Deep drawing

Introduction

The bare, coated or organic coated sheet delivered by the steelmaker is generally cold formed by the client using one or more processes, from simple bending to the production of highly complex shapes.

The most commonly used sheet forming process is cold drawing, which converts prestamped flat blanks into parts whose shape is composed of surfaces that cannot be obtained by simple bending.

The formed part is often referred to as a shell or cup, and must conserve a good surface condition, without local thinning or wrinkling. Drawing is performed on mechanical or hydraulic presses equipped with special tools, and is used in most of the major industrial sectors, including automotive engineering and the manufacture of consumer goods, furniture and domestic appliances.

The drawn part is usually not the finished component but more often represents an intermediate stage of fabrication. It must generally be trimmed to remove excess material necessary for successful drawing, and then flanged to produce the profile required for assembly with other parts in the final structure.

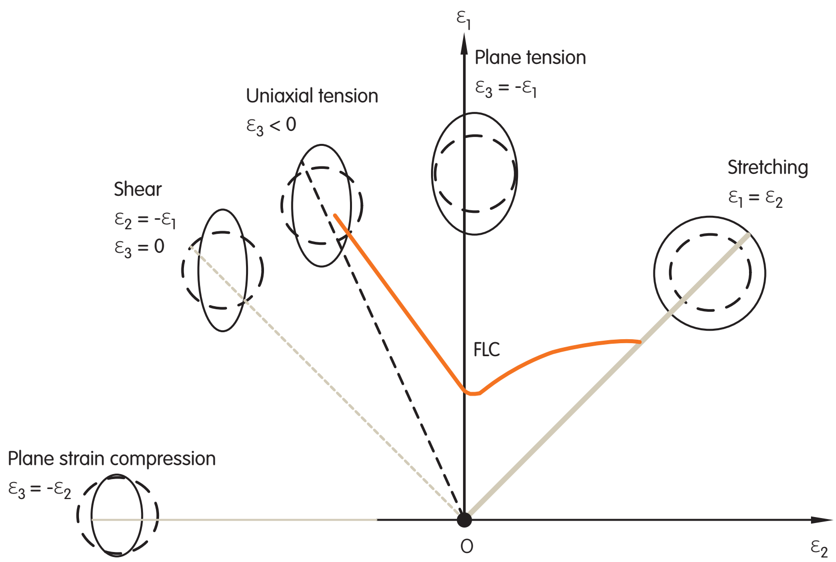
The drawability of a sheet depends on the capacity of the material to tolerate the associated deformations. The more malleable the metal, the easier it will be to form, but the lower its mechanical strength.

The steel used must thus have the requisite mechanical properties to allow correct behaviour during the appropriate deformation process, whilst at the same time it must be ensured that the structural properties of the final product are preserved. Through the use of numerical modelling, combined with increasingly powerful computing techniques, it is now possible to predict both the behaviour of the steel during forming and the properties of the finished component.

The different deformation modes

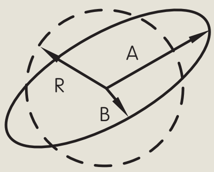
Let us now analyse the different modes of deformation that can occur in drawing.

By convention, any type of deformation in a sheet can be represented by a point in the ε_1 vs ε_2 diagram below, where ε_1 is the principal strain in the plane of the sheet and ε_2 is the strain perpendicular to ε_1. The thickness strain ε_3 is obtained from the law of conservation of volume: $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$



$\varepsilon_1 = \text{Log}(A/R)$
$\varepsilon_2 = \text{Log}(B/R)$

R = radius of the initial circle



Strain diagram for sheet forming, showing a typical forming limit curve (FLC) for steel

The previous diagram illustrates the different types of deformation possible during drawing. The deformation mode is visually represented in the chart by the deformation of the circle. In reality, the magnitude and mode of deformation of a component are each measured by optical measurement of a full pattern of circles or dots printed on a blank before deformation. Characteristic cases or deformation modes are:

- Stretching, or biaxial tension: this is accompanied by thinning and typically occurs in spherical shapes such as at the punch nose. The magnitude of deformation is largely defined by the shape and the restraining force on the flange, exerted by the blankholder.
- Plane strain tension: generally occurs in the vertical walls of the part, due to the tensile stress caused by retention under the blankholder, or just before the end of forming when sliding in the tool is restricted.
- Uniaxial tension: this is the situation encountered in a tensile test on a specimen, and it occurs in transition regions between zones of plane strain tension and plane strain compression.
- Shear deformation: represents the ideal forming mode; here, all tensile strains are being compensated by compressive strains, so that the thickness remains constant. This type of deformation can occur beneath the blankholder if the flow is uniform (axisymmetric drawing).
- Drawing: involves thickening due to a reduction in width (circumference). It is mostly unavoidable during deep drawing but can be controlled beneath the blankholder. However, its occurrence in unsupported areas will lead to wrinkling or folding.

This diagram is used to plot a forming limit curve for a particular steel grade, corresponding to the strain combinations that produce either failure or the onset of local necking, determined by laboratory tests.

The figure on the previous page shows a typical forming limit curve for drawing steels, corresponding to the appearance of necking, which represents the real limit for all practical purposes. It can be seen that the most critical forming path is plane strain, and this is effectively found to be the type of deformation responsible for most industrially observed forming failures.

To establish forming limit curves, numerous parameters (sheet thickness, size of the circles used for strain measurement, necking criterion, test method etc) must be checked.

In practice, the forming limits also depend on the strain path, which can be very complex, particularly when forming is carried out in several steps. Furthermore, forming limit curves do not give a good indication of behaviour in pure drawing operations.

Nevertheless, the forming limit curve of a certain steel grade is a practical tool in the analysis of the formability. Strain measurements on drawn parts enable retrospective evaluation of the influence of tool adjustments on the position of the ε_1, ε_2 points with respect to the forming limit curve for the material.

Drawability tests

The tensile test is undoubtedly the most comprehensive test technique, providing the largest amount of information on the inherent properties of the metal, independent of surface conditions (since there is no friction).

By suitable adaptation, it can be performed at a wide range of strain rates and temperatures.

The determination of true stress-strain curves provides even more fundamental data, including the strain hardening exponent (n) and the plastic strain ratio (r).

Hardness testing has little technical significance. It measures a mixture of various properties, including the yield strength, strain hardening component and friction behaviour. Nevertheless, this type of testing is always used, as it has the advantage of being non-destructive, inexpensive and can be carried out using very small specimens.

Swift-type tests, in which cylindrical cups are drawn on a laboratory press, provide a good means of evaluating behaviour in this deformation mode. However, it must be emphasised that friction between the sheet and the tool is extremely important, making these tests sensitive to the chemistry and lubrication of the surface and to coatings.

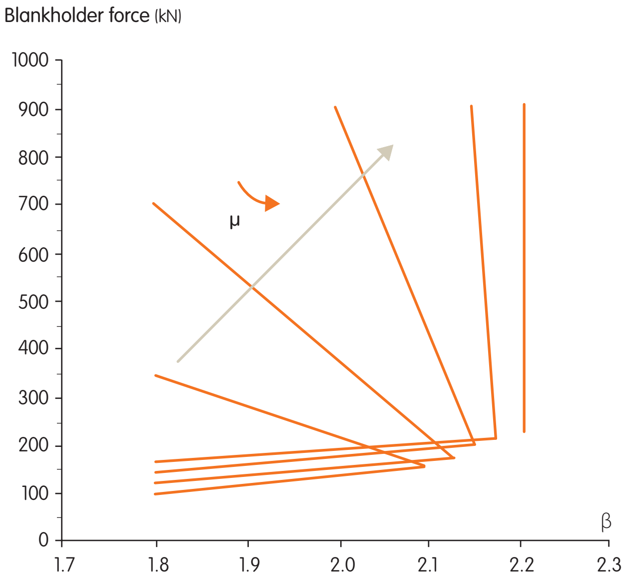
One particular application is to determine the permissible range of the blankholder force (see the figure below). Circular blanks of different diameters are therefore drawn on the same tool. A larger blank diameter will lead to more severe deep drawing conditions. The ratio between the initial blank diameter and the diameter of the deep drawn cup is called the drawing ratio

$\beta = D_{blank} / D_{die}$

For a constant blank diameter, cups are drawn with different blankholder forces, in order to determine the minimum value where no wrinkles appear in the flange and the maximum value beyond which tearing occurs.

By repeating this procedure for different blank diameters, a blankholder force vs drawing ratio diagram can be produced showing the window in which these parameters can be changed safely:

- The wider the permissible zone, the more "tolerant" the material is with respect to adjustments.
- The intersection point of the wrinkling limit and fracture limit curves corresponds to the limiting drawing ratio (LDR). The further it is situated to the right, the more severe the permissible drawing strain can be, and hence the fewer the number of passes required.



Latitude for adjusting the blankholder force

Another frequently used laboratory technique is the bulge test, in which the sheet specimen is hydraulically expanded, without friction or draw-in from the flange, giving information on both stretching and work hardening behaviour.

Description of the tensile test

Tensile testing is the most commonly used method for determining the mechanical properties of materials, due to two major advantages:

- Its simplicity and ease of execution
- Detailed and careful analysis of the load-elongation curves provides a wealth of information

The basic principle is to impose a gradually increasing longitudinal elongation on a long thin specimen of the material until the point of rupture is reached. The specimen can be either flat, cylindrical or prismatic, with larger end sections, fixed in the tensile machine clamps, which are moved apart to apply the deformation.

The variation of the load necessary to elongate the specimen at the imposed rate is measured during the test. This load characterises the resistance of the material to unidirectional deformation. The measured load is recorded as a function of specimen elongation, providing the basic tensile curve.

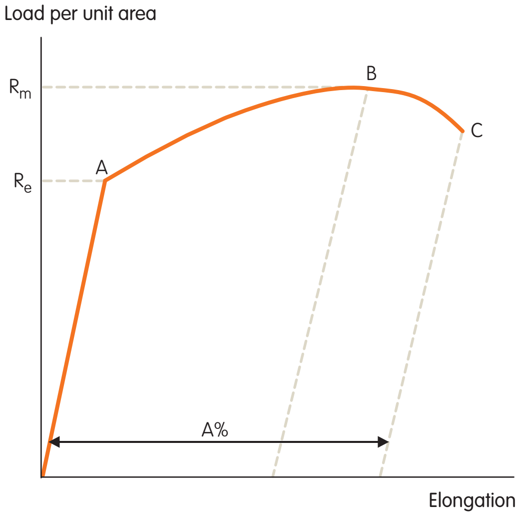
A common method of analysing tensile test results is to plot the recorded force displacement curve:

- On the abscissa, the relative nominal strain, or elongation A in %, of an initial gauge length L_0 parallel to the loading direction:

$$A(\%) = 100 \frac{L - L_0}{L_0}$$

- On the ordinate, the nominal stress, corresponding to the instantaneous load or force divided by the initial specimen cross-sectional area A_o

Using this graph, it is possible to determine the nominal, conventional or engineering tensile properties of the material concerned, which are defined in detail for metals in the European standard EN ISO 6892-1, and illustrated schematically in the figure below.



At the start of the test, a rapid linear increase in load with elongation is observed, corresponding to the elastic region. Here, the deformation is reversible and proportional to the load according to Hooke's law. This region corresponds to a total elongation of only a few tenths of a percent.

At the end of the elastic range, the deformation is essentially irreversible, or plastic, and the curve becomes roughly parabolic. It goes through a maximum, corresponding to the appearance of necking. Beyond this elongation, the deformation is no longer uniform and concentrates at a particular point on the specimen gauge length.

The rapid decrease in local cross-section leads to a drop in load, until the specimen breaks at the neck root.

The conventional parameters used to characterise tensile behaviour are:

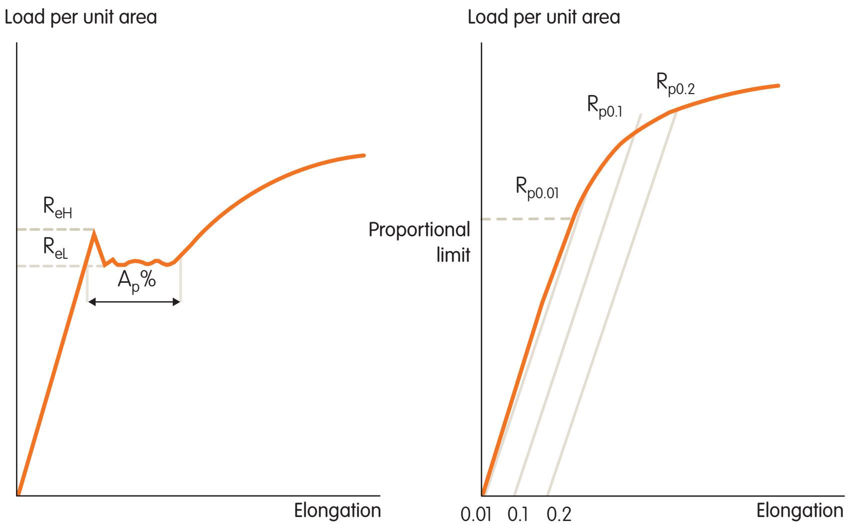
- The apparent yield point, yield stress or yield strength (R_e), corresponding to the load per unit area (of the initial section), separating the elastic and plastic regions (point A in the figure below)
- The ultimate tensile stress or strength (R_m), corresponding to the maximum load per unit area (of the initial section) attained during the test (point B)

  R_e and R_m characterise the mechanical strength of the material.
- The elongation to failure, as a % (e_f), corresponding to the plastic elongation at fracture (point C)
- The elongation at the maximum load, as a % (e_u) (point B)

  The values e_f and e_u characterise the ductility of the material.

Yield points and yield strength

Generally, two types of stress-strain curves can be distinguished, depending on whether or not a load "plateau" is observed after the apparent yield point. When such a plateau occurs, it is generally preceded by a sharp maximum, followed by a sudden drop. The maximum is termed the upper yield point, while the plateau value is called the lower yield point.



The strain that occurs at the lower yield point is called the yield point elongation or Lüders strain. The upper yield point depends on the form of the test-piece and its surface condition, together with the testing parameters and machine characteristics.

The lower yield point is less sensitive to geometrical defects of the specimen, but the plateau itself is rarely horizontal, since the specimen yields non-uniformly. In the case of stress-strain curves without a plateau, the transition from elastic to plastic behaviour is gradual. When this part of the curve is magnified, it is found that the elastic region is not really linear. This is principally due to geometrical imperfections in the test-piece, and to the presence of microscopic residual stresses, particularly in multiphase or heat-treated steels.

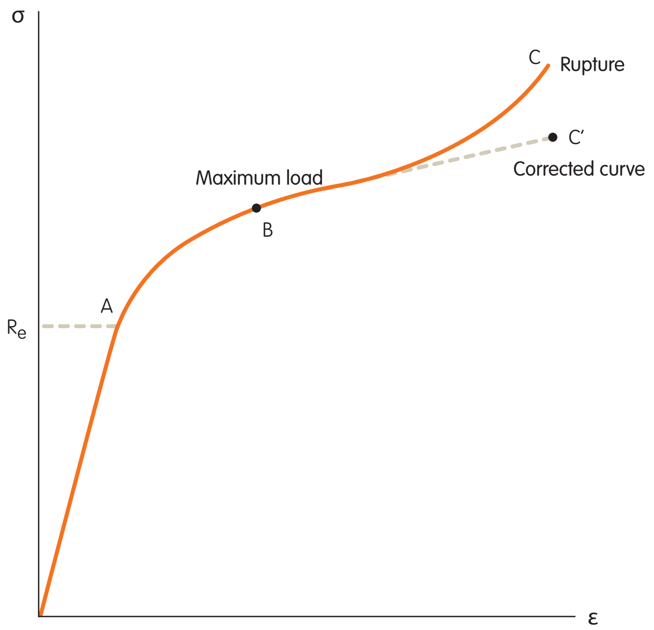
It is therefore necessary to define a conventional yield stress, or proof stress, PS, corresponding to the stress value for a small, but precisely measurable permanent (plastic) strain. The most commonly used value for this is 0.2% plastic strain, called the 0.2% proof stress (0.2% PS).

True stress-strain curve

The parameters used for the conventional analysis of test results have the disadvantage of not having a precise physical meaning. Indeed, the nominal stress is not the real effective stress, since it represents the instantaneous load divided by the initial specimen section, whereas the nominal strain is not very useful, since it can easily be shown that it is not additive.

Equation for the true stress-strain curve

In its parabolic region, the true stress-strain curve describes the homogeneous strain hardening of the material under uniaxial tension. A simple description of this part of the curve is thus extremely useful, particularly for plasticity calculations.



The most frequently employed expression is the Ludwik equation:

$\sigma = \sigma_0 + k\,\varepsilon^n$

where σ_0, k and n are constants.

This corresponds to a generalisation of the parabolic region, ignoring the contribution of elastic strain.

In the case of mild steels, the value determined for σ_0 is low, or even zero, so that the expression proposed by Hollomon can be used:

$\sigma = k\,\varepsilon^n$

The empirical exponent n in this relation is called the strain hardening exponent.

An important feature of this equation is the fact that n is numerically equal to the uniform strain (i.e. the strain up to the onset of necking). Since the latter is difficult to measure directly on the tensile curve, the strain hardening can be used to evaluate this parameter, which characterises the ductility of the metal and its ability to resist necking.

Strain hardening exponent n

This is determined by calculating the slope of the linear regression between log σ and log ε based on at least eight points taken from the uniform plastic strain region of the true stress-strain curve (i.e. between the yield point and the start of necking).

The strain hardening exponent is particularly important for describing the capacity of a sheet to withstand deformation (especially during stretching) and its propensity to strain harden (increase in its yield point).

Since its value varies depending on the orientation of the specimen axis, it is measured in three directions: n_0 (in the rolling direction), n_{90} (perpendicular to the rolling direction) and n_{45}, from which the mean n can be calculated.

Plastic strain ratio r

Classic elasticity and plasticity theories assume that the metal deforms in a uniform and isotropic manner. In practice, whenever a crystallographic texture is present, the behaviour is no longer isotropic. This is particularly true in cold rolled and annealed thin sheets, where the processing cycles are designed to enhance the formation of a texture favourable for drawing.

The anisotropy is evaluated from a tensile test on a sheet specimen, by determining the ratio r between the strains in the width W and thickness t directions.

$$r_\theta = \frac{\varepsilon_w}{\varepsilon_t}$$

$$\varepsilon_w = \mathrm{Log}\,\frac{W}{W_0}$$

Since the value of r depends on the total strain, the symbol r is modified by a superscript giving the percentage elongation for which it was measured. An elongation of 20% is usually recommended (r^{20} value).

The plastic strain ratio is a measure of a sheet's resistance to thinning and is therefore important during deep drawing, as thinning precedes failure in sheet metal deformation.

The value of r also depends on the orientation of the specimen axis with respect to the sheet rolling direction, and this angle is indicated by a subscript.

In practice, r is measured in the longitudinal and transverse directions, and at 45° to the rolling direction, and the mean anisotropy is characterised by two parameters:

- the normal strain ratio $\bar{r}$ calculated from the relation

$$\bar{r} = \frac{r_0 + 2r_{45} + r_{90}}{4}$$

- the planar strain ratio Δr, given by

$$\Delta r = \frac{r_0 + r_{90} - 2r_{45}}{2}$$

The parameter Δr measures the tendency of a sheet to deform non-uniformly during drawing, producing "ears" on an originally circular blank.

The value of $\bar{r}$ is usually close to 1 in hot rolled strip, but can be as high as 3 in premium quality thin sheet.

►

Technical assistance

Steel is a material that is constantly evolving in response to user requirements concerning formability, mechanical properties and surface coatings. Ongoing work and research on all aspects of drawing has provided us with a more detailed understanding of the behaviour of steel in different deformation modes, enabling the development of new forming techniques. Forming problems can be predicted before tool fabrication through the use of software that can be integrated into production routes which rely increasingly on computer technology.

The prediction of forming difficulties at the component design stage ensures that the chosen geometry is compatible with the drawability of steel.

Drawing has become a highly technical process, and the development of a steel forming route no longer involves simple trial and error methods. Close collaboration between component designers, drawing engineers and steelmakers guarantees the industrial feasibility of new parts with very short development times.

On demand ArcelorMittal can provide data for modelling the behaviour of its steels (tensile curves, forming limit curves, friction coefficients of various coatings etc).

As part of its technical support service, ArcelorMittal can perform simulations to optimise the choice of products and forming processes. The ArcelorMittal laboratories have test facilities and standard CAD and simulation software and the technicians have the expertise to ensure an efficient service is provided.

New opportunities are opening up for steel with the use of thinner sheets offering excellent mechanical properties, thus guaranteeing that users' specifications can be met.

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Credits

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