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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

Reference number
ISO 12004-2:2008(E)

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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.

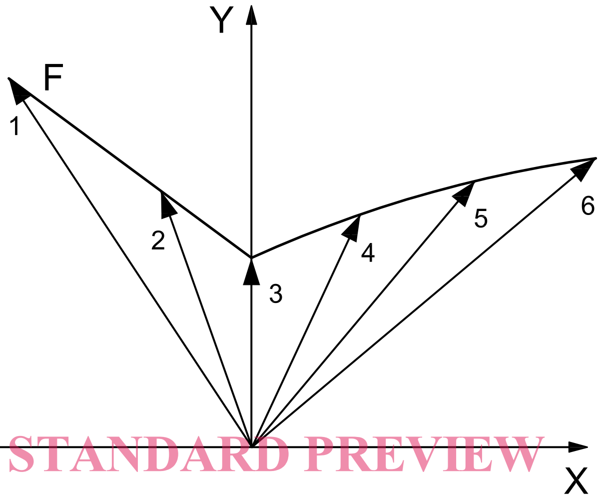
The measurement should be performed using a “position-dependent” method (see 5.2).

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

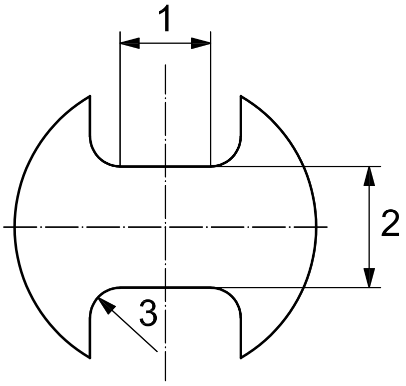
4.1.1 Thickness of test pieces

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.

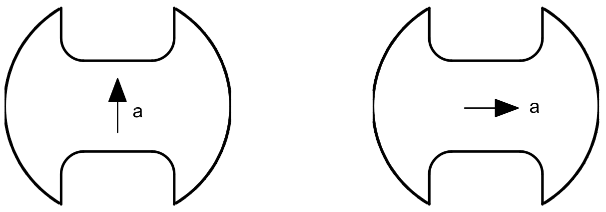
4.3 Test equipment

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) **Steel** b) **Aluminium**

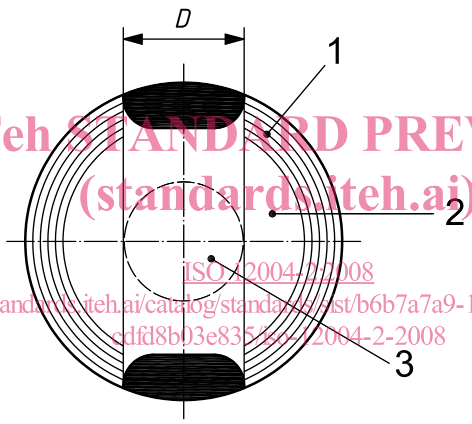
[a] Rolling direction (RD).

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...).