Forming Limits and Strain Analysis

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Tensile testing is fast, easy, and well understood.

Characterizes sheet metal
Characterizing Part Formability with Tensile Testing
Effect of Gauge Length

Measuring peak strain: How small can we get?
Repeating Pattern = Grid

- Start with a circle with initial diameter $L_i$. Deform the blank.
- The circle is now an ellipse.
- The length of the longest dimension of the ellipse is $L_{Ma}$.
- The length perpendicular to the longest dimension is $L_{mi}$.

$e_{Ma} = \text{Major Strain (\%)} = 100 \times \left( \frac{L_{Ma} - L_i}{L_i} \right)$

$e_{mi} = \text{Minor Strain (\%)} = 100 \times \left( \frac{L_{mi} - L_i}{L_i} \right)$

The major strain is always positive, and always greater than the minor strain.
Measuring Strains on a Tensile Bar
Characterizing Part Formability with Tensile Testing
Each Sheet Metal Grade and Thickness has its own Forming Limit Curve

- Just one strain path
- Need many strain paths
Each Sheet Metal Grade and Thickness has its own Forming Limit Curve
Forming Limit Curves are a MATERIAL Property

A unique curve shape and location can be produced for
Every sheet metal type (aluminum, stainless, copper, etc.)
Every sheet metal grade (AA6061, AA6111, AA6022, etc.)
Every sheet metal supplier (Arconic, Novelis, Aleris...)
Every thickness

Except...
Steel (most)

FLC₀ = (23.3 + 14.2*t) * (n/0.21)
[t = sheet thickness in millimeters]

FLC₀ = (23.3 + 360*t) * (n/0.21)
[t = sheet thickness in inches]
Computer Forming Simulation (virtual forming)

Include FLC in Virtual Forming

Is this good enough for tooling development and buyoff?
Tooling Development & Buyoff... Why Not Rely on Simulation?

Many assumptions:

- known friction
- uniform friction
- ideal mechanical properties
- ideal draw bead representation
- no effect of surface roughness
- no effect of die material, die coating or wear
Each grade has a **range** of normal properties

- Specification requires yield strength between 210 MPa and 300 MPa
  - (30,500 psi to 43,500 psi or 30.5 ksi to 43.5 ksi)
- During development, you receive sheet metal with 220 MPa Yield Strength
- During production, you receive sheet metal with 290 MPa Yield Strength
- Both are within specification and are within normal range for the grade

**Tooling must be sufficiently robust to handle this normal range.**
Determining if Tooling Can Produce Good Parts over Range of Material Properties

Hands-on manual and optical (non-contact) strain analysis

- Thickness Strain Analysis
- Circle Grid Strain Analysis
- Square Grid Strain Analysis
Benefits of Strain Analysis

Split-free panels over entire property range?

What if?

- Thicker (better formability) or thinner (lighter/cheaper)
- Less formable grade (cheaper)

Troubleshooting

Reference panel documentation

Statistical Process Control
Thinning Strain Analysis

Should be done on all parts.

- Rapid

- Limited training needed

- If passing thinning strain analysis, then by default it will pass grid strain analysis

- Even if a part fails thinning strain analysis, it may still pass square/circle grid analysis

  - You will not know this until a square / circle grid strain analysis is done.
Types of Strain Analysis: Sample Preparation

Hands-on manual and optical (non-contact) strain analysis

- Thickness Strain Analysis
- Circle Grid Strain Analysis
- Square Grid Strain Analysis
Thickness Strain Analysis
Sample Prep and Measurement Tools
Grid Strain Analysis
Sample Prep

Take blank off lift

Clean off residual oil

Electrochemically etch surface with grid pattern

Reapply lube
Deformation Modes

- **Draw Deformation**
  - Negative minor strain
  - Circle diameter is greater than the ellipse minor axis

- **Plane Strain Deformation**
  - Zero minor strain
  - Circle diameter is equal to the ellipse minor axis

- **Stretch Deformation**
  - Positive minor strain
  - Circle diameter is less than the ellipse minor axis
Forming Limit Curve
Safety Margin (Safety Factor)
Forming Limit Curve

\[ FLC_0 = (23.3 + 14.2t) \times (n/0.21) \]
Constant Volume

\[(e_{Ma} + 1) \times (e_{mi} + 1) \times (e_t + 1) = 1\]
Forming Limit Curve

\[ FLC_o = (23.3 + 14.2t) \times \left( \frac{n}{0.21} \right) \]

\[ (e_{Ma} + 1) \times (e_{mi} + 1) \times (e_t + 1) = 1 \]

\[ e_t = \frac{1}{(e_{Ma} + 1) \times (e_{mi} + 1)} - 1 \]
Thinning Limit Curve

\[ FLC_0 = (23.3 + 14.2t) \times (n/0.21) \]

\[ (e_{Ma} + 1) \times (e_{mi} + 1) \times (e_t + 1) = 1 \]

\[ e_t = \frac{1}{(e_{Ma} + 1) \times (e_{mi} + 1)} - 1 \]

\[ TLC_0 = e_{tf} = \frac{1}{(FLC_0 + 1) \times (0 + 1)} - 1 \]
Thinning Strain instead of Grid Strain Analysis

To pass thinning strain analysis, all locations must have thinning strains lower than the bottom dashed line.

For minor strains at zero or negative, the part will pass if thinning strain is less than 29%. [this example only]

For positive minor strains, the threshold is > 29%.

Most conservative: Use max 29% for all minor strains.

- If thinning <29% at all areas, then the part is safe. No grid analysis is needed. Thinning analysis alone is sufficient.

What if part thins by more than 29% and there are positive minor strains? This is the case that square or circle grid analysis is best used for.
Grid Strain Analysis (Square or Circle) vs Thinning Strain Analysis

Must interrupt the normal process flow.


Measurement error possibility

- The template/stencil has a 2% error maximum in it.
- The thickness of the etched line that makes up the perimeter of the circle is close to the thickness of the line that makes up the diverging lines of the calibrated Mylar scale (the railroad tracks)
- Lighting/parallax can influence the reading

Significantly more time consuming in grid application & strain analysis.

But... you lose “bonus zone” on the RH side (positive minor strains).
Circle Grid Strain Analysis vs Square Grid Strain Analysis

10% minor strain 60% major strain
Measuring Strains: Calibrated Mylar Strip

10% minor strain  
60% major strain
Measuring Strains: Calibrated Mylar Strip

**Wrong** – diverging scale lines are inside the ellipse etched lines

**Wrong** – diverging scale lines are outside the ellipse etched lines

**Wrong** – diverging scale lines are not perpendicular to the minor axis

**Correct** – proper position on the diverging scale lines to the minor axis and the ellipse etched line
Circle Grid Strain Analysis

Must use proper technique to get accurate result

Correct

Incorrect

Incorrect

Line width
= 0.008 inch
= 0.020 mm
= 20 microns
Circle Grid Strain Analysis

Must use proper technique to get accurate result

Correct  Incorrect  Incorrect

<table>
<thead>
<tr>
<th>Location</th>
<th>Major Strain (%)</th>
<th>Minor Strain (%)</th>
<th>Safety Margin (%)</th>
<th>Status</th>
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<tr>
<td>E</td>
<td>28</td>
<td>8</td>
<td>7</td>
<td>marginal</td>
</tr>
</tbody>
</table>
Confirming Measurements
Thinning strain (%) = $e_t = \frac{\text{formed part thickness} - \text{initial blank thickness}}{\text{initial blank thickness}} * 100\%$
Square Grid Strain Analysis

Same math and science as circle grid strain analysis

- Still need clean/crisp grid pattern

Main difference is cameras instead of eyes

- Full field (some)
- Objective
- Accurate
Square Grid Strain Analysis
One Square at a Time

Need to know where to look
Square Grid Strain Analysis
Full Field

Multiple Images needed to blanket part

Image from www.Shiloh.com
Forming Limit Curve – Forming Limit Diagram

FLC – Dependent on sheet metal grade

Measured strains - Dependent on stamping process, part design, and metal flow (radii, beads, lubricant...)

FLD – Combination of measured strains and FLC

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What is the grid strain analysis on this part formed today telling us?

Area G needs some work, and areas J and M could use some touchup to get slightly better metal flow. Probably not too much effort needed.
What if worst case properties are used?

The part/process/sheet metal is NOT robust!
Must have all strains below the lowest line...
Do not buy off tools yet!
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