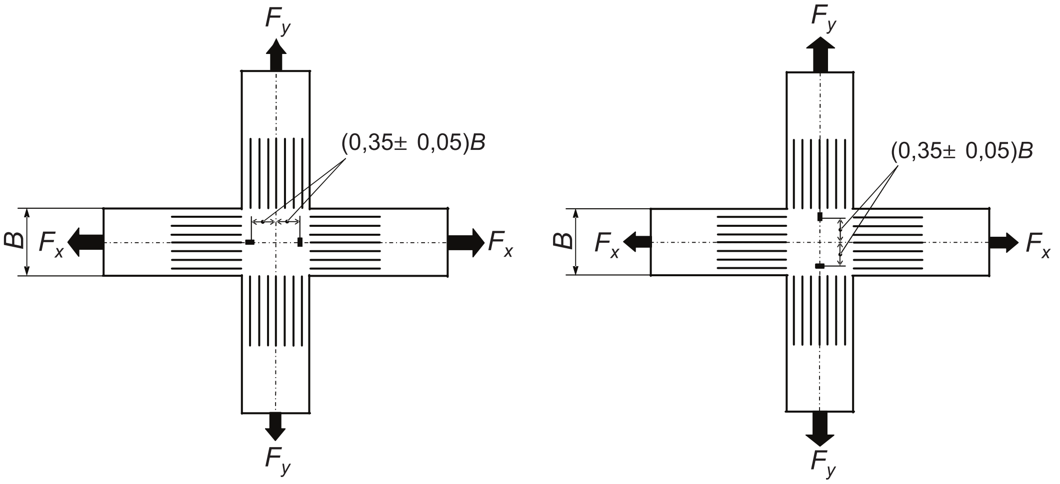
NOTE According to the finite element analyses of the cruciform test piece as recommended in Clause 5 and the strain measurement position as specified in Figure 2, the stress calculation error is estimated to be less than 2,0 %.[2][3]



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 foil 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 pieces of uniaxial strain gauge

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 test piece with that 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 achieving the desired strain or stress level, or should be ended when fracture or localized necking occurred 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 Annex 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):

$$A_{Sx} = a \times B_{Sy} \tag{1}$$

$$A_{Sy} = a \times B_{Sx} \tag{2}$$

where

a is the sheet thickness, 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):

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

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

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, as described in 6.2;

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

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):

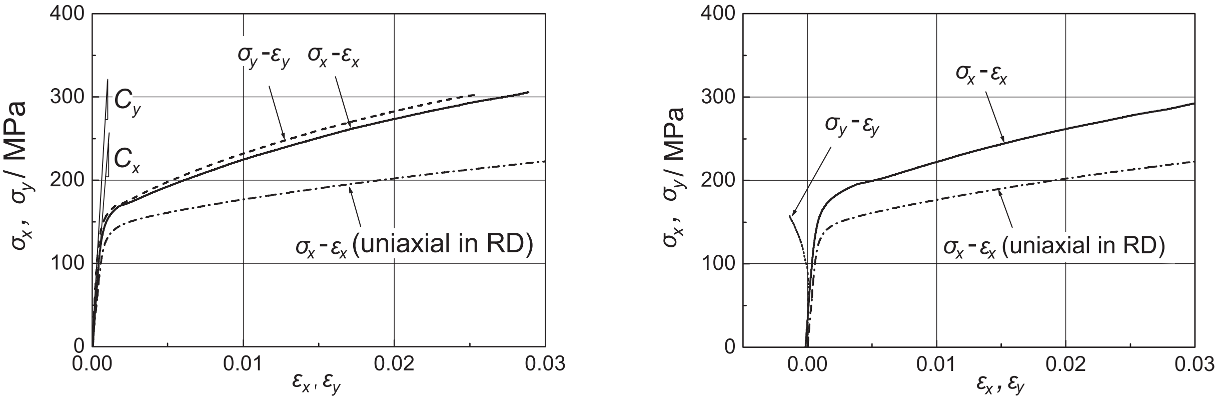
$$\varepsilon_x^p = \varepsilon_x - \frac{\sigma_x}{C_x} \tag{7}$$

$$\varepsilon_{\mathrm{y}}^{\mathrm{p}} = \varepsilon_{\mathrm{y}} - \frac{\sigma_{\mathrm{y}}}{C_{\mathrm{y}}} \tag{8}$$

where

C_{x}	is the slope of the elastic part of the $\sigma_{\mathrm{x}} - \varepsilon_{\mathrm{x}}$ curve measured in the biaxial tensile test, expressed in MPa;
C_{y}	is the slope of the elastic part of the $\sigma_{\mathrm{y}} - \varepsilon_{\mathrm{y}}$ 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.

$\varepsilon_{\mathrm{x}}^{\mathrm{p}}$ and $\varepsilon_{\mathrm{y}}^{\mathrm{p}}$ 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.



a) A case of F_{x}:F_{y} = 1:1

b) A case of F_{x}:F_{y} = 2:1

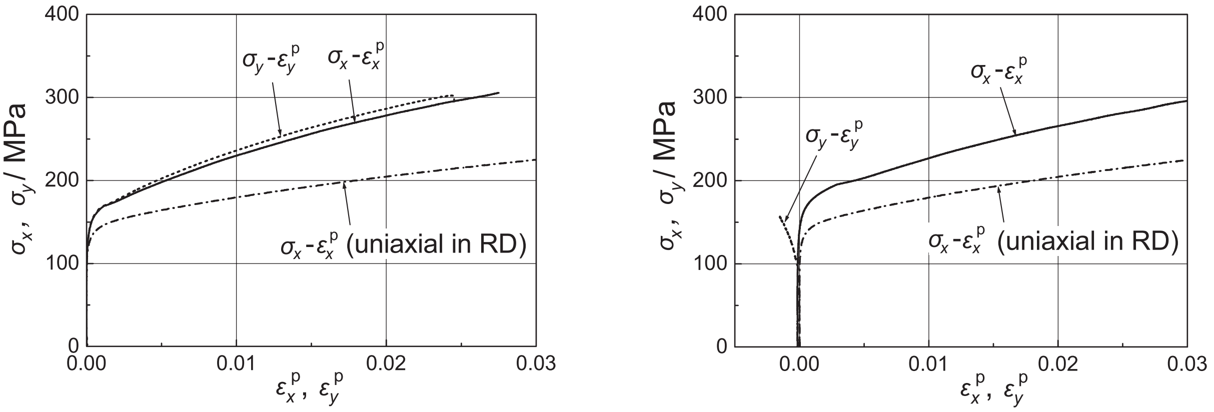
Key

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

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

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

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

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 and the test piece;

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 (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)

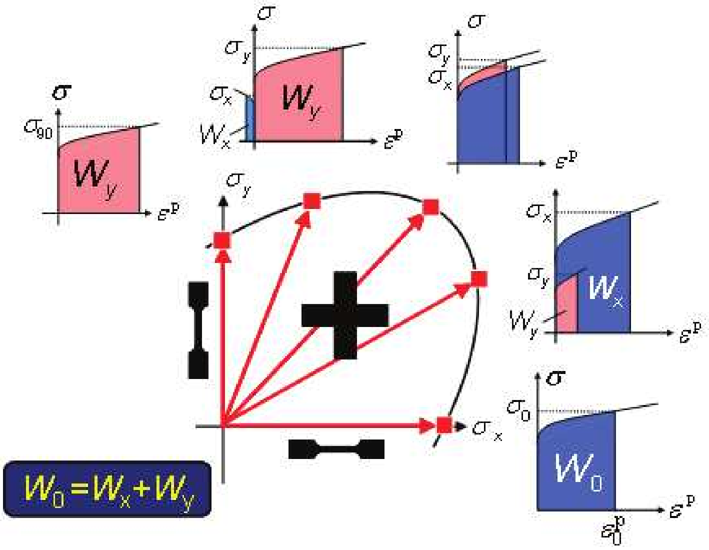
Method for measuring a yield surface

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 to improve 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, $\varepsilon_0^{\mathrm{p}}$. 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, σ_{x}:σ_{y}, held at specific proportions and the uniaxial tensile test in the transverse direction are also carried out. Finally, groups of true stress points, (σ_0, 0), (σ_x, σ_y), and (0, σ_{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 $\varepsilon_0^{\mathrm{p}}$. When $\varepsilon_0^{\mathrm{p}}$ is sufficiently small, the associated work contour can be practically viewed as an initial yield surface for the material.

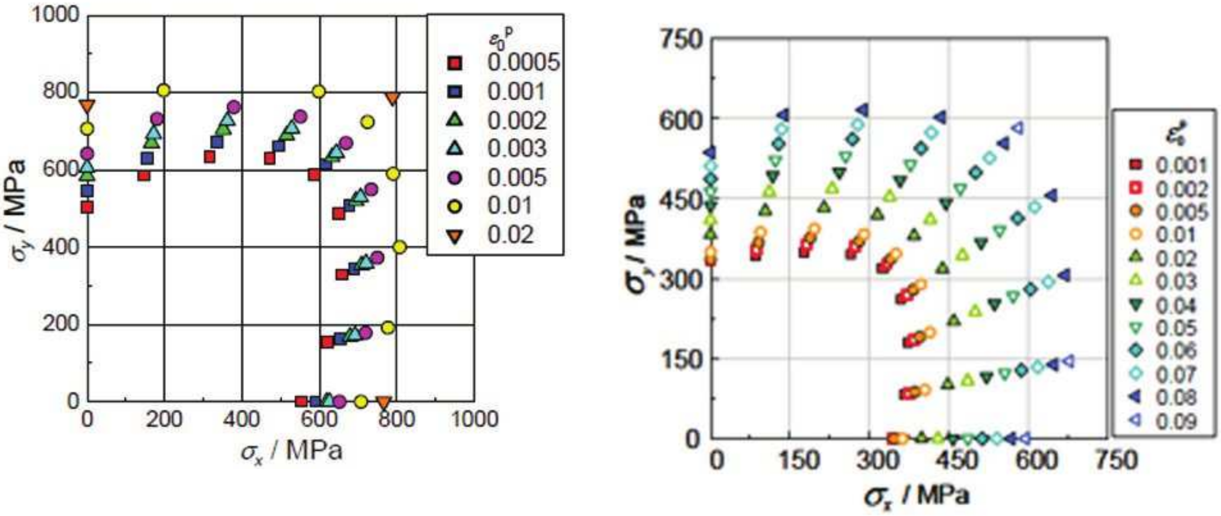


Key

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
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

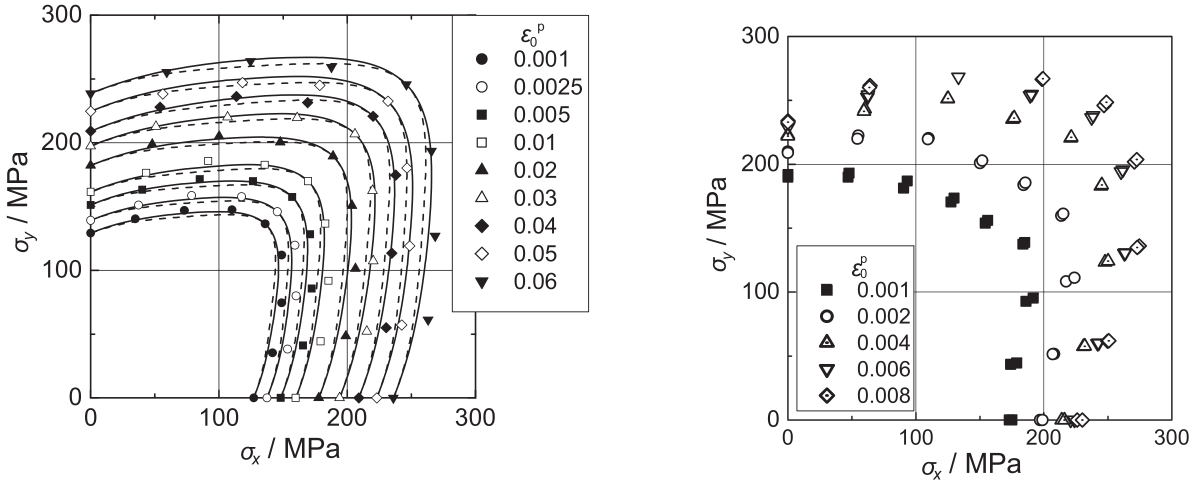
Figure A.1 — A schematic diagram for the determination of a contour of plastic work

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

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

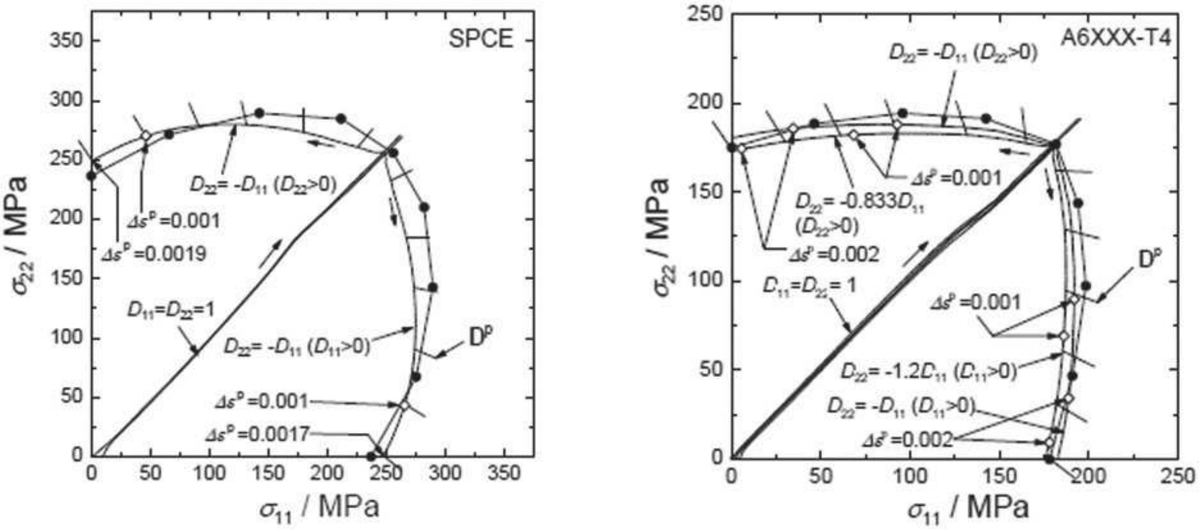
A.3 Use of abrupt strain path change for detecting a yield vertex and subsequent yield surface

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. They prescribe a proportional strain path until the loading point of interest has been reached, and prescribe an abrupt strain path that will cause the stress point to move quickly along the yield surface. This determination can be done 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

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)

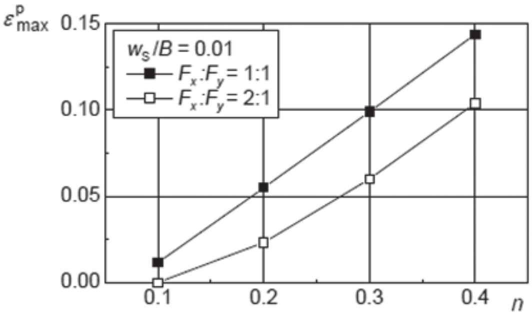
Factors affecting the maximum equivalent plastic strain applicable to the gauge area of the test piece

B.1 General

For the cruciform test piece covered by this International Standard, 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, $\varepsilon^{\mathrm{p}}_{\mathrm{max}}$, applicable to the gauge area can be estimated using the Considère condition for maximum load in a strip in tension.[11] $\varepsilon^{\mathrm{p}}_{\mathrm{max}}$ 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 $\varepsilon^{\mathrm{p}}_{\mathrm{max}}$.

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

Figure B.1 shows the effect of n-value on $\varepsilon^{\mathrm{p}}_{\mathrm{max}}$ 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, $\varepsilon^{\mathrm{p}}_{\mathrm{max}}$ 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 $\varepsilon^{\mathrm{p}}_{\mathrm{max}}$ 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.



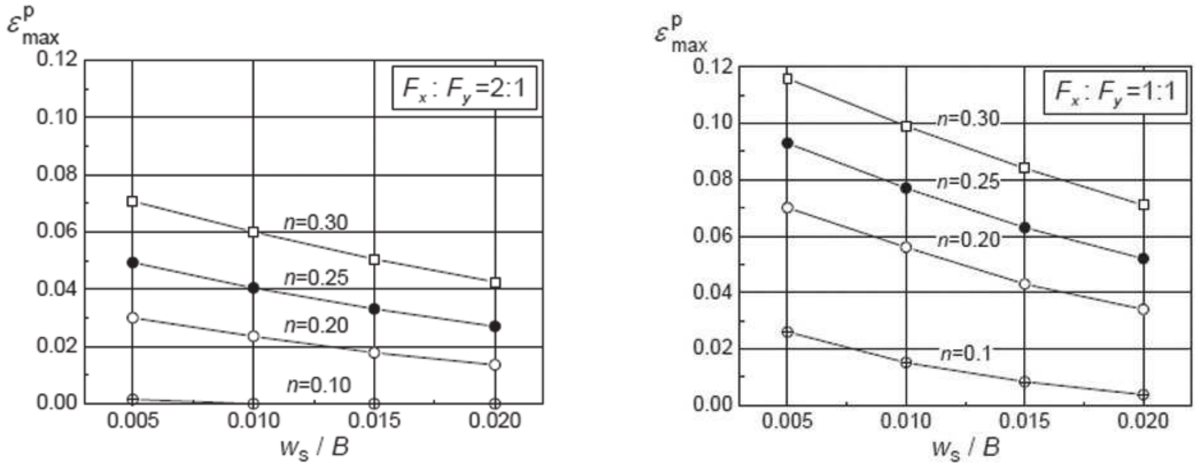
Key

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)
$\varepsilon^{\mathrm{p}}_{\mathrm{max}}$	maximum equivalent plastic strain applicable to the gauge area

Figure B.1 — Effects of *n*-value on the maximum equivalent plastic strain applicable to the gauge area of a cruciform test piece. Material model: Von Mises yield criterion

B.3 Effect of slit width

Figure B.2 shows the effects of the slit width on $\varepsilon^{\mathrm{p}}_{\mathrm{max}}$ 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 $\varepsilon^{\mathrm{p}}_{\mathrm{max}}$. 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.



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)
$\varepsilon^{\mathrm{p}}_{\mathrm{max}}$	maximum equivalent plastic strain applicable to the gauge area

Figure B.2 — Effects of the slit width on the maximum equivalent plastic strain applicable to the gauge area of a cruciform test piece. Material model: Von Mises yield criterion[2]

Annex C
(informative)

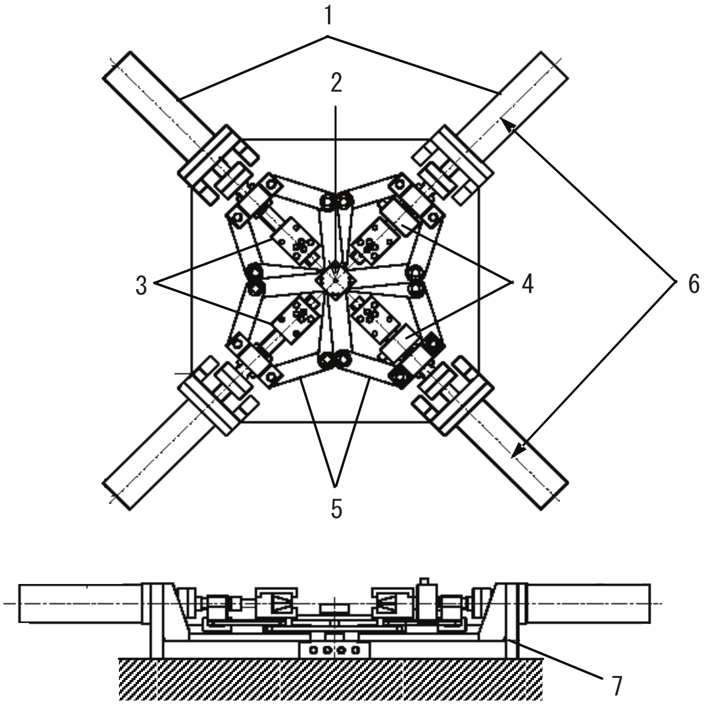
Biaxial tensile testing machine

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.



Key

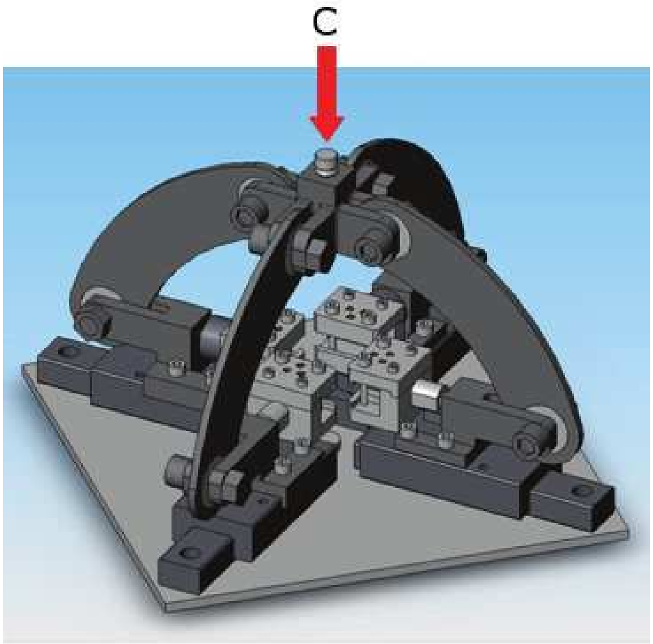
1	actuator
2	centre of the testing machine
3	grip
4	load cell
5	link mechanism
6	loading axis
7	frame

Figure C.1 — Example of servo-controlled biaxial tensile testing machine[12][13]

C.3 Link type biaxial tensile testing machine

C.3.1 Link type biaxial tensile testing mechanism with adjustable displacement ratio

Figure C.2 shows the link type biaxial tensile testing mechanism.[15] A user can easily apply biaxial tensile forces to a cruciform test piece by simply installing the mechanism into an existing uniaxial tensile testing machine and applying a uniaxial compressive force “C” to the top of the machine. It is capable of keeping the displacement-rate ratio between the orthogonal grips constant.



Key

C compressive force

Figure C.2 — Link type biaxial tensile testing machine[15]

C.3.2 Link type biaxial tensile testing machine with adjustable force ratio

Figure C.3 shows a high-force biaxial testing machine with a centralized application of force through a lifting gear and adjustable force ratio.[16] The adjustment of the tensile force in each direction is carried out with variable angles. The tensile force is measured with load cells in each direction. With the link type testing machine, it is possible to set different force ratios without expensive control.

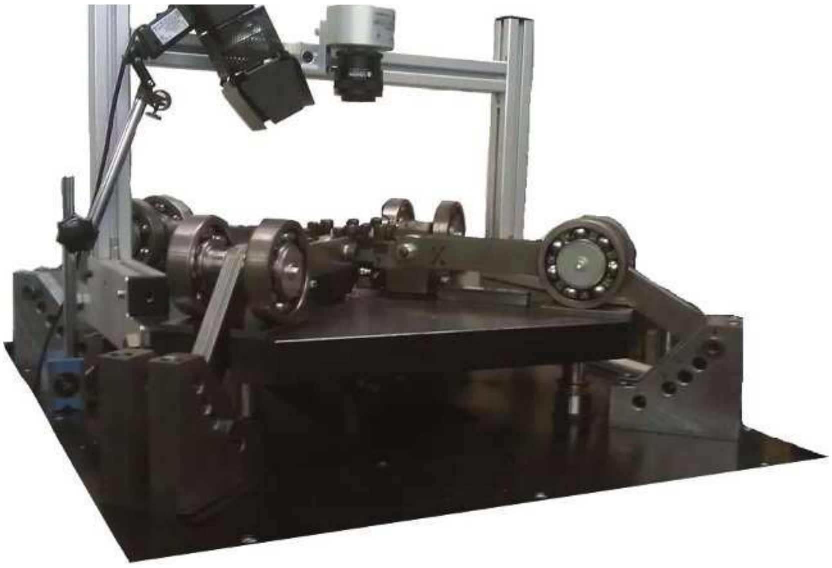
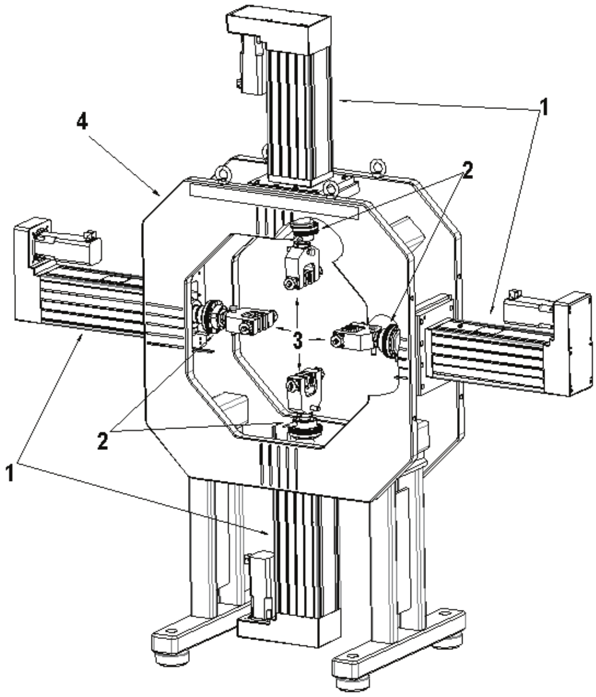


Figure C.3 — Link type biaxial tensile testing machine[16]

C.4 Biaxial testing machine with electro-mechanically driven spindle drives

Figure C.4 shows the structural example of a servo-controlled biaxial tensile testing machine with a vertical frame (horizontal frame is also possible).[17][18] There are four orthogonally arranged electro-mechanically driven spindle drives. Each of the four actuators is individually controlled. Each actuator includes sensors for position, force, and strain. Position stability of the test piece centre is video-optically controlled. Because of independent and combined control of each actuator, any variety of stress ratio and strain ratio can be applied.



Key

1 electromechanical actuator

2 load cell

3 grips

4 load frame

Figure C.4 — Biaxial tensile testing machine with electro-mechanically driven spindle drives and vertical frame[17][18]

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