J Fail. Anal. and Preven.
https://doi.org/10.1007/s11668-026-02444-3

TOOLS AND TECHNIQUES

Understanding and Avoiding Sheet Forming Failures

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Submitted: 27 January 2026 / in revised form: 24 March 2026 / Accepted: 1 April 2026

Abstract Fabricated sheet metal parts remain susceptible to formability-related failures that can significantly disrupt operations and result in costly downtime. This paper defines failure in sheet forming as the onset of necking rather than final fracture and presents a practical, measurement-based framework to predict and prevent it. The paper demonstrates why hardness testing alone is inadequate for assessing coil-to-coil formability and advocates comprehensive tensile characterization beyond YTE (yield strength, tensile strength, total elongation) to include uniform elongation, strain-hardening exponent (n-value), plastic anisotropy (r-value), and characterization of elastic modulus behavior during deformation. Forming capability is quantified through Forming Limit Curves (FLCs) and Forming Limit Diagrams (FLDs), supported by grid-based strain mapping with circles/squares and non-contact camera systems. The related Thinning Limit Curve (TLC), derived via constant volume assumptions, enables rapid screening with ultrasonic thickness measurements. Guidance is also provided for robust virtual troubleshooting, and targeted corrective actions are recommended. The combined approach shortens troubleshooting cycles, reduces necking/splitting risk, and improves production reliability across alloys, tempers, and thicknesses.

Keywords Sheet metal formability · Necking · Forming limit curve (FLC) · Forming limit diagram (FLD) · Thinning limit curve (TLC) · Tensile testing · n-value · r-value · Elastic modulus · Simulation

Introduction

Manufacturing companies in nearly every industry create stamped parts from sheet metals. Over the years, improved understanding of forming processes has allowed for more robust production, but forming failures still periodically occur. Sheet forming failures divert resources from normal business activities and have significant bottom-line impact. Accurately defining the problem is a critical first step in determining effective corrective actions in any failure analysis. For many decades, hardness testing was used to assess the ease by which sheet metals can be converted into the targeted engineered shape. While hardness testing is the standard method to confirm the proper heat treatment of metal forming tools, it is not sufficiently sensitive to discern formability differences between multiple coils of the same sheet metal grade. This is partly because of the deformation mode differences: Hardness measures the resistance to indentation, whereas sheet forming processes bend, draw, and stretch the workpiece. To characterize sheet formability in these deformation modes, tensile testing is the preferred method.

This article is an invited paper selected from Failure Analysis Society programming presentations at IMAT 2025, held October 20–23, 2025, in Detroit, Michigan, and has been expanded from the original presentation. The issue was organized by Adam Boesenberg, Danfoss, on behalf of the ASM International Failure Analysis Society.

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Properties Determined from Tensile Testing of Sheet Metals

Tensile testing routinely characterizes the yield strength, tensile strength, and elongation to fracture—colloquially called the YTEs based on the first initial of each parameter. Determining YTE may be sufficient for thicker structural products that are made from bars or plates where bending is the primary deformation mode, but more information is needed to characterize stretchability and drawability.

For these, there needs to be an understanding of uniform elongation, n-value (also known as the strain-hardening exponent), and r-value (also known as plastic anisotropy or the Lankford coefficient). If simulation is used to predict dimensional conformance, then accurate measurements of elastic modulus in the sheet from the production mill—rather than relying on textbook values—is beneficial, as is capturing how the modulus changes with deformation during the forming process.

Uniform elongation is the engineering strain at the tensile strength. Prior to reaching uniform elongation, the gauge region in a tensile bar remains a rectangle, albeit longer, narrower, and thinner from the deformation. In this positive-sloping region of the engineering stress–strain curve, the strength increase from work hardening is greater than the loss of the load-carrying capability associated with the shrinking cross-sectional area.

A visual depiction of these parameters is given in Figure 1.

On tensile dogbones or stampings made from sheet metal, necking is the term given to regions of localized thinning. The metal is still contiguous and has not separated locally. Necks occur when strains generated during forming exceed the deformation capability of the chosen sheet metal. A stamped part will neck first prior to coming apart, with ductile fracture ultimately occurring at the location of the neck. The additional strain needed to progress from a neck to a fracture depends on the metal type and grade. Figure 2 shows necking in a formed part.

Diffuse necking begins once the strain exceeds uniform elongation. This post-uniform elongation is the negative-slope region of the engineering stress–strain curve where the influence of the decreasing thickness and width overtakes the impact of the work hardening strength increase. Additional strain from continued deformation concentrates in this zone, eventually leading to fracture.

In many applications, failure is defined as fracture. However, in sheet forming processes, necking is the initial failure mode. Once a stamping shows signs of necking, it can no longer withstand the design-intent stress. Applied stress may come from additional deformation from forming or during in-field usage including from durability based aspects like fatigue.

Forming strains are affected by metal flow, which is a function of part design, binder/addendum design, radii, lubricant, and the surface of both the sheet metal and the tooling. Wrinkles may restrict metal flow, leading to higher strains.

Work hardenability is the process by which all metals strengthen when deformed and is characterized by the strain-hardening exponent, abbreviated as the n-value. The strain-hardening exponent (n-value) is covered in ASTM Test Method E646 [2] and ISO 10275 [3] and is calculated as the slope of the ln(true stress) versus ln(true plastic strain) relationship, evaluated over a specified plastic strain interval prior to the onset of necking. Conventionally, this calculation incorporates stress–strain pairs between 10% and 20% strain or 10% and uniform elongation if uniform elongation is less than 20%. [See Appendix 1 for a brief discussion of the relationship between true and engineering stress–strain units] Rather than this constant n-value, constitutive models in forming simulation software make use of the changing n-value throughout the deformation process to more accurately characterize the strength at a given level of deformation. Although n-value does change somewhat with test sample orientation to rolling direction, many forming simulation software packages consider only the value in the rolling direction.

$$n = \frac{d(\ln\sigma)}{d(\ln\varepsilon)} \qquad \text{(Eq 1)}$$

Higher n-value can be visualized as a bigger gap between yield strength and tensile strength in an engineering stress–strain curve. In metal stampings, higher n-value manifests as an improved ability to distribute strains over a larger area and delay the strain localization that leads to necking and splitting.

The Plastic Anisotropy Ratio, also known as the Lankford Coefficient and abbreviated as the r-value, characterizes the sheet metal's resistance to thinning. The Lankford coefficient (r-value) is covered in ASTM Test Method E517 [4] and ISO 10113 [5] and is determined during uniaxial tensile deformation as the ratio of true plastic strain in the width direction to that in the thickness direction.

$$r = \frac{\varepsilon_w^p}{\varepsilon_t^p} \qquad \text{(Eq 2)}$$

Like n-value calculations, r-value is evaluated over a specified plastic strain interval prior to uniform elongation and necking. There is significant variation of r-value with the sample orientation relative to the rolling direction. Improved material characterization occurs with r-value measurement in the longitudinal, diagonal, and transverse (0°, 45°, and 90°) orientations rather than one direction alone.

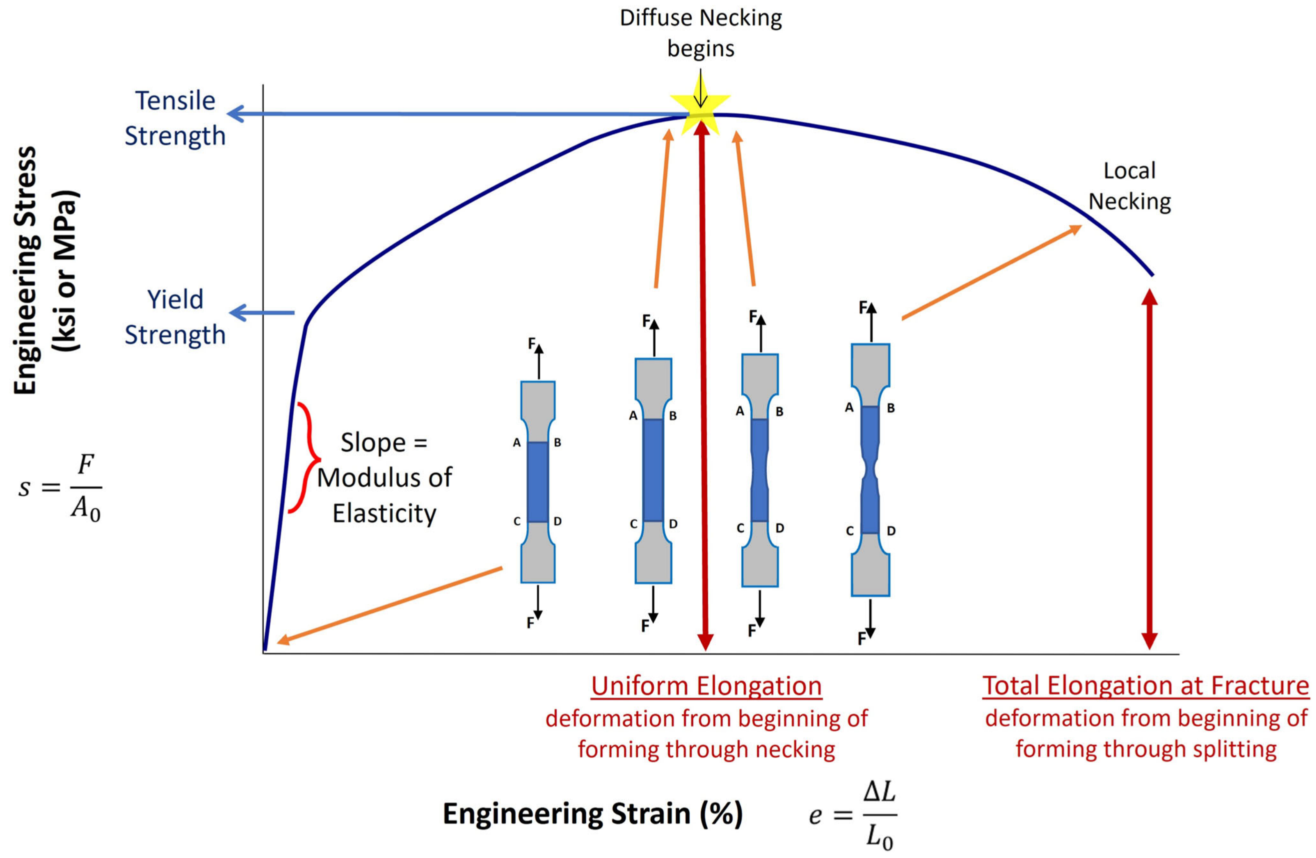

Fig. 1 Engineering stress–strain curve showing shape changes in the reduced section during testing.

Furthermore, thickness strains are challenging to measure directly during the tensile test. Here, incompressibility of the sheet metal is assumed, which based on constant volume, means that the true plastic strain in the thickness direction is the negative of the sum of the true plastic width strain plus the true plastic length strain.

$$\varepsilon_l^p + \varepsilon_w^p + \varepsilon_t^p = 0 \tag{Eq 3}$$

$$\varepsilon_t^p = -\left(\varepsilon_l^p + \varepsilon_w^p\right) \tag{Eq 4}$$

$$r = \frac{\varepsilon_w^p}{-\left(\varepsilon_l^p + \varepsilon_w^p\right)} \tag{Eq 5}$$

A way to visualize metal flow as characterized by r-value: During a tensile test, the test coupon elongates in the longest direction. The metal to feed this elongation must come from either the width or the thickness of the test coupon. A higher r-value means the width preferentially feeds the length. A lower r-value means that a more rapid thickness reduction occurs as the length of the tensile coupon increases.

Characterizing Necking Failure Limits in Metal Stampings

Metal forming tests attempt to replicate specific deformation modes. A tensile test determines the forming capability of a flat sample deformed in the plane of the sample by pulling in uniaxial tension. Necking failure is characterized by uniform elongation, with total elongation representing the fracture strain.

However, engineered stampings are formed with an out-of-plane punch forcing metal flow in different amounts in all directions from what might be a planar blank constrained at all edges. Here, failure characterization of metal stampings requires more than uniaxial tensile tests.

Metal flow can be visualized by affixing a grid pattern of circles to the flat blank surface, typically by etching or painting. The forming process changes the circles to ellipses, with the dimensions of the ellipse directly related to the magnitude of the surface strain. At each ellipse location, the longest dimension is related to the major strain, with the minor strain perpendicular. The change in thickness relative to the incoming sheet is the thickness strain.

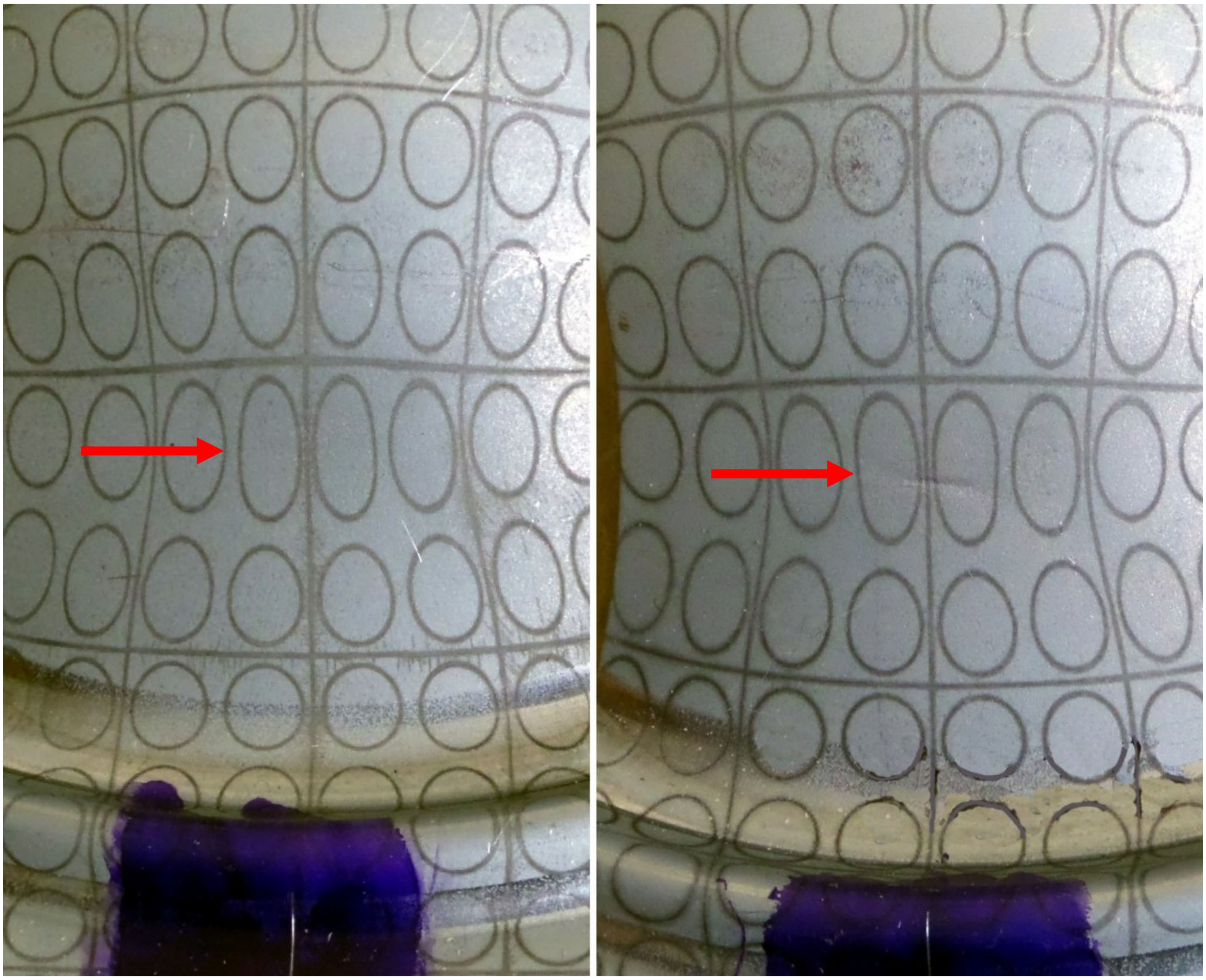

Fig. 2 Necking in a formed part. (a) Start of necking is easier to feel than see. (b) Visible neck not yet split open. [1] Reprinted with permission from Metal Forming Magazine and the Precision Metal Forming Association. Obtain figure from: https://www.metalformingmagazine.com/assets/issue/images/2019/01/Science/Example_of_necking_in_a_formed_part.jpg

Forming strains primarily are a function of part and process design, with sheet metal properties having only a small influence. It is possible to quantitatively compare the strain magnitude in different areas, but forming strains alone cannot assess whether the stamping process is sufficiently robust to the forming capabilities of the ordered sheet metal grade.

In contrast, the Forming Limit Curve (FLC) quantifies the ability of a given sheet metal to resist necking failure. The FLC is defined as the locus of points in a graph plotting major strain against minor strain representing the maximum strain just prior to necking initiation as a function of minor strain. [6–12]

When the forming strains are below the Forming Limit Curve by whatever safety margin is deemed appropriate, then the forming process is said to be robust with that sheet metal grade and the forming conditions used to produce the analyzed stamping.

Experimentally determining the FLC requires detailed testing on specialized equipment. Unlike a tensile test where the procedure is well understood and standardized equipment is available worldwide, FLC testing primarily is performed in research laboratories or universities. FLC determination by experimental means is covered in ASTM Test Method E2218 [13] and ISO 12004-2 [14].

Sheet metal forming capability is a function of the metal type, alloy, temper, and thickness. In some cases, it is also a function of the method of production available at different metal suppliers. Limited FLCs are available in the public domain due to the time and cost involved in their generation.

There is one exception: Keeler and Brazier [12] discovered that the FLC for low-carbon sheet steels can be estimated by an equation related only to the sheet thickness and strain-hardening exponent (n-value). The lowest point on the FLC, known as FLC_0, is estimated in engineering strain space as:

$$FLC_0 = (23.3 + 14.17t) \text{ x } (n/0.21), \qquad \text{(Eq 6)}$$

where t is the sheet thickness in mm and n is the strain-hardening exponent.

Major true strains on the left hand side of the FLC are calculated from constant thinning assumptions at each minor true strain. The major true strain–minor true strain relationship on the right hand side is linear with a slope of + 0.6 until the minor true strain reaches about 0.15, which encompasses the majority of stamped parts.

A related characterization is the Thinning Limit Curve (TLC), which assumes the sheet metal is incompressible. A metal stamping is formed from a flat blank of known dimensions. Prior to trimming, the volume of metal in the formed part is the same as the volume of the metal in the blank. Similarly, within each circle of precisely known diameter and thickness, forming changes only the dimensions but not the volume. The constant volume principle relates the major strain, minor strain, and thickness strain. These equations are in engineering strain space.

$$(e_{Ma} + 1) * (e_{mi} + 1) * (e_t + 1) = 1 \qquad \text{(Eq 7)}$$

Solving for thickness strain:

$$e_t = [1/((1 + e_{Ma}) \times (1 + e_{mi}))] - 1 \qquad \text{(Eq 8)}$$

The Forming Limit Curve shows the maximum major strain the metal can withstand prior to necking. The major–minor strain pair values of the FLC can be used in this equation to determine corresponding points on the Thinning Limit Curve, which plots Thinning Strain against Minor Strain.

Figure 3 shows graphically the relationship between the Thinning Limit Curve and a Forming Limit Curve with FLC_0 of 38%.

Characterizing Necking Failure Risk in Metal Stampings

Forming strain analysis is a well-established approach to determine if strains induced from stamping exceed the sheet metal forming capability. Understanding this technique involves the use of forming limit curves and forming limit diagrams. Schaeffler and Vineberg (2006) provide a detailed explanation [15].

In summary, a repeating grid pattern of circles or squares over the entire blank or in critical areas is used to establish initial dimensions from which forming strains are measured. After forming, the now-rectangles or now-ellipses are measured. Figure 1 shows an example of the ellipses present after forming. Since the metal flow is not constantly measured throughout the forming process and is instead measured only after the forming is complete, these measurements are made in the units of engineering strain.

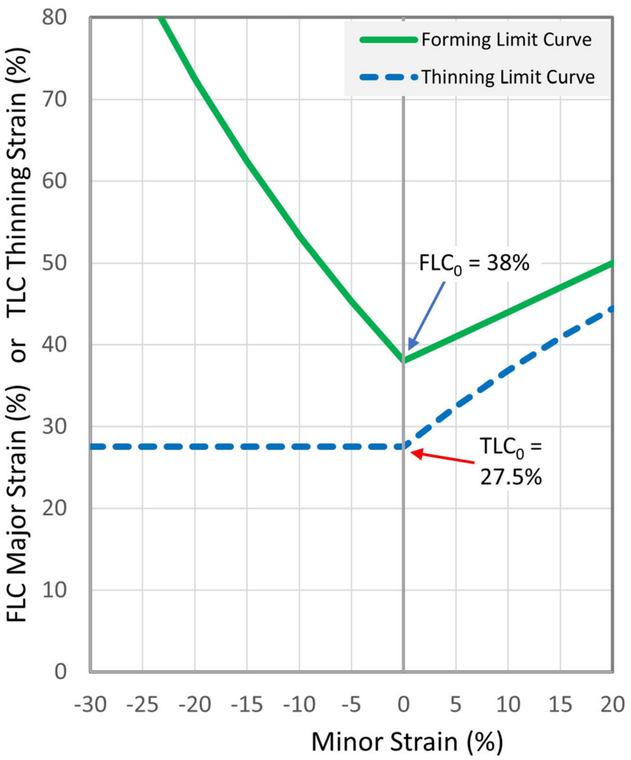

Fig. 3 Forming Limit Curve with the lowest point at 38% major strain and the associated Thinning Limit Curve generated based on constant volume assumptions. Using Equation 6, 0.80 mm extra deep drawing steel, as might be found on automotive body panels, can have FLC_0 = 38%.

Calibrated Mylar^{TM} strips are available to directly measure strains on deformed ellipses. Smaller diameter grid patterns allow for strain measurement in precisely localized areas, but typically comes at the expense of reduced accuracy.

Where circles/ellipses are easiest for visual measurements, squares/rectangles are preferred for camera-based systems. In this approach, the nodes at the corners of square/rectangle are tracked to determine forming strains. Camera-based systems are typically associated with increased accuracy, albeit at a substantially higher purchase price than the equipment needed for circle grid strain analysis analyzed with calibrated Mylar^{TM} strips.

Plotting the forming strains and the FLC together in the same graph creates the Forming Limit Diagram, or FLD. This approach gives a visual representation highlighting the panel areas with strains closest to the metal forming capability. Figure 4 shows the relationship between the FLC, the forming strains, and the FLD.

With this information, the user can then focus corrective actions in the areas most at risk for failure. Some options include additional tool polishing, using an engineered lubricant, or increasing the local tool radii. More extreme possibilities are product design concessions or a change in the sheet metal grade.

Thickness Strain Analysis is done using the same principles. The appropriate Forming Limit Curve is converted to a Thinning Limit Curve using Equation 8. Sectioning the part and measuring thickness with micrometers is one method to determine thinning strains. However, it is more efficient to use an ultrasonic thickness gauge calibrated for the alloy, coating, and thickness.

If all thickness strain measurements fall below TLC_0, the lowest point on the Thinning Limit Curve, then all locations will fall below the Forming Limit Curve—no grid measurements are needed. Locations with thinning strains above TLC_0 and negative minor strains are above the FLC, and therefore are areas of splitting concern. Locations measuring greater than TLC_0 but having positive minor strains may still be lower than the Forming Limit as a result of the FLC shape to the right of FLC_0. This is one of the merits of using grid strain analysis rather than thinning strain analysis.

Predicting Necking Failures Using Simulation

Virtual Forming Simulation can help solve sheet forming problems without needing the time and resources required for trial and error troubleshooting on the shop floor. Simulation can accurately predict forming strains when proper material properties are included along with the correct mechanics of the forming process combined with the current tooling geometry. Since there are sometimes significant changes from the tooling CAD file at the time of tool production, it is important to scan the current tools if formability troubleshooting is needed. When the current state can be modeled accurately, then rapid “what-if” scenarios can be evaluated virtually before making permanent changes to the tooling and process.

Most commercially available simulation software packages allow the user to input Forming Limit Curves for metals under investigation. Some provide a dropdown menu allowing for input of n-value and thickness and use Equation 6 to generate the Forming Limit Curve. However, since this equation was empirically developed using only low-carbon steels, there is a risk that the software user will improperly apply this approach to other alloys.

Simulation inputs must include complete and realistic material values to provide optimal benefit. Ideally, the simulation evaluates the impact of all potential property combinations possible within the metal specification. This requires knowing the minimum and maximum values for yield strength, tensile strength, total elongation, uniform elongation, strain-hardening exponent (n-value) and plastic anisotropy (r-value), in orientations parallel (longitudinal), perpendicular (transverse), and diagonal to the rolling direction. Typically, only longitudinal results are available, and only minimum values for yield strength, tensile strength and total elongation are defined. In reality, however, minimum yield strength is associated with total elongation at the high side of the property range, not the low side. Also, despite uniform elongation being a much more important measure of necking and formability, it is rarely included in industry metal specifications or on the metal production mill certified material property documents.

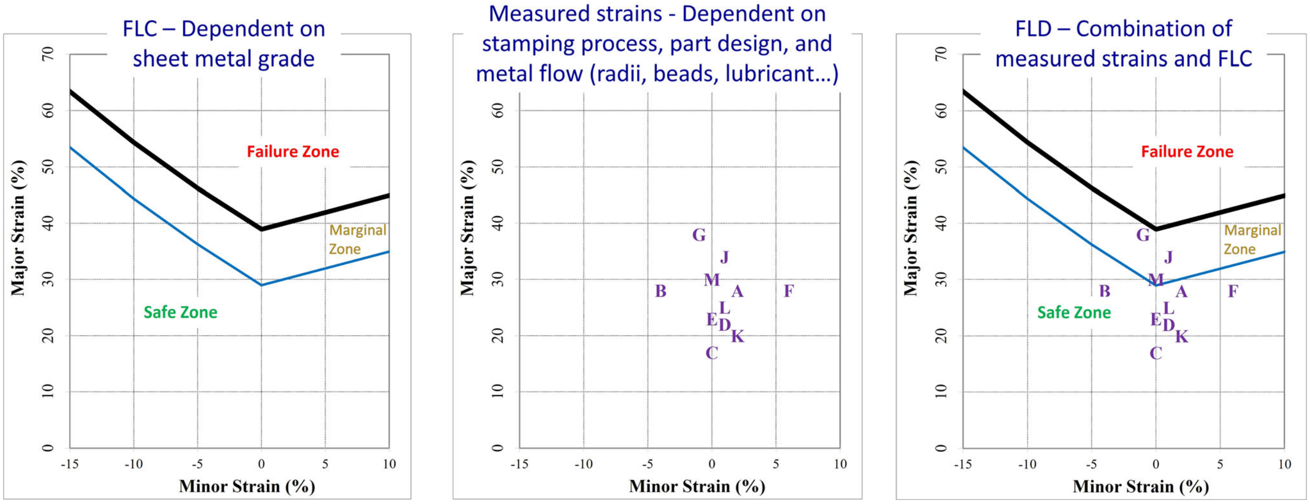

Fig. 4 Relationship between the Forming Limit Curve, the strains on the formed part, and the Forming Limit Diagram.

Simulations capturing Kinematic Hardening parameters have been shown to dramatically improve dimensional accuracy predictions [16–18], and as such are preferred tools to assess springback risk and make virtual adjustments to the die process before starting tool construction. These complexities of real-world behavior include Incorporation of accurate measurements of elastic modulus in the sheet from the production mill, the modulus decreases occurring with deformation during the forming process, and the Bauschinger effect introduced as the sheet bends and unbends as it goes over draw beads or moves over radii.

Summary

Sheet forming failures carry significant operational and financial impact. Robust sheet forming depends on characterizing the right mechanical properties, using FLC/FLD/TLC-based strain analysis, and feeding accurate, complete inputs into simulation tied to actual tool geometry. This combined approach minimizes necking and splitting risk, shortens troubleshooting cycles, and improves production reliability. Key takeaways are as follows:

- Traditional hardness testing is insufficient for assessing sheet metal formability; tensile testing is preferred and must go beyond YTE (yield strength, tensile strength, total elongation) to include uniform elongation, n-value (strain-hardening exponent), r-value (plastic anisotropy/Lankford coefficient), and accurate elastic modulus behavior during deformation.
- Necking—not fracture—is the primary failure mode in sheet forming. Uniform elongation marks the onset of diffuse necking; once necking appears, the part can no longer meet design-intent stresses and is vulnerable to further forming loads and in-service conditions (e.g., fatigue). Higher n-values delay strain localization and improve robustness; r-values characterize resistance to thinning and depend strongly on orientation (0°, 45°, 90° to rolling direction).
- Forming Limit Curves (FLCs) define the strain boundary for necking initiation across minor strain states, enabling a robust process when measured strains sit below the FLC by an appropriate margin.
- FLC shape and position varies with metal type, alloy, temper, thickness, and sometimes other supplier processes. An empirical approximation developed in the 1960s applies only to low-carbon steels and is based on the sheet thickness and strain-hardening exponent (n-value).
- Experimentally determining the FLC requires specialized laboratory equipment and testing methods such as ASTM E2218 and ISO 12004-2.
- Forming strain analysis via circle/square grids measured manually or non-contact camera systems combined with the FLC yields a Forming Limit Diagram (FLD), highlighting areas closest to failure. Corrective actions can then be targeted (e.g., tool polishing, engineered lubricants, larger radii, product design changes, or material grade changes).
- Thinning Limit Curves (TLCs) derived from constant volume relate major/minor strains to thickness strain. Ultrasonic thickness measurement can efficiently measure thinning without the need to cut the sample into smaller sections to facilitate measurement with micrometers or calipers. If all measured thinning strains are below the critical threshold, it is mathematically equivalent to state that the part will be below the FLC everywhere; locations with thinning above the threshold may indicate splitting risk.
- Simulation can accelerate troubleshooting when it reflects the true current state. Successful simulation requires accurate material inputs, correct process mechanics, and up-to-date tool geometry. Beware of software shortcuts that auto-generate FLCs from n-value and thickness, as they were developed for low-carbon steels and may mislead for other alloys.

Appendix 1

Engineering Stress–Strain vs. True Stress–Strain

Strain measurements are always given relative to a starting dimension. A common example is elongation, which is presented as XX% elongation in 50 mm. When the reference dimensions are fixed, such as the initial width and thickness of a tensile dogbone sample, then those measurements are in engineering units.

Reality, however, is different. During a tensile test, the width and thickness continuously decrease as the length increases. When the instantaneous stress and instantaneous strain are measured relative to the exact dimensions of the sample at that particular time, then those measurements are in true units. True units provide a much better representation of how the material behaves as it is being deformed, which explains its use in forming simulations.

Of course, unless thickness and width are continuously monitored during the test, it is impossible to derive true stress and true strain directly from the test. For this, the relationships shown in Table 1 are used.

Table 1 Relationships between engineering and true properties

P = load	
A_o = initial cross-sectional area	A_i = instantaneous cross-sectional area
l = length of deformed gauge section	l_o = initial length of gauge section
l_i = instantaneous gauge length	Δl = change of length of gauge section
Engineering Stress = s = P/A_o	True Stress = σ = P/A_i
Engineering Strain = e = $(l-l_o)/l_o = \Delta l/l_o$	True Strain = ε = $\ln(A_o/A_i) = \ln(l_i/l_o)$
Stress:	$\sigma = s\,(1 + e)$
Strain:	$\varepsilon = \ln(1 + e)$

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