Elimination of the Dependence of Forming Limits for AHSS on Testing Process Conditions

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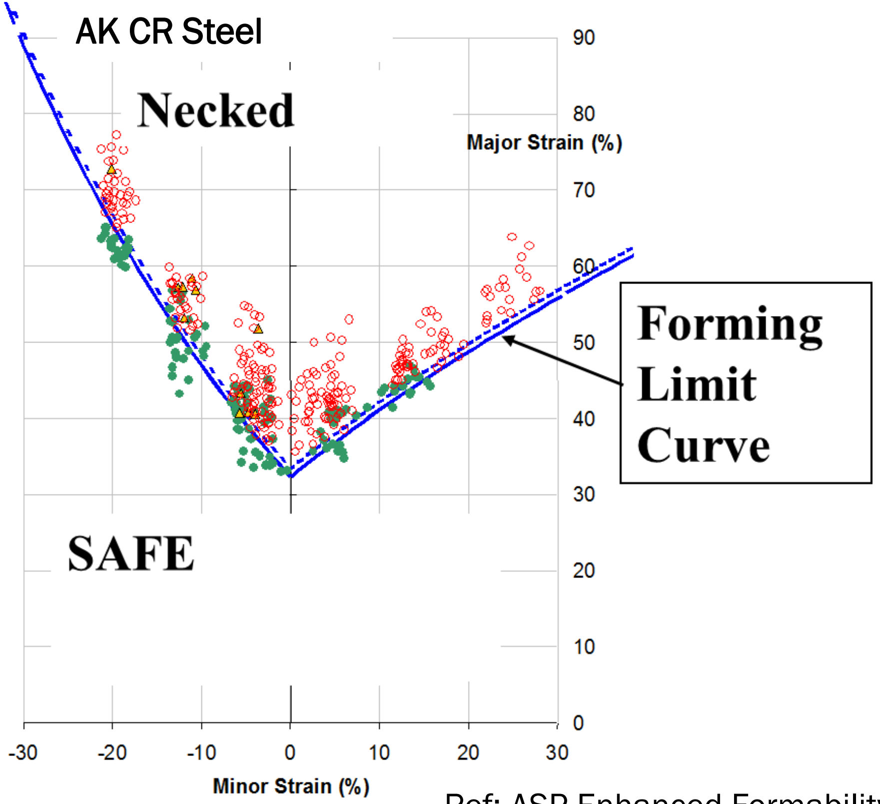
Acknowledgements

Junying Min, Tongji University
John E. Carsley, General Motors Company

Mark Tharrett, General Motors Company
Jeong-Whan Yoon, Deakin University and KAIST

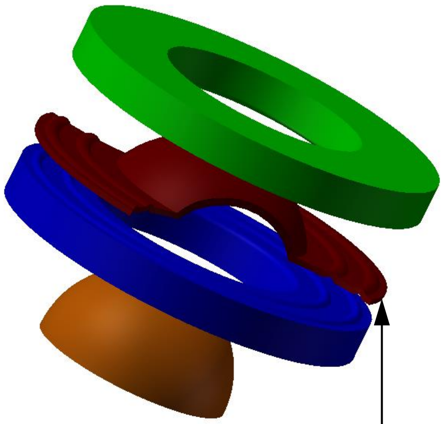
The Conventional FLD



- Introduced by Keeler in 1960's and adopted by industry in late '60s
- Used in tryout and stamping plants
- Applied to assess formability in "virtual" tryout since mid '80s
- Most reliably determined empirically
- Theoretical models require calibration

Ref: ASP Enhanced Formability Project, 2003

Two Ways to Measure the FLC



Specimen

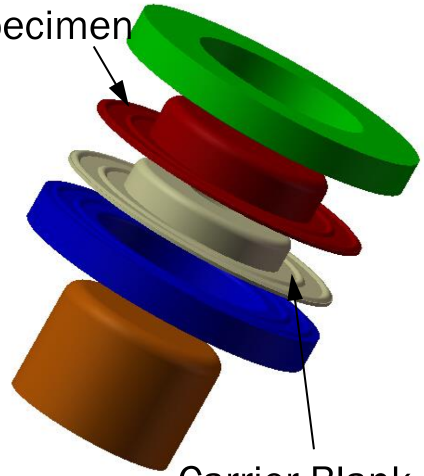
Out-of-plane

Nakazima Tool

In-plane

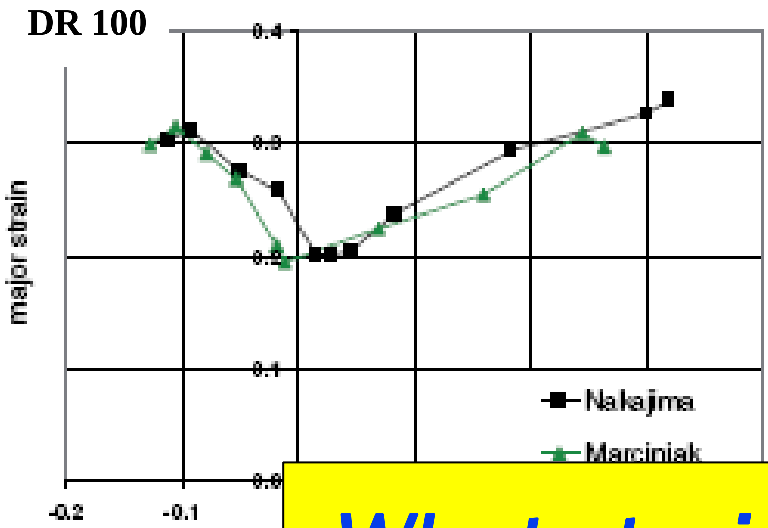
Marciniak Tool

Specimen

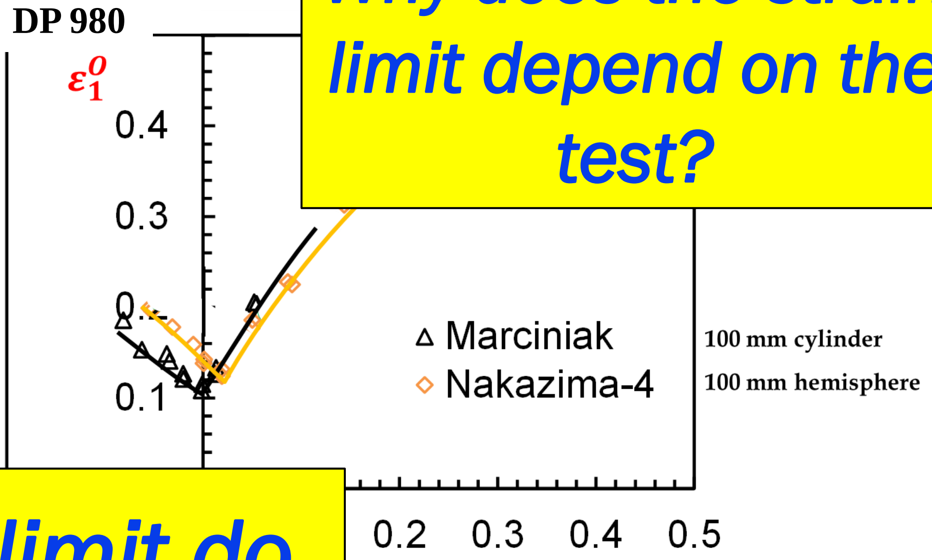


Carrier Blank

Two Different Characterizations of the FLC



Ref: Leppin e

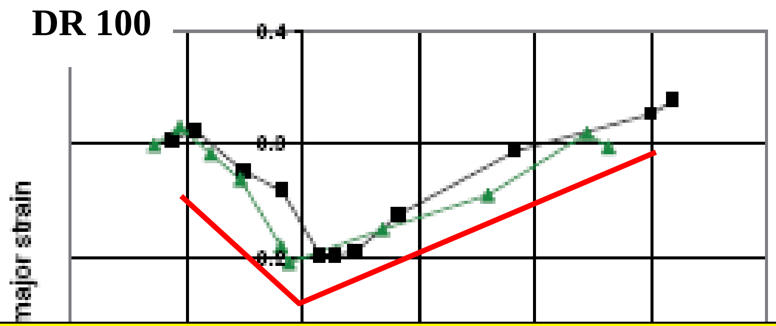


Ref: Min et al., IJMS, 2016

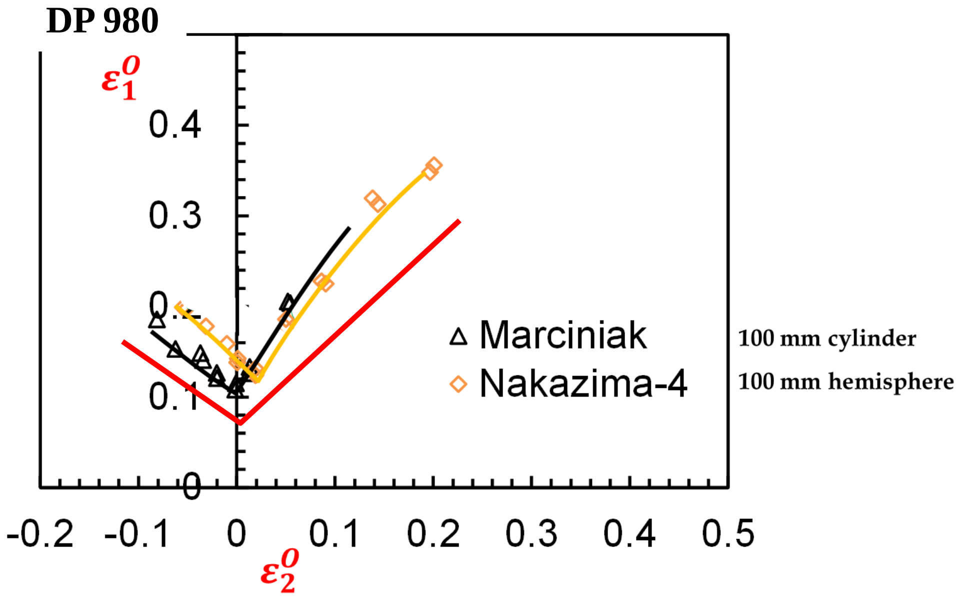
Why does the strain limit depend on the test?

What strain limit do we use in practice?

We Use a Safety Margin, so Who Cares?

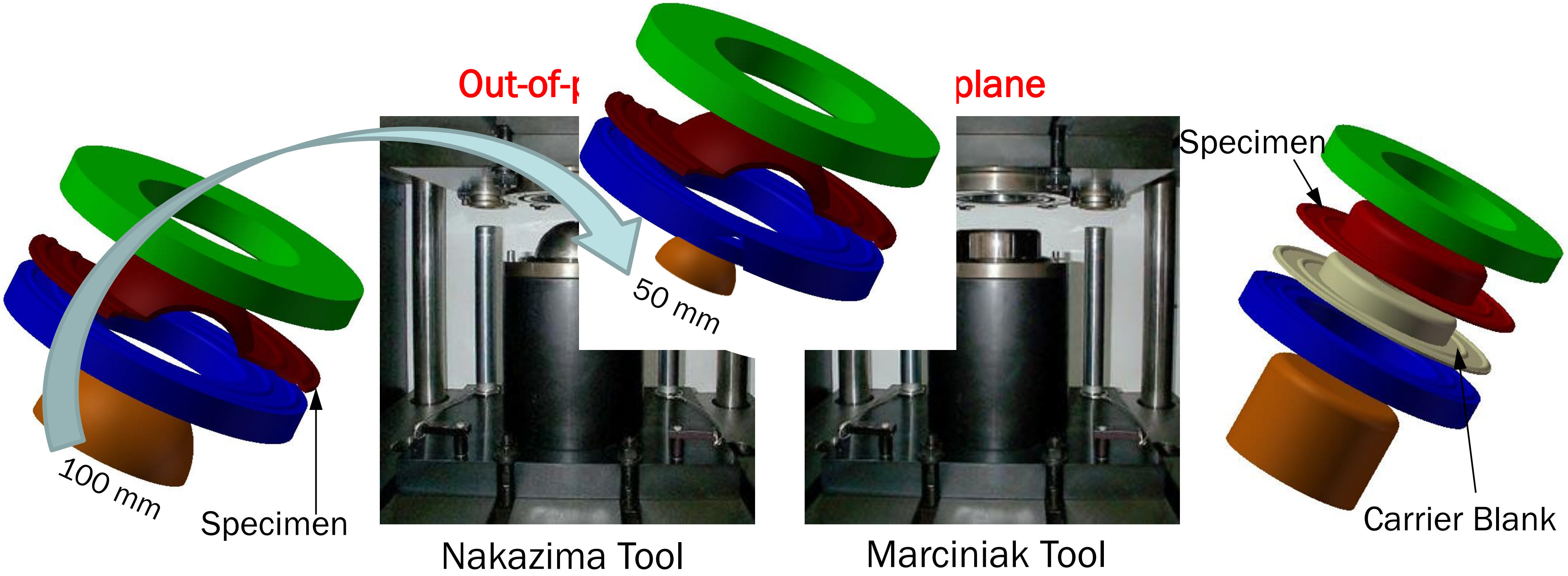


We care when it limits use of AHSS.

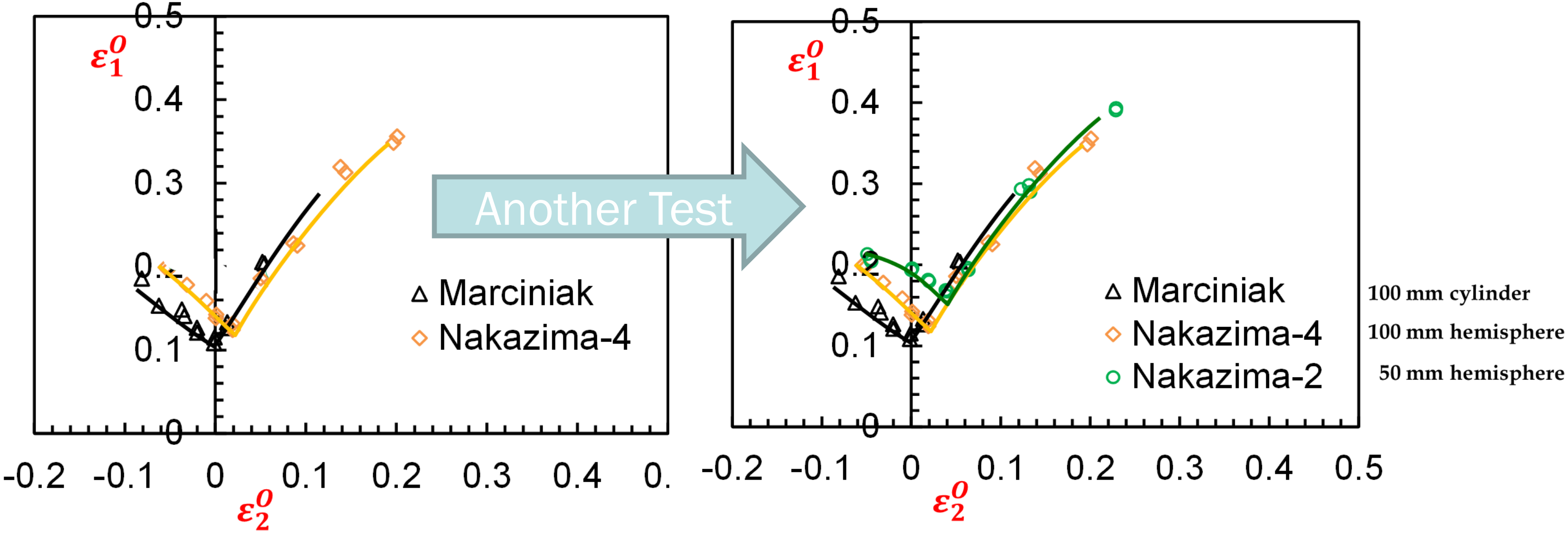


Ref: Min et al., IJMS, 2016

Unconventional Ways to Measure the FLC

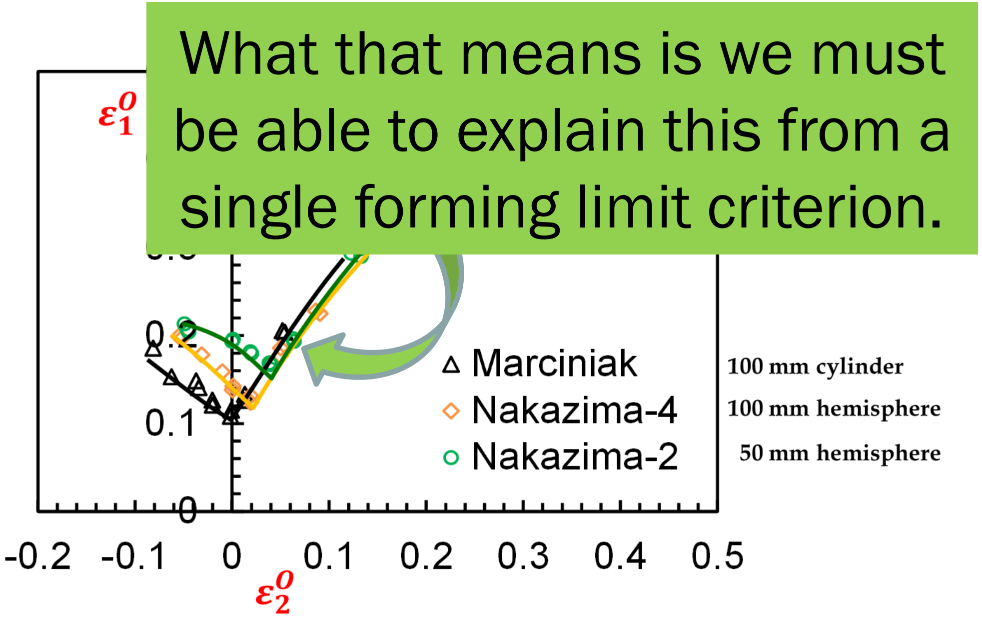


Now the Problem with the FLC Ambiguity is Clear



Objective

1) Understand the cause of this ambiguity
2) Find a solution to it

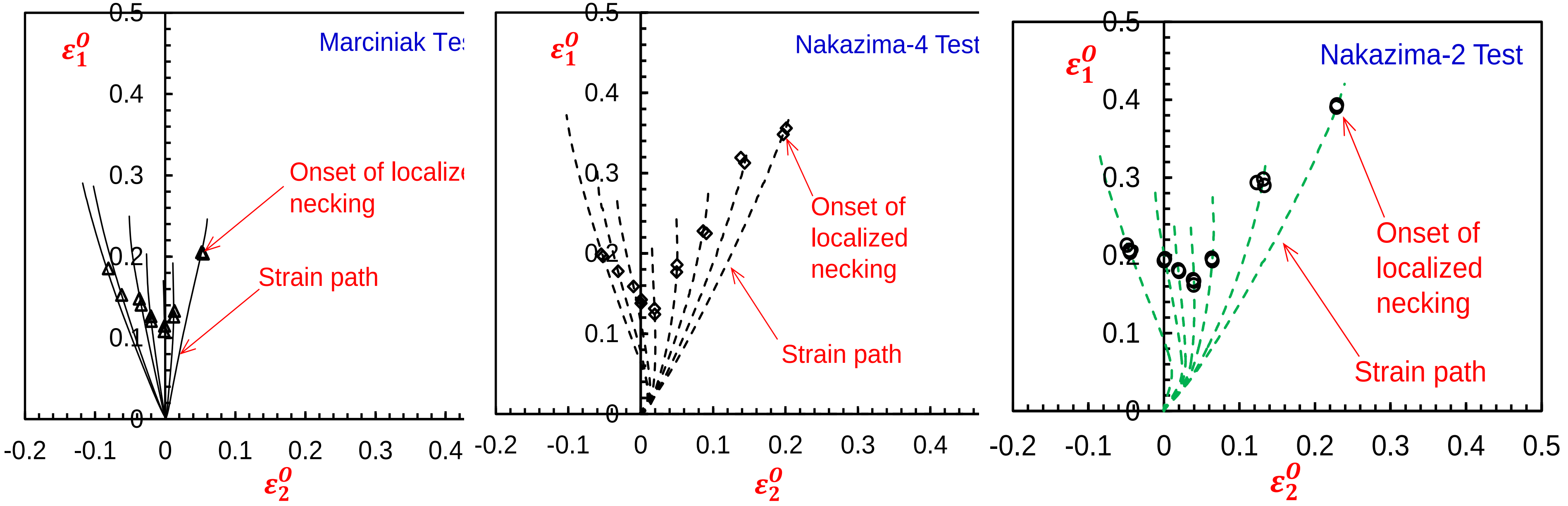


What does a solution look like?

1) A unique forming limit, regardless of test
2) An understanding how to use this forming limit

DIC Helps Identify Something Unique to Each Test

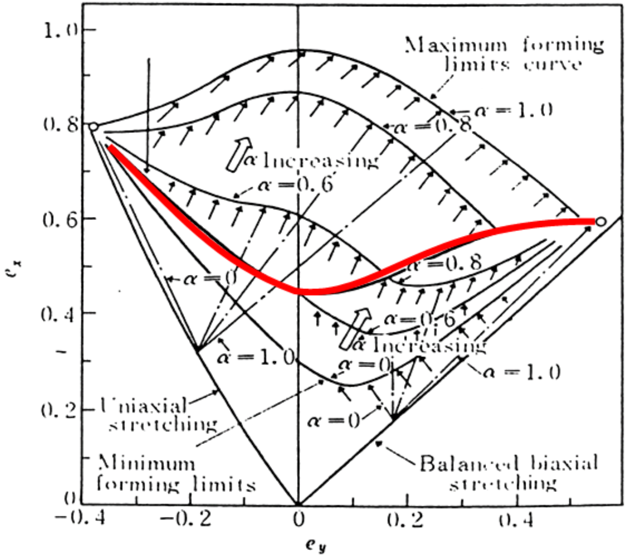
We can measure the strain path for each test done to determine the FLC



Each test results in different (unique) degrees of nonlinear strain paths

Why is the Degree of Linearity Important?

Nakazima et al., 1968, Yawata Tech. Rep., No. 264, 8517-8530.



The strain FLC is NOT a static forming limit.

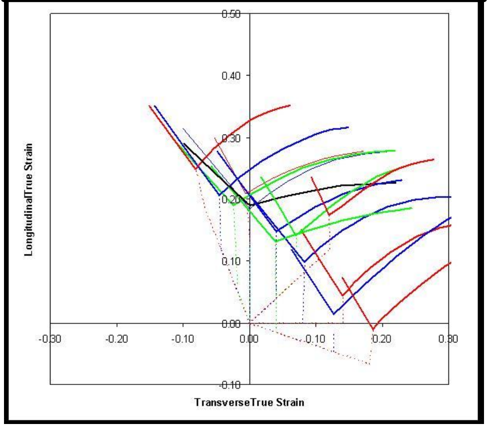
The strain FLC is a DYNAMIC limit.

Question: Could this fact impact our measurement of the FLC?

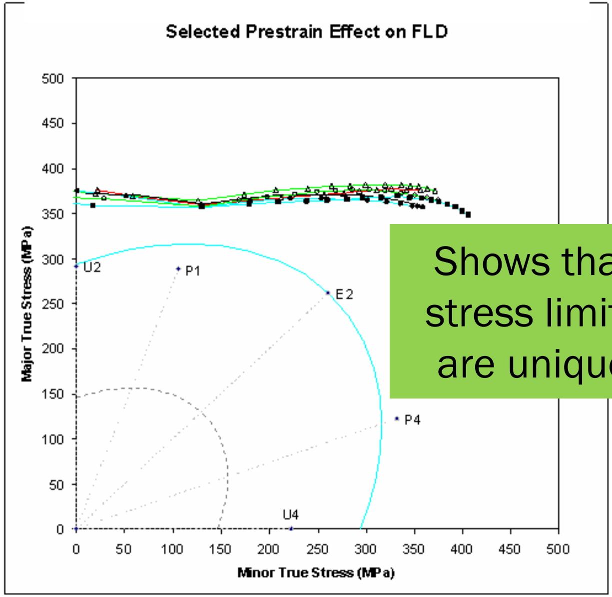
Fortunately We Have a Way to Compensate for It

Graf and Hosford, 1993, Met Trans A, 24, 2497-2501.

Measured FLC's after various strains illustrating the DYNAMIC nature of strain limits

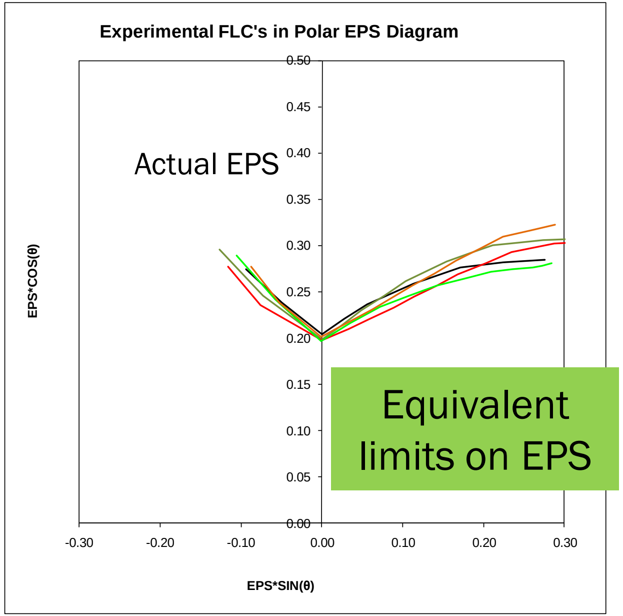


Stoughton, IJMS, 2000.



Shows that stress limits are unique

Stoughton & Yoon, Numisheet 2011.



Equivalent limits on EPS

The Manufacturing Line That Calculates The Stress

$EPS=0$

$\sigma_i=0$ $\Delta\varepsilon_j$ Model Parameters

Output

Input

$$(\Delta\sigma_i, \Delta EPS)=UMAT(\sigma_i, EPS, \Delta\varepsilon_j, P_k)$$

$$\sigma_i = \sigma_i + \Delta\sigma_i$$

$$EPS = EPS+\Delta EPS$$

The Manufacturing Line That Calculates The Stress

The deformation of the mesh in metal forming simulations define the values of the $\Delta\varepsilon_j$

With the next $\Delta\varepsilon_j$

Model Parameters

Output

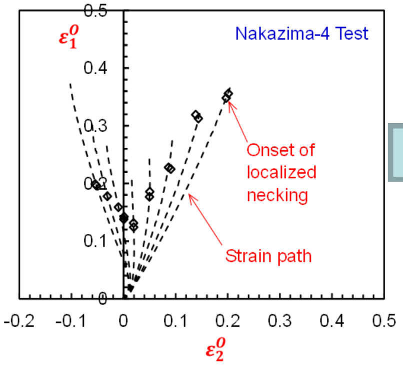
Input

$$(\Delta\sigma_i, \Delta EPS) = UMAT(\sigma_i, EPS, \Delta\varepsilon_j, P_k)$$

$$\sigma_i = \sigma_i + \Delta\sigma_i$$

$$EPS = EPS + \Delta EPS$$

The Same Process Works on DIC Measurements



With the next $\Delta\varepsilon_j$

Model Parameters

Output

Input

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$$\sigma_i = \sigma_i + \Delta\sigma_i$$

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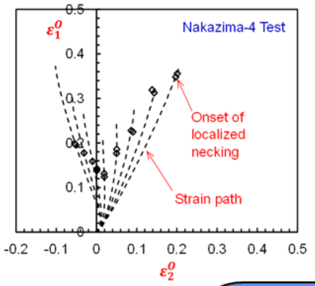
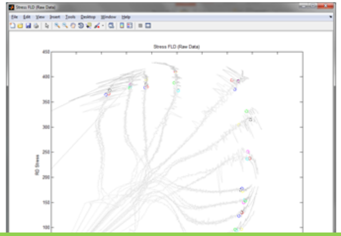
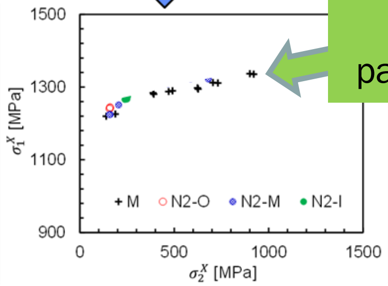
How to Compensate for Nonlinear Strain Paths



DIC Strain Path → **UMAT** → **Stress Increments**



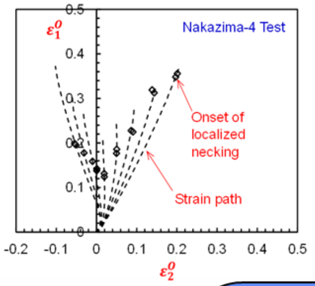
Stress Integration



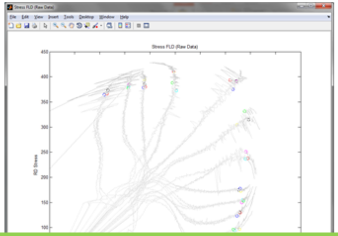
These stress limits apply for the unique strain paths involved in the test

Science tells us that these stress limits apply for ANY strain path, including linear strain paths

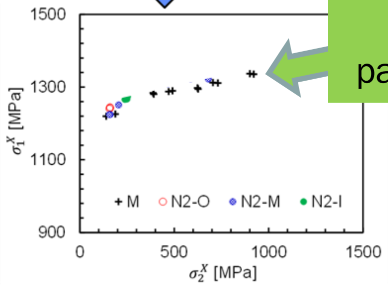
How to Compensate for Nonlinear Strain Paths



DIC Strain Path → UMAT → Stress Increments



Stress Integration



These stress limits apply for the unique strain paths involved in the test

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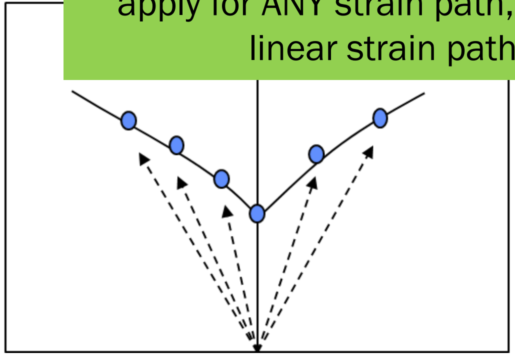
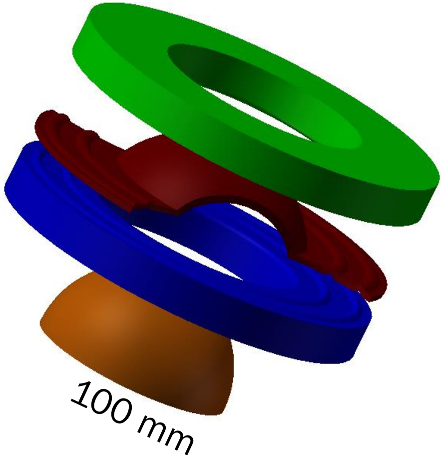
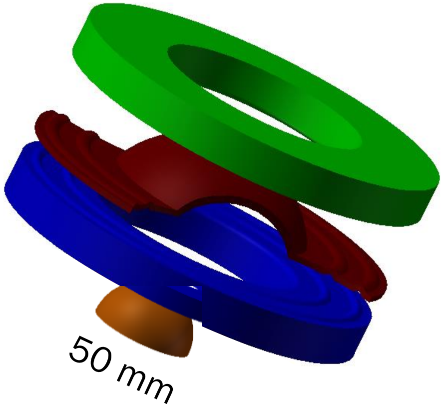
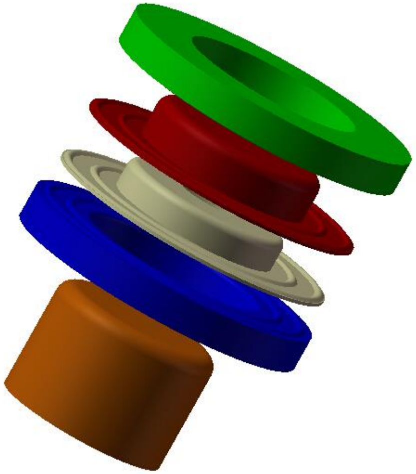
→ UMAT^{-1} →



Another Difference Between These Tests





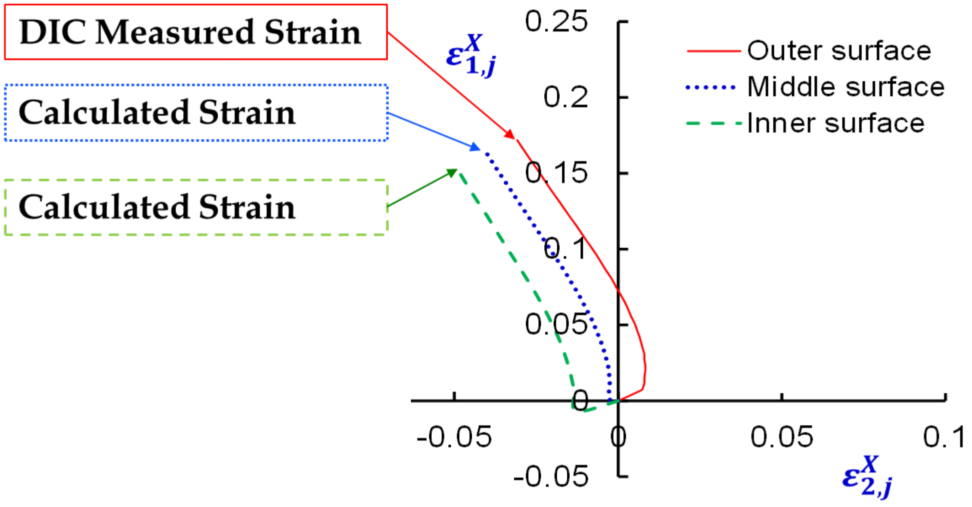


Sheet Curvature

...Gives Rise to Differences in Strain Levels Through the Sheet Thickness

How Large are These Strain Differences?

One Nakajima Test Result



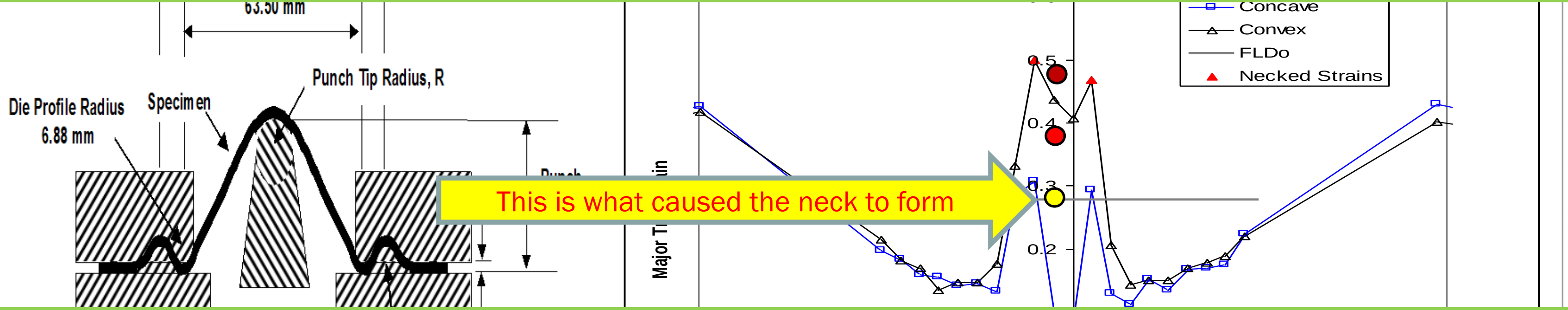
1) 3% difference in strain between the top and bottom surface
2) What strain defines the limit?
3) Intuition suggests to use the average
4) Is this intuition correct?

Fortunately We Know the Answer

Stretch-Bending Study Reported By: Tharrett & Stoughton SAE Report 2003-01-1157

Conclusion of the Study:

In every test specimen in which a neck was detected, the MEASURED strain on the CONCAVE side was found to be above the forming limit for in-plane stretching

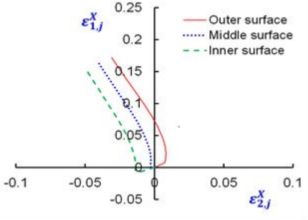


These experimental results make perfect sense from a theoretical perspective

Necking is an instability that affects the plastic flow of ALL layers through the sheet thickness

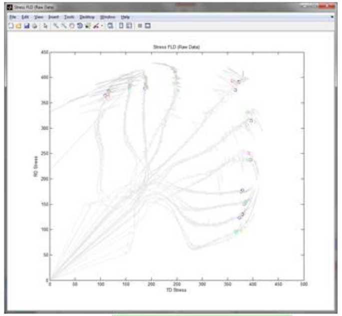
So the instability cannot proceed until all layers satisfy the instability condition.

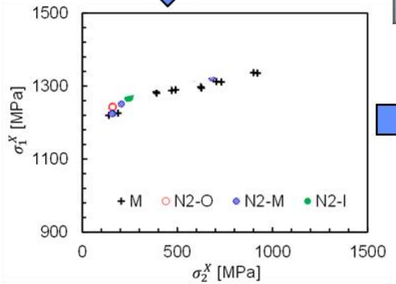
How to Compensate for Thru-Thickness Strain Differences



3 Strain Paths → **UMAT** → **Stress Increments**

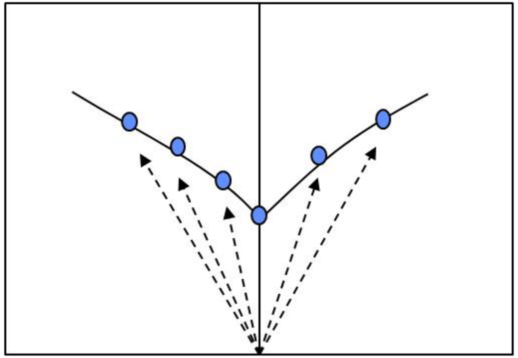
Stress Integration



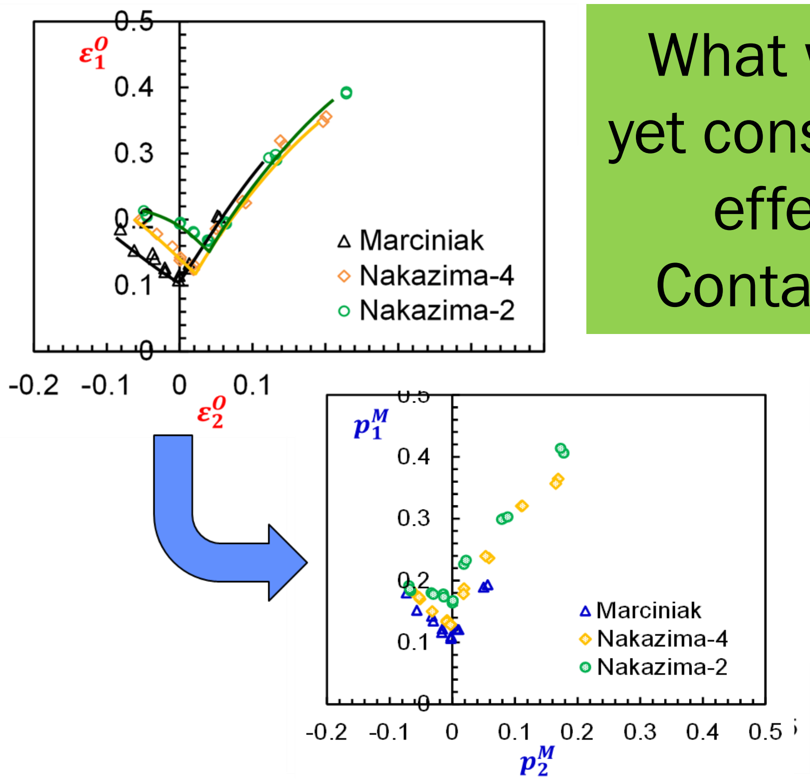


Pick Least Critical Layer

UMAT^{-1}



Result of Compensations for Path and Curvature



What we have not yet considered is the effect of Tool Contact Pressure

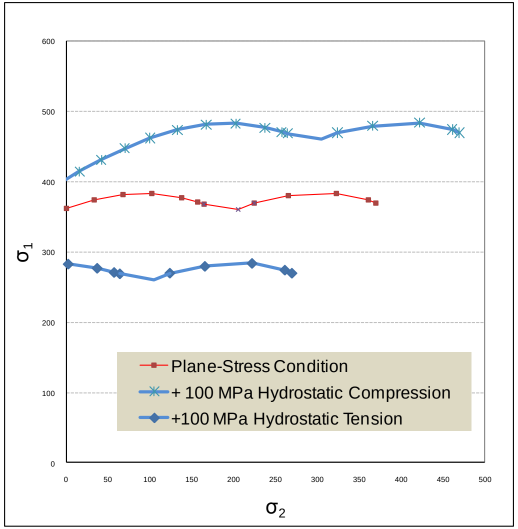
While it is tempting to think these two FLC's are close enough

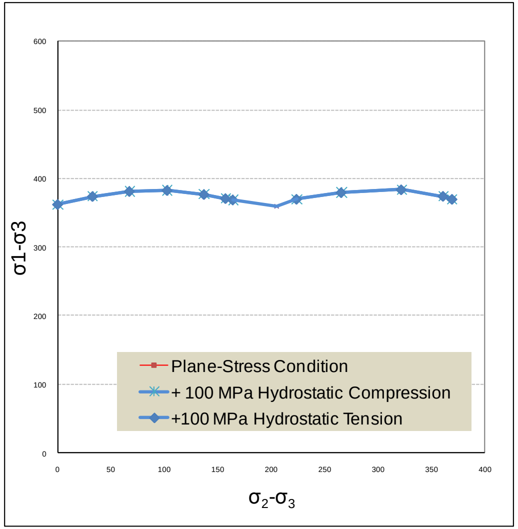
The Nakazima Test results are systematically higher

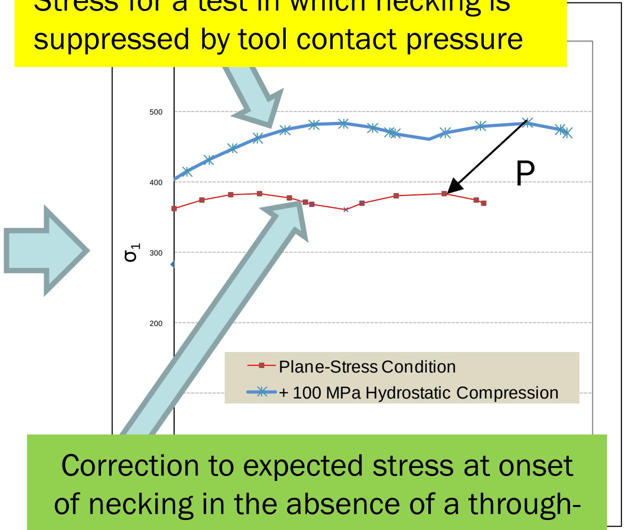
… which suggests we have missed something in the compensation

This becomes more obvious when we add the 50 mm test

Fortunately We Know the Effect of Pressure on Necking







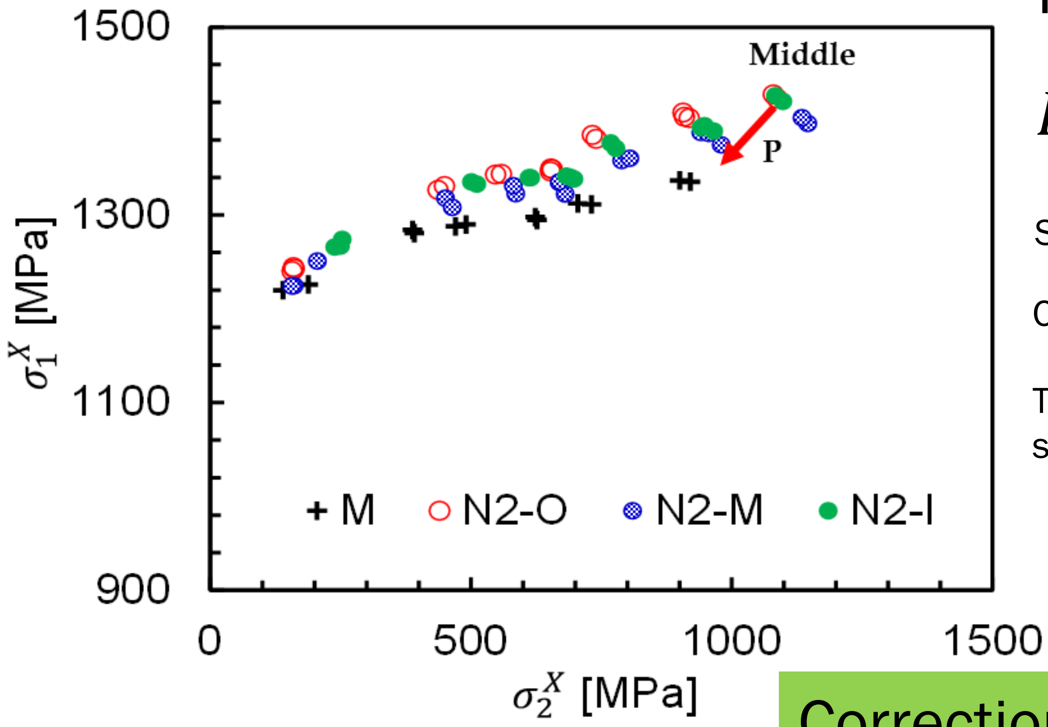
Stress for a test in which necking is suppressed by tool contact pressure

Correction to expected stress at onset of necking in the absence of a through-thickness pressure equal to P

Effect of Superimposed Hydrostatic Stress

Stoughton & Yoon, Numisheet 2011

How to Compensate for Contact Pressure



Force Balance Equation

$$P = t\kappa^I(1 + 0.5t\kappa^I)(\sigma_1 + \sigma_2)$$

Sheet thickness (from DIC)

Curvature (1/Punch Radius)

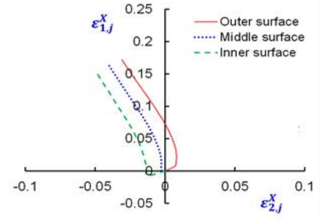
Two in-plane stress components (average of stresses)

$$\sigma_i = 0.25 * (\sigma_i{}^I + 2 * \sigma_i{}^M + \sigma_i{}^O)$$

from UMAT processed DIC strain data

Corrections $\sigma_i{}^I \rightarrow \sigma_i{}^I$-P $\quad \sigma_i{}^M \rightarrow \sigma_i{}^M$-P/2

How to Compensate for All of It

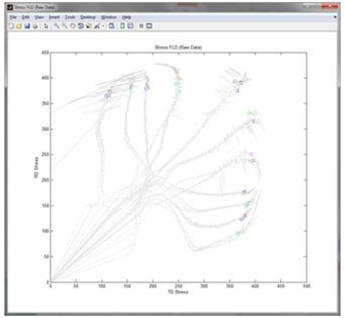


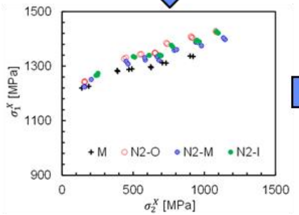
3 Strain Paths

UMAT

Stress Increments

Stress Integration

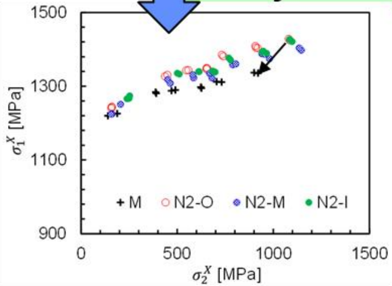




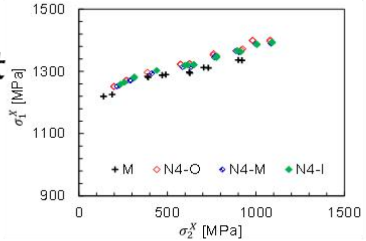
Pressure Calculation

$$P = t\kappa^I(1 + 0.5t\kappa^I)(\sigma_1 + \sigma_2)$$

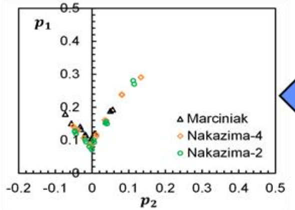
Correction to Middle and Inner Layers



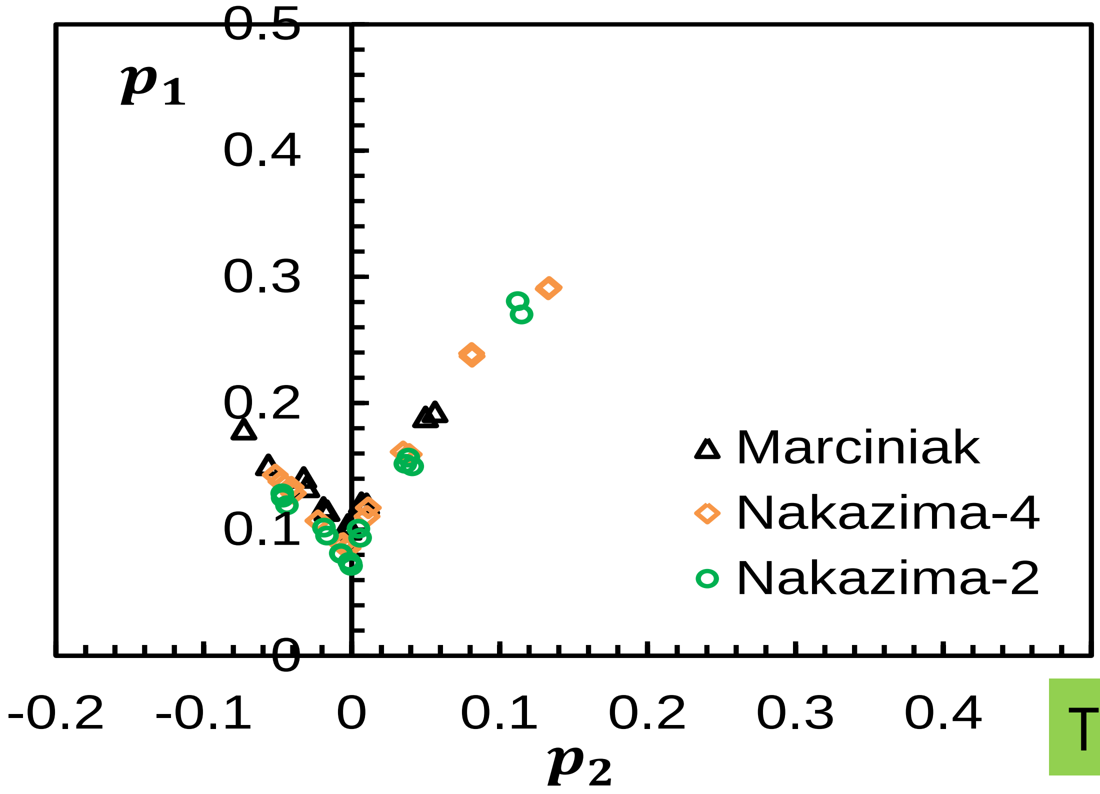
Pick Least Critical Layer



Convert to Strain



The Result

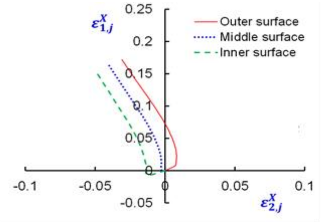


One Material

One FLC

That's the GOOD news

Recommend Industry Standard To Correct FLC Data

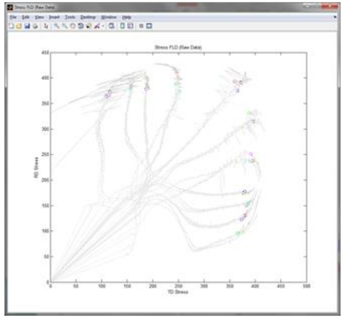


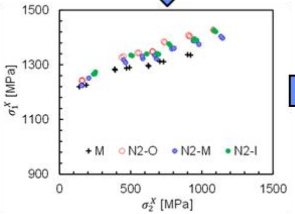
3 Strain Paths

UMAT

Stress Increments

Stress Integration

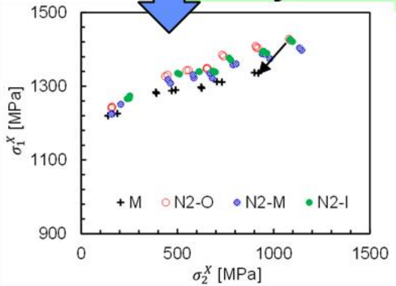




Pressure Calculation

$$P = t\kappa^I(1 + 0.5t\kappa^I)(\sigma_1 + \sigma_2)$$

Correction to Middle and Inner Layers



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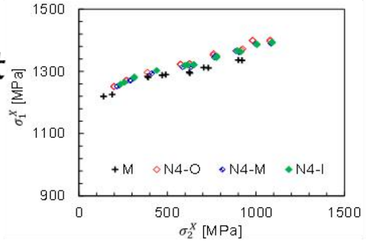
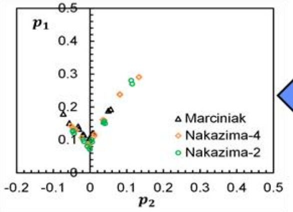
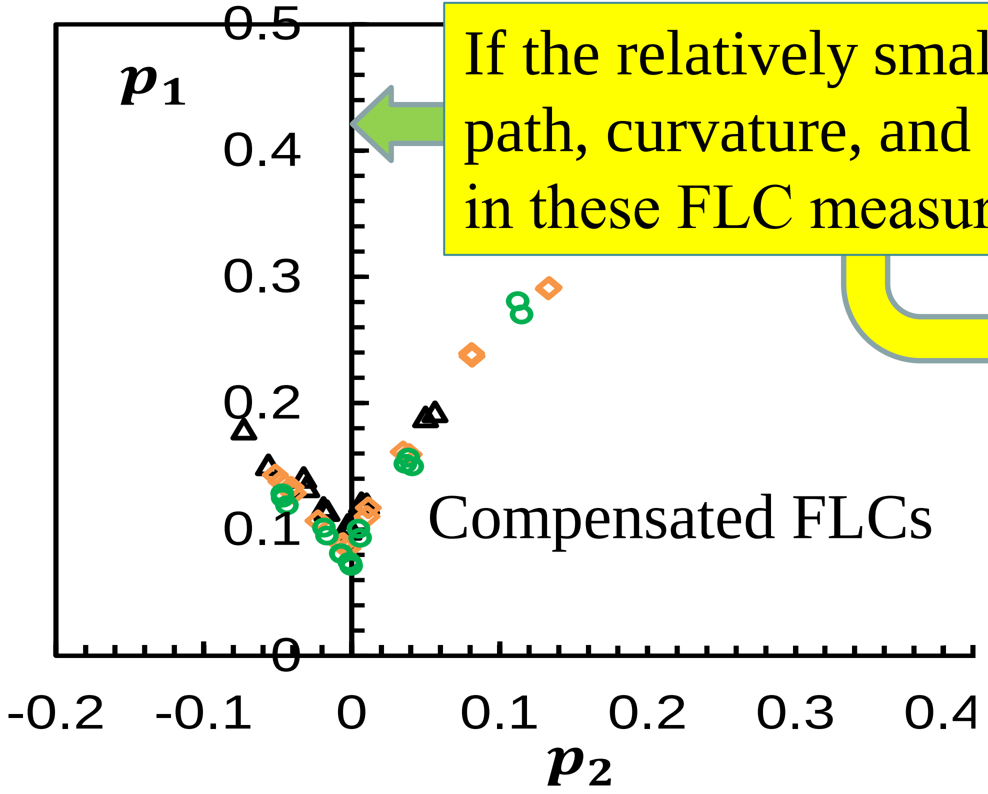


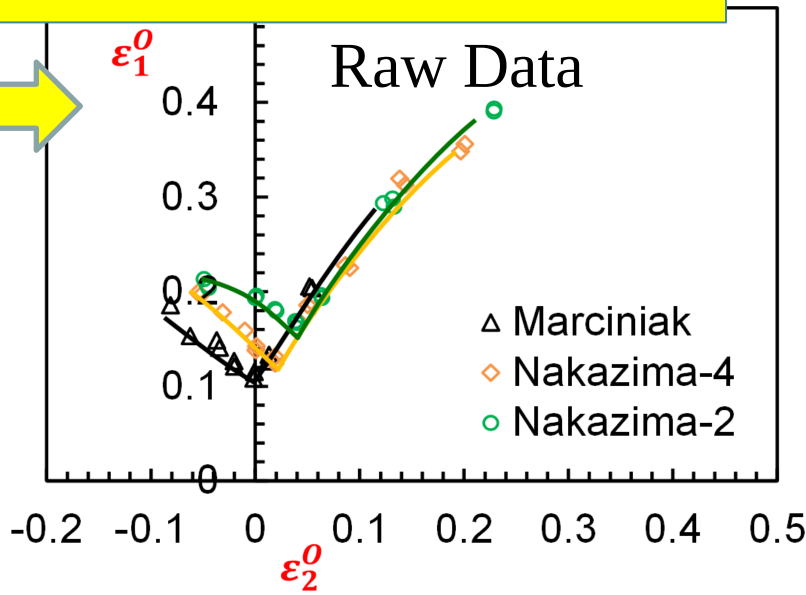
Convert to Strain



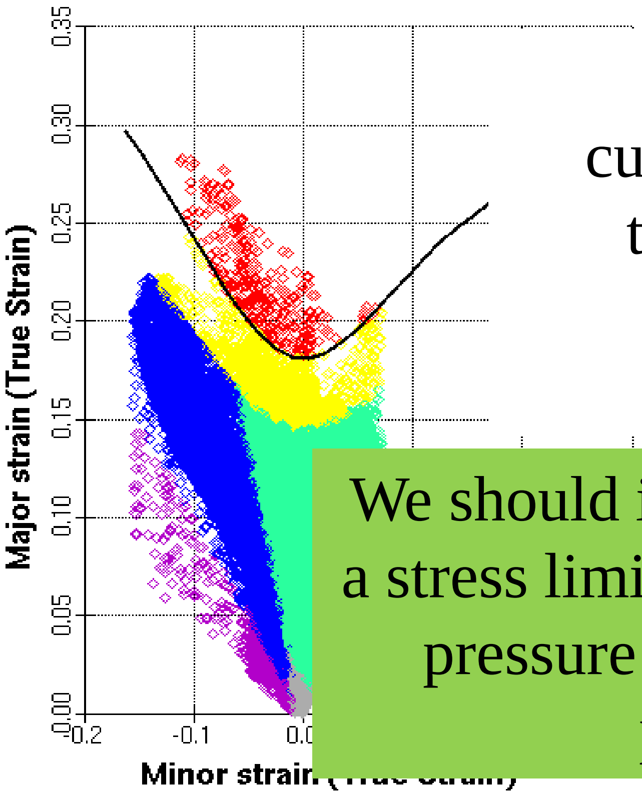
There is perhaps a downside that needs attention…



If the relatively small degree of nonlinear strain path, curvature, and contact pressure that occurs in these FLC measurements can cause this…



Does it EVER make sense to assess manufacturability based on a static strain limit…



… when the degree of nonlinearity, curvature of the sheet, and contact pressures that are involved in stamping automotive components are more than 10 TIMES LARGER?

We should instead ALWAYS convert the strain limit to a stress limit, and account for the curvature and contact pressure in our assessments of the severity of the process with respect to necking.

For More Information

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Compensation for Process-dependent Effects
in the Determination of Localized Necking Limits
Junying Min, Thomas B. Stoughton, John E. Carsley, Jianping Lin
International Journal of Mechanical Sciences, 2016, 117, 115-134

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