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Metallic materials — Sheet and strip — Determination of biaxial stress-strain curve by means of bulge test with optical measuring systems

Matériaux métalliques — Tôles et bandes — Détermination de la courbe contrainte-déformation biaxiale au moyen de l'essai de gonflement hydraulique avec systèmes de mesure optiques

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Foreword

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

Metallic materials — Sheet and strip — Determination of biaxial stress-strain curve by means of bulge test with optical measuring systems

1 Scope

This International Standard specifies a method for determination of the biaxial stress-strain curve of metallic sheets having a thickness below 3 mm in pure stretch forming without significant friction influence. In comparison with tensile test results, higher strain values can be achieved.

NOTE In this document, the term "biaxial stress-strain curve" is used for simplification. In principle, in the test the "biaxial true stress-true strain curve" is determined.

2 Symbols and abbreviated terms

The symbols and designations used are given in Table 1.

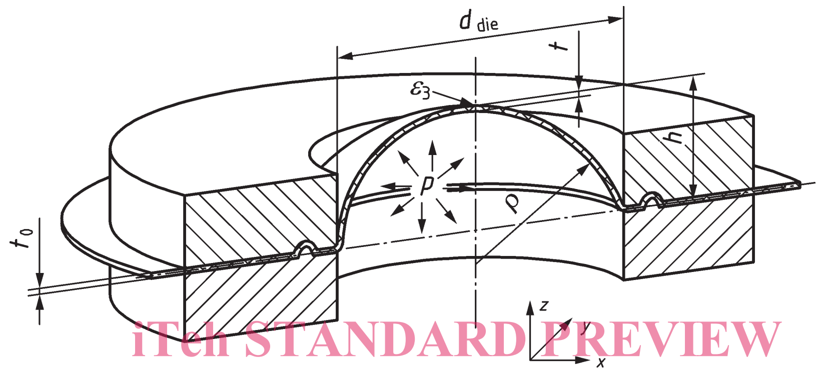
Table 1

Symbol	Designation	Unit
d_{die}	Diameter of the die (inner)	mm
d_{BH}	Diameter of the blank holder (inner)	mm
R_1	Radius of the die (inner)	mm
h	Height of the drawn blank (outer surface)	mm
t_0	Initial thickness of the sheet (blank)	mm
t	Actual thickness of the sheet	mm
p	Pressure in the chamber	MPa
rms	Standard deviation (root mean square)	-
ρ	Radius of curvature	mm
r_1	Surface radius for determining curvature	mm
r_2	Surface radius for determining strain	mm
r_{1_100}	Surface radius to determine curvature with a die diameter of 100 mm	mm
a_i , b_i	Coefficients for response surface	-
σ_B	Biaxial stress	MPa
e	Engineering strain	-
ε_1	Major true strain	-
ε_2	Minor true strain	-
ε_3	True thickness strain	-
ε_E	Equivalent true strain	-
l_s	Coordinate and length of a section	mm
dz	Displacement in the z-direction	mm
dz_{mv}	Displacement after movement correction	mm

3 Principle

A circular blank is completely clamped at the edge in a tool between die and blank holder. A bulge is formed by pressing a fluid against the blank until final fracture occurs (Figure 1). During the test, the pressure of the fluid is measured and the evolution of the deformation of the blank is recorded by an optical measuring system.[1],[2],[3] Based on the recorded deformation of the blank, the following quantities near the centre of the blank are determined: the local curvature, the true strains at the surface, and, by assuming incompressible deformation of the material, the actual thickness of the blank. Furthermore, assuming the stress state of a thin-walled spherical pressure vessel at the centre of the blank, the true stress is calculated from the fluid pressure, the thickness and the curvature radius.

NOTE In addition to the bulge test procedures with optical measurement systems introduced in Reference [1] and described in the following, there are also laser systems[4],[5],[6] or tactile systems[7],[8],[9] valid for bulge test investigation, which are not covered in this International Standard.



Key

h height of the drawn blank (outer surface)

p pressure in the chamber

ε_3 true thickness strain (at the apex of the dome)

d_{die} diameter of the die (inner)

ρ radius of curvature

t_0 initial thickness of the sheet (blank)

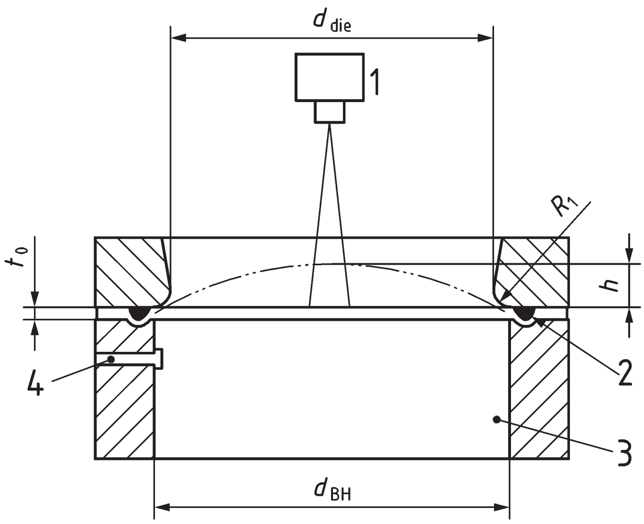
t actual thickness of the sheet

Figure 1 — Principle of the bulge test

The coordinate origin shall be in the centre of the blank holder. The XY-plane should be parallel to the surface of the blank holder (parallel to the clamped metal sheet before forming). Herein, the *x*-direction corresponds to the rolling direction. The *z*-direction shall be normal to the clamped metal sheet before forming, with the positive direction towards the optical sensor.

4 Test equipment

4.1 The bulge test shall be carried out on a machine equipped with a die, a blank holder and a fluid chamber. The proposed equipment is illustrated in Figure 2.



Key

1 deformation measurement system

2 lock bead

3 chamber with fluid

4 pressure measurement system

Figure 2 — Proposal of a testing equipment (principle drawing)

4.2 The lay out of the test equipment shall be such that it is possible to continuously measure the outside surface of the test piece continuously during the test, i.e. to be able to determine the deformation of the geometry by recording the evolution of X, Y, Z coordinates of a grid of points on the bulging blank surface, in order to calculate the shape and the true strains in the central area of interest until failure occurs.

4.3 During the test, the system shall be able to measure optically (without contact) the X, Y, Z coordinates of a grid of points on the bulging surface of the specimen. Out of these coordinates, the true strains ε_1 and ε_2 for each point of the selected area, the thickness strain ε_3 and the curvature radius ρ for the apex of the dome are calculated.

4.4 The system should be equipped with a chamber fluid pressure measurement system. An indirect measurement system is also possible. Starting from 20 % of the maximum measured pressure value, the precision should be 1 % of the actual measured value.

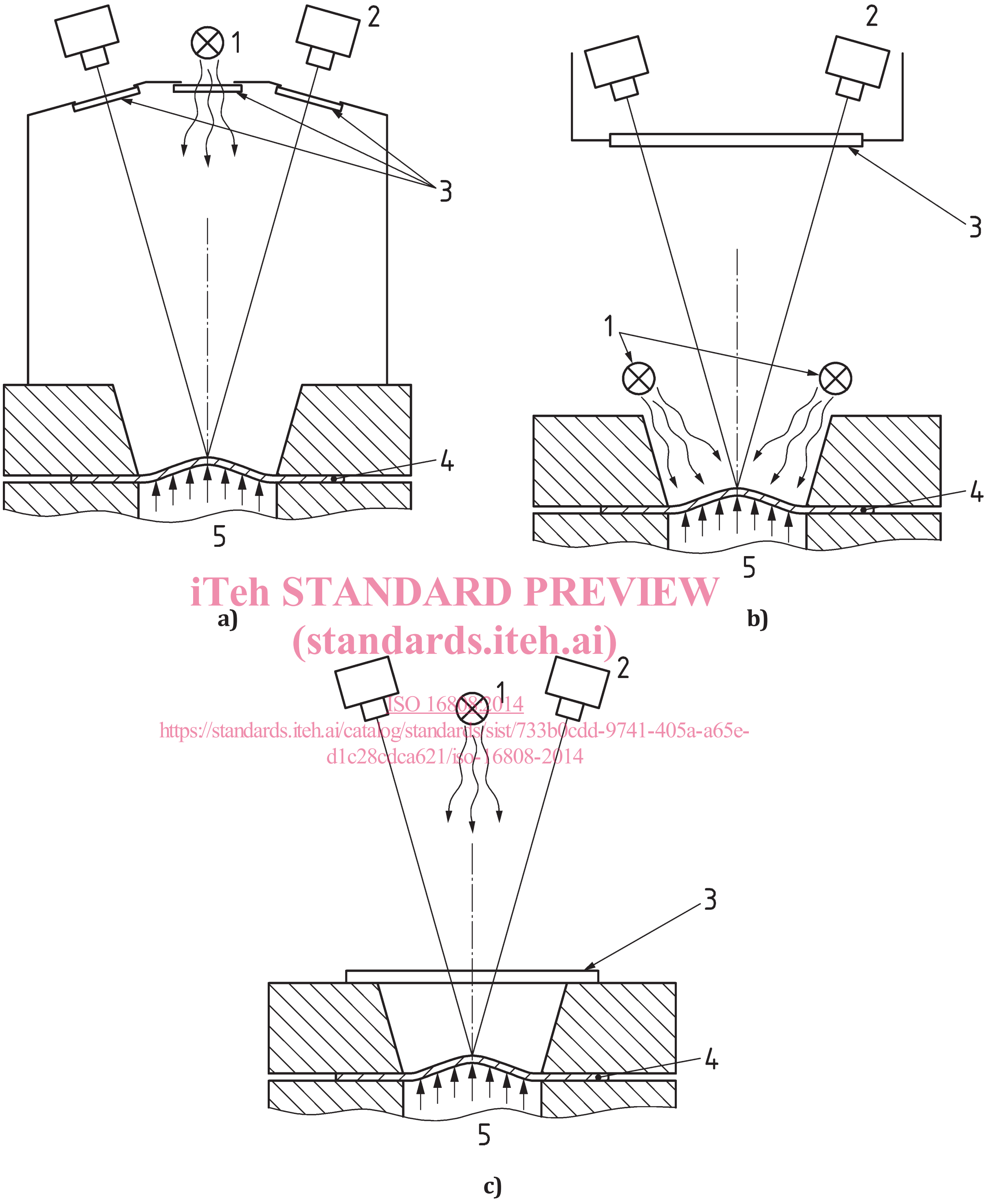
4.5 The die, the blank holder and the fluid chamber shall be sufficiently rigid to minimize deformation during testing. The blank-holder force shall be high enough to keep the blank holder closed. Any movement of the test piece between the blank holder and die should be prevented. Typically during the test, the bulge pressure is acting on parts of the blank holder reducing the effective blank-holder force. This shall be taken in consideration when defining the necessary blank-holder force.

4.6 The fluid shall be in contact with the blank surface (without any air bubbles) to prevent energy storage during the test through compressed air bubbles which would lead to higher energy release and greater oil splashing at failure. No fluid shall be lost through the blank holder, die and sheet or elsewhere during the test until failure occurs.

4.7 A lock bead (or comparable geometry in the circular surface), designed to suppress any material flow, is recommended. The lock bead shall not initiate cracks in the material. The lock bead shall be located between blank holder and die. A location close to the die radius is recommended. The lock bead geometry should avoid a curvature and a wrinkling of the blank when closing the tool and prevent the sliding of the blank during the test.

4.8 It is recommended to place glass plates in front of the lenses and the illumination in order to protect the optical measuring system from oil splashing due to blank failure at the end of the test.[7],[12] The plates can be fixed on the blank holder (thick glass) or near the camera lenses and illumination (thinner glass); see Figure 3. The inserted protection shall not to disturb the optical measurement quality (see Clause 5). After each test, the glass plates shall be well cleaned without damaging or scratching them and precisely repositioned to not alter calibration. Typically, a calibration of the optical system including the protection increases the measurement quality.

4.9 The smallest die diameter recommended should have a ratio of die diameter to initial thickness $d_{die} / t_0 \geq 33$ (see Figure 2). The radius of the die should not lead to cracks in the blank during the test. A recommendation is $(5 \times t_0)$ to $(15 \times t_0)$ (maximum 15 mm).



Key

1 lamp
2 cameras
3 glass plates
4 test piece
5 fluid

Figure 3 — Examples for possible positions of oil shielding plates and lamps

5 Optical measurement system

For the determination of the radius of curvature ρ, and the true strains ε_1 and ε_2, an optical-deformation field measurement system with the following characteristics is recommended:

— Optical sensor based on two or more cameras;

— Measurement area, whereas $d_{\text{measurement area}} \geq 1/2\ d_{\text{die}}$;

The used measurement area should be larger than a concentric diameter of half the diameter of the blank holder. This area should be observable during the entire forming process for all heights of the drawn blank.

— Local resolution (grid distance between the independent measurement points): The distance g_{max} between two adjacent points on the unformed blank should follow the requirement:

$$g_{\text{max}} \leq \frac{d_{\text{die}}}{50}$$

— The determination of the curvature requires an accuracy of the z-coordinates in an area with a diameter of $1/2\ d_{\text{die}}$ concentric to the blank holder of

$$rms(dz)_{\text{n}} = \frac{rms(dz) \cdot 100\ \text{mm}}{d_{\text{die}}} \leq 0{,}015\ \text{mm}$$

NOTE The accuracy of the shape measurement can be checked with a test of the optical measurement system (see Annex B).

Accuracy for strain measurement: $rms\ (\varepsilon_1) = 0{,}003$ $rms\ (\varepsilon_2) = 0{,}003$

For each real strain value for the mentioned $rms\ (\varepsilon)$ above, the acceptable measurement values are:

$\varepsilon_{\text{real}} = 0$ acceptable measurement range: $-0{,}003 \ldots 0{,}003$

$\varepsilon_{\text{real}} = 0{,}5$ acceptable measurement range: $0{,}497 \ldots 0{,}503$

— Missing measurement points: In order to avoid unbalanced curvature approximations, only the absence of less than 5 % of the measurement points in the concentric area with a diameter = $1/2\ d_{\text{die}}$ is acceptable (without interpolation). If adjacent points are missing, the inscribed circle of this area shall not be larger than 2 points.

6 Test piece

6.1 General

The test piece shall be flat and of such shape that the blank is clamped and material flow is stopped. The use of lock beads is recommended. The edge of the blank shall be outside the lock bead.

The preparation of the blank does not influence the results as long as the surface of the test piece was not damaged (scratches, polishing). The dimension of the outer edges can be circular (preferred) or angular.

6.2 Application of grid

6.2.1 Type of grid

For optical full-field measurement devices, the grid shall fulfil two objectives:

a) the curvature radius determination of the specimens' surface;

b) the strain calculation of the material deformation.

6.2.2 Grid application

Deterministic grids (e.g. squares, circles, dots) should have a strong contrast and have to be applied without any notch effect and/or change in microstructure. Some common application techniques are:

— electrochemical etching, photochemical etching, offset printing and grid transfer,

— stochastic (speckle) patterns which can be applied by spraying paint on the surface of test piece surfaces. Paint adherence to the surface after deformation should be checked. It is possible first to spray a thin, matt, white base layer to reduce reflections from the test piece surfaces, then to spray a cloud of randomly distributed black spots (e.g. black spray paint or graphite). The spray shall be both elastic and tough enough not to crack or peel off during deformation. The random distribution of the fine sprayed spots allows the determination of each point of the virtual grid on the specimen. The pattern should have sufficient black/white density and appropriate size features in each point position search area as required by the optical system used.

7 Procedure

7.1 The test shall be carried out at ambient temperature of (23 ± 5) °C.

7.2 Determine the initial thickness of the test piece to the nearest 0,01 mm.

7.3 Clamp the test piece between blank holder and die. Avoid air bubbles between test piece and fluid to prevent formation of compressed air during testing, leading to stronger oil splashing at failure.

7.4 A constant strain rate of 0,05 s^{-1} is recommended. If a constant strain rate is not possible, a constant forming velocity of the punch or fluid should be guaranteed. In order to avoid big influences in the biaxial stress-strain curve of temperature or strain rate sensitive materials, the bulge test should be conducted in (2 to 4) min. This time frame guarantees slow and acceptable strain rates and a cost-effective testing time.

The plot of the strain rate versus time is recommended.

7.5 Measure the fluid pressure during the test.

7.6 Measure the X, Y, Z coordinates of the grid on the test piece surface during the test.

7.7 The fluid pressure data and forming data shall be measured and saved at the same time scale. A minimum of 100 values is recommended. In order to represent the whole strain and pressure development, at least 100 images of the bulge testing are recommended.

7.8 The failure of the test piece shall be considered as obtained when a through crack, i.e. a crack which goes through the thickness of the test piece, has occurred. The failure is detected by decreasing fluid pressure; this defines the end of the test.

7.9 A sufficient number of test pieces should be prepared in order to achieve at least three valid tests.

8 Evaluation methods for the determination of the curvature and strains at the pole

For the following explanation of the calculation of the curvature and strains, a spherically shaped surface near the pole is assumed (best-fit sphere). On the last image before failure, as defined in 7.8, the area of the dome with the highest deformation is selected and defined as the position where to determine the true stress and the true thickness strain ε_3. To obtain a stable radius of curvature of the dome, a best-fit sphere can be calculated based on a selected area of points. For this selection, a radius r_1 is defined around the apex of the dome in the last image before bursting and the fit is performed for all forming stages with the same selection of points (Figure 4).

A certain number of the first forming stages (images) are rejected, since the specimen is still too flat for a reliable determination of the best-fit sphere, since the bending radius is very high and the fit is not stable. For robust values of the true strain and thinning in the apex, the average value of a number of selected points is taken. Therefore, a second area is defined by a radius r_2 in a similar manner (see Figure 4).

Based on this procedure, for every forming stage (image) the radius of curvature, the average thickness strains, as well as the corresponding thickness and stress values at the dome apex are calculated. This evaluation can be carried out for different r_1 and r_2 values (see Figure 4).

For a good convergence and robust values, the recommended range of r_1 and r_2 is defined:

$$r_1 = (0{,}125 \pm 0{,}025) \times d_{\text{die}} \quad (1)$$

$$r_2 = (0{,}05 \pm 0{,}01) \times d_{\text{die}} \quad (2)$$

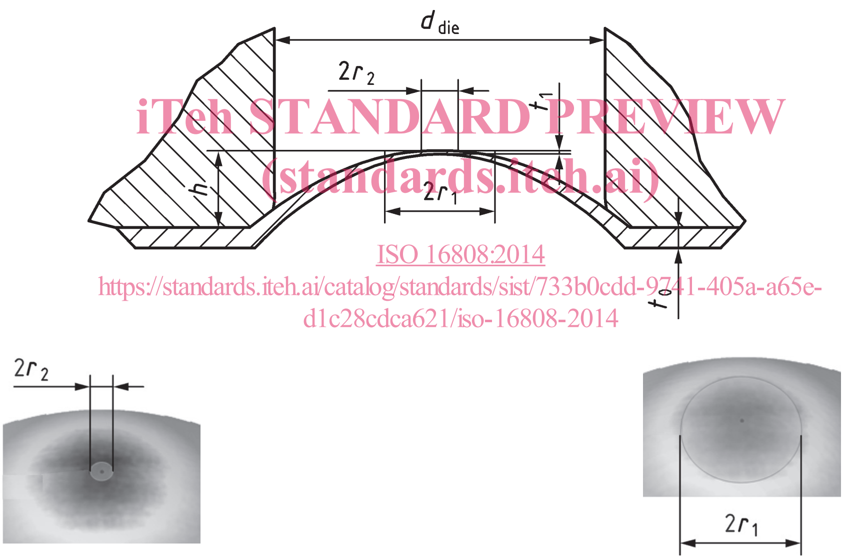


Figure 4 — Choice of r_1 and r_2 for calculation of true stress and true strain for each forming stage

An alternative proposal for the calculation of the curvature and strains is given in the Annex C.

9 Calculation of biaxial stress-strain curves

For the calculation of the biaxial stress-strain curves, a simple membrane stress state of a thin-walled spherical pressure vessel is assumed at the centre of the blank. This implies the following simplifications:

a) equi-biaxial stress state:

$$\sigma_1 = \sigma_2 = \sigma_B \quad (3)$$

b) representation of the curvature by the mean curvature radius:

