Forming Limits and Strain Analysis

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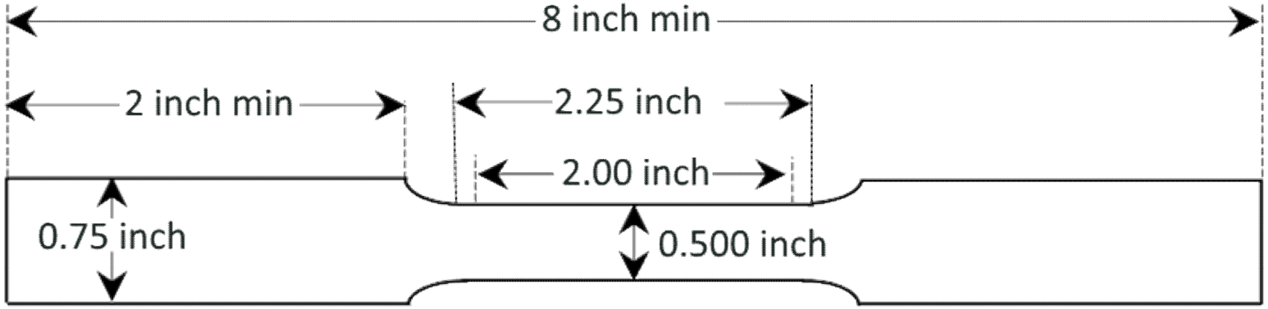
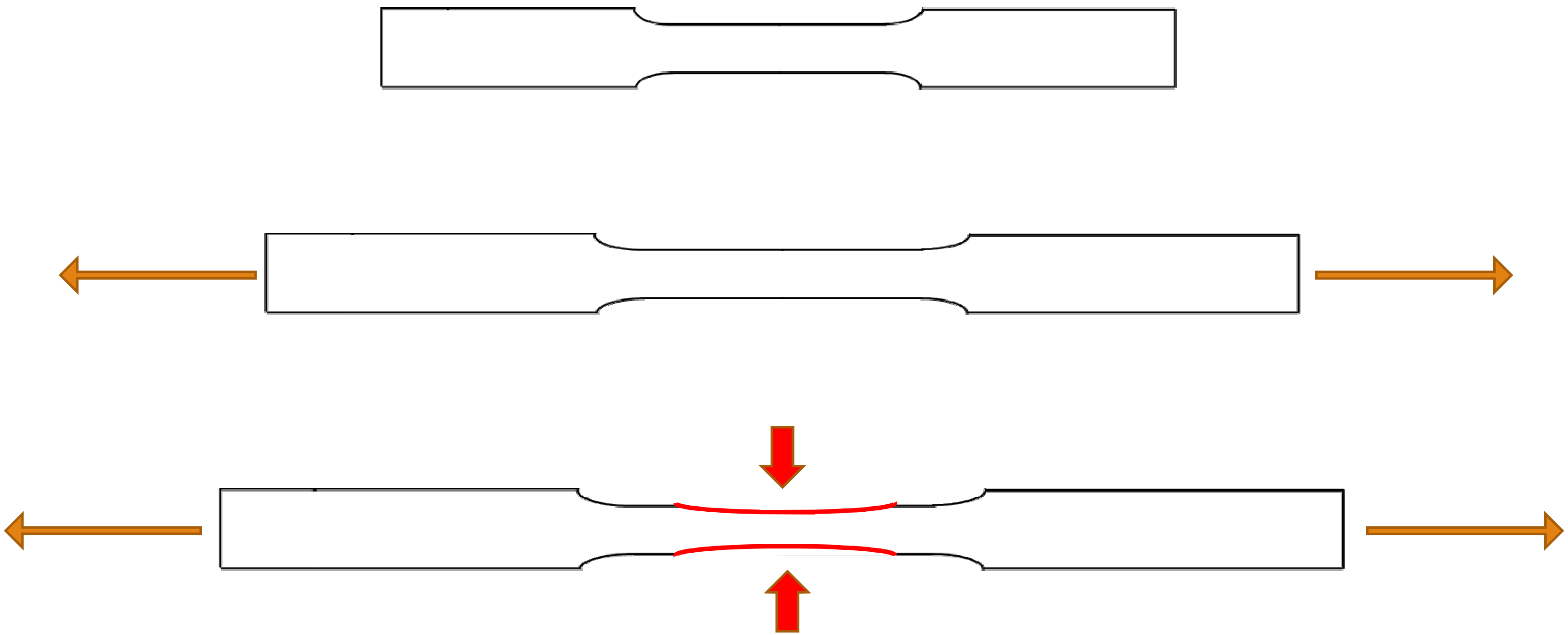
Tensile Testing

Tensile testing is fast, easy, and well understood.

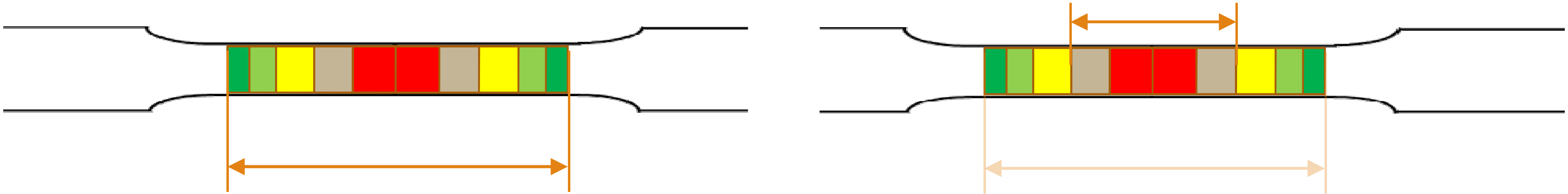
Characterizes sheet metal

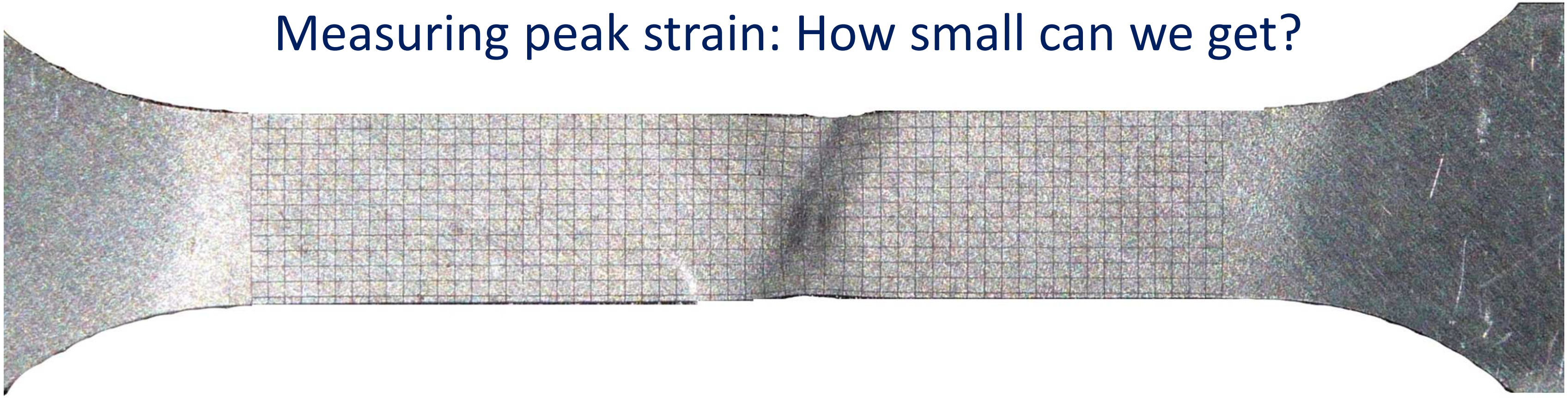


Characterizing Part Formability with Tensile Testing

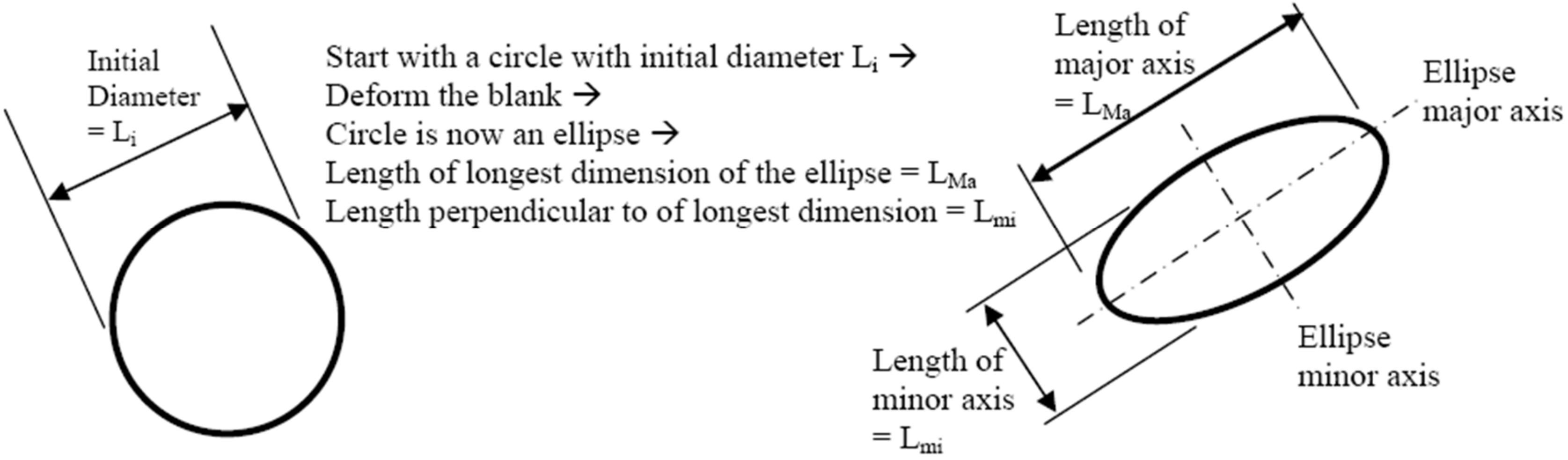


Effect of Gauge Length





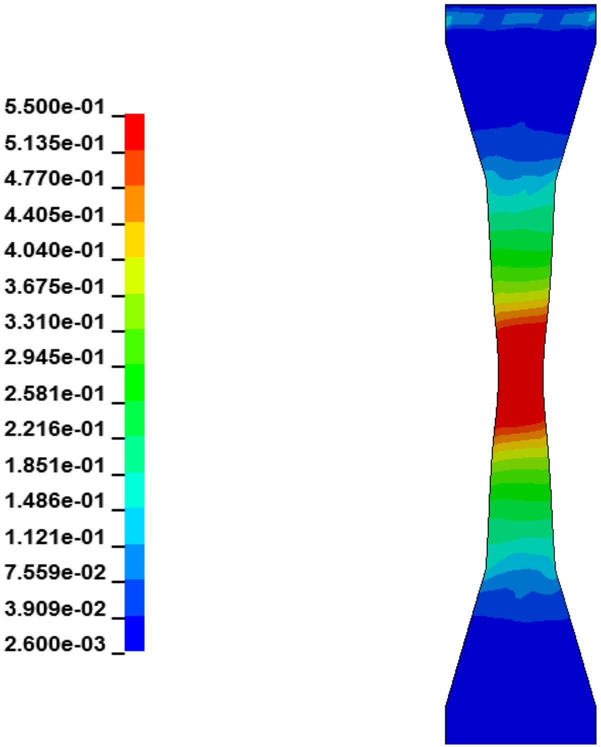
Repeating Pattern = Grid

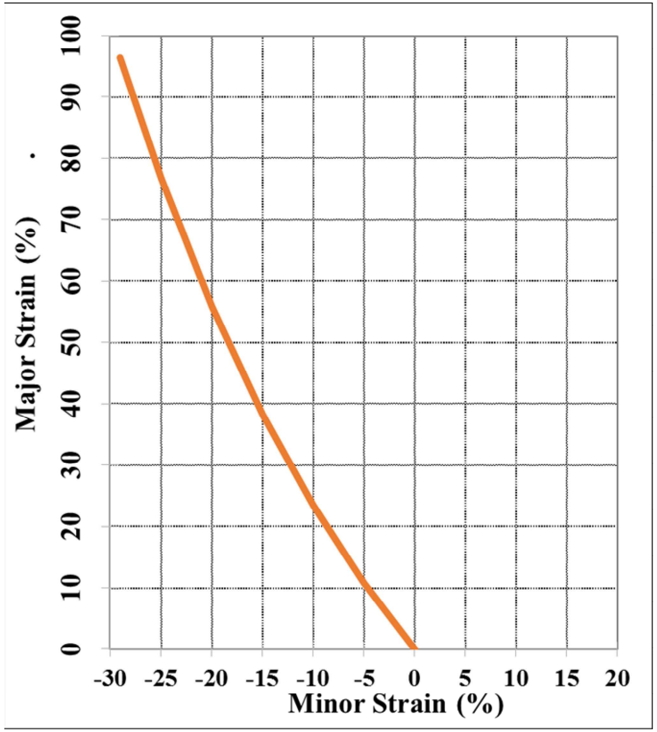


e_{Ma} = Major Strain (%) = $100 * \left(\frac{L_{Ma} - L_i}{L_i}\right)$ e_{mi} = Minor Strain (%) = $100 * \left(\frac{L_{mi} - L_i}{L_i}\right)$

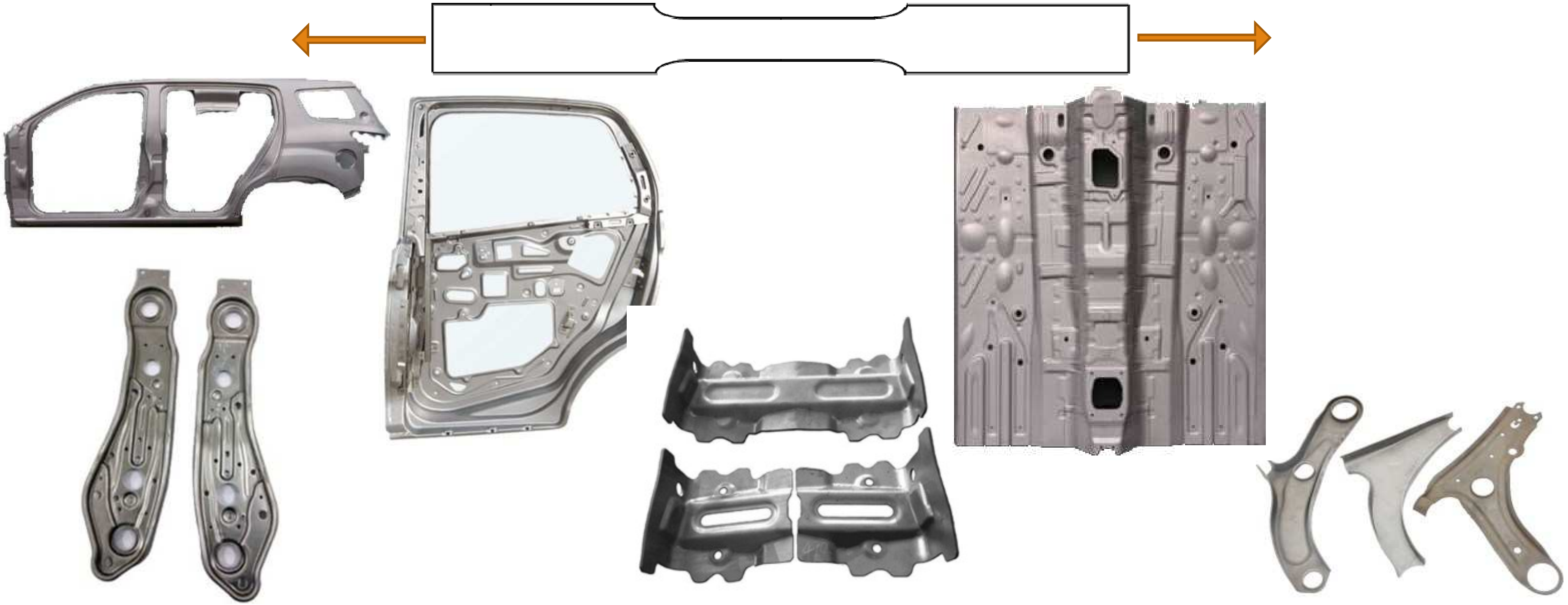
The major strain is always positive, and always greater than the minor strain.

Measuring Strains on a Tensile Bar

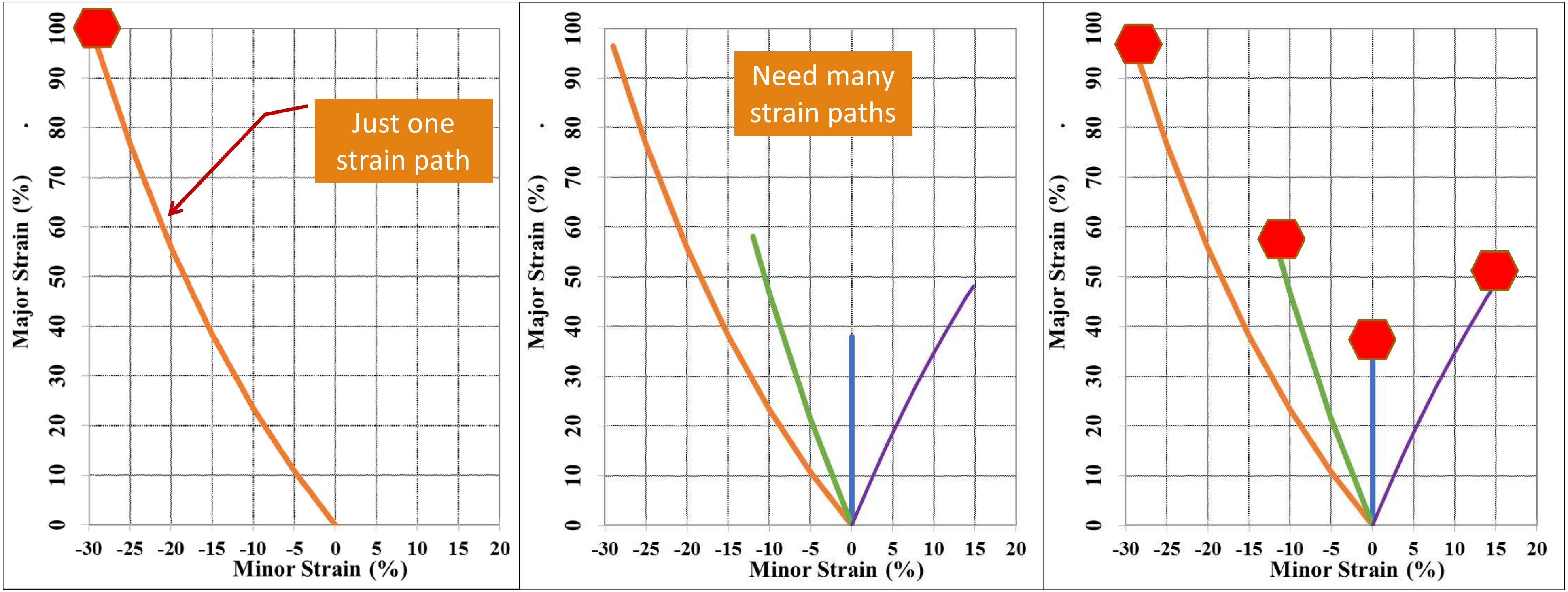




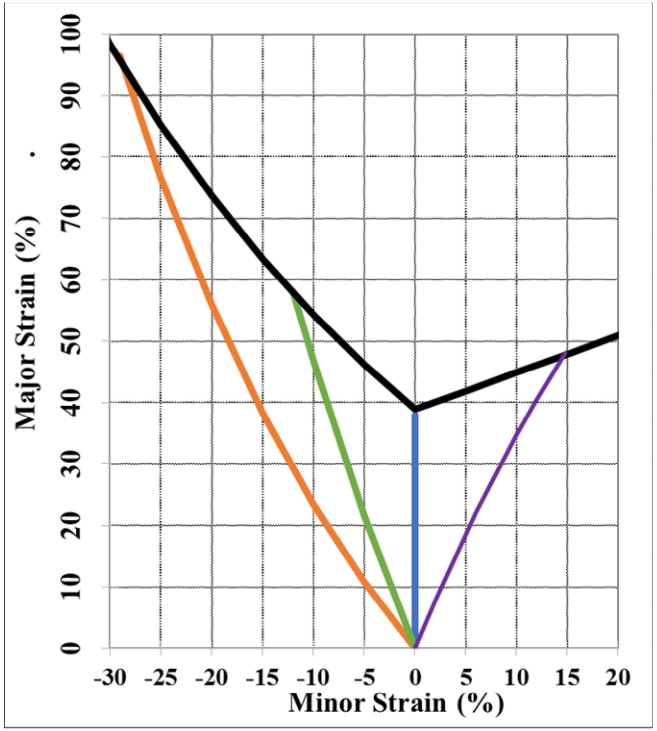
Characterizing Part Formability with Tensile Testing



Each Sheet Metal Grade and Thickness has its own Forming Limit Curve



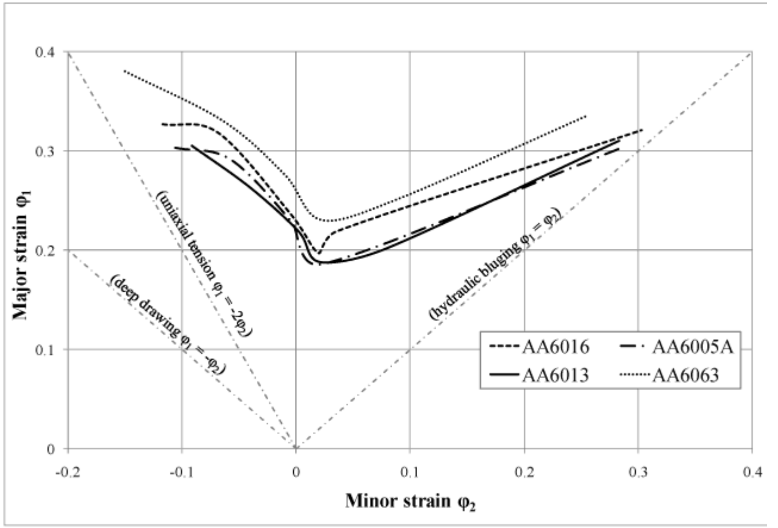
Each Sheet Metal Grade and Thickness has its own Forming Limit Curve



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

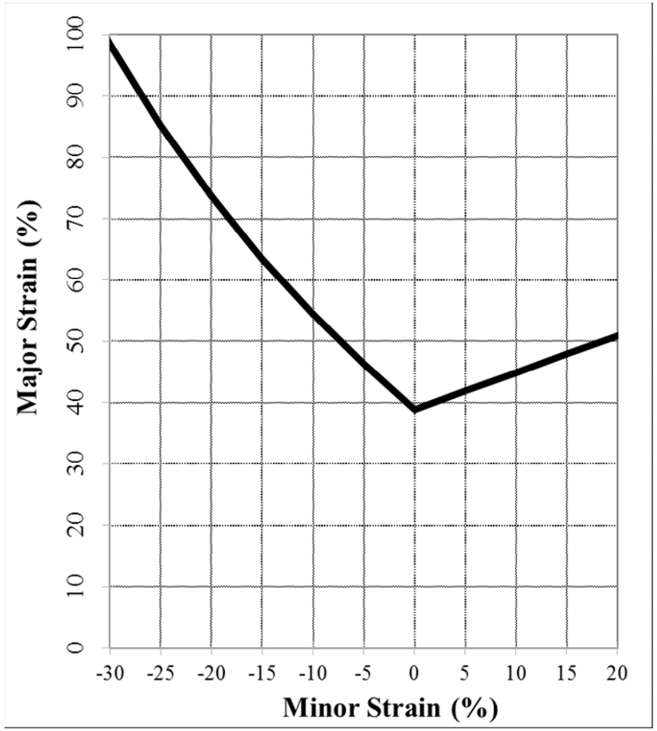


Except…

Steel (most)

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

$FLC_o = (23.3 + 360*t) * (n/0.21)$
[t = sheet thickness in inches]



Computer Forming Simulation (virtual forming)

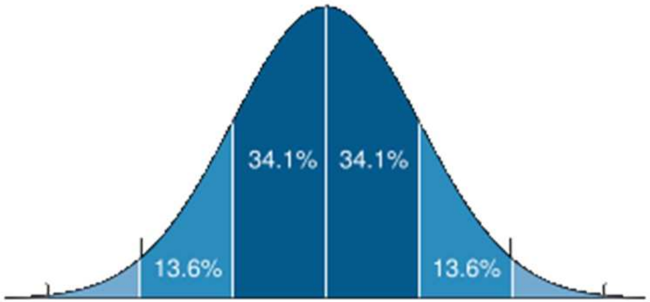
Include FLC in Virtual Forming

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



Tooling Development & Buyoff

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

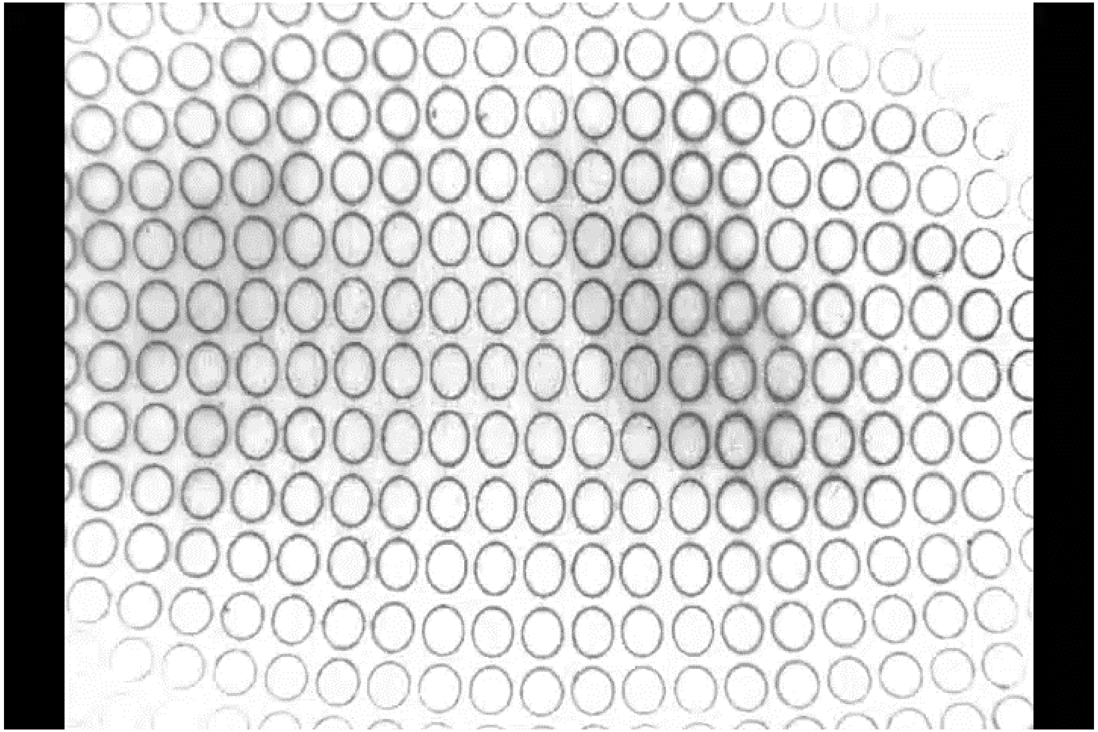
Grid Strain Analysis
Sample Prep

Take blank off lift

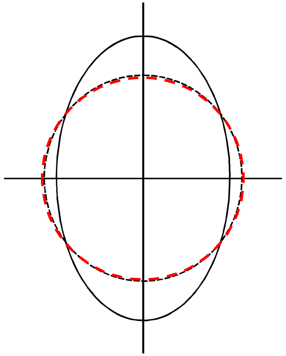
Clean off residual oil

Electrochemically etch surface with grid pattern

Reapply lube



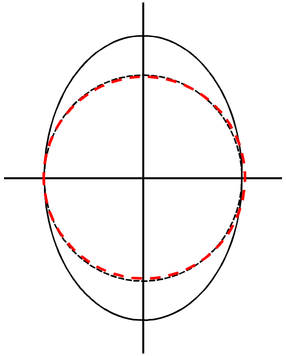
Deformation Modes



Draw Deformation

Negative minor strain

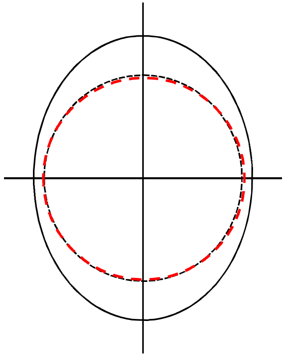
Circle diameter is greater than the ellipse minor axis



Plane Strain Deformation

Zero minor strain

Circle diameter is equal to the ellipse minor axis

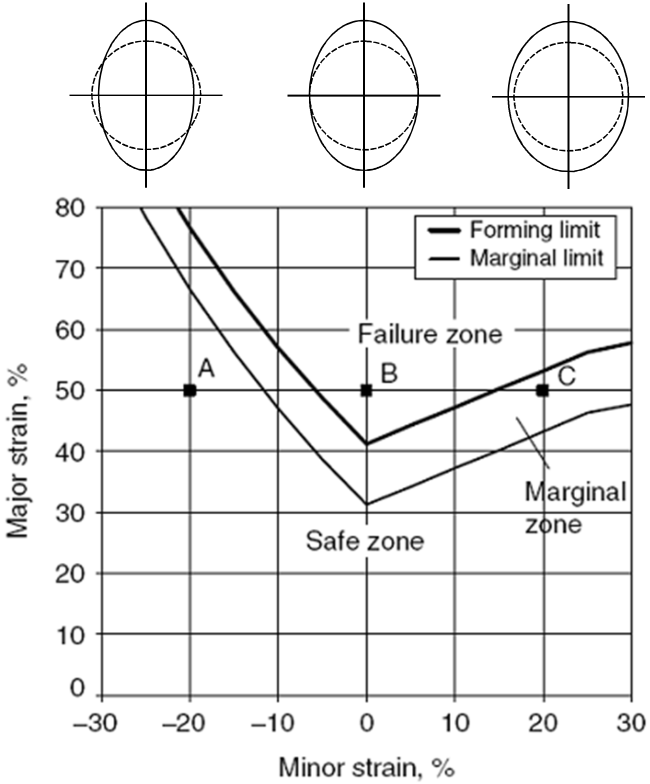


Stretch Deformation

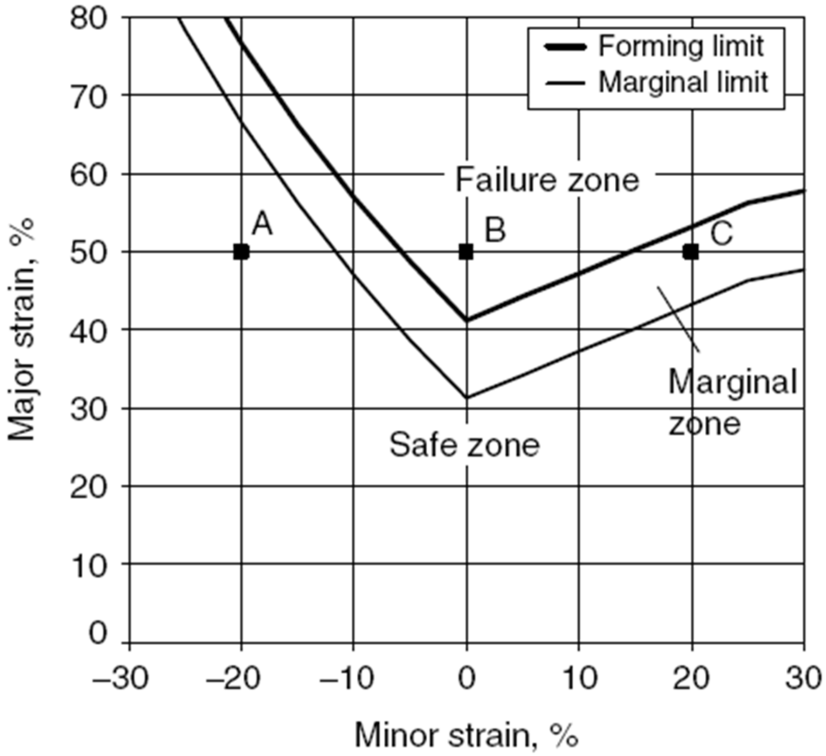
Positive minor strain

Circle diameter is less than the ellipse minor axis

Forming Limit Curve

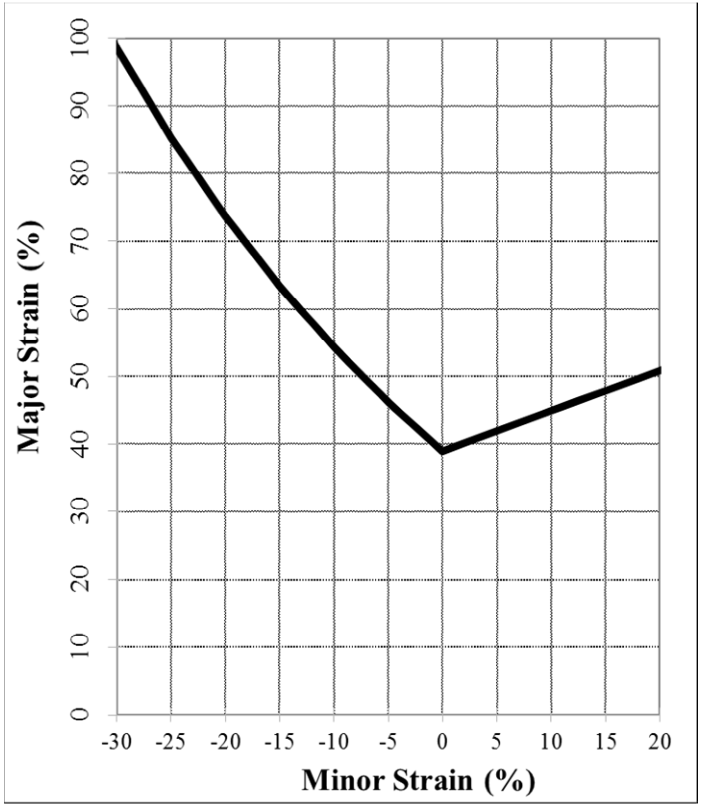


Safety Margin (Safety Factor)



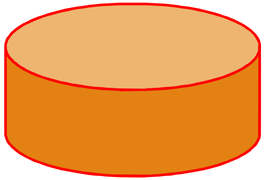
Forming Limit Curve

$FLC_o = (23.3 + 14.2*t) * (n/0.21)$

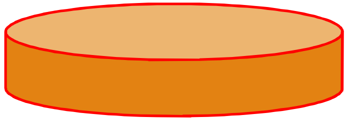


Constant Volume

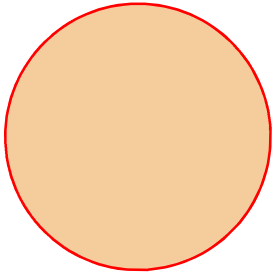
$$(e_{Ma}+1) * (e_{mi}+1) * (e_t+1) = 1$$



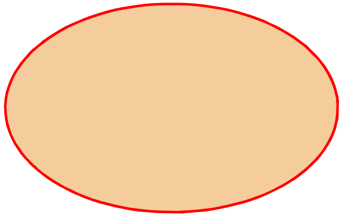
Side view before forming



Side view after forming



Top view before forming



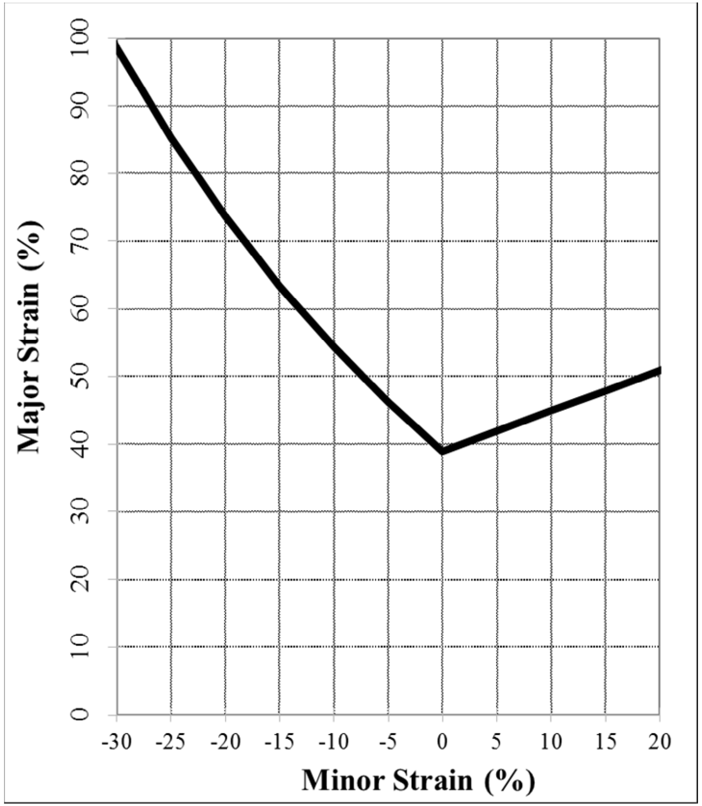
Top view after forming

Forming Limit Curve

$$FLC_o = (23.3 + 14.2*t) * (n/0.21)$$

$$(e_{Ma} + 1) * (e_{mi} + 1) * (e_t + 1) = 1$$

$$e_t = \frac{1}{(e_{Ma} + 1) * (e_{mi} + 1)} - 1$$



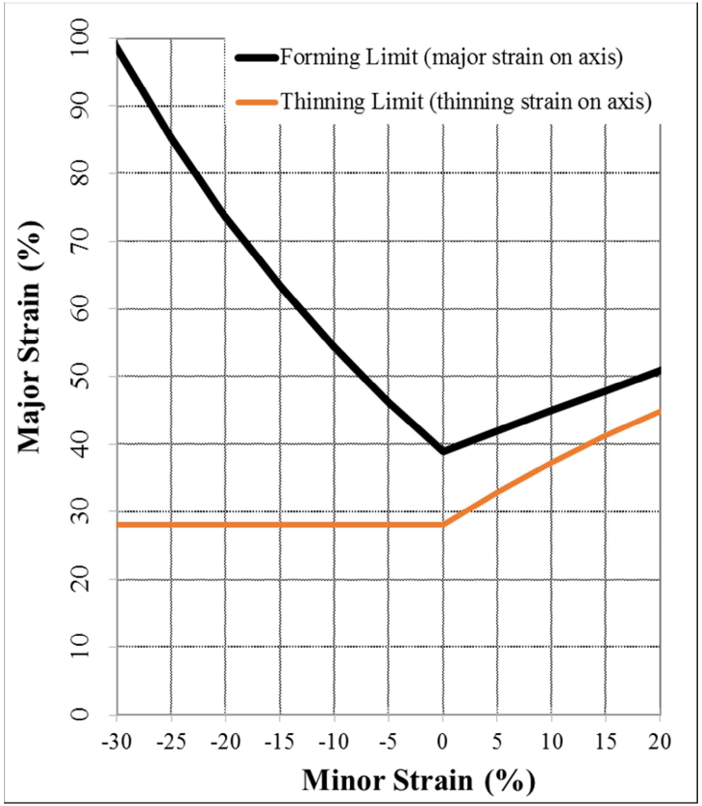
Thinning Limit Curve

$$FLC_o = (23.3 + 14.2*t) * (n/0.21)$$

$$(e_{Ma} + 1) * (e_{mi} + 1) * (e_t + 1) = 1$$

$$e_t = \frac{1}{(e_{Ma} + 1) * (e_{mi} + 1)} - 1$$

$$TLC_0 = e_{tf} = \frac{1}{(FLC_o + 1) * (0 + 1)} - 1$$



Thinning Strain instead of Grid Strain Analysis

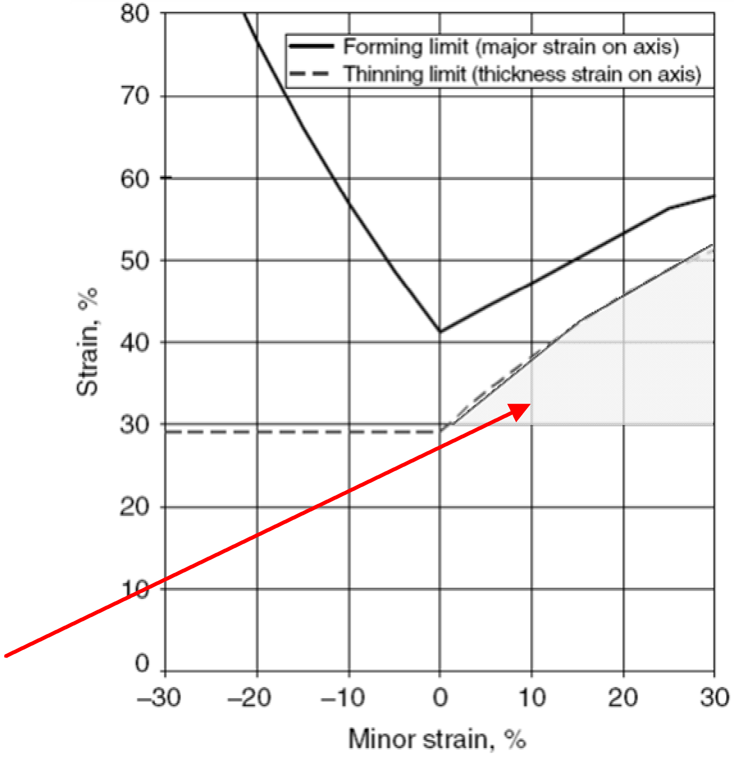
To pass thinning strain analysis, all locations must have thinning strains lower than the bottom dashed line.

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

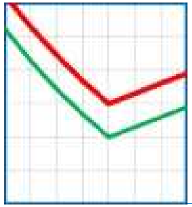
For positive minor strains, the threshold is > 29%.

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.

- Take blank off stack. Clean off residual oil. Electrochemically etch surface. Reapply lube in the same manner/quantity/distribution.

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

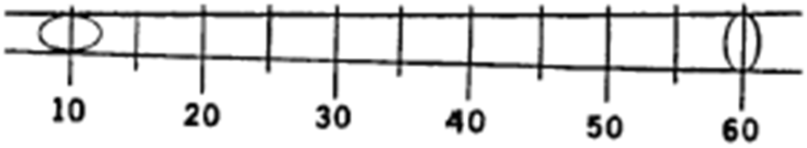
Significantly more time consuming in grid application & strain analysis.

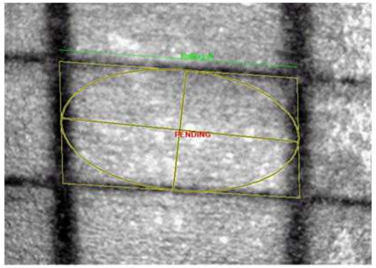
But... you lose “bonus zone” on the RH side (positive minor strains).

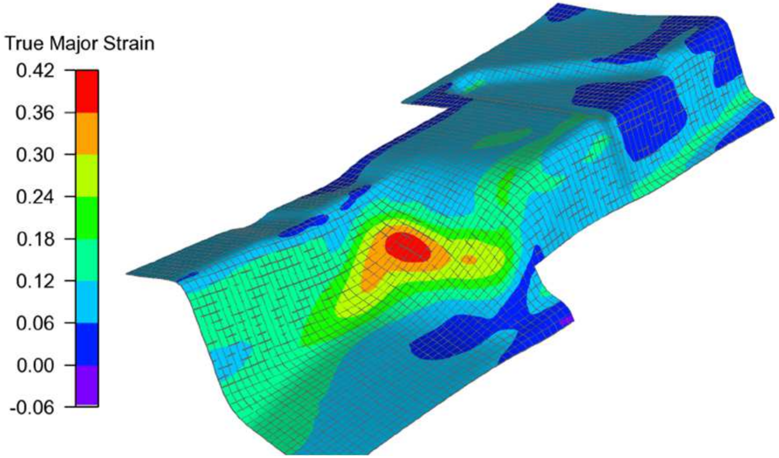
Circle Grid Strain Analysis vs Square Grid Strain Analysis

10% minor strain

60% major strain



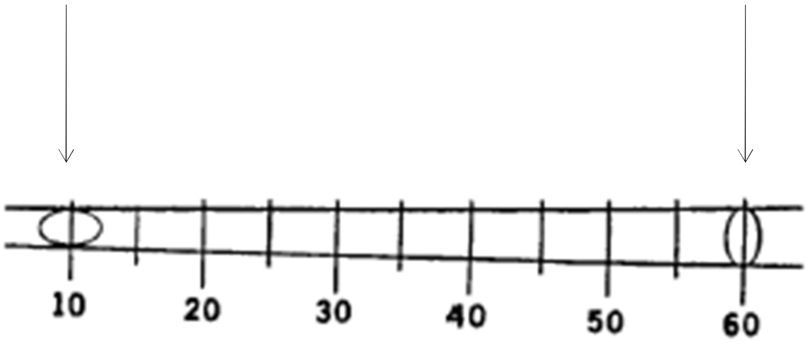




Measuring Strains: Calibrated Mylar Strip

10% minor strain

60% major strain



Measuring Strains: Calibrated Mylar Strip

Wrong – diverging scale lines are inside the ellipse etched lines

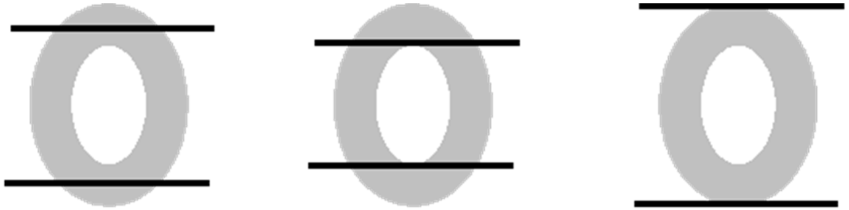
Wrong – diverging scale lines are outside the ellipse etched lines

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

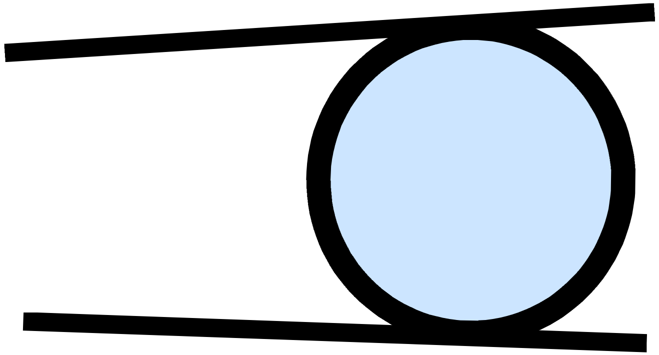
Correct – proper position on the diverging scale lines to the minor axis and the ellipse etched line

Circle Grid Strain Analysis

Must use proper technique to get accurate result



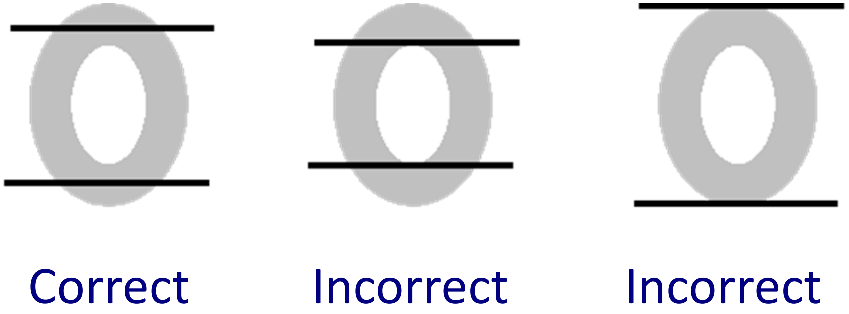
Correct Incorrect Incorrect



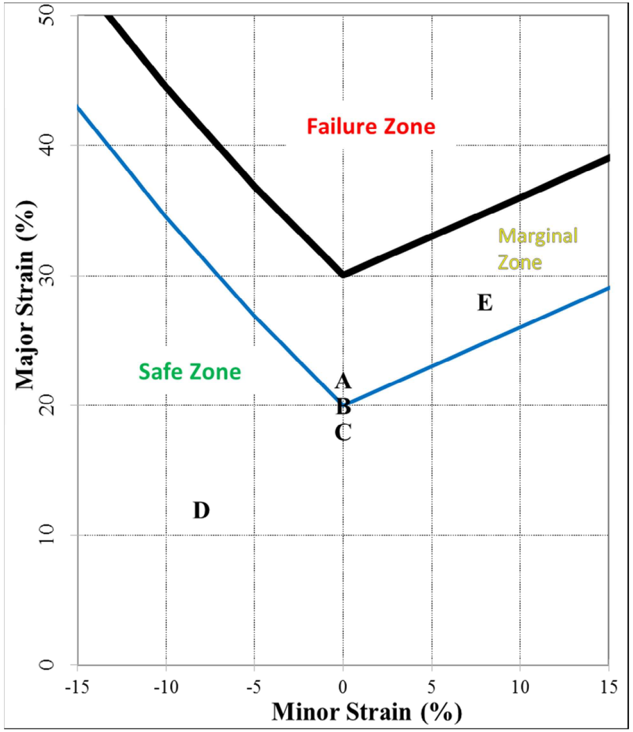
Line width
= 0.008 inch
= 0.020 mm
= 20 microns

Circle Grid Strain Analysis

Must use proper technique to get accurate result



Location	Major Strain (%)	Minor Strain (%)	Safety Margin	
			(%)	Status
A	22	0	8	marginal
B	20	0	10	safe
C	18	0	12	safe
D	12	–8	29	safe
E	28	8	7	marginal



Confirming Measurements

Thinning Must Equal Thinning

$$(e_{Ma} + 1) * (e_{mi} + 1) * (e_t + 1) = 1, \quad \text{or} \quad e_t = \frac{1}{(e_{Ma} + 1) * (e_{mi} + 1)} - 1$$

$$\text{Thinning strain (\%)} = e_t = \frac{\text{formed part thickness} - \text{initial blank thickness}}{\text{initial blank thickness}} * 100\%$$

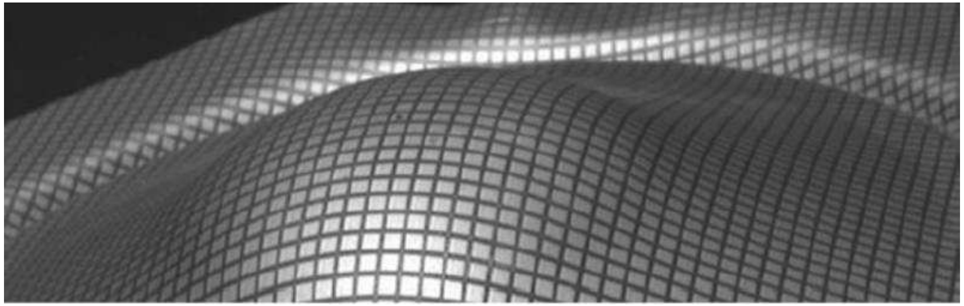
Square Grid Strain Analysis

Same math and science as circle grid strain analysis

- Still need clean/crisp grid pattern

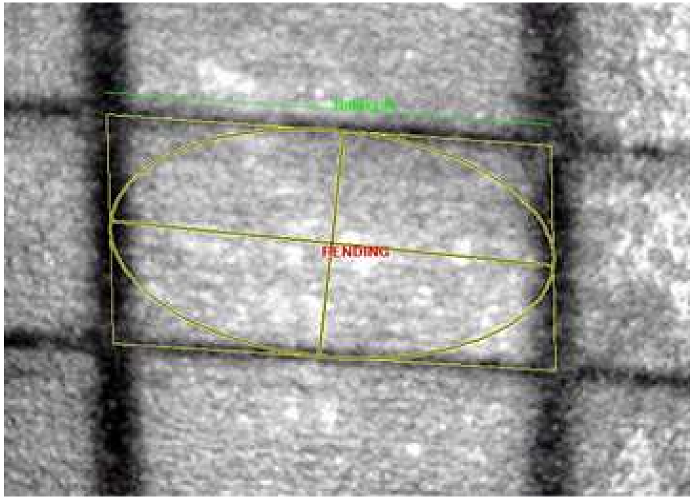
Main difference is cameras instead of eyes

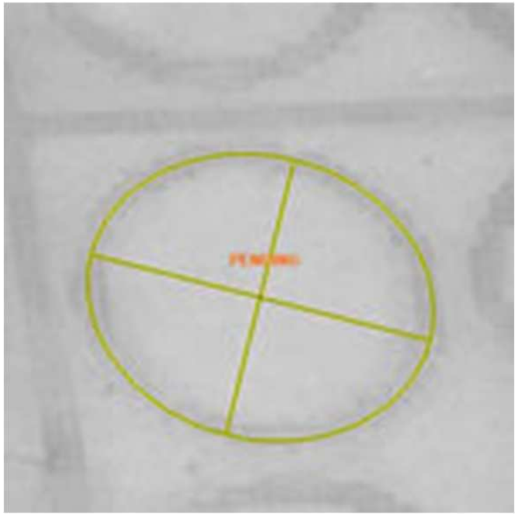
- Full field (some)
- Objective
- Accurate



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

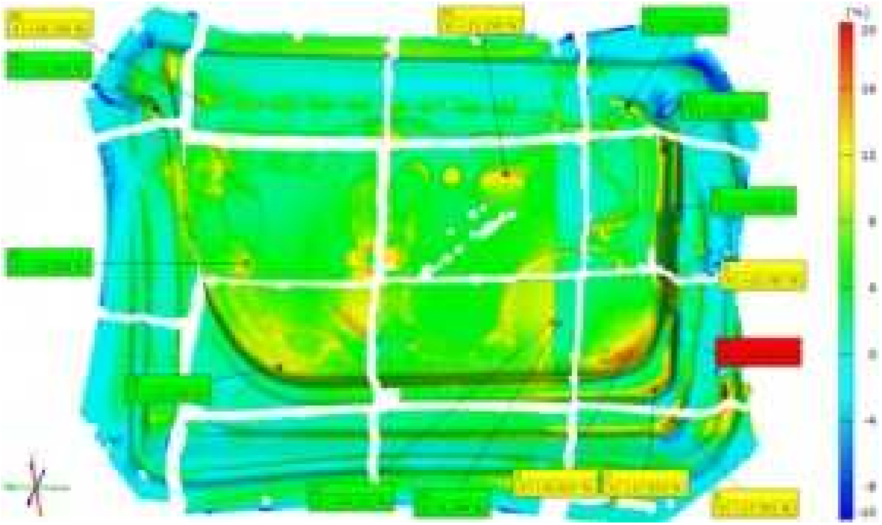
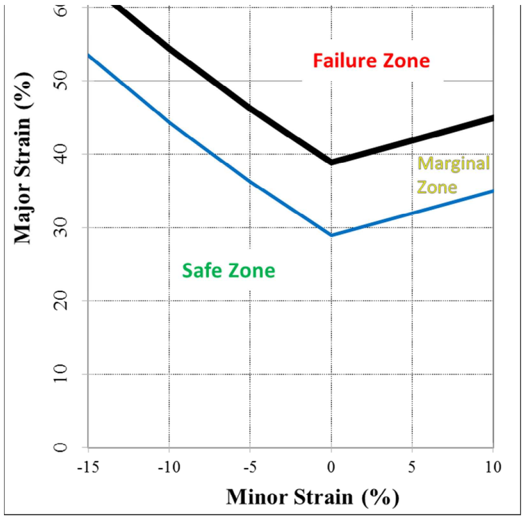


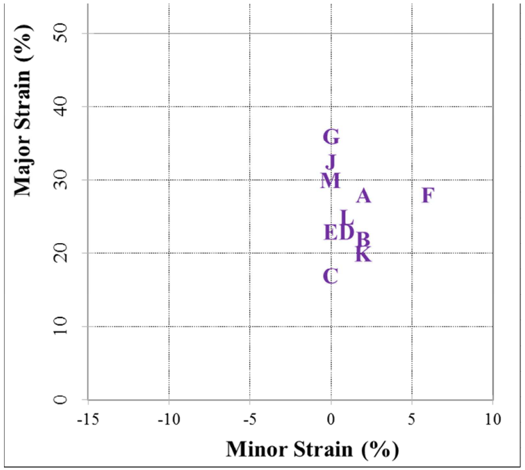
Image from www.Shiloh.com

Forming Limit Curve – Forming Limit Diagram

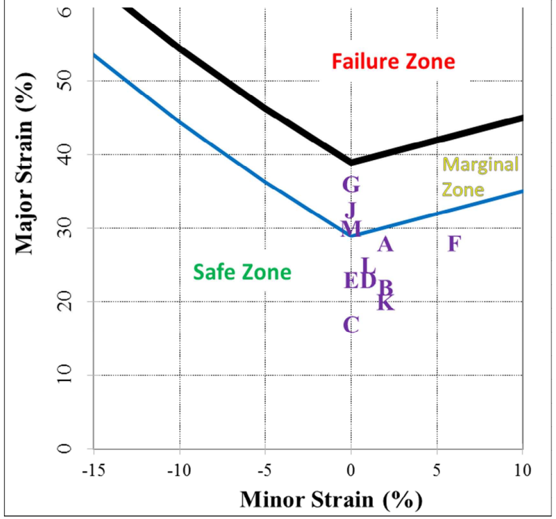
FLC – Dependent on sheet metal grade



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

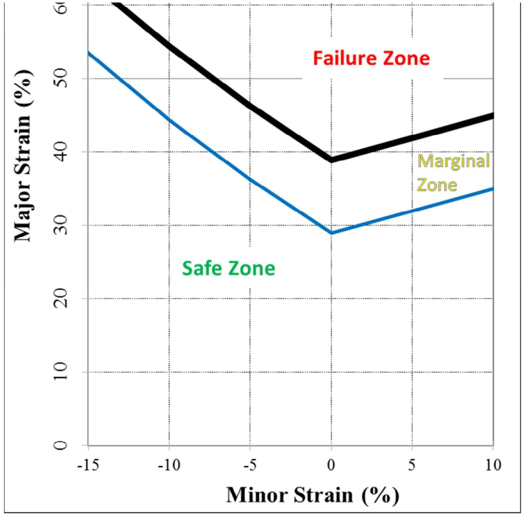


FLD – Combination of measured strains and FLC



Forming Limit Curve – Forming Limit Diagram

FLC – Dependent on sheet metal grade



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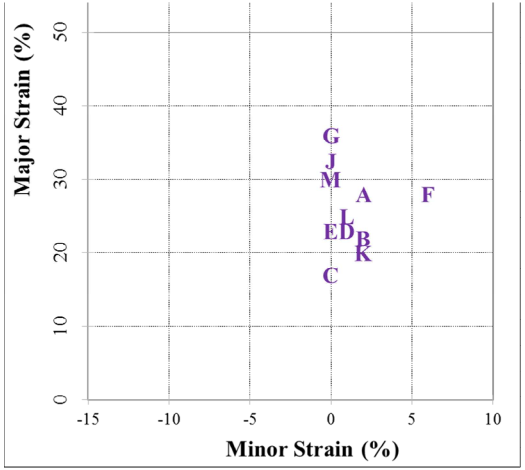
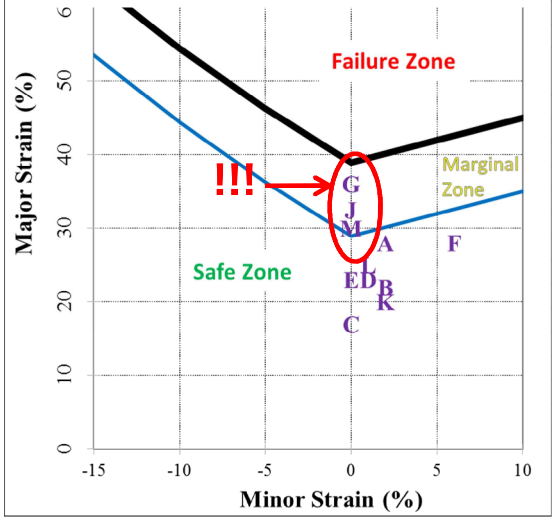


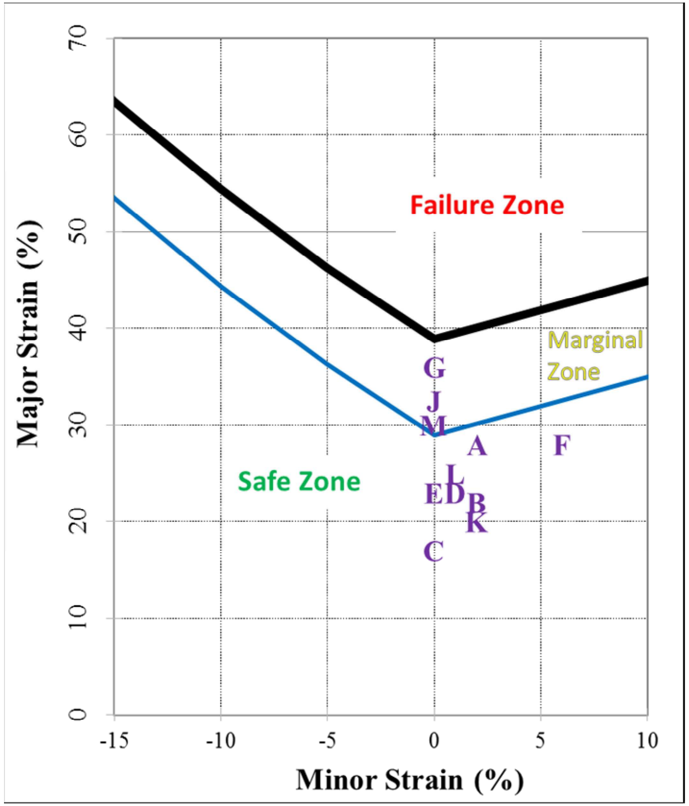
FLD – Combination of measured strains and FLC



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

	actual properties
marker in FLD	———
n-value	0.23
initial thickness (mm)	0.895
FLDo (%)	38.9
% thinning	28.0
thin - out limit (mm)	0.644

Location	Major Strain (%)	Minor Strain (%)	Thickness Strain Gauge (mm)	Thickness Strain Thinning (%)	Actual Props Safety (%)	Actual Props Status
A	28	2	0.686	23	12	safe
B	22	2	0.719	20	18	safe
C	17	0	0.765	15	22	safe
D	23	1	0.720	20	17	safe
E	23	0	0.728	19	16	safe
F	28	6	0.660	26	15	safe
G	36	0	0.658	26	3	marginal
J	32	0	0.678	24	7	marginal
K	21	2	0.725	19	19	safe
L	25	1	0.709	21	15	safe
M	30	0	0.688	23	9	marginal



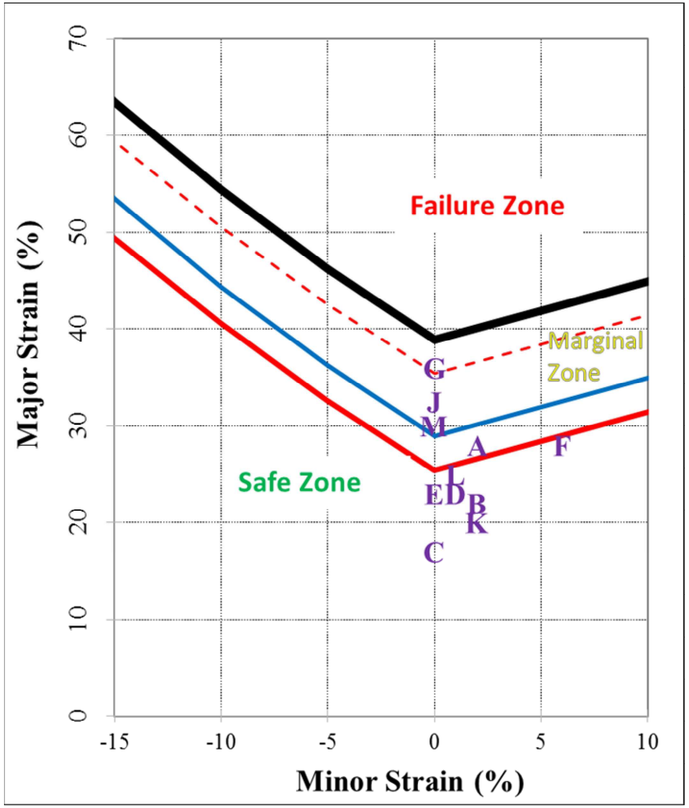
Area G needs some work, and areas J and M could use some touchup to get slightly better metal flow.

Probably not too much effort needed.

What if worst case properties are used?

	actual properties	worst case scenario
marker in FLD	————	- - - - - - - -
n-value	0.23	0.21
initial thickness (mm)	0.895	0.889
FLDo (%)	38.9	35.5
% thinning	28.0	26.2
thin - out limit (mm)	0.644	0.656

Location	Major Strain (%)	Minor Strain (%)	Thickness Strain Gauge (mm)	Thickness Strain Thinning (%)	Actual Props Safety (%)	Actual Props Status	Worst Case Props Safety (%)	Worst Case Props Status
A	28	2	0.686	23	12	safe	9	marginal
B	22	2	0.719	20	18	safe	15	safe
C	17	0	0.765	15	22	safe	18	safe
D	23	1	0.720	20	17	safe	13	safe
E	23	0	0.728	19	16	safe	12	safe
F	28	6	0.660	26	15	safe	11	safe
G	36	0	0.658	26	3	marginal	-1	failure
J	32	0	0.678	24	7	marginal	3	marginal
K	21	2	0.725	19	19	safe	16	safe
L	25	1	0.709	21	15	safe	11	safe
M	30	0	0.688	23	9	marginal	5	marginal



The part/process/sheet metal is NOT robust!

Must have all strains below the lowest line…

Do not buy off tools yet!

For more information, please visit

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