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Metallic materials — Sheet and strip — Determination of forming-limit curves —

Part 2: Determination of forming-limit curves in the laboratory

Matériaux métalliques — Tôles et bandes — Détermination des courbes limites de formage —

Partie 2: Détermination des courbes limites de formage en laboratoire

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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.

ISO 12004-2 was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 2, *Ductility testing*.

This first edition of ISO 12004-2, together with ISO 12004-1, cancels and replaces ISO 12004:1997 which has been technically revised.

ISO 12004 consists of the following parts, under the general title *Metallic materials — Sheet and strip — Determination of forming-limit curves*:

— *Part 1: Measurement and application of forming-limit diagrams in the press shop*

— *Part 2: Determination of forming-limit curves in the laboratory*

Introduction

A forming-limit diagram (FLD) is a diagram containing major/minor strain points.

An FLD can distinguish between safe points and necked or failed points. The transition from safe to failed points is defined by the forming-limit curve (FLC).

To determine the forming limit of materials, two different methods are possible.

1) Strain analysis on failed press shop components to determine component and process dependent FLCs:

   In the press shop, the strain paths followed to reach these points are generally not known. Such an FLC depends on the material, the component and the chosen forming conditions. This method is described in ISO 12004-1.

2) Determination of FLCs under well-defined laboratory conditions:

   For evaluating formability, one unique FLC for each material in several strain states is necessary. The determination of the FLC has to be specific and it is necessary to use different linear strain paths. This method should be used for material characterization as described in ISO 12004-2.

For this part of ISO 12004 (concerning determination of forming-limit curves in laboratory), the following conditions are also valid.

— Forming-limit curves (FLCs) are determined for specific materials to define the extent to which they can be deformed by drawing, stretching or any combination of drawing and stretching. This capability is limited by the occurrence of fracture, localized necking. Many methods exist to determine the forming limit of a material; however, it should be noted that results obtained using different methods cannot be used for comparison purposes.

— The FLC characterizes the deformation limit of a material in the condition after a defined thermo-mechanical treatment and in the analysed thickness. For a judgement of formability, the additional knowledge of mechanical properties and the material's history prior to the FLC-test are important.

To compare the formability of different materials, it is important not only to judge the FLC but also the following parameters:

a) mechanical properties at least in the main direction;

b) percentage plastic extension at maximum force, according to ISO 6892-1;

c) r-value with given deformation range, according to ISO 10113;

d) n-value with given deformation range, according to ISO 10275.

Metallic materials — Sheet and strip — Determination of forming-limit curves —

Part 2:
Determination of forming-limit curves in the laboratory

1 Scope

This part of ISO 12004 specifies the testing conditions to be used when constructing a forming-limit curve (FLC) at ambient temperature and using linear strain paths. The material considered is flat, metallic and of thickness between 0,3 mm and 4 mm.

NOTE The limitation in thickness of up to 4 mm is proposed, giving a maximum allowable thickness to the punch diameter ratio.

For steel sheet, a maximum thickness of 2,5 mm is recommended.

2 Symbols and abbreviated terms

For the purposes of this document, the symbols and terms given in Table 1 apply.

Table 1 — Symbols and abbreviated terms

Symbol	English	French	German	Unit
e	Engineering strain	Déformation conventionnelle	Technische Dehnung	%
ε	True strain (logarithmic strain)	Déformation vraie (déformation logarithmique)	Wahre Dehnung (Umformgrad, Formänderung)	—
ε_1	Major true strain	Déformation majeure vraie	Grössere Formänderung	—
ε_2	Minor true strain	Déformation mineure vraie	Kleinere Formänderung	—
ε_3	True thickness strain	Déformation vraie en épaisseur	Dickenformänderung	—
σ	Standard deviation	Ecart-type	Standardabweichung	—
D	Punch diameter	Diamètre du poinçon	Stempeldurchmesser	mm
D_{bh}	Carrier blank hole diameter	Diamètre du trou du contre-flan	Lochdurchmesser des Trägerblechs	mm
X(0), X(1) X(m) ....X(n)	X-position	Position en X	X-Position	mm
$f(x) = ax^2 + bx + c$	Best-fit parabola	Parabole de meilleur fit	Best-Fit-Parabel	—
$f(x) = 1/(ax^2 + bx + c)$	Best-fit inverse parabola	Parabole inverse de meilleur fit	Inverse Best-Fit-Parabel	—

Table 1 (*continued*)

Symbol	English	French	German	Unit
S(0), S(1)...S(5)	Section	Section	Schnitt	—
n	Number of X-positions	Nombre de points en X	Nummer der X-Positionen	—
m	Section number of the failure position	Numéro de la section correspondant à la rupture	Nummer des Schnittes zum Riss	—
w	Width of the fit window	Largeur de la fenêtre de fit	Breite des Fit-Fensters	mm
t_0	Initial sheet thickness	Épaisseur initiale de la tôle	Ausgangsblechdicke	mm
r	Plastic strain ratio	Coefficient d'anisotropie plastique	Senkrechte Anisotropie	—

Table 2 gives a comparison of the symbols used in different countries.

Table 2 — Comparison of symbols used in different countries

English	French	German	German symbol	Anglo-American symbol	Format	Unit
Engineering strain	Déformation conventionelle	Technische Dehnung	ε	e	—	%
True strain (logarithmic strain)	Déformation vraie (Déformation logarithmique)	Wahre Dehnung (Umformgrad, Formänderung)	φ	ε	Decimal	—
$\varepsilon = \ln(1 + e)$	$\varepsilon = \ln(1 + e)$	$\varphi = \ln(1 + \varepsilon)$	—	—	—	—

The symbol used for true strain in Anglo-American-speaking countries is "ε"; in German-speaking countries, the symbol "φ" is used for true strain.

In German-speaking countries, the symbol "ε" is used to define engineering strains.

The notation for true strain used in this text is "ε" following the Anglo-American definition.

3 Principle

The FLC is intended to represent the almost intrinsic limit of a material in deformation assuming a proportional strain path. To determine the FLC accurately, it is necessary to have a nearly frictionless state in the zone of evaluation.

A deterministic grid of precise dimensions or a stochastic pattern is applied to the flat and undeformed surface of a blank. This blank is then deformed using either the Nakajima or the Marciniak procedure until failure, at which point the test is stopped.

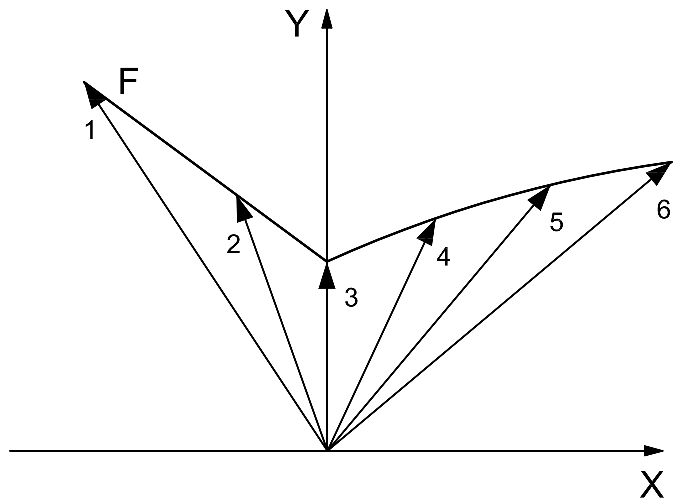
The measurement should be performed using a "position-dependent" method (see 5.2).

NOTE A "time-dependent" method is under development.

The deformation (strain) across the deformed test piece is determined and the measured strains are processed in such way that the necked or failed area is eliminated from the results. The maximum strain that can be imposed on the material without failing is then determined through interpolation. This maximum of the interpolated curve is defined as the forming limit.

The forming limits are determined for several strain paths (different ratios between ε_1 and ε_2). The determined strain paths range from uniaxial tension to biaxial tension (stretch drawing). The collection of the individual forming limits in different strain states is plotted as the forming-limit curve. The curve is expressed as a function of the two true strains ε_1 and ε_2 on the sheet surface and plotted in a diagram, the forming-limit diagram. The minor true strains ε_2 are plotted on the X-axis and the major principal true strains ε_1 on the Y-axis (see Figure 1).

Standard conversion formulae permit the calculation of major (ε_1) and minor true strains (ε_2). In the following, the word strain implies the true strain, which is also called logarithmic strain.



Key

X minor true strain, ε_2

Y major true strain, ε_1

F FLC

1 uniaxial tension, $\varepsilon_2 = -[r/(r+1)]\varepsilon_1$

2 intermediate tensile strain

3 plane strain

4 intermediate stretching strain state

5 intermediate stretching strain state

6 equi-biaxial tension (= stretching strain state) $\varepsilon_2 = \varepsilon_1$

Figure 1 — Illustration of six different strain paths

4 Test pieces and equipment

4.1 Test pieces

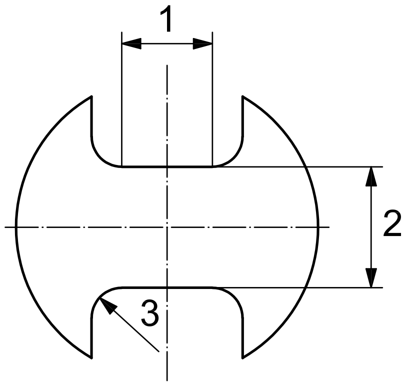
4.1.1 Thickness of test pieces

This procedure is intended for flat, metallic sheets with thickness between 0,3 mm and 4 mm.

4.1.2 Test piece geometry

The following geometries are recommended.

Waisted blanks with a central, parallel shaft longer than 25 % of the punch diameter (for a 100 mm punch: preferable shaft length 25 mm to 50 mm; fillet radius 20 mm to 30 mm) (see Figure 2).



Key

1 shaft length

2 remaining blank width

3 fillet radius $= R =$ 20 mm to 30 mm

Figure 2 — Waisted test piece geometry with parallel shaft length (dog bone shape)

For $\varepsilon_2 > 0$, blanks with semi-circular cut-outs with different radii are possible.

For steel (mainly soft steel grades), rectangular strips with different widths are sufficient if test pieces do not fail at the die radius, otherwise use the test piece geometry as described above.

With outer circular shape of the blanks, a more uniform distribution of the experimental forming-limit points is attainable than when rectangular strips are used.

4.1.3 Test piece preparation in test area

Milling or spark-erosion or other methods that do not cause cracks, work hardening or microstructure changes can be used ensuring that fracture never initiates from the edges of test pieces.

4.1.4 Number of different test piece geometries

At least five geometries for the description of a complete FLC are necessary. (A uniform allocation of the FLC from uniaxial to equi-biaxial tension is recommended.)

If the description of a complete FLC is not necessary, then a lower number of geometries is allowed but this shall be mentioned in the test report.

4.1.5 Number of tests for each geometry

As many test pieces as are necessary to achieve at least three valid samples.

4.2 Application of grid

4.2.1 Type of grid

The recommended grid size is approximately one times the material thickness (grid size is related to the material thickness due to necking width), a maximum grid size of 2,5 times the material thickness is allowed and the largest grid dimension allowed for a 100 mm punch is 2,54 mm (0,1 in). In general, grid sizes of 1 mm or 2 mm are used. Small grid sizes are often limited because of their lack of accuracy (if the undeformed grid is not measured before beginning of test).

For a stochastic pattern, the “virtual” grid size should correspond to the recommended grid size. A smaller “virtual” grid size may be used.

4.2.2 Grid application

Deterministic grids (e.g. squares, circles, dots) should have a rich contrast and have to be applied without any notch effect and/or change in microstructure. Some common application techniques are electrochemical, photochemical, offset print and grid transfer.

Stochastic (speckle) patterns can be applied by spraying paint onto the test piece surfaces. Paint adherence to the surface should be checked after deformation. It is possible to spray a thin, matt, white base layer to reduce back reflections from the test piece surfaces. Following this, a cloud of randomly distributed black spots can be sprayed (e.g. black spray paint or graphite).

4.2.3 Accuracy of the undeformed grid

To achieve the required system accuracy of 2 %, the initial grid accuracy should be better than 1 % based on one times the standard deviation (1σ). This is only required for systems where the undeformed condition is not considered for evaluation.

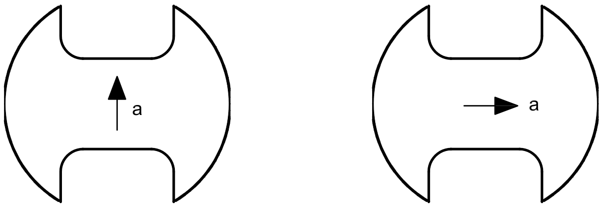
4.3 Test equipment

4.3.1 General

The following parameters are valid for both Nakajima and Marciniak tests.

Punch velocity:	(1,5 ± 0,5) mm/s
Prevention of material’s draw-in:	Draw-in shall be prevented as much as possible to ensure nearly linear strain paths. Possible measures are: using draw beads, suitable blank holder forces, serrated or knurled tools (providing that the two last methods do not involve risk of strain localization or fracture).
Blank holder force, in kN:	Draw-in shall be prevented as much as possible.
Test temperature:	(23 ± 5) °C
Test direction:	For a given FLC, the main direction of all test pieces shall be the direction of lowest limit strain e_1 or e_2 and same relative to the rolling direction, see Figure 3.
Aluminium:	Longitudinal (shaft parallel to rolling direction).
Steel:	Transverse (shaft perpendicular to rolling direction); exceptional cases are allowed, but have to be reported.

In the case that the preferred failure direction is not known, it should be checked using a biaxial strain test or any other suitable method



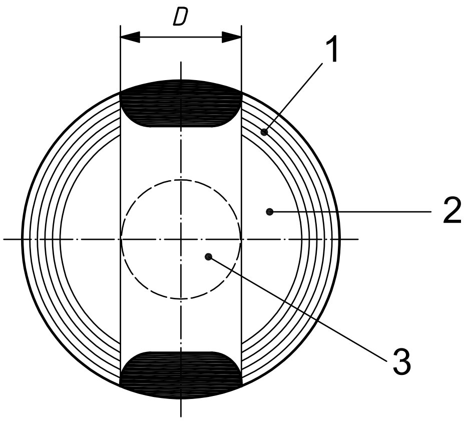
a Rolling direction (RD).

Figure 3 — Shaft orientation with respect to the rolling direction (RD)

Surface roughness of punch: The contacting area of the punch surface should be polished.

Die material and hardness: Hardened steel.

Blank holder shape: Full circular blank holder, see Figure 4.



Key

D cut-out width, equal to punch diameter

1 serrated blank holder with cut-out

2 blank

3 punch

NOTE To come closer to ideal linear strain paths and to reach a more uniform distribution of true strain values, a circular blank holder with a cut-out might be useful (recommended width of cut-out = punch diameter).

Figure 4 — Blank holder with cut-out

Test stop criterion: Crack occurrence.

Crack detection: Visual or force drop.

4.3.2 Strain measurement

Total system accuracy:

The total accuracy of the measurement system should be better than 2 % based on one times the standard deviation (1σ) (accuracy depends on grid accuracy/resolution, camera resolution, measuring field, calculation algorithm...).

Accuracy of the undeformed grid:

Initial grid accuracy should be better than 1 % based on one times the standard deviation (1 σ) (only required for systems where the undeformed condition is not used in evaluation).

Measurement instrument:

Any convenient grid-measuring device is accepted; the uncertainty of the measurement device shall be less than 1 % of the measured length. Cameras and software allowing total measuring accuracy better than 2 % based on one times the standard deviation (1 σ) are recommended.

Strain measurement:

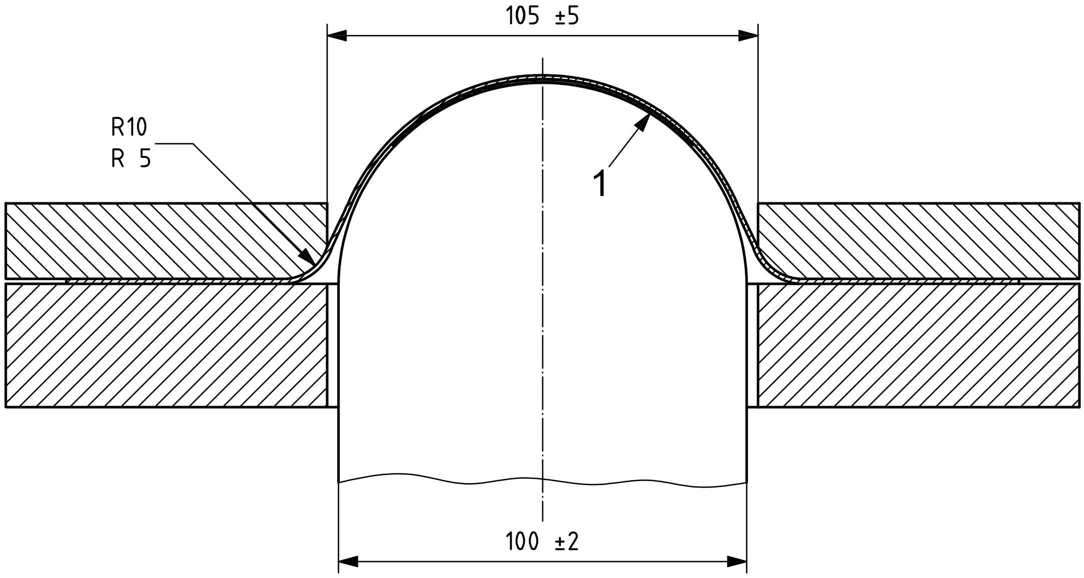
Strain measurement can be performed either by measurement of only the final grid dimension, where the precision of the initial grid is known ($<$ 1 %), or by comparison of the final grid dimension relative to the initial one, or using an incremental method, which refers to the initial grid size for the strain calculation.

4.3.3 Nakajima test

4.3.3.1 General

The Nakajima forming method uses a hemispherical punch, see Figure 5.

Dimensions in millimetres



Key

1 lubrication layer

Figure 5 — Illustration of the cross section of the tool used for Nakajima testing

4.3.3.2 Tool

Punch diameter: (100 ± 2) mm

Die diameter: Preferably 105 mm and ⩾ punch diameter plus 2,5 times the material thickness

Die radius: Preferably 8 mm with a minimum of either 5 mm or 2 times the material thickness, whichever is the greater value.

4.3.3.3 Test conditions

Type of lubricant:

The tribo-system should be adjusted so that fracture occurs within a distance less than 15 % of the punch diameter away from the apex of the dome. The test is only valid in this case. With an optimal tribo-system, it is possible to induce fracturing very near to the apex of the dome. In this case, the problem of pronounced double necking symmetrical to the apex of the dome (where afterwards one of the two necked zones is fractured) is drastically reduced. The strong double peaks in the strain profile cross section are reduced. This makes automatic evaluation of ε_1 - ε_2 pairs more accurate. The tribo-system may not be changed during the measurement of one specific FLC.

Recommended lubricant systems are:

a) for low punch forces (thinner sheets or materials with relative low tensile strength, e.g. for Al-sheets < 2 mm):

1) oil or grease (e.g. lanolin);

2) circular blanks of PE or PTFE foil (e.g. 0,05 mm thick);

3) oil or grease.

b) for high punch forces (thicker sheets or materials with higher tensile strength):

1) simple:

as a) but with soft PVC instead of PTFE.

2) complex:

i) oil or grease (e.g. lanolin);

ii) circular blanks of PE or PTFE foil (0,05 mm to 0,1 mm thick);

iii) oil or grease;

iv) soft PVC sheet (3 mm thick);

v) oil or grease;

vi) circular blanks of PE or PTFE foil (0,05 mm to 0,1 mm thick);

vii) oil or grease.

Layers i and vii are optional.

With these two lubrication systems, most of the tests meet the condition of a fracture on the top of the dome. From previous testing experience on different material types, no general tribo-system (suitable for all materials and all thickness ranges) could be recommended. The most difficult conditions are encountered during the testing of high strength materials of large thickness. Alternative lubrication systems can be used based on personal practice and experience. In such cases, it is recommended that the lubrication systems be tested in advance during hemispherical punch stretching. The tribo-system providing the largest limiting dome height, and meeting the condition of a fracture on the top of the dome, is considered to be the most suitable.

The diameter of the foil blank should be smaller than the punch diameter to prevent the foil wrinkling.

4.3.4 Marciniak test

4.3.4.1 General

The Marciniak forming method uses a flat punch, see Figure 6.

Dimensions in millimetres

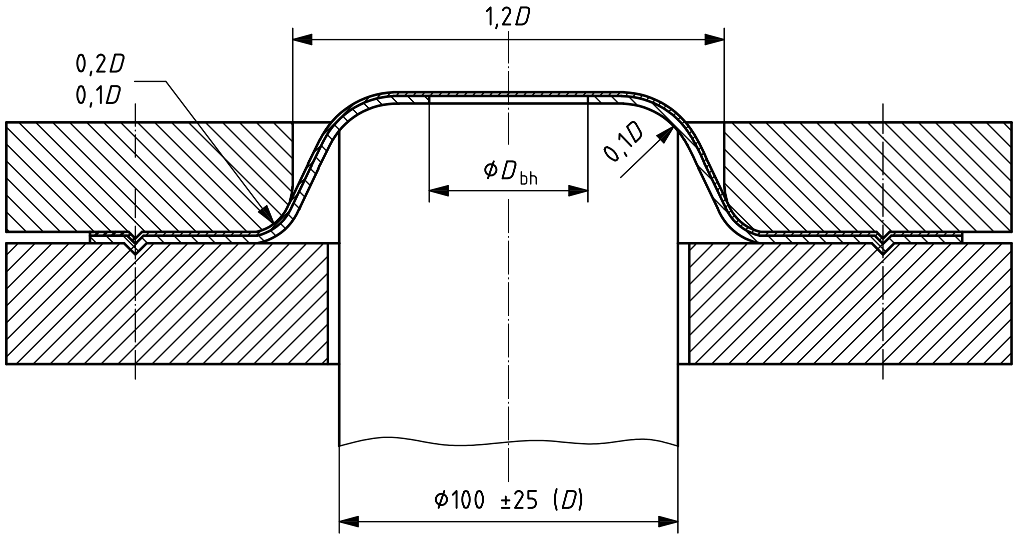


Figure 6 — Illustration of the cross section of the tool used for Marciniak testing

4.3.4.2 Tool

Punch diameter:	Flat punch of diameter (100 ± 25) mm
Punch nose radius:	Suggested 10 % of punch diameter
Die diameter:	Suggested 120 % of punch diameter
Die radius:	Between 10 % and 20 % of punch diameter

4.3.4.3 Carrier blanks

In order to prevent contact between the test piece and the plane surface of the punch, it is necessary to use carrier blanks. This ensures fracture occurs in the correct position and ensures a homogeneous strain distribution.

Carrier blanks should be cut out of a material at least as ductile as the material being tested. Rupture of the carrier blank should never occur before the fracture of the sheet material being studied.

The minimum thickness of the carrier blank shall be around 0,8 times the thickness of the blank tested; one or more carrier blanks can be used.

The carrier blank size should be equal to the tested specimen or to the size of the blank used for the biaxial strain path (facilitating the manufacture and storage of carrier blanks).

The carrier blank shall have a central hole of diameter D_{bh} (normally 32 mm to 34 mm) that will be centred relative to the punch. This hole shall have an edge quality sufficient to avoid premature cracking. The final diameter of the hole at the time of test piece rupture shall remain smaller than the diameter of the plane zone of the punch. If necessary, the carrier blank may be cut in two parts (perpendicular to strain direction).

It is useful to have a higher surface roughness of the carrier blank towards the specimen's surface (e.g. sand blasting) to enhance the frictional force between the carrier blank and the test piece.

4.3.4.4 Test conditions

Lubrication is not permitted between the carrier blank and specimen, but it is often necessary between the punch and the carrier blank.

Validity of test: The rupture shall start in the plane zone above the hole of the carrier blank.

4.3.5 Measuring instrument

Camera and software allowing total measuring accuracy better than 1 % based on one times the standard deviation (1σ).

5 Analysis of strain profile and measurement of ε_1 - ε_2 pairs

5.1 General introduction

The measurement using camera(s) can be done in various ways using different analysis methods (AM) by evaluation of cross-sectional data.

AM1 — Evaluation of the cracked sample (offline)

Analyse an image set just after the deformation but not directly on the forming machine.

AM2 — Evaluation of the cracked sample with grid calibrated from starting dimensions (offline)

Analyse an image set before and just after the deformation but not directly on the forming machine.

AM3 — Evaluation of the situation directly before the crack will happen (online)

With the camera(s) fixed directly on the forming machine, record the starting image and the image sequence during the last steps of deformation before failure. This is used for position-dependent measurement online. Define the cross-section positions perpendicular to the crack on the image with fracture and then transferring it back to the last image before the crack becomes visible, in order to get the cross section for sorting ε_1 - ε_2 values without crack opening.

These three cases use the concept of sorting ε_1 - ε_2 values from sections approximately perpendicular to the crack and are described in 5.2.

The evaluation of the time-dependent method has been carried out and may be added during the next revision of this part of ISO 12004.

5.2 Evaluation using cross sections (position-dependent measurement)

5.2.1 General

The basic concept of this method is the analysis of the measured strain distribution along predefined cross sections. By removing the strain points in the necked area, the strain distribution just before the onset of necking is reconstructed in this region by curve fitting of the remaining part of the strain distribution on both sides of the neck. The following steps can be identified:

— defining the relevant sections containing the neck (described in 5.2.2);

— marking of the neck region by an objective mathematical criterion; in this way the inner limits of the curve fit window are defined (described in 5.2.3);

— defining outer limits in order to obtain an optimal width of the fit window, that enables the best curve approximation relevant for both sides of the neck. In the next subsections, these steps are described in detail (described in 5.2.4).

NOTE For those who are not so familiar with the mathematics involved in the last two steps (5.2.3 and 5.2.4), the outcome of the procedure is represented in Figure 8 under 5.2.3.

Some materials show inhomogeneous deformation leading to multiple peaks not caused by friction. In these cases the cross-section method cannot be used automatically. In Annex G, some critical cross-sectional data are presented.

Other methods (automatic or manual) can be used if the measurement accuracy is sufficient (see Annex D).

5.2.2 Position and processing of measurement

To allow a reproducible evaluation of forming limits, the intersection line has a length of at least 20 mm on each side of the crack with at least 10 points, see Figure 7. A virtual line of about 10 mm length in the middle of the crack defines the orientation of the crack.

1) For $\varepsilon_2 \geqslant 0$, the intersection lines should be as perpendicular as possible (within ± 25°) to the crack.

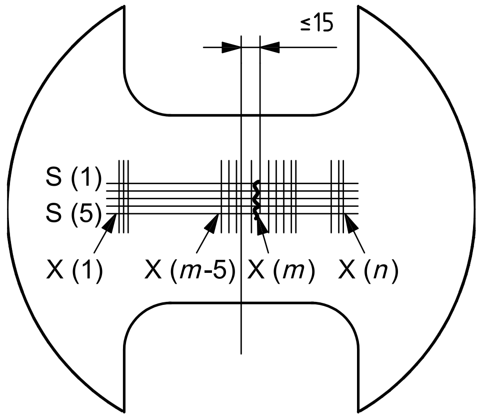
2) For $\varepsilon_2 < 0$ (small widths of the specimen), the intersection lines should be parallel to the shaft direction. This prevents a parallel offset between left and right sides of the intersection line caused by a large crack width.

For stability of automatic evaluation after cracking, it is recommended in both cases that the intersection lines correspond to the (virtual) grid orientation in the main strains direction.

The first intersection line goes through the centre of the crack; a further 1 or 2 intersection lines are positioned on both sides of the first section at a distance of approximately 2 mm. The positions of these lines correspond with the position of the maximum ε_1 in the crack region so that the fracture passes through the centre of the cross section. In case of multiple fracture lines (fracture with different arms, balanced stretching), the specimen shall be rejected.

For the following calculation, the X-position, ε_1 and ε_2 for each section point are needed. The X-position is given over the arc length of the section on the surface counting from the first intersection point [e.g. starting with X(0) = 0 mm at the beginning of the section].

Dimensions in millimetres



Key

X(1) X(1)-position
X(m – 5) X(m – 5)-position
X(m) X(m)-position
X(n) X(n)-position
S(1) S(1)-section
S(5) S(5)-section

Figure 7 — Positioning of the cross sections

Store the whole profile length in table format for evaluation with software. One can store these in ASCII format using one file for all FLC data or store one file for each intersection line (m). For convenience, it is preferable to add for all data the sample geometry, sample number and the section number leading to the following file format.

X-position mm	ε_1	ε_2	**Sample geometry**	**Sample number**	**Section**
X(1)-position-section(m)	ε_1 (1)-section(m)	ε_2 (1)-section(m)	1	A	m
X(2)-position-section(m)	ε_1 (2)-section(m)	ε_2 (2)-section(m)	1	A	m
…	…	…			
X(n)-position-section(m)	ε_1 (n)-section(m)	ε_2 (n)-section(m)	1	A	m
…	…	…	…	…	…
X(n)-position-section(m)	ε_1 (n)-section(m)	ε_2 (n)-section(m)	2	B	m
…	…	…	…	…	…

Recommended format X-position: ##,#

Recommended format true strain: #,###

The sample geometry number (1, 2, 3 …), the sample number per geometry (A, B, C …) and the section (m, given by a number a, b, c …) is in alignment with the way FLC values will be stored in one file as given in Annex F.

5.2.3 Extraction of the "bell-shaped curve" and determination of the inner limits for the best-fit curve through experimental points

The following steps should be followed for the determination of the fit boundaries.

a) Define the crack position.

1) For **AM1** and **AM2,** the actual X position of the points on the intersection line are taken. The crack position is defined by the real position of the crack – if known – otherwise, it shall be determined by a best fit of a parabola $[f(x) = ax^2 + bx + c]$. Before further calculations, the crack width should be subtracted from the centre of the bell-shaped intersection if it is larger than 0,5 mm (optical judgement, 0,5 mm precision). The width of the fit range on both sides of the crack should be at least 4 mm or 3 points on each side. The maximum of the parabola defines the crack position.

2) For **AM3,** the path of the crack and the direction of the intersection lines are defined on the first image following crack initiation and transferred to the image recorded just before crack opening. The image before crack initiation, with intersection lines, is used for the determination of the forming-limit strains of the test piece. For online measurements, an image sequence of 10 or more images per second shall be chosen during the last deformation steps before cracking. The crack position shall be determined by best fit to a parabola $[f(x) = ax^2 + bx + c]$. The centre of the range is given by the highest value of ε_1 of the section data. The width of the range is 8 mm but at least 5 points. The maximum of the parabola defines the crack position.

b) Calculate the second derivative (see Annex A) of the ε_1 data without smoothing and without filtering separately for both sides of the crack (to determine the inner boundaries required for the subsequent curve regression).

c) Determine the position of the highest of all peaks (local maximum with smaller values on both sides) of the second derivative (see Annex A) within a range of 6 mm but at least 4 points. A maximum at the edge of the crack is defined as a peak if the second derivative has the highest value at the crack side.

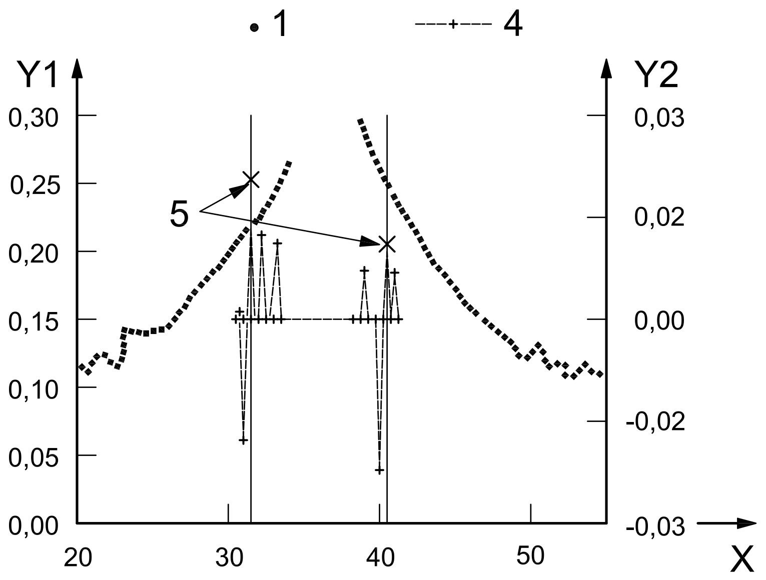
d) Repeat the calculation of the "filtered" second derivative using a range of 5 points for the parabolic fit (see Annex A).

e) Conduct the following check separately for both sides of the crack position.

Check if the position of the corresponding maximum of the second derivative with a range of 5 points [see d)] is within ± 1 point of the original position according to c).

1) If yes, then the position of the inner boundary on that side of the crack required for the subsequent curve regression is defined by c). In Figure 8, the outcome of this method is shown on a major strain distribution, including its second derivative.

2) If no, then the inner boundary is defined as 3 mm away from the crack position [see 5.2.3 a)]. This position shall be at least 1 point away from the crack.



Key

X arc length, in millimetres

Y1 major true strain, ε_1

Y2 second derivative of major true strain ε_1 to arc length

1 measured strain distribution

4 second derivative over a distance of 6 times the original thickness

5 maximum points of the second derivative, marking the inner limits of the regression

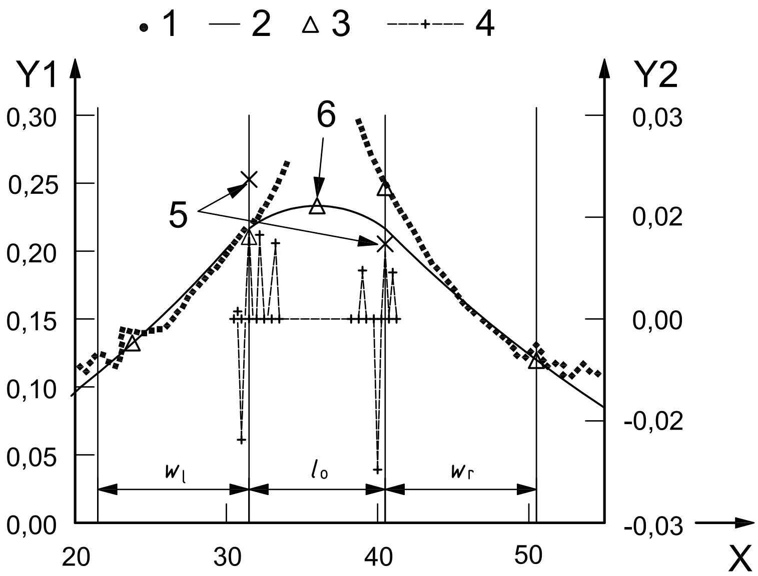
Figure 8 — Definition of the two inner boundaries using the maximum peak of the second derivative on both sides of the crack

5.2.4 Definition of outer limits for best-fit windows and evaluation of the inverse best-fit parabola on the “bell-shaped curve”

a) The two positions defined above are the two inner boundaries [5.2.3 c) to e)] of the two fit windows. The window width w is at least 5 points and shall be determined as described in Annex B as a function of the ε_1 and ε_2 border values on the left and the right sides of the window. By making use of the best-fit approximation of the strains over the defined fit windows, the limit strains ε_1 and ε_2 are determined as described in Figure 9 and Annex C including Figure C.1.

b) For each “bell-shaped curve”, one ε_1 - ε_2 pair is determined.

c) For each test piece, all ε_1 - ε_2 values from the different cross sections are taken. This means, for example, for 3 test samples for one geometry and 3 cross sections, 9 ε_1 - ε_2 pairs are produced; for 3 test pieces for one geometry and 5 cross sections, 15 ε_1 - ε_2 pairs are produced.



Key

X arc length, in millimetres

Y1 major true strain, ε_1

Y2 second derivative of major true strain ε_1 to arc length

1 measured strain distribution

2 an inverse parabola over the fit windows 5, 7 and 9

3 marking points of the fit window on the strain distribution

4 second derivative over a distance of 6 times the original thickness

5 maximum points of the second derivative, marking the inner limits of the regression

6 major forming-limit strain, ε_1

w_l left fit window width

l_o omitted length between the inner fit limits left and right to crack

w_r right fit window width

Figure 9 — Definition of the two inner boundaries (Figure 8), the outer boundaries (Annex B), the curve fit of the major strain distribution and the limit strain determination

The description of the evaluation method from the measured strains on the samples to the calculation of ε_1 - ε_2 pairs for the FLC is completed. Some examples meant for validating in house calculation programmes based on this standard are found in Annex E. In Annex H, a flowchart is presented for clarification and as a summary. This is of particular interest for those who want to write a computer programme for this evaluation.

6 Documentation

The test parameters and the pairs of values of ε_1 - ε_2 of measurements should be documented by data tables and diagrams. For diagrams, a decimal scale should be used (see Annex F).

Tables/diagrams of the engineering strains calculated from ε_1 - ε_2 pairs of values may also be added. For these diagrams, a percentage scale is used.

If any parameters deviate from those mentioned, this should be documented.

7 Test report

The test report shall contain the following information:

a) a reference to this part of ISO 12004;

b) identification of the laboratory that measured the FLD, including the name of operator;

c) the forming method used (Nakajima or Marciniak);

d) identification of material (e.g. name, coil number);

e) thickness of sheet;

f) direction of test piece with respect to the rolling direction;

g) grid used (e.g. size, precision, application mode);

h) lubricant system used;

i) number of geometries and number of repetitions.

Annex A
(normative)

Second derivative and "filtered" second derivative

For the determination of the second derivative, the following method is proposed.

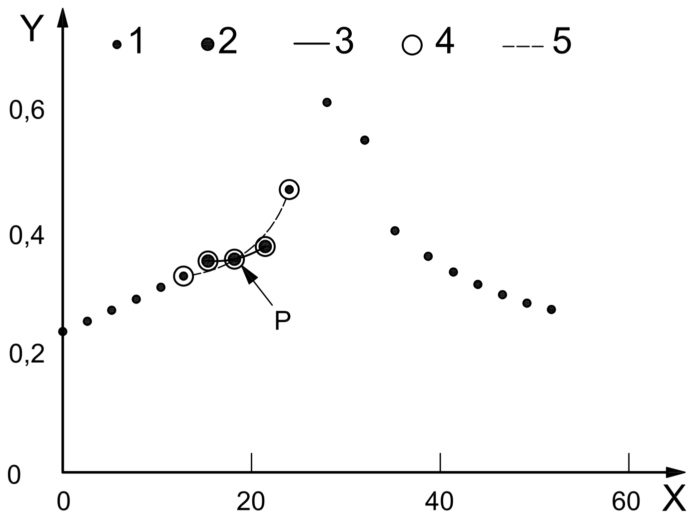
Take 3 consecutive points x_1, y_1; x_2, y_2; x_3, y_3. Determine the second order parabola through the 3 points and use twice the coefficient of the quadratic term. This value is the second derivative in the midpoint x_2.

$$f(x) = ax^2 + bx + c; \quad \Rightarrow \quad f''(x) = 2a$$

For this calculation, it is not allowed to take points from both sides of the crack. The points closest to the crack (on both sides) have no value in $f''(x)$.

This method can be expanded by using more than 3 points; this determination is known as the "filtered" second derivative. To get the same midpoint, an odd number of points have to be used. Also, in this case, a least-squares parabolic fit is made. For the second derivative at the midpoint, the coefficient of the quadratic term is doubled. This method has a filtering effect over the second derivative value without filtering the starting curve.

Again, no collection of points originated from both sides of the crack is allowed. For a range of 5 points, for example, the 2 points closest to the crack (on both sides) have no value in $f''(x)$.



Key

X arc length, in millimetres

Y major true strain, ε_1

P point to determine second derivative

1 measured major true strain profile

2 3 points used for determination of the second derivative

3 parabola of the second derivative determination using 3 points

4 5 points used for determination of the second derivative

5 parabola of the second derivative determination using 5 points will be smoother than that using 3 points

Figure A.1 — Determination of the second derivative of the strain profile, separately left and right from the crack

Annex B
(normative)

Calculation of the width of the fit window

The width of the window w should have at least 5 points and shall be calculated as follows:

$$w = 10\left[1 + \left(\bar{\varepsilon}_2 / \bar{\varepsilon}_1\right)\right]$$

with

$$\bar{\varepsilon}_2 = 1/2\left(\varepsilon_{2,\mathrm{Bl}} + \varepsilon_{2,\mathrm{Br}}\right)$$

$$\bar{\varepsilon}_1 = 1/2\left(\varepsilon_{1,\mathrm{Bl}} + \varepsilon_{1,\mathrm{Br}}\right)$$

The index “Bl” is used for ε_1 and ε_2 of the left inner boundary. The index “Br” is used for ε_1 and ε_2 values of the right inner boundary. The inner boundaries are defined in 5.2.3 e).

Annex C
(normative)

Evaluation of the inverse best-fit parabola on the "bell-shaped curve"

To evaluate the inverse best-fit parabola on the "bell-shaped curve", proceed as follows.

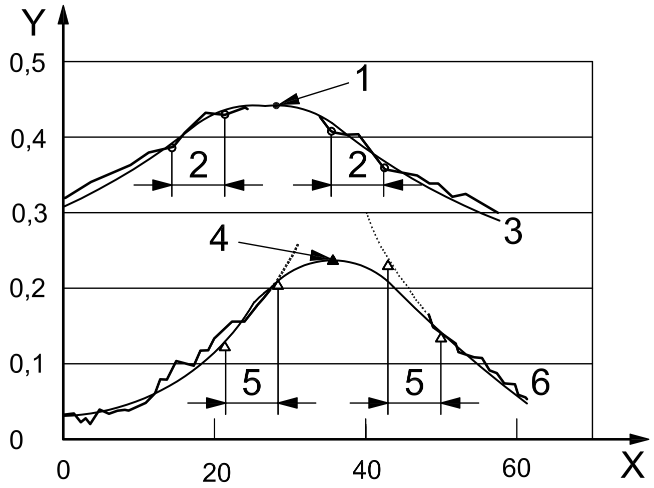
a) Use the best fit with an inverse parabola of second order $f_1(x) = 1/(ax^2 + bx + c)$ using both windows to calculate the ε_1 values. The resulting value in the crack position is the wanted limit for ε_1. In the fit procedure, check the following.

   1) Avoid hyperbolic instability, i.e. it is not allowed that the denominator of $f_1(x)$, $ax^2 + bx + c$, has zero values. This condition is fulfilled if $b^2 - 4ac < 0$.

   2) For the major strain evaluation, this method is used for identification of a maximum meaning the constant $a > 0$.

   If these conditions are not met, decide if these data are suitable for further use or not. A linear fit procedure or an average of the strain values at the position of the inner limits of the fit window can be used (see Figure 9). If such a special method is used, this shall be reported.

b) Determine ε_2 indirectly through the best fit based on the thickness true strain [$f_3(x)$] values. The thickness strain values are obtained by: $\varepsilon_3 = -(\varepsilon_1 + \varepsilon_2)$ $\{f_3(x) = -[f_1(x) + f_2(x)]\}$. The best fit to an inverse parabola of second order $f_3(x) = 1/(ax^2 + bx + c)$ is used within the boundaries of a). The resulting value in the crack position is the wanted limit for ε_3. Also, in this case, check the hyperbolic instability as mentioned in a). The limit for $\varepsilon_2[f_2(x)]$ is then calculated from the determined limit values of the thickness true strain $\varepsilon_3[f_3(x)]$ and $\varepsilon_1[f_1(x)]$ in the crack position as: $\varepsilon_2 = -(\varepsilon_3 + \varepsilon_1)$.



Key

X arc length, in millimetres

Y major true strain, ε_1

1 forming-limit biaxial stress state

2 fit windows for the biaxial case

3 strain distribution for the biaxial case

4 forming-limit uniaxial stress state

5 fit windows for the uniaxial case

6 strain distribution for the uniaxial case

Figure C.1 — Example for the determination of the ε_1 value (necking start) in the case of a uniaxial and in the case of a biaxial strain profile

Annex D
(normative)

Application/Measurement of grid — Evaluation with magnifying glass or microscope

For the evaluation with magnifying glass or microscope, the following specifications are used.

— Type of grid:	Circular grid with overlap
— Accuracy of the undeformed grid:	1 % of grid size
— Measurement instruments:	Magnifying glass or microscope
— Accuracy of instruments:	1 % of grid size
— Position and processing of measurement:	Determine the “bell-shaped curve” by measuring ellipses perpendicular to the crack at the position of the maximum strain (approximately 20 mm on each side of the crack).

Annex E
(informative)

Tables of experimental data for validation of calculation programme

Experimental data for validation of the calculation programme are given below. The following data sets and allowable scatter can be found in files on the internet (see Reference [4] in the Bibliography).

Case	Description of the file name	Minor limit strain ε_2	Major limit strain ε_1
A)	06-0-4_section5	0,246	0,301
B)	06-0-4_section6	0,244	0,299
C)	06-0-4_section7	0,244	0,300
D)	06-75mod-1_section0	−0,112	0,350
E)	06-75mod-1_section1	−0,121	0,375
F)	06-75mod-1_section2	−0,119	0,372
G)	DC06-45-1_section0	−0,023	0,392
H)	DC06-45-1_section1	−0,019	0,387
I)	DC06-45-1_section2	−0,023	0,413
J)	ZStE-45-1_section0	0,007	0,267
K)	ZStE-45-1_section1	0,008	0,263
L)	ZStE-45-1_section2	0,008	0,275

Annex F
(normative)

Representation and mathematical description of FLC

For a graphical representation of the pairs of values of ε_1 - ε_2 for all sections, proceed as follows.

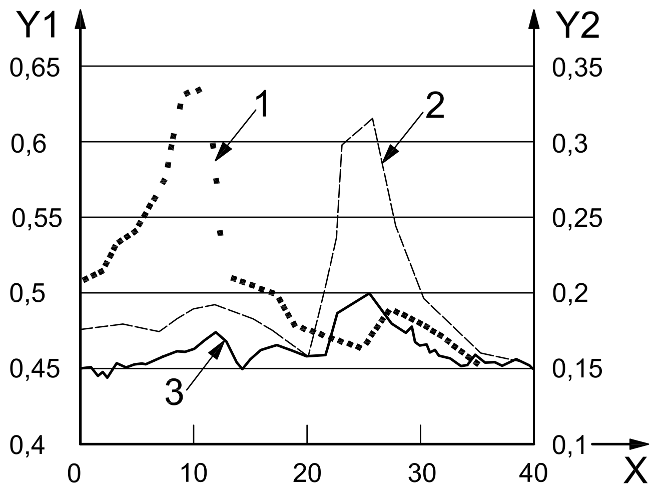
- List the ε_1 and ε_2 values in table format (see Table F.1).
- Identify the ε_1 - ε_2 values belonging to the same sample (different cross sections) and the samples with equal geometry which belong together, e.g. 1Aa, 1Ab, 1Ac, 1Ba, 1Bb, 1Bc, 1Ca, 1Cb, 1Cc, 2Aa, 2Ab, …
- Calculate the mean values and standard deviation for each sample and for each geometry.
- Additionally, a regression can be made using in-house functions. The algorithm/function used to determine the FLC curve should be reported.
- Determine the standard deviation from the scatter of all sections of all test pieces with equal geometry.

Table F.1 — Format of the list of values

Value		Mean sample		Mean geometry		Sample geometry	Sample number	Section
ε_1	ε_2	ε_1	ε_2	ε_1	ε_2			
#,###	#,###					1	A	a
#,###	#,###					1	A	b
#,###	#,###	#,###	#,###			1	A	c
#,###	#,###					1	B	a
#,###	#,###					1	B	b
#,###	#,###	#,###	#,###			1	B	c
#,###	#,###					1	C	a
#,###	#,###					1	C	b
#,###	#,###	#,###	#,###	#,###	#,###	1	C	c
#,###	#,###					2	A	a
#,###	#,###					2	A	b
#,###	#,###	#,###	#,###			2	A	c
#,###	#,###					2	B	a
#,###	#,###					2	B	b
#,###	#,###	#,###	#,###			2	B	c
#,###	#,###					2	C	a
#,###	#,###					2	C	b
#,###	#,###	#,###	#,###	#,###	#,##	2	C	c

Annex G
(informative)

Examples of critical cross-sectional data



Key

X arc length, in millimetres

Y1 major true strain, ε_1, for the formable steel

Y2 major true strain, ε_1, for the Al-Mg-alloy

1 measured strain distribution of a formable steel with insufficient lubrication, one sided peak

2 measured strain distribution of an Al-Mg-alloy with insufficient lubrication, multiple peak

3 measured strain distribution of an Al-Mg-alloy with inhomogeneous deformation due to dynamic strain ageing

Figure G.1 — Examples of critical cross-sectional data

Three examples are given of measured strain distributions leading to unrealistic FLC-values.

1) One-sided peak in the formable-steel:

   The fracture does not occur in the centre of the dome due to insufficient lubrication. In this case, the second derivative method works (5.2.3, Figure 8) but the inverse parabola fit (5.2.4, Figure 9) does not lead to a realistic fit for the remaining strain distribution. Moreover, it is necessary to consider fewer points on one side (here the left side) for a best-fit approximation.

2) Multiple peaks in a sample of an Al-Mg-alloy:

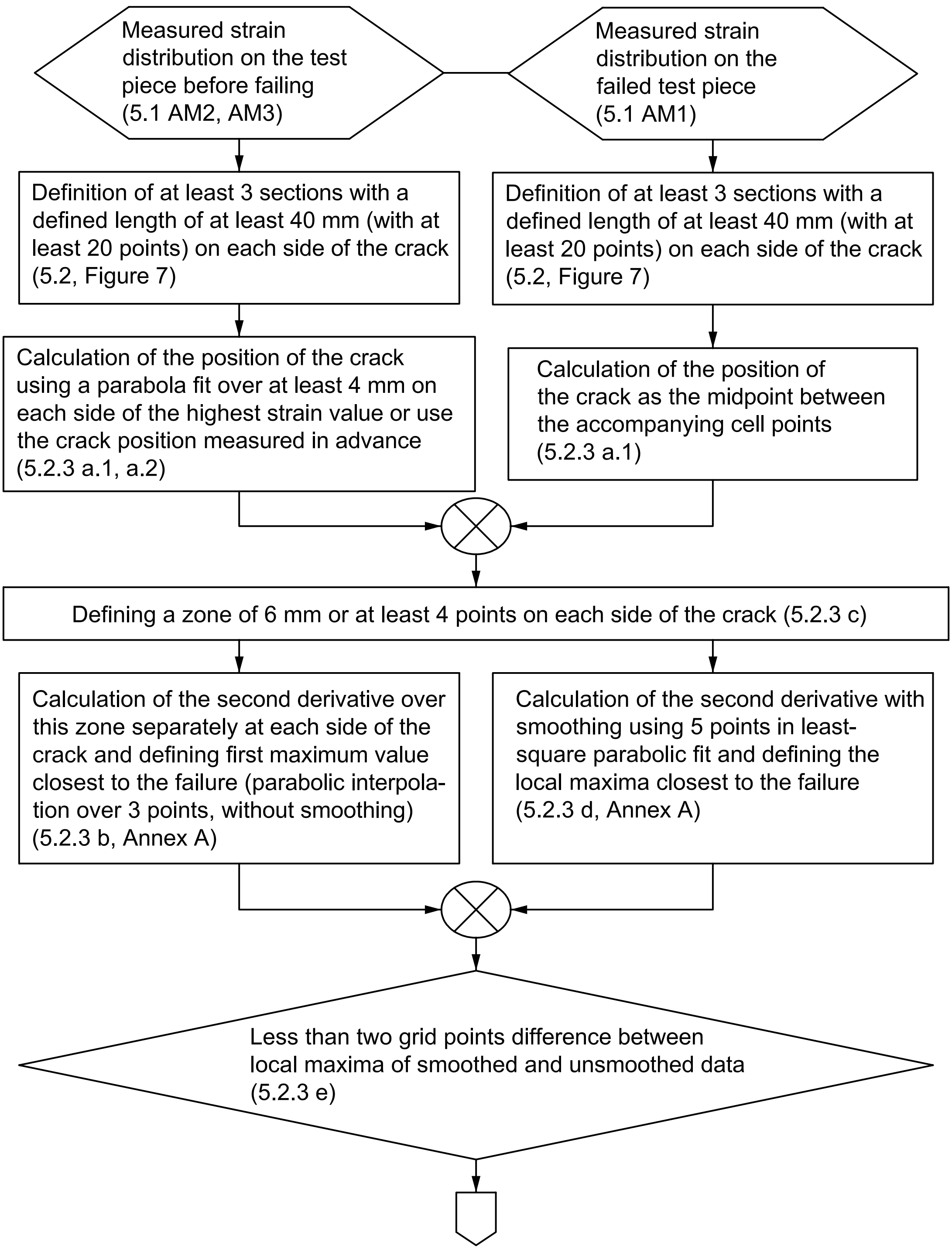
   The cause of multiple peaks is the same as described in 1), but is a more severe example. The left best-fit window can contain a part of the second peak leading to a wrong best fit of the inverse parabola. In a worst case scenario, a minimum in the best-fit approximation is calculated leading to the underestimation of the limit strain values.

3) Inhomogeneous strain distribution of an Al-Mg-alloy with many small peaks due to occurrence of dynamic strain ageing, a common effect in this type of material.

   Both the second derivative method (5.2.3, Figure 8) and the best fit by means of an inverse parabola do not necessarily give good results. A minimum in the best-fit approximation can be calculated leading to the underestimation of the limit strain values.

Annex H
(normative)

Flowchart from measured strain distributions to FLC values



Yes / No

Yes: Use the position of the local maxima of the unsmoothed second derivative as marker for the necked zone (5.2.3 e.1, Figure 8)

No: Use a fixed distance of 3 mm from the crack position as a marker for the necked zone (5.2.3 e.2)

Marker points inner fit limits are fixed and strain ratios in these points are determined (5.2.3)

Calculation of the fit window, w, using mean strain ratio in limit points:

$$w = 10[1 + (\bar{\varepsilon}_2/\bar{\varepsilon}_1)]$$

with: $\bar{\varepsilon}_2 = 1/2(\varepsilon_{2,\mathrm{Bl}} + \varepsilon_{2,\mathrm{Br}})$

$\bar{\varepsilon}_1 = 1/2(\varepsilon_{1,\mathrm{Bl}} + \varepsilon_{1,\mathrm{Br}})$

(5.2.4 a, Annex B)

By making use of the fit window on both sides of the crack, make a least-squares approximation of the best inverse parabola in this region for both the major strain and thickness strain; minor strain is calculated using principle of volume conservation (5.2.4, Figure 9, Annex C a, b, Figure C.1)

Calculation of the values of major and minor strains using at the failure position delivers the forming limit strains of the section considered (5.2.4, Figure 9, Annexe C a, b, Figure C.1)

Collect calculated forming limit data of every section per sample and calculate average values, i.e. the individual FLC-value per test piece (Clause 7, Annex F)

Collect average FLC values per test piece of every geometry and calculate average values, i.e. the average value per geometry (Clause 7, Annex F)

Bibliography

[1] ISO 6892-1, *Metallic materials — Tensile testing — Part 1: Method of test at room temperature*

[2] ISO 10113, *Metallic materials — Sheet and strip — Determination of plastic strain ratio*

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

[4] Software calibration data file: Datasets_12004.zip, available (2008-06-04) at the following address: http://isotc.iso.org/livelink/livelink?func=ll&objId=1065739&objAction=browse&sort=name

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