Plasticity

Thomas Stoughton

Feb 8-9, 2012

AHSS Workshop

Objective

Presentation on the current state of knowledge of plasticity, constitutive behavior, and forming limits with a focus on opportunities, roadblocks, threats and requirements for use of AHSS in automotive applications.

Outline

❑ Microstructure/Polycrystalline vs. Continuum

Application Needs; Texture & High Exponent Yield Functions; Forming Limits of AHSS; Lessons from Metallic Glass

❑ Elasto-plasticity

Young's Modulus variation, quasiplastic strain

❑ Distortional Hardening Behavior

Isotropic, kinematic, distortional hardening

❑ Forming Limits

Nonlinear Strain Path Effects, Curvature Effects, Necking vs. Fracture, Heightened importance for AHSS

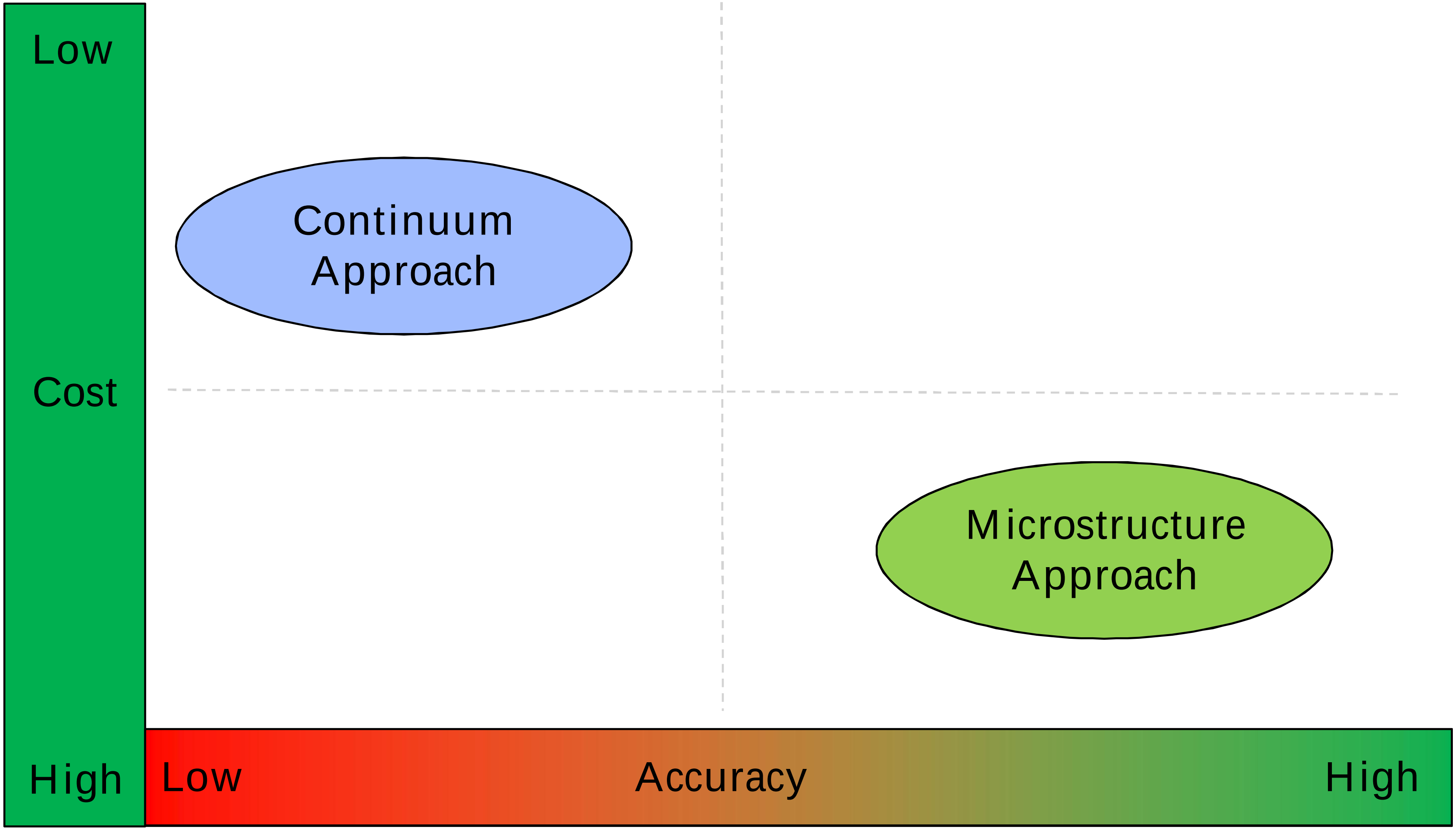
Challenges

Microstructure vs. Continuum Approach

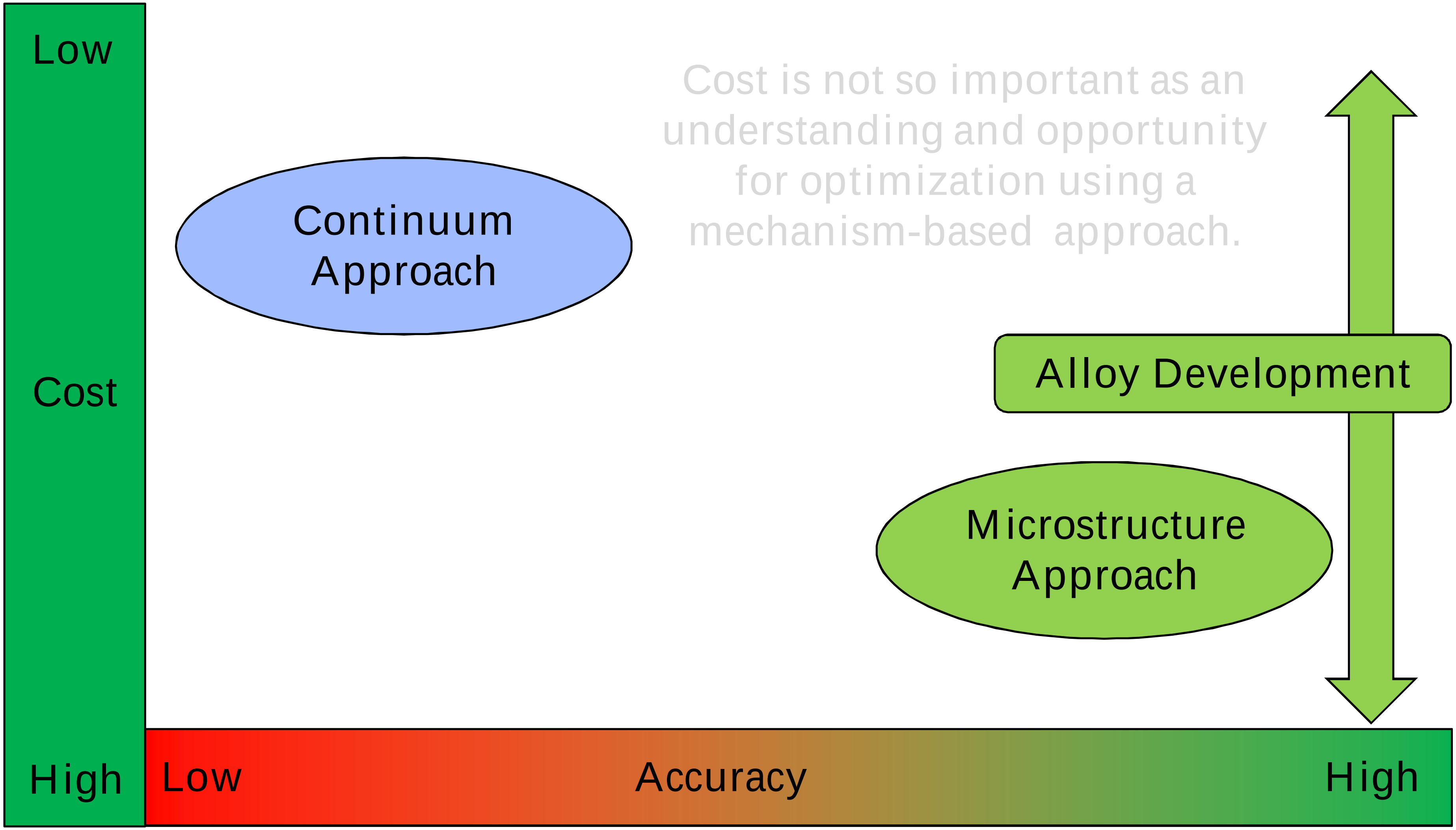
Phenomenon suggesting use of Micro-level Model

- Tripping and/or Twinning mechanisms
- Dual and Complex phases
- Highly textured alloys
  - Limited Slip Systems (FCC & HCP)
  - Elongated Grain Shapes
  - Large Grains and/or Ultra-thin sheet
- Unusual Hardening or Failure Behaviors

Perceived Characteristics of the Two Approaches to Modeling



Reliability is the Primary Driver For Alloy Development



Low

Cost

High

Continuum Approach

Cost is not so important as an understanding and opportunity for optimization using a mechanism-based approach.

Alloy Development

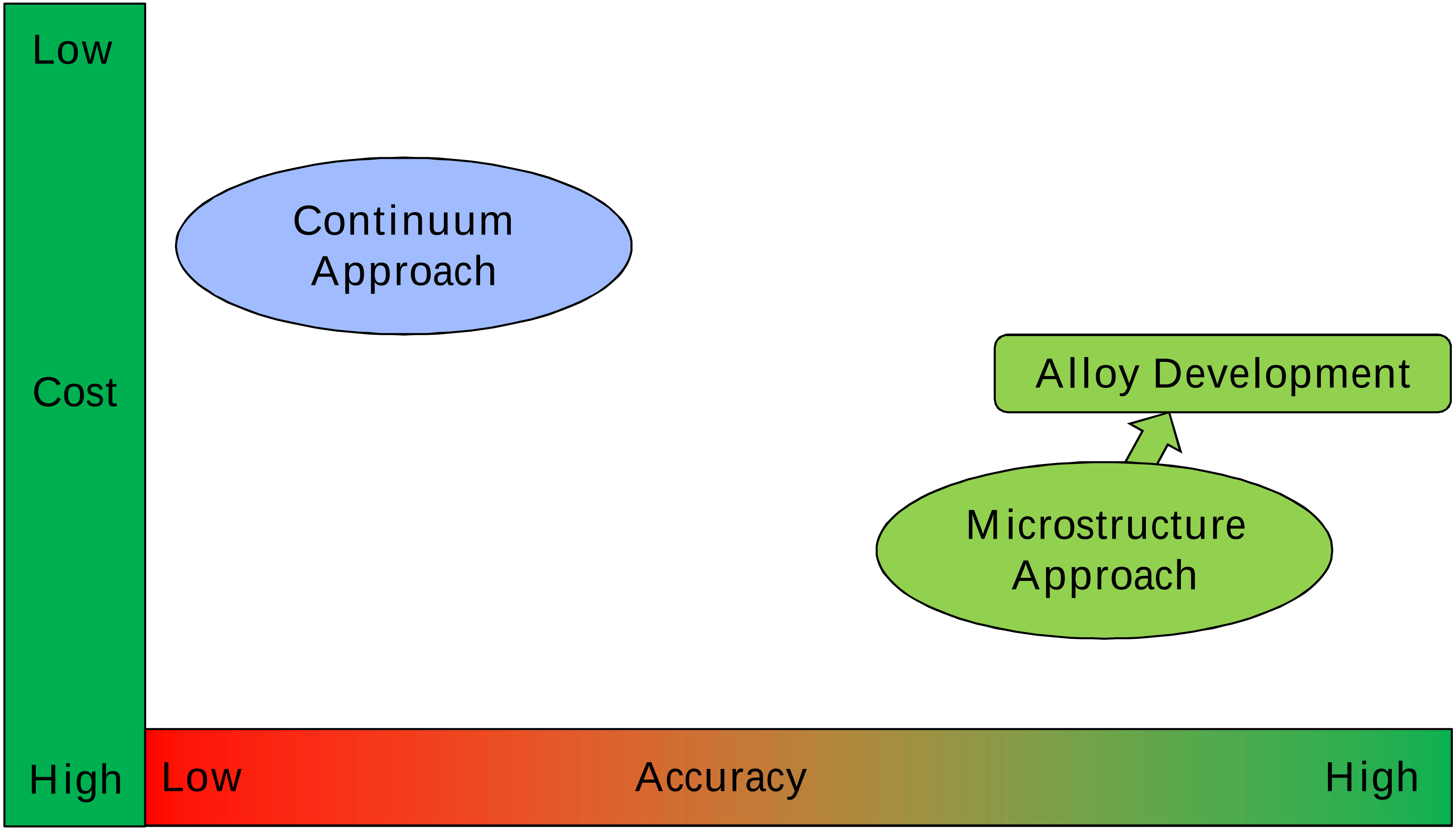
Microstructure Approach

Low

Accuracy

High

Microstructure Approach is Ideal For Alloy Development



Low

Cost

High

Continuum Approach

Alloy Development

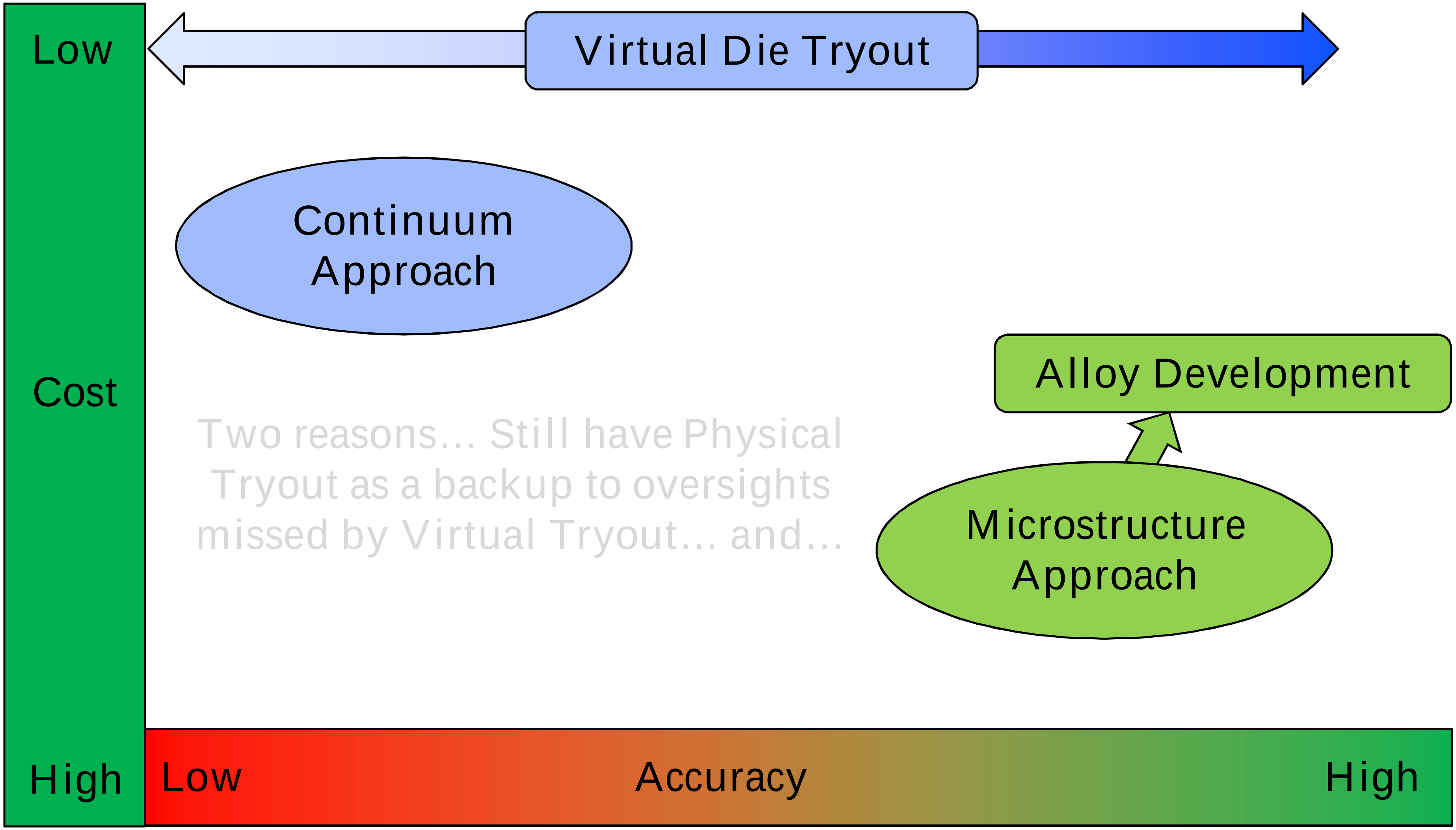
Microstructure Approach

Low

Accuracy

High

Cost is the Primary Driver For Virtual Die Tryout



Low

Cost

High

Virtual Die Tryout

Continuum Approach

Two reasons… Still have Physical Tryout as a backup to oversights missed by Virtual Tryout… and…

Alloy Development

Microstructure Approach

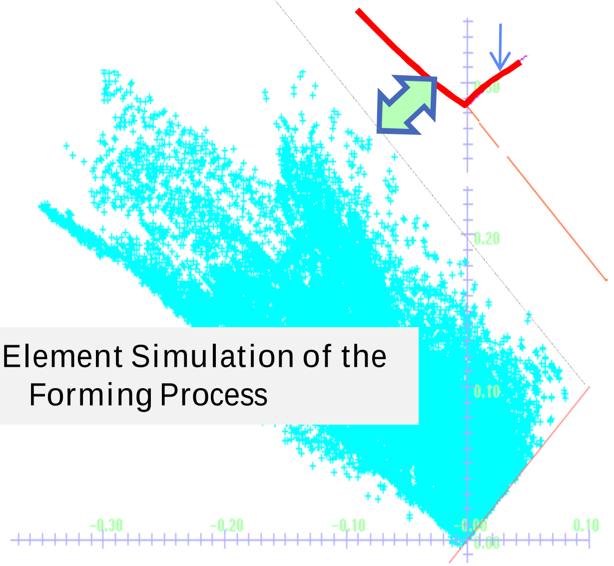
Low

Accuracy

High

Why COST is so Important in Virtual Tryout

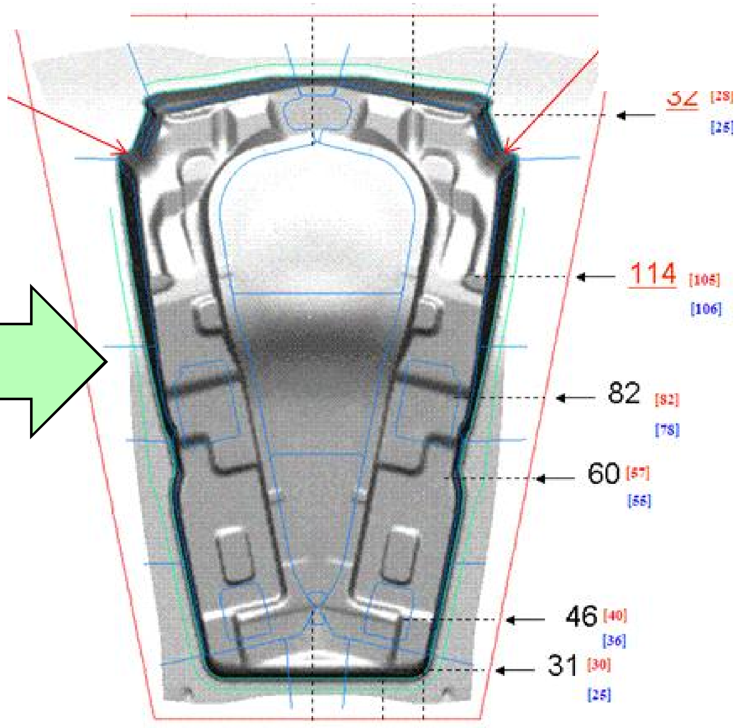
Strain FLC



Finite Element Simulation of the Forming Process

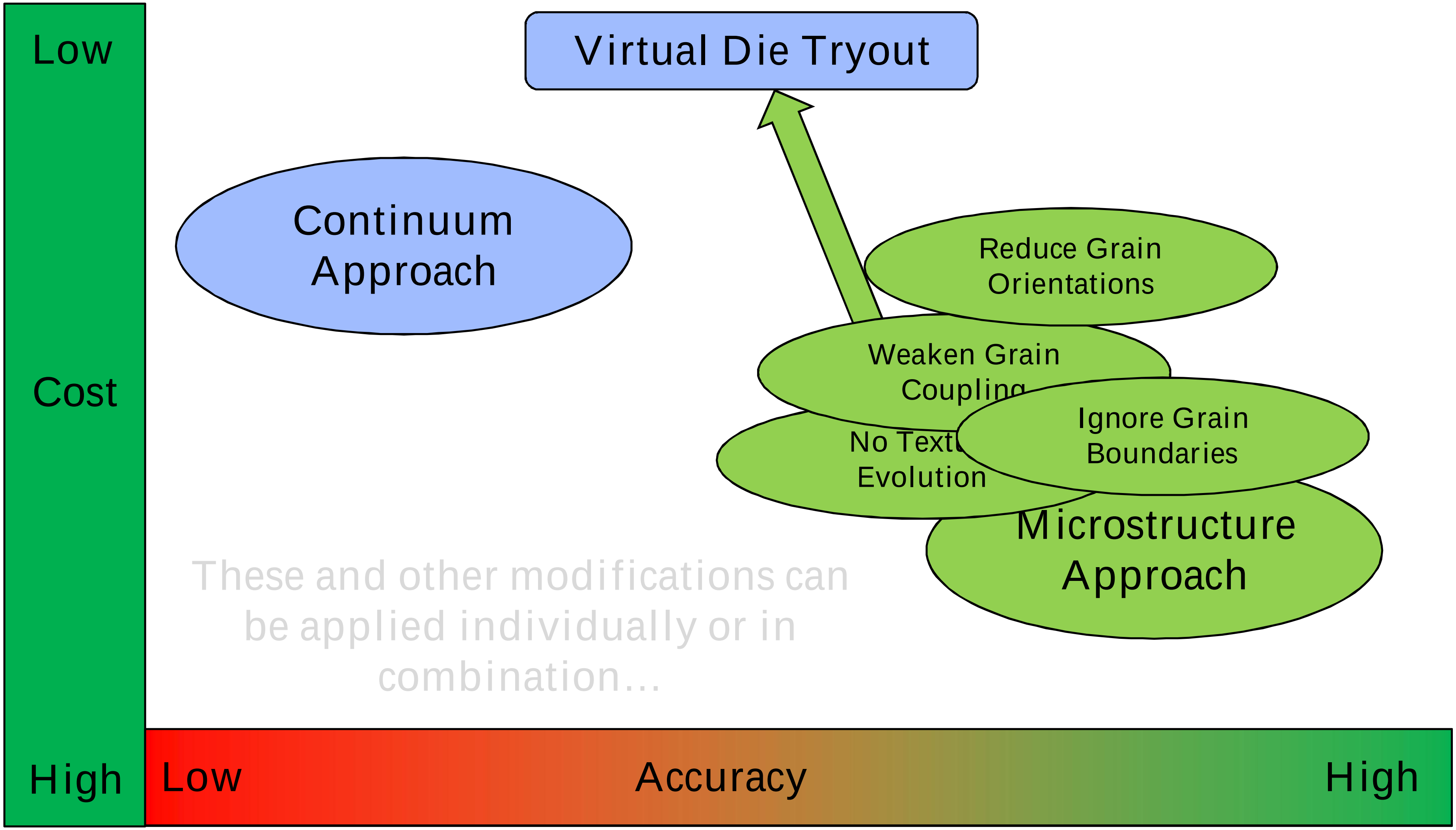
Finding the right forming conditions for a given panel requires SCORES of iterations on blank size, restraining forces, and tool/product shape to get it right…

Approve for Die Build



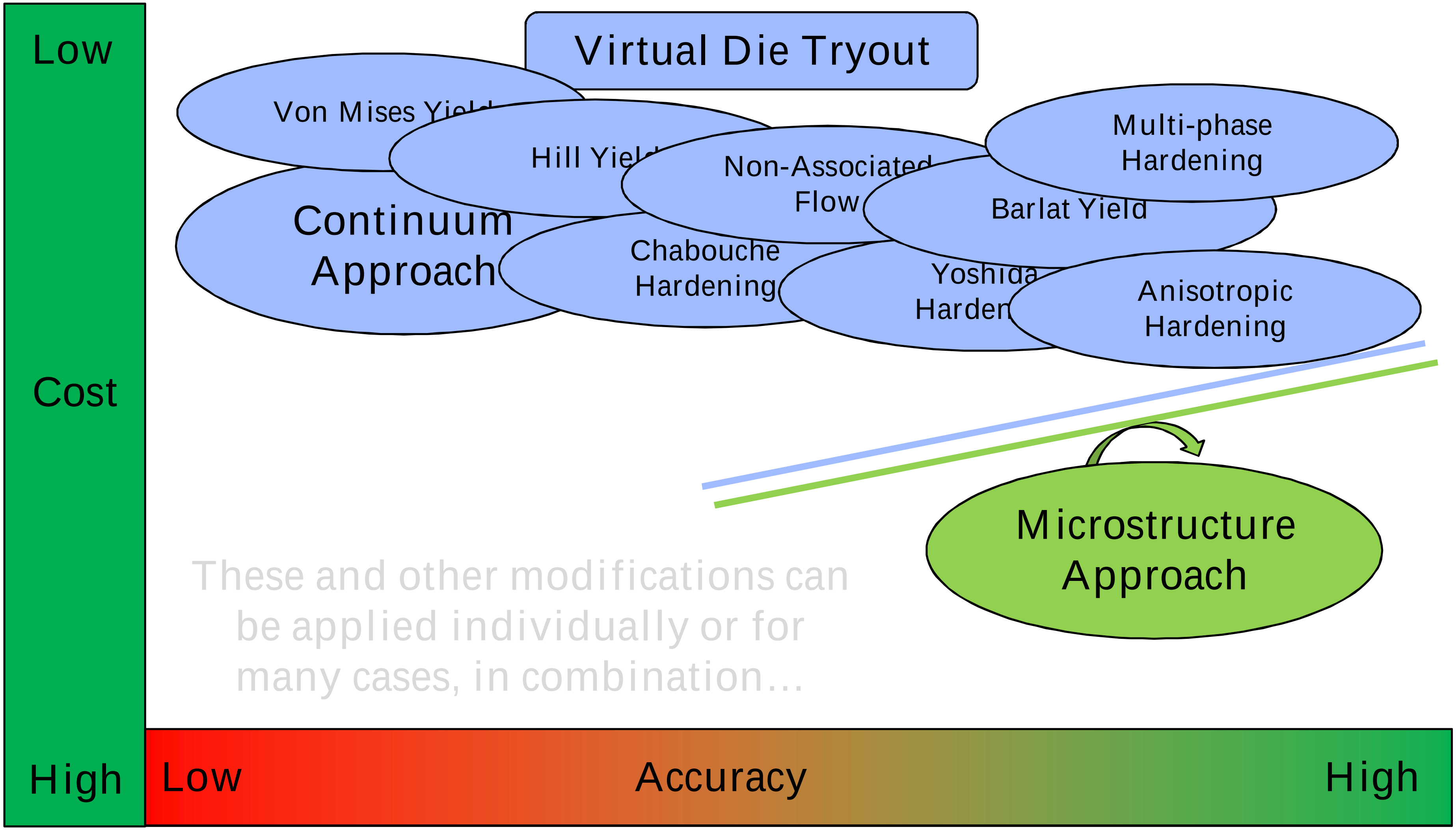
Multiply this by the 100’s of dies necessary to form the panels of a vehicle… the need for minimizing cost per analysis is clear.

Can the Micro Approach become more efficient to handle Virtual Die Tryout?



These and other modifications can be applied individually or in combination…

Can the Macro Approach become sufficiently reliable to satisfy the needs?



Low

Cost

High

Virtual Die Tryout

Von Mises Yiel

Hill Yiel

Non-Associated Flow

Multi-phase Hardening

Barlat Yield

Continuum Approach

Chabouche Hardening

Yoshida Harden

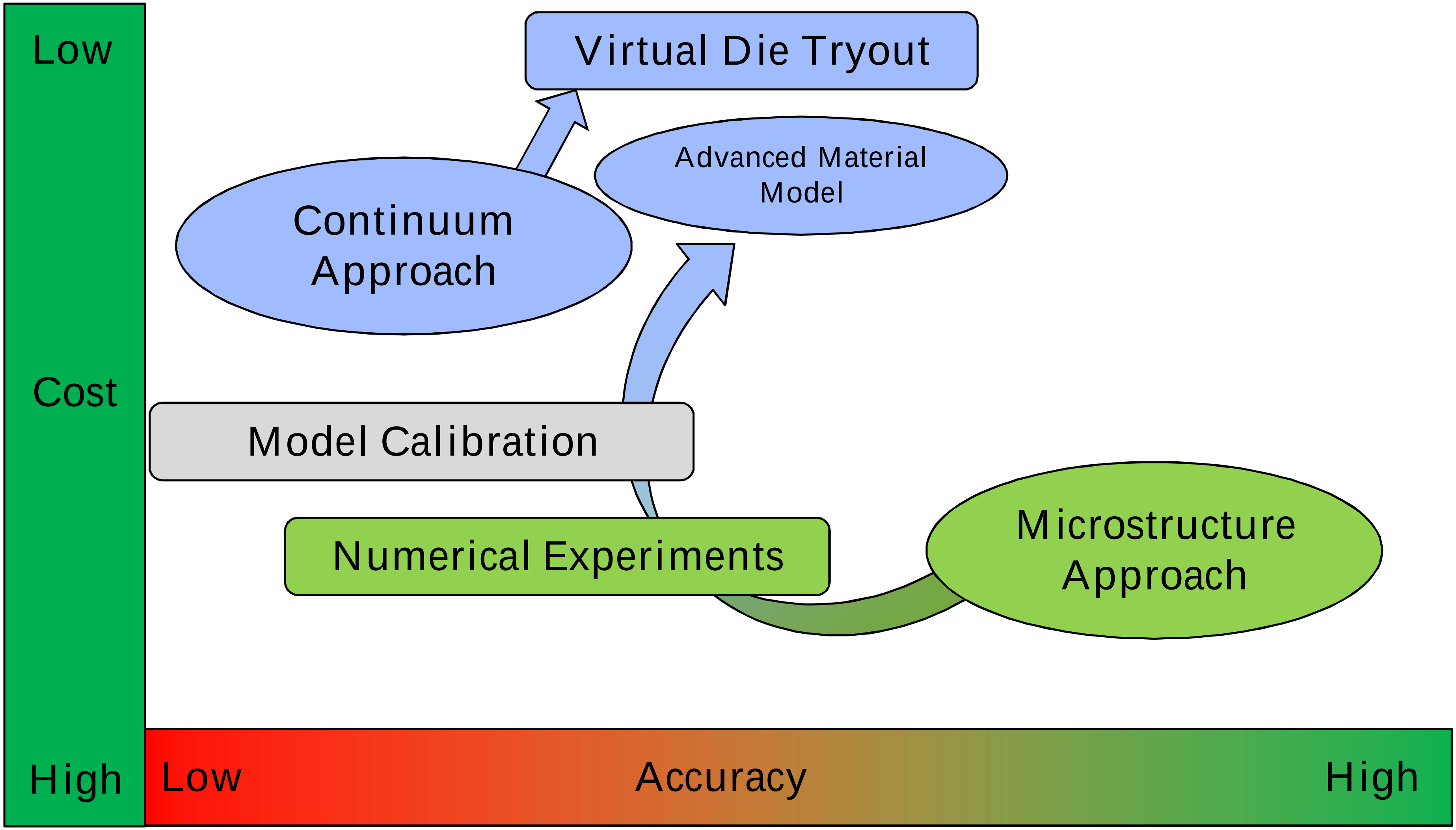
Anisotropic Hardening

Microstructure Approach

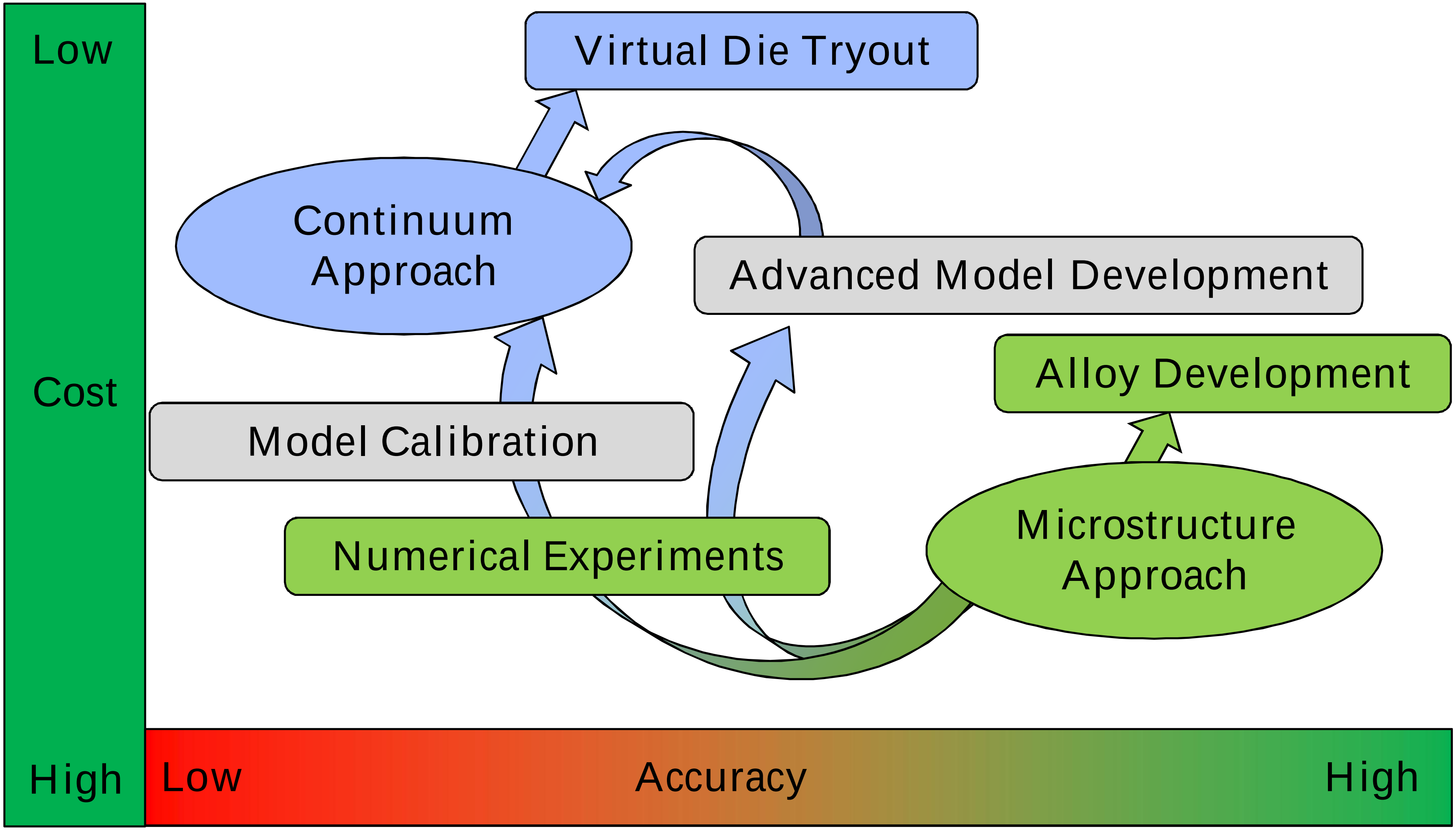
These and other modifications can be applied individually or for many cases, in combination…

Low Accuracy High

Synergy Between Approaches



Synergy Between Approaches



Low

Cost

High

Virtual Die Tryout

Continuum Approach

Advanced Model Development

Alloy Development

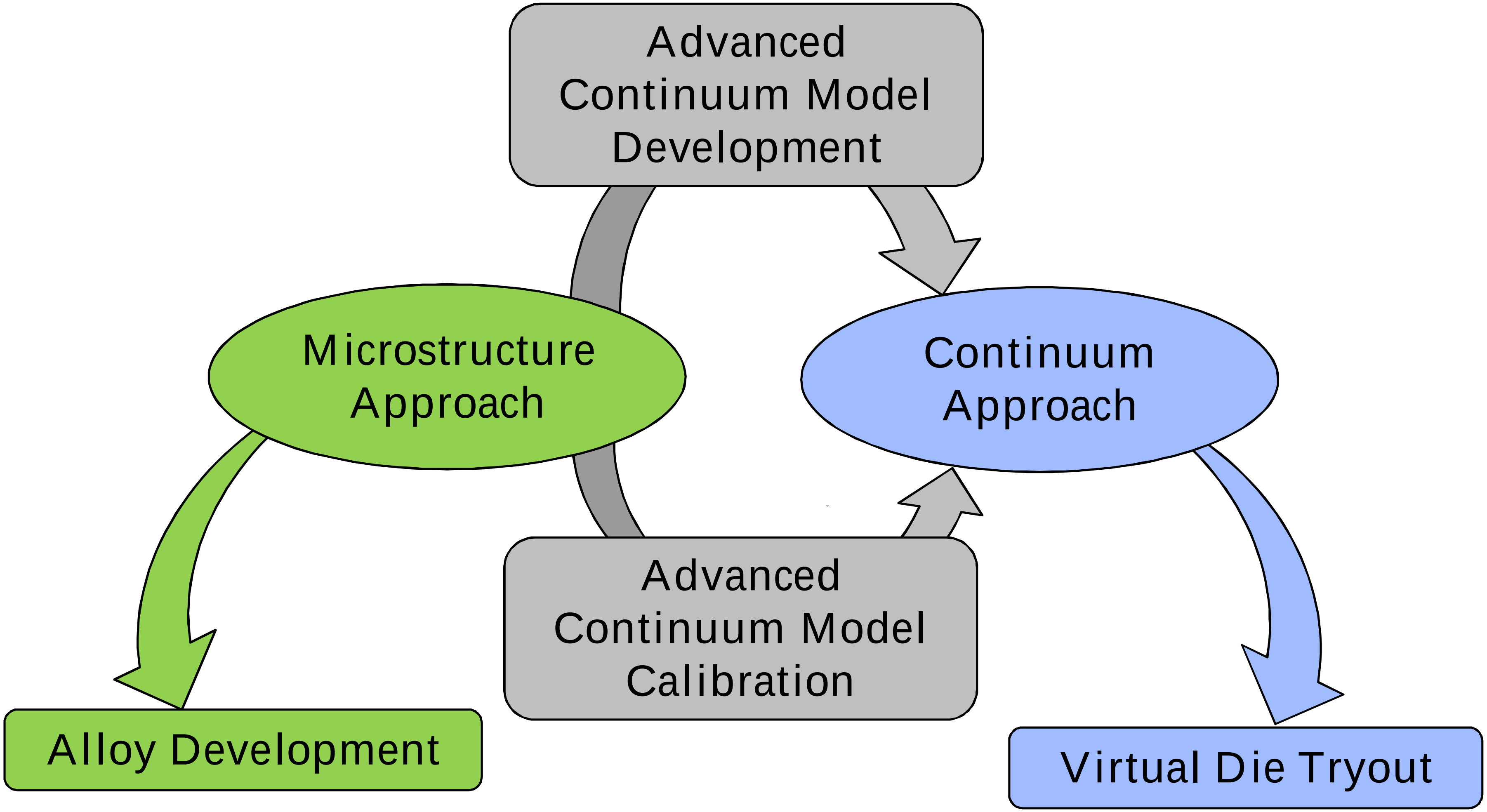
Model Calibration

Numerical Experiments

Microstructure Approach

Low Accuracy High

Simplified View of Application Areas



Advanced Continuum Model Development

Microstructure Approach

Continuum Approach

Advanced Continuum Model Calibration

Alloy Development

Virtual Die Tryout

Outline

- Microstructure/Polycrystalline vs. Continuum
  Application Needs; Texture & High Exponent Yield Functions; Forming Limits of AHSS; Lessons from Metallic Glass
- Elasto-plasticity Hysterisis
  Young's Modulus variation, quasiplastic strain
- Distortional Hardening
  Isotropic, kinematic, distortional hardening
- Forming Limits
  Nonlinear Strain Path Effects, Curvature Effects, Necking vs. Fracture, Heightened importance for AHSS

Challenges

Hysterisis of loading/unloading

Uniaxial Loading-Unloading Test

Complex Unloading Model for Springback Prediction

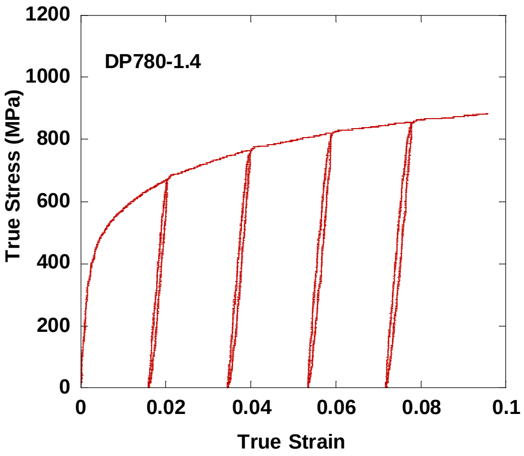
Oral Examination for the Degree of Doctor Philosophy
Feb 23, 2011

Li Sun

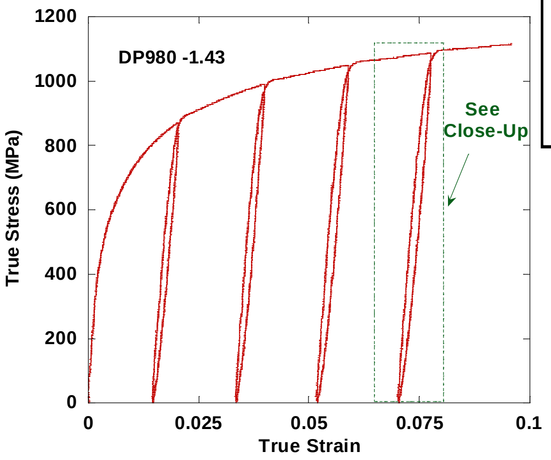
Dissertation Committee
Dr. Robert H. Wagoner, Advisor
Dr. June Key Lee
Dr. Stephen Eric Bechtel
Dr. Rebecca B. Dupaix

Dept. of Mechanical Engineering
The Ohio State University

DP 780

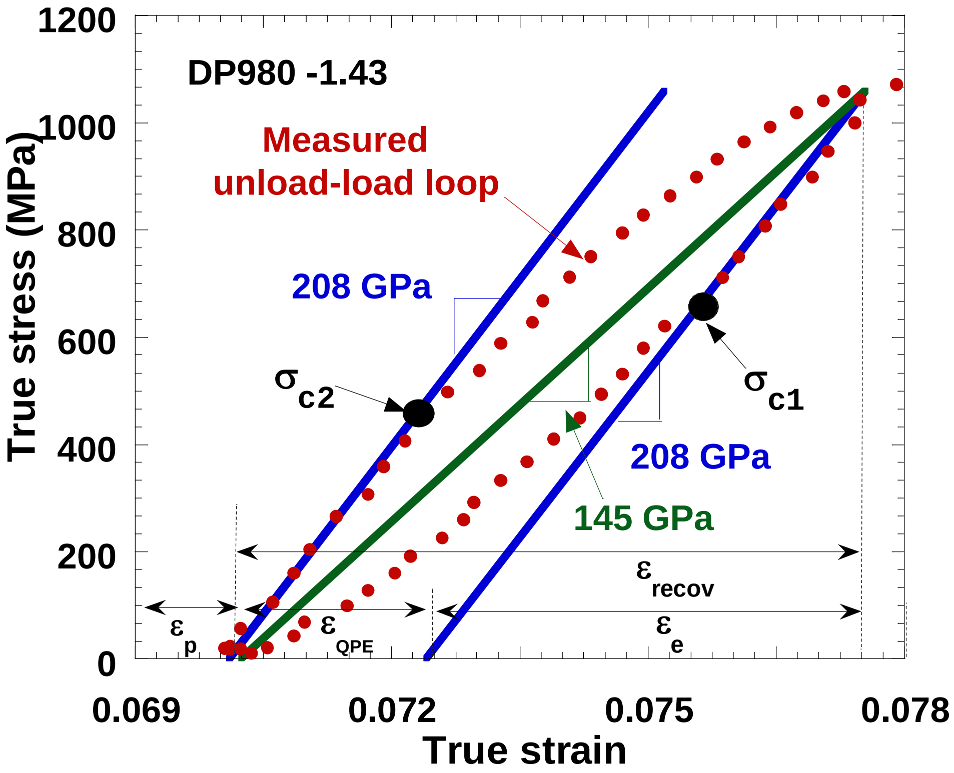


DP 980



Three ways to model the behavior

Expanded View of Loading-Unloading Test

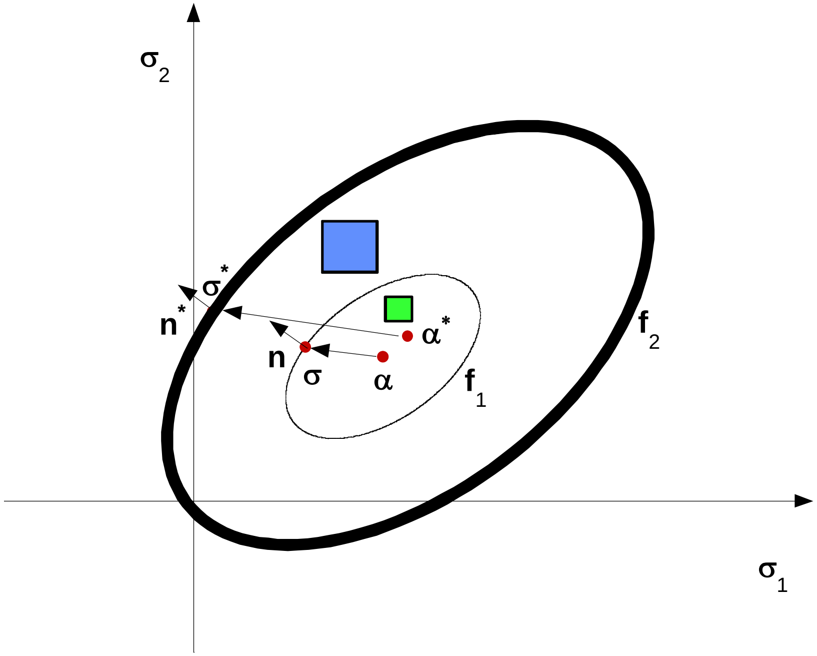


1) Ignore hysterisis and treat it as a change in Elastic Modulus (GREEN Line)

2) Define yield stress near to the proportional limit and treat the nonlinear post-yield behavior as a micro-plasticity domain of conventional plasticity,

3) Leave elasticity and plasticity the same, but include a new type of quasi-plastic strain, QPE.

2 Surface Framework of QPE Model



Apparent Young's Modulus

$$E = E_0 - E_1\left[1 - \exp\left(-b\int \left\| d\boldsymbol{\varepsilon} - d\boldsymbol{\varepsilon}_p \right\|\right)\right]$$

Elastic State

$$d\boldsymbol{\sigma} = \mathbf{C_0} : d\boldsymbol{\varepsilon}_\mathbf{e}$$

Elastic + QPE State

$$d\boldsymbol{\sigma} = \mathbf{C}_0 : d\boldsymbol{\varepsilon}_e = \mathbf{C} : d\boldsymbol{\varepsilon}$$

$$d\boldsymbol{\varepsilon} = d\boldsymbol{\varepsilon}_e + d\boldsymbol{\varepsilon}_{\mathbf{QPE}}$$

$$d\boldsymbol{\varepsilon}_e / \left\| d\boldsymbol{\varepsilon}_e \right\| = d\boldsymbol{\varepsilon}_{\mathbf{QPE}} / \left\| d\boldsymbol{\varepsilon}_{\mathbf{QPE}} \right\|$$

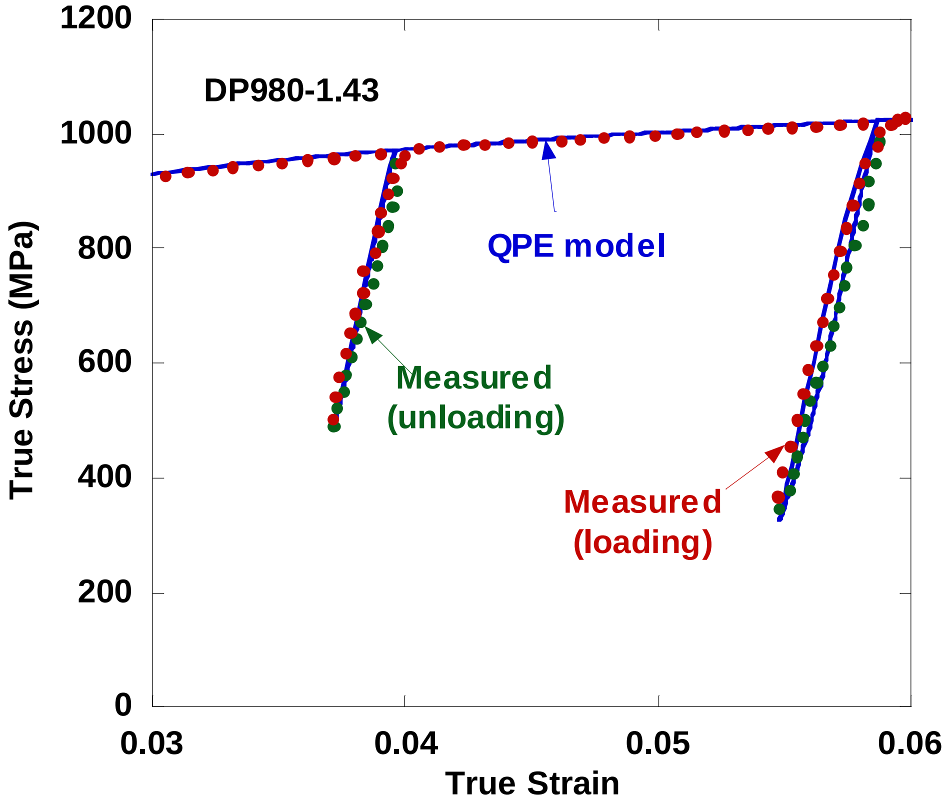
Elastic + QPE +Plastic State

$$d\boldsymbol{\sigma} = \mathbf{C}_0 : d\boldsymbol{\varepsilon}_e = \mathbf{C} : (d\boldsymbol{\varepsilon} - d\boldsymbol{\varepsilon}_\mathbf{p})$$

$$d\boldsymbol{\varepsilon} = d\boldsymbol{\varepsilon}_e + d\boldsymbol{\varepsilon}_{\mathbf{QPE}} + d\boldsymbol{\varepsilon}_\mathbf{p}$$

Advantages of QPE Model

Unfinished Cycles of Loading-Unloading Test



Partial Unloading of Forming Stresses is Common in Curved Areas of the Product

Outline

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  Isotropic, kinematic, distortional hardening

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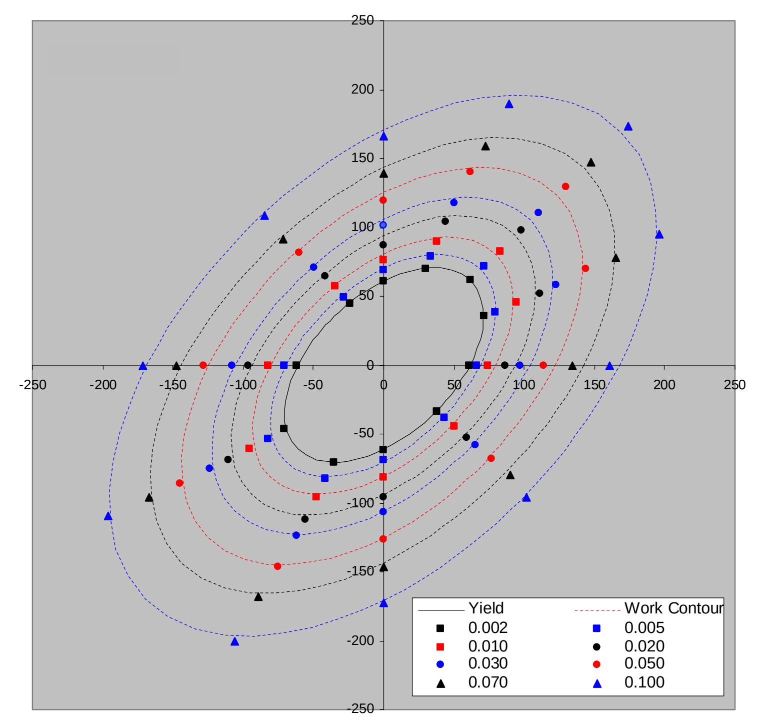
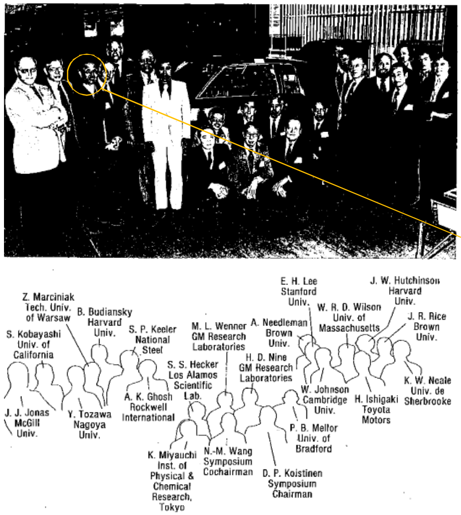
} Challenges

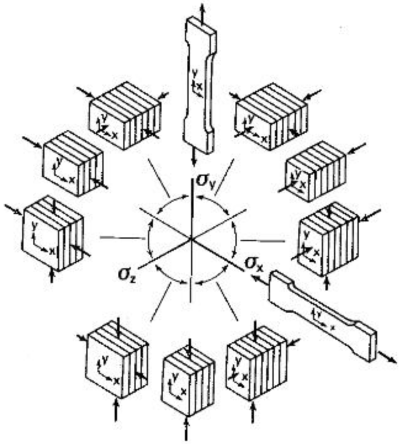
Nature of Distortional Hardening



Experimental Probing of the Yield Surface Evolution



Organizers, Session Chairmen and Authors



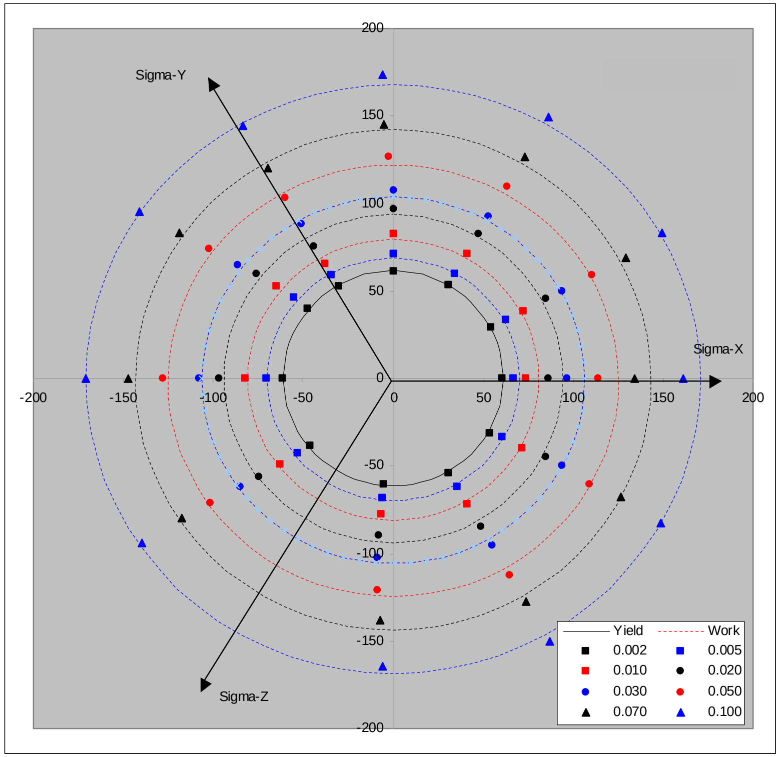
1977 GMR Symposium

Deformation Behavior Under Conditions of Combined Stress

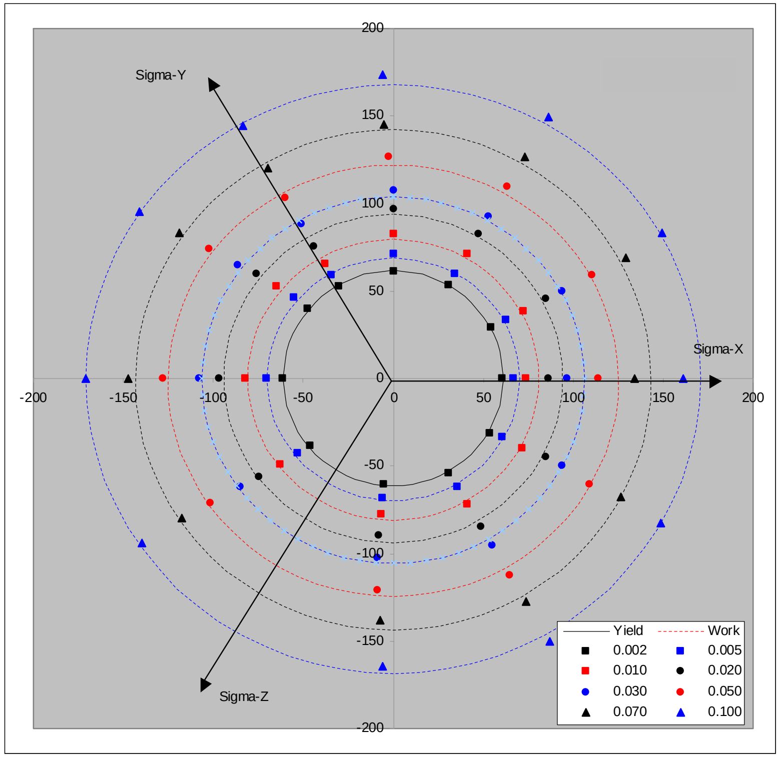
- Prof. Y. Tozawa

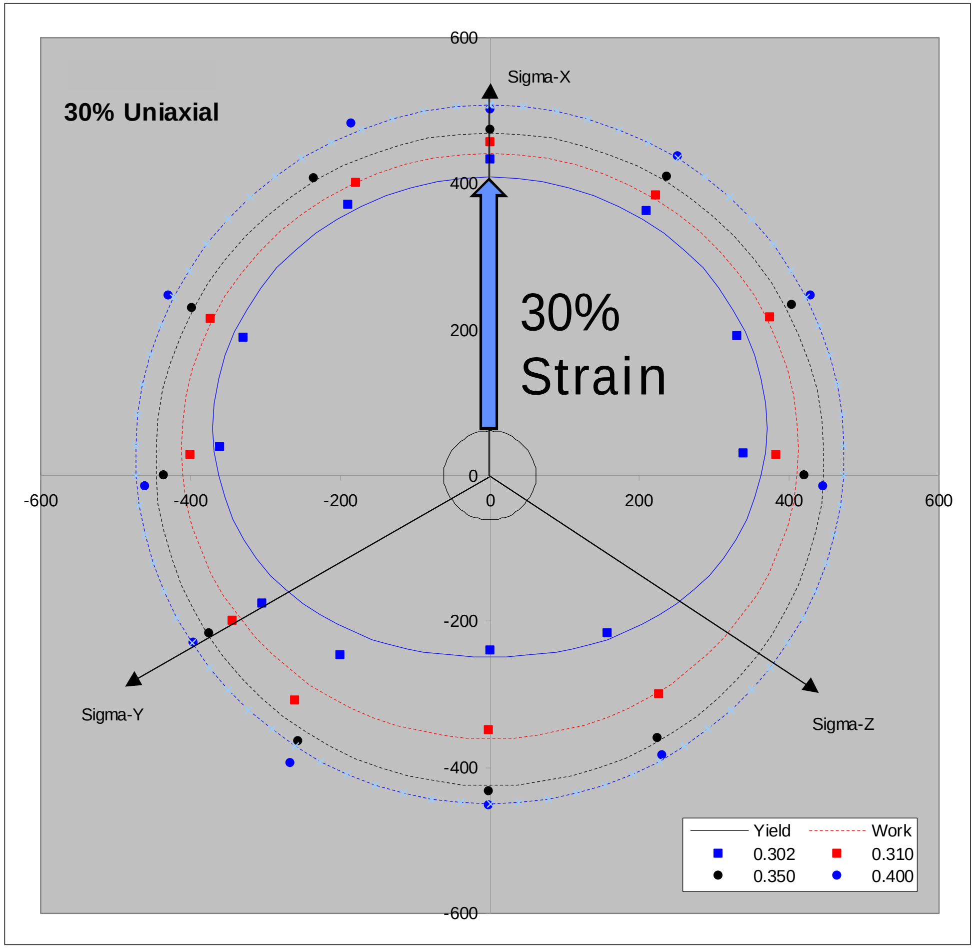
Proportional Loading Tests Suggest Isotropic Hardening

Pi-plane view shows a
von Mises behavior for brass



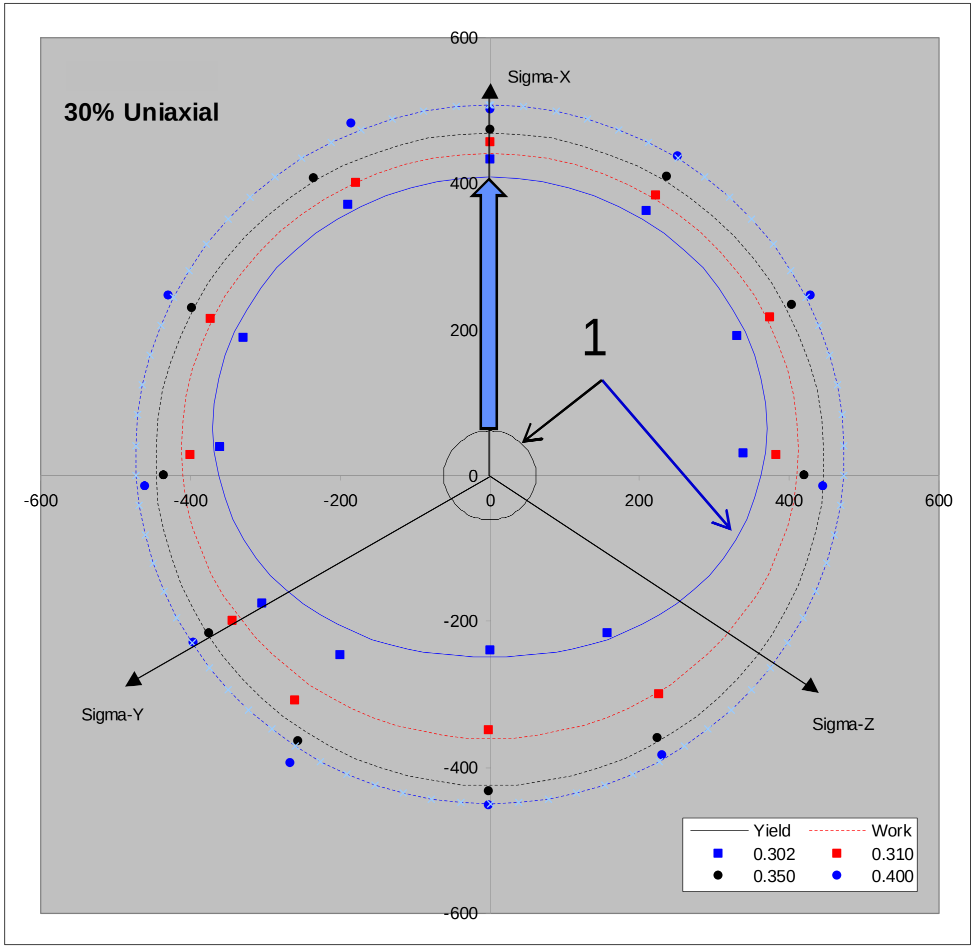
Complete Non-Proportional Loading Tests Show Complex Hardening Behavior





Complete Non-Proportional Loading Tests Show Complex Hardening Behavior

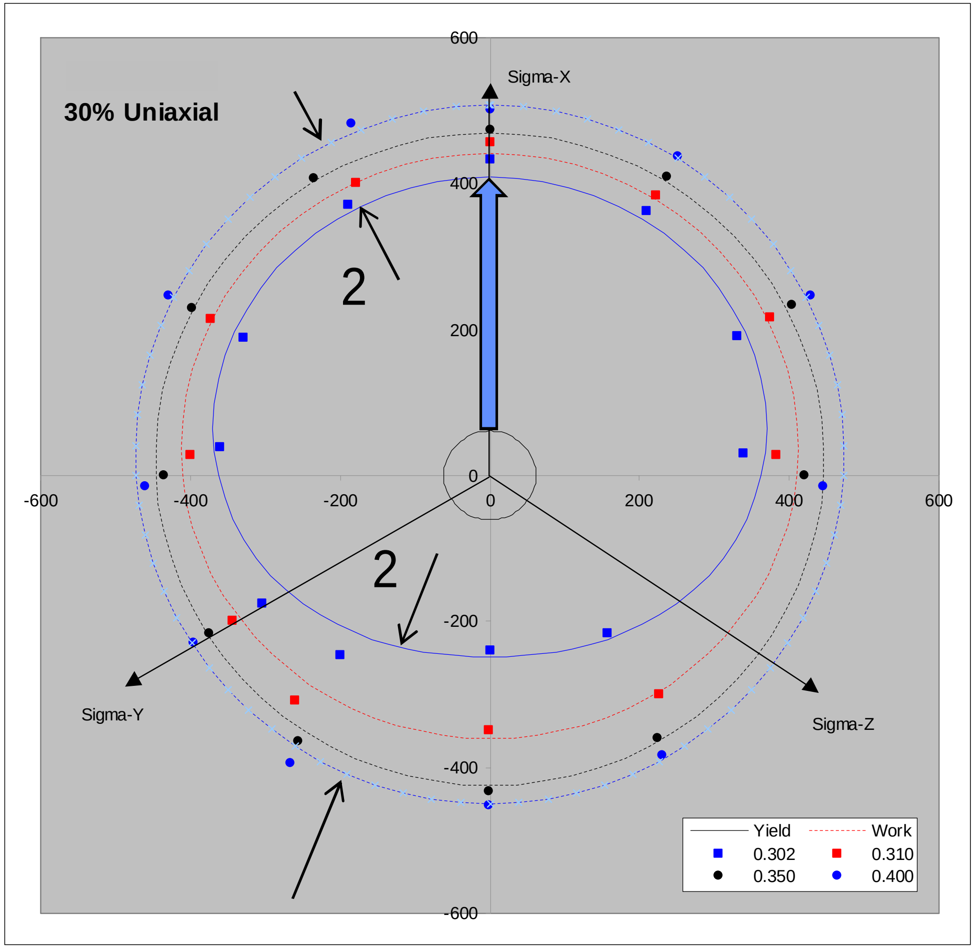
1) Distortion of the Yield Surface



Complete Non-Proportional Loading Tests Show Complex Hardening Behavior

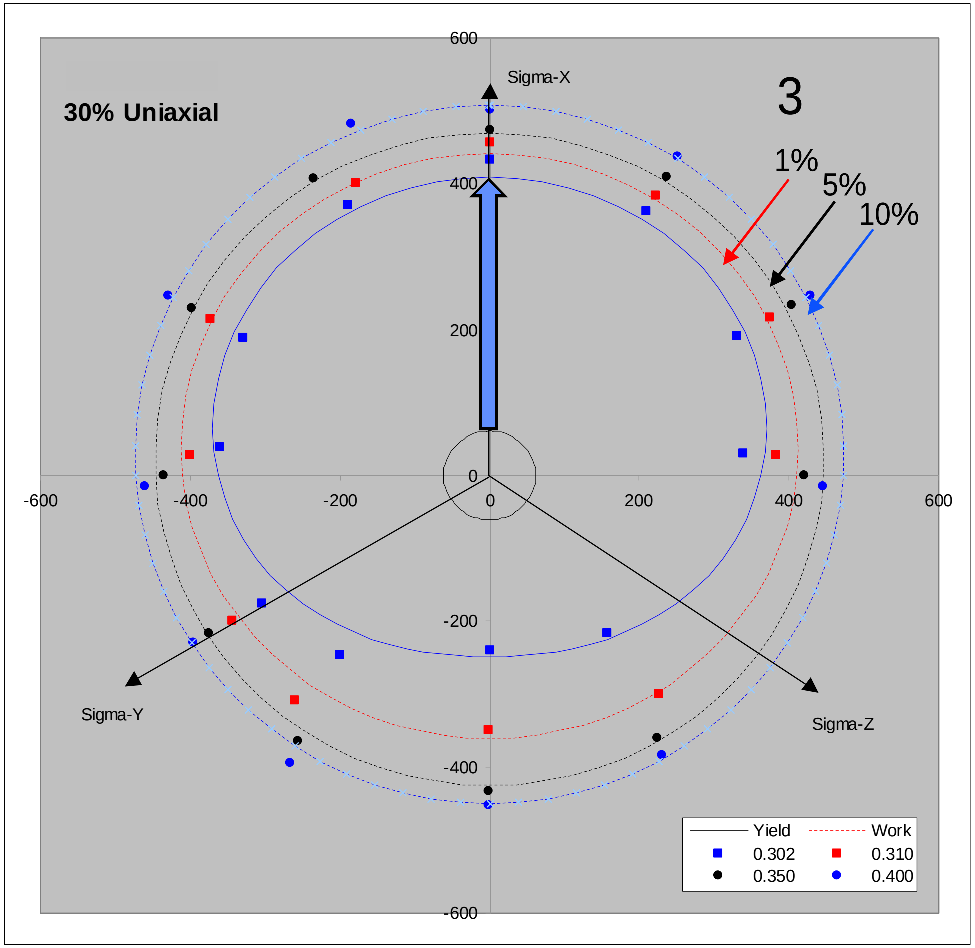
1) Distortion of the Yield Surface

2) Anisotropic hardening



Complete Non-Proportional Loading Tests Show Complex Hardening Behavior

1) Distortion of the Yield Surface
2) Anisotropic hardening
3) Shape stabilizes after 1% and before 5% strain



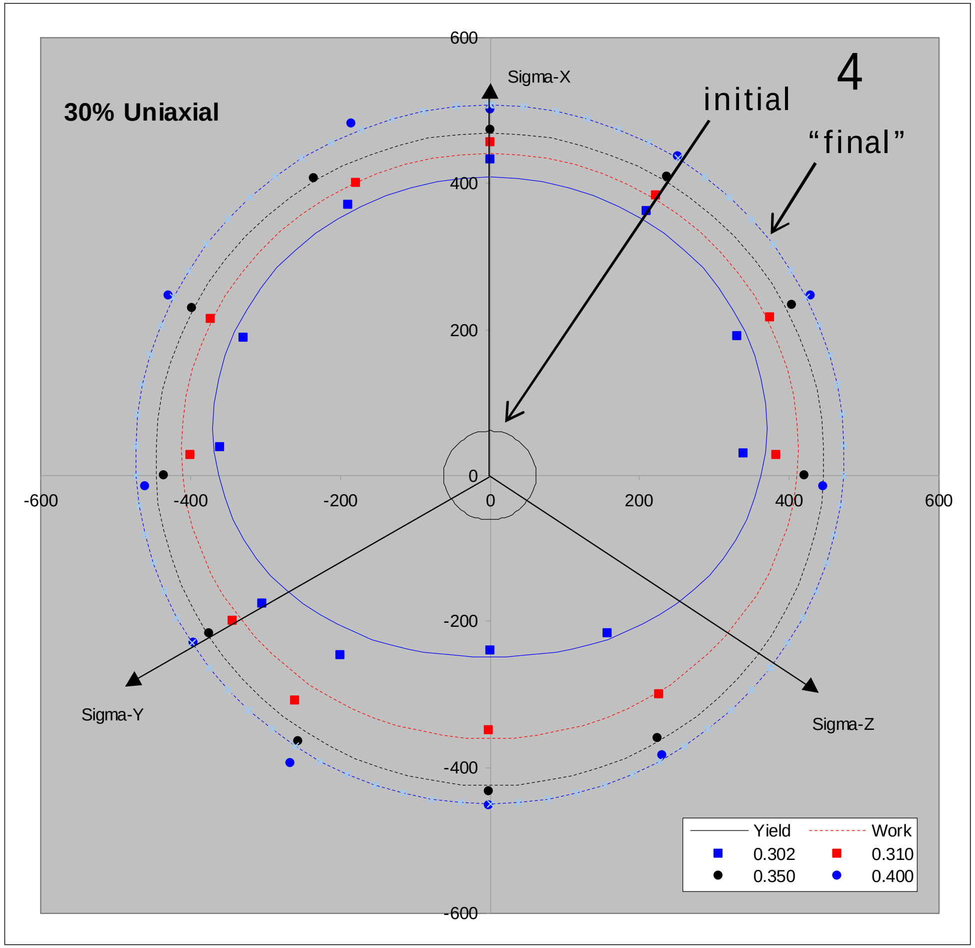
Complete Non-Proportional Loading Tests Show Complex Hardening Behavior

1) Distortion of the Yield Surface

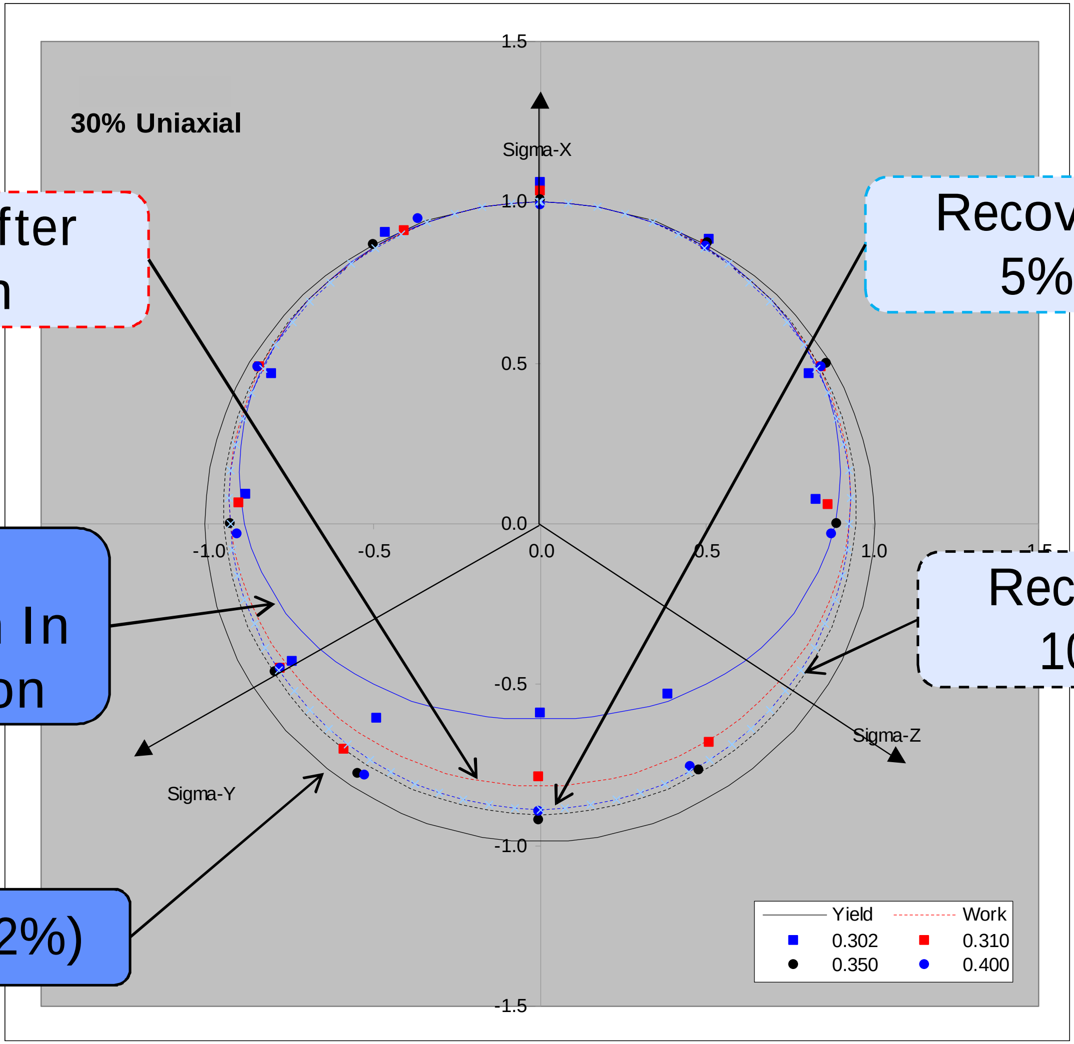
2) Anisotropic hardening

3) Shape stabilizes after 1% and before 5% strain

4) Stabilized shape is different from the Initial Yield Surface



Normalized Yield Behavior to Unit Circle



Recovery After 1% Strain

Recovery After 5% Strain

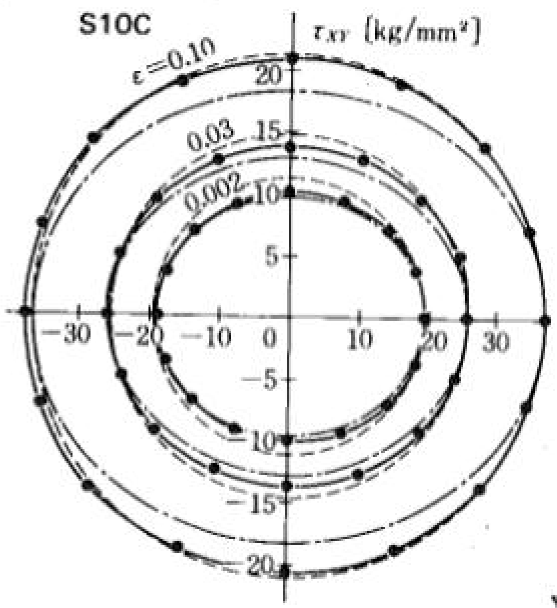
Yield (0.2%) After 30% Strain In Uniaxial Tension

Recovery After 10% Strain

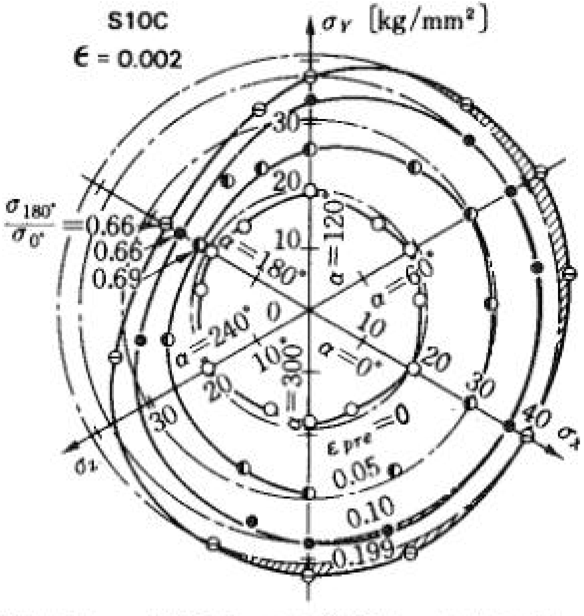
Initial Yield (0.2%)

Interesting Question: Can one model this with kinematic hardening?

Similar Distortion Observed In Steel

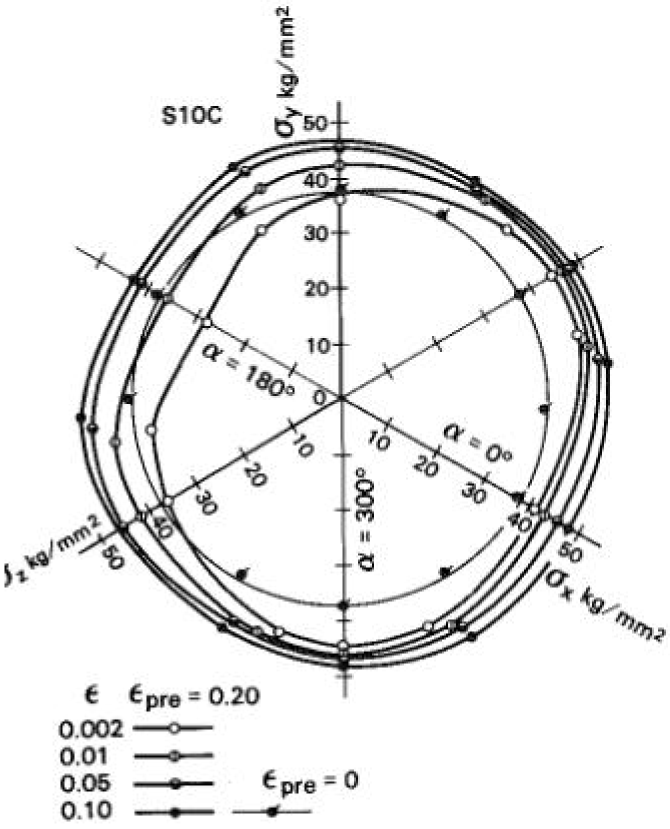


Proportional Loading Tests Suggest Isotropic Hardening



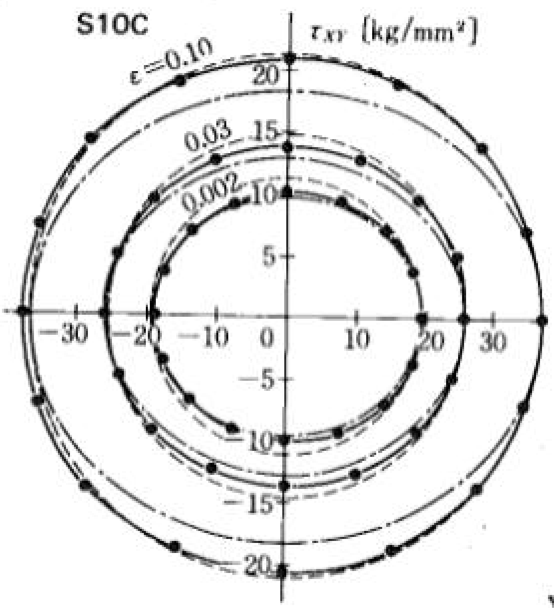
Yield loci at ϵ = 0.002 for steel (S10C) prestretched by

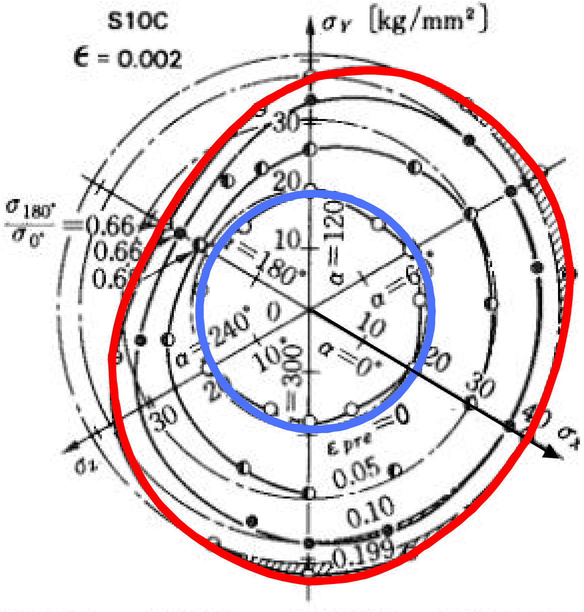
Uniaxial Prestrain to 5%, 10%, and 20% Show Distortion of the Subsequent Yield



Anisotropic Hardening After 20% Strain

Advanced Kinematic Hardening Models





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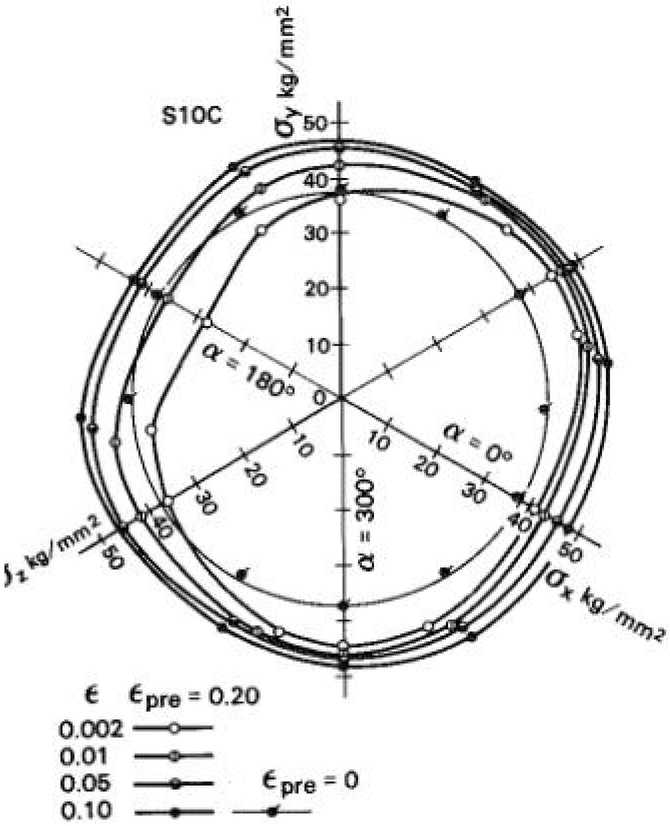
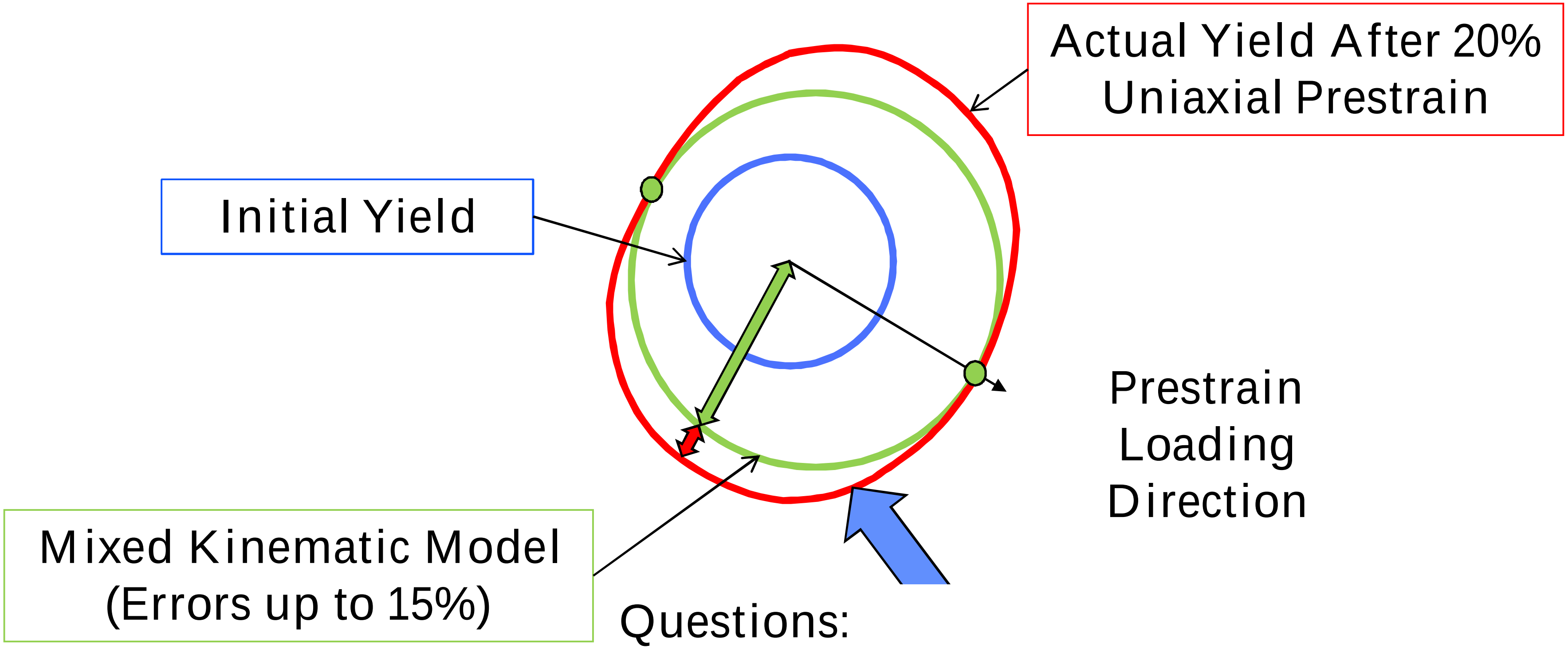


Proportional Loading Tests Suggest Isotropic Hardening

Uniaxial Prestrain to 5%, 10%, and 20% Show Distortion of the Subsequent Yield

Anisotropic Hardening After 20% Strain

Advanced Kinematic Hardening Models



Actual Yield After 20% Uniaxial Prestrain

Initial Yield

Prestrain Loading Direction

Mixed Kinematic Model (Errors up to 15%)

Questions:

How do we accurately model this behavior?

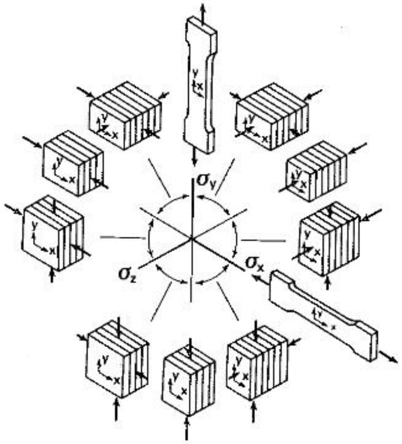
What happens under non-linear loading?

Characterizing Distortional Hardening is a prime example to benefit from this plan

Advanced Continuum Model Development

Microstructure Approach

Continuum Approach



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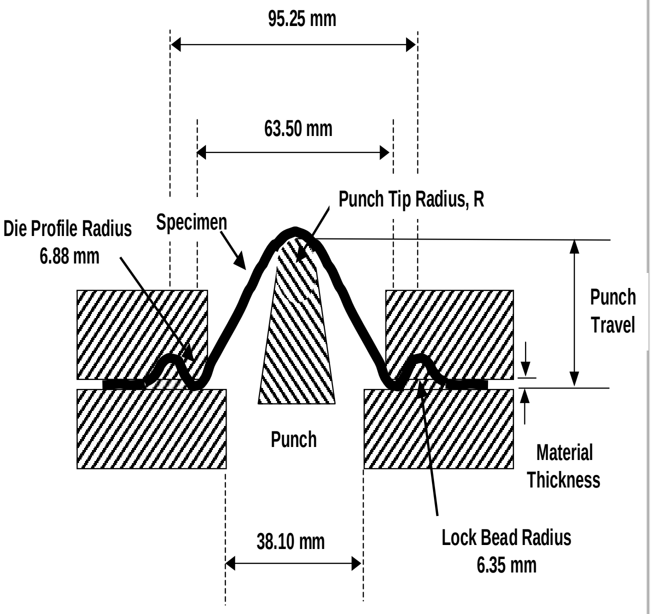
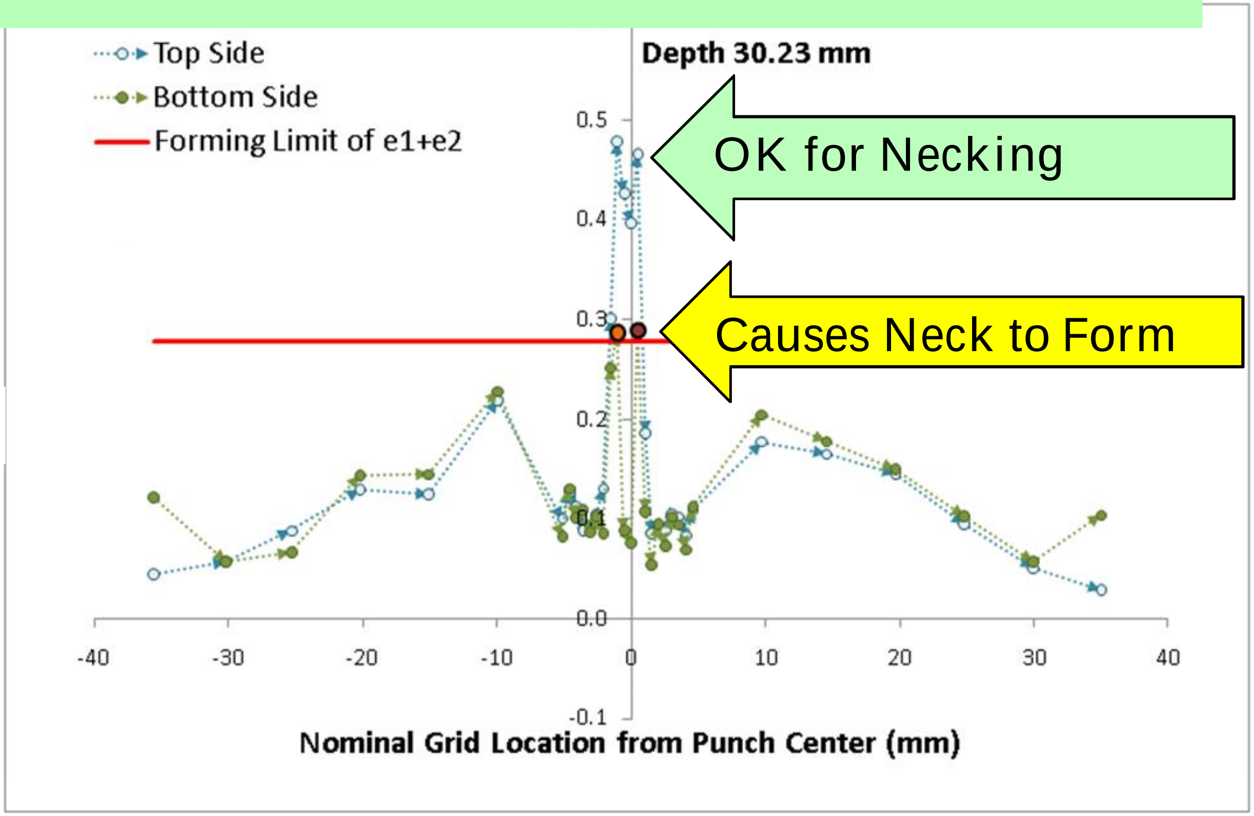
Challenges

Effect of Bending On Forming Limits

When does necking occur if the sheet metal is curved?

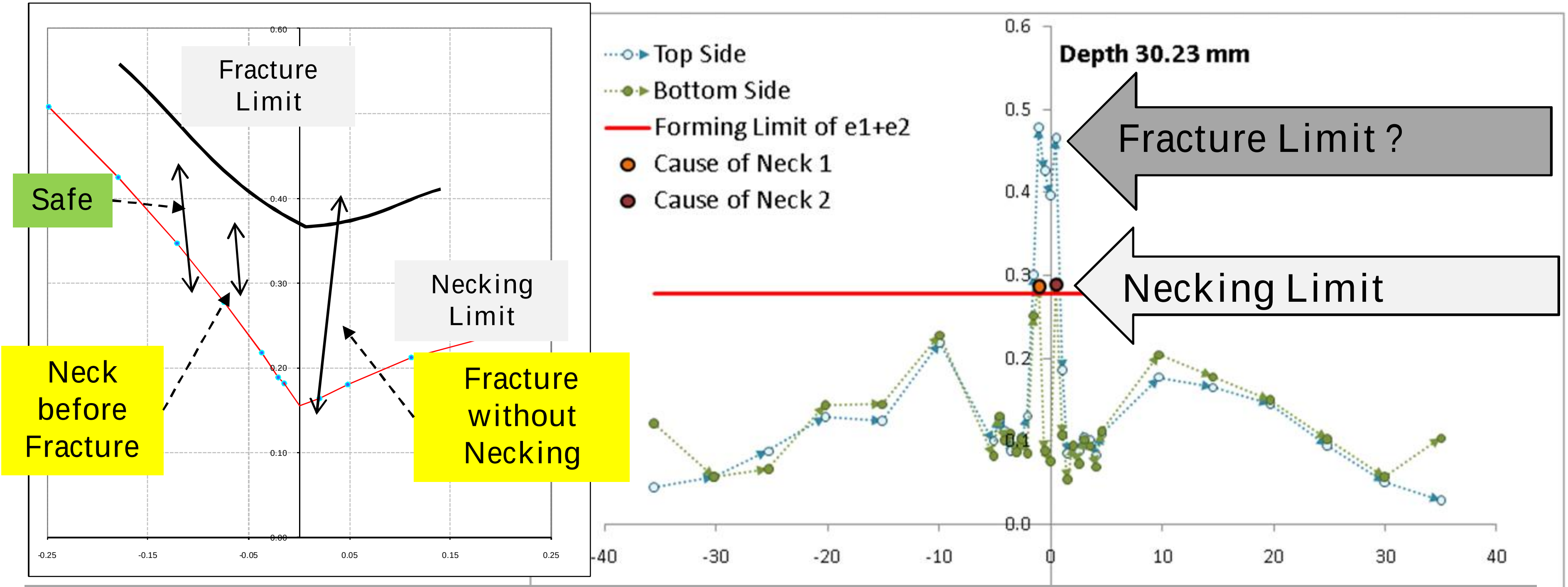




OK for Necking

Causes Neck to Form

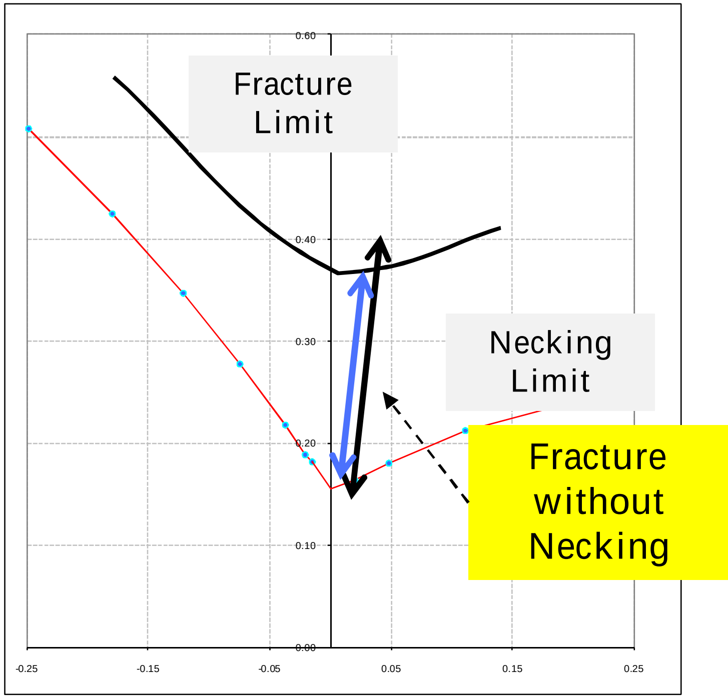
Suppression of Necking
Can Lead to Fracture Without Necking



Fracture is not considered in traditional manufacturing

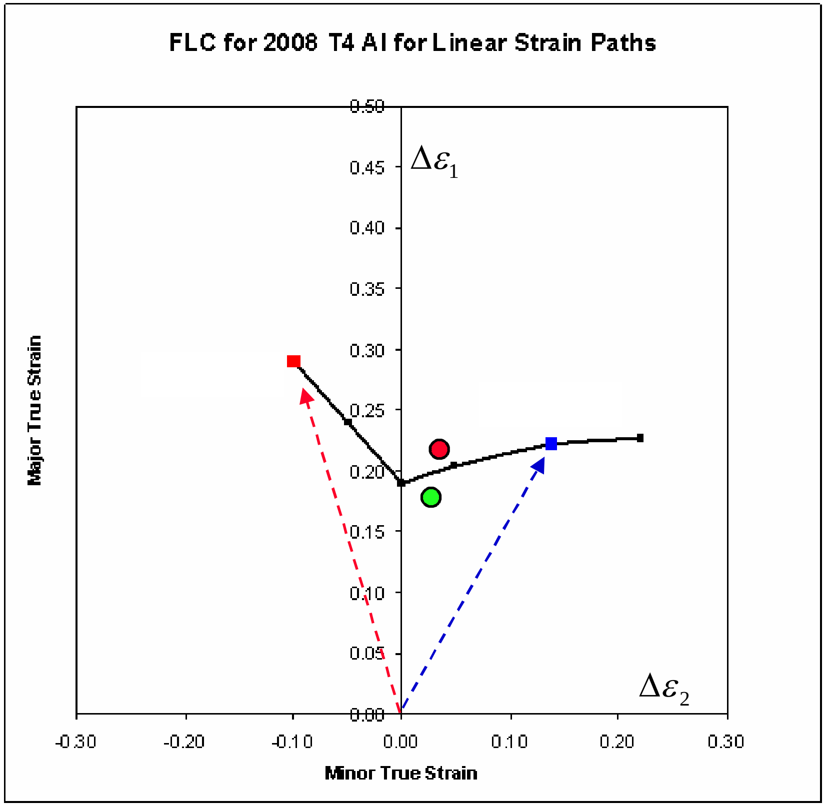
… now recognized as a problem with AHSS

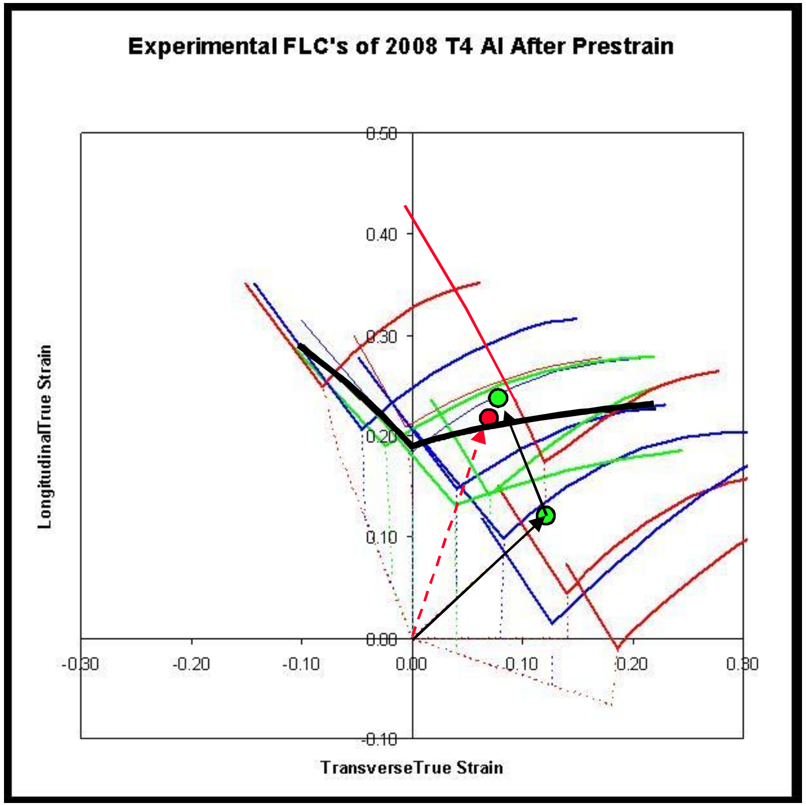
Why Fracture is More Important for AHSS



The possibility of Fracture Without Necking depends only on geometry, which defines the strain difference through the curved sheet {=ln(1+t/R) } , ↔ and its relation to the strain gap ↔ between the Necking and Fracture Limits.

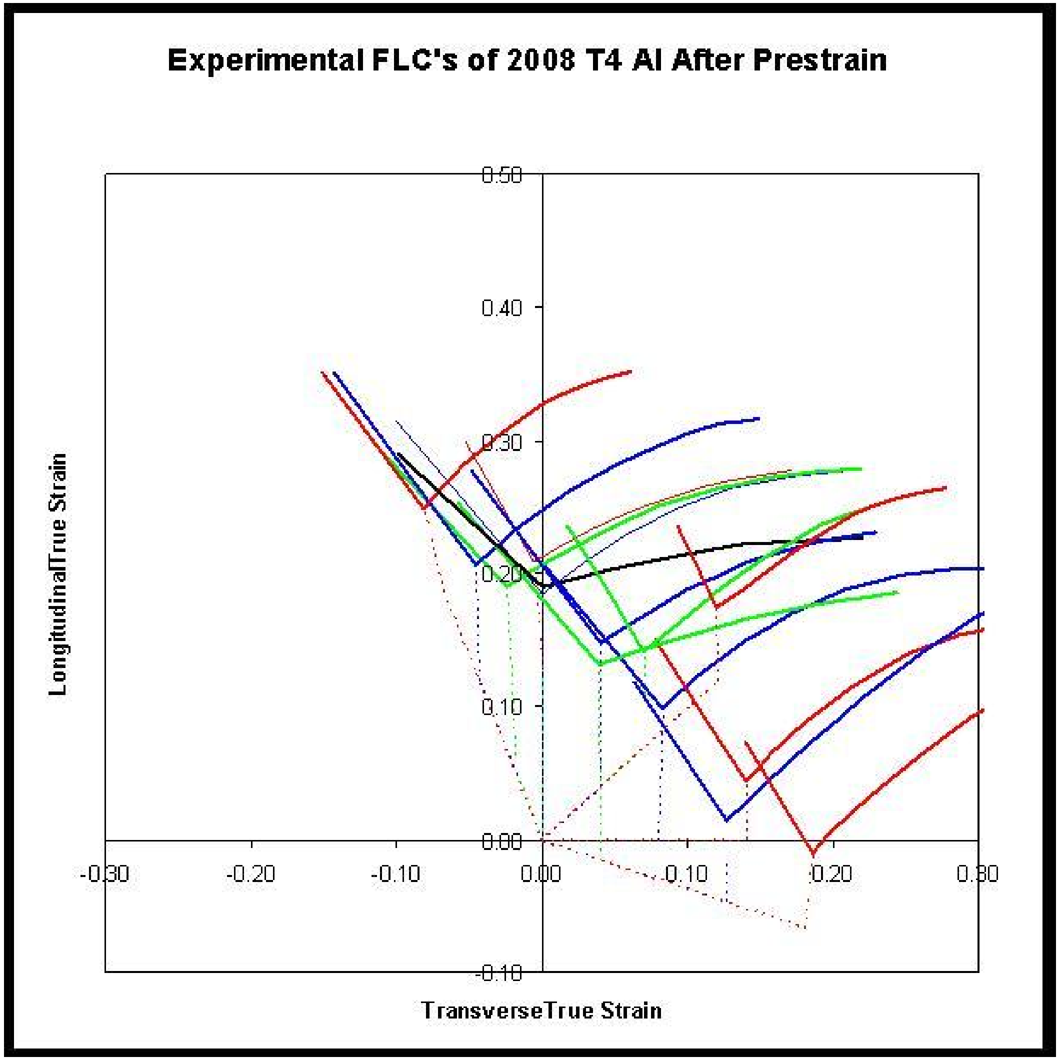
The Challenge of Nonlinear Paths



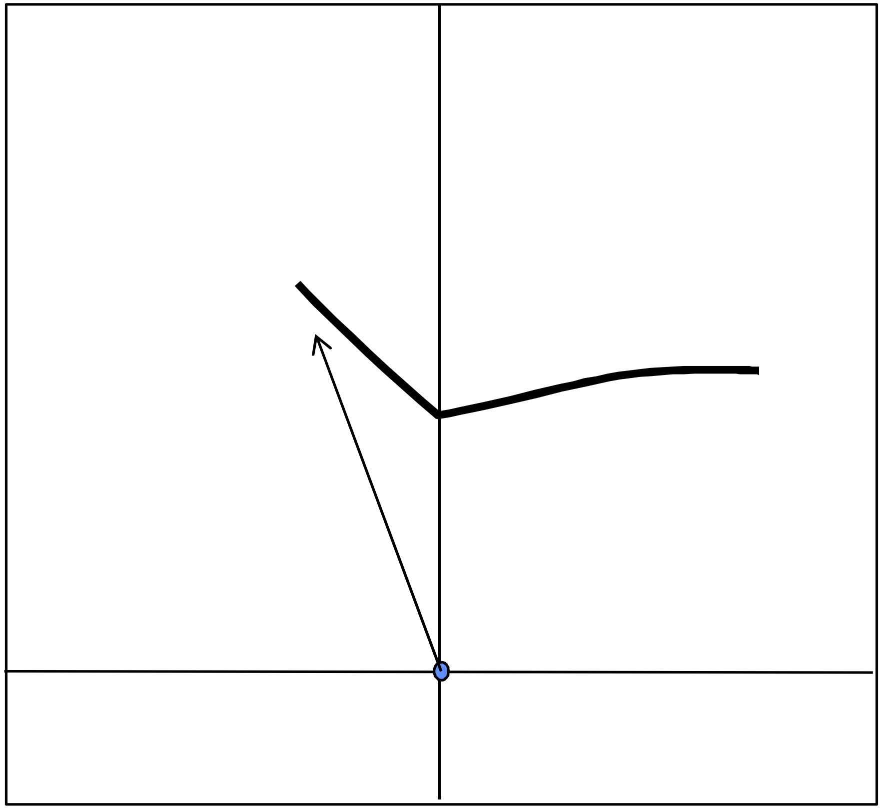


What is SAFE?

What does this data mean for Linear Paths?

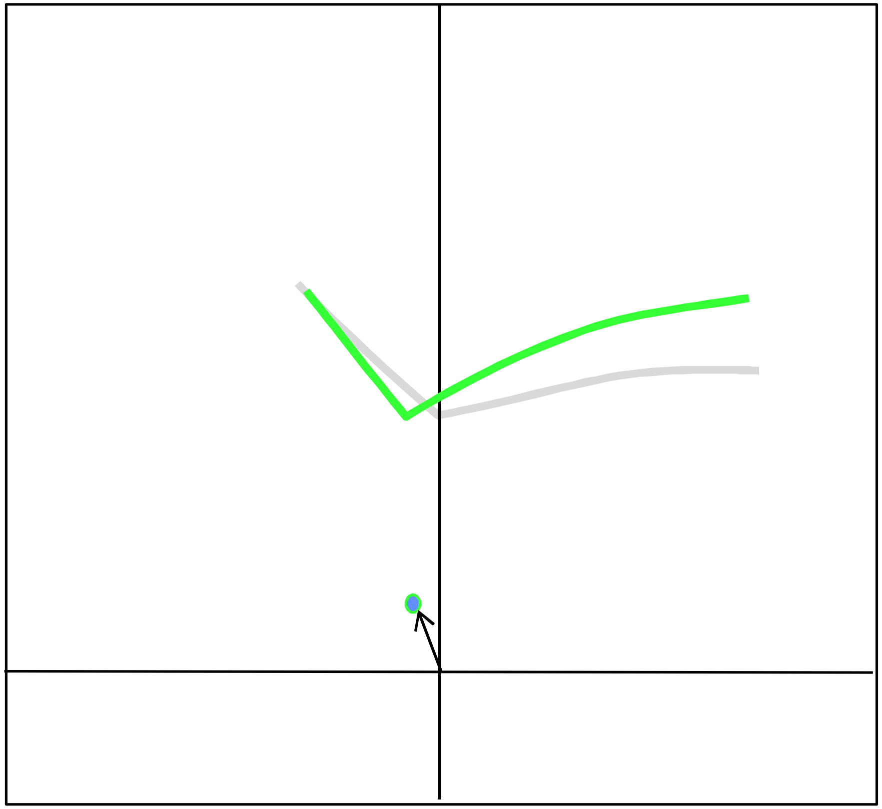


Uniaxial Tension Strain History



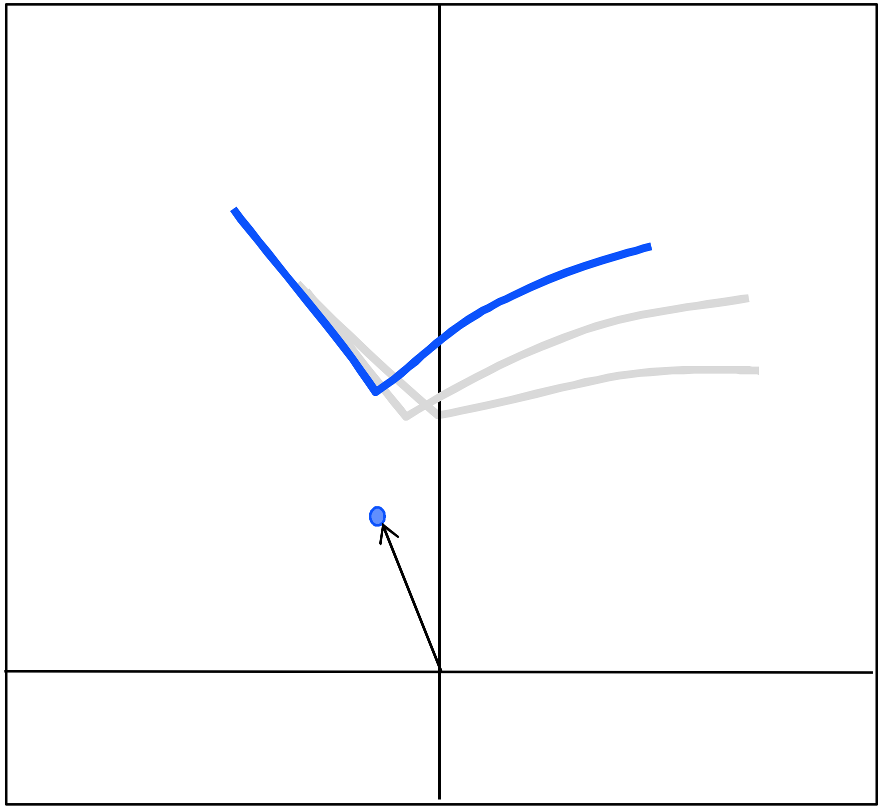
0% Strain

Uniaxial Tension Strain History



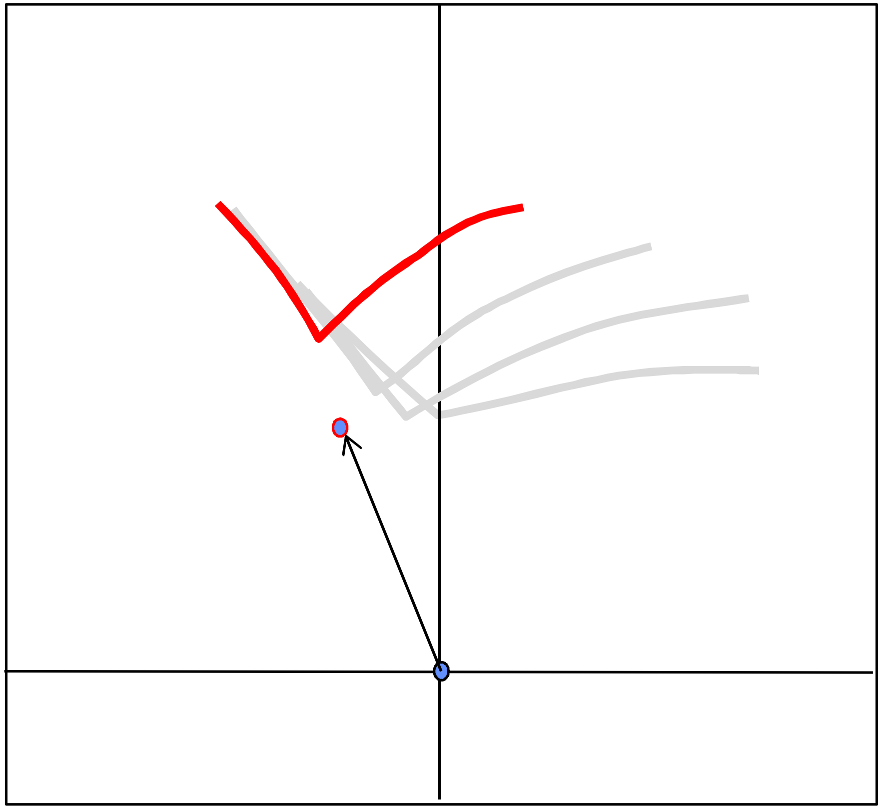
5% Strain

Uniaxial Tension Strain History



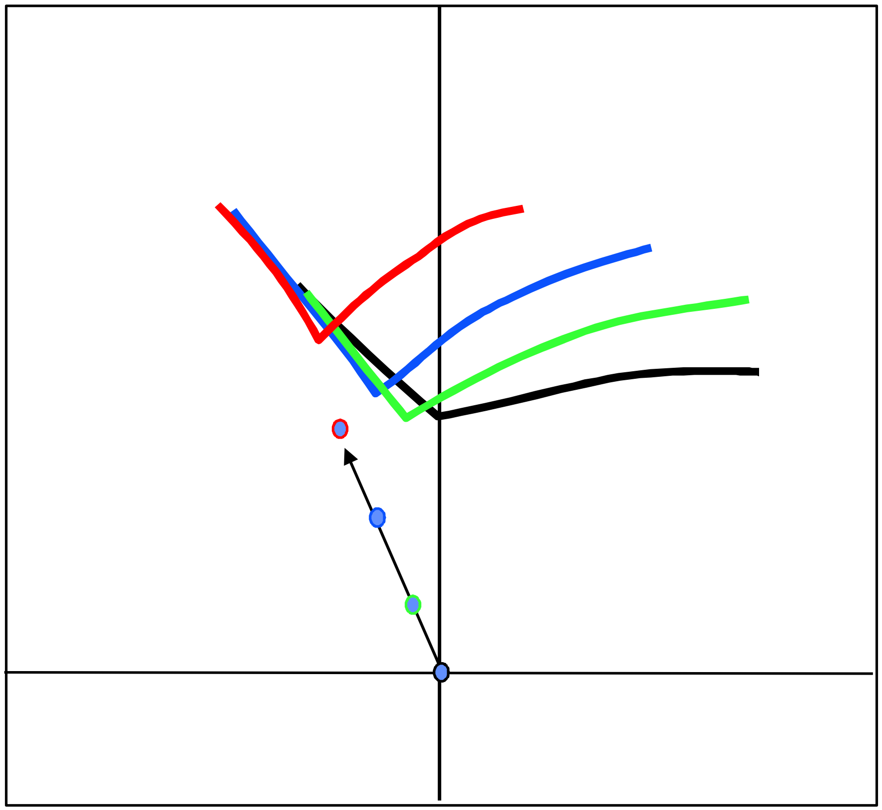
12% Strain

Uniaxial Tension Strain History

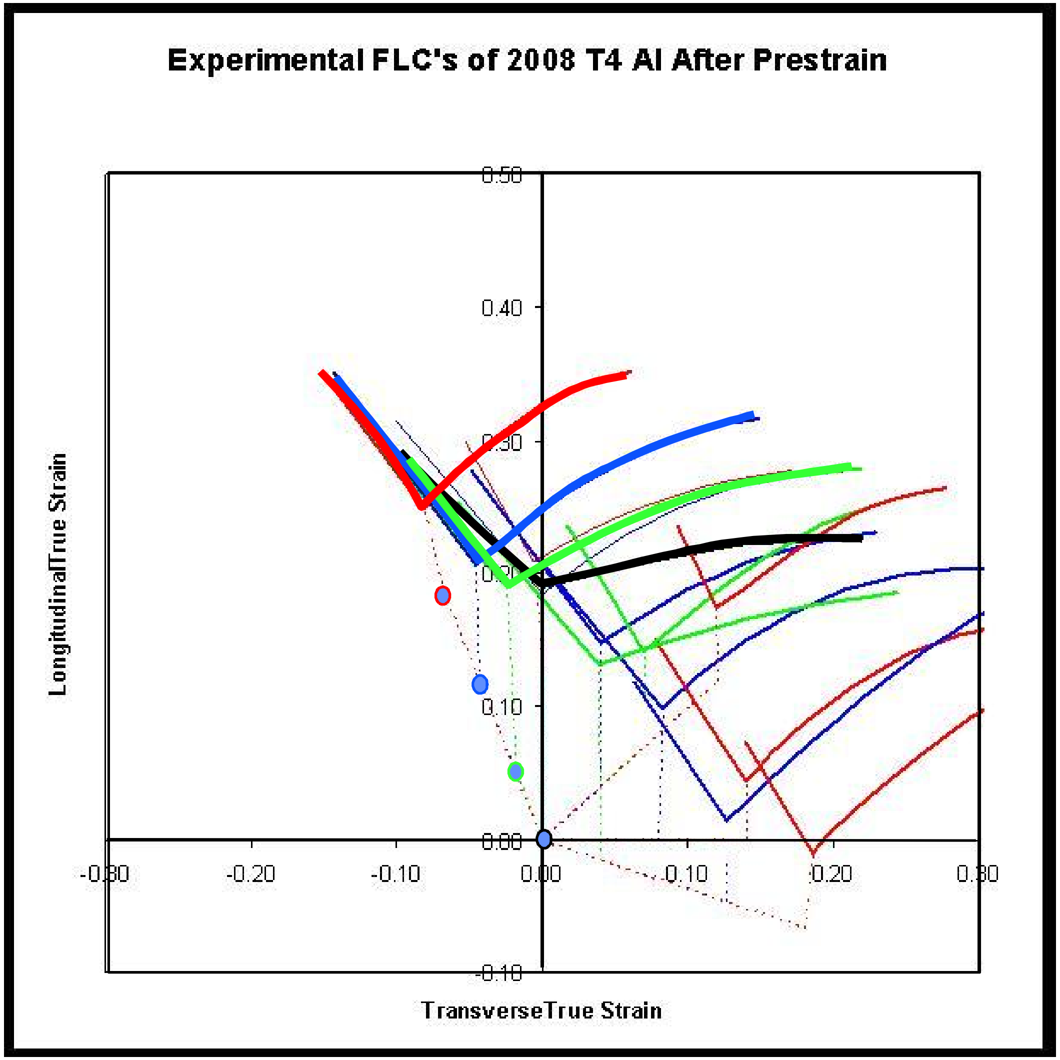


17% Strain

The Strain-Based FLC is DYNAMIC

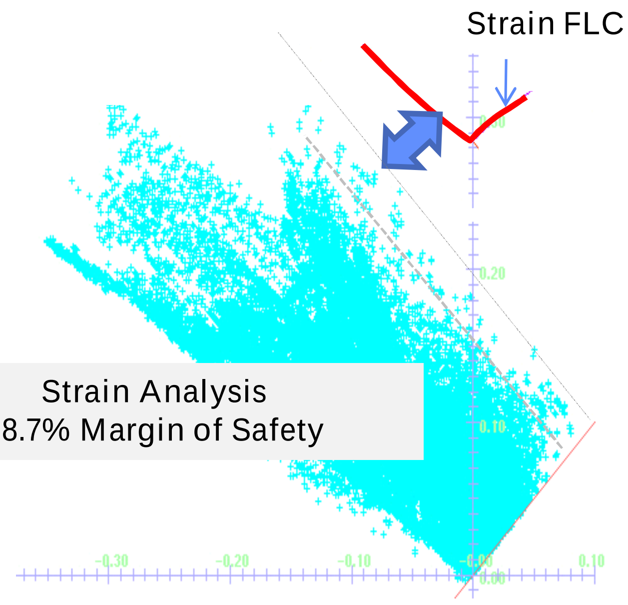


How can we reliably assess formability?

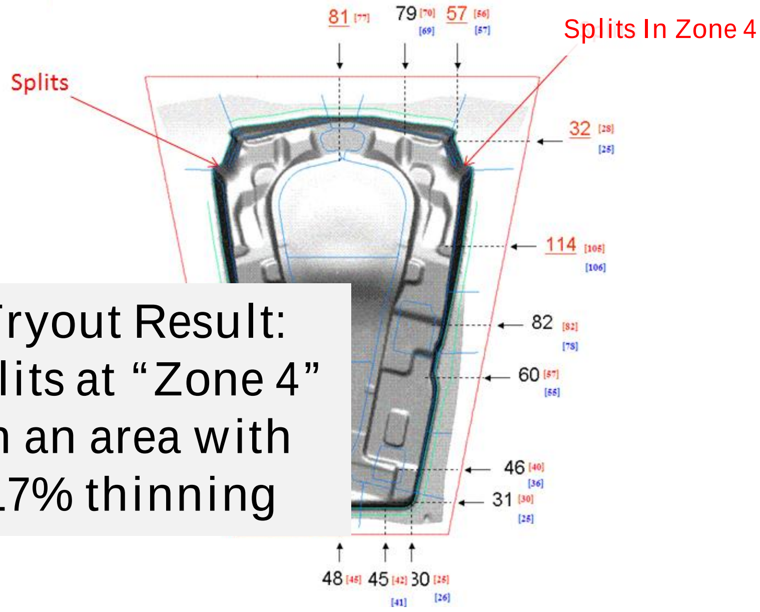


Ignoring the DYNAMIC nature of the FLC has costly consequences

Complex parts & processes designed base solely on net strain and the strain FLC, even with what seems to be high margin of safety…



Strain Analysis
+8.7% Margin of Safety



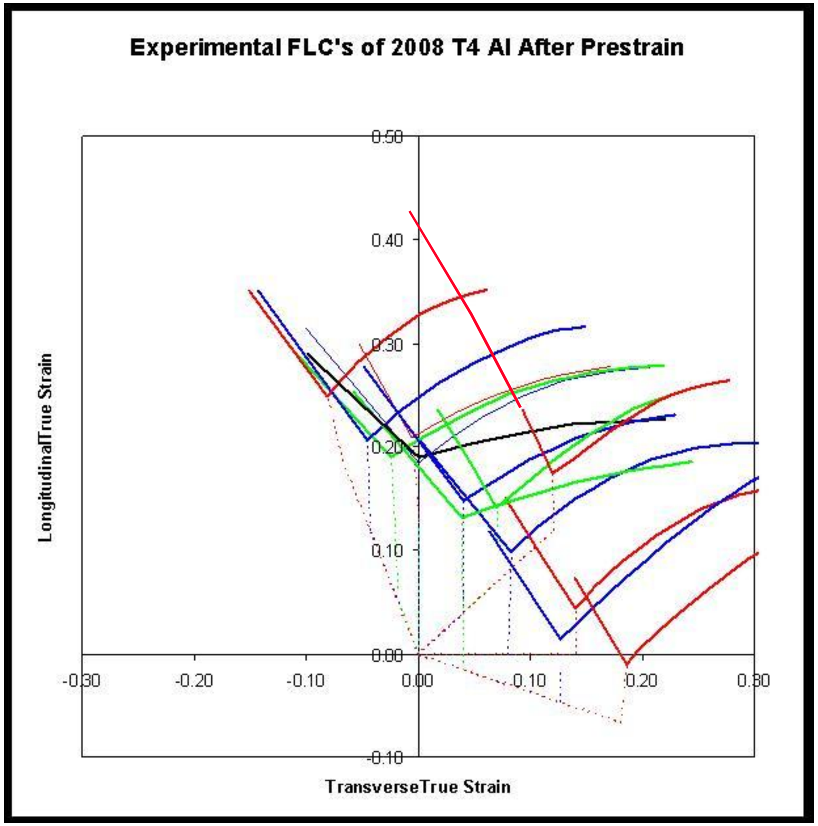
Tryout Result:
Splits at "Zone 4"
in an area with
17% thinning

…may still fail in tryout and require additional changes to product and tooling shape or processing conditions.

Paradigm Change: a new perspective

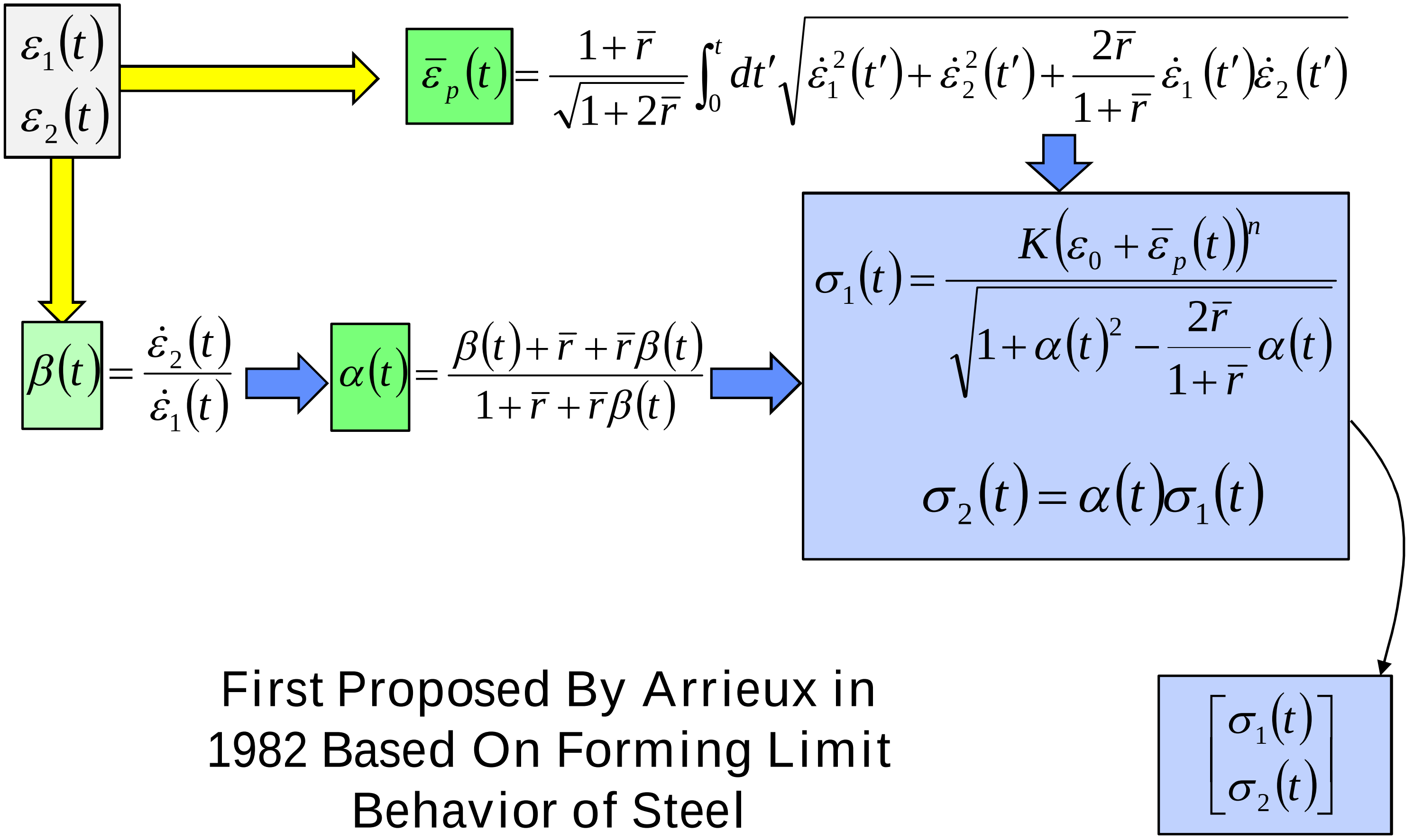
No assumptions, just a simple question…

Are these experimental results LESS complex in stress-space?



Transformation equations for an arbitrary time record of plastic strain

Normal Anisotropic Hill Model



$$\begin{bmatrix}\varepsilon_1(t)\\ \varepsilon_2(t)\end{bmatrix}$$

$$\bar{\varepsilon}_p(t)=\frac{1+\bar{r}}{\sqrt{1+2\bar{r}}}\int_0^t dt'\sqrt{\dot{\varepsilon}_1^2(t')+\dot{\varepsilon}_2^2(t')+\frac{2\bar{r}}{1+\bar{r}}\dot{\varepsilon}_1(t')\dot{\varepsilon}_2(t')}$$

$$\beta(t)=\frac{\dot{\varepsilon}_2(t)}{\dot{\varepsilon}_1(t)}$$

$$\alpha(t)=\frac{\beta(t)+\bar{r}+\bar{r}\beta(t)}{1+\bar{r}+\bar{r}\beta(t)}$$

$$\sigma_1(t)=\frac{K\left(\varepsilon_0+\bar{\varepsilon}_p(t)\right)^n}{\sqrt{1+\alpha(t)^2-\frac{2\bar{r}}{1+\bar{r}}\alpha(t)}}$$

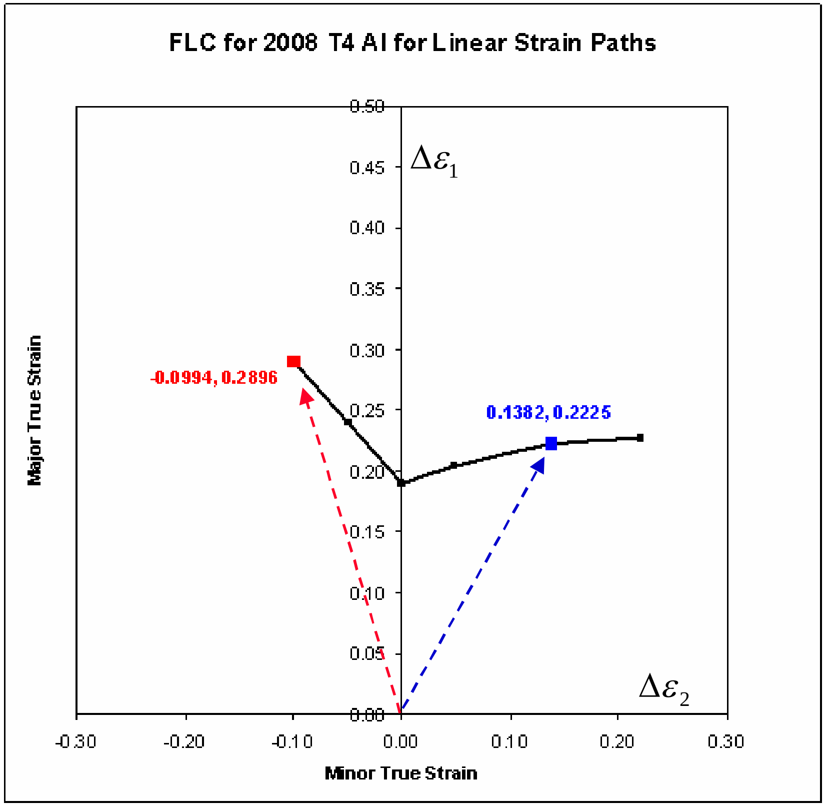
$$\sigma_2(t)=\alpha(t)\sigma_1(t)$$

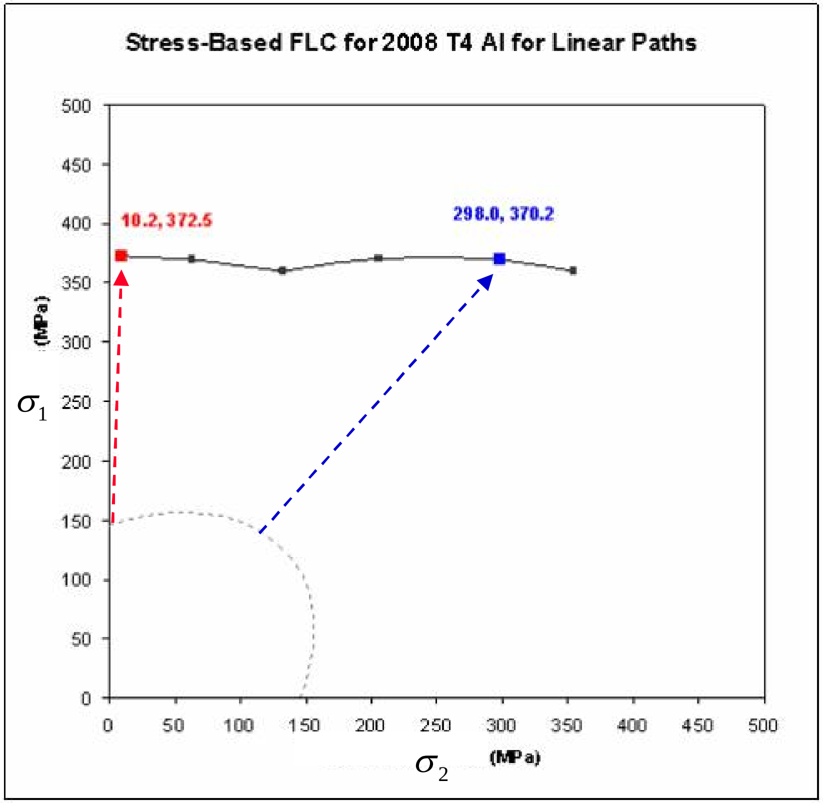
$$\begin{bmatrix}\sigma_1(t)\\ \sigma_2(t)\end{bmatrix}$$

Arrieux, et al., 1982

First Proposed By Arrieux in 1982 Based On Forming Limit Behavior of Steel

Strain FLC to Stress FLC For Linear Strain Paths

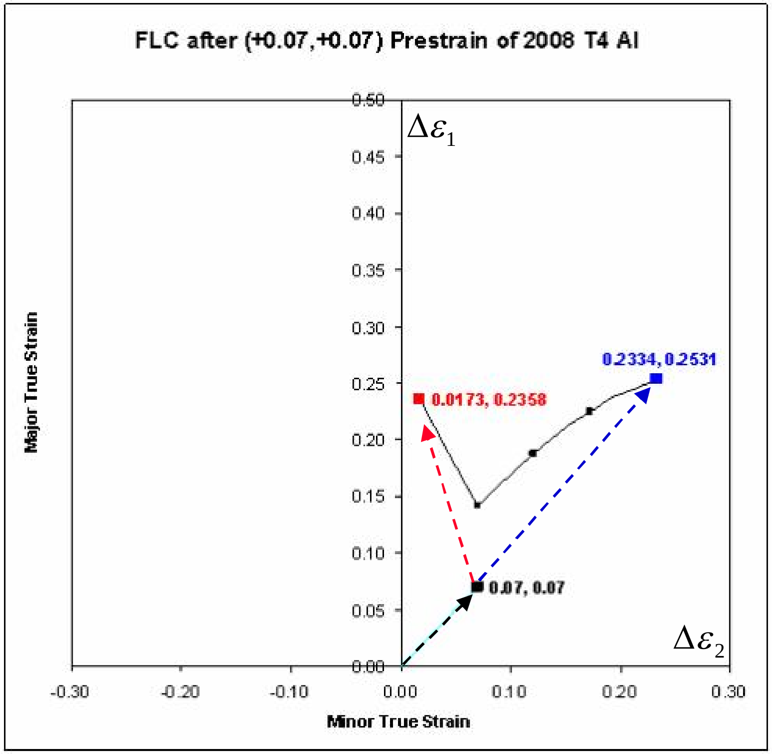


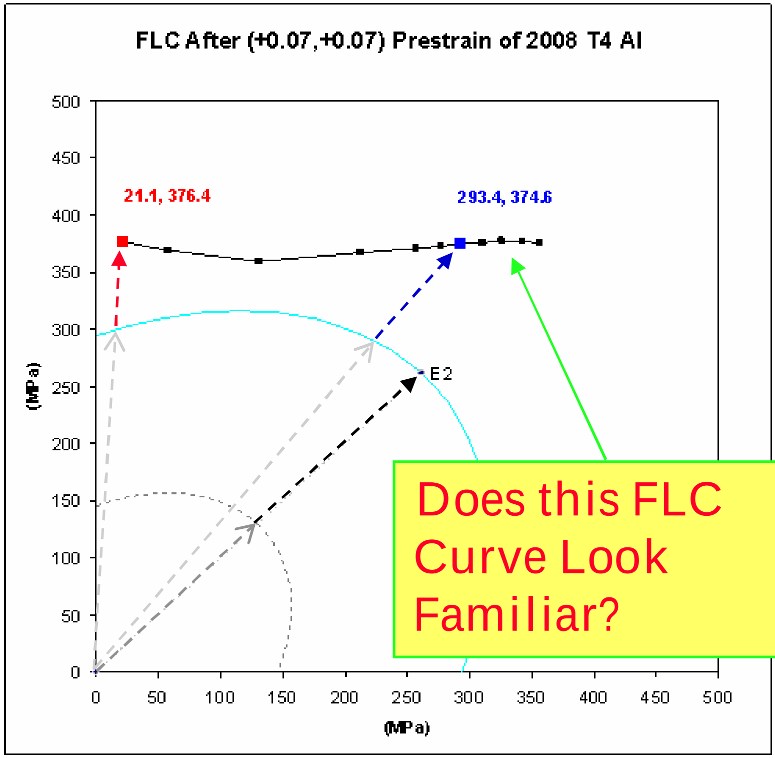


Numerical Example

$$\left.\boxed{\begin{aligned}\Delta\varepsilon_2 &= -0.0994\\ \Delta\varepsilon_1 &= +0.2896\end{aligned}}\right\}\qquad \begin{aligned}\bar{\varepsilon}_p &= 0.2897\\ \alpha &= 0.02730\end{aligned}\qquad \longrightarrow\left\{\boxed{\begin{aligned}\sigma_2 &= 10.2\ \text{MPa}\\ \sigma_1 &= 372.5\ \text{MPa}\end{aligned}}\right.$$

Strain FLC to Stress FLC For Bi-Linear Strain Paths





Does this FLC Curve Look Familiar?

Numerical Example

$$\Delta\varepsilon_{2A} = +0.070 \qquad \Delta\varepsilon_{1A} = +0.070$$

$$\Delta\varepsilon_{2} = +0.0173 \qquad \Delta\varepsilon_{1} = +0.2358$$

Input

$$\Delta\bar{\varepsilon}_{pA} = 0.1244$$

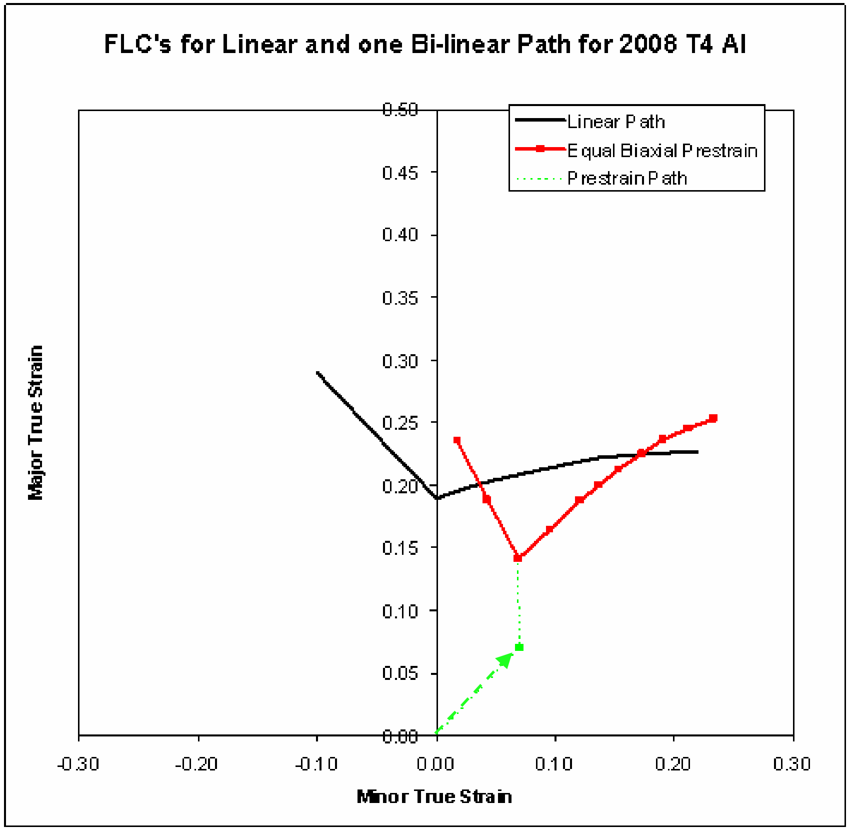
$$\Delta\varepsilon_{1B} = -0.0527 \qquad \Delta\varepsilon_{2B} = +0.1658$$

$$\Delta\bar{\varepsilon}_{pB} = 0.1661$$

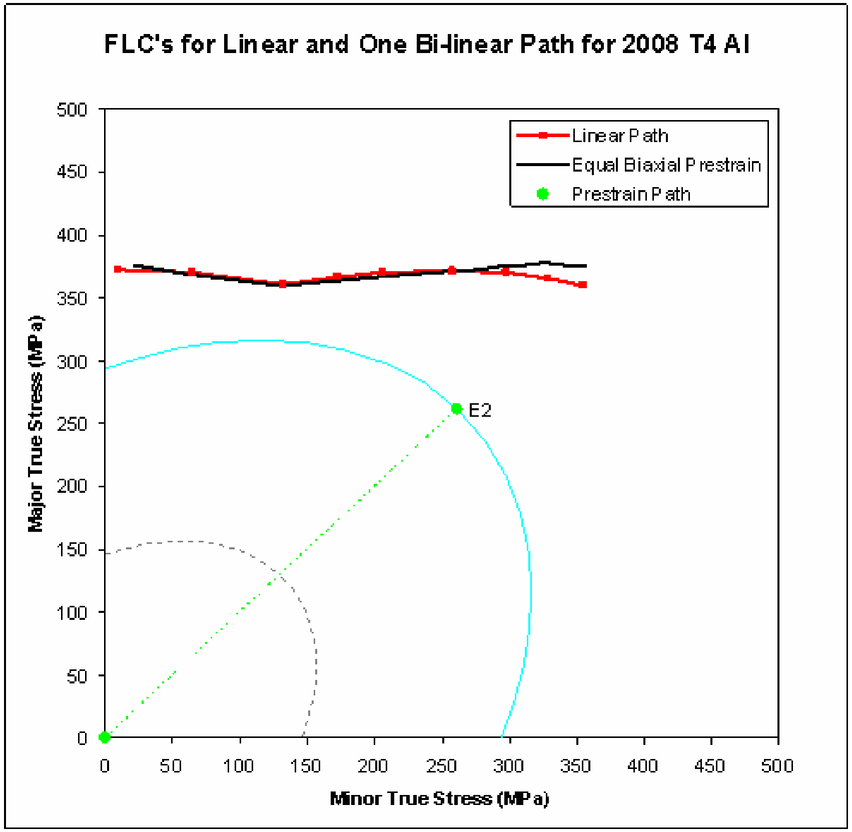
$$\bar{\varepsilon}_p = 0.2905 \qquad \alpha = 0.05578$$

$$\rightarrow \quad \sigma_2 = 21.1\,\text{MPa} \qquad \sigma_1 = 376.4\,\text{MPa}$$

Observation Leads to New Solution



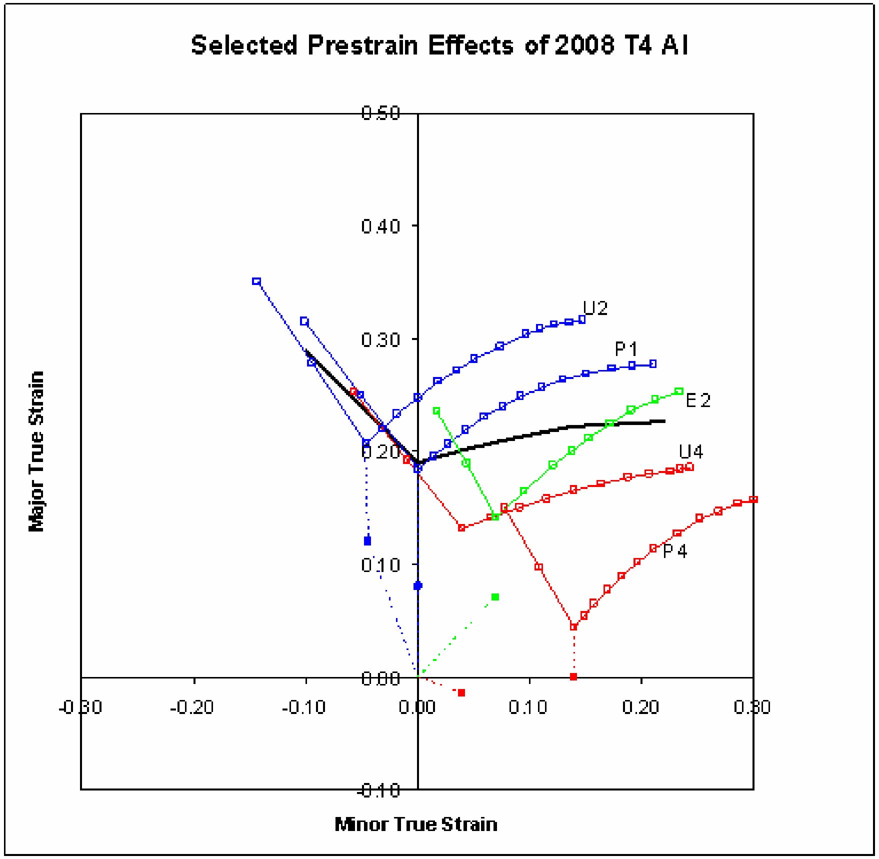
FLC's for Linear and one Bi-linear Path for 2008 T4 Al

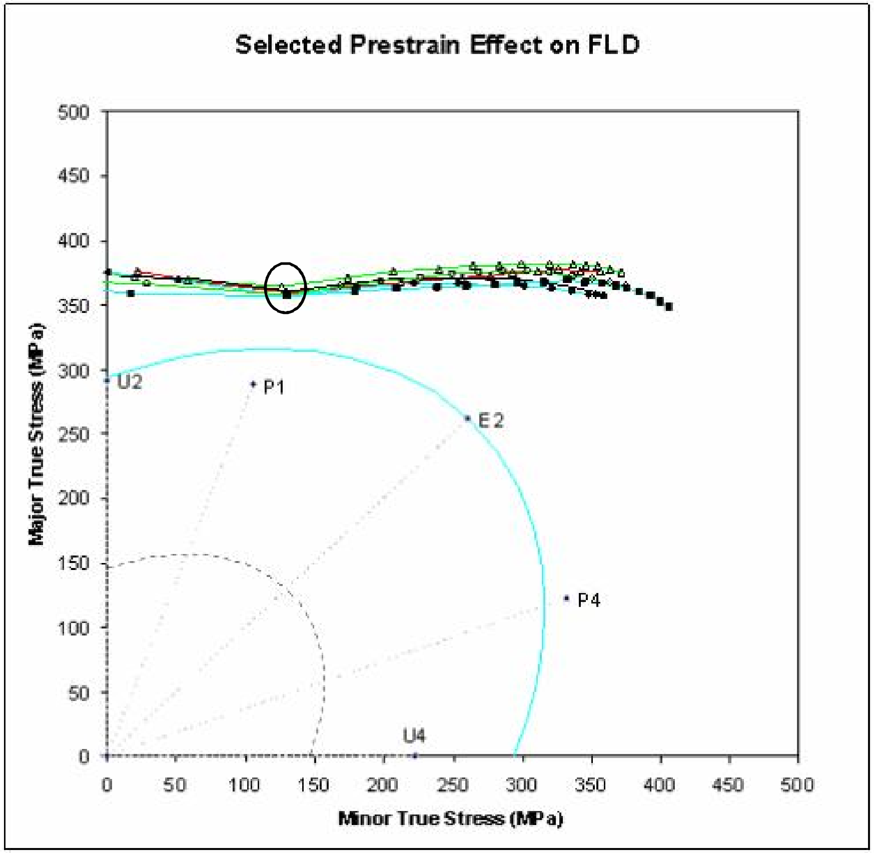


FLC's for Linear and One Bi-linear Path for 2008 T4 Al

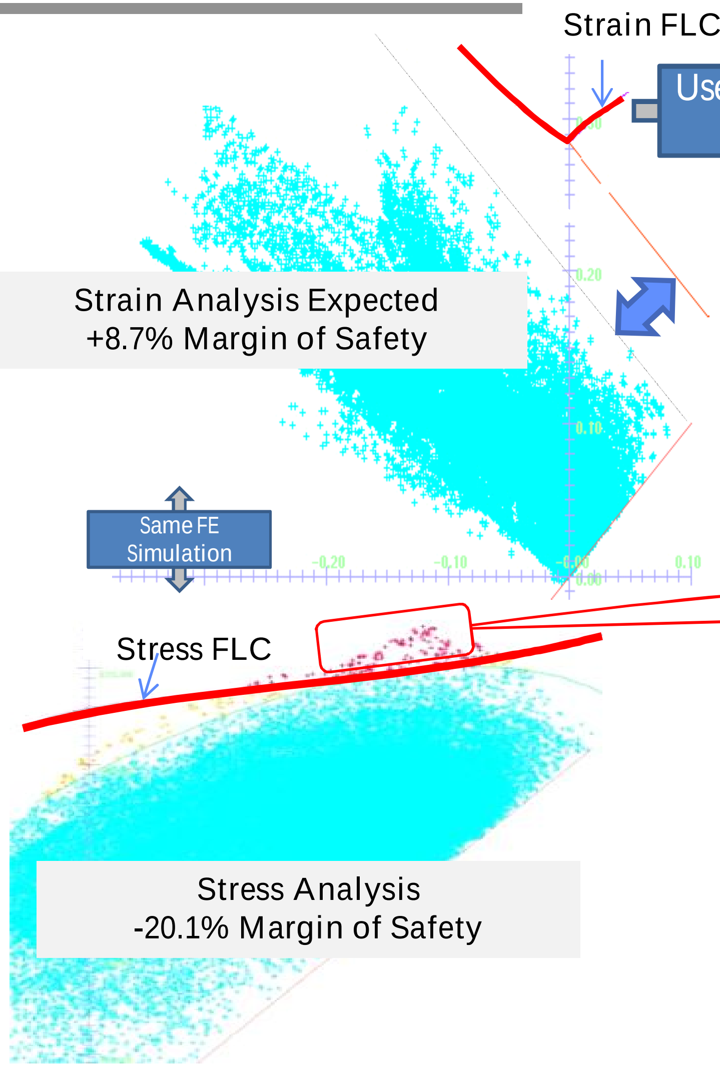
Stress-Based FLC’s do not appear to be sensitive to changes in strain path

Stress Based FLC's are not Sensitive to Path





Body Side Component



Strain FLC

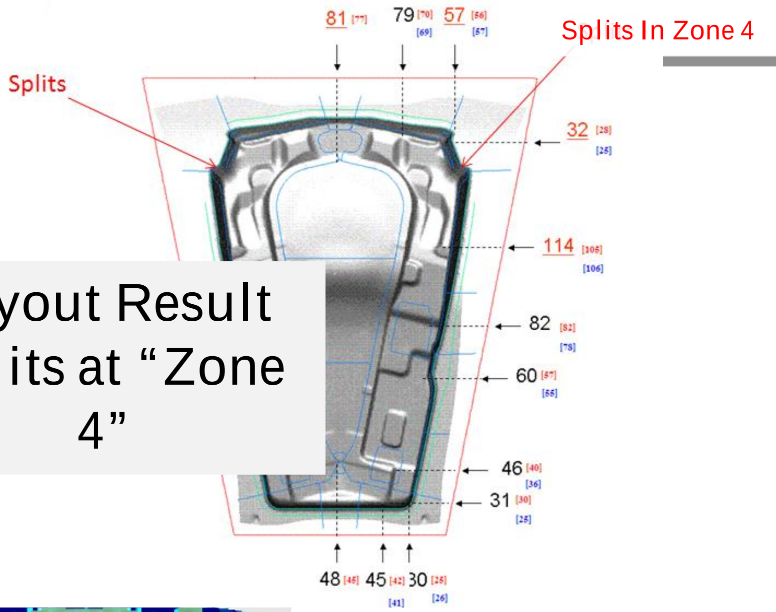
Used to Approve Die Build

Strain Analysis Expected
+8.7% Margin of Safety

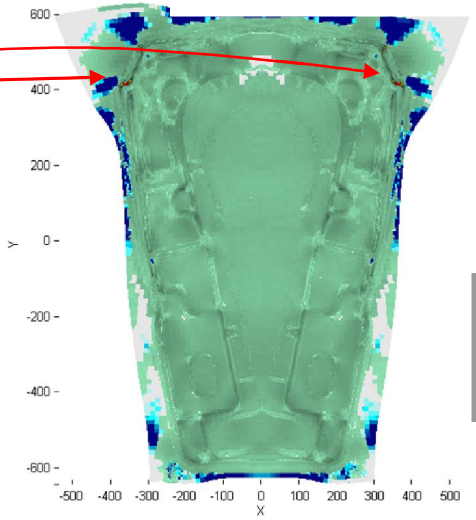
Same FE Simulation

Stress FLC

Stress Analysis
-20.1% Margin of Safety



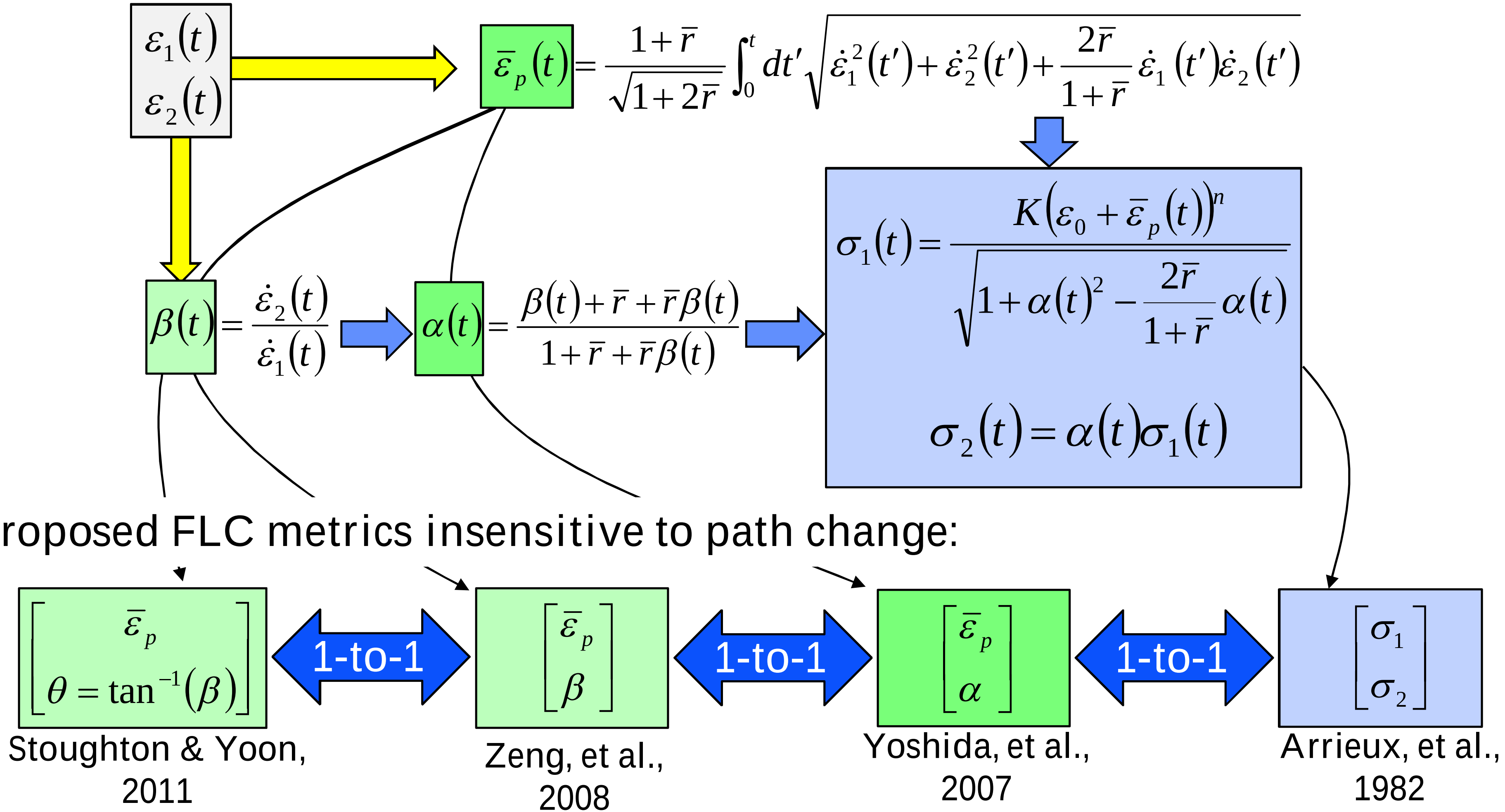
Tryout Result Splits at “Zone 4”



Stress Map of Critical Areas

Other Stress-Equivalent Solutions

Normal Anisotropic Hill Model



$$\varepsilon_1(t) \qquad \varepsilon_2(t)$$

$$\bar{\varepsilon}_p(t) = \frac{1+\bar{r}}{\sqrt{1+2\bar{r}}}\int_0^t dt' \sqrt{\dot{\varepsilon}_1^2(t') + \dot{\varepsilon}_2^2(t') + \frac{2\bar{r}}{1+\bar{r}}\dot{\varepsilon}_1(t')\dot{\varepsilon}_2(t')}$$

$$\beta(t) = \frac{\dot{\varepsilon}_2(t)}{\dot{\varepsilon}_1(t)}$$

$$\alpha(t) = \frac{\beta(t)+\bar{r}+\bar{r}\beta(t)}{1+\bar{r}+\bar{r}\beta(t)}$$

$$\sigma_1(t) = \frac{K\left(\varepsilon_0 + \bar{\varepsilon}_p(t)\right)^n}{\sqrt{1+\alpha(t)^2 - \frac{2\bar{r}}{1+\bar{r}}\alpha(t)}}$$

$$\sigma_2(t) = \alpha(t)\sigma_1(t)$$

Proposed FLC metrics insensitive to path change:

$$\begin{bmatrix} \bar{\varepsilon}_p \\ \theta = \tan^{-1}(\beta) \end{bmatrix} \xleftrightarrow{\text{1-to-1}} \begin{bmatrix} \bar{\varepsilon}_p \\ \beta \end{bmatrix} \xleftrightarrow{\text{1-to-1}} \begin{bmatrix} \bar{\varepsilon}_p \\ \alpha \end{bmatrix} \xleftrightarrow{\text{1-to-1}} \begin{bmatrix} \sigma_1 \\ \sigma_2 \end{bmatrix}$$

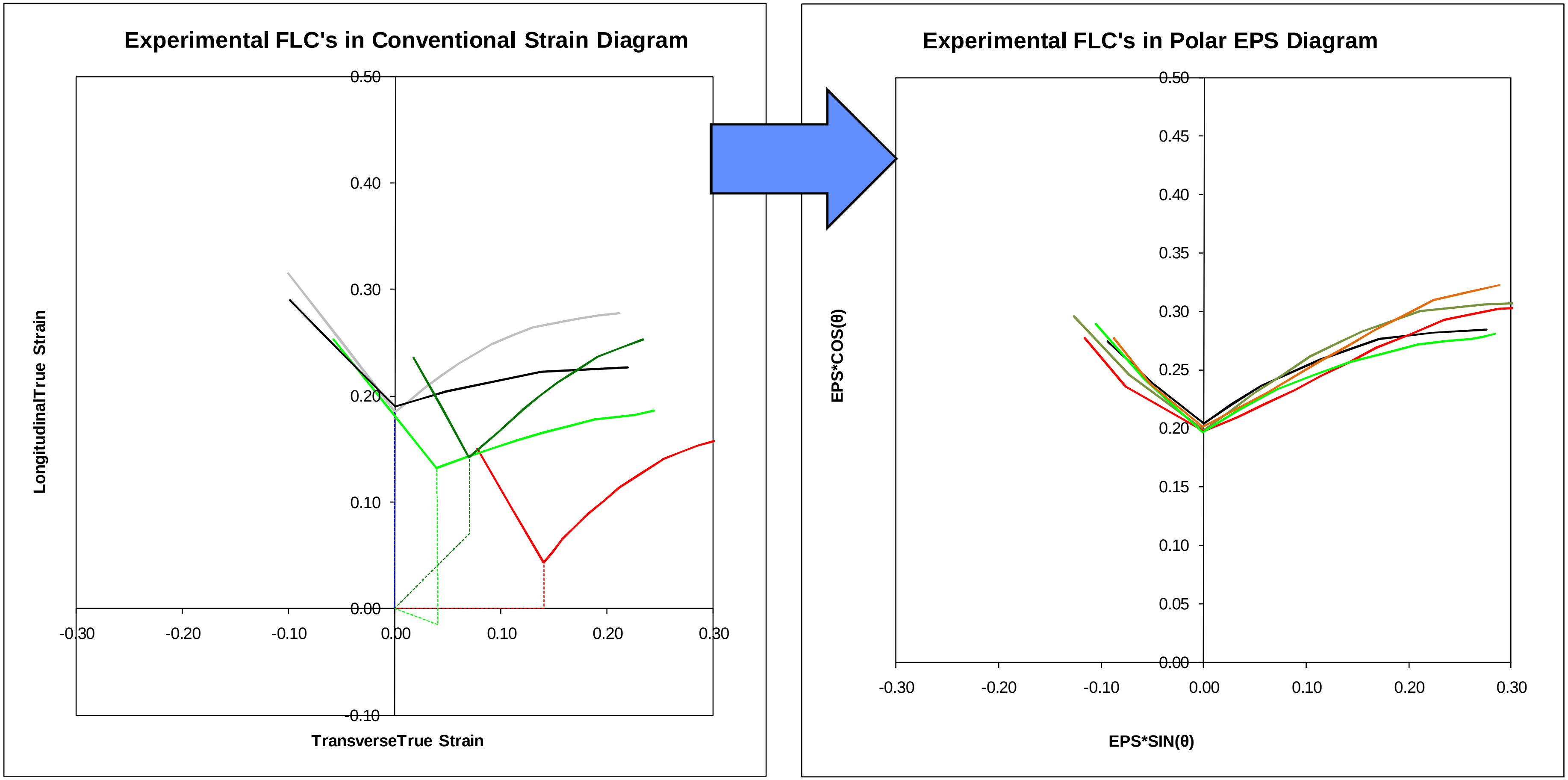
Stoughton & Yoon, 2011

Zeng, et al., 2008

Yoshida, et al., 2007

Arrieux, et al., 1982

Polar Diagram of the EPS

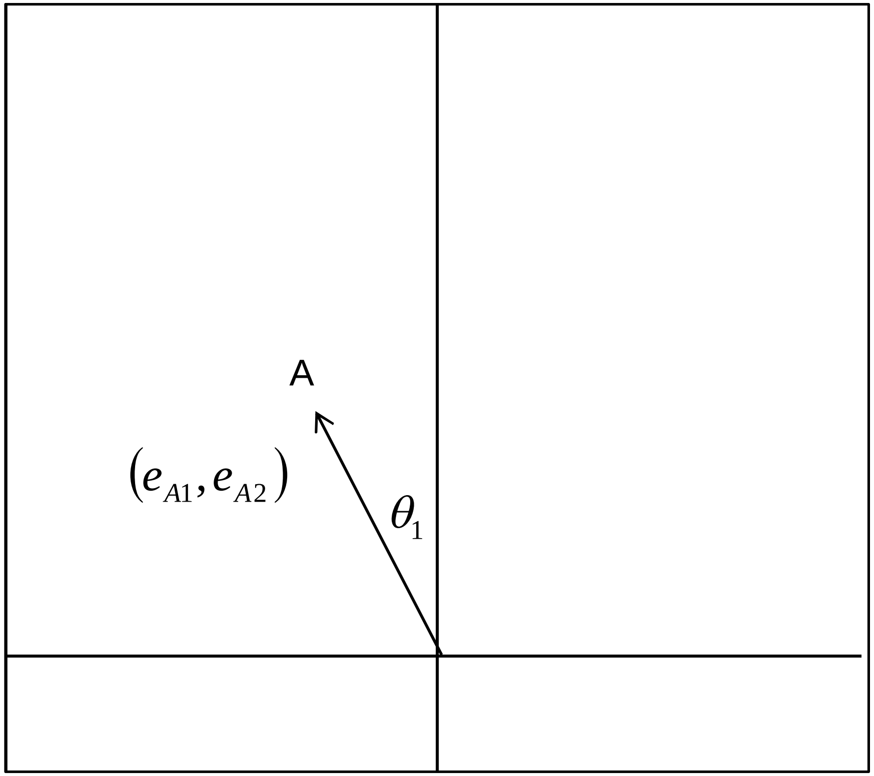


Experimental FLC's in Conventional Strain Diagram

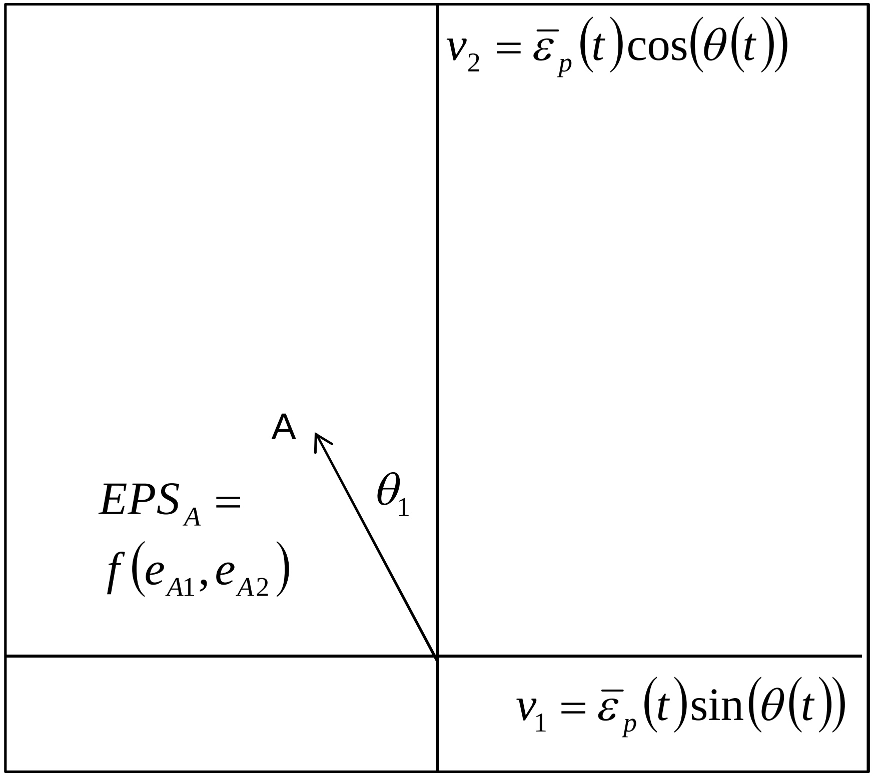
Experimental FLC's in Polar EPS Diagram

Illustration of Similarity & Differences

$$\begin{bmatrix}\varepsilon_1(t)\\ \varepsilon_2(t)\end{bmatrix} \xrightarrow{\theta=\tan^{-1}(\beta(t))=\tan^{-1}(\dot{\varepsilon}_2(t),\dot{\varepsilon}_1(t))} \begin{bmatrix}\bar{\varepsilon}_p(t)\\ \theta(t)\end{bmatrix}$$

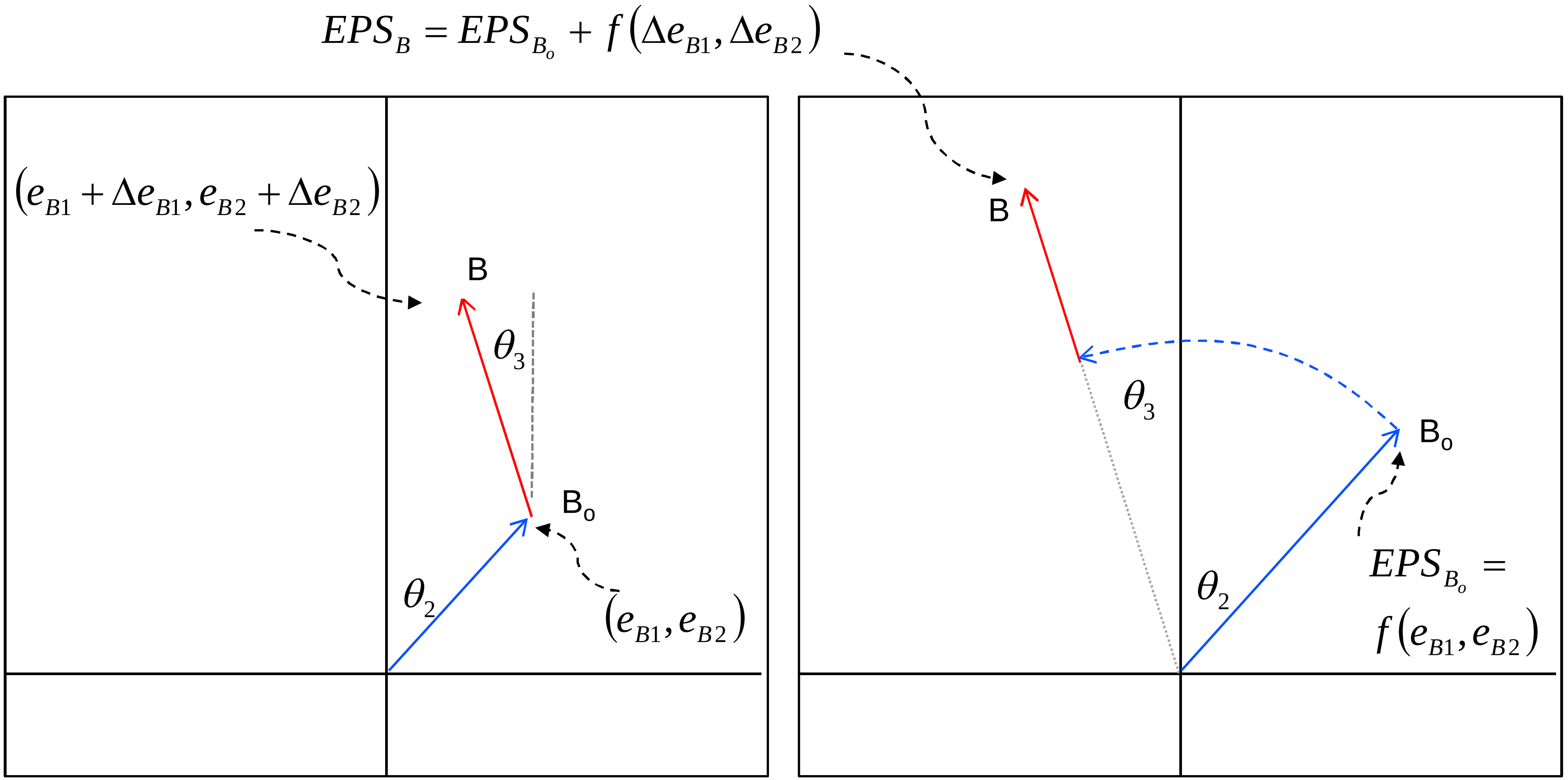


Path Sensitive Strain FLD



Polar EPS Diagram

Illustration of Similarity & Differences



$$EPS_B = EPS_{B_o} + f\left(\Delta e_{B1}, \Delta e_{B2}\right)$$

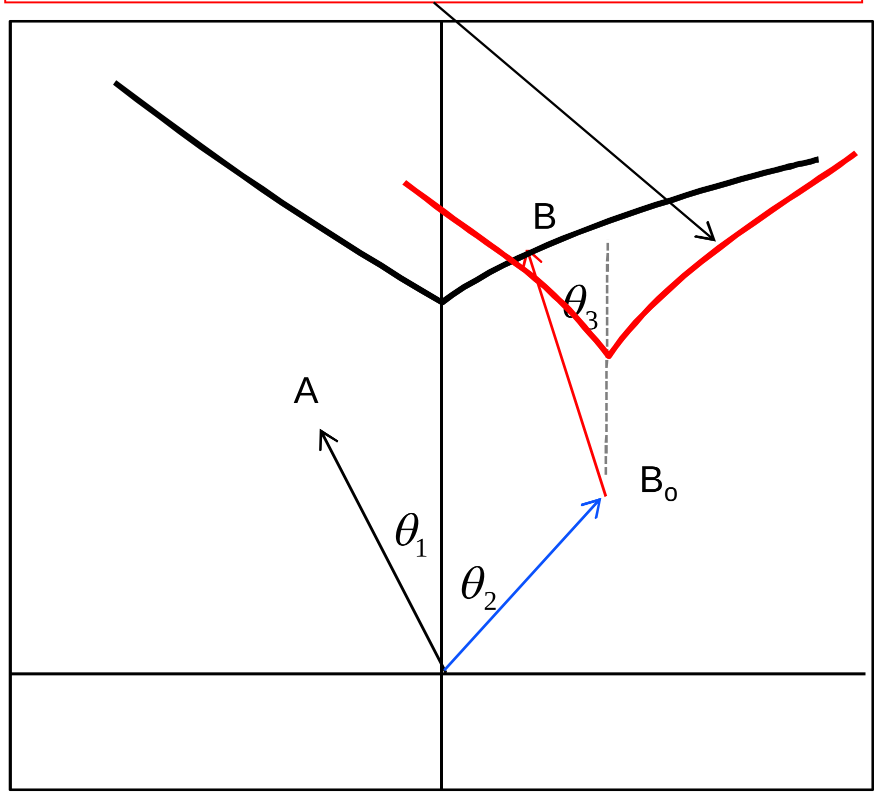
Path Sensitive Strain FLD

Polar EPS Diagram

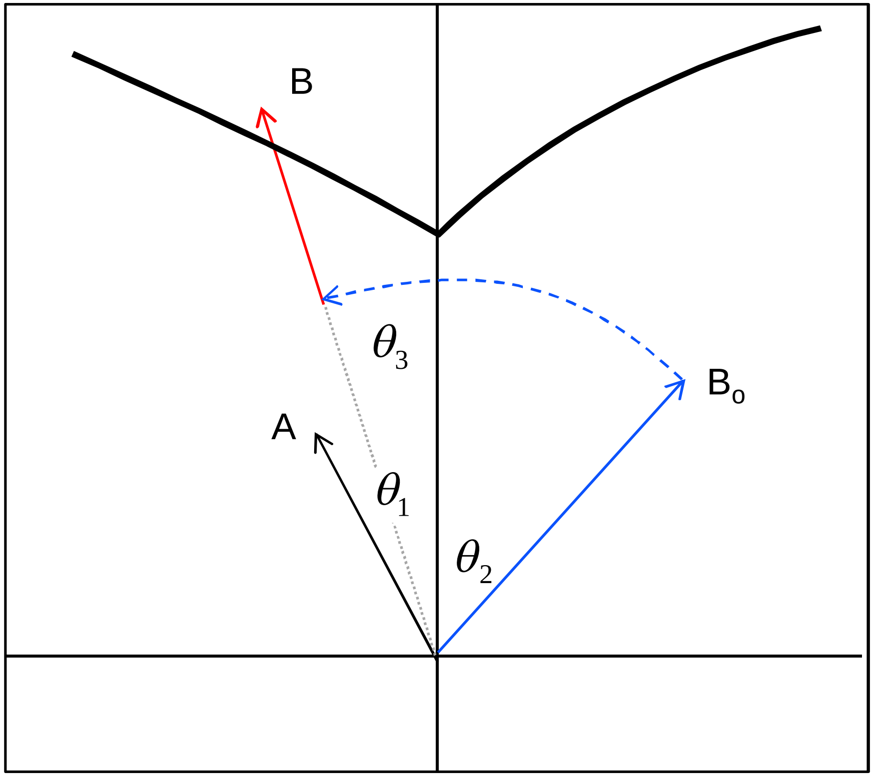
The Reason

Apriori Unknown Evolution of the Strain Limit

Static EPS Limit



Path Sensitive Strain FLD



Polar EPS Diagram

Importance of Nonlinear Path for AHSS

- In the past, anomalous failures caused by ignoring the effect of nonlinear paths on formability… i.e., treating strain limits as static limits… have led industry to limit strains in future applications to even lower limits…
- Industry cannot afford this solution using AHHS with lower ductility than low carbon steel… not when a solution is available to maximize the use of the available ductility.

Thank you for your attention.

Questions?