Aluminum Stamping and Forming

The Aluminum Transportation Group

Presenter

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Commonwealth Rolled Products

Engineering Manager

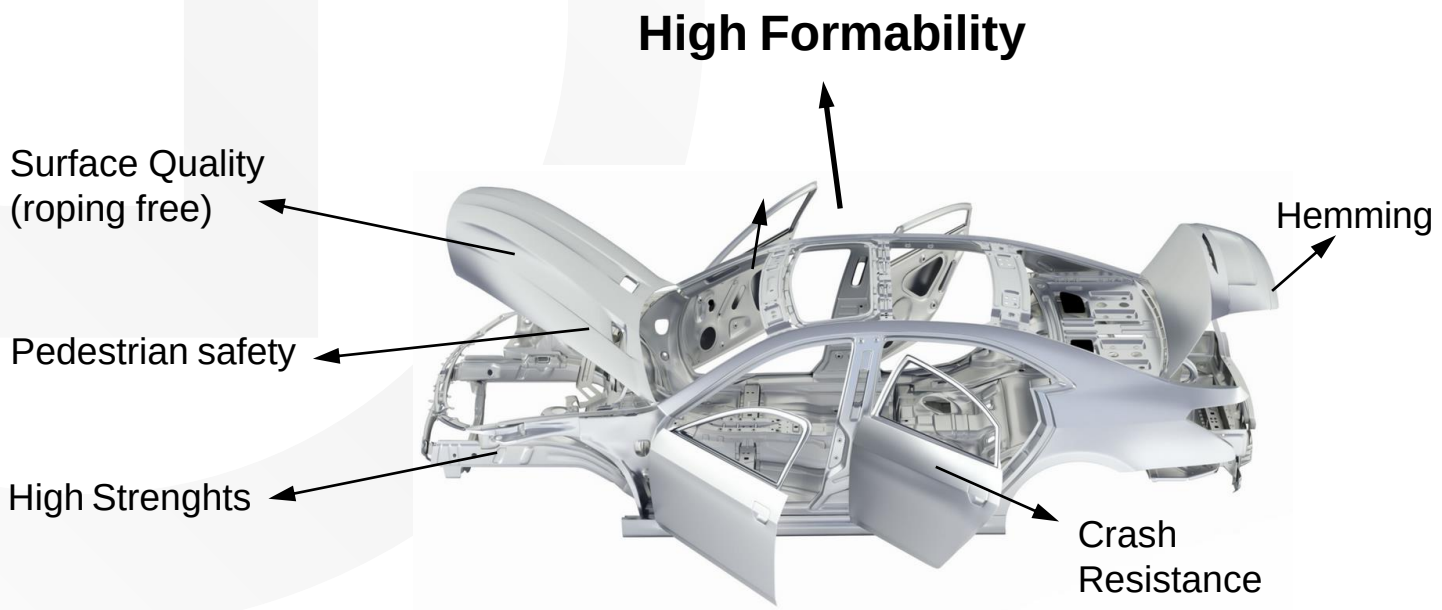


Outline

- Formability Sheet metal forming and formability
- Formability evaluation criterion and application
- Formability considerations in stamping processes
  splits, edge cracking, …
- Quality considerations in stamping processes
  wrinkling, springback, surface quality, …
- Stamping production and manufacturing considerations
  die wear, galling, lubrication, …
- Stamping feasibility analysis and simulation accuracy

Focus of Aluminum Alloy Development

1985～1990	1990～1998	1999～2005	2005～2017
• **High formability** • High strength	• **High formability** • High bake hardenability	• **High formability** • High bake hardenability • Stretcher strain mark free (A-Lüderlines)	• **High Formability** • High bake hardenability • High Hemmability • Dent Resistance • Natural Aging Control • Roping free • Corrosion Resistance • High-luster paint finish • Weldability



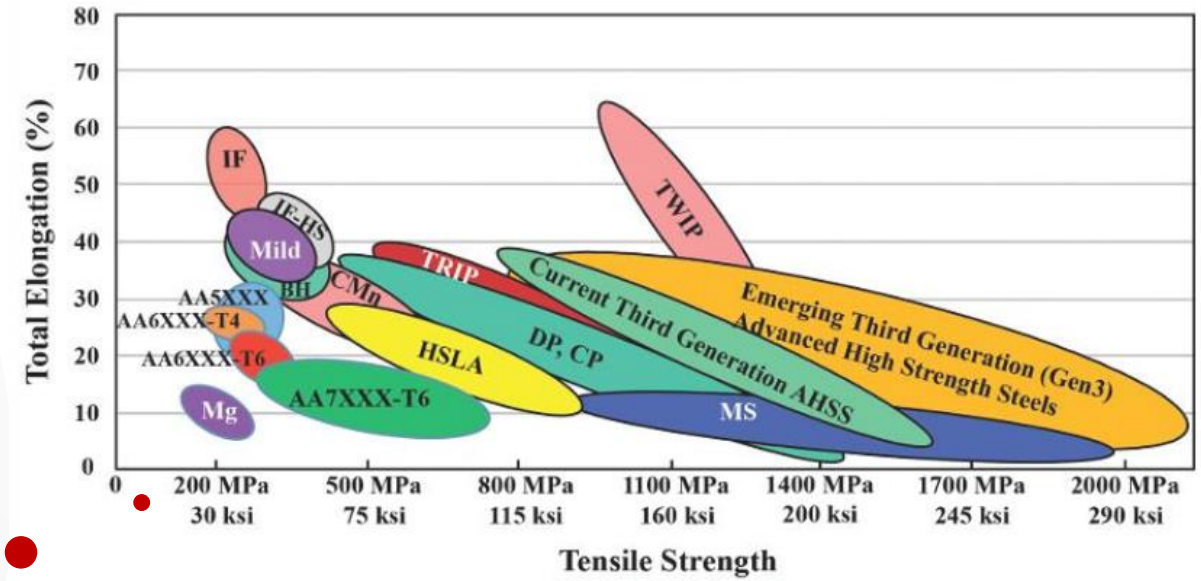
Sheet Metal Formability

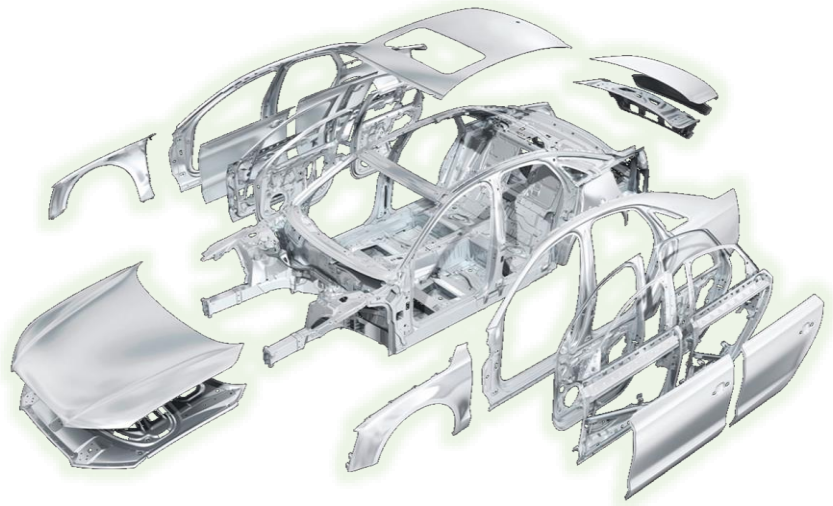
Automotive Stamping:

- sheet metal forming (t = 0.5~4.0 mm)
- 2D blank to 3D geometry
- Cold stamping at room temperature
- Permanent shape change derived from rigid tools (stamping dies), instead of gas or liquids



Can we make the part? and how??





Sheet Metal Formability

Formability is the capability of sheet metal to undergo plastic deformation to a given shape without being damaged (defects).

DEFECTS: splits/cracking, excessive thinning
(not include springback, skid/impact line, cutting edge quality etc.)

FORMABILITY is a complicated concept, varies with

Materials (steels, aluminum alloys, …)

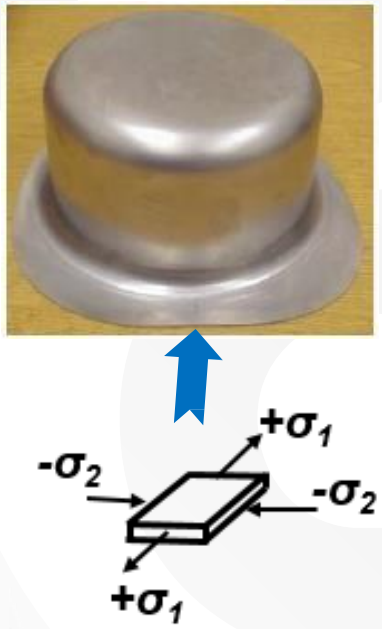
Forming conditions (lubrication, speed, temperature,…)

Stress state (part geometry, forming process, die design, …)

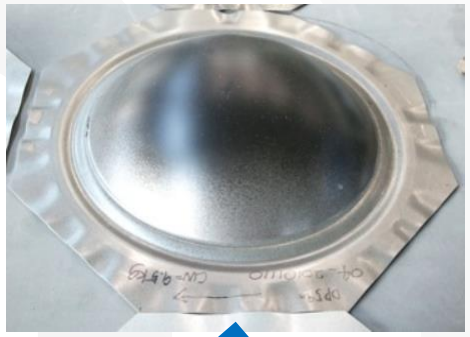
Sheet Metal Formability

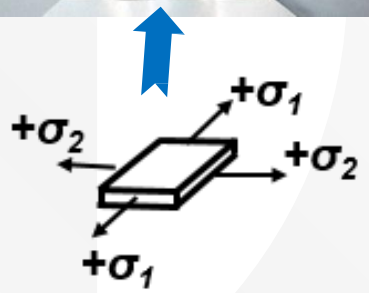
Formability Evaluation - Based on stress/strain state

Drawability

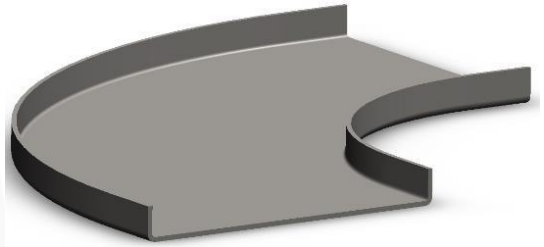


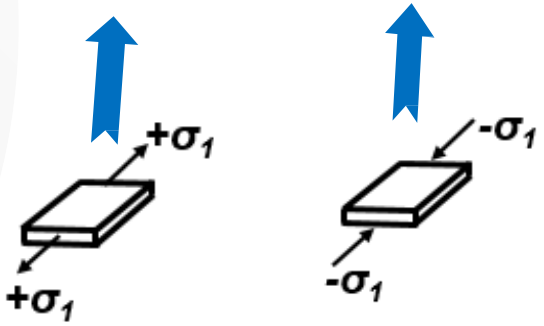
Stretchability



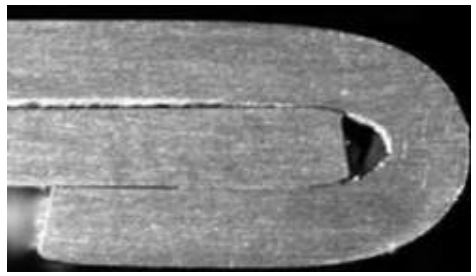


Flangeability



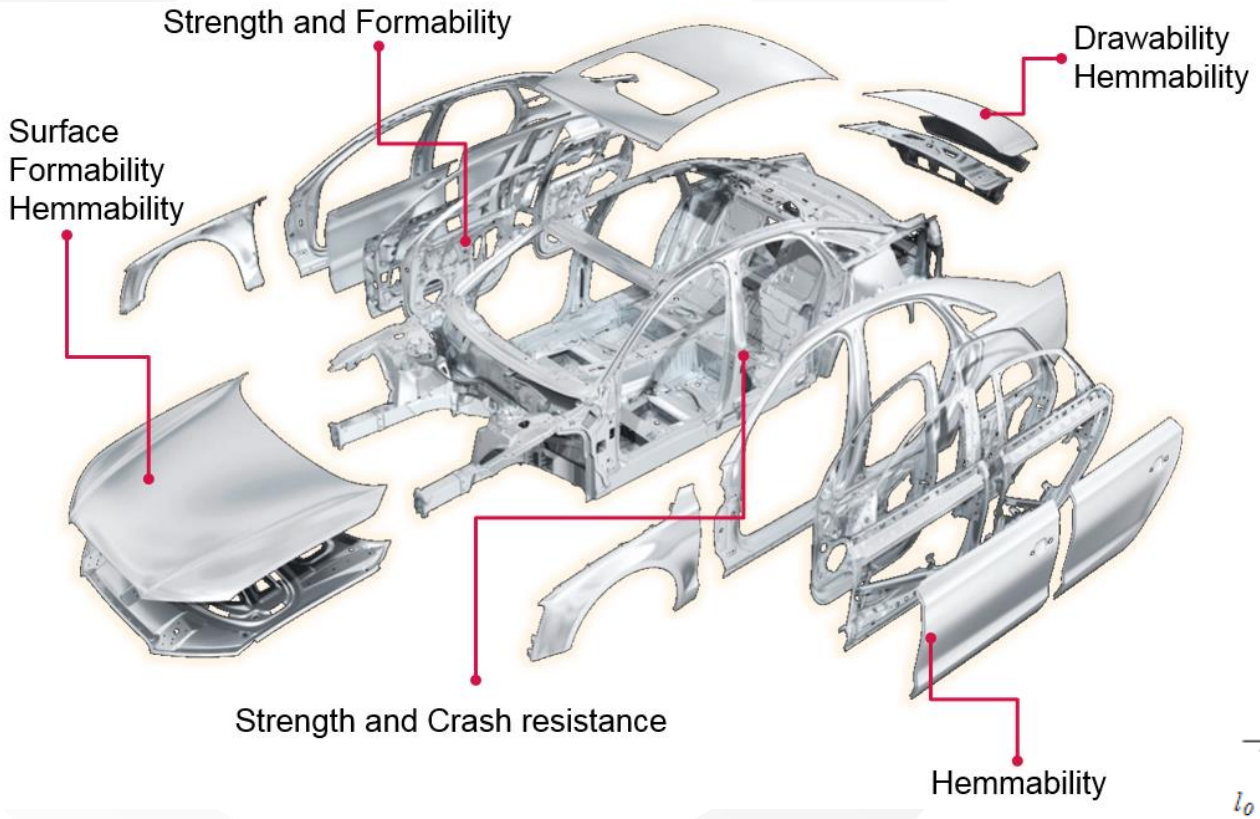


Bendability



- Drawing – Transfer material from one area to other area
- Stretching – No material transformation, purely thickness reduction for area expansion
- Flanging – Mainly a complicated bending process, change in length of line
- Bending – Hemming operation, little change in length of line

Aluminum Auto Body Applications



In-Plane Stress

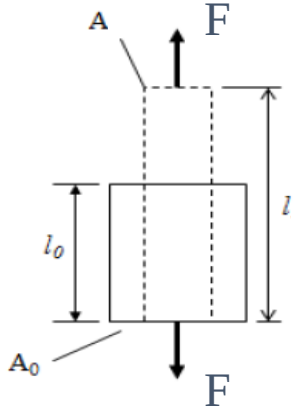
Thickness stress = neglectable

Stress = force per unit area N/mm^2

Surface Strain

Positive strain = stretch

Negative strain = compression



Engineering Stress: $\sigma = \frac{F}{A_0}$

Engineering Strain: $e = \frac{l - l_0}{l_0}$

True Stress: $\sigma = \frac{F}{A}$

True Strain: $\varepsilon = \ln\frac{l}{l_0} = \ln(1+e)$

Formability in Cold Stamping



Four Dominated Forming Modes (Stress States)

Drawing → **Drawability**

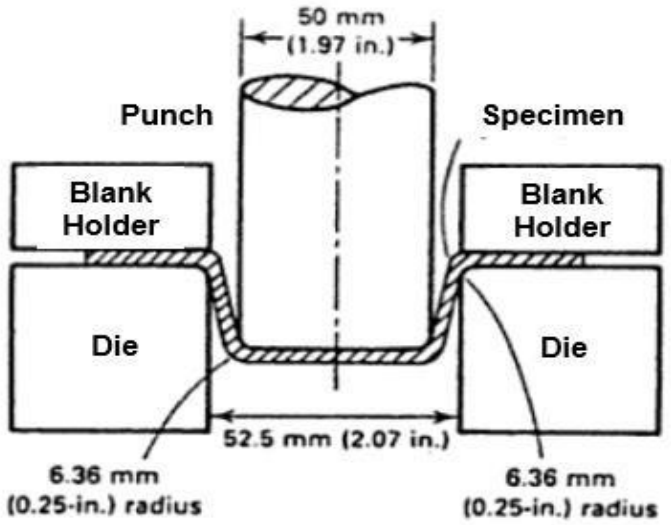
Stretch → **Stretchability**

Flanging → **Flangeability**

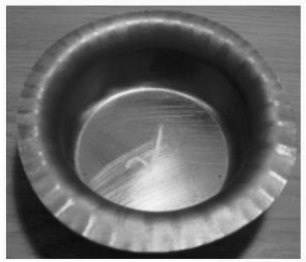
Bend → **Bendability**

Sheet Metal Drawability

Drawability



Swift Cup Test



Cup with wrinkling



Cup with split

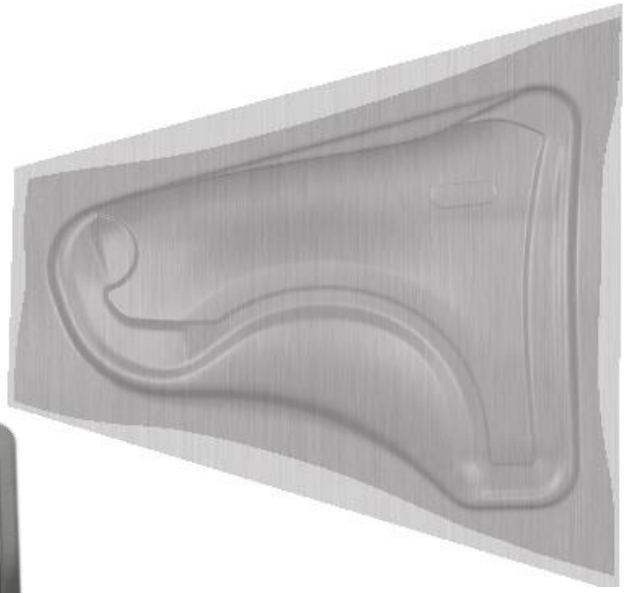


Good drawn Cup

Testing Parameter

Limiting Draw Ratio (LDR) = Max. Blank Diameter / Punch Diameter

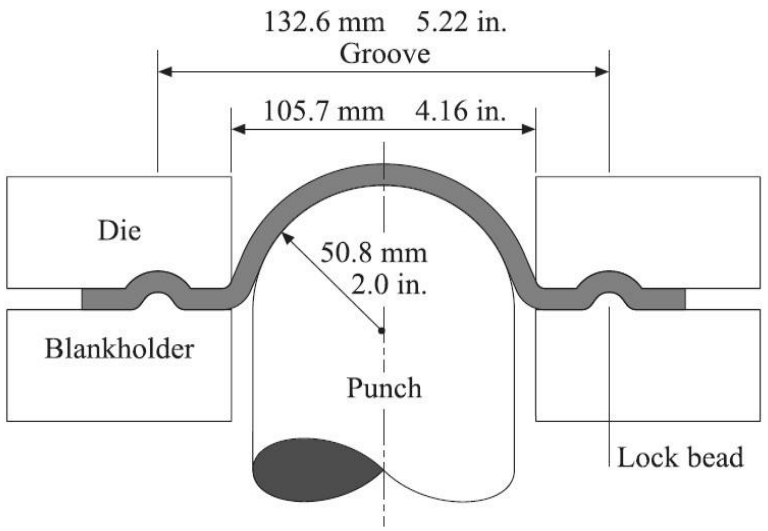




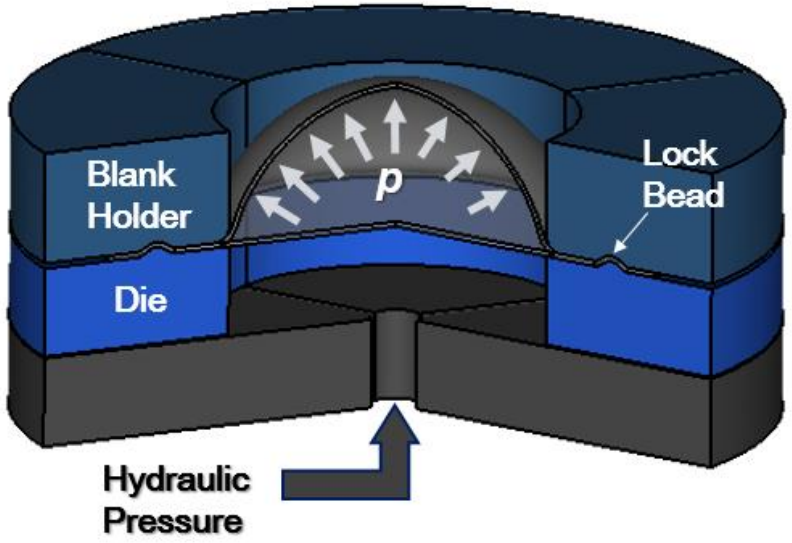


Sheet Metal Stretchability

Stretchability

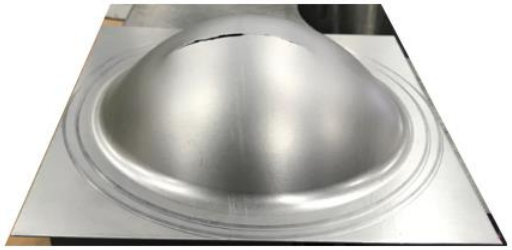


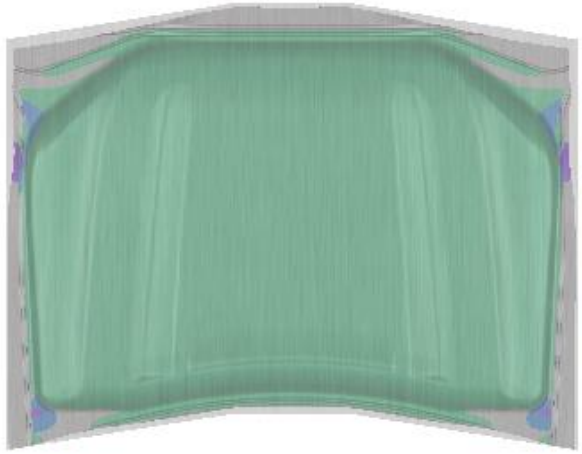
Limiting Dome Height (LDH) Test



Hydraulic Bulge Test





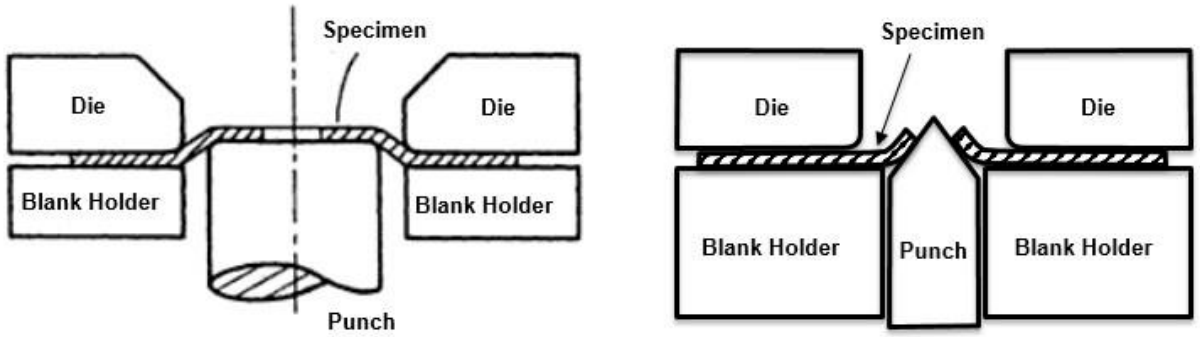


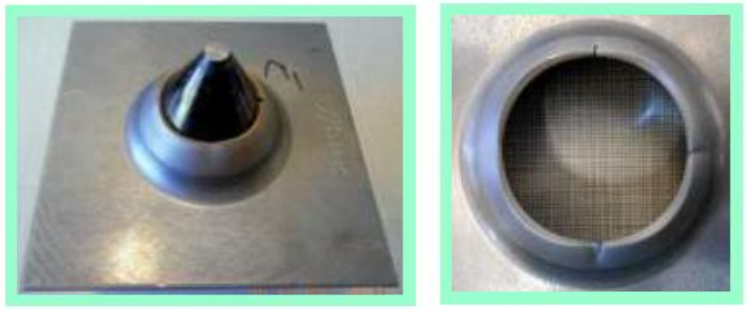
Testing Parameter

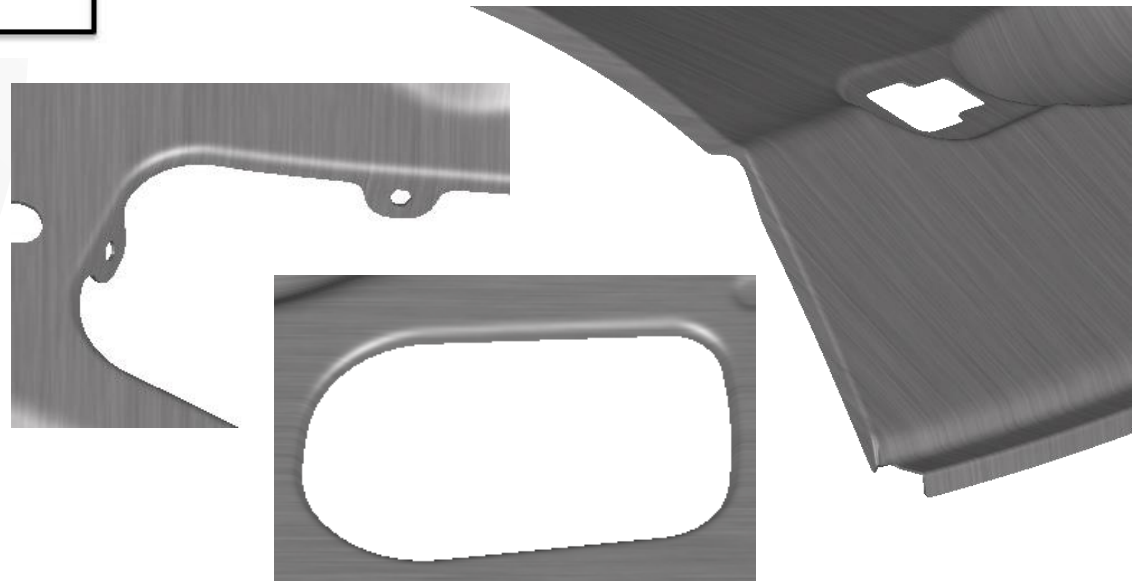
LDH Index = Max. Dome Height before Cracking

Sheet Metal Flangeability

Flangeability







Hole Expansion Test

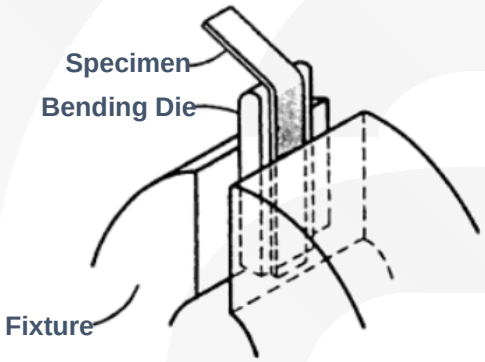
Testing Parameter

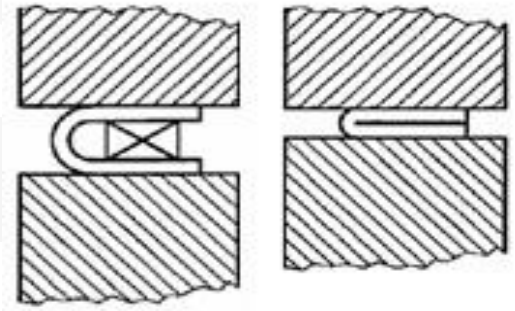
Hole expansion ratio (%) = $\frac{D_f - D_0}{D_0}$ x 100

(D_0, D_f are the original and final hole diameters.)

Sheet Metal Bendability

Bendability







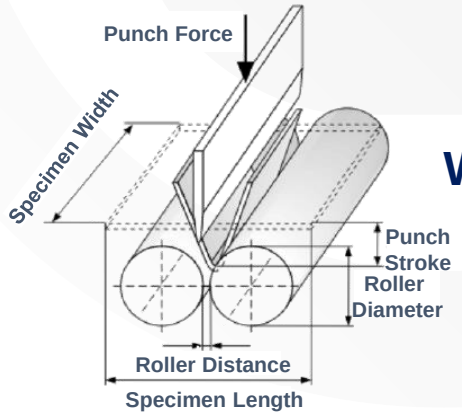




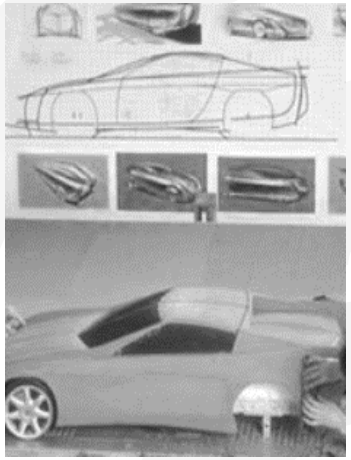
Simple Bend Test



Wedge Bend Test



From Concept to Production



Early Stamping Feasibility Analysis

Concept Design → Product Design → Product Engineering → Production Planning

Process Engineering → Die Design & Engineering → Tryout → Production



Stamping Feasibility Analysis

FLC
For formability judgement

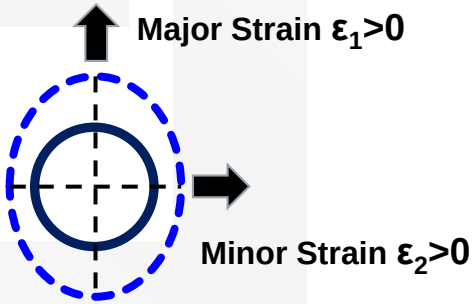
FLC and FLD

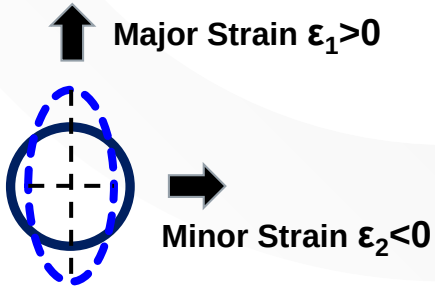
FLC – Forming Limit Curve

FLD – Forming Limit Diagram

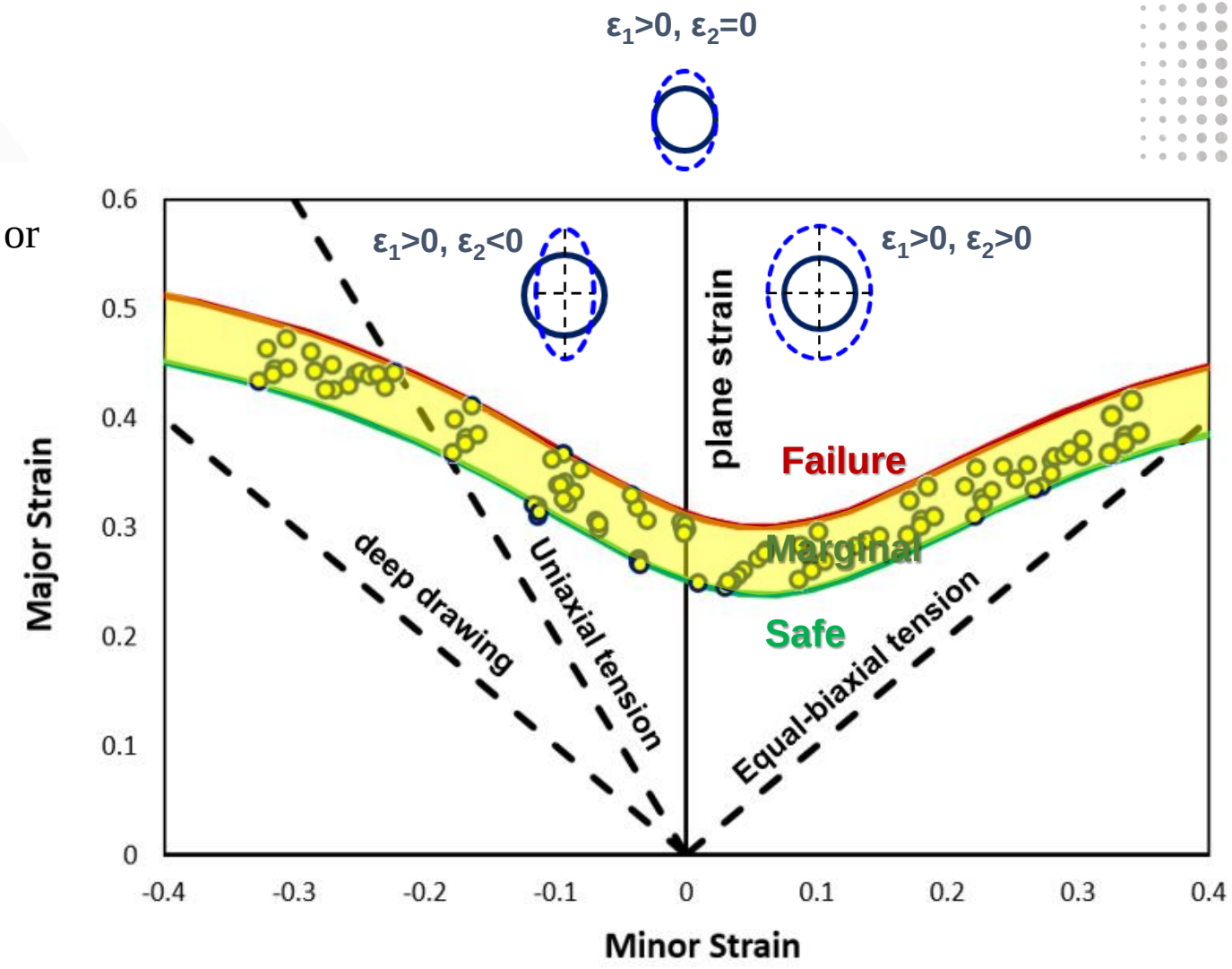
A graphic representation of a series of the limit major and minor strain combinations, associated with the onset of the through-thickness or localized necking under certain loading conditions.





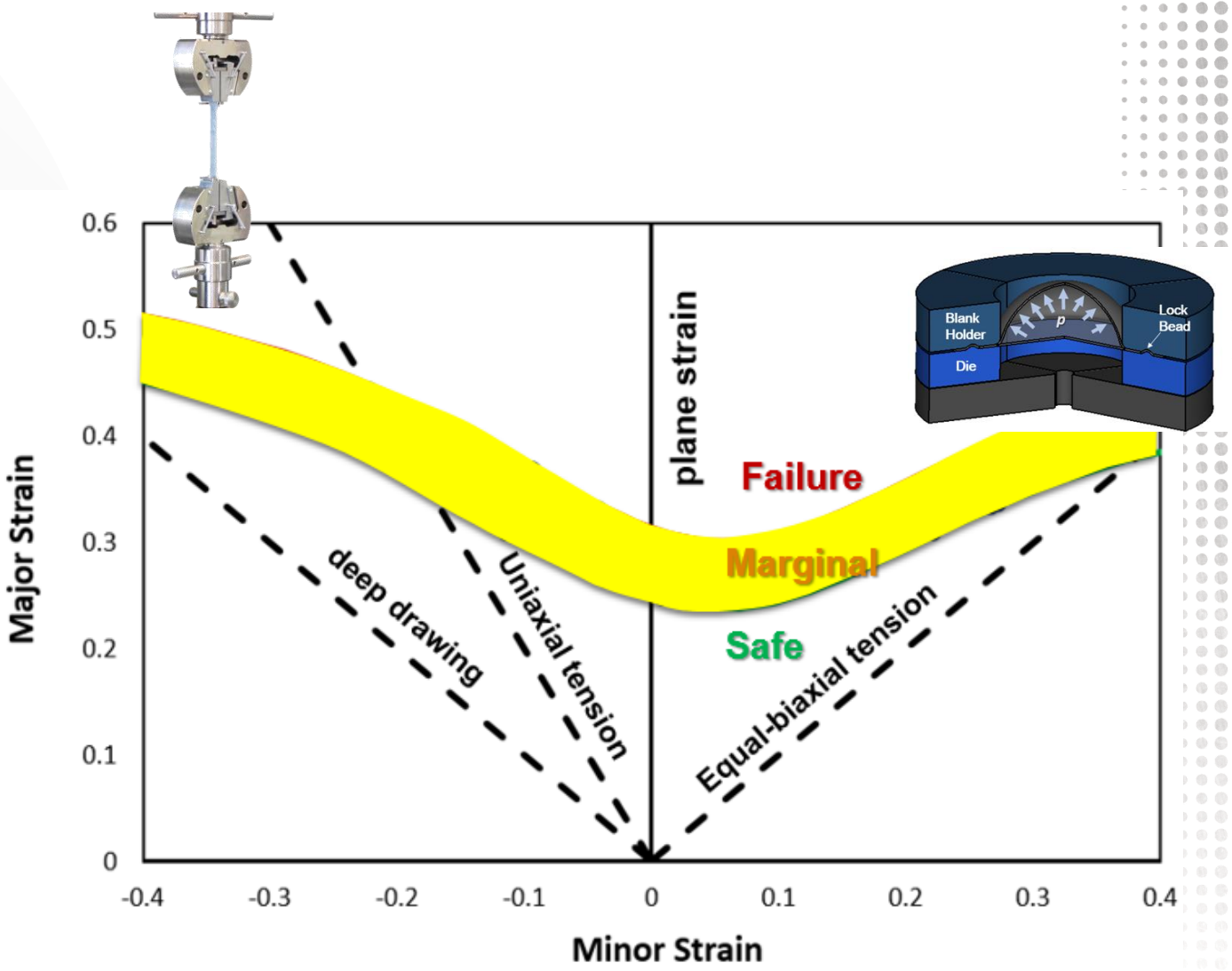


Along ε_1 and ε_2 directions, shear strain = 0.



Characteristics of FLC

- Not a flat curve – formability varies with strain state and die design can change/control it
- Plan strain state gives the worst formability
- Both uniaxial tensile test and hydraulic bulge test only represent single point on FLC, do not give an good indication of formability
- Not applicable to evaluate edge cracking, wrinkling, surface quality issues, …



FLC Test

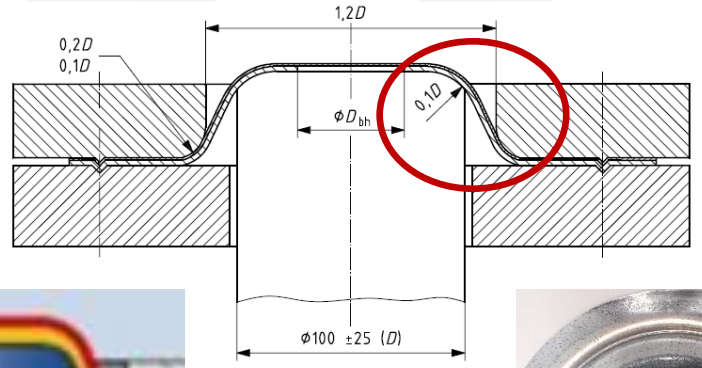
INTERNATIONAL STANDARD **ISO 12004-2**

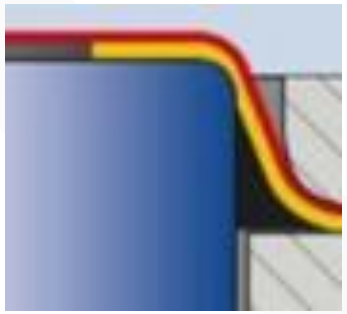
Metallic materials — Sheet and strip — Determination of forming-limit curves —

Part 1:
Measurement and application of forming-limit diagrams in the press shop

Part 2:
Determination of forming-limit curves in the laboratory

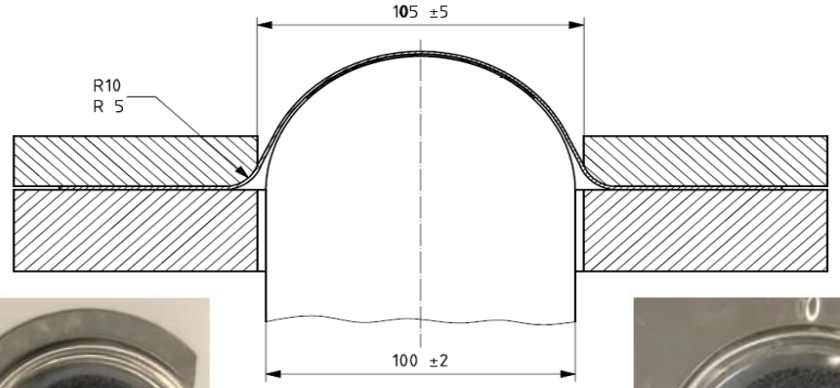
Marciniak Test



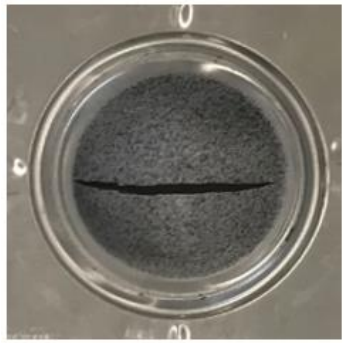




Nakajima Test

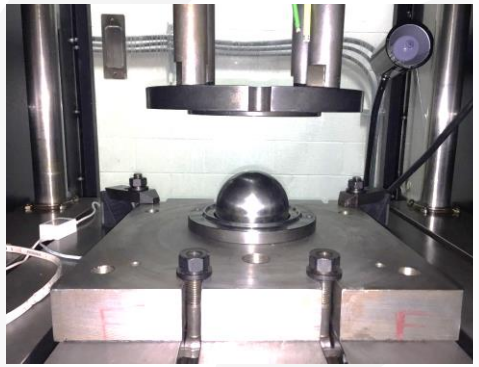


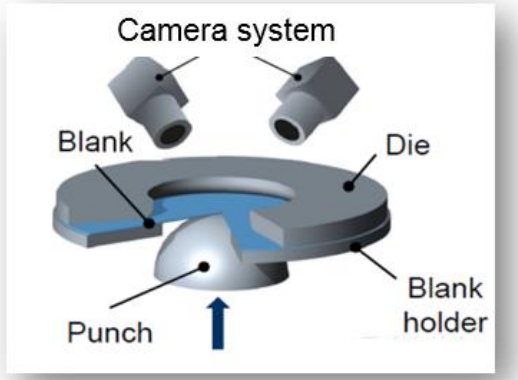




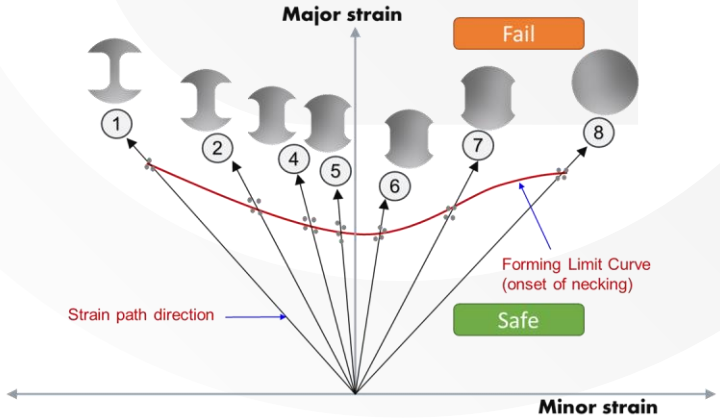
FLC Measurement

Nakajima Test



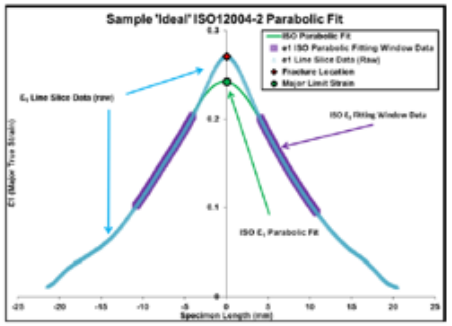






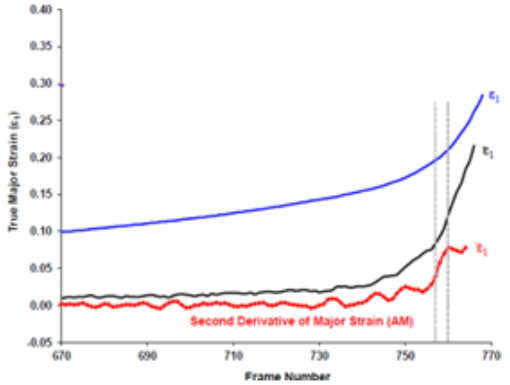
ISO 12004-2 Standard

curve fitting to the strain distribution profile across crack line before fracture



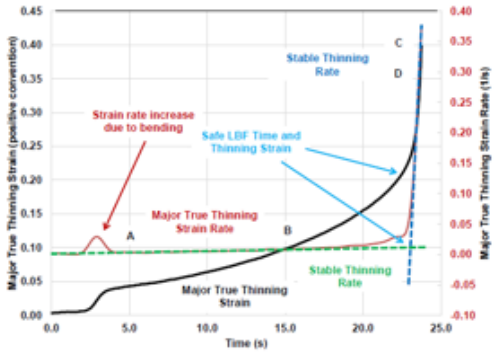
Strain Rate Acceleration

major strain rate acceleration in a local neck



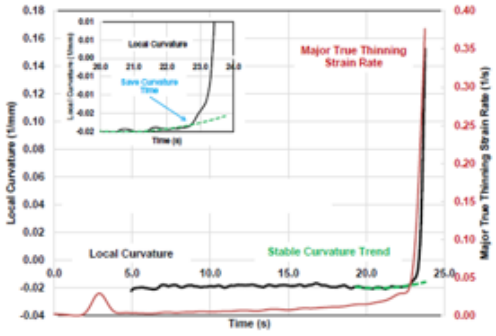
Linear Best Fit

change in the rate of thinning in a local neck



Curvature-Based

strain rates at various locations inside and out of a local neck

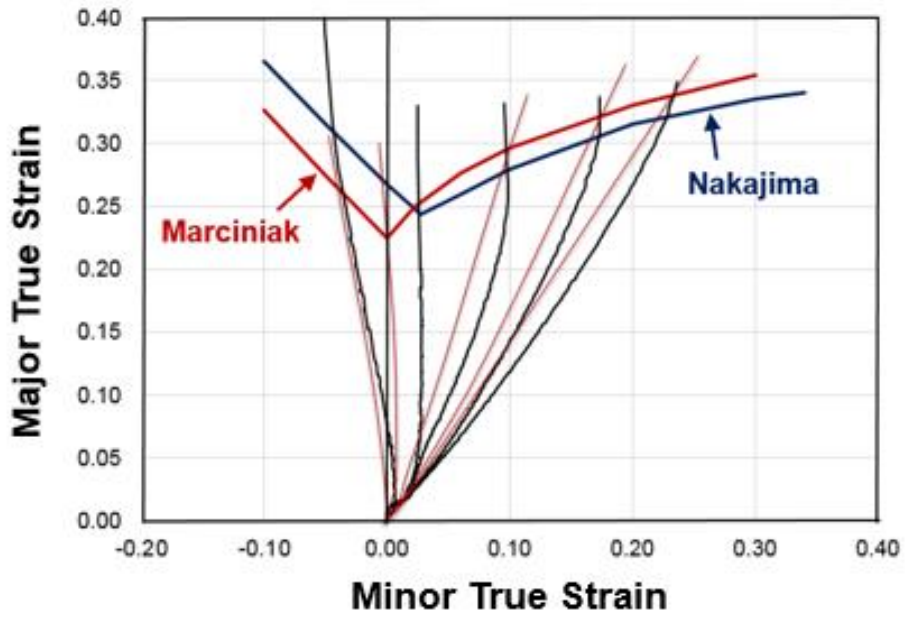


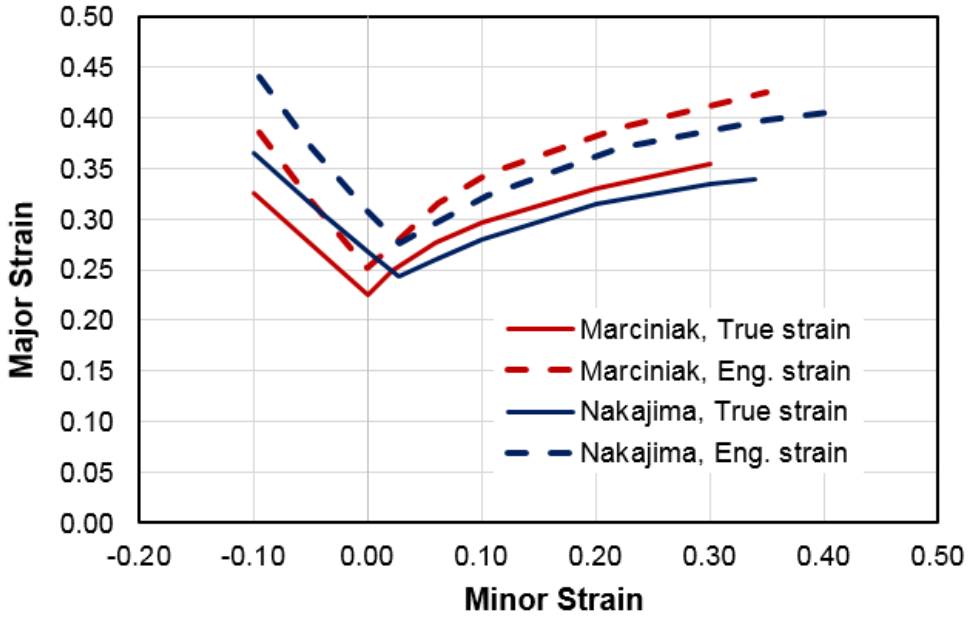
FLC Measurement

Marciniak Test

Nakajima Test

More difficult in operation	More widely used
In-plane deformation	Out of plane deformation
No frictional effect	Sensitive to frictional condition
Linear strain path	Non-linear strain path
FLC_0 at plane strain axis	FLC_0 shifts to the right

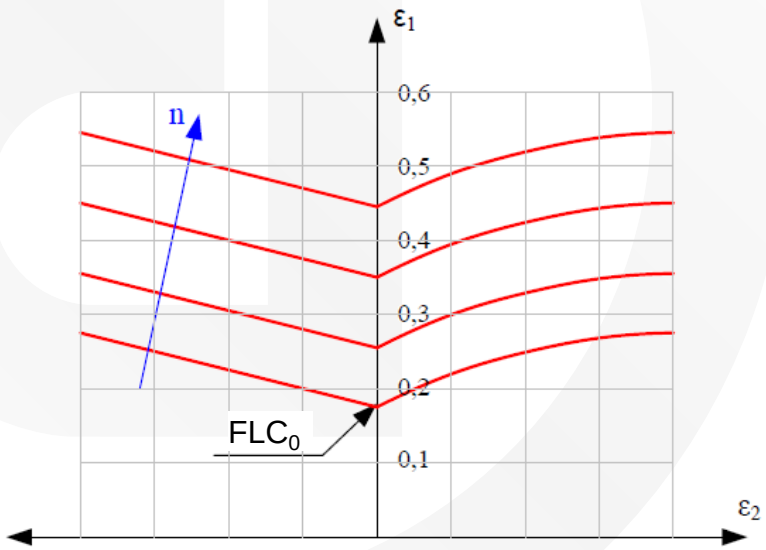




Influence of n-Value and r-Value

Material stretchability is better represented by the right-hand side of forming limit curve (FLC). The LDH test is a simple way to evaluate material stretchability, but the LDH value may not be sensitive enough to material property changes.

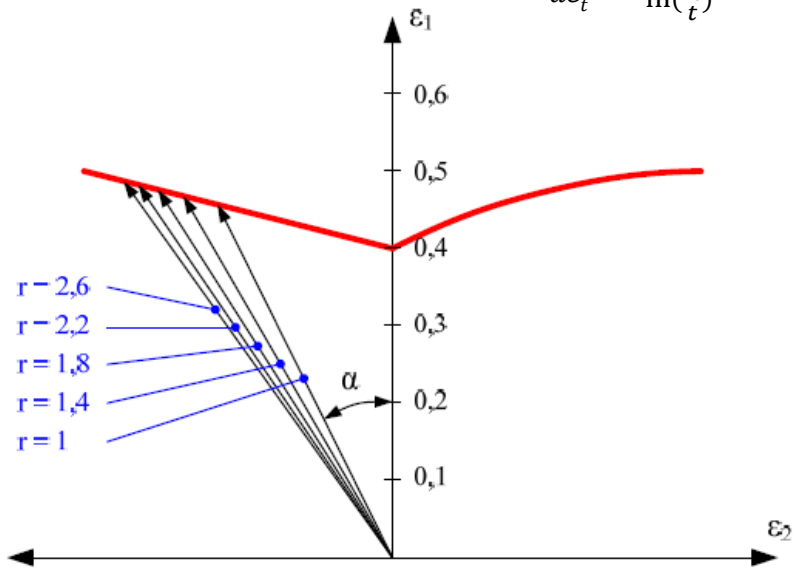
Material strain hardening exponent: $n = \frac{d(ln\sigma)}{d(ln\varepsilon)} = \frac{\varepsilon d\sigma}{\sigma d\varepsilon}$



Influence of n value on FLC

Material anisotropic parameter:

Plastic Strain Ratio: $r = \frac{d\varepsilon_w}{d\varepsilon_t} = \frac{\ln(\frac{w_0}{w})}{\ln(\frac{t_0}{t})}$



Influence of r value on FLC

Applications of FLC/FLD



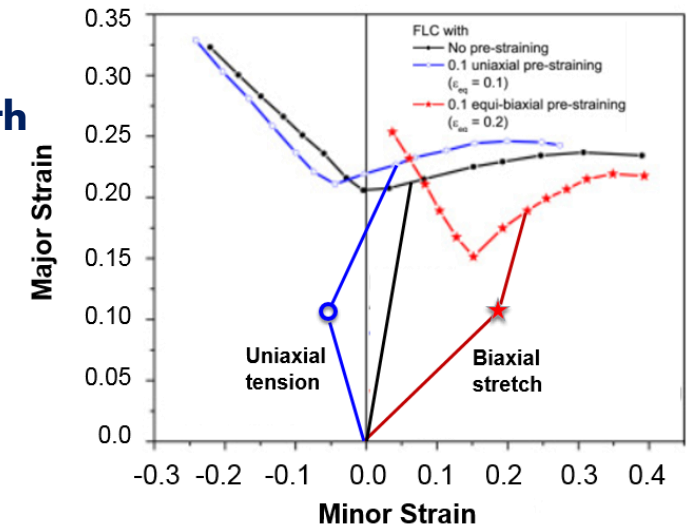


Less stretch
More mat flow

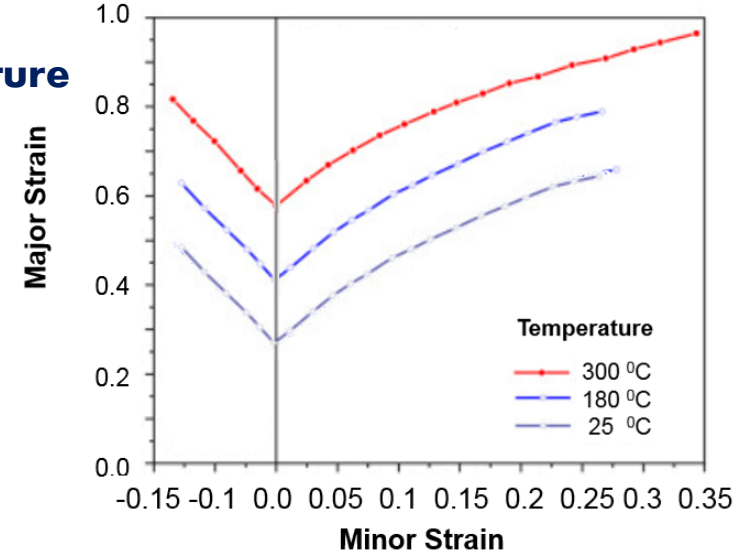
Applications of FLC/FLD

- Strain path dependent, best to use it for first operation
- Forming temperature dependent, difficult to use it for warm/hot stamping
- Not applicable to evaluate edge cracking, wrinkling, surface quality issues, …

Effect of strain path



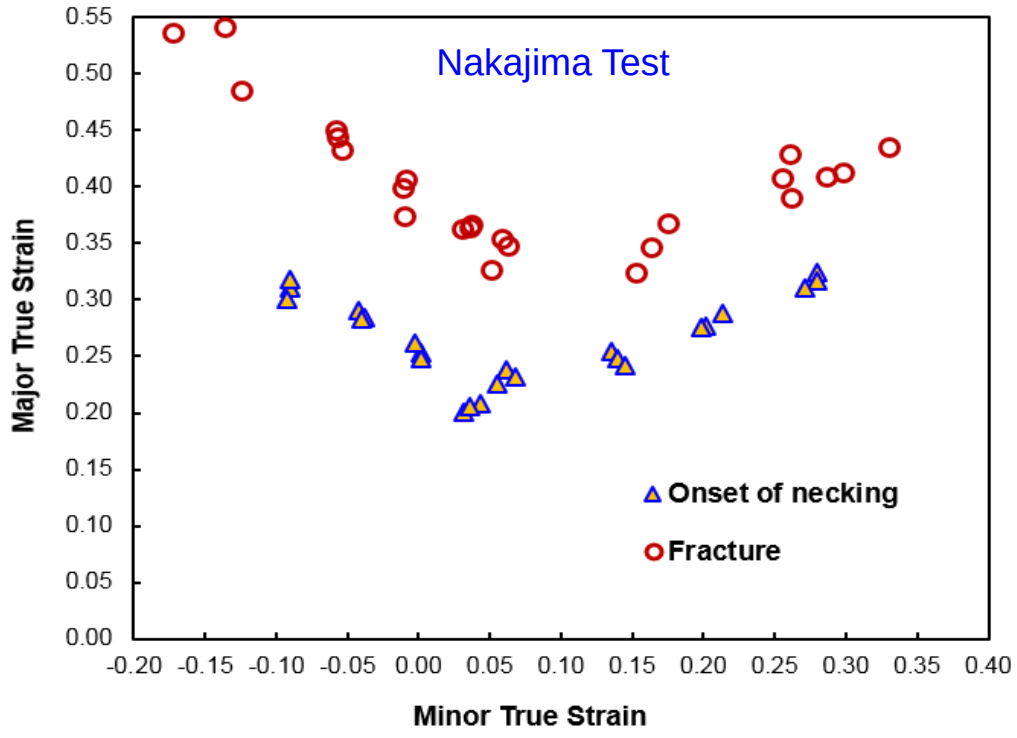
Effect of temperature



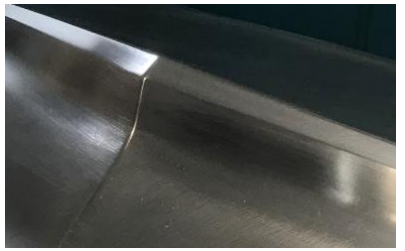
Applications of FLC/FLD

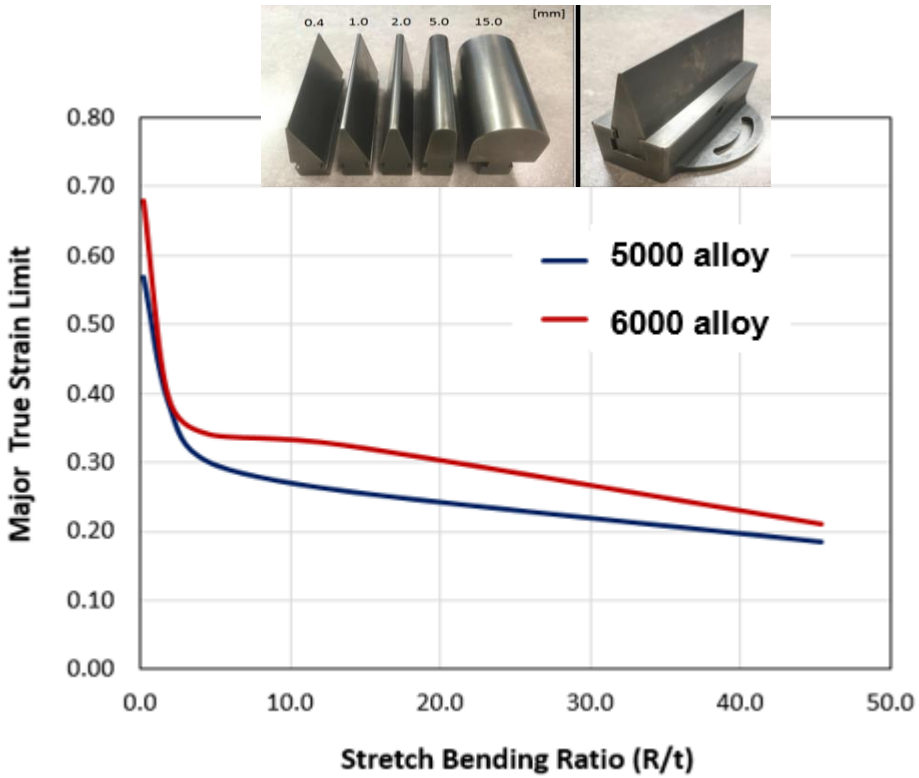
- Limit strains: Onset of necking vs. fracture

  Effect of testing tool geometry









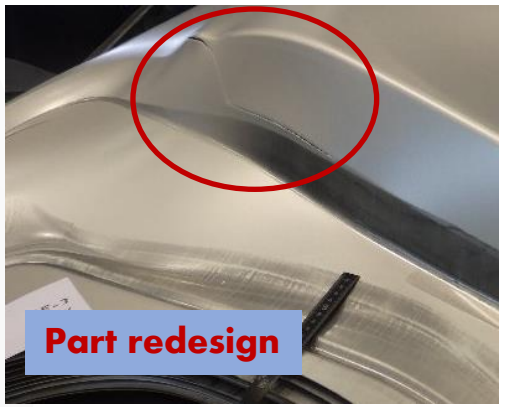
Stamping Formability Issues

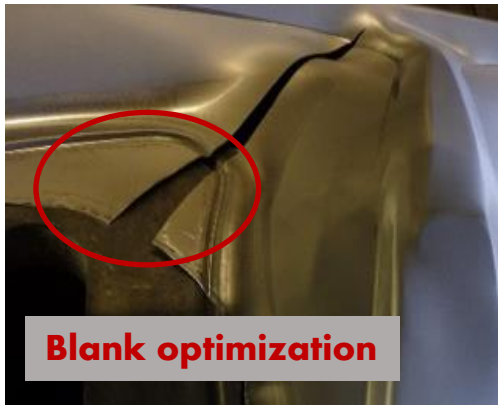
Splits in Draw Operation

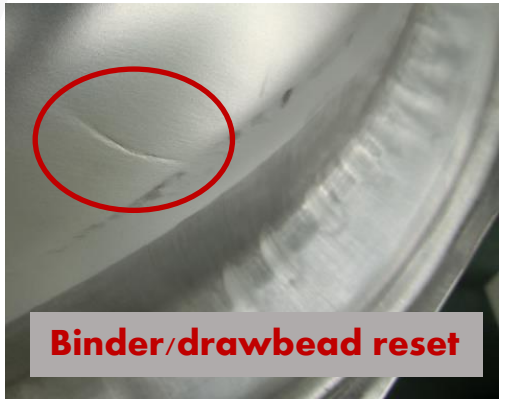


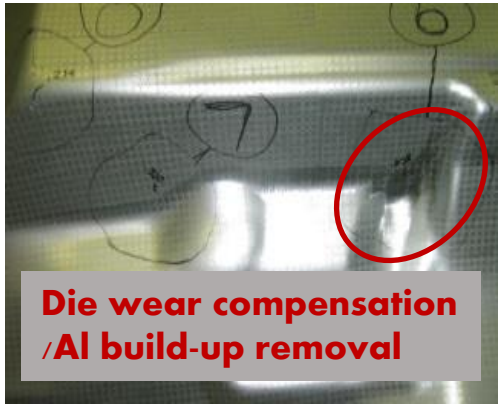
- Part design change
- Adjust binder force / change draw bead to allow easier material flow
- Better spotting for uniform contact
- Optimize blank, add cuts/lance on blank
- Compensate die wear
- .....

Too less material in the needed area





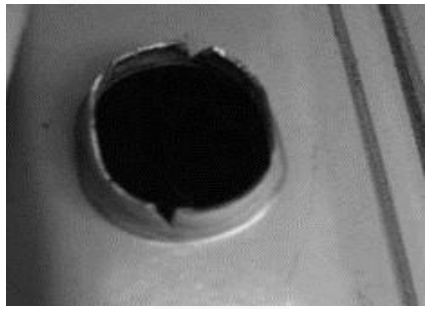




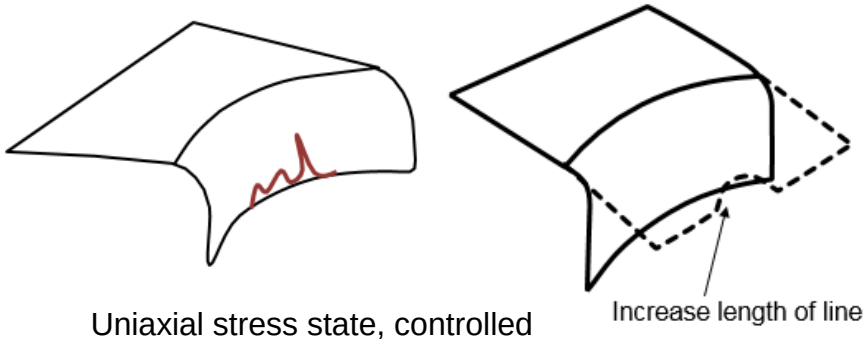
Stamping Formability Issues

Splits at the Edge





Splits during Flanging



Uniaxial stress state, controlled by uniform elongation

- Reduce the flange height
- Increase the length of line (metal gainers, ...)
- Preform some flange features for full flange latter

- Improve cutting edge quality
- Maintain cutting tool well at all time
- .....

Edge cracking



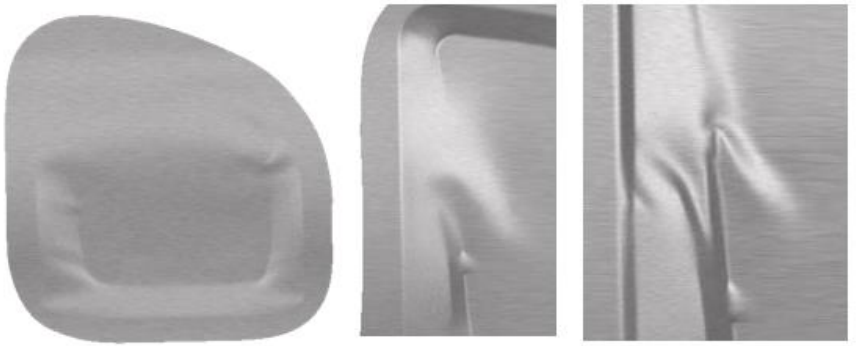
Stamping Quality Issues

Wrinkles

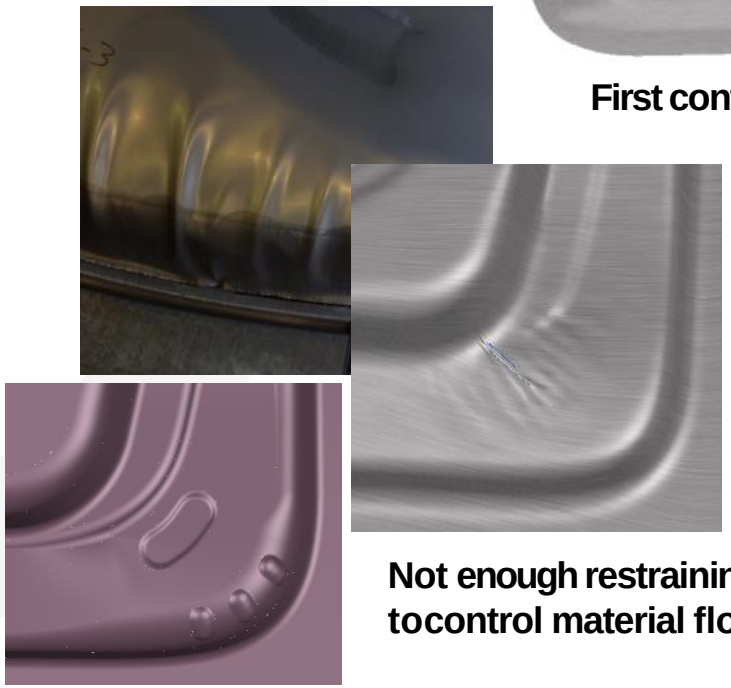


- Increase binder force
- Better spotting for more contact
- Strengthen/add beads to control material flow
- Reduce flange length of line
- Part design change
- Die design change
- .....

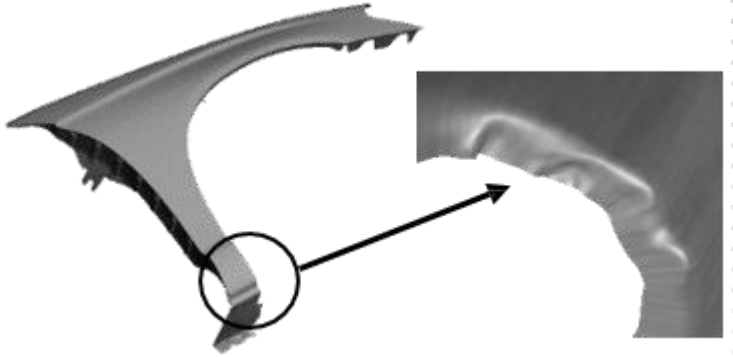
Too much material in the needed area



First contact gathering too much local material



Not enough restraining force to control material flow



Flange width too large or incorrect flanging die path

Stamping Quality Issues

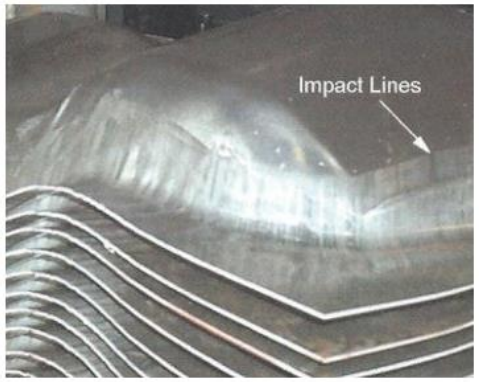
Skid/Impact Lines



- Change die design – binder, draw bar to delay earlier feature line contact, …
- Better spotting for uniform contact
- Adjust binder force and/or draw bead layout/profile to control material flow
- Compensate die wear
- ……

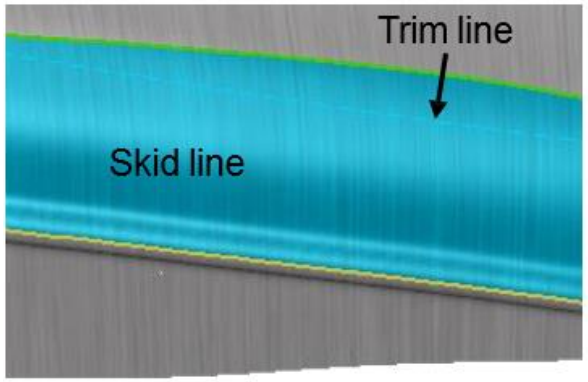
Mostly not a part design issue

Mostly die/process design issue



Impact lines shown on the panel exposed area.

- Unbalanced stretch
- Incorrect spotting



Skid line moves beyond the trim line and show on the class A surface.

- Inappropriate local control
- Die wear
- ……

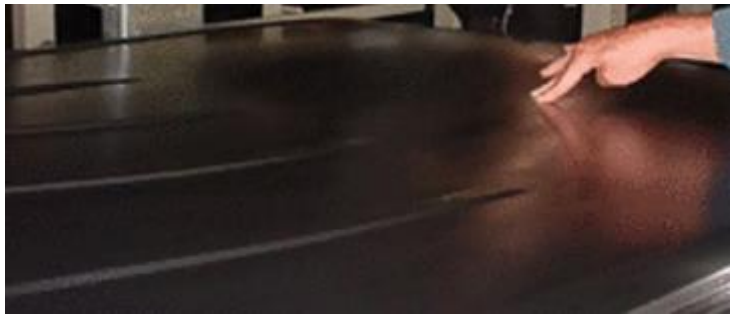
Stamping Quality Issues

Outer Panel Surface Defects



- Change die design – die tip, binder shape, draw bar to apply extra stretch, ...
- Add draw beads, or even double beads
- Increase binder force
- Better spotting for uniform contact and balanced stretch
- .....

Material is not stretched enough



Surface low or oil canning caused by insufficient stretch deformation

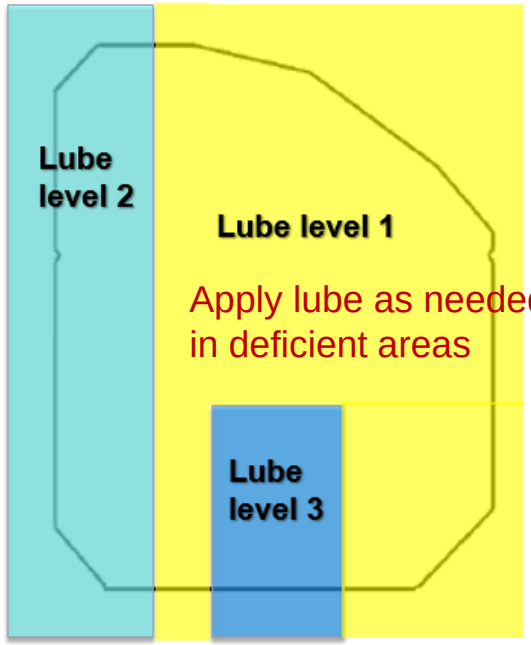
Target: Minimum thinning ≥ 2%

Improving Formability in Manufacturing

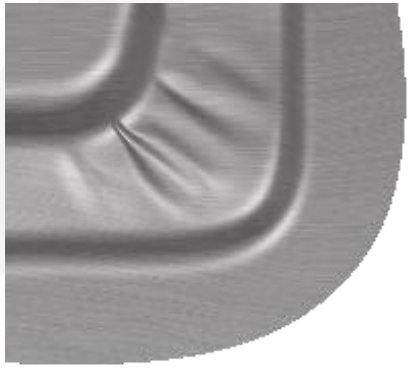
Stroke Speed → **As faster as possible. Use mechanical press!**

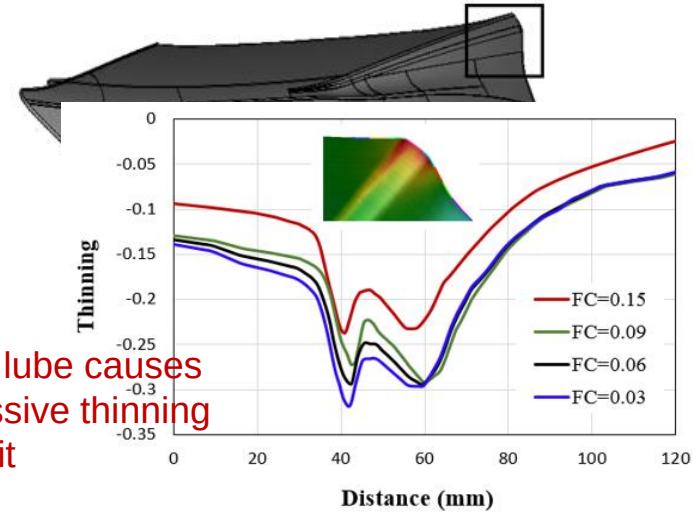
Lubrication → **Good lubrication practice significantly improves formability**

Only apply lube in the needed area



Extra lube causes wrinkling

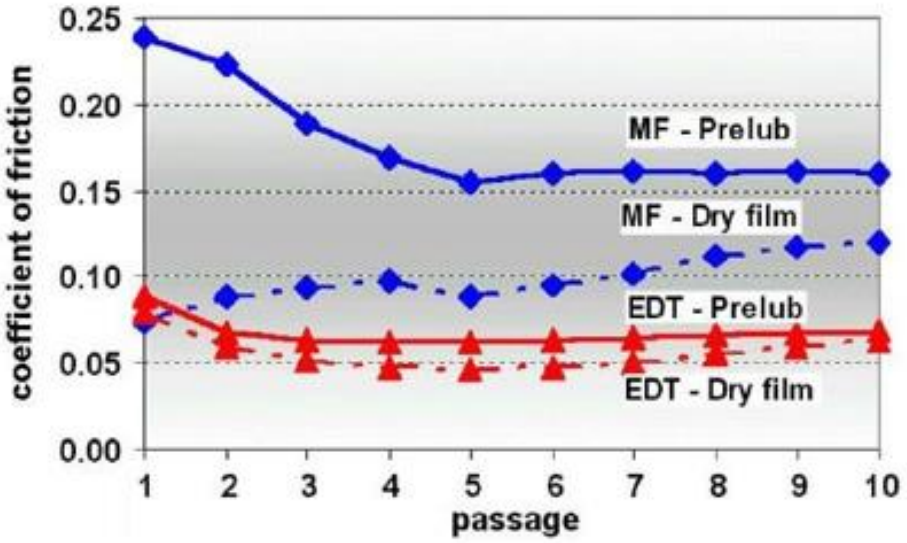




Extra lube causes excessive thinning or split

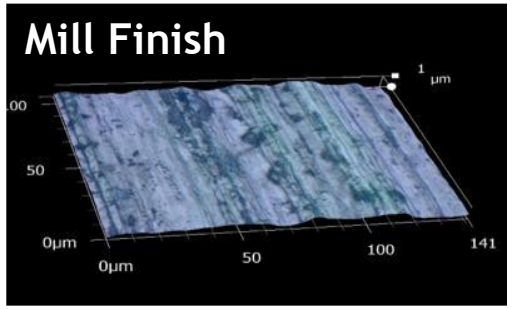
Improving Formability in Manufacturing

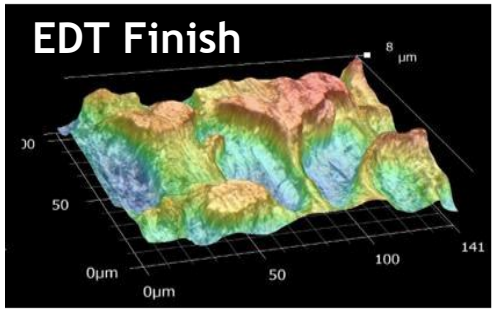
Lubrication



Sheet surface finish:

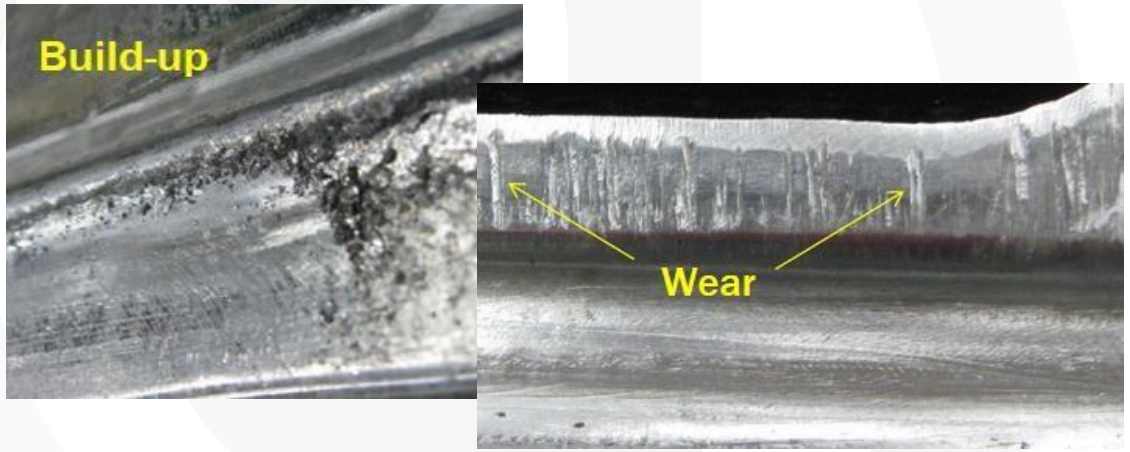
- Surface roughness and waviness can largely change the lubrication regime.
- EDT finish has a relatively higher roughness, which is capable of generating micro pockets containing lubricant.
- These micro pockets act as a source of extra lubrication during asperity flattening.





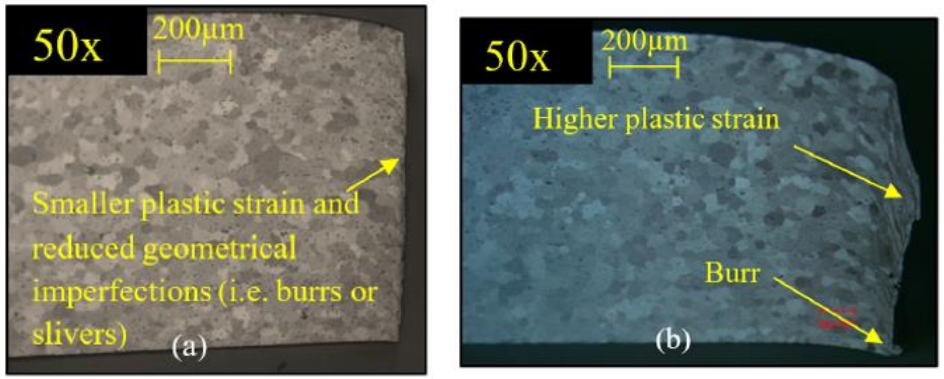
Improving Formability in Manufacturing

Tooling Maintenance



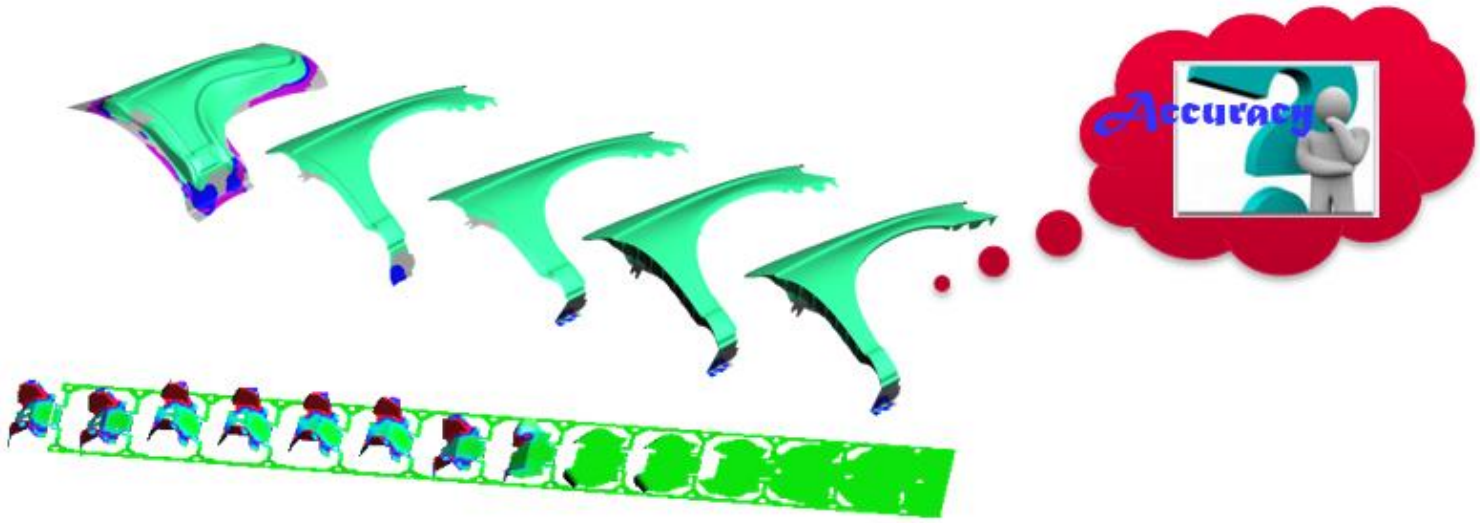
Aluminum is softer and more easily scratched, affecting formability, cutting edge quality, surface quality, ...

Good tooling maintenance schedule and practice are necessary



Cross-sectional profiles cut with
(a) sharper blade and (b) dull blade

Stamping Feasibility Analysis



Material modeling

Frictional modeling

Binder force modeling

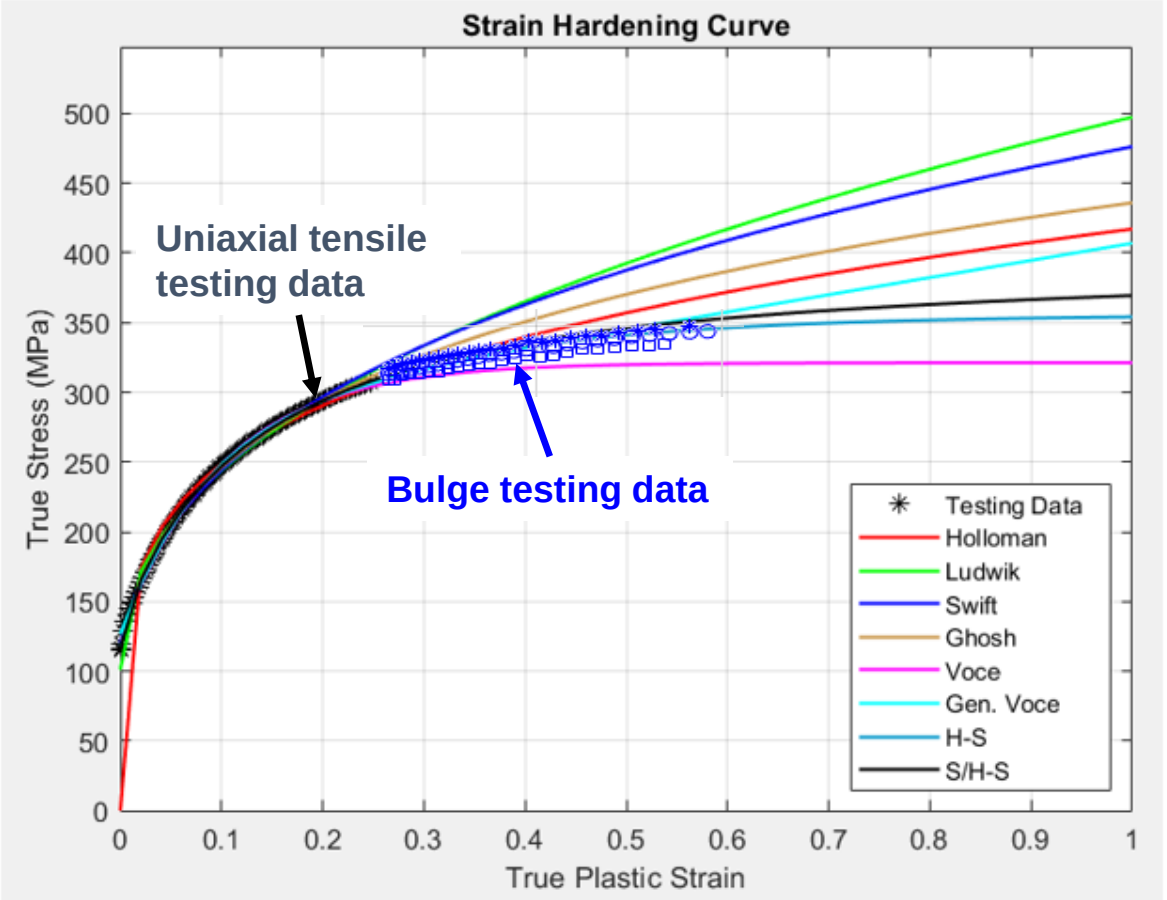
Simulation Accuracy

Stamping Feasibility Analysis

Material modeling

Strain Hardening

- Ludwik
- Swift
- Ghosh
- Hockett-Sherby
- Swift/Hockett-Sherby
- .....



Strain Hardening Model

Holloman: $\sigma = K * \varepsilon^n$

Swift: $\sigma = C * (\varepsilon_0 + \varepsilon)^m$

Ghosh: $\sigma = C * (\varepsilon_0 + \varepsilon)^m - D$

Ludwik: $\sigma = C + K * \varepsilon^n$

Generalized Voce: $\sigma = \sigma_{sat} + (\sigma_{si} + \sigma_i * \varepsilon) * (1 - e^{-a*\varepsilon})$

Hockett-Sherby: $\sigma = \sigma_{sat} - (\sigma_{sat} - \sigma_i) * e^{-a*\varepsilon^p}$

Voce: $\sigma = \sigma_{sat} + (\sigma_i - \sigma_{sat}) * e^{-a*\varepsilon}$

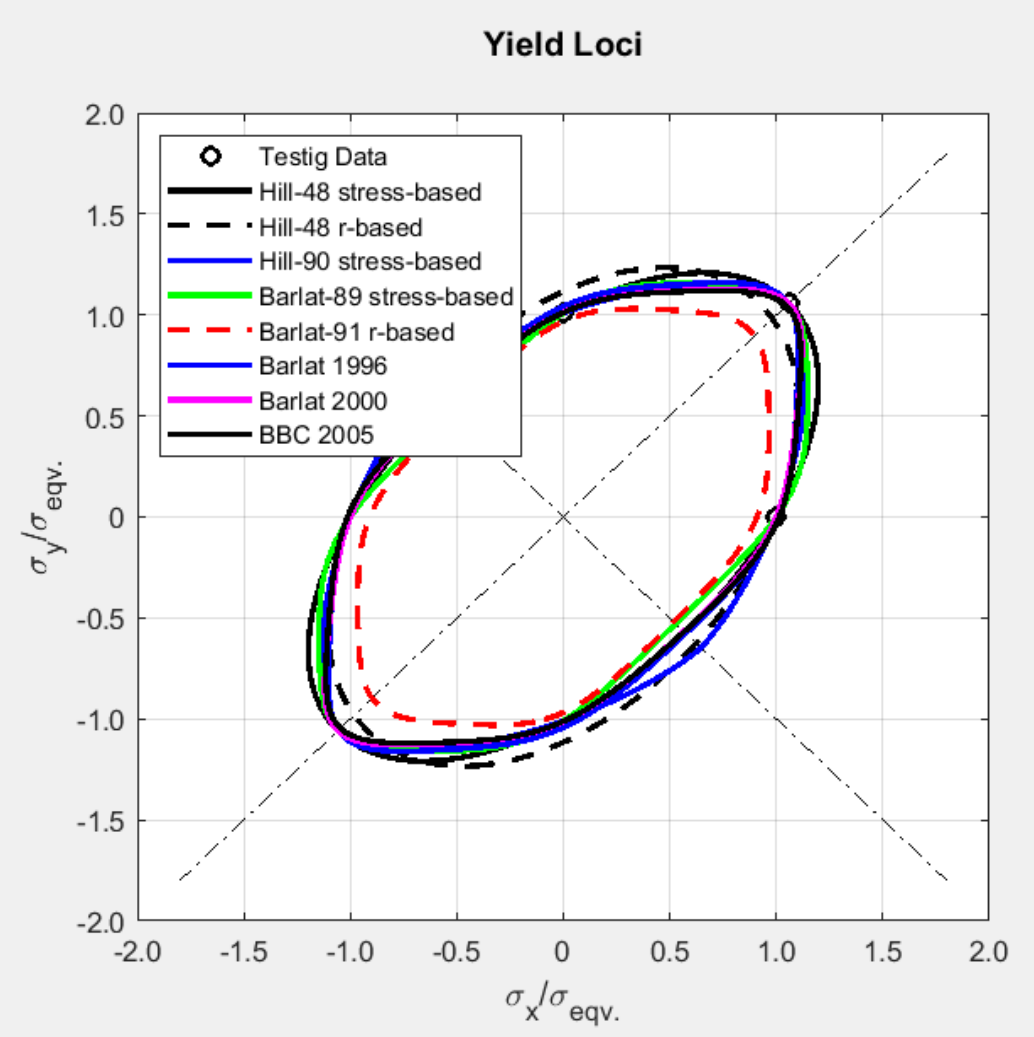
Combined Swift/H-S: $\sigma = (1 - \alpha) * [C * (\varepsilon_0 + \varepsilon)^m] + \alpha * [\sigma_{sat} - (\sigma_{sat} - \sigma_i) * e^{-a*\varepsilon^p}]$

Stamping Feasibility Analysis

Material modeling

Yield Criteria

- Hill's Family
- Barlat's Family
- BBC's Family
- Vegter's Criteria
- ……

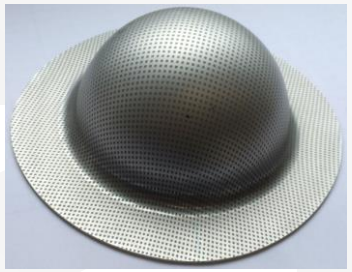


Stamping Feasibility Analysis

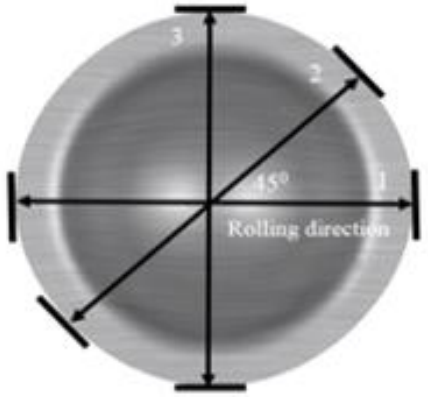
Benchmark Study



Deep Ellipse

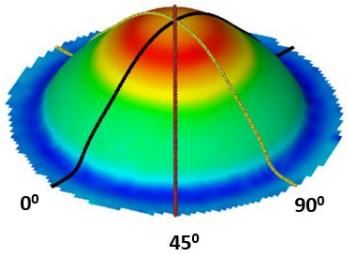


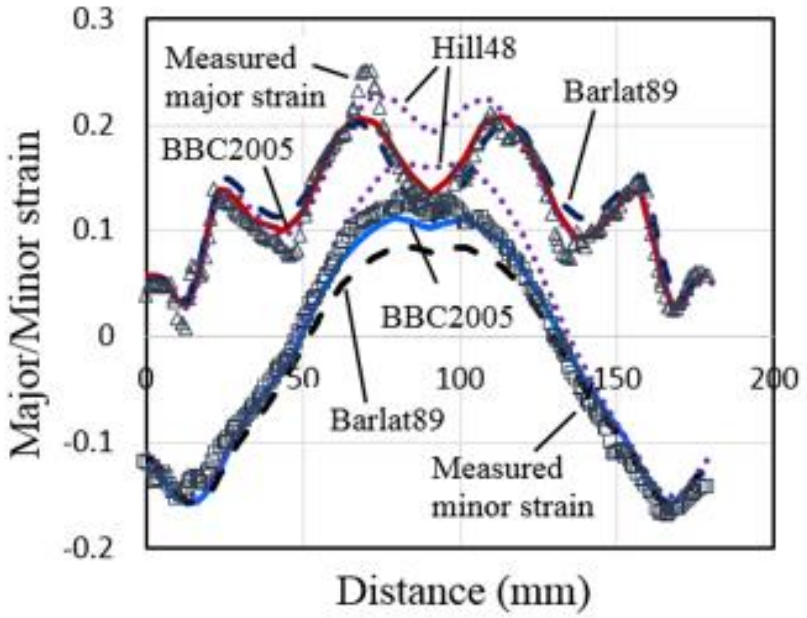
Hemisphere



Blank draw-in match

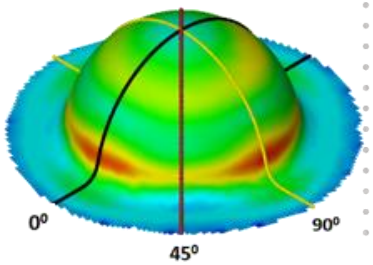
Deep Ellipse

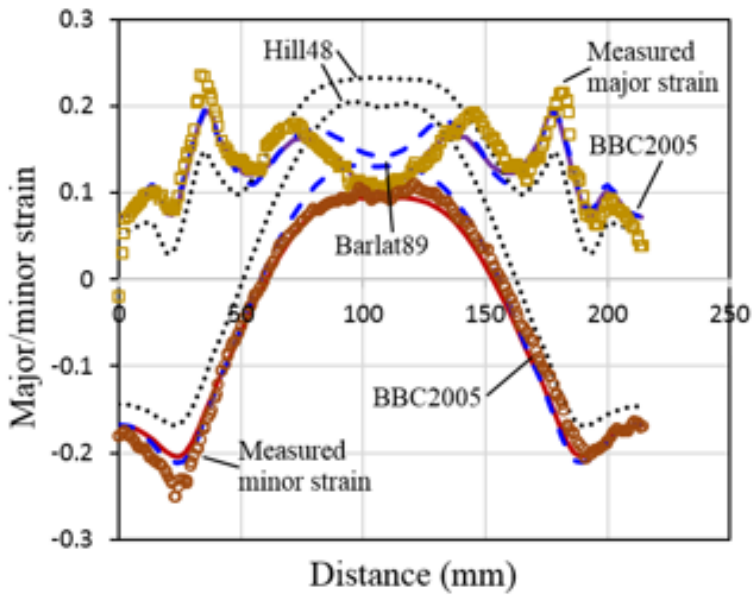




Deep ellipse, Φ160 mm, BHF=14 kN
Mill oil; 0^0 Section

Hemisphere





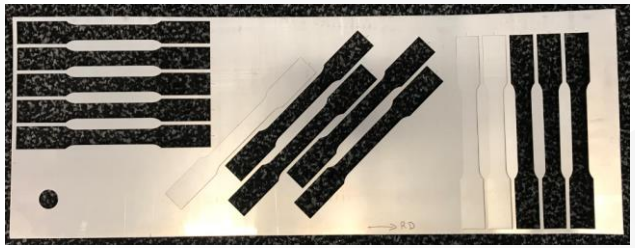
Hemisphere, Φ190 mm, BHF=32.4 kN
Mill oil; 45^0 Section

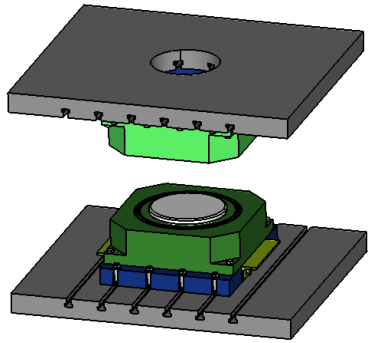
Stamping Feasibility Analysis

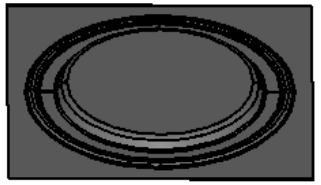
Formability Testing at CRP





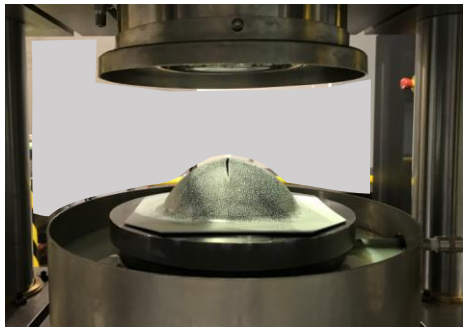






Pie-Pan

Bulge

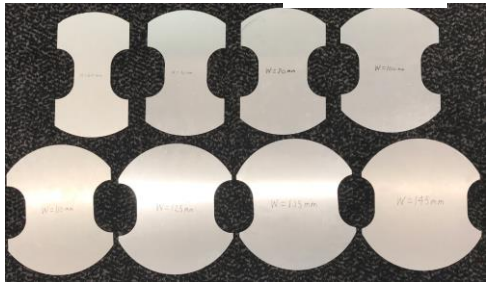


Marciniak



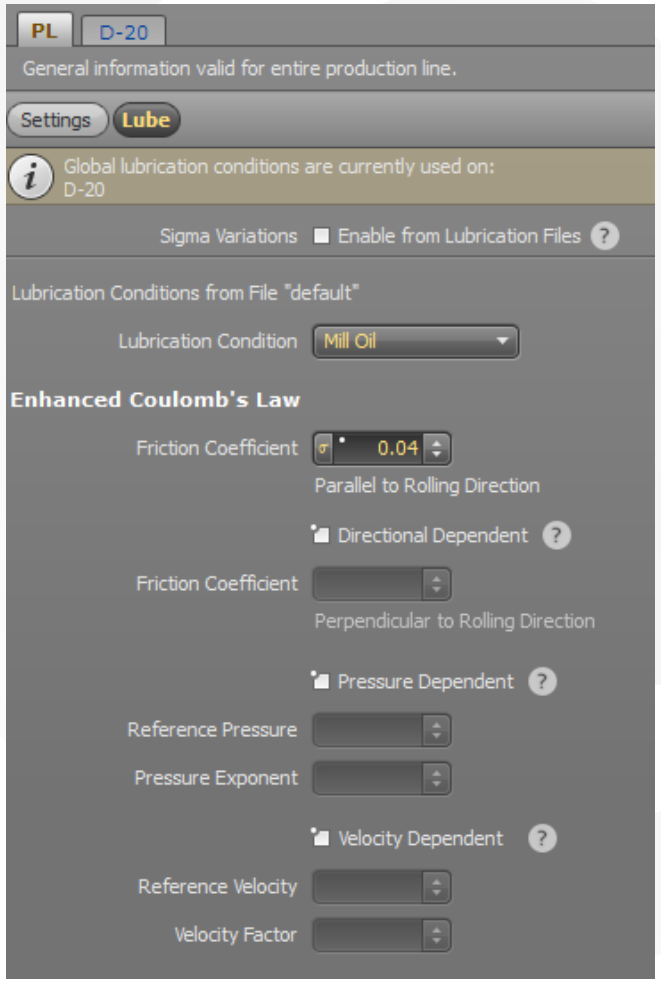
Nakajima



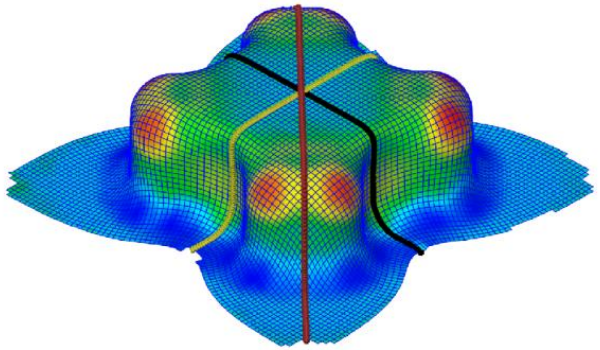


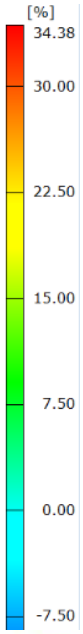
Stamping Feasibility Analysis

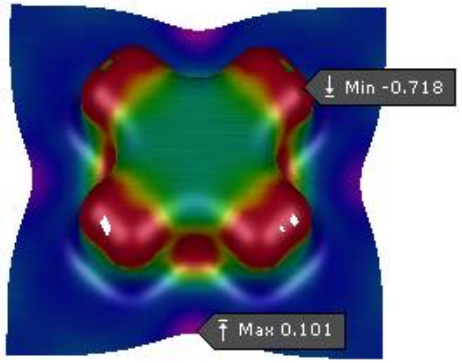
Frictional modeling

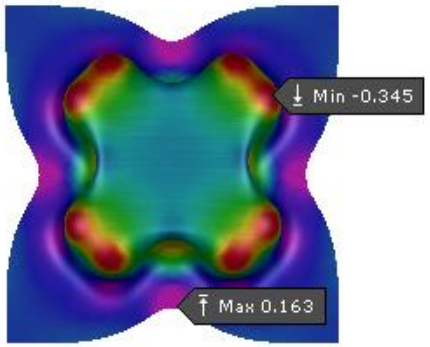


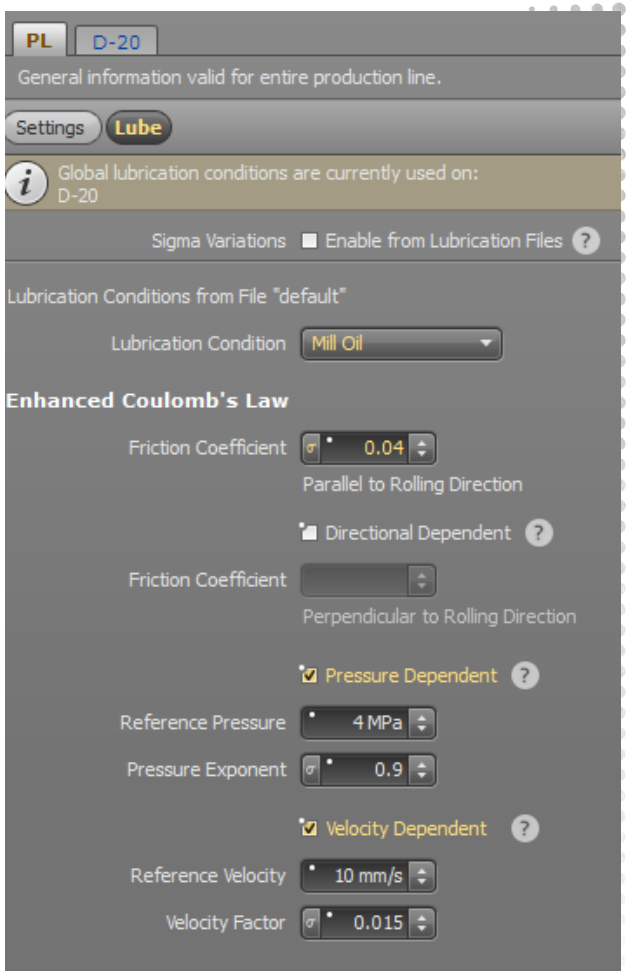










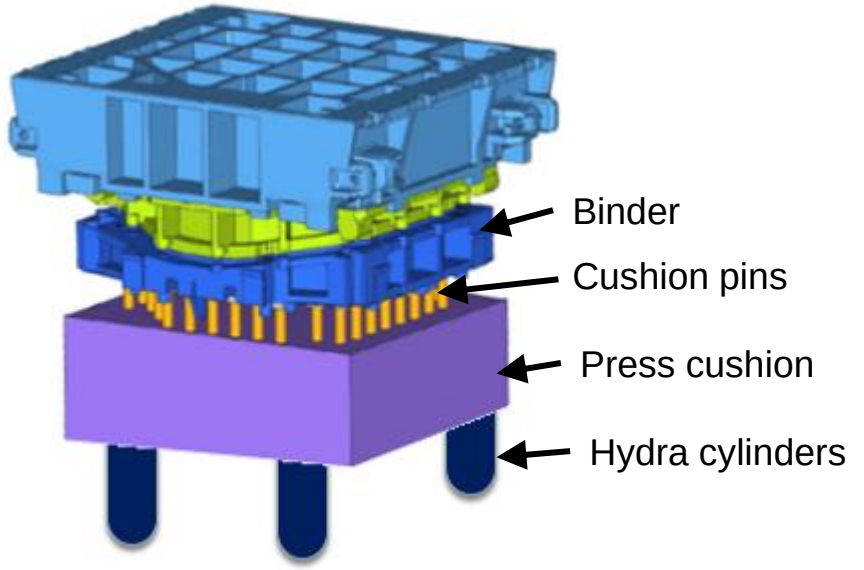


Stamping Feasibility Analysis

Binder Force modeling

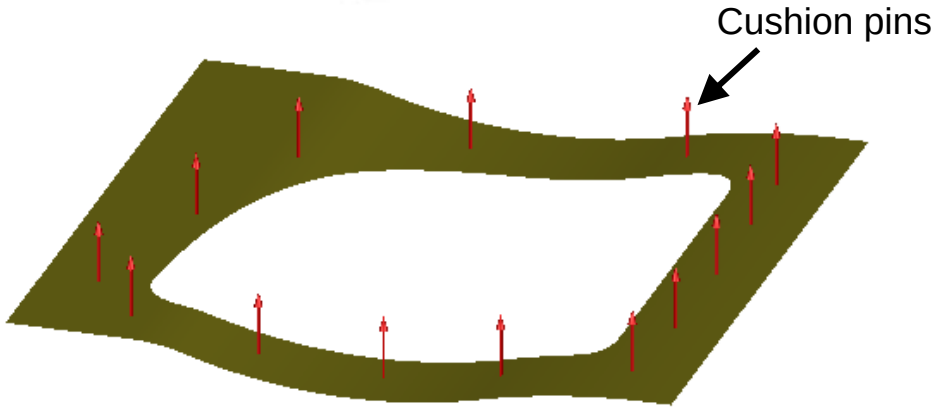
Force control

Do not apply uniform binder force
Define cushion pins or cylinders as used
Use physical beads to determine binder tonnage



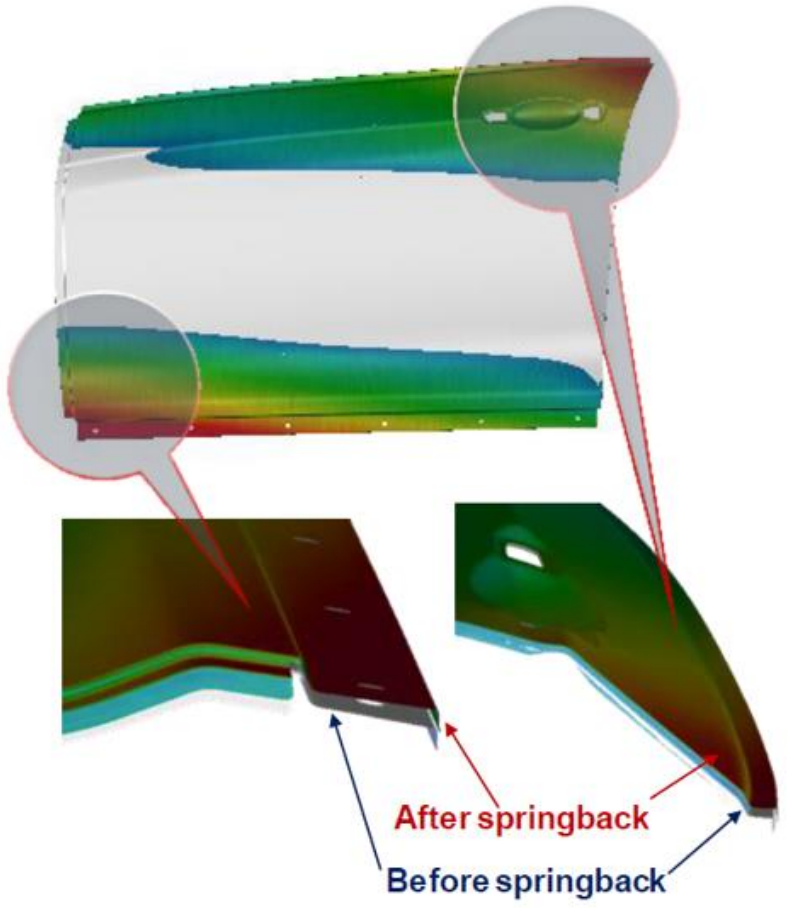
Gap control

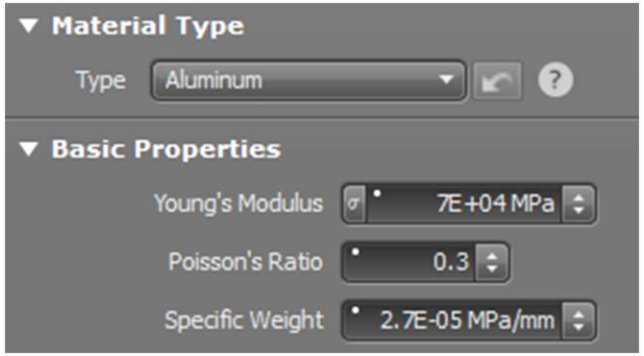
Constant gap over the forming process
Binder force keep changing to keep the gap
Difficult to predict wrinkling



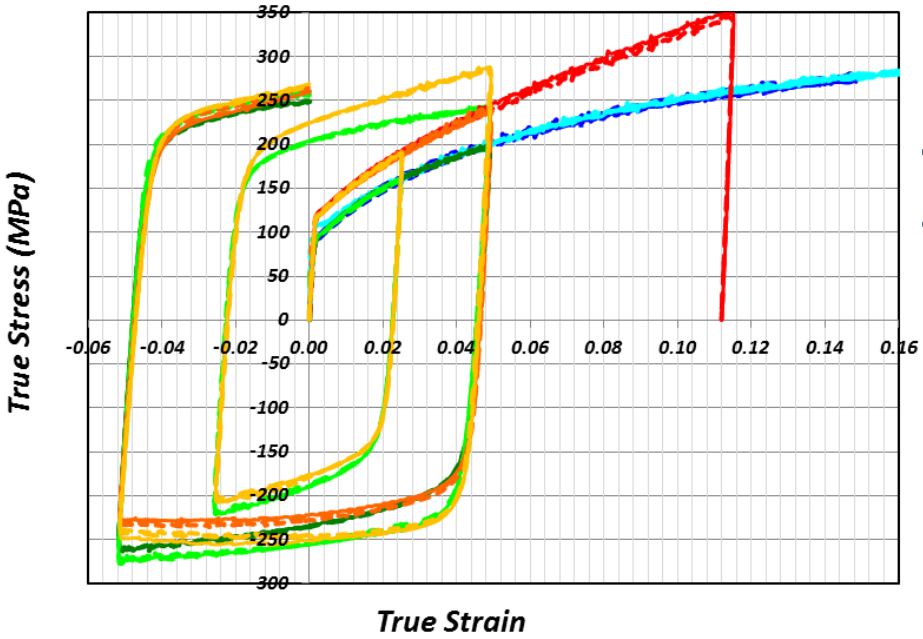
Stamping Feasibility Analysis

Springback Prediction





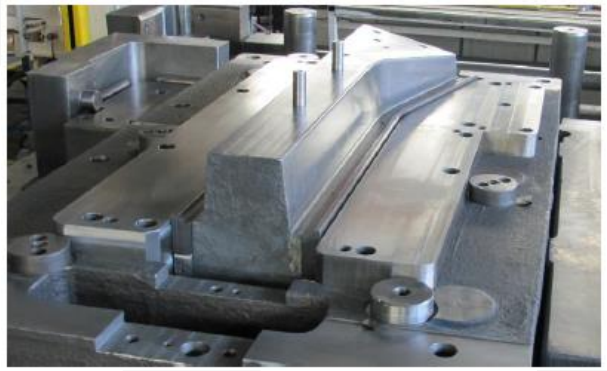
The way used to be

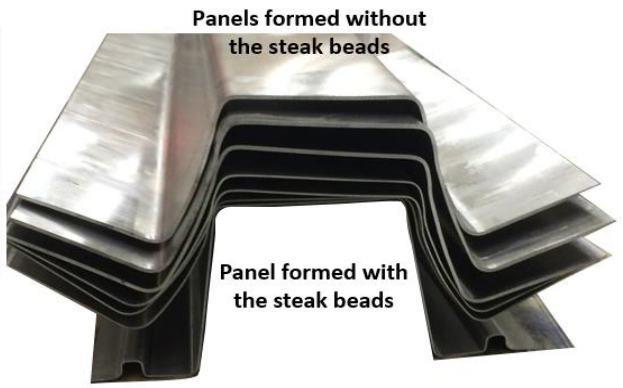


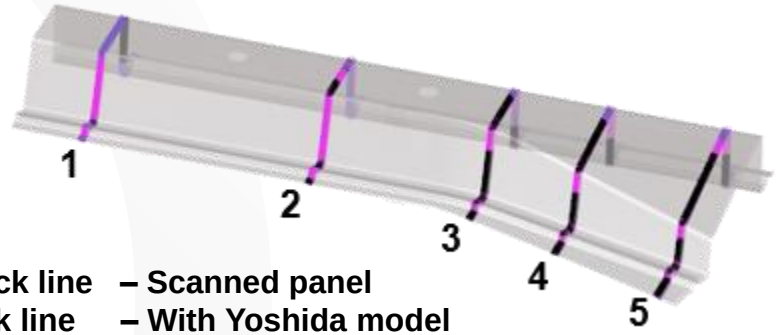
The way to be

Stamping Feasibility Analysis

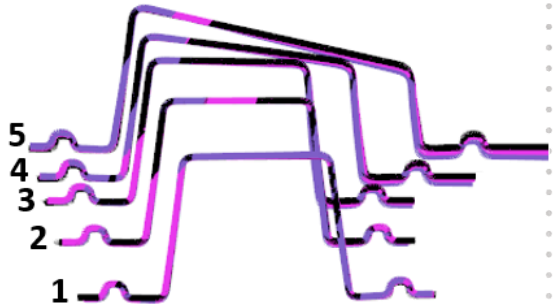
Springback Prediction

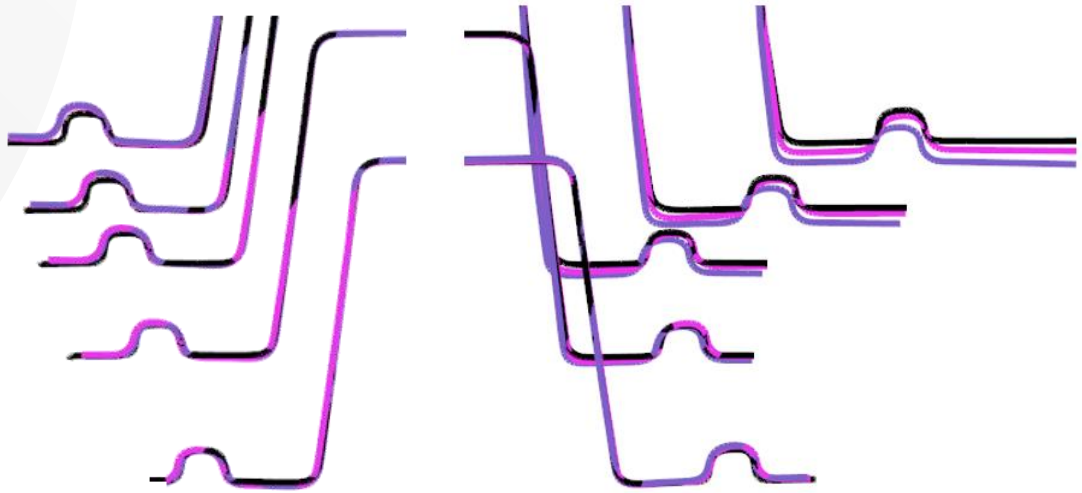






Black line – Scanned panel
Pink line – With Yoshida model
Purple line – Without Yoshida model



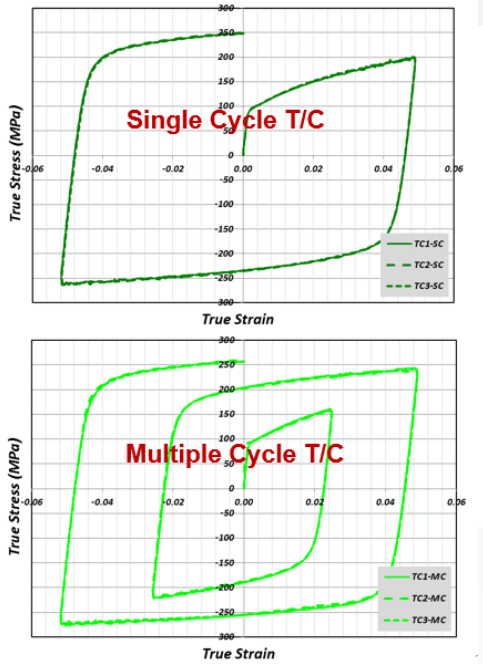


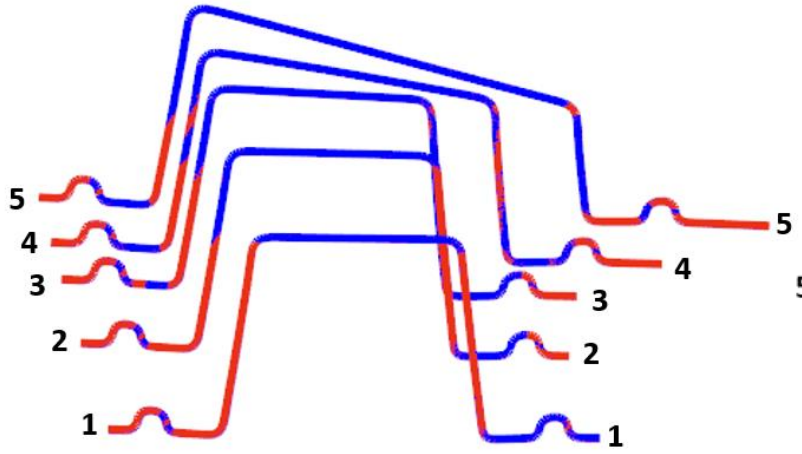
Stamping Feasibility Analysis

Springback Prediction

Multi-Cycle vs. Single-Cycle

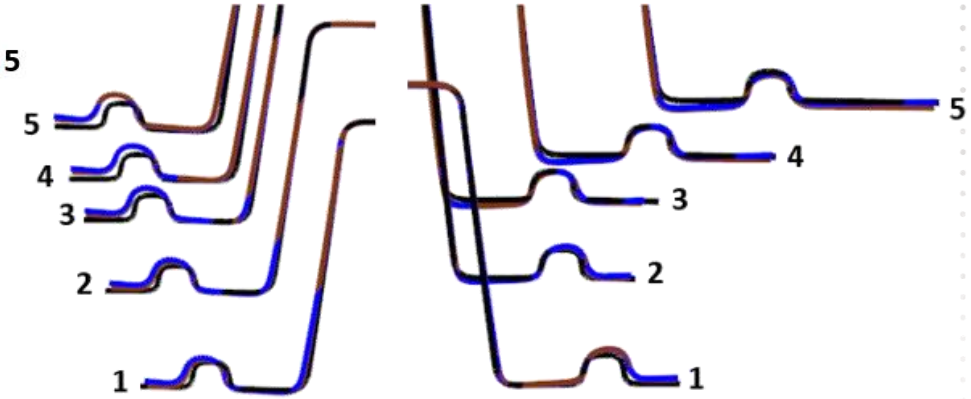
Red line – Multi-cycle tension-compression test
Blue line – Single cycle tension-compression test





T-C vs. C-T

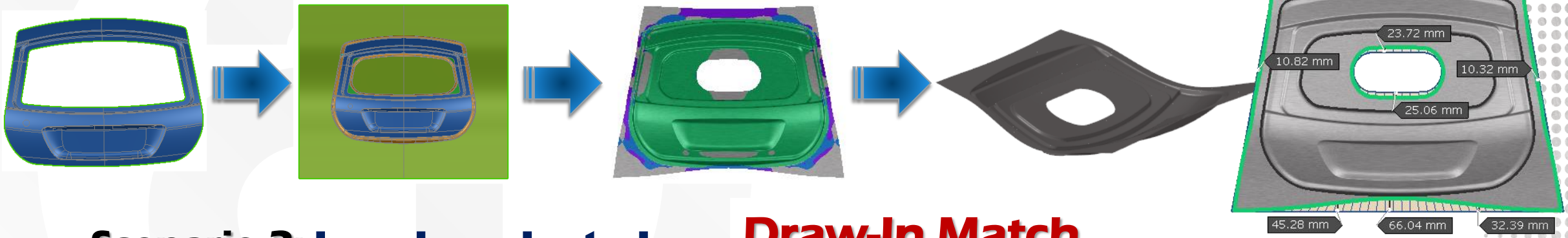
Blue line – Tension-compression test
Brown line – Compression-tension test



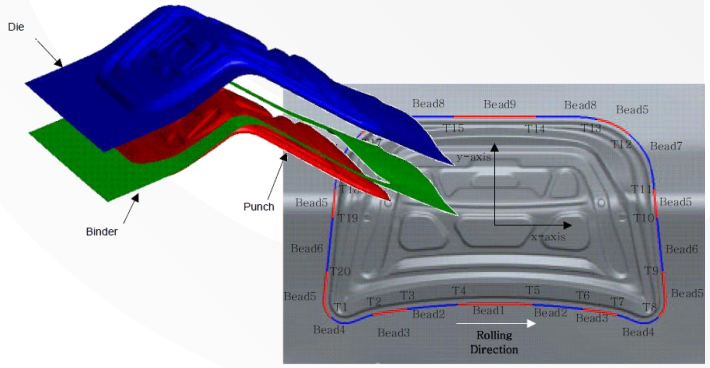
Stamping Feasibility Analysis

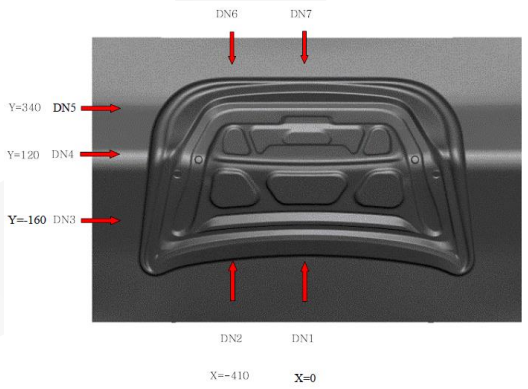
Simulation vs. Reality

Scenario 1: from design to tryout/production

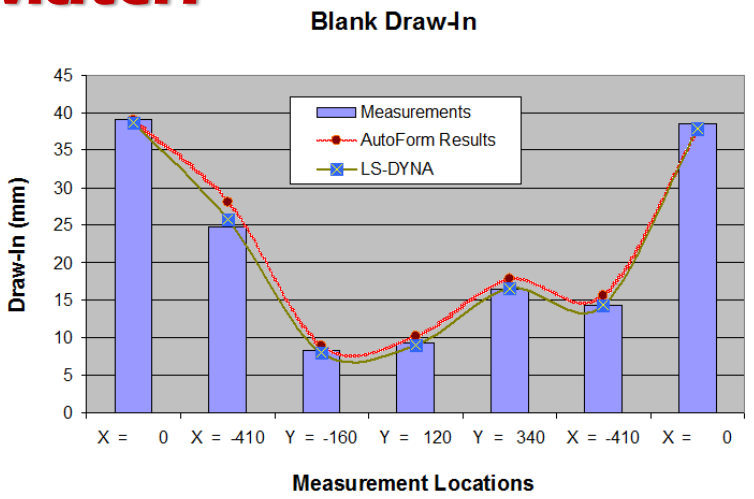


Scenario 2: benchmark study





Draw-In Match



2022 Design Workshop Program Archive

https://www.youtube.com/playlist?list=PLJhPoDFvCALI5BU6nAtlIRWK2522kL8Qw



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Questions?

Thank You for Your Attention!