GREAT DESIGNS IN STEEL

Damage-Based Fracture Modelling of Mild And Advanced High Strength Steel

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(Presenting for Auto/Steel Partnership)

Project Team

GDIS

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Outline

Overview of Stress-State Dependent Fracture Modelling

Characterization of Anisotropic Plasticity

Fracture Characterization in Proportional Loading

Fracture Characterization in Anisotropic Non-Linear Strain Paths (NLSP)

Evaluation of Damage-indicator Models: DDQ & DP1180 steel

Overview of Fracture Modelling For Crash

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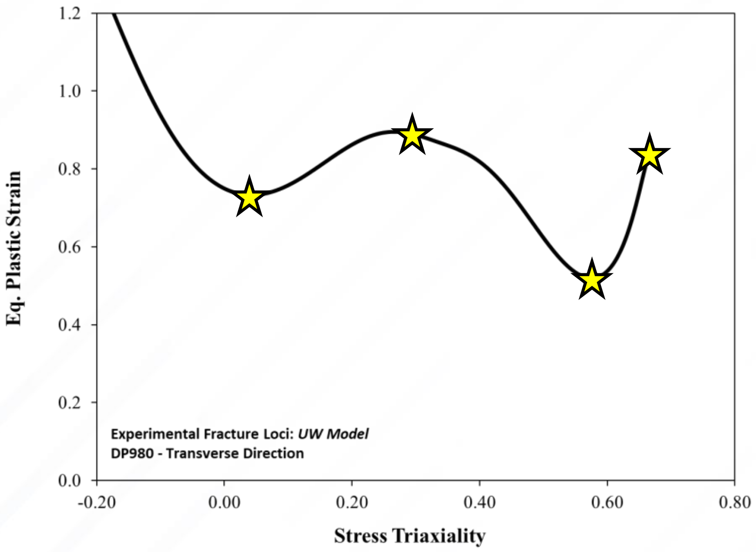
1. Construct Proportional Fracture Loci from Coupon Tests:
Experimental or Inverse FE Approaches Used

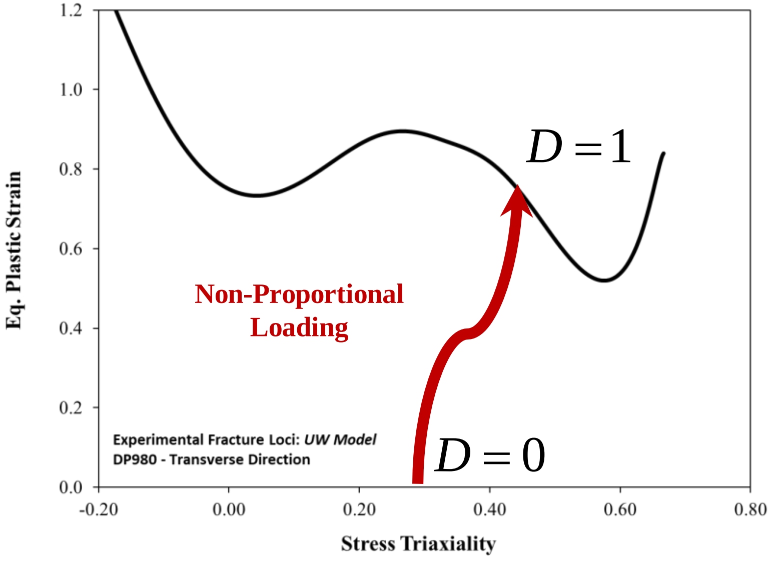


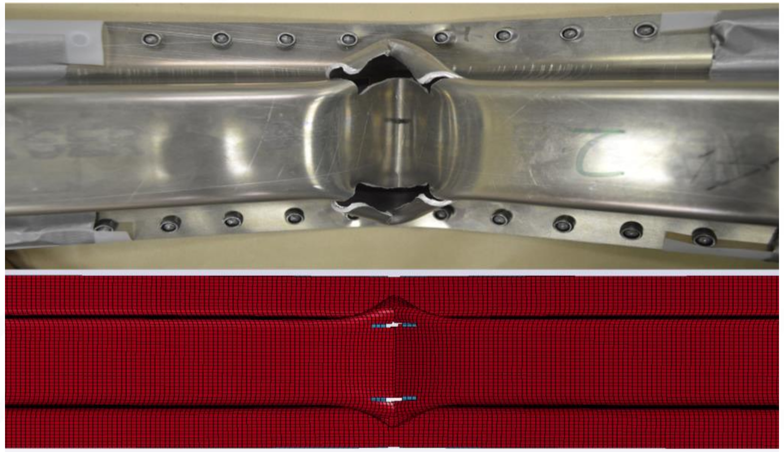
Step 2. Assume Damage Model for
Non-Linear Loading. Pair with Fracture Locus

$$\Delta D^{GISSMO} = \left[\frac{n}{\varepsilon_f^{\exp}(T)} D^{\left(1-\frac{1}{n}\right)} \right] \Delta \varepsilon^p$$

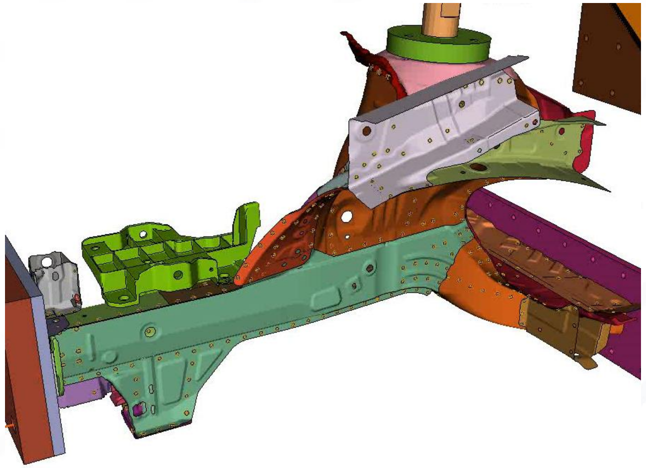
Step 3. Regularize for element size
& apply to structural CAE models

Need Objective Evaluation of
Phenomenological Fracture Models





3-Point Bend of Rail Section



Axial Crush of Front End Crush Structure

Axial Crush of Hot Stamped Rail

ANISOTROPIC PLASTICITY: DDQ MILD STEEL

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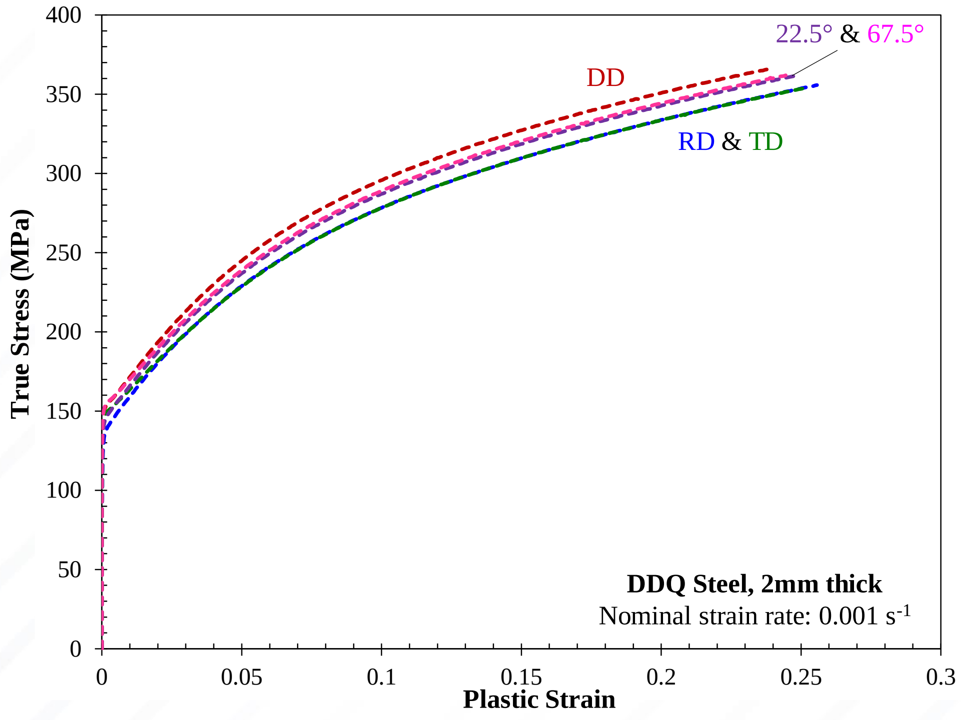
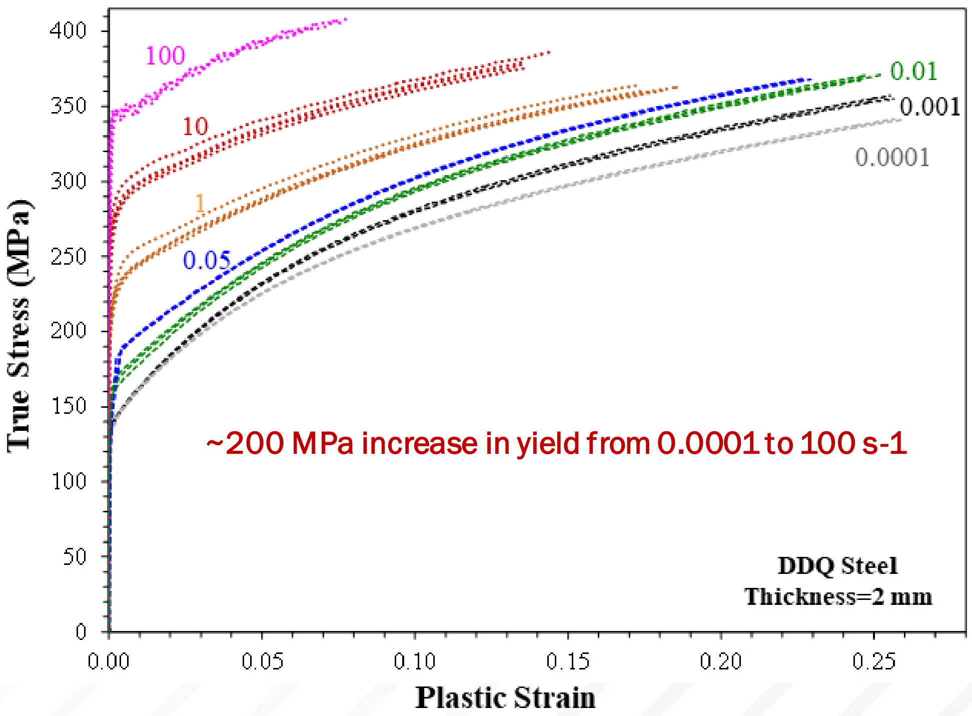
Detailed experimental characterization of anisotropic plasticity: DDQ (CR04) Steel, 2 mm thick

- Uniaxial tension (5 directions); Strain rate characterization in RD from 0.0001 to 100 s-1
- Simple shear (3 directions)
- Plane Strain tension (3 directions)
- Disc compression test for biaxial R-value



Diagonal is limiting direction for DDQ unlike TD for AHSS



Very high rate sensitivity unlike AHSS. Even at low rates

R-VALUE MEASUREMENT

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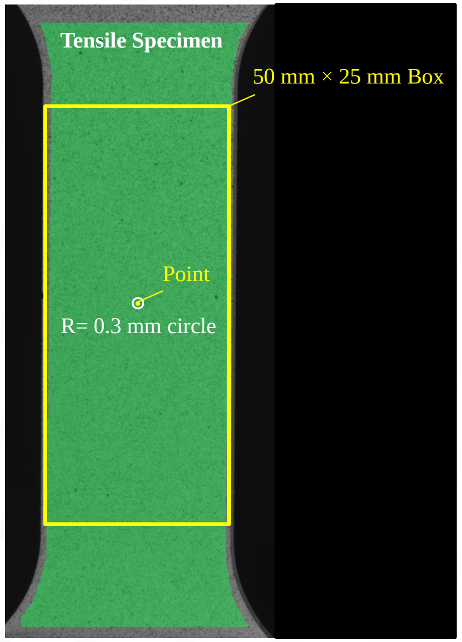
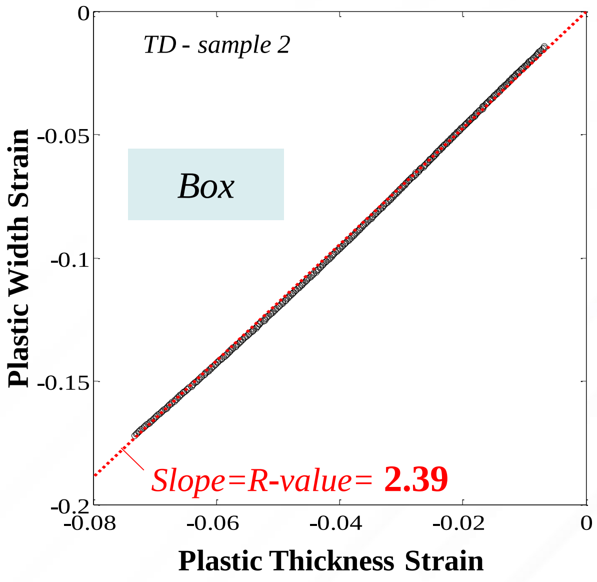
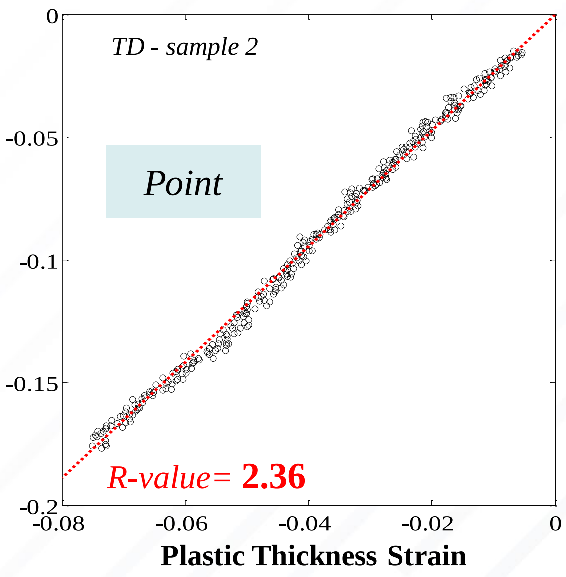
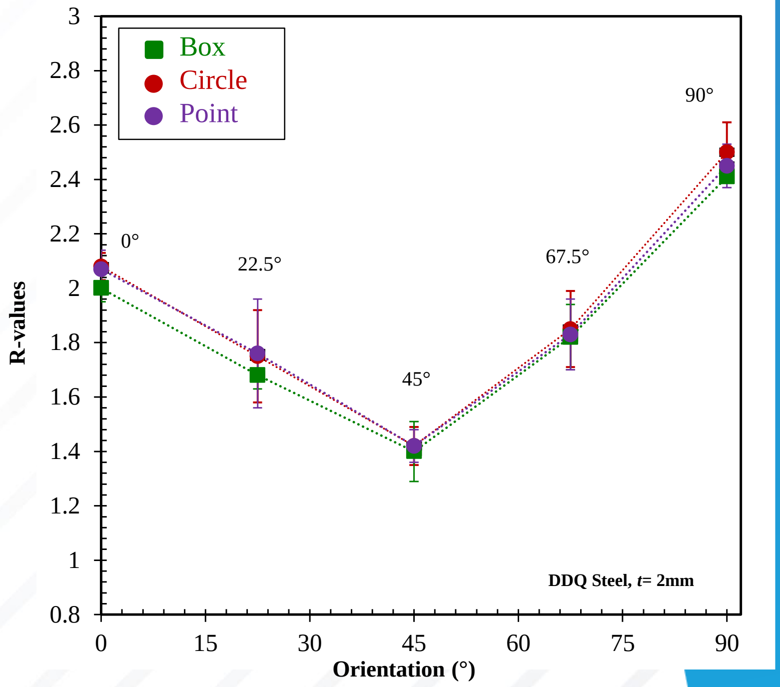
- R-values measured from 0.01 strain to 80% of uniform elongation
- DIC analysis methods: Point, Circle & Box evaluated
- *Minimal evolution in R-value with plastic work. R0 & R90 > 2.0 unlike AHSS with R~1.0*





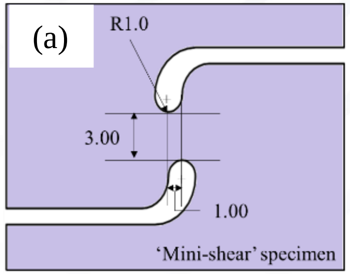


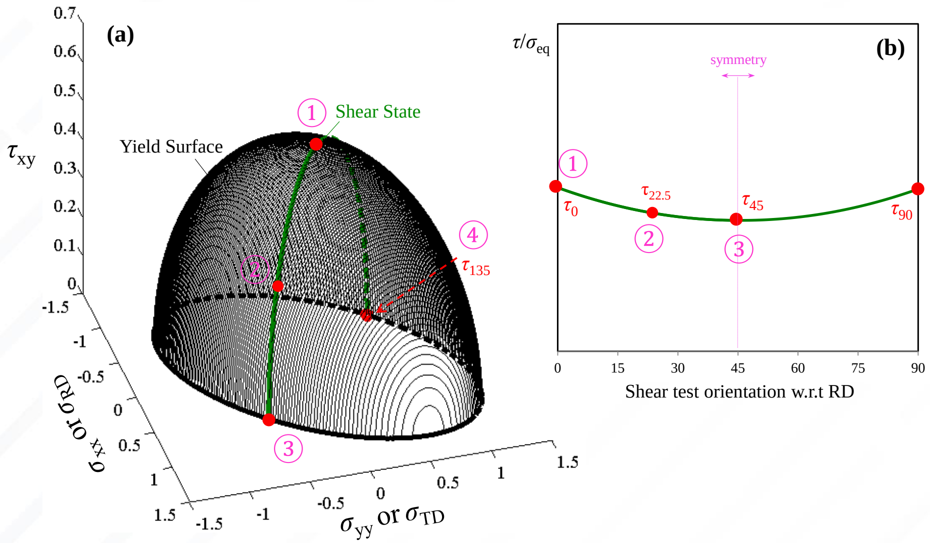


Box is average over gage region, reduces variation, and consistent with FEA idealization of homogeneous material

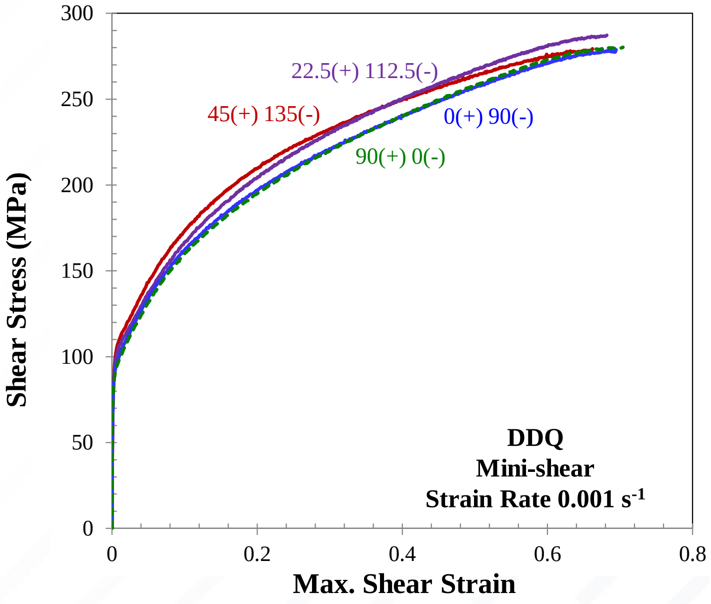
SHEAR ANISOTROPY

- Simple shear tests in 4 orientations using mini-shear geometry
- **Must extract samples -56° to target orientation (45° shift + 11° eccentricity)**
- Simple shear is equal and opposite loading in tension and compression
- *Shear anisotropy typical to AHSS and approximately von Mises*

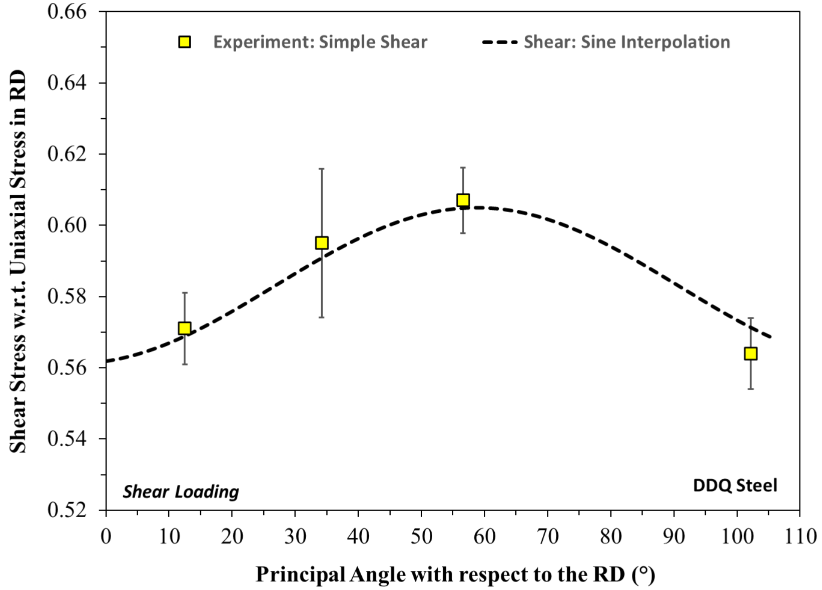




Shear locations on plane stress yield surface



Shear in RD-TD and TD-RD are identical → orthotropic material



Shear anisotropy similar to AHSS

Peirs J, Verleysen P, Degriek, *Experimental Mechanics*, 2012, 52:729-741

BIAXIAL R-VALUE

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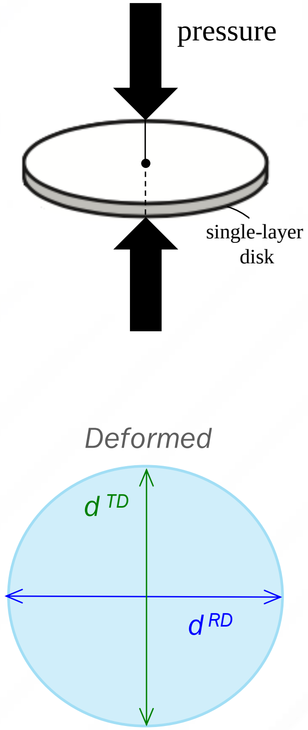
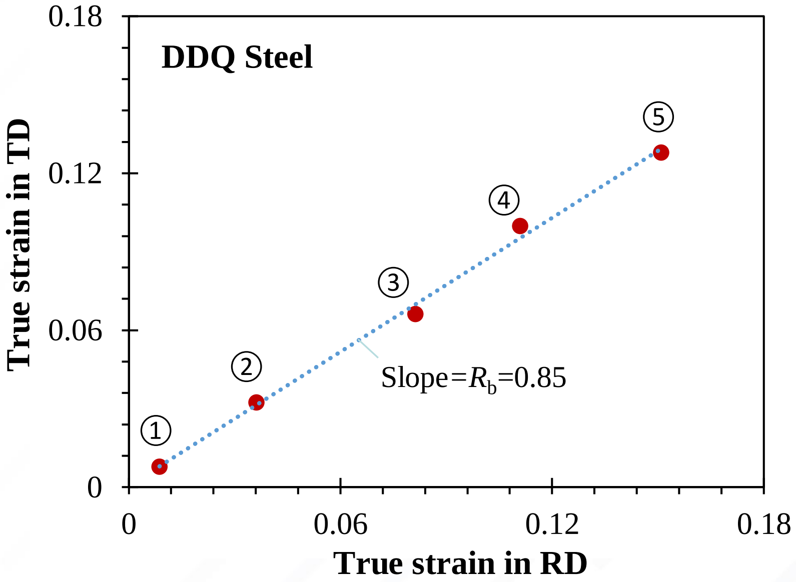
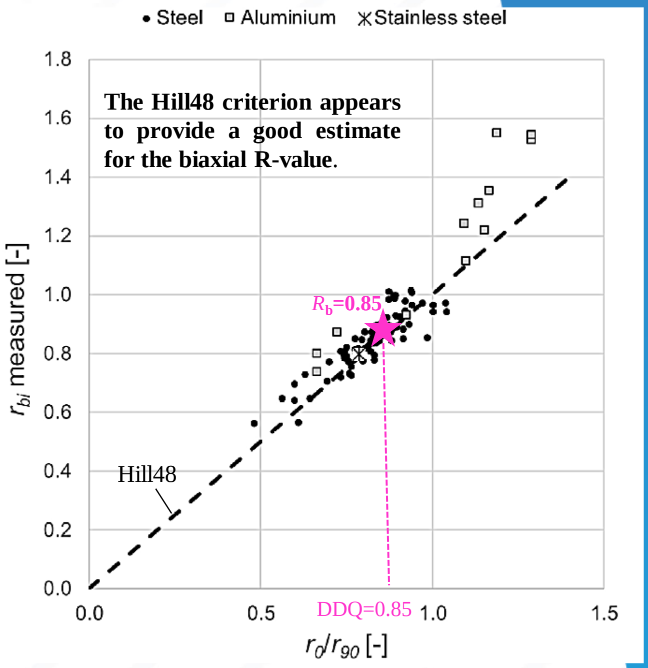
Disc compression test performed: 8 mm diameter disc, PTFE spray, 5 load levels

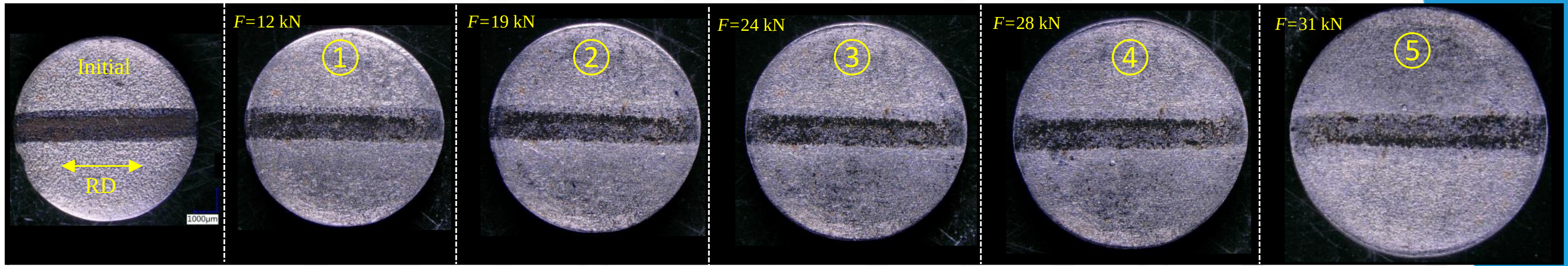
- Analysis assumed pressure-independent plasticity. Polish platens and use microscope to measure
- *Excellent repeatability. Agrees with experimental correlation using R0/R90*



$R_b = \varepsilon^{TD}/\varepsilon^{RD}$







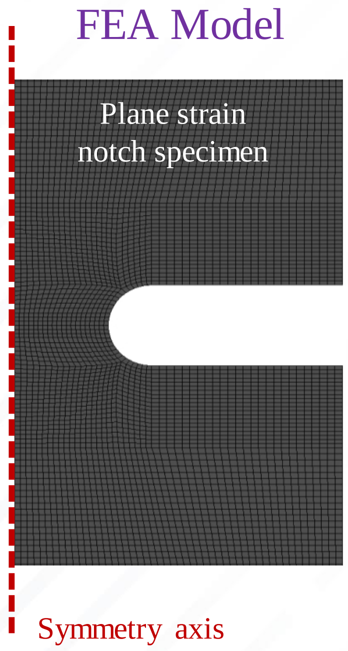
Abspoel M, Scholting M E, Lansbergen M, An Y, Vegter H, *Journal of Materials Processing Technology*, 2017, 248:161-177.

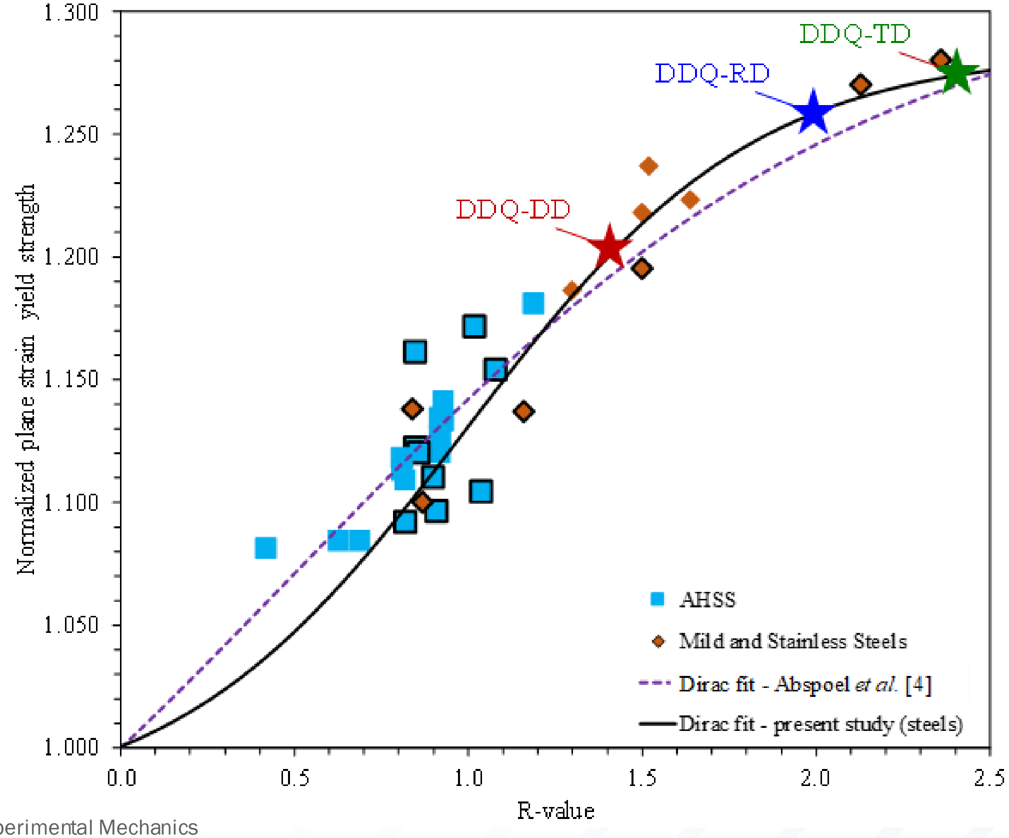
PLANE STRAIN CHARACTERIZATION

GDIS

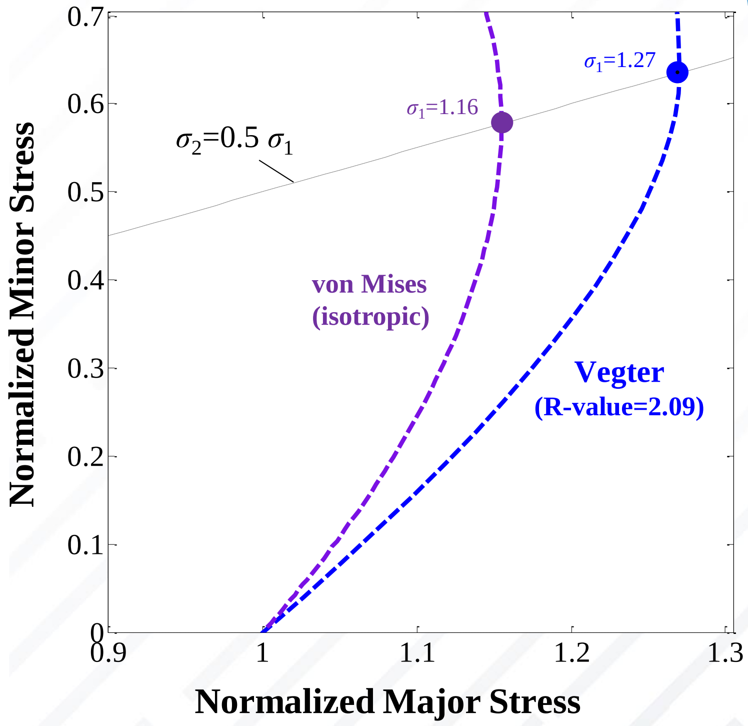
UW developed constrained inverse analysis to analyze plane strain notch tests

- Deviatoric plasticity is enforced with plane strain occurring
- Analysis only requires R-value, tensile data to uniform elongation, and to vary yield exponent
- *Developed correlation using R-value to predict plane strain yield strength*





Von Mises not accurate for DDQ



Fast-Irvine, J., Abedini, A., Butcher, C. (2021). Experimental Mechanics
Narayanan A, Bourque C, Fast-Irvine C, Abedini A, Butcher C, Anderson D, *Proceedings of the SAE World Congress*, 2022.

ANISOTROPIC YIELD SURFACE

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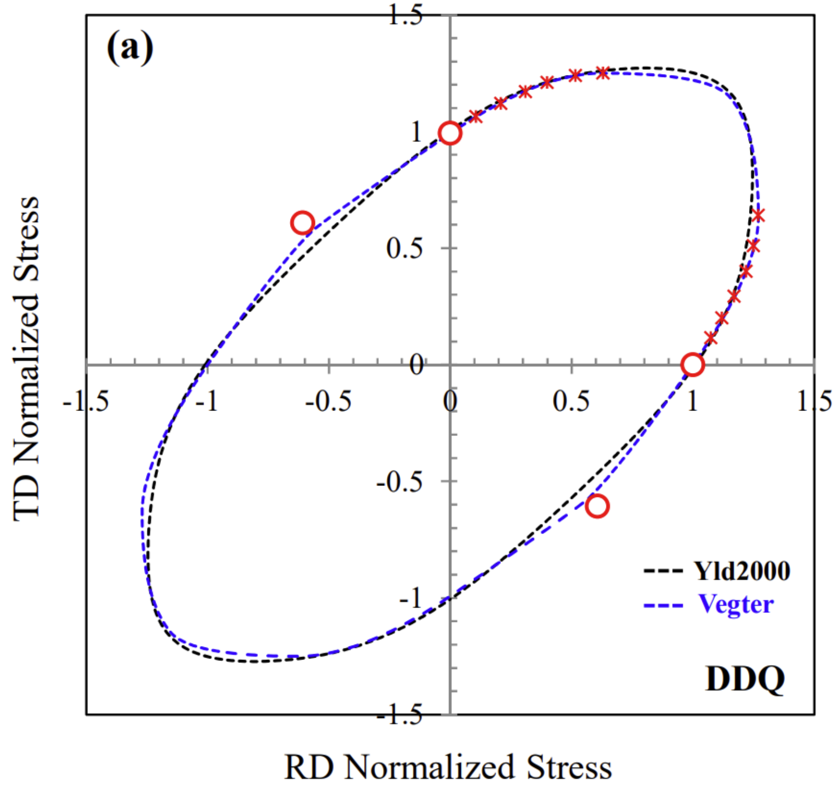
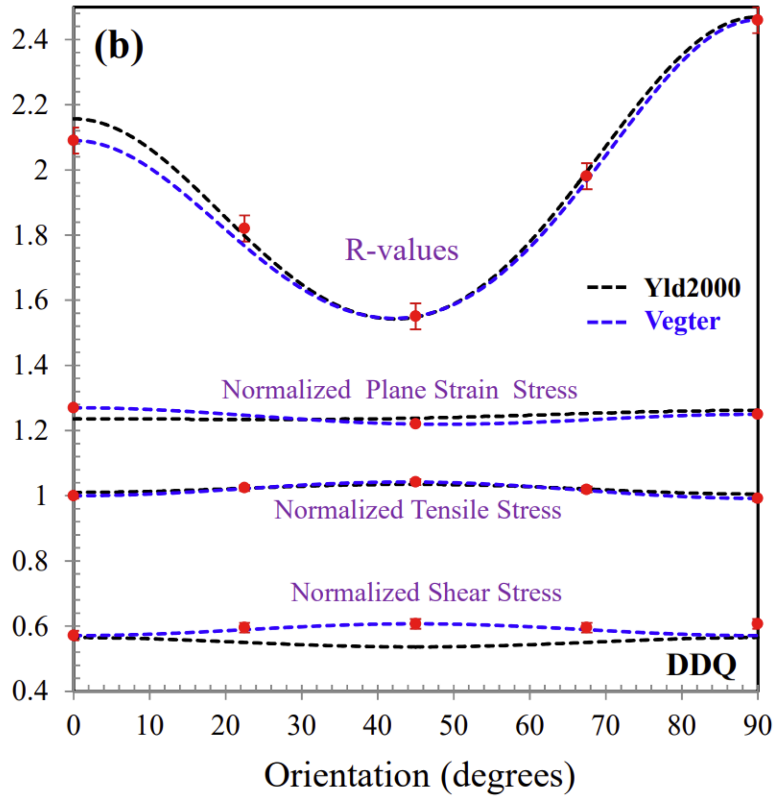
Calibration biased towards tensile-stress states as primary focus of fracture tests

- Interpolative Vegter yield function in LS-DYNA able to capture strong anisotropy of DDQ steel
- Barlat Yld2000 performed well, except in shear, and has closed form solution





Yld2000 Coefficients.
Vegter model is interpolative without coefficients

Coefficient	DP1180	DDQ
α_1	0.9684	1.0125
α_2	0.9864	1.0752
α_3	1.0303	0.7966
α_4	0.9855	0.8816
α_5	1.0066	0.9032
α_6	0.9582	0.8092
α_7	0.9943	0.9883
α_8	1.0158	1.0213
a	6.0	6.0

Abedini, A., Narayanan, A, Butcher C., 2022.. *Applied Mechanics 3,* , pp. 905-934.

HARDENING CHARACTERIZATION: TENSION TEST

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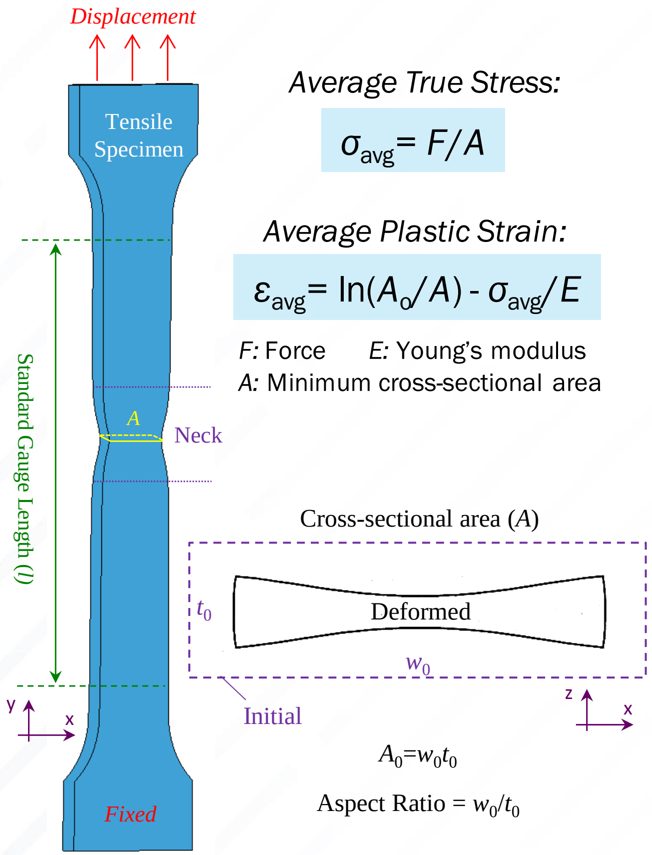
Developed Area Reduction Method (ARM): Use DIC to measure area of minimum cross-section

→ With correction factor, stress response accurately determined to large strains from single tensile test

→ No inverse FEA required!



Average True Stress:

$$\sigma_{avg} = F/A$$

Average Plastic Strain:

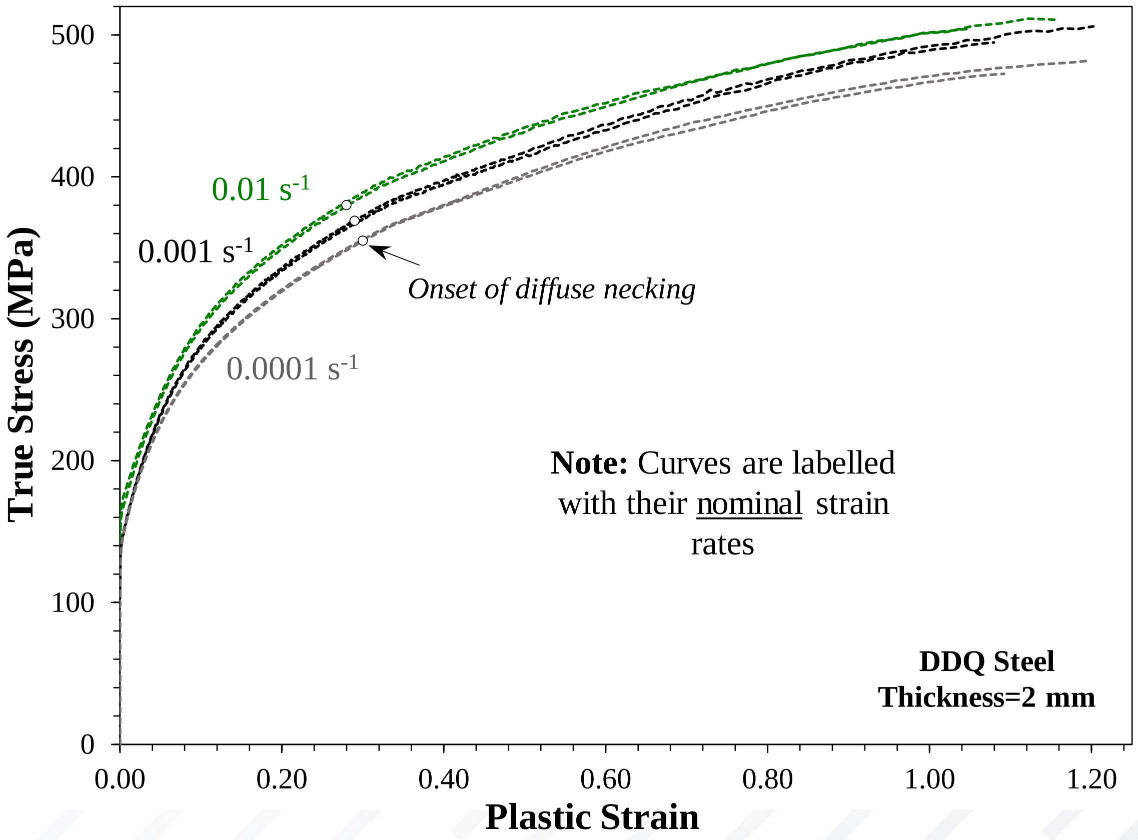
$$\varepsilon_{avg} = \ln(A_o/A) - \sigma_{avg}/E$$

F: Force *E:* Young's modulus
A: Minimum cross-sectional area

$$\sigma_{corrected} = \zeta\, \sigma_{avg}$$

$$\zeta = \begin{cases} 1 & \text{for } \varepsilon < 1.4n \\ \alpha\varepsilon^2 + \beta\varepsilon + \gamma & \text{for } \varepsilon > 1.4n \end{cases}$$

$\alpha = -0.0704n - 0.0275$
$\beta = 0.4550n - 0.2926$
$\gamma = 0.1592n + 1.024$



A. Abedini, et al. (2022), Forces in Mechanics 7

HARDENING CHARACTERIZATION: SIMPLE SHEAR

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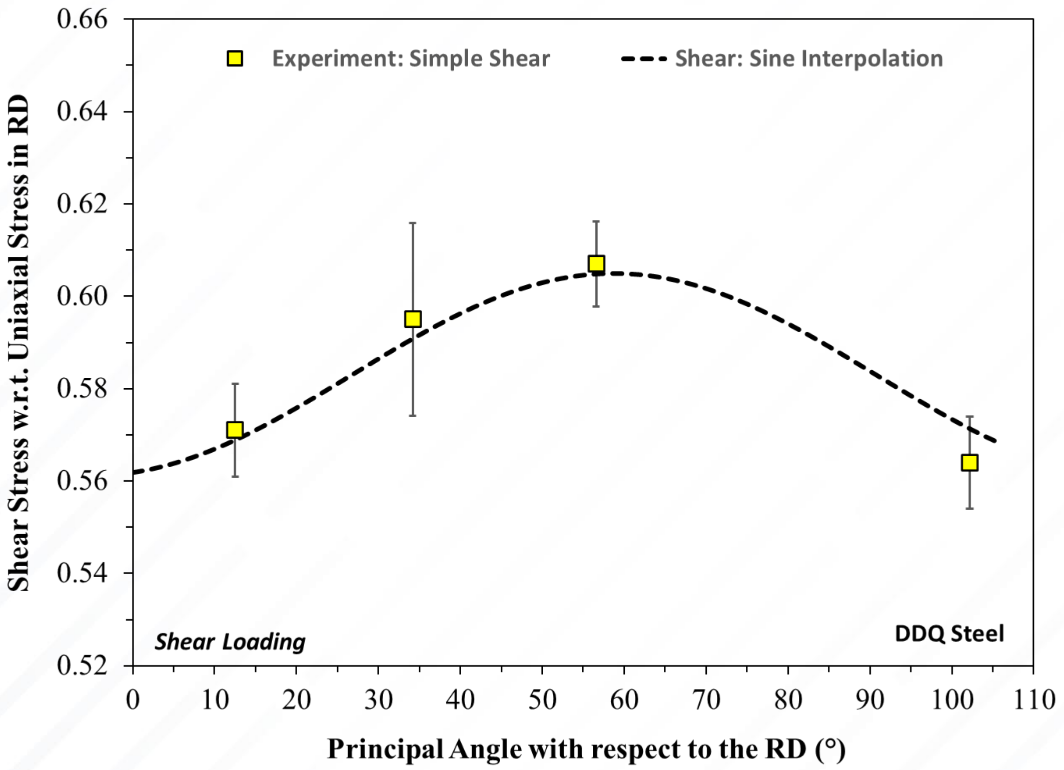
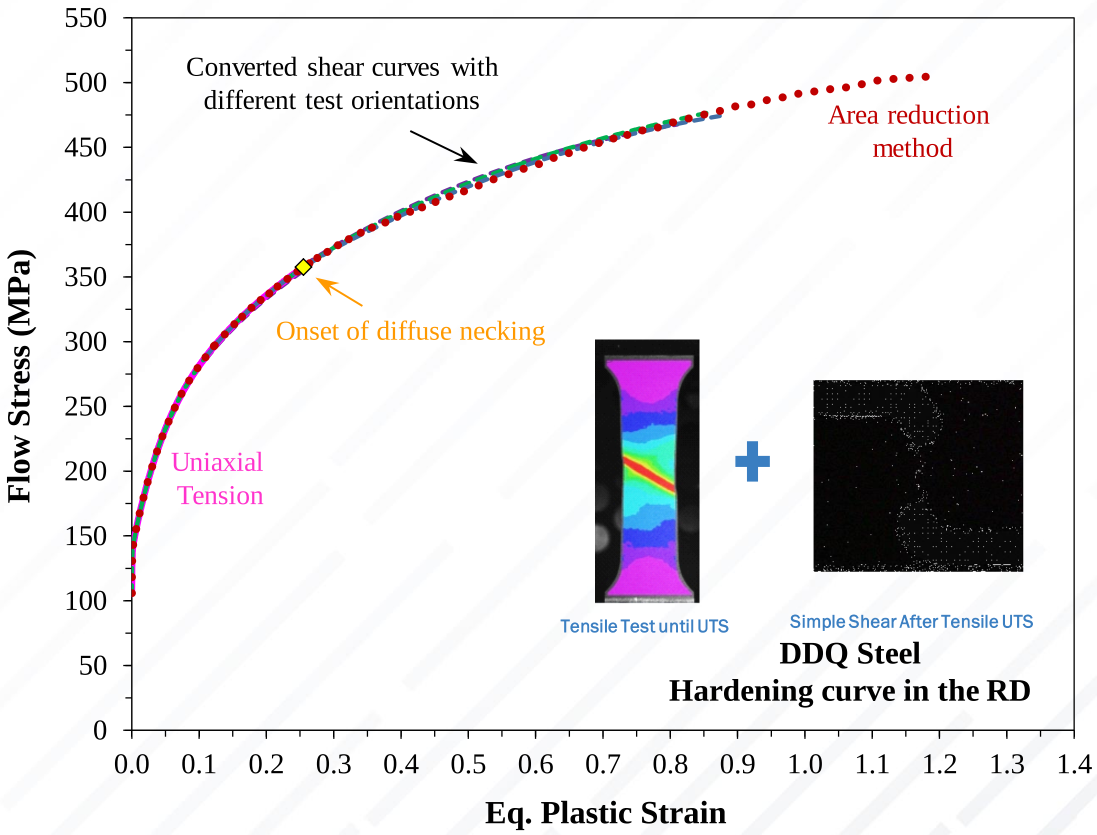
UW developed simple tensile + shear conversion methodology using plastic work equivalence

→ Shear anisotropy can be considered due to material frame rotation in shear test

→ No inverse FEA required and excellent agreement with tensile ARM





Abedini A, Noder J, Kohar C, Butcher C, *Mechanics of Materials*, 2020, 148:103419

HARDENING CHARACTERIZATION: TORSION

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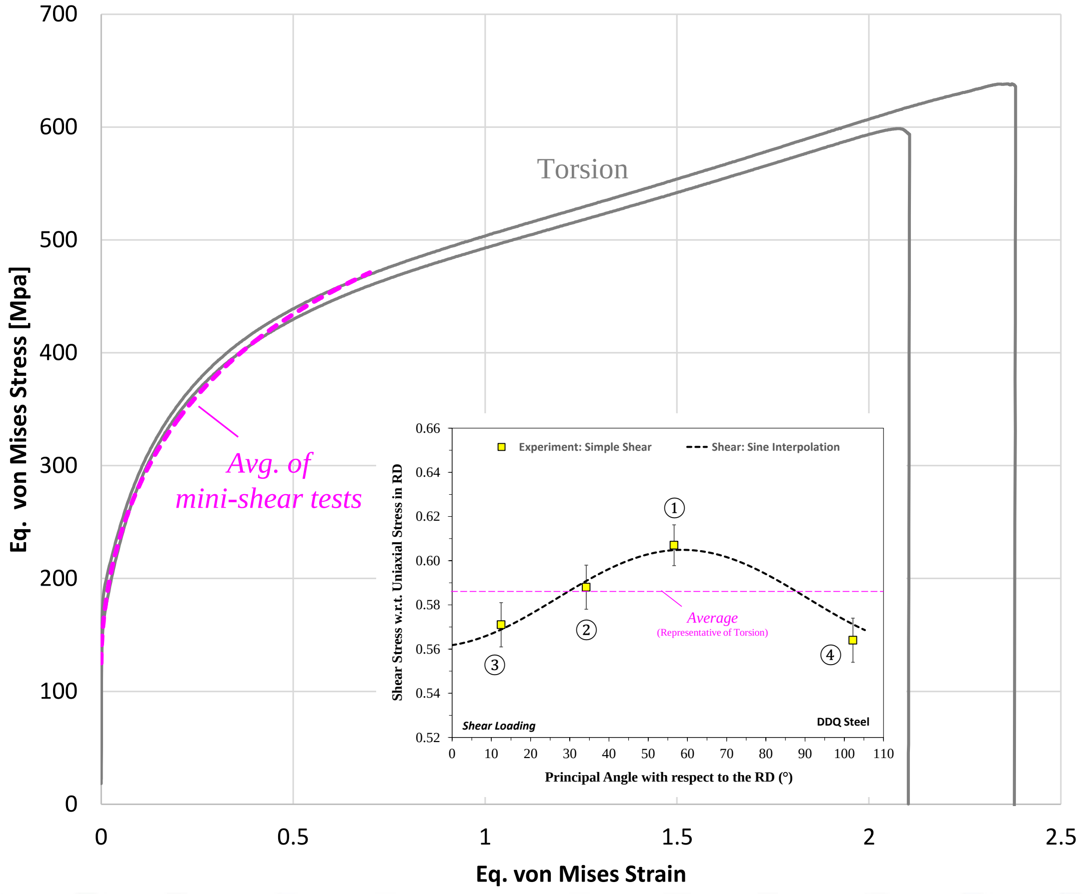
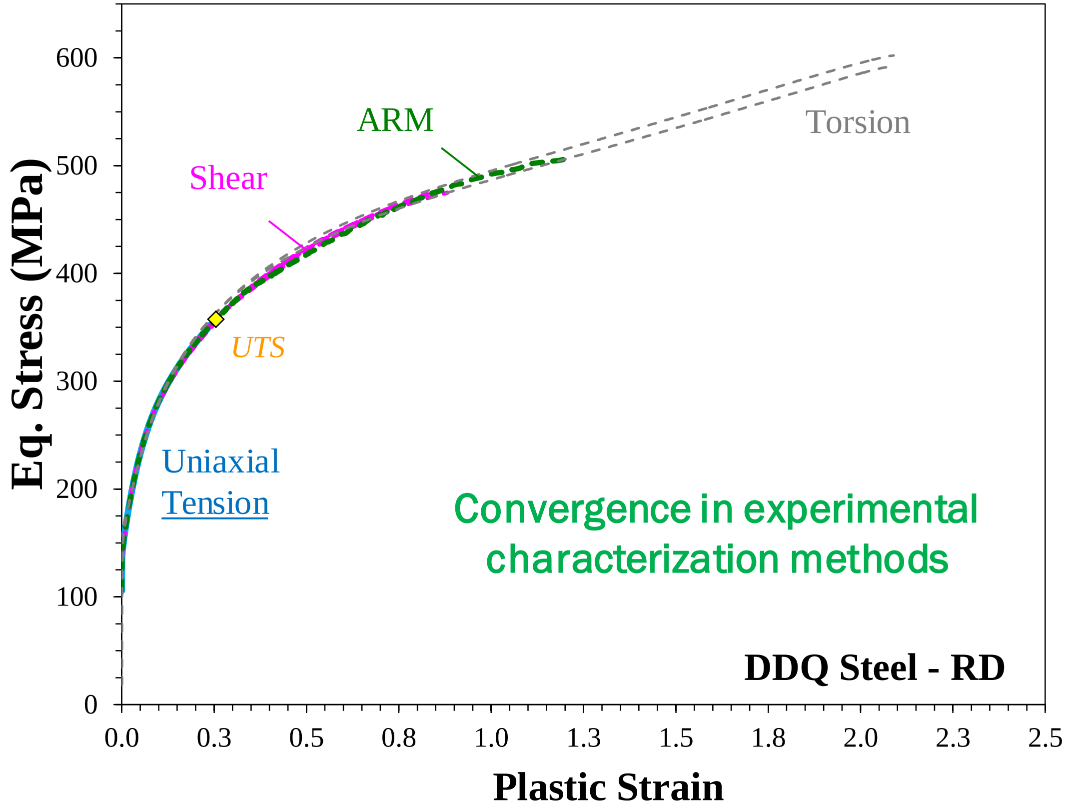
Profs. Mohr and Roth of ETH Zurich performed in-plane torsion tests of DDQ steel

→ In-plane torsion reaches very large strains: Characterizes average shear response

→ Convergence of three independent test methods. Avoid inverse FEA. Can measure hardening!





FORMABILITY CHARACTERIZATION FOR PRE-STRAINING

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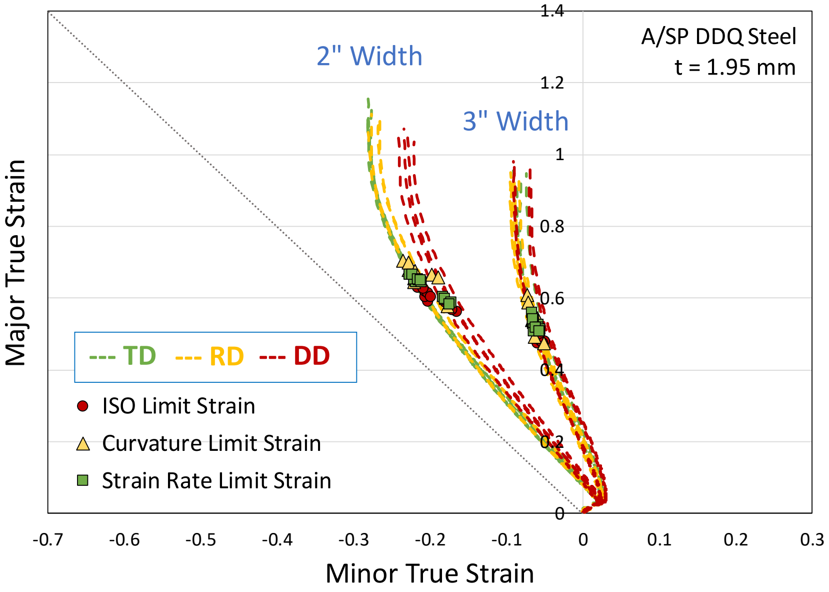
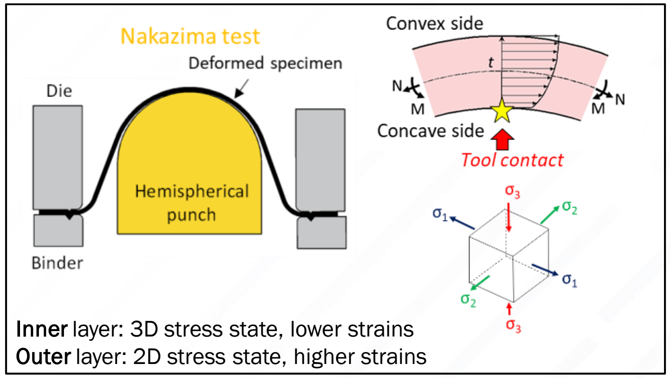
Forming limit curve (FLC) required to identify pre-straining limits for fracture tests

Nakazima tests performed as Marciniak tests were not successful: DDQ formability > mild steel carrier

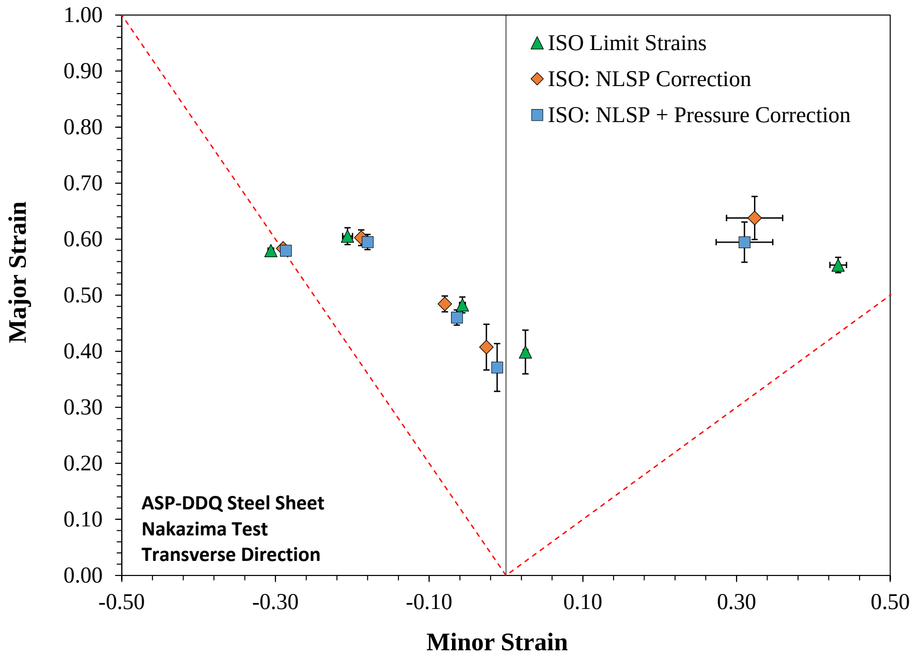
→ Process corrections applied to Nakazima to approximate in-plane FLC for Marciniak pre-straining



Negligible Anisotropy in Limit Strains



Nakazima Process Effects



Nakazima Limit Strains + Corrections

Min, J., Stoughton, T. B., Carsley, J. E., Lin, J. (2016). International Journal of Mechanical Sciences, 117, 115-134.
Butcher et al. (2021). Journal of Materials Processing Technology. 287, 1-18

FRACTURE IN SIMPLE SHEAR

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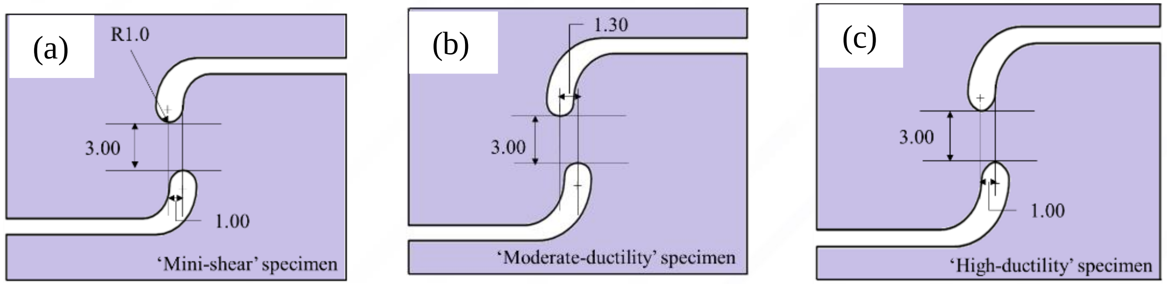
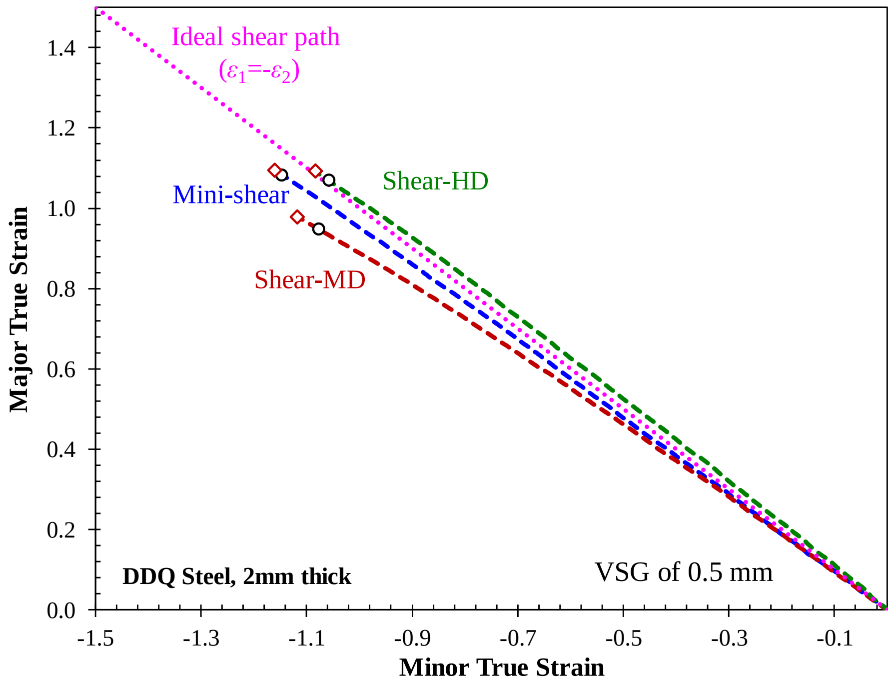
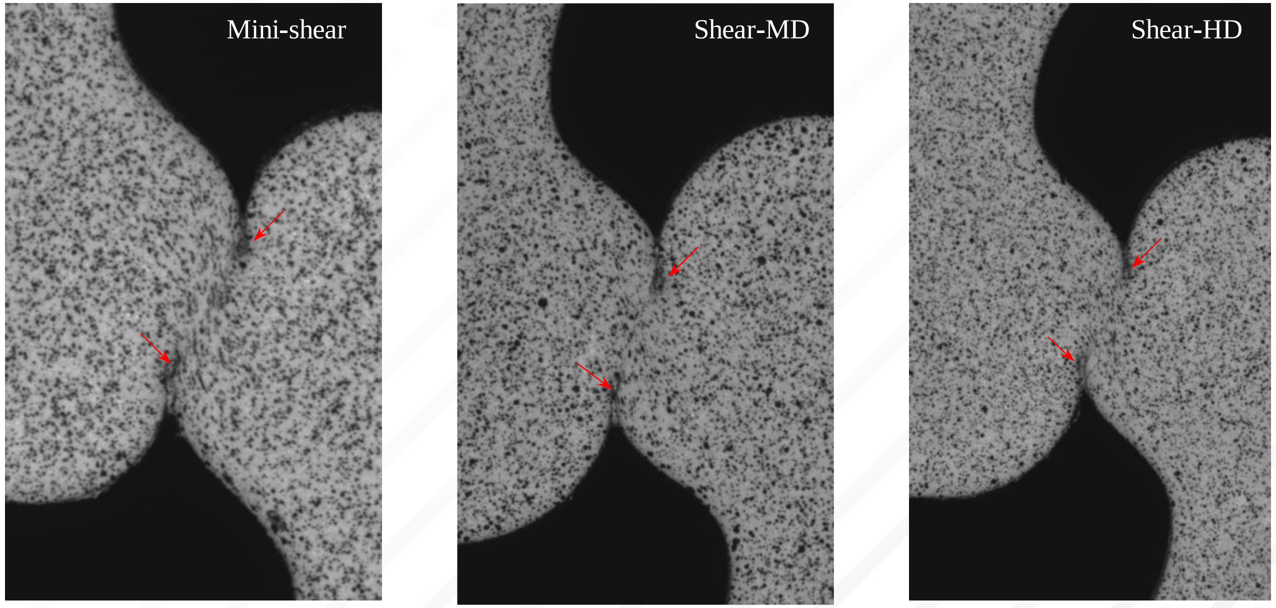
- Evaluated three in-plane shear geometries without through-thickness machining
- Premature edge fracture occurred in each geometry





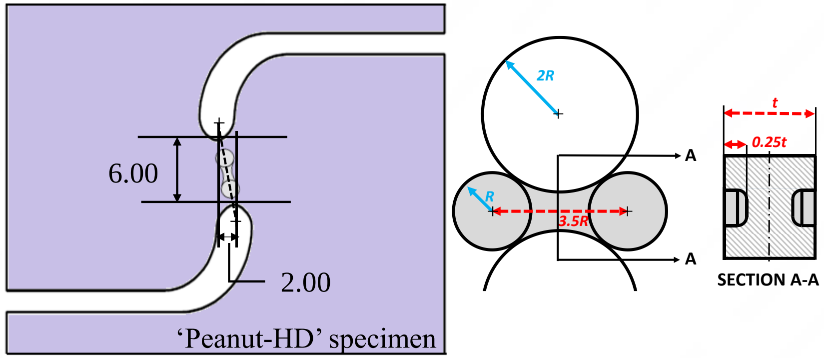
Peirs J, Verleysen P, Degriek, *Experimental Mechanics*, 2012, 52:729-741

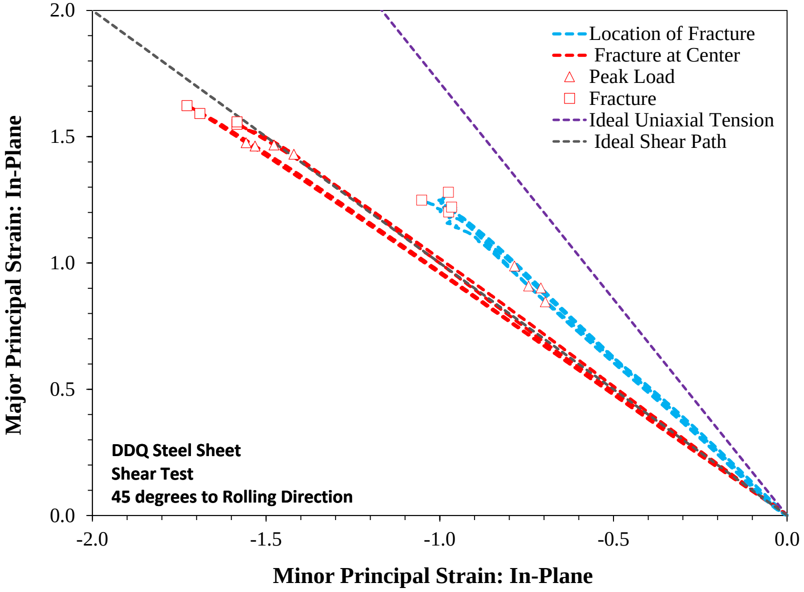


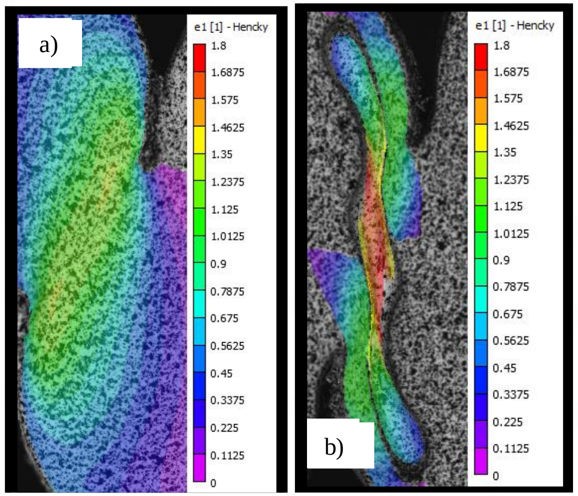
Roth C, Mohr D, *International Journal of Mechanical Sciences*, 2018, 129:224-240

NEW “PEANUT SHEAR” GEOMETRY

- Developed peanut-shaped groove to protect edge (Pilozo-Hibbit et al., SAE 2024)
- Fracture in combined tension and shear but reached over 100% larger strains

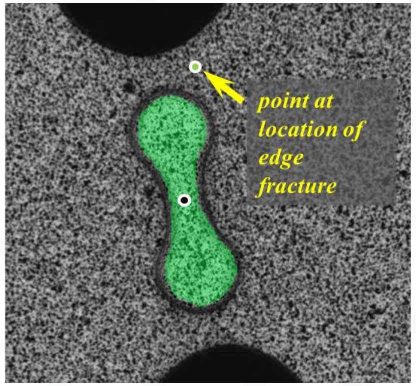


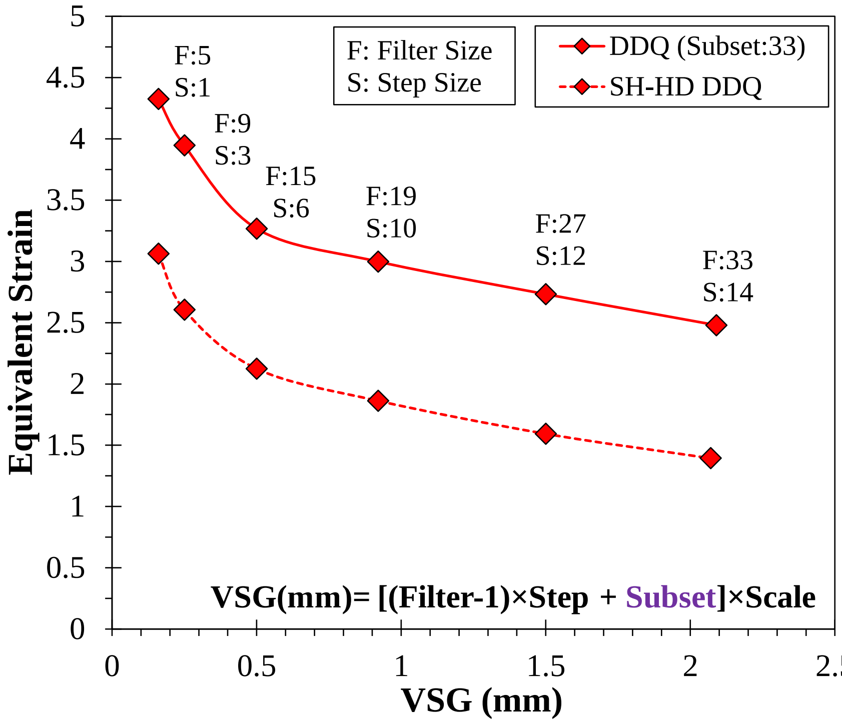




SH-HD – image at 5% load drop

Peanut-HD – image at 5% load drop





Serious DIC lengthcale effects!

UNIAXIAL FRACTURE

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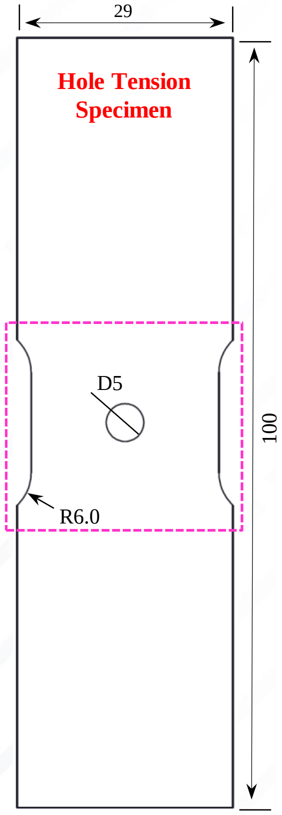
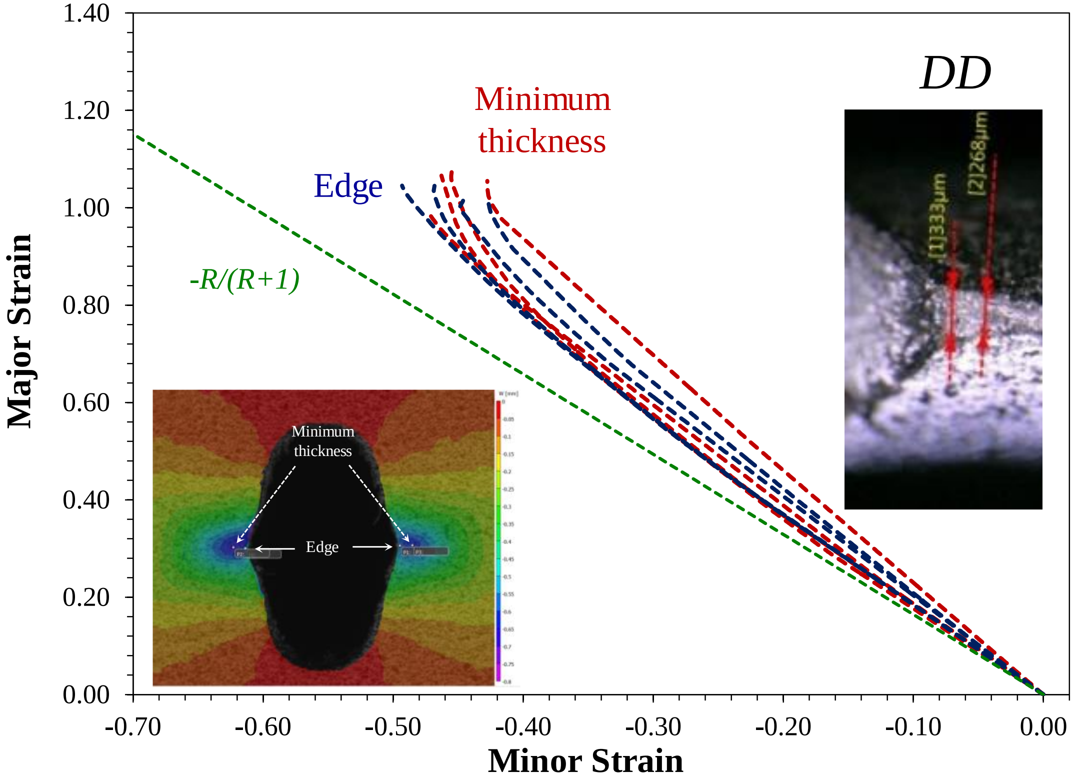
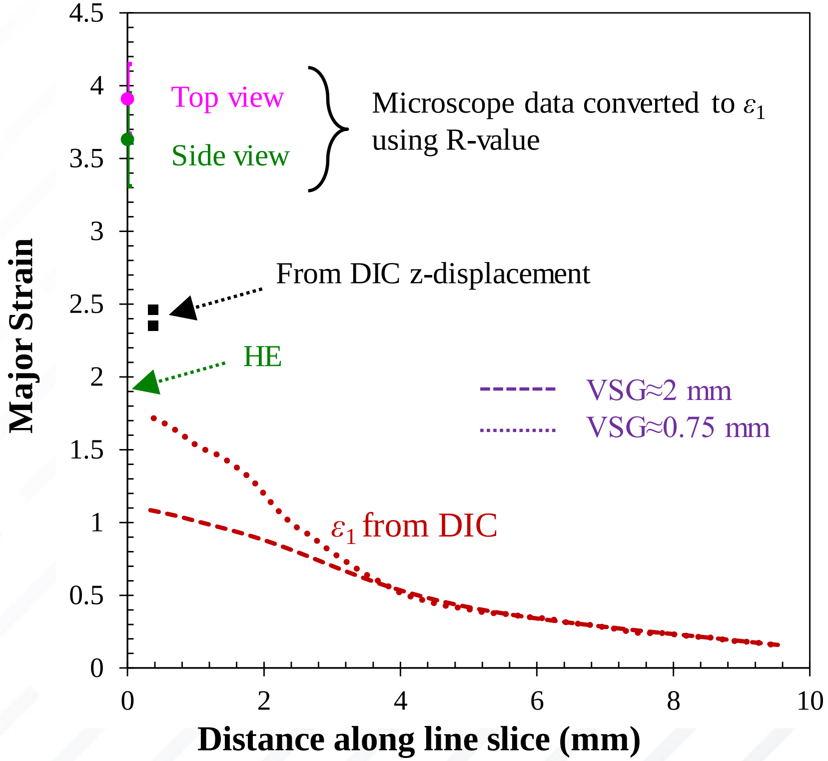
- Hole tension with machined edge used to characterize fracture anisotropy
- Fracture initiates behind edge at location of maximum thinning
- Strong DIC lengthscale effect, conical hole expansion was higher, rupture strain not reliable







PLANE STRAIN FRACTURE

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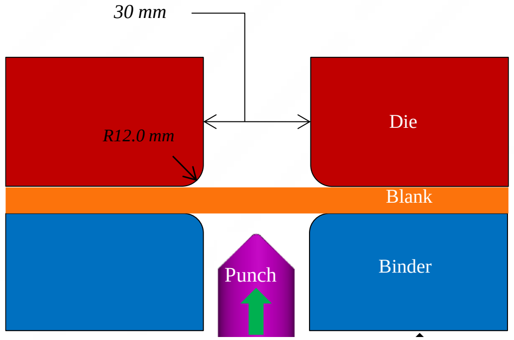
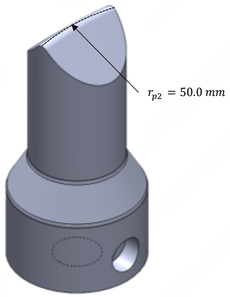
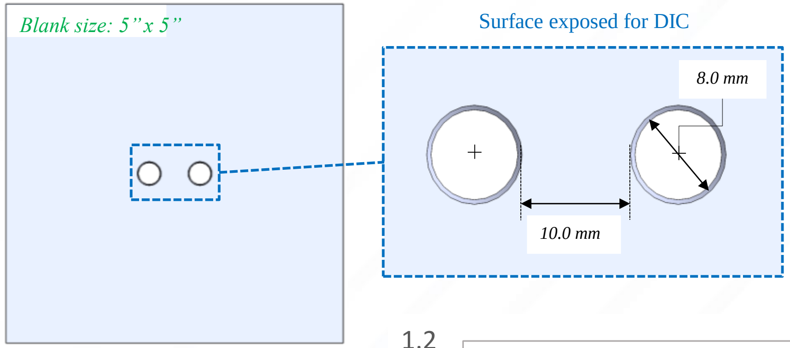
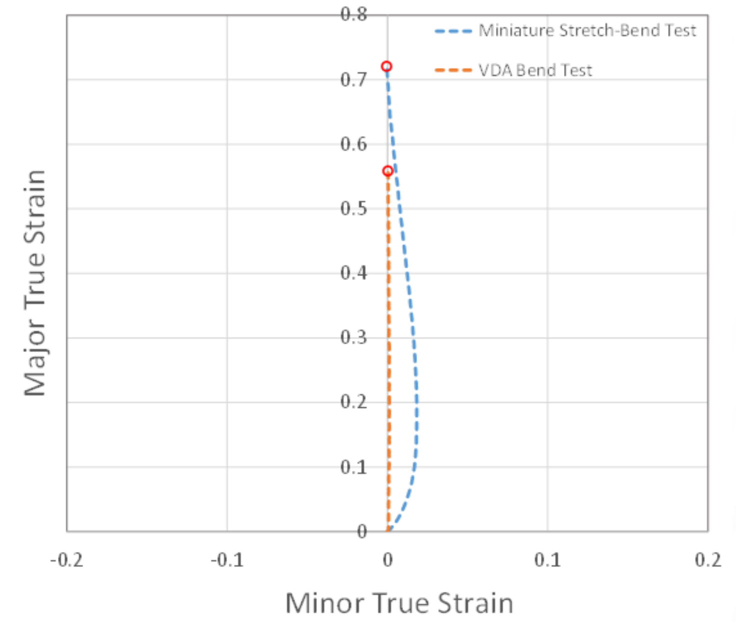
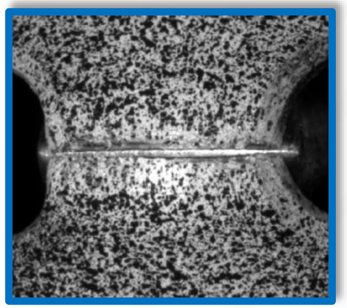
- Use dihedral punch test (mini-stretch bend) from ETH Zurich (Grolleau et al., 2019)
- Fracture without necking achieved in near linear strain path like v-bend test

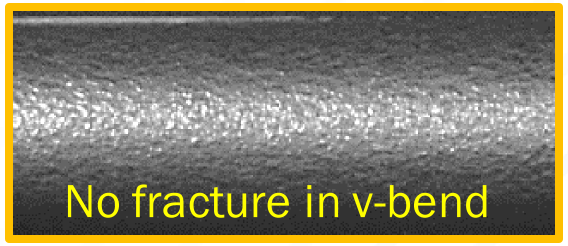


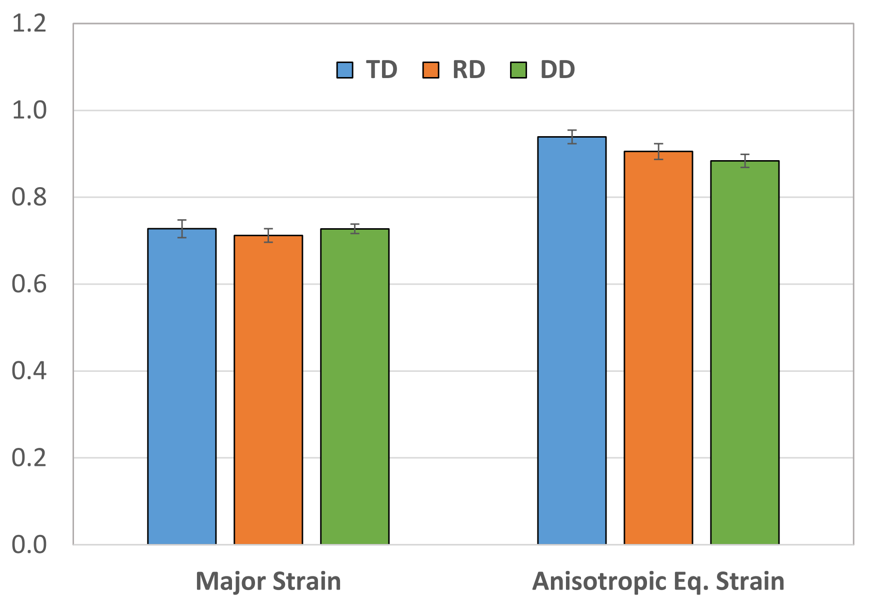












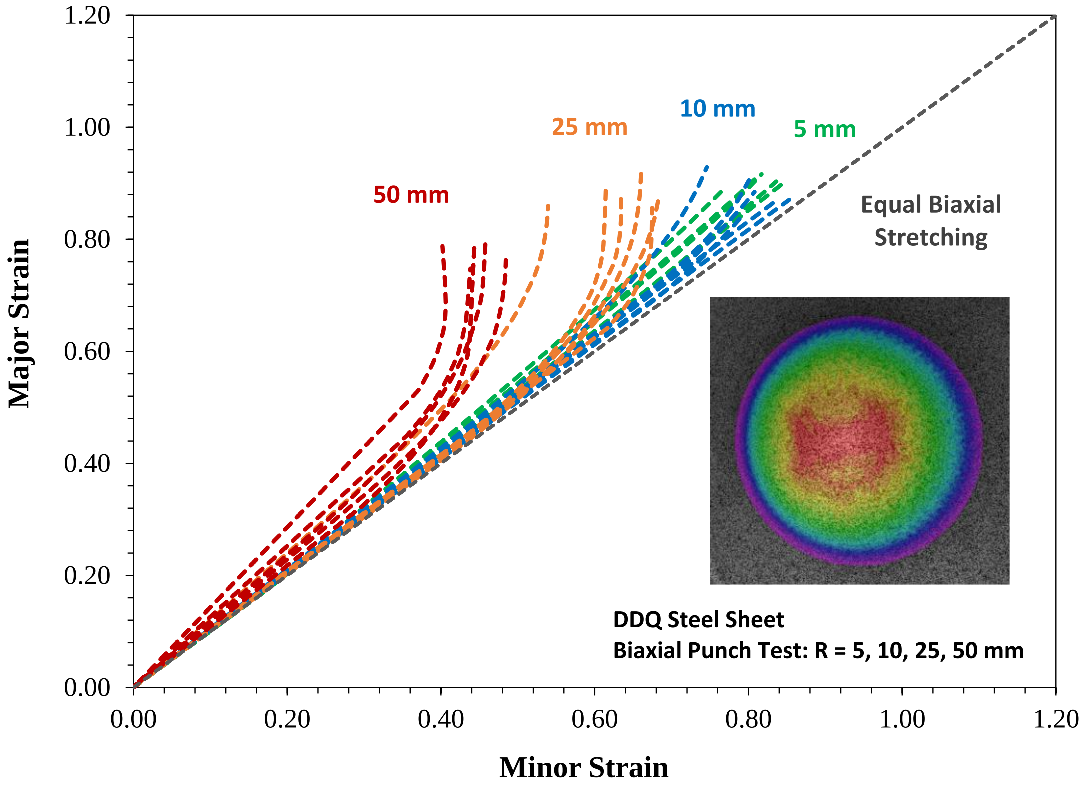
Negligible fracture anisotropy

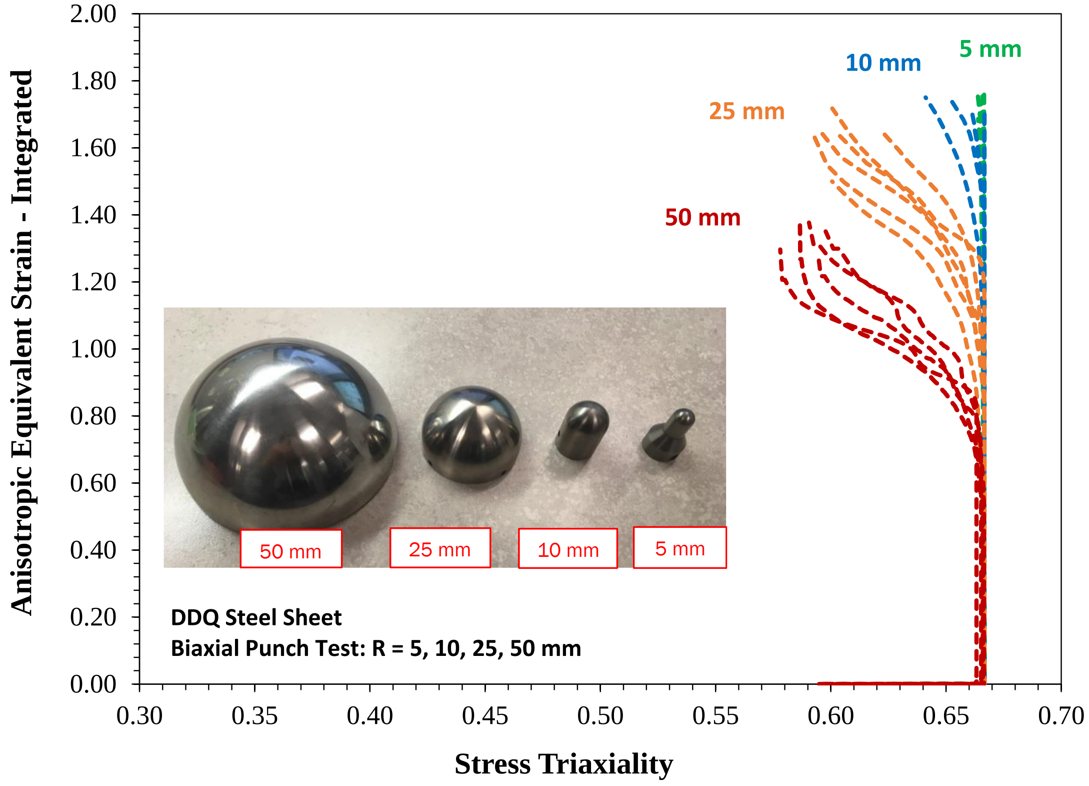
Grolleau, V., Roth, C.C., Lafilé, V., Galpin, B. and Mohr, D., 2019.. *Int. J. Mech. Sci.*, *152*, pp.329-345.

BIAXIAL FRACTURE

GDIS

- Smaller radius punches increase biaxial bending and suppress necking prior to fracture
- Best results with 5 mm radius punch for DDQ, similar results for DP980, DP1180 & GEN3





PROPORTIONAL FRACTURE LOCUS

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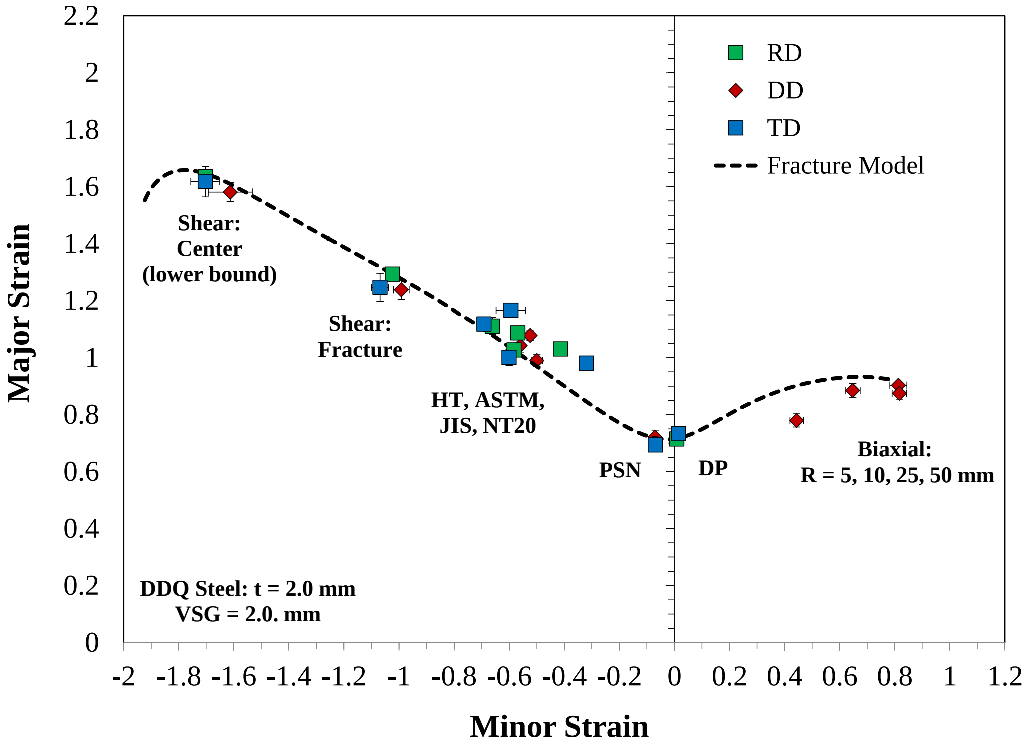
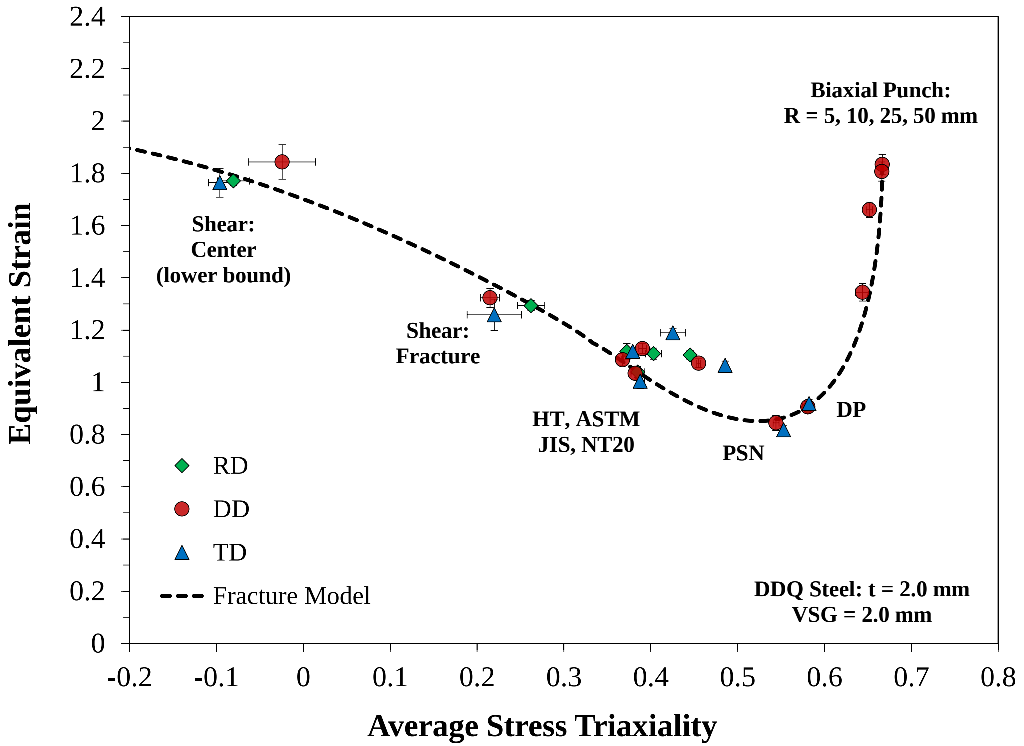
Proportional fracture model calibrated with: Peanut shear, Dihedral punch, Hole tension, Mini-punch

<u>*DIC used virtual strain gage (VSG) with VSG = 2.0 mm equal to sheet thickness*</u>

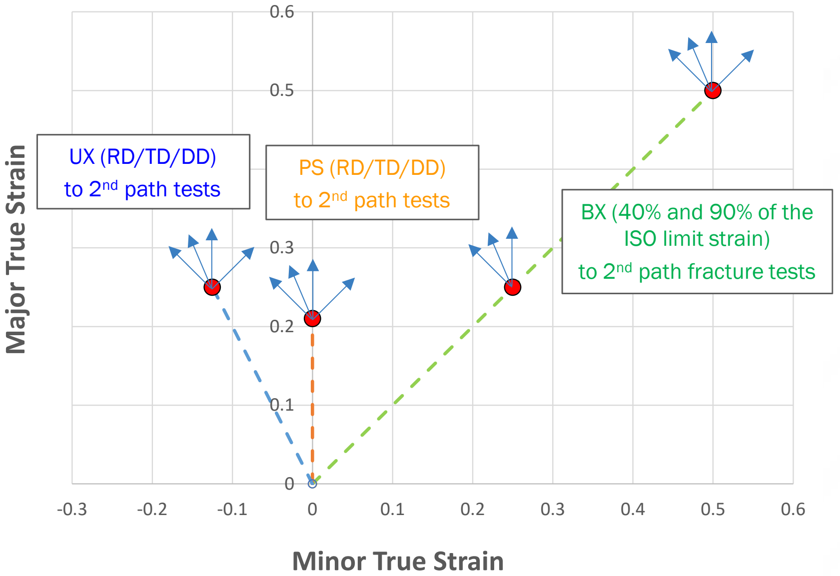
Stress-based fracture model, Generalized Drucker Prager (GDP) model

No meaningful fracture anisotropy in DDQ steel. Now apply to anisotropic strain paths to evaluate





OVERVIEW OF ANISOTROPIC NON-LINEAR STRAIN PATHS



Pre-Strain levels: Thinning from 20 to 100%

Pre-Straining

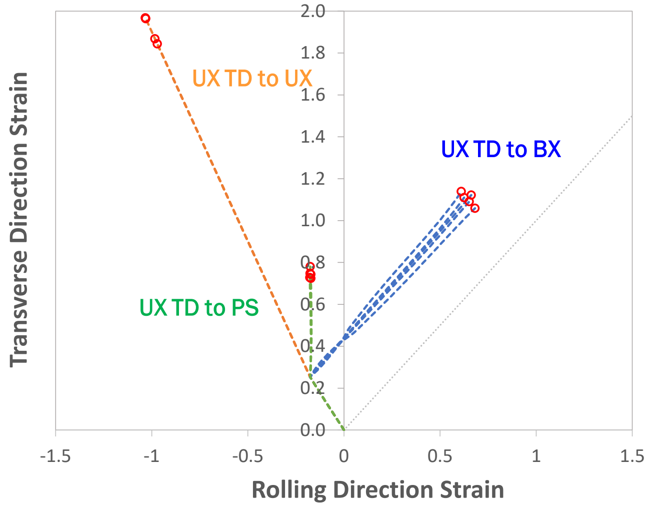
UX (RD/TD/DD)
PS (RD/TD/DD)
BX (40/90)

Secondary Tests

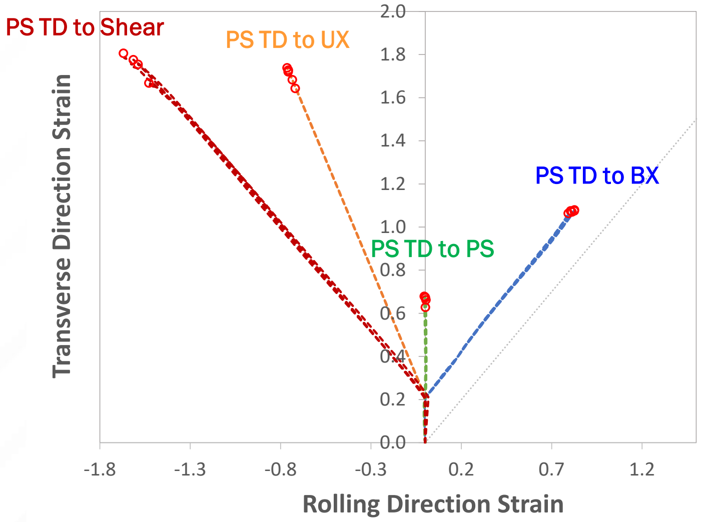
Mini Hole Tension
Dihedral Punch Test
Mini Punch Test
Peanut-Shear

Pre-straining Condition	Target Strain		
	e1	e2	e3
BX40	0.25	0.25	-0.5
BX90	0.5	0.5	-1
PS	0.21	0	-0.21
UX	0.25	-0.125	-0.125

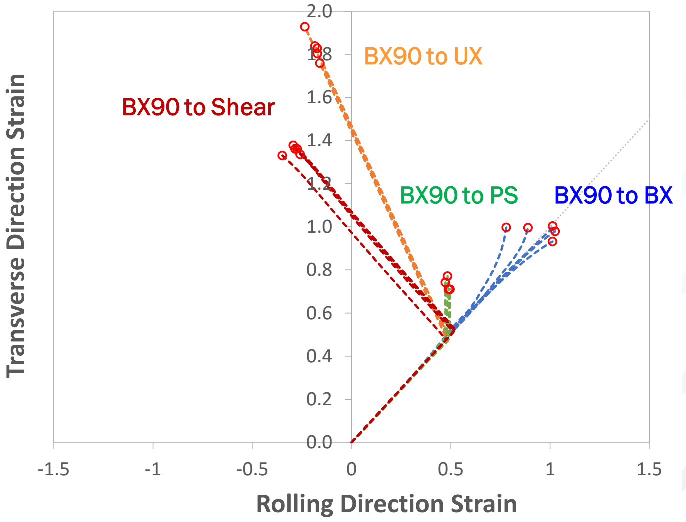
UX TD Pre-Straining Cases



PS TD Pre-Straining Cases



BX90 Pre-Straining Cases



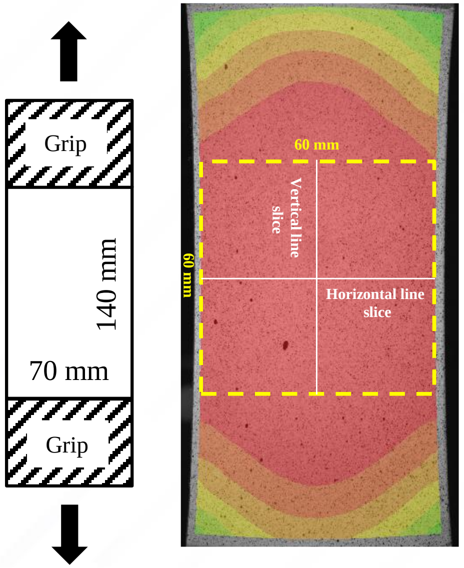
NLSP TESTING: IN-PLANE PRE-STRAIN

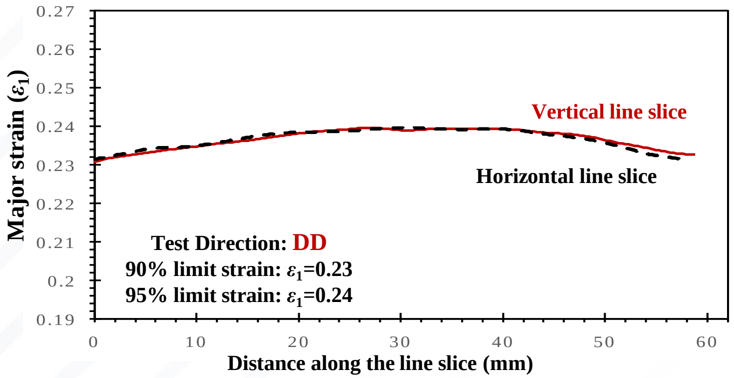
GDIS

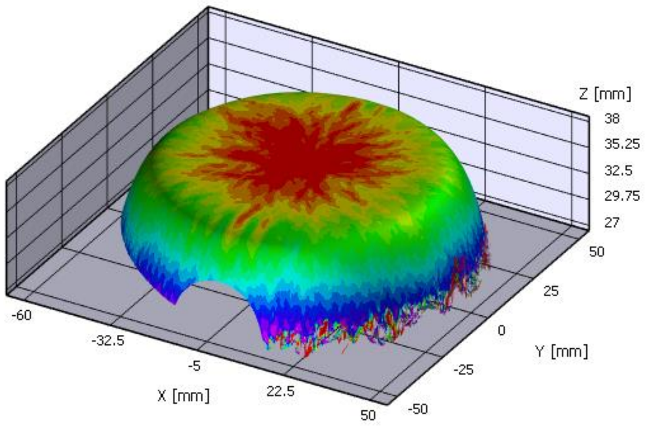
Uniaxial Pre-Straining: Oversized rectangular samples (strain variation < 1%)

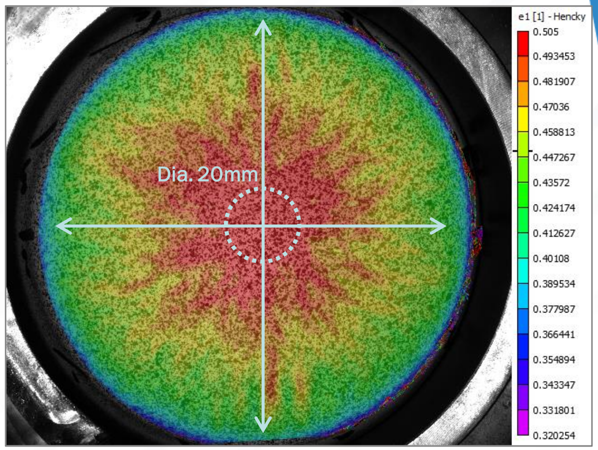
Plane Strain & Biaxial Pre-Straining: Marciniak tests (strain variation of 2% or less)

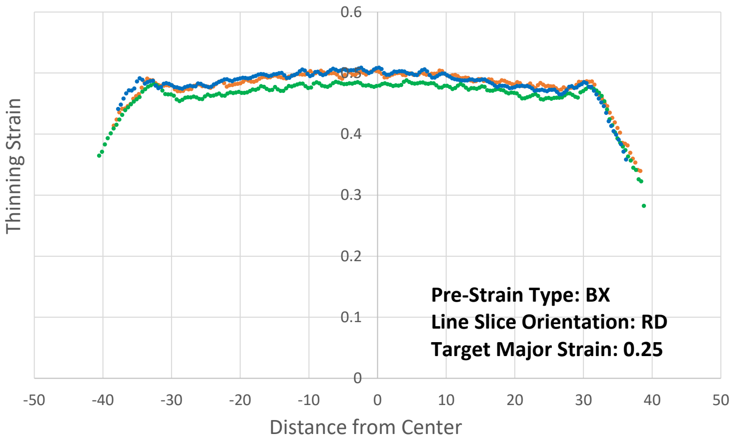
Local DIC strain history tracked for mapping to secondary fracture tests

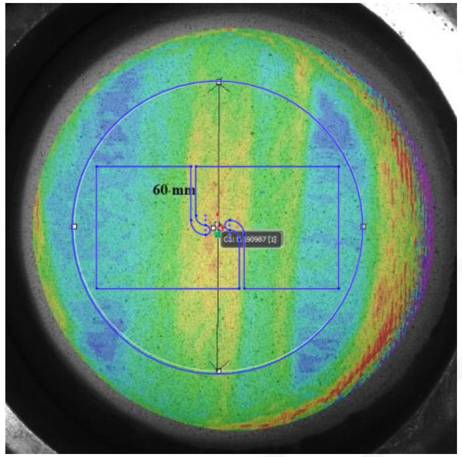












Demonstration of shear gage region centered on Marciniak test of DP1180

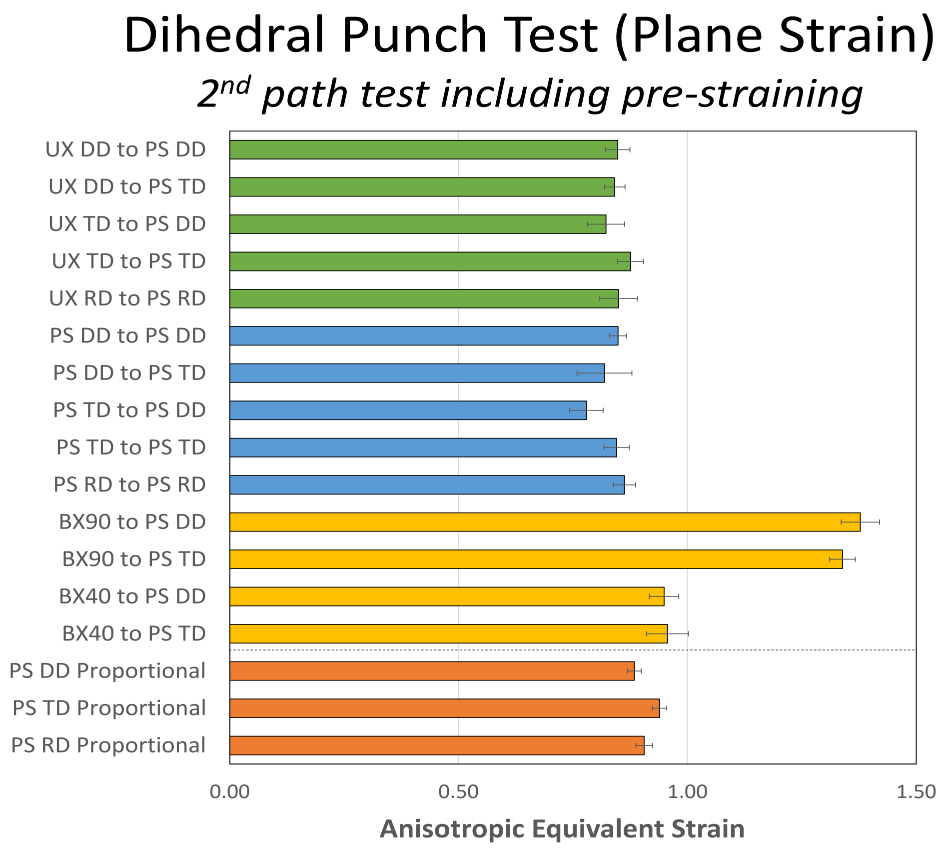
FRACTURE IN ANISOTROPIC NLSP: PLANE STRAIN & BIAXIAL

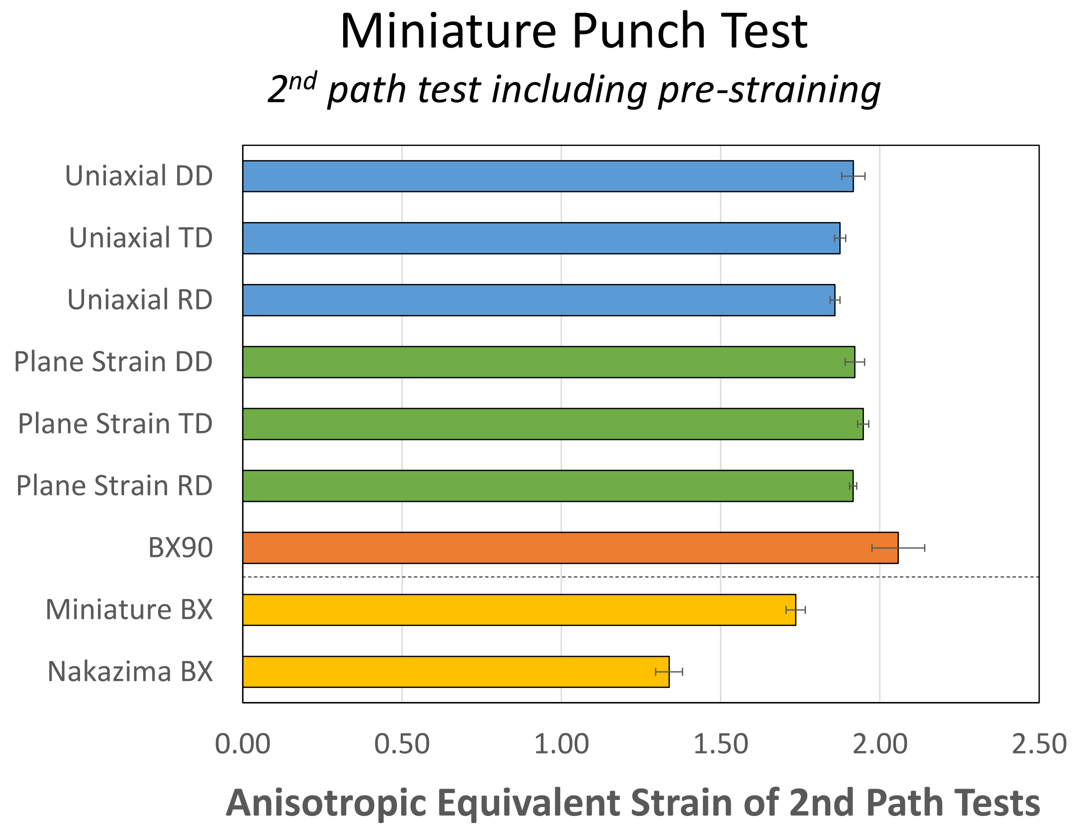
GDIS

No significant anisotropy in fracture strains of DDQ in NLSP

Plane strain largely unaffected by NLSP except in severe biaxial pre-strain BX90 case

Biaxial tests had similar increase in cumulative fracture limits with pre-strain

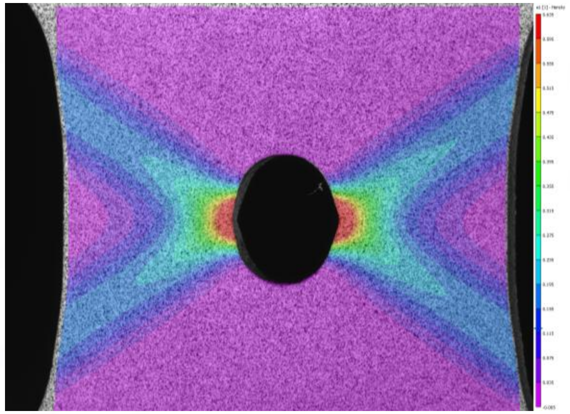


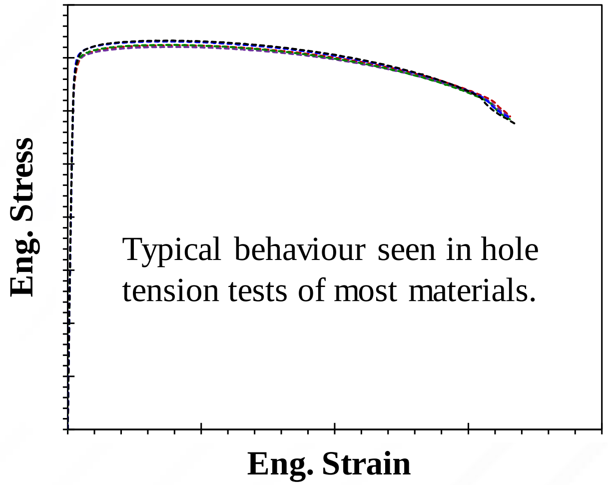


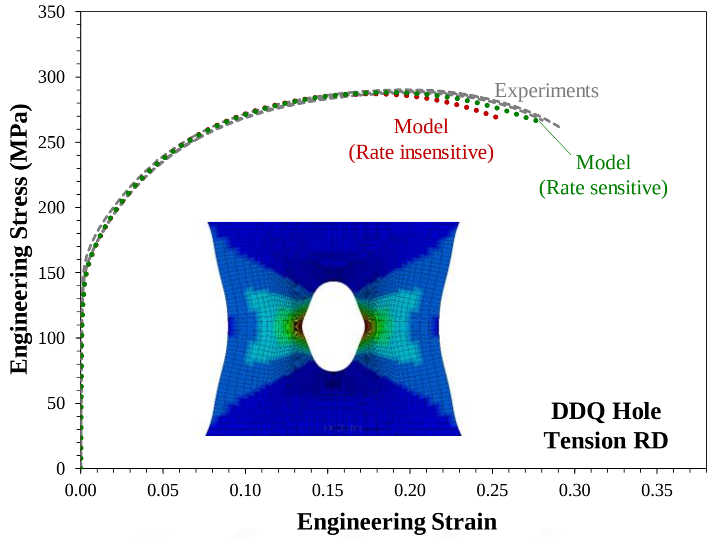
UNIAXIAL FRACTURE IN ANISOTROPIC NLSP

Complex localization in anisotropic strain paths → integrate DIC strains instead of using inverse FEA

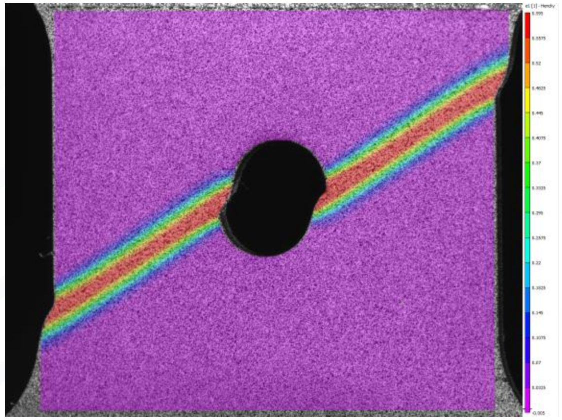
Hole Tension: Proportional Loading

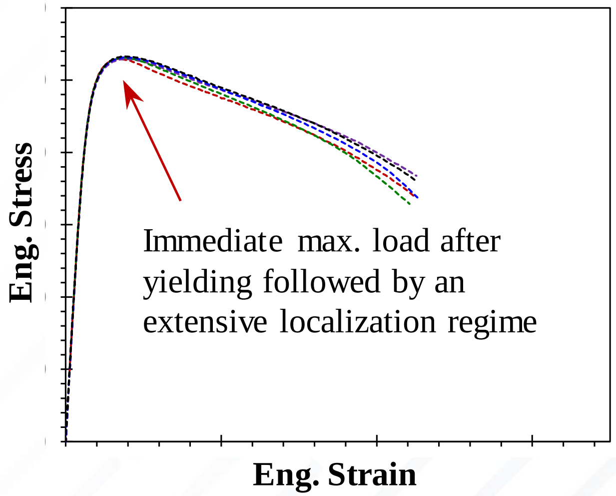


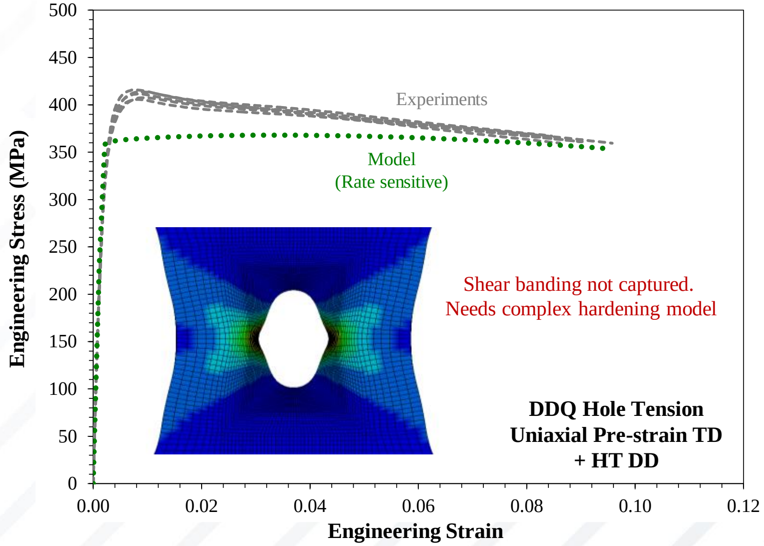




Hole Tension: Anisotropic Pre-Strain







FRACTURE CHARACTERIZATION & PREDICTION IN NLSP

GDIS

Large data set: Over 200 tests with strain history integrated in over 33 NLSP cases

For evaluation of multiple damage models, need high level metrics to assess.

Data structure for fracture model evaluation:

a) **Classify *by second-stage path***

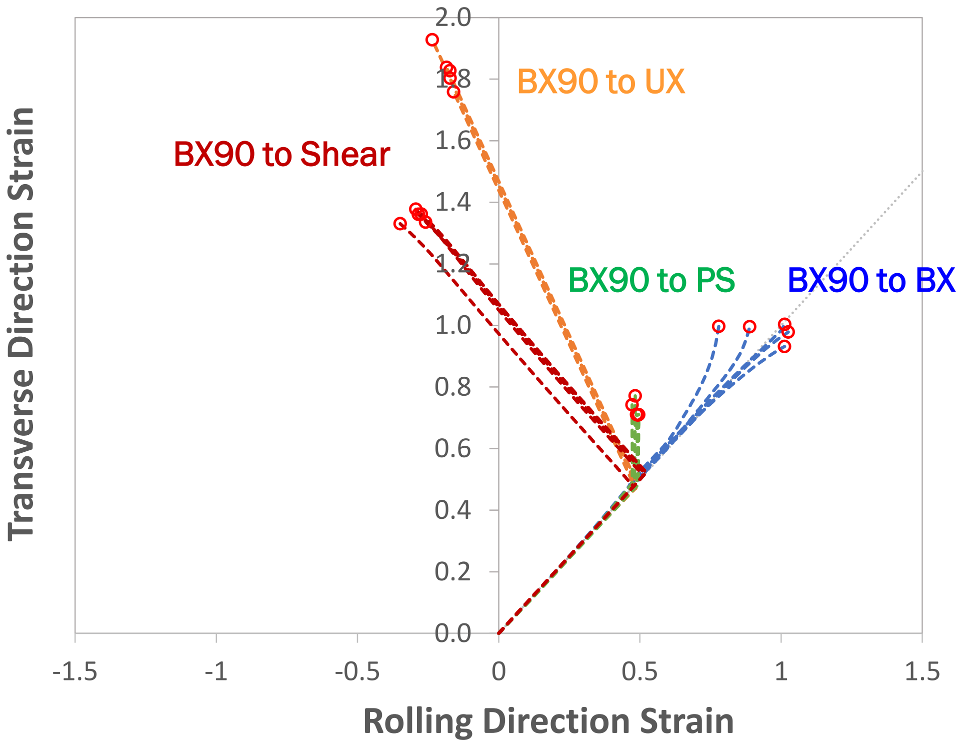
→ shear, plane strain, uniaxial and biaxial tension

b) Reporting metric based on eq. strain at fracture:

$$D = \frac{\varepsilon^{f}_{eq-\text{Predicted}}}{\varepsilon^{f}_{eq-\text{Test}}} \qquad D = 1 \quad \text{Perfect correlation}$$

c) **Secondary Paths ranked by experimental confidence**

Plane Strain > Biaxial > Shear > Uniaxial Tension



Ex: NLSP of DDQ for Biaxial Pre-strain

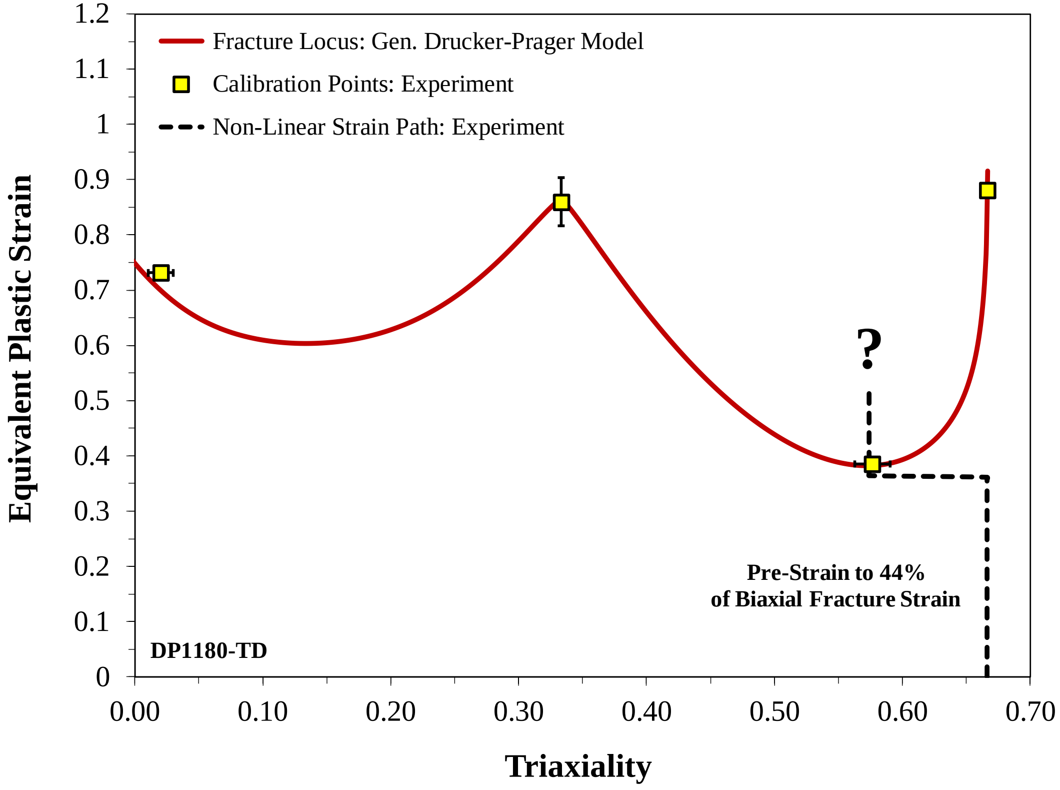
DAMAGE ACCUMULATION AND FRACTURE MODELS:

APPLYING PROPORTIONAL FRACTURE DATA TO NON-LINEAR STRAIN PATHS

GDIS

All models are equally valid in proportional loading… but what happens in non-proportional loading?

Equivalent strain representations employ phenomenological damage models (no physical foundation)



Linear damage (Johnson & Cook, 1983) commonly used

$$D = \int \frac{d\varepsilon_{eq}}{\varepsilon_f(T,L)} \qquad Fracture:\ D = 1$$

Power Law Damage (Xue, 2007)

$$\frac{\Delta D}{\Delta \varepsilon_{eq}^p} = \frac{n_D}{\varepsilon_f(T,L)} \boxed{\left(\frac{\varepsilon_{eq}^p}{\varepsilon_f(T,L)}\right)^{n_D(1-1/n_D)}} \qquad D^{prop.} = \left(\frac{\varepsilon_{eq}^p}{\varepsilon_f(T,L)}\right)^{n_D}$$

GISSMO: Based on Power Law but implemented differently

$$\frac{\Delta D^{GISSMO}}{\Delta \varepsilon_{eq}^p} = \frac{n_D}{\varepsilon_f(T,L)} \boxed{D}^{(1-1/n_D)}$$

$D_{initial} \neq 0,$

LS-DYNA uses $D_{initial} = 1.0e^{-20}$

Neukamm, F., Feucht, M., Haufe, A. Consistent damage modelling in the process chain of forming to crashworthiness simulations. LS-DYNA Anwenderforum, Bamberg 2008

Xue, L., (2007). International Journal of Solids and Structures 44,

GISSMO DAMAGE MODEL EVALUATION

GDIS

GISSMO Damage Accumulation: $D = \int \frac{n_D}{\varepsilon_f(T)} D^{(1-1/n_D)} d\varepsilon_{eq}^p$ Assume Damage exponent : $n_D = 1, 2$

Advantages: *Widely used and* available in LS-DYNA, Linear form = Johnson-Cook model
Eq. Strain based (relatively convenient)

Disadvantages: *No physical foundation* – user assumes damage exponent;
Damage accumulation unrelated to hardening ability

Damage Model		**GISSMO Damage Model**							
Damage Metric & Parameters		**Eq. Strain** *Damage Exponent = 1*		**Eq. Strain** *Damage Exponent = 1.5*		**Eq. Strain** *Damage Exponent = 2*		**Eq. Strain** *Damage Exponent = 3*	
Fracture Metric: $\varepsilon_f^{\text{model}} / \varepsilon_f^{\text{exp}}$		**Average**	**Std. Dev**	**Average**	**Std. Dev**	**Average**	**Std. Dev**	**Average**	**Std. Dev**
Secondary Path	**Plane Strain Tension**	1.12	± 0.09	1.13	± 0.09	1.14	± 0.09	1.15	± 0.09
	Biaxial Stretching	0.80	± 0.08	0.82	± 0.08	0.82	± 0.08	0.83	± 0.08
	Shear	0.93	± 0.05	0.94	± 0.05	0.95	± 0.05	0.96	± 0.05
	Uniaxial Tension	0.92	± 0.05	0.93	± 0.05	0.94	± 0.05	0.95	± 0.05

Observations: *GISSMO damage overestimates ductility when second stage has lower fracture strain*
GISSMO was very conservative in second stage path of biaxial
No clear choice for damage exponent, conventional linear and quadratic forms comparable

POWER LAW DAMAGE MODEL EVALUATION

GDIS

Power Law Damage Accumulation: $D = \int \frac{n_D}{\varepsilon_f(T)} \left(\frac{\varepsilon_{eq}^p}{\varepsilon_f(T)} \right)^{n_D - 1} d\varepsilon_{eq}^p$ Assume Damage exponent : $n_D = 1, 1.5, 2$

Advantages: Appears to be consistent version of damage model GISSMO was based upon

Equivalent to GISSMO and Johnson-Cook for Linear Damage

Disadvantages: Same as GISSMO - No physical foundation – user assumes damage exponent

Damage accumulation unrelated to hardening ability

Damage Model		Xue Power Law Damage Model							
Damage Metric & Parameters		Eq. Strain *Damage Exponent = 1*		Eq. Strain *Damage Exponent = 1.5*		Eq. Strain *Damage Exponent = 2*		Eq. Strain *Damage Exponent = 3*	
Fracture Metric: $\varepsilon_f^{\text{model}} / \varepsilon_f^{\text{exp}}$		Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
Secondary Path	Plane Strain Tension	1.12	± 0.09	1.07	± 0.07	1.04	± 0.08	1.01	± 0.10
	Biaxial Stretching	0.80	± 0.08	0.85	± 0.05	0.87	± 0.04	0.89	± 0.04
	Shear	0.93	± 0.05	0.94	± 0.05	0.94	± 0.05	0.94	± 0.06
	Uniaxial Tension	0.92	± 0.05	0.90	± 0.03	0.88	± 0.04	0.86	± 0.06

Observations:

Power Law Damage was an improvement over GISSMO with exponent 1.5, same result as for DP1180

Overall, same trends as GISSMO. Not as large of an improvement for DDQ

COMPARISON OF DDQ AND DP1180 STEELS

GDIS

DP1180: Presented at GDIS 2023

Damage Model		GISSMO				Power Law Damage			
Damage Metric & Parameters		Eq. Strain *Damage Exponent = 1*		Eq. Strain *Damage Exponent = 2*		Eq. Strain *Damage Exponent = 1.5*		Eq. Strain *Damage Exponent = 2*	
Fracture Metric: $\varepsilon_f^{model} / \varepsilon_f^{exp}$		Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
Secondary Path	Plane Strain Tension (12 Paths)	1.05	± 0.08	1.09	± 0.08	0.99	± 0.05	0.96	± 0.05
	Biaxial Stretching (9 Paths)	0.91	± 0.02	0.95	± 0.02	0.95	± 0.02	0.96	± 0.03
	Shear (12 Paths)	0.94	± 0.08	0.97	± 0.08	0.94	± 0.09	0.94	± 0.09
	Uniaxial Tension (12 Paths)	0.90	± 0.06	0.93	± 0.06	0.93	± 0.06	0.94	± 0.06

DDQ

Damage Model		GISSMO Damage Model				Power Law Damage Model			
Damage Metric & Parameters		Eq. Strain *Damage Exponent = 1*		Eq. Strain *Damage Exponent = 2*		Eq. Strain *Damage Exponent = 1.5*		Eq. Strain *Damage Exponent = 2*	
Fracture Metric: $\varepsilon_f^{model} / \varepsilon_f^{exp}$		Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
Secondary Path	Plane Strain Tension	1.12	± 0.09	1.14	± 0.09	1.07	± 0.07	1.04	± 0.08
	Biaxial Stretching	0.80	± 0.08	0.82	± 0.08	0.85	± 0.05	0.87	± 0.04
	Shear	0.93	± 0.05	0.95	± 0.05	0.94	± 0.05	0.94	± 0.05
	Uniaxial Tension	0.92	± 0.05	0.94	± 0.05	0.90	± 0.03	0.88	± 0.04

Consistent trends with DP1180 and DDQ for all damage models in NLSP.

Accuracy was better for relatively low ductility DP1180.

CONCLUSIONS AND FUTURE WORK

GDIS

Fracture prediction in NLSP requires <u>accurate proportional test data and constitutive modelling</u>

→Choice of characterization tests is crucial. Convergence in experimental methods for hardening

→Efficient methodology developed for DP1180 worked well for most challenging case of DDQ

→Peanut shear successful for being intermediate tension & shear loading case

→Choice of DIC parameters and VSG for fracture tests remains open question

<u>Fracture Models</u>:

Same trends for DP1180 and DDQ: Power law damage better than GISSMO (esp. for lower ductility grades)

DDQ had significant plastic anisotropy but marginal fracture anisotropy → also second order effect in DP1180

All models overestimated ductility in second path of plane strain (vital for crash CAE)

→ Lengthscale transition for practical simulations may wash out advances in modelling (not considered)

For more information

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