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Metallic materials — Determination of forming-limit curves for sheet and strip —

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

Matériaux métalliques — Détermination des courbes limites de formage pour les tôles et bandes —

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.

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

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

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

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

This document was prepared by Technical Committee ISO/TC 164, Mechanical testing of metals, Subcommittee SC 2, *Ductility testing*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 459/SC 1, *Test methods for steel (other than chemical analysis)*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This second edition cancels and replaces the first edition (ISO 12004-2:2008), which has been technically revised.

The main changes compared to the previous edition are as follows:

1) The title was changed to have three elements

2) Clause 2 and Clause 3 were added from the previous edition, and the subsequent clauses were renumbered.

3) The descriptions of when to use ISO 12004-1 or ISO 12004-2 (this document) was revised in the Introduction.

4) Permissions and requirements were clarified in 6.1.3, 6.1.5, 6.2.2, 6.2.3, 6.3.2, 6.3.3.3, 6.3.4.3, 7.2.2, and 7.2.3.

5) In 6.3.1, the punch velocity range was expanded and permission for exceptional cases in aluminium alloys, as well as steel, was added.

6) Clarification was added that although the Nakajima method is known to have non-linear strain paths (6.3.3.1), it is still acceptable. Clarification as to why the failure is required to be near the apex of the dome was added to 6.3.3.3. In 6.3.3.3, the “validity of test” requirement for the Nakajima test was made explicit in a similar format to that shown for the Marciniak test in 6.3.4.4. In 6.3.3.3 and 6.3.4.4, a statement regarding rejection of specimens not meeting the valid test requirements was added.

7) The “Measuring instrument” clause (4.3.5 in the previous edition) was removed since it is a repetition of the “Measurement instrument” section of 6.3.2 but had a different accuracy requirement. The required accuracy is now shown as originally described in 6.3.2.

8) The requirement on the second derivative range was clarified in 7.2.3(c), and the requirements in the keys of Figures 8 and 9 were changed to match 7.2.3(c).

9) The permission to use other methods of measurement was moved from 7.2.1 to 7.1 and was clarified.

10) The statement regarding the “time-dependent method” was removed from 7.1 but now a statement admitting the use of other methods including both the “time-dependent method” or “time and position dependent methods” appears in Clause 5.

11) In 7.2.2, the method of selecting the section line locations based on the crack position was clarified, and permission was added to use the maximum strain location, as long as the test validity requirements are still met.

12) The use of the procedure in 7.2.3 when extracting the “bell-shaped curve” for use in evaluating the section lines using the position-dependent method has been changed to being required rather than just suggested. This seems to be consistent with the original intent.

13) In Annex A, the method was changed to be required rather than proposed. Annex C was clarified to show that the procedure is required. Clarification to the text of Annex D was added, and its use is explicitly permitted. In Annex F, explicit permission to use a regression using in-house functions was added, as well as the requirement that the function be reported.

14) Editorial changes and clarifications were made throughout the document.

A list of all parts in the ISO 12004 series can be found on the ISO website.

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

Introduction

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 and is not intended to determine one unique FLC for each material.

2) Determination of FLCs under well-defined laboratory conditions

   For evaluating formability, one unique FLC for each material in several strain states can be measured. The determination of the FLC must be specific and uses multiple linear strain paths. This document, i.e. ISO 12004-2, is intended for this type of material characterization.

For this document (concerning determination of forming-limit curves in laboratory), the following conditions are also of note.

— 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 localized necking and/or fracture. Many methods exist to determine the forming limit of a material; but 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 to judge not only 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 — Determination of forming-limit curves for sheet and strip —

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

1 Scope

This document specifies testing conditions for use 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.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 Symbols and abbreviated terms

For the purposes of this document, the symbols and abbreviated 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

Table 1 *(continued)*

Symbol	English	French	German	Unit
$f(x) = ax^2 + bx + c$	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	—
S(0), S(1)...S(5)	Section	Section	Schnitt	—
n	Number of X-positions	Nombre de points en X	Nummer der X-Positionen	—
m	Number of the X-position at the failure/crack position	Numéro du point en X correspondant à la rupture	Nummer der X-Position am 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	International symbol	German symbol	Format	Unit
Engineering strain	e	ε	—	%
True strain (logarithmic strain)	ε	φ	Decimal	—
$\varepsilon = \ln(1 + e)$	—	—	—	—

The symbol typically used for true strain is “ε”, but in German-speaking countries the symbol “φ” is used for true strain. Additionally, 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 typical international definition.

5 Principle

The FLC is intended to represent the almost intrinsic limit of a material in deformation assuming a linear strain path. To determine the FLC accurately, it is necessary to have as nearly linear a strain path as possible.

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.

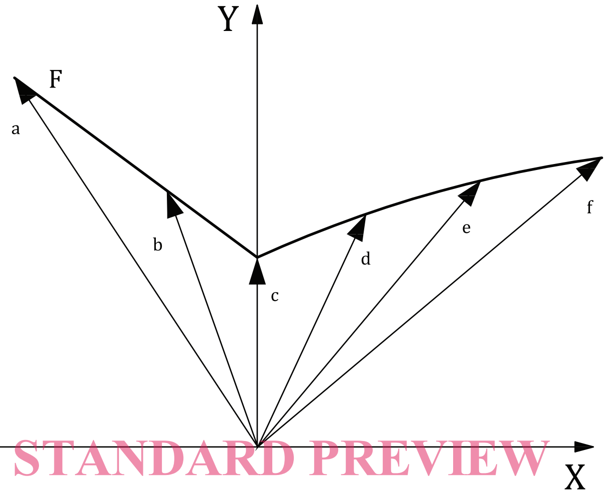
The FLC determination from the measurements should be performed using the “position-dependent” method described in 7.2.

Other methods (e.g. “time-dependent” or “time and position dependent” methods) of FLC determination from the measurements exist. If agreed to by the interested parties, one of the other methods may be used and, if used, shall be indicated in the test report.

The deformation (strain) across the deformed test piece is determined and the measured strains are processed in such a 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) from measured length changes or engineering strains. 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

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

[b] Intermediate tensile strain

[c] Plane strain

[d] Intermediate stretching strain state

[e] Intermediate stretching strain state

[f] Equi-biaxial tension (= stretching strain state) $\varepsilon_2 = \varepsilon_1$.

Figure 1 — Six different strain paths

6 Test pieces and equipment

6.1 Test pieces

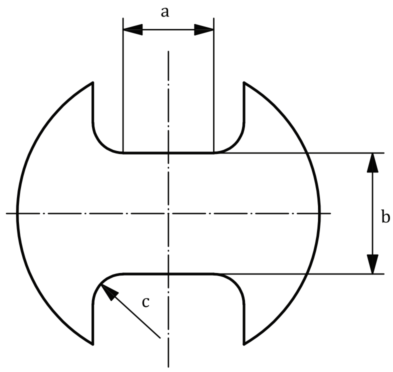
6.1.1 Thickness of test pieces

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

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

6.1.2 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).



a Shaft length

b Remaining blank width

c Fillet radius

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

6.1.3 Test piece preparation in test area

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

6.1.4 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.

6.1.5 Number of tests for each geometry

As many test pieces as are necessary shall be tested to achieve at least three valid samples for each test piece geometry.

6.2 Application of grid

6.2.1 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.

6.2.2 Grid application

Deterministic grids (e.g. squares, circles, dots) should have a rich contrast and shall 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. 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).

Grid/pattern adherence to the surface should be checked after deformation for both the deterministic grids and stochastic patterns.

6.2.3 Accuracy of the undeformed grid

To achieve the required total system accuracy of 2 % (see 6.3.2), the initial grid accuracy should be measured to an accuracy better than 1 % based on one times the standard deviation (1σ). This recommendation only applies for systems where the local undeformed condition is not measured as part of the evaluation.

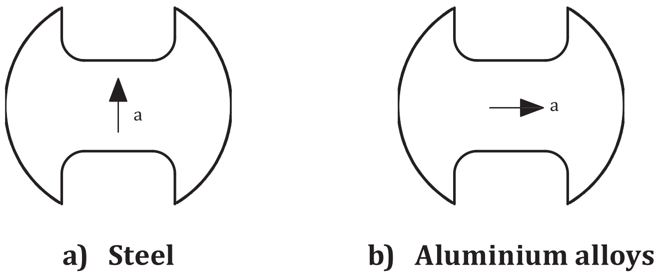
6.3 Test equipment

6.3.1 General

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

Punch velocity:	0,5 mm/s to 2 mm/s
Prevention of material's draw-in:	Draw-in shall be prevented as much as possible to ensure nearly linear strain paths. Possible methods of mitigation 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 orientation of all test pieces shall be the direction of lowest limit strain e_1 and the same orientation relative to the rolling direction, see Figure 3.
Aluminium alloys:	Longitudinal (shaft orientation parallel to rolling direction); exceptional cases are allowed but shall be reported.
Steel:	Transverse (shaft orientation perpendicular to rolling direction); exceptional cases are allowed but shall be reported.

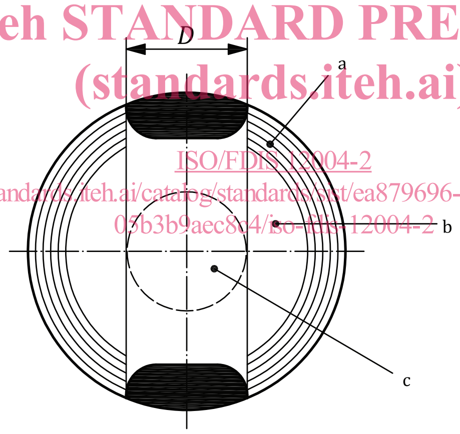
In the case that the preferred failure direction is not known, it should be checked using a biaxial strain test or any other suitable method.



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 or blank holder with cut-out; see Figure 4.



Key

D cut-out width, equal to punch diameter

a Serrated blank holder with cut-out.

b Blank.

c 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 can 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.