Fracture Characterization of Advanced 980 MPa Steels

- collaborative project between Steel Marketing Development Institute, Honda Research America, and University of Waterloo

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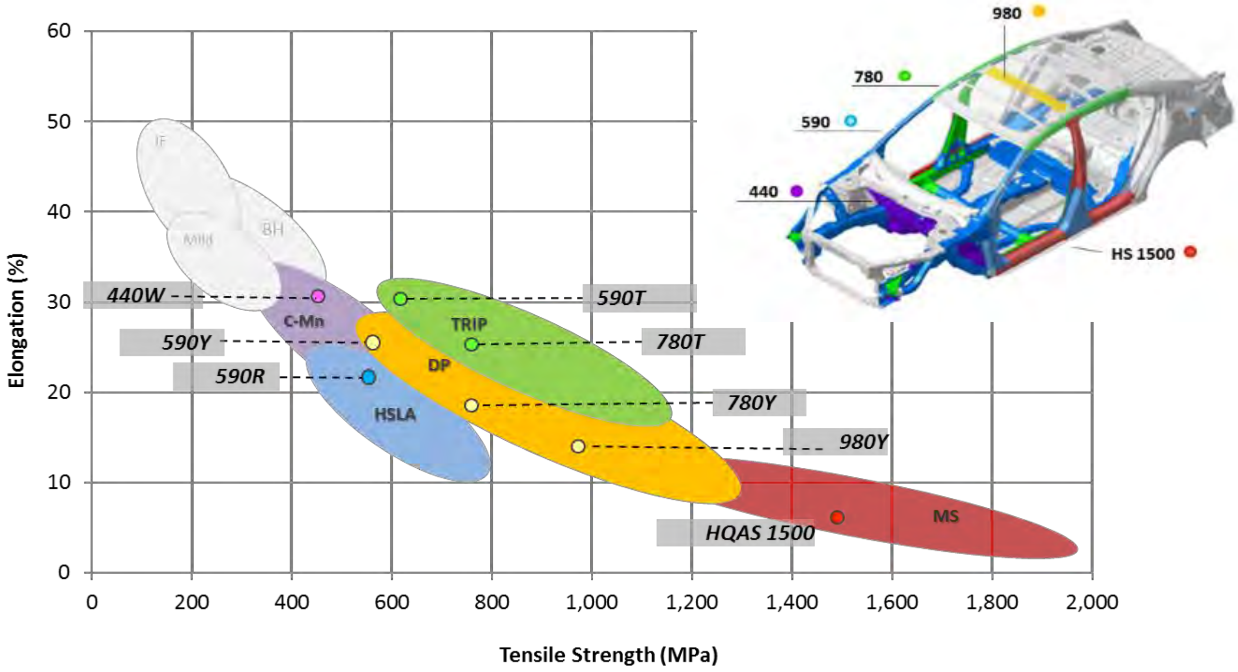
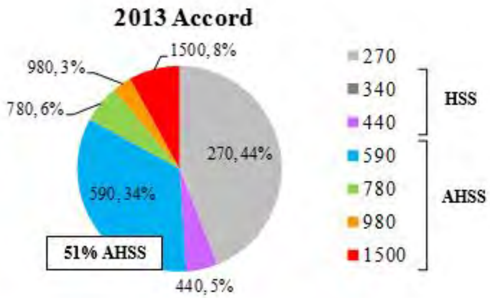
Overview

- Background
- Objective
- Study Materials
- Fracture Test Methodology and Results
- Component Testing
- Conclusions

Recent evolution of Advanced High Strength Steel



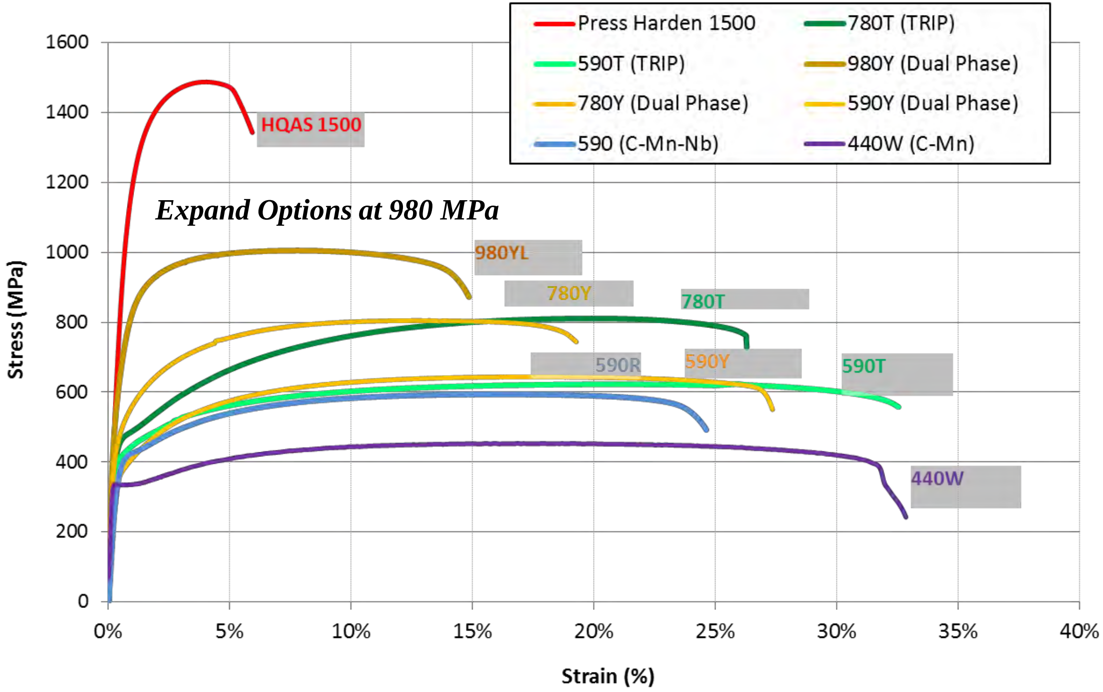


Common AHSS grades and their application areas

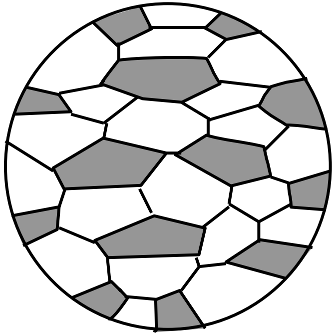
Need for Grade Diversification at 980 Strength Level

- Specialized grades now exist at the 590 and 780 MPa strength level. (dual phase, TRIP, etc).

- Expand Grades at 980 MPa for enhanced:
  - bending
  - flanging
  - energy absorption



Background

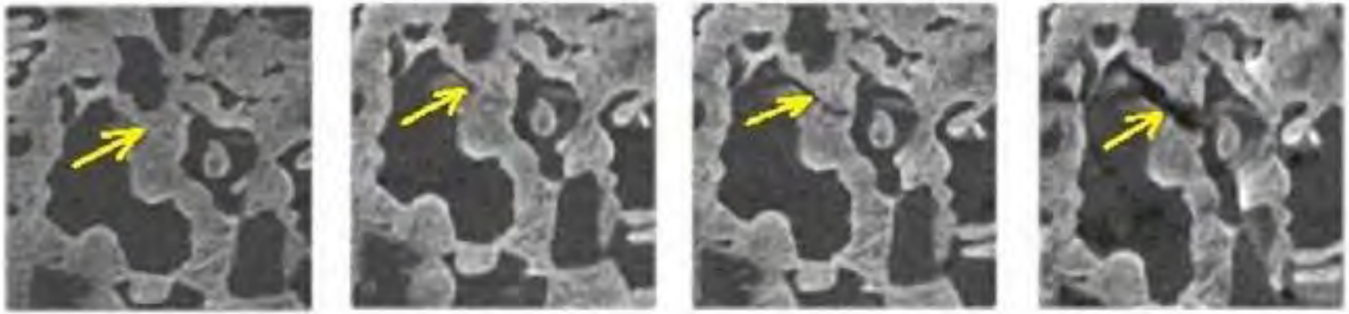


CONV 980YL

Initial Microstructure*

Fracture of martensite

Void Growth



*Damage in dual phase steel DP1000 (Alharbi, K)

- *Increasing Strain* -

- Microstructures of early DP980 not optimized for bending and edge stretch
- These property limitations restricted the application of DP980.
  - Complex part shapes and features could not be formed.
  - Energy absorption targets could not be meet due to fracture problems.

Objectives

1. Characterize properties of various Dual Phase 980 grades selected by Steel Marketing Development Institute (*Blind Study*)

2. Investigate optimized fracture testing methodology for Advanced High Strength Steel → ***Industrial Friendly and Efficient Methods Required***

3. Perform experimental axial and bend crush experiments and assess fracture performance

Project Structure

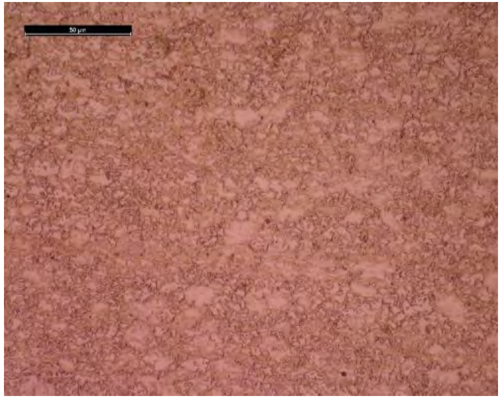
1. Each Supplier Submits One DP980 to SMDI Sample Bank

2. Material identification removed:

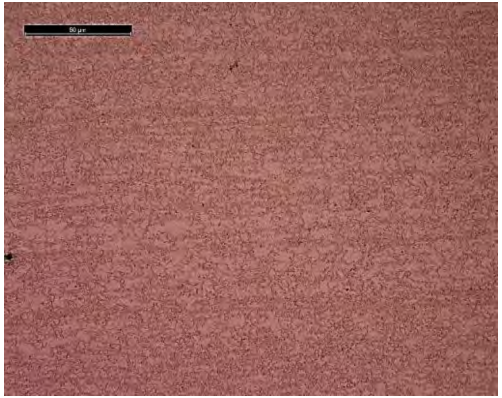
Sent to UW and Honda for Fracture Characterization from Coupons to Crash

Study Materials: Composition

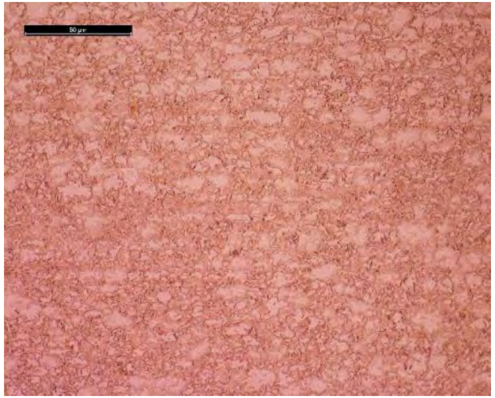
980 #1



980 #2



980 #3

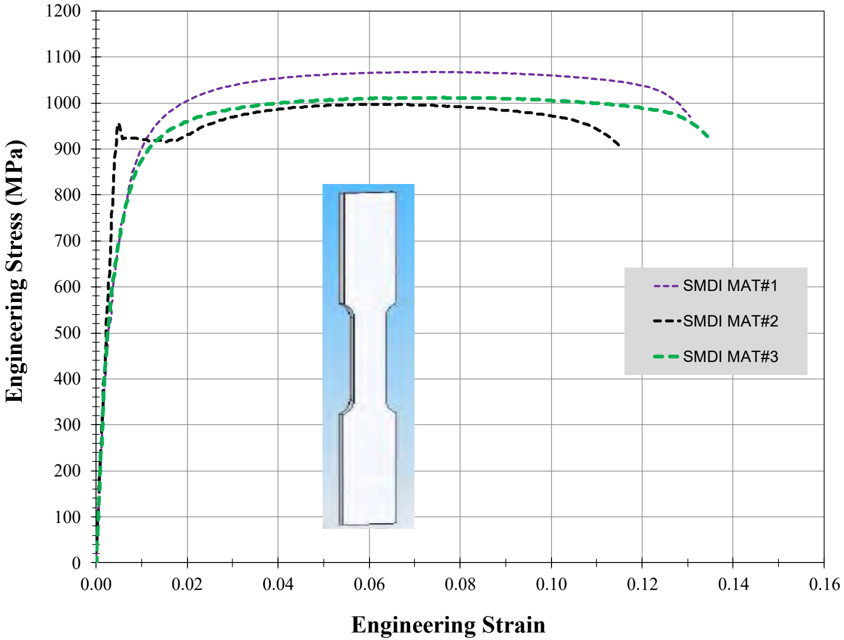


SMDI Grades	Thickness (mm)	Type	General Composition	Coating
980 Mat#1	1.2	Dual Phase	C-Mn-Si	Bare
980 Mat#1	1.6	Dual Phase	C-Mn-Cr-Mo-Nb	Zinc
980 Mat#3	1.4	Dual Phase	C-Mn-Si	Zinc

Materials can generally be described as DP with fine, uniform microstructure.

Grades represent recent optimization in processing / chemistry *(but are not Gen 3 level)*

Study Materials: Tensile Properties

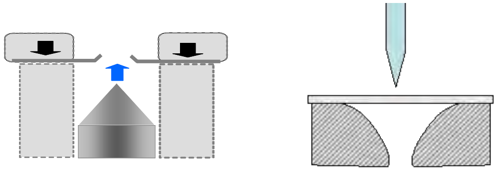


Tensile Properties - JIS Test Specimen

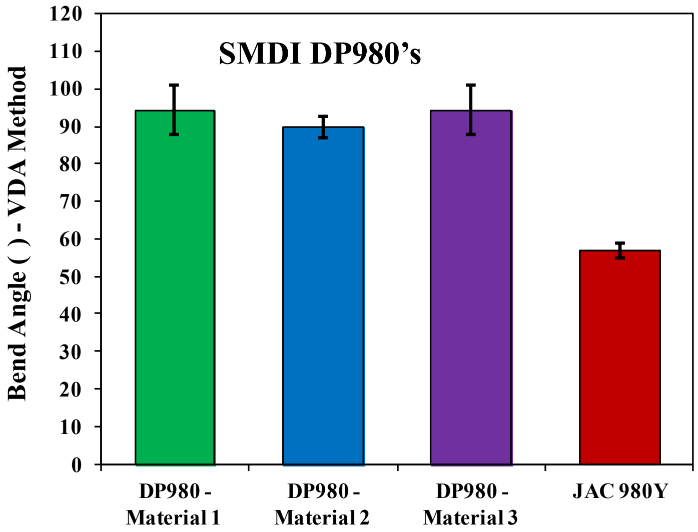
Grade		TS (MPa)	YS (MPa)	YS/TS Ratio	TE (%)
#1	L	1046	806	0.81	12.7
	T	1067	787	0.74	13.5
#2	L	971	912	0.94	12.9
	T	998	934	0.94	12.0
#3	L	989	776	0.78	13.8
	T	1012	757	0.75	13.0

- All grades exhibited total elongation typical of 980 level material.
- Relatively high YS/TS ratios suggested all grades favor local formability.
- Material #2 had unique yield point elongation behavior.

Local Ductility Properties - Hole Expansion and Bendability



Grade		Hole Expansion (punched) (%)	Bend (VDA Angle)
#1	L	36	105°
	T		95°
#2	L	44	102°
	T		90°
#3	L	39	110°
	T		95°



- Performance of these grades is consistent with or above current commercial products.
- VDA bend data is of growing industrial importance as means to evaluate material.

➥ *The potential use of the VDA test for fracture prediction will be elaborated on in next section*

Characterization for Formability & Fracture

Priority Focus Areas

1) Material characterization at large strains and strain rates

2) Efficient method to determine forming limit strains (FLD) (*Global formability*)

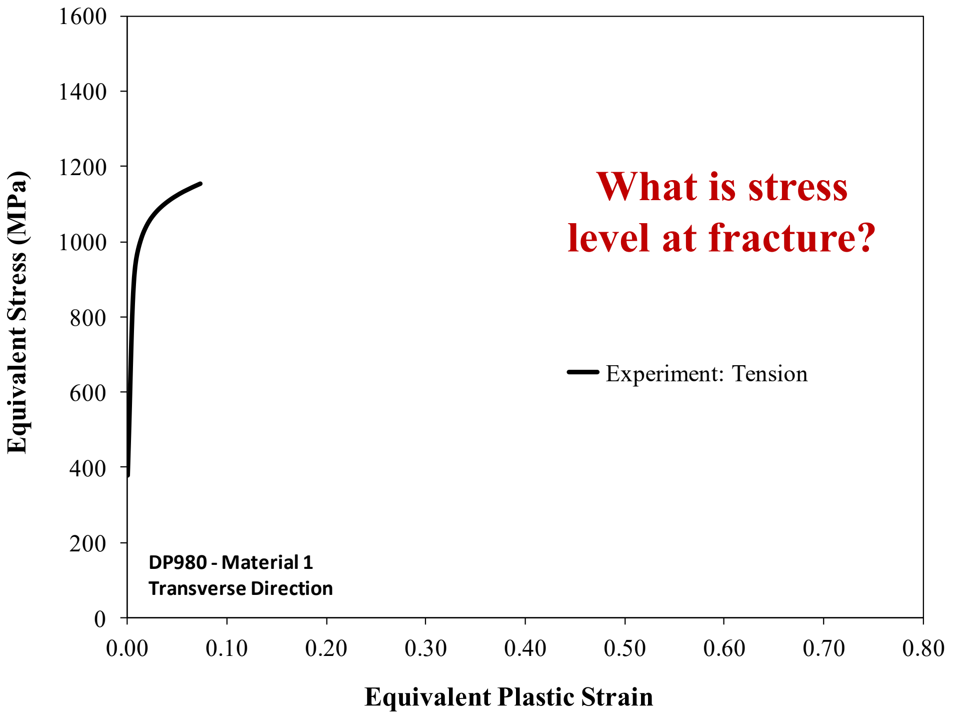
3) Characterization in tight radius bending (*Local formability/fracture*)

4) Establish best practices and tests for experimental fracture characterization

*Extensive numerical characterization study pursued in tandem

1. Material Characterization at Large Strains

- Limited hardening data available in tensile tests
- Inverse FE modeling used to identify hardening at large strains for fracture
- Hardening data becomes a function of numerical model assumptions…



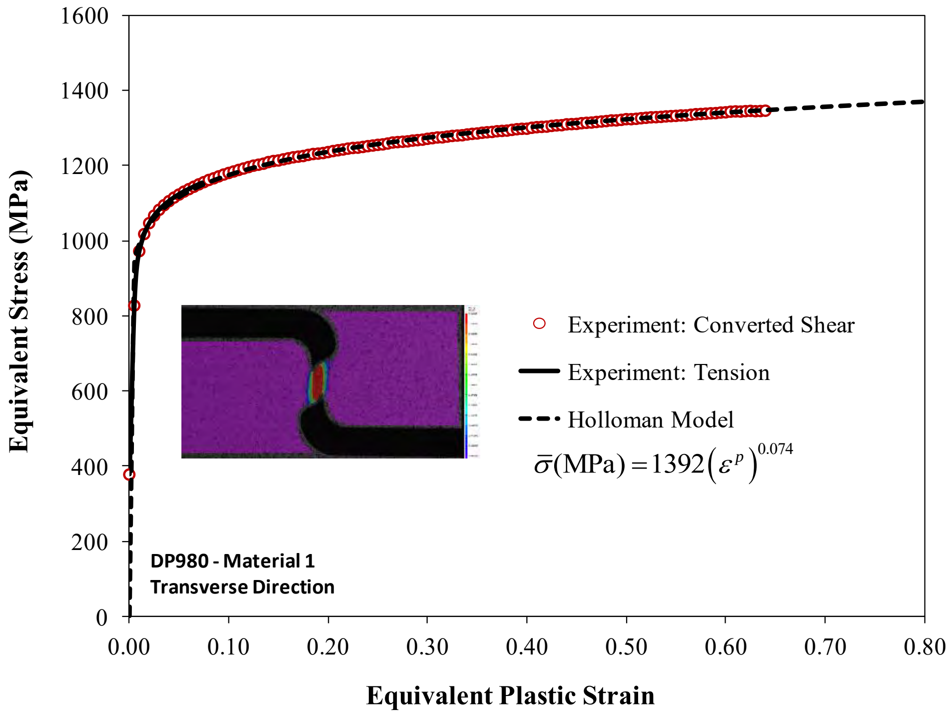
1. Material Characterization at Large Strains

- UW developed simple method to use tensile & shear test data to obtain hardening to large strain levels

- DP980 data to 60% strain!

- **Not related to FE model**

Methodology in Rahmaan, T., et al., *Int. J. Impact. Eng.*, 2017 (in-press)

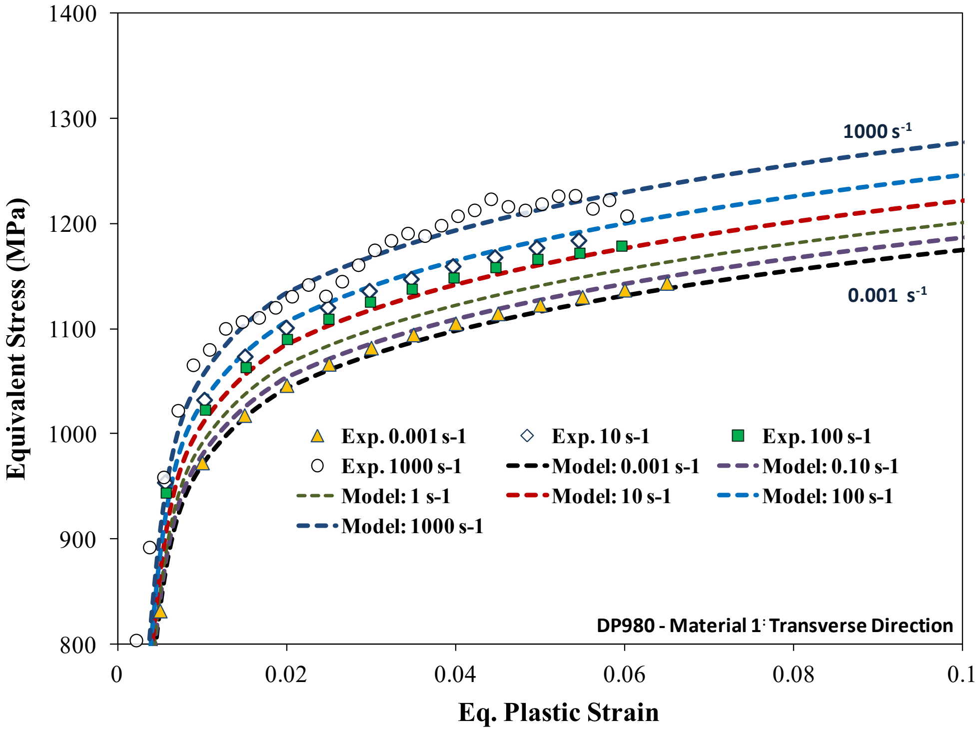


1. Material Characterization at Large Strains *and Strain Rates*

- Tensile characterization from 0.001 to 1000 s-1
- Scale quasi-static data obtained to large strains for strain rates

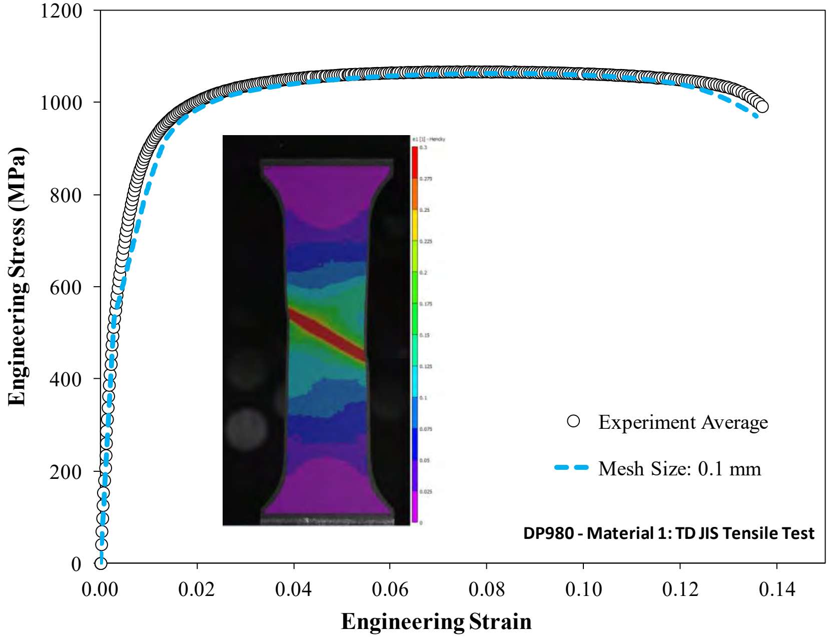
$$\bar{\sigma}\left(\varepsilon^{p},\dot{\varepsilon}^{p}\right)=\bar{\sigma}^{QS}\cdot F\left(\dot{\varepsilon}^{p}\right)$$

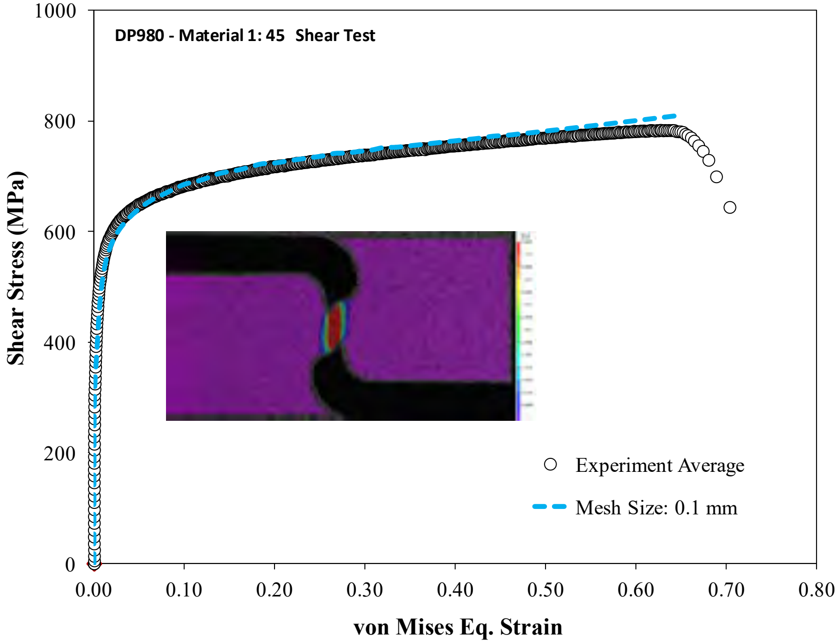
- **Efficient experimental method for constitutive characterization**



1. Material Characterization at Large Strains *and Strain Rates*

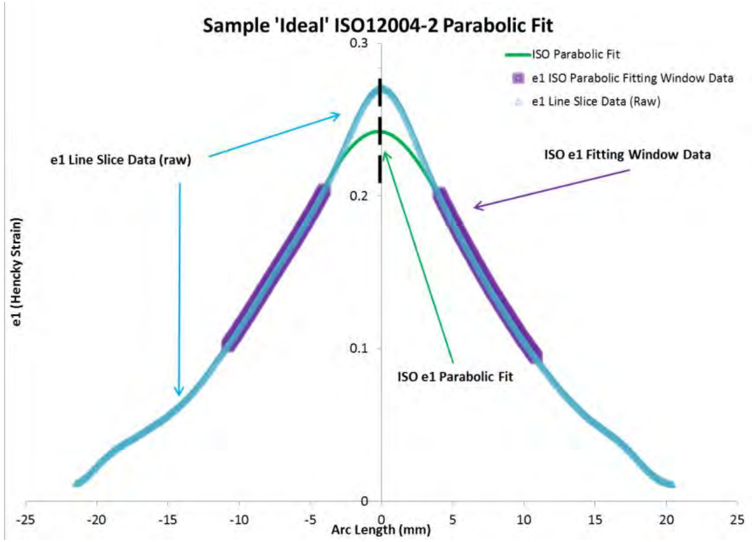
FE Simulations using Experimental Hardening Model and Von Mises Perform Well: Efficient



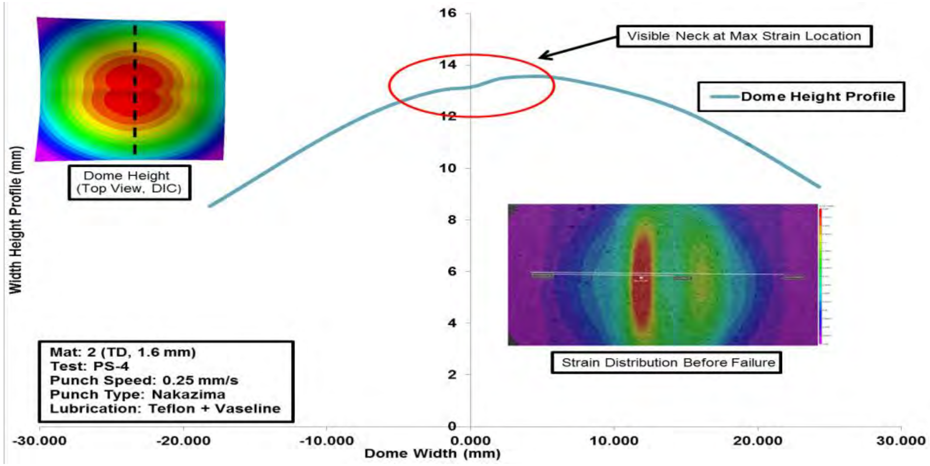


2. Global Formability – FLD Methodology

Physically-motivated FLD detection methods are needed



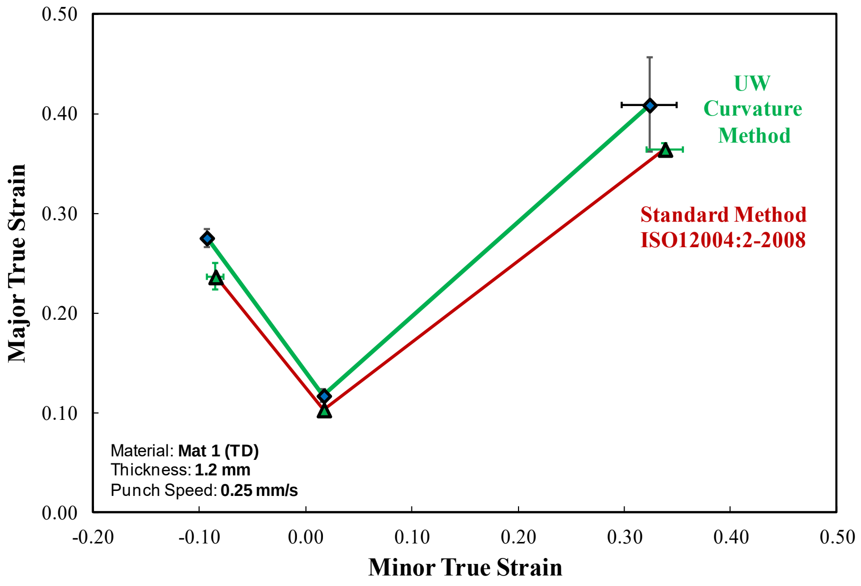
<u>ISO 12004-2 Standard Method</u>
Curve fitting of strain distributions
(arbitrary, little physical foundation)



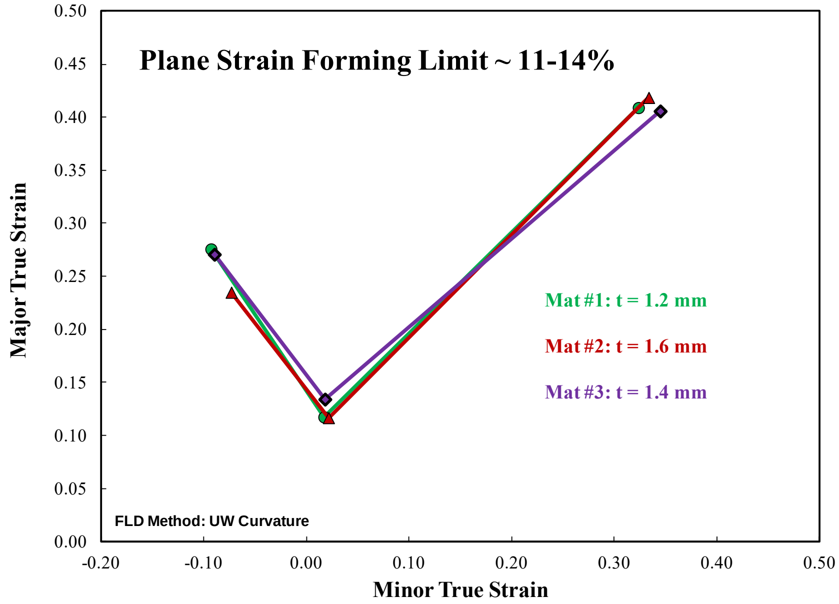
<u>UW Curvature Method: "Digital Finger Test"</u> –
Detects surface discontinuity
(DiCecco et al., Exp. Mechanics. Submitted)

2. Forming Limits

Curvature provides physical upper limit



Comparable FLDs for Three Grades



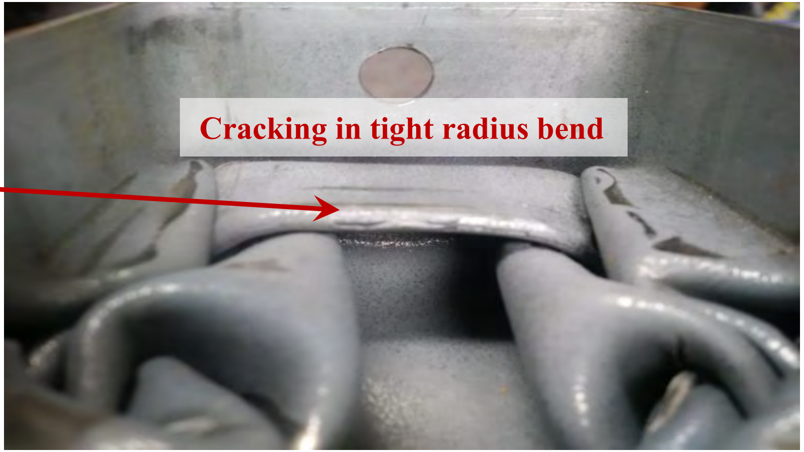
3. Formability and Fracture in Tight Radius Bending

Formability in tight-radius bending indentified as key factor in crash performance

VDA 238-100 bend test promising but only reports bend angle

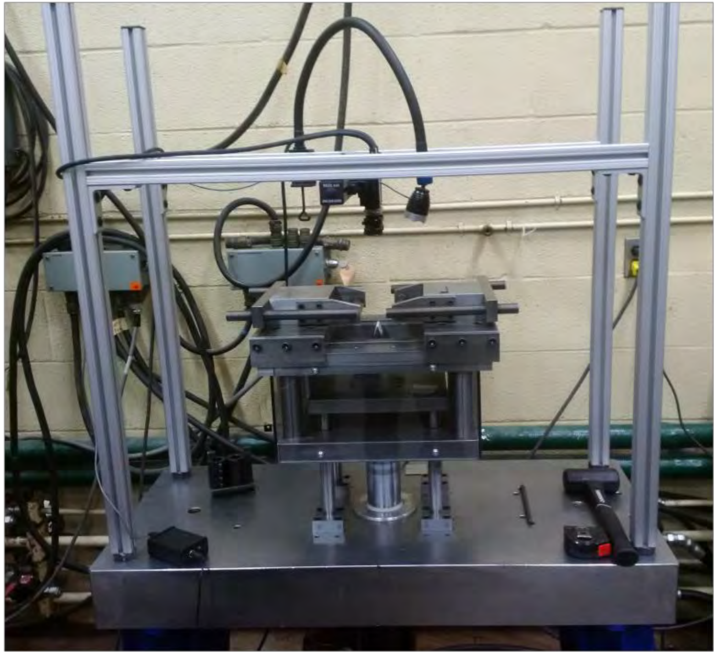
UW-HRA Tailored Hot Stamped Rail
(Omer et al., 2017, Int. J. Impact. Eng)

DP980 Material 2
Global Buckling and Folding

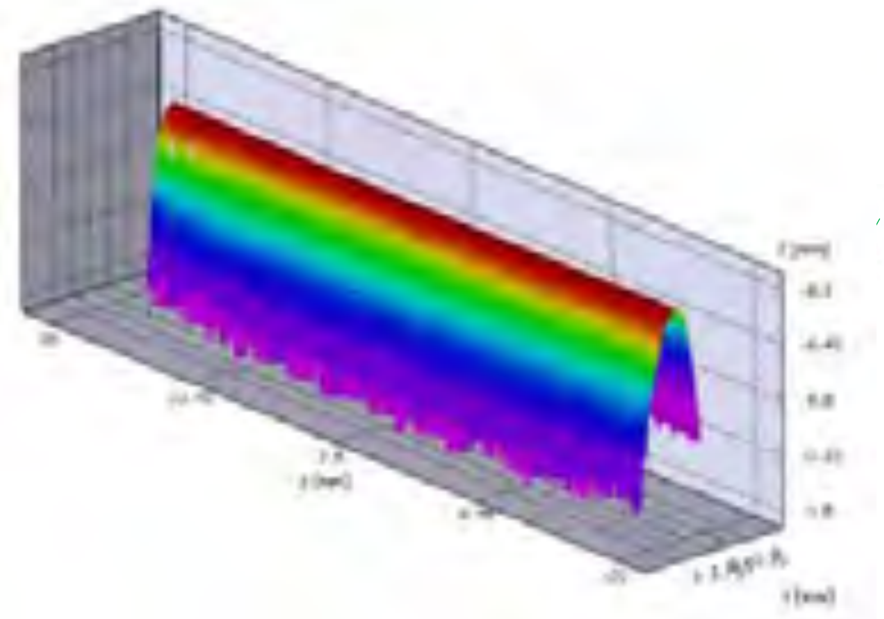


Optical VDA238-100 Test Frame

UW & HRA Developed an Inverted Bend Test for Optimal DIC Strain Measurement (*IDDRG Conf., 2017*)



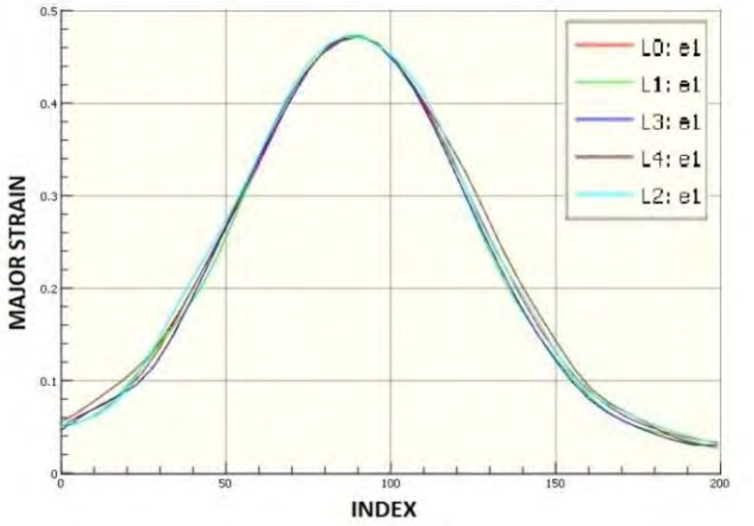
UW's VDA238 configuration with DIC

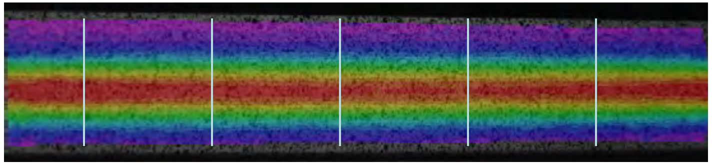


Measure Fracture Strain & Bend Angle!

V-Bending with DIC

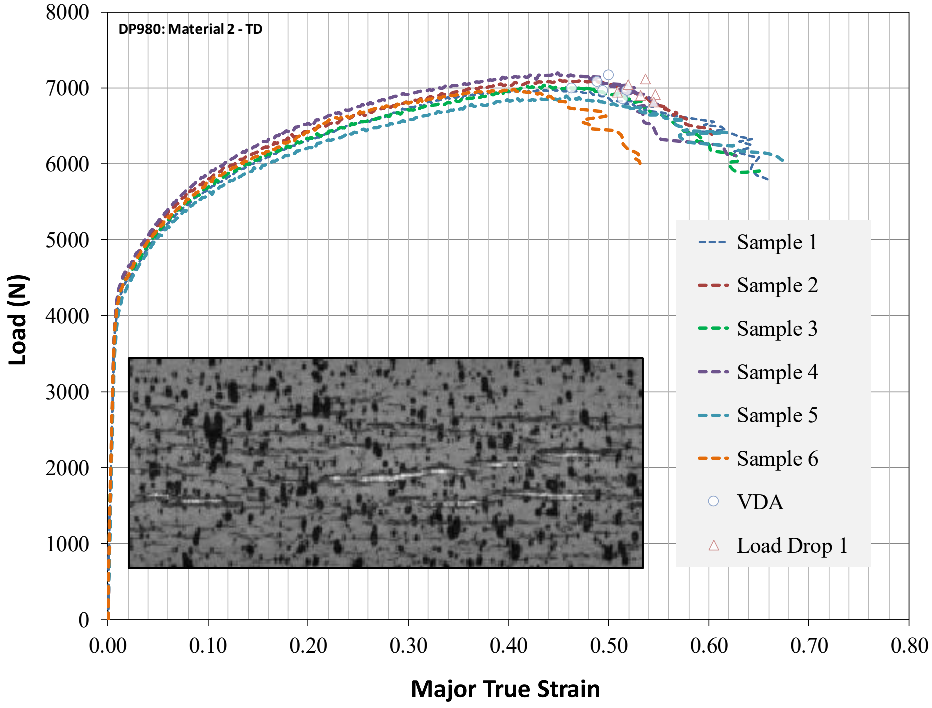
Homogeneous Strain Distribution along Width





Measures width of specimen (res. < 0.02 mm/pixel)

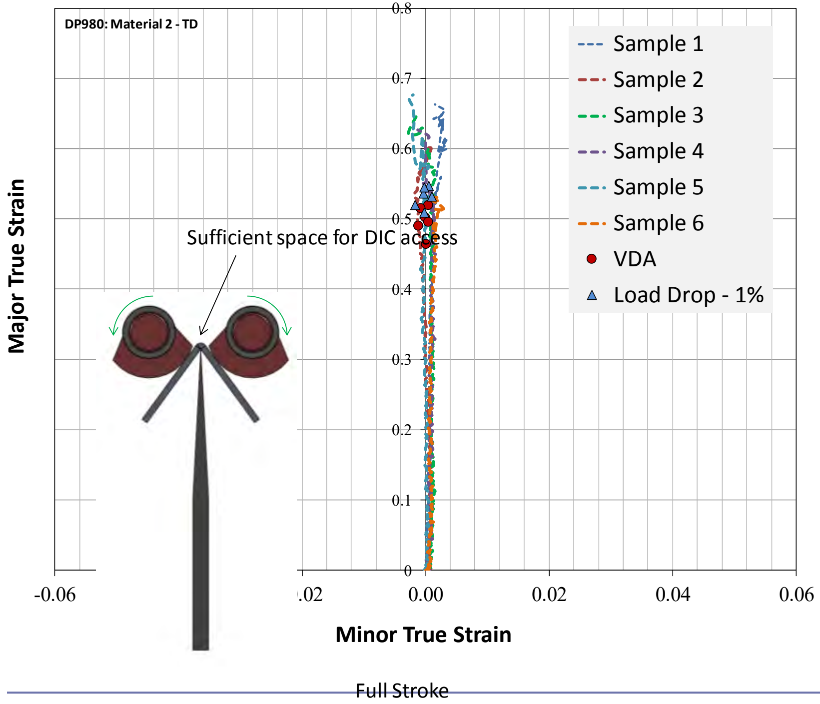
Detect fracture using Load drop (VDA) or visual cracking



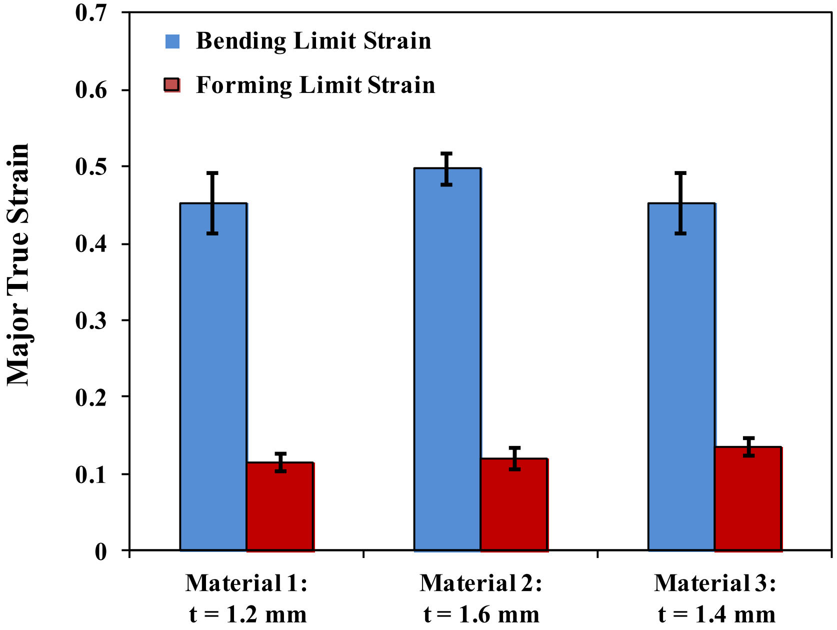
Load vs Major Strain (Ex: 980 Mat#2)

V-Bending with DIC Strain Measurement

Achieves Ideal Plane Strain Loading until Onset of Cracking

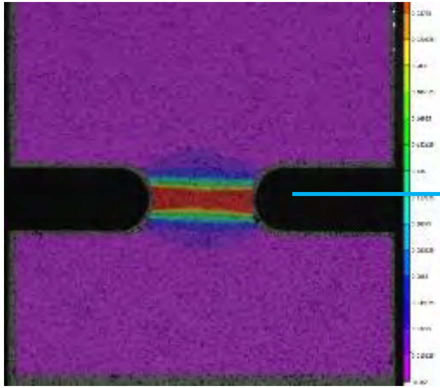


DP980 Plane strain fracture limits of 45-50%!
Forming limit strains ~ 12%

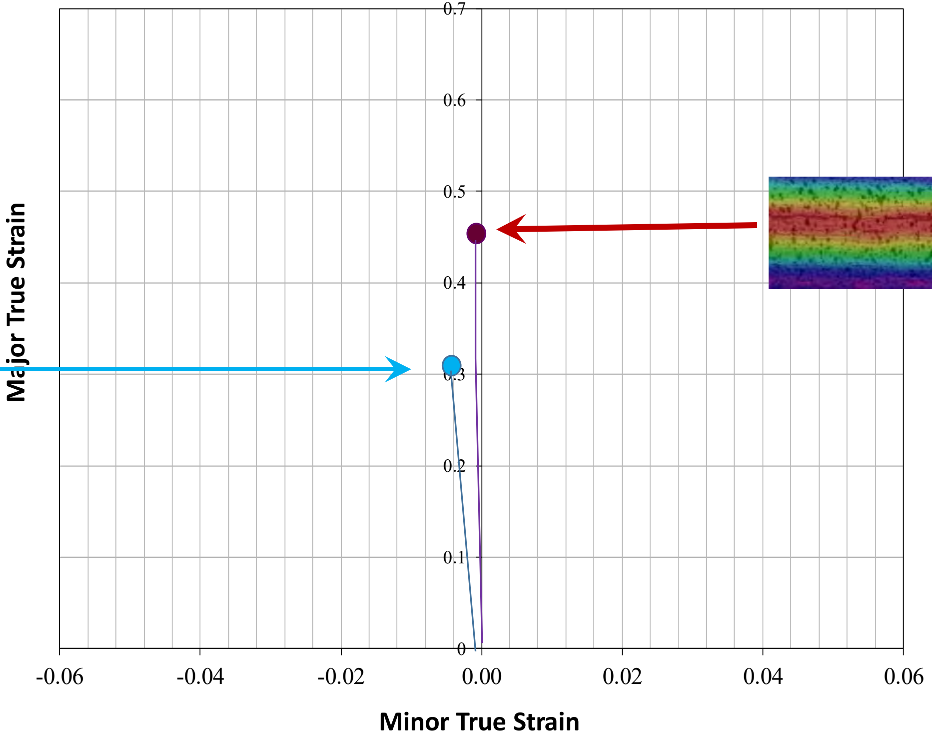


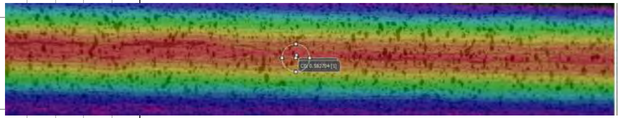
Comparison of V-Bend with Plane Strain Notch

Disagreement between tests: Notch test is lower…



Traditional Plane Strain Notch Tensile Sample



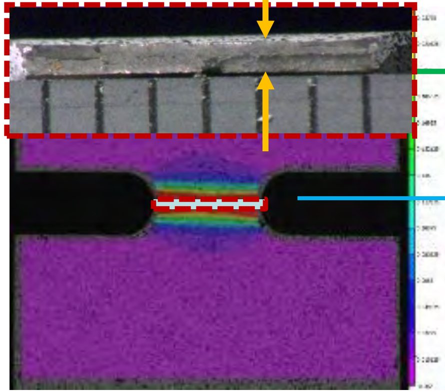


V-Bend with DIC

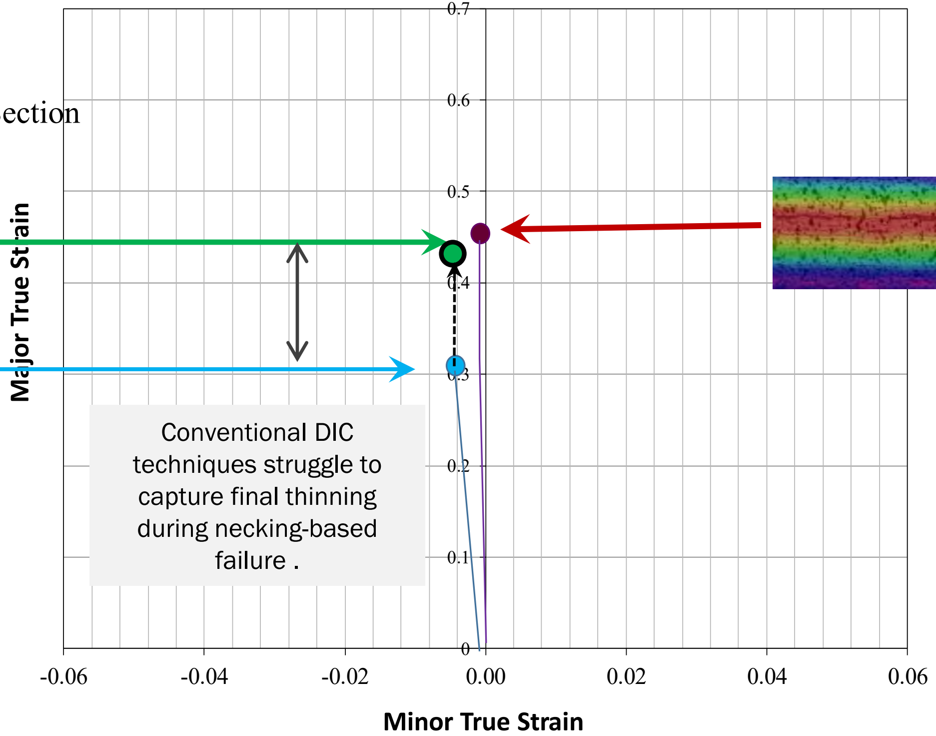
Comparison of V-Bend with Plane Strain Notch

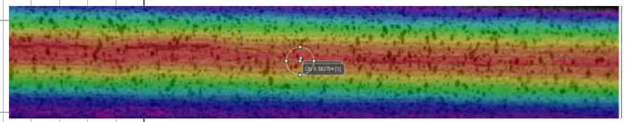
But a thickness correction on the notch resolves the difference

Thickness measurement of Cross-Section



Traditional Plane Strain Notch Tensile Sample



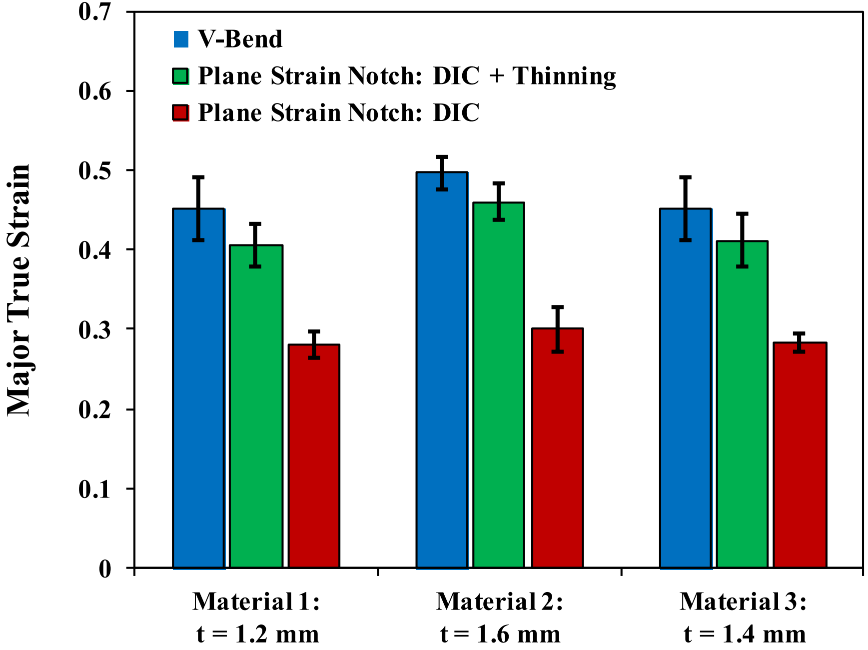


V-Bend with DIC

Comparison of V-Bend with Plane Strain Notch

Plane Strain notch provides lower bound estimate if thinning correction performed

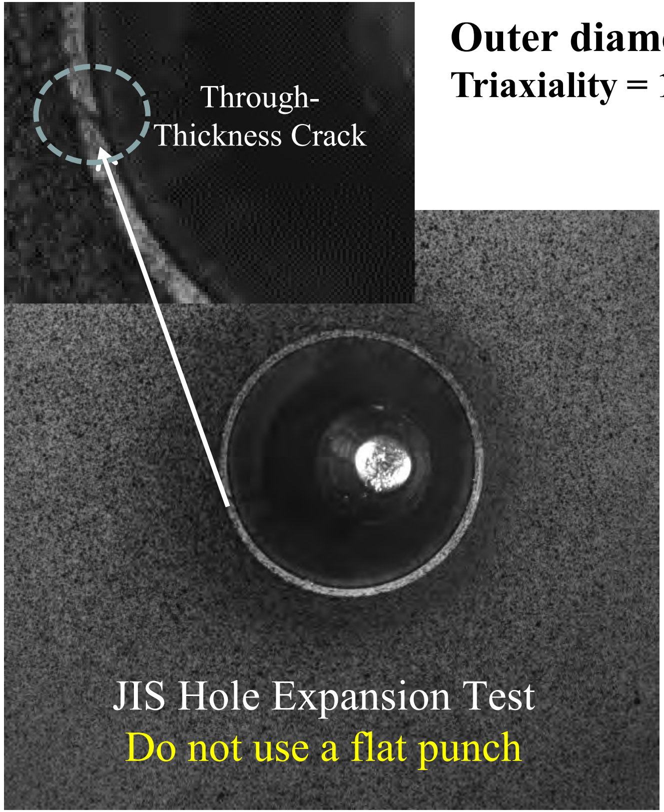
Correction also required for plane strain dome tests



<u>Optical V-Bend Test is Superior</u>

1. No necking
2. Minimal to No Machining
3. Ideal plane strain loading
4. Efficient – low time per test

Conical Hole Expansion Test for Fracture in Uniaxial Tension



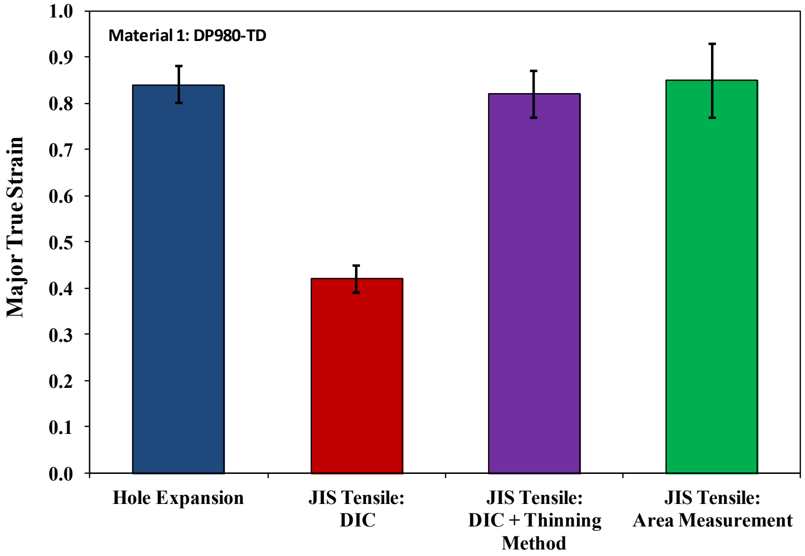
Outer diameter is in uniaxial tension and does not contact the punch

Triaxiality = 1/3 (Butcher et al., SAE, 2013, Pathak et al., JMEP, 2016; Numisheet 2016)

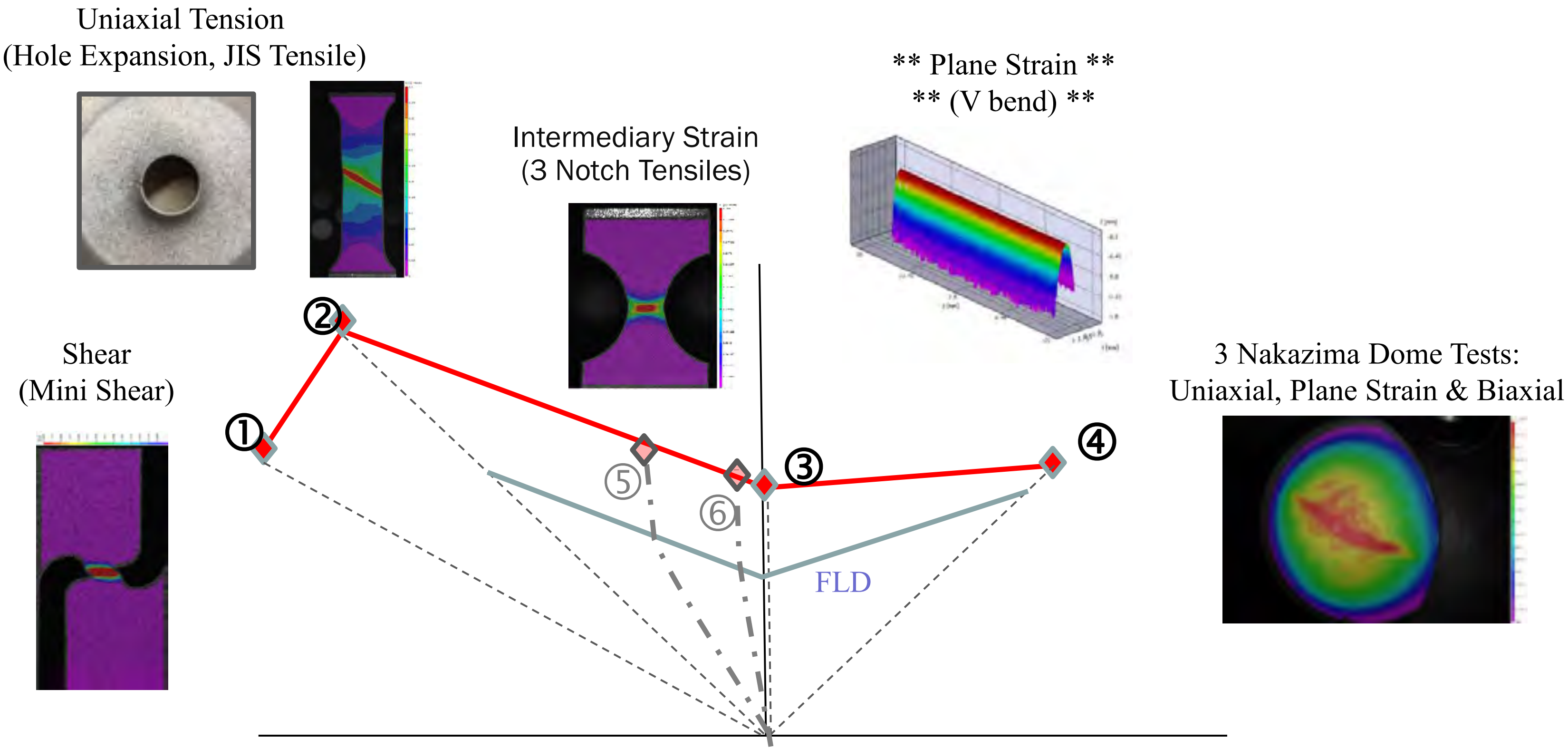
$$HER(\%) = 100\left(\frac{d^f_{inner} - d_o}{d_o}\right)$$

$$\boxed{\varepsilon^f_{eq} = \varepsilon^f_c = \ln\left(\frac{d^f_{outer}}{d_o}\right)}$$

Try it !
You'll like it

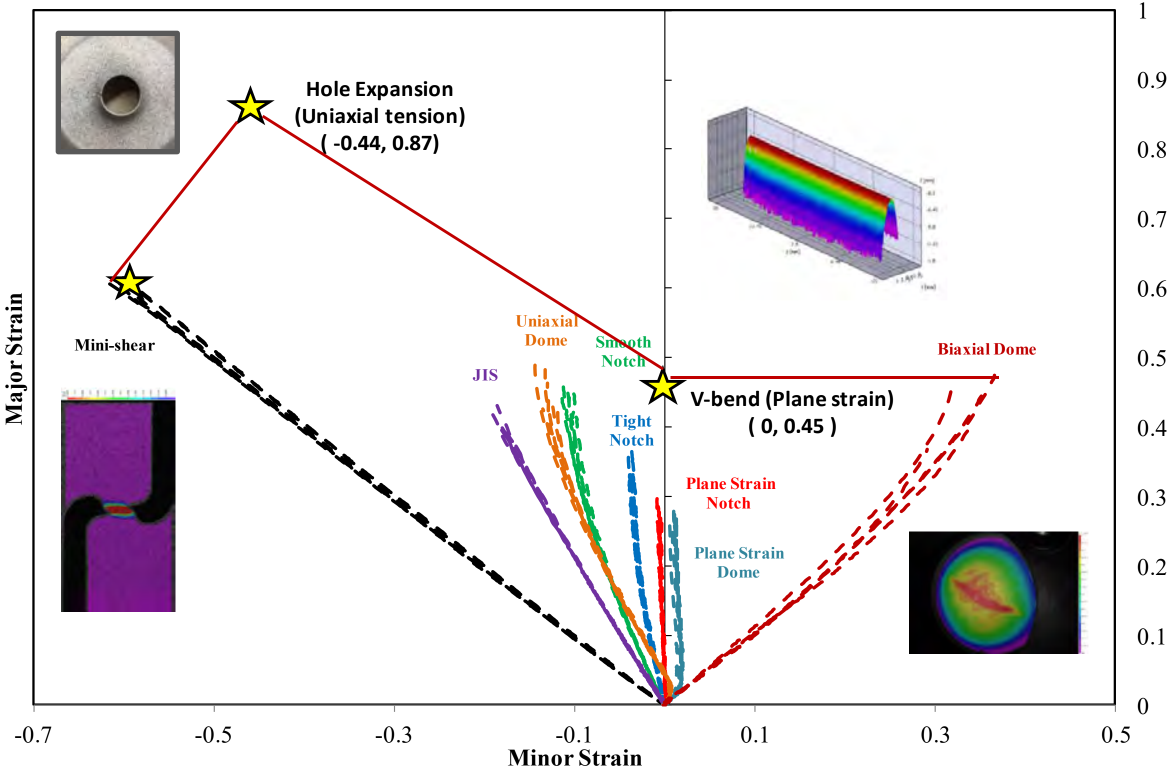


4. Fracture Characterization: 10 Test Geometries



4. Fracture Characterization Results

- Conflicting limits provided by different specimen types if thinning correction not applied



Min. of 4 Tests can describe the fracture locus

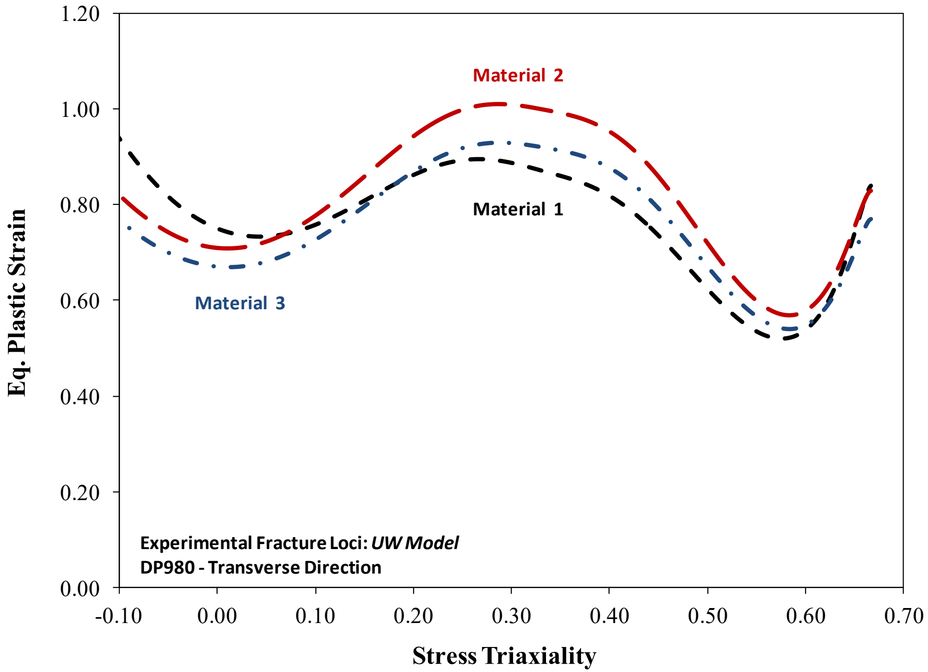
<u>Four Relatively Simple Tests:</u>

1. Mini-shear
2. Hole expansion (reamed)
3. V-Bend
4. Biaxial/Bulge

4. Experimental Fracture Locus

Four tests can be used to generate physically-meaningful fracture loci

Not the product of a simulation exercise – Real material performance can be assessed

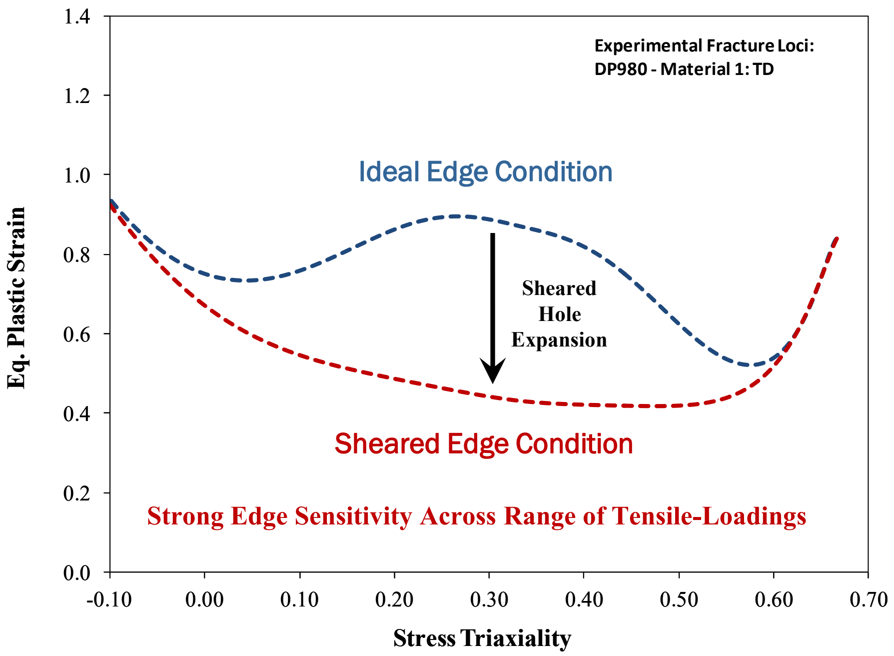


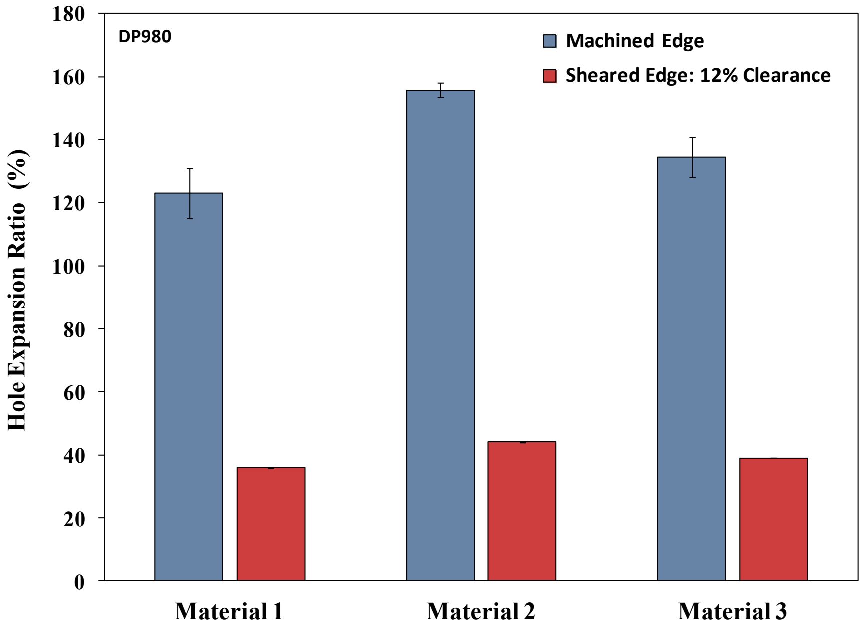
- **Relatively comparable fracture loci**
- **Mat 2 had the *lowest hardening rate*, *highest hole expansion* and *v-bend***

4. Experimental Fracture Locus with Edge Effects

Sheared Edge Failure is a Uniaxial Tensile Mode:

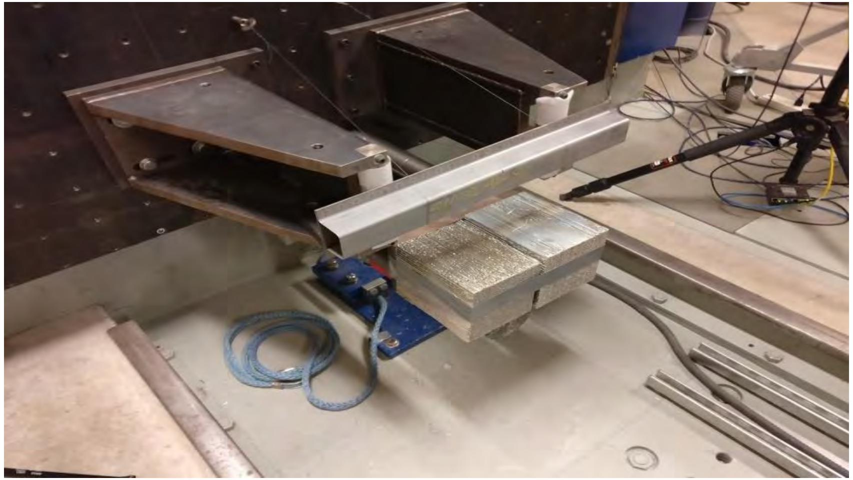
Use Punched Hole Expansion Tests to Obtain Uniaxial Failure Strain with Sheared Edge





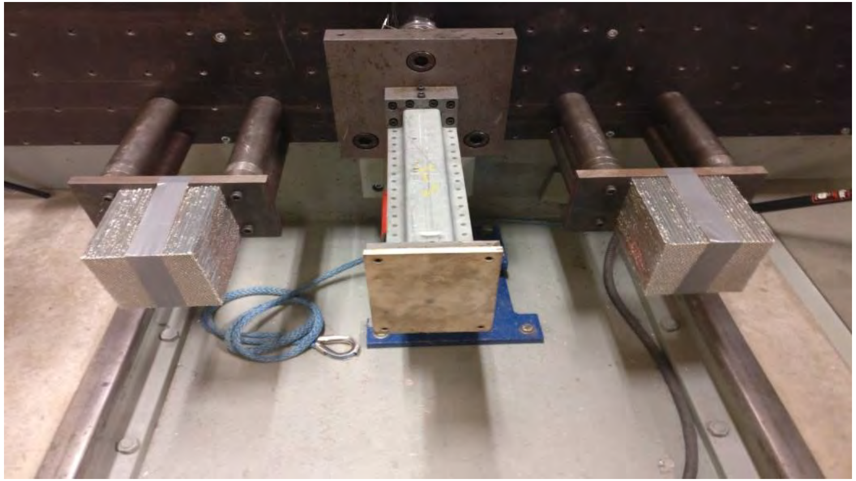
Dynamic Structural Component Evaluation

3-Point Bend Dynamic Crash Test at UW



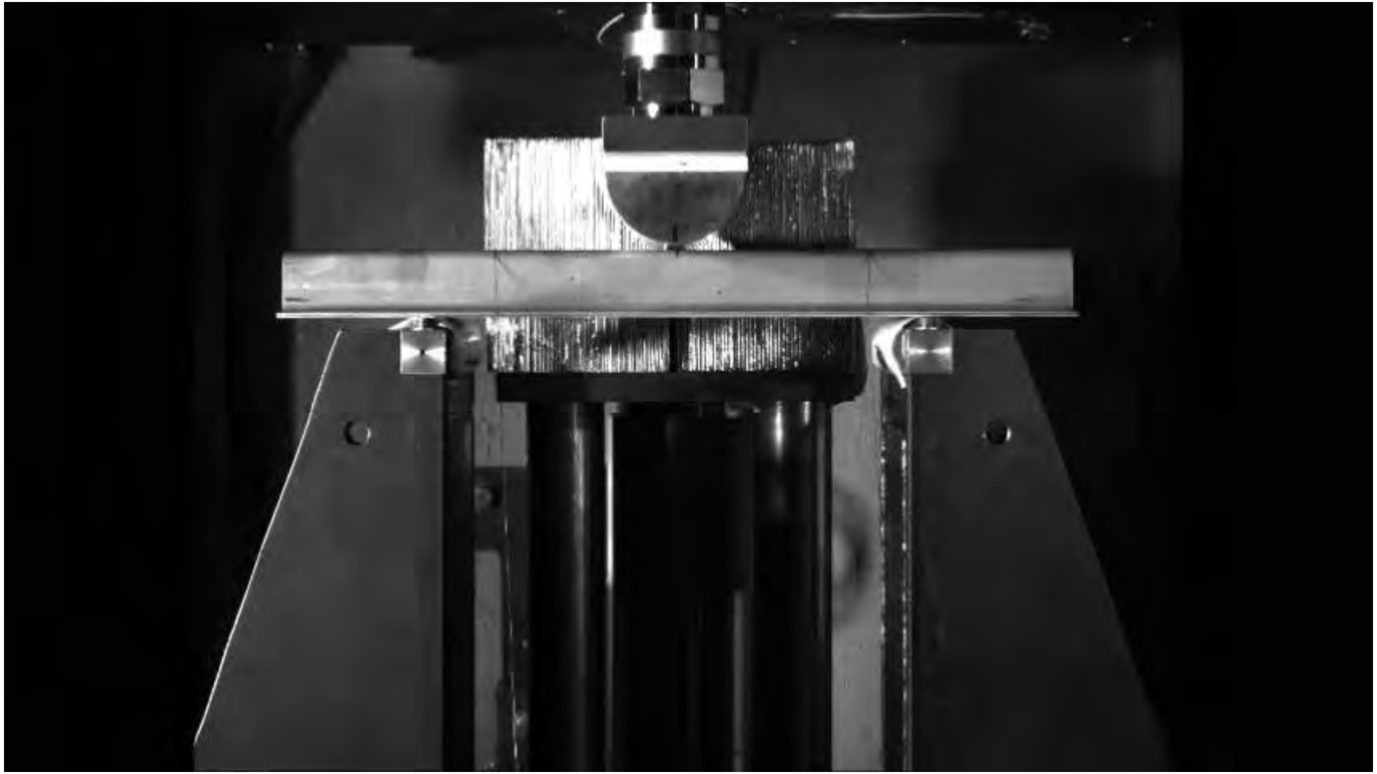
- Sled Mass: 855kg
- Sled Velocity: 25.5km/h
- Total Energy: 21kJ
- Free Crush Distance: 100mm
- Total Crush Distance: 160mm

Axial Crush Dynamic Crash Test at UW



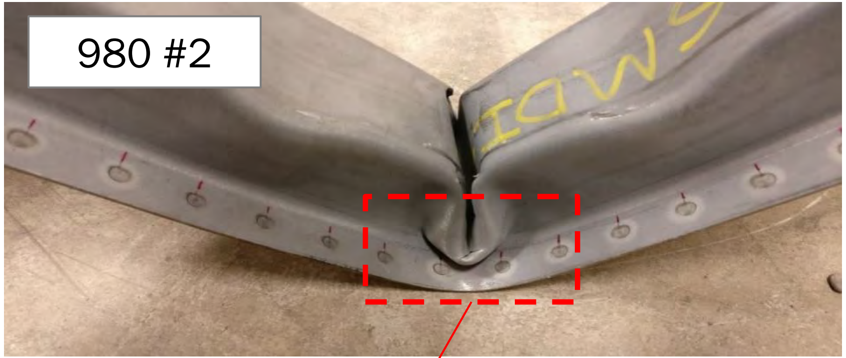
- Sled Mass: 855kg
- Sled Velocity: 25.5km/h
- Total Energy: 21kJ
- Free Crush Distance: 115 mm
- Total Crush Distance: 135mm

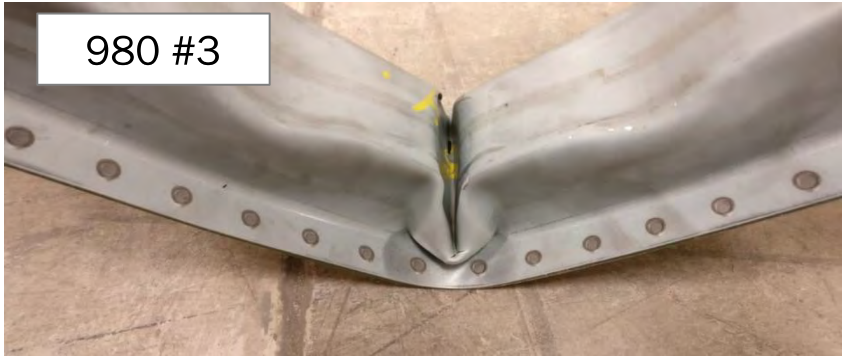
Dynamic 3-Point Bend Test at UW



Dynamic 3-Point Bend Test Results

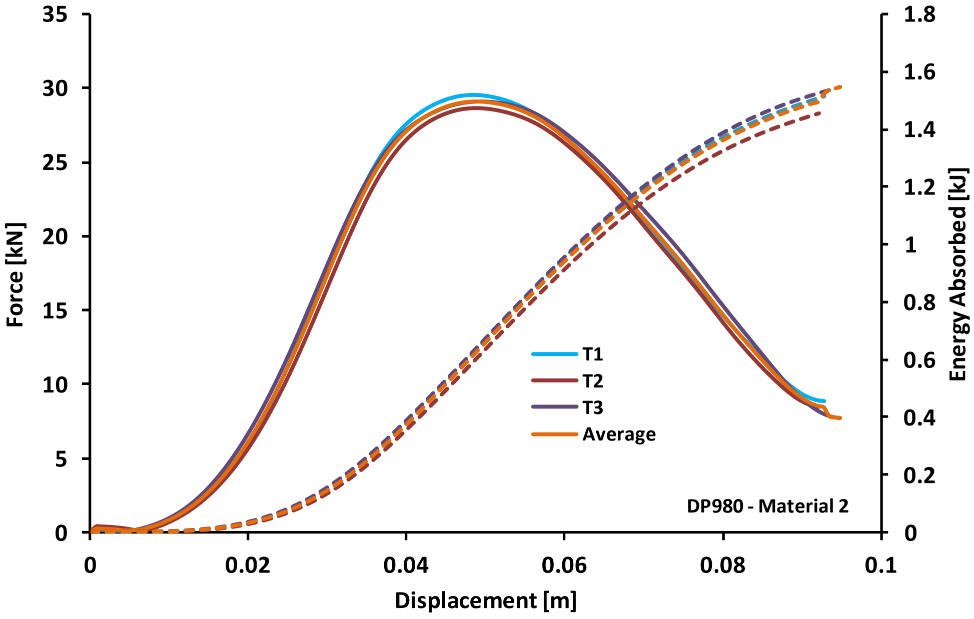
Minimal Cracking for the 3 Grades

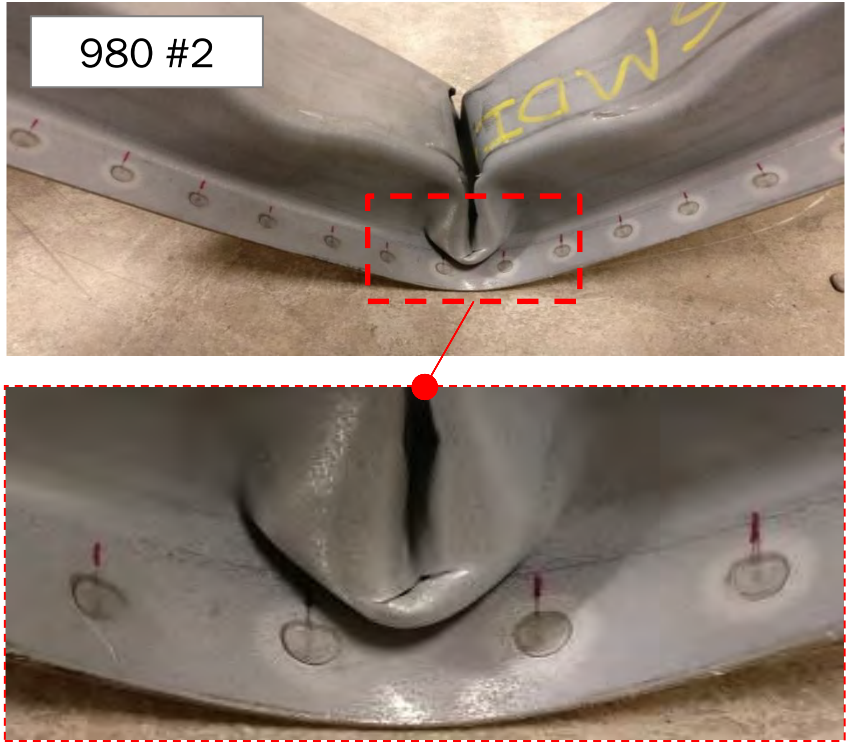




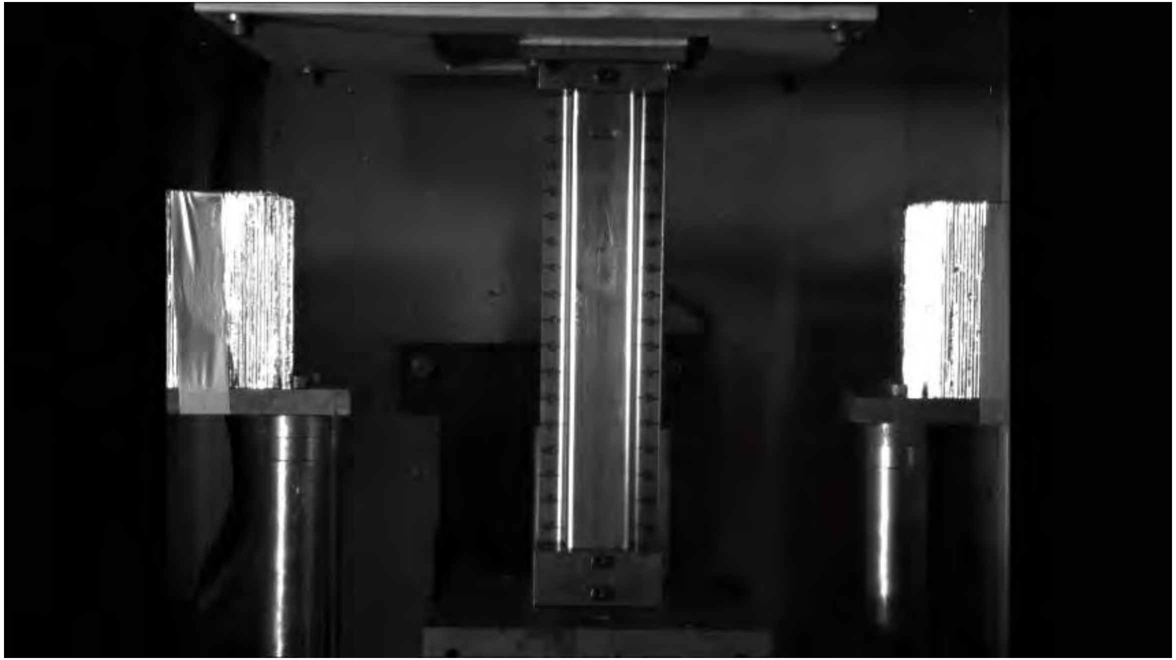
Dynamic 3-Point Bend Test Results: Mat. 2

Minor cracking not detected in load response



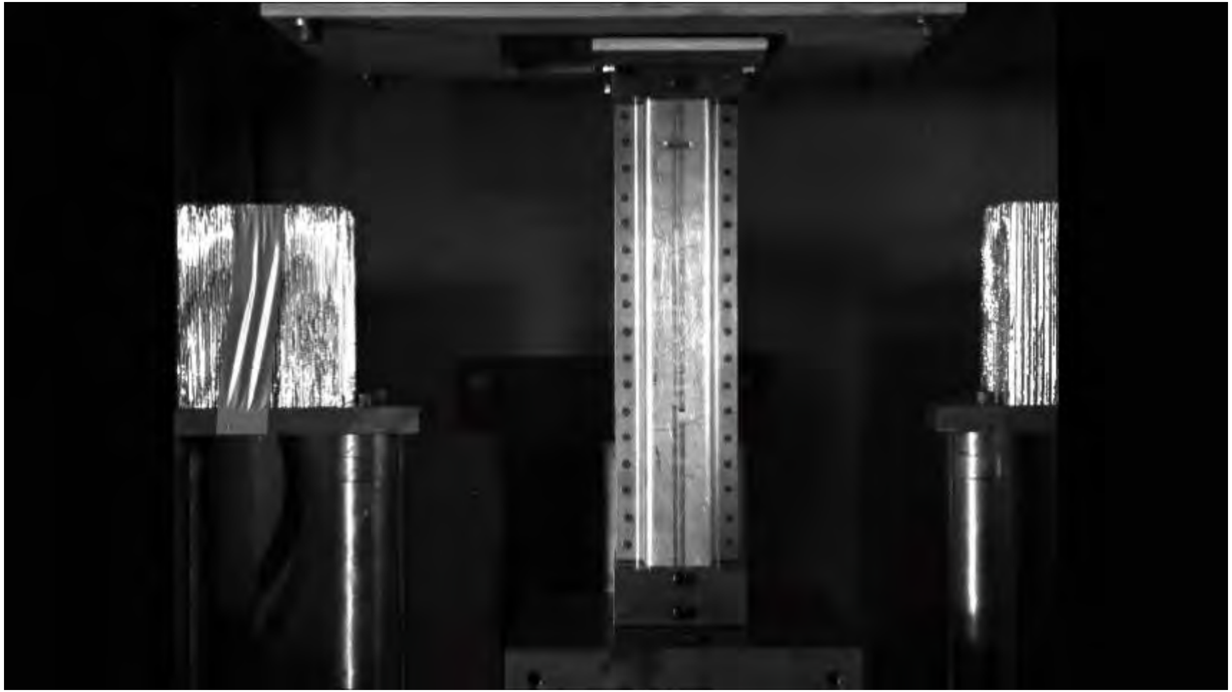


Dynamic Axial Crush Test: Material 1



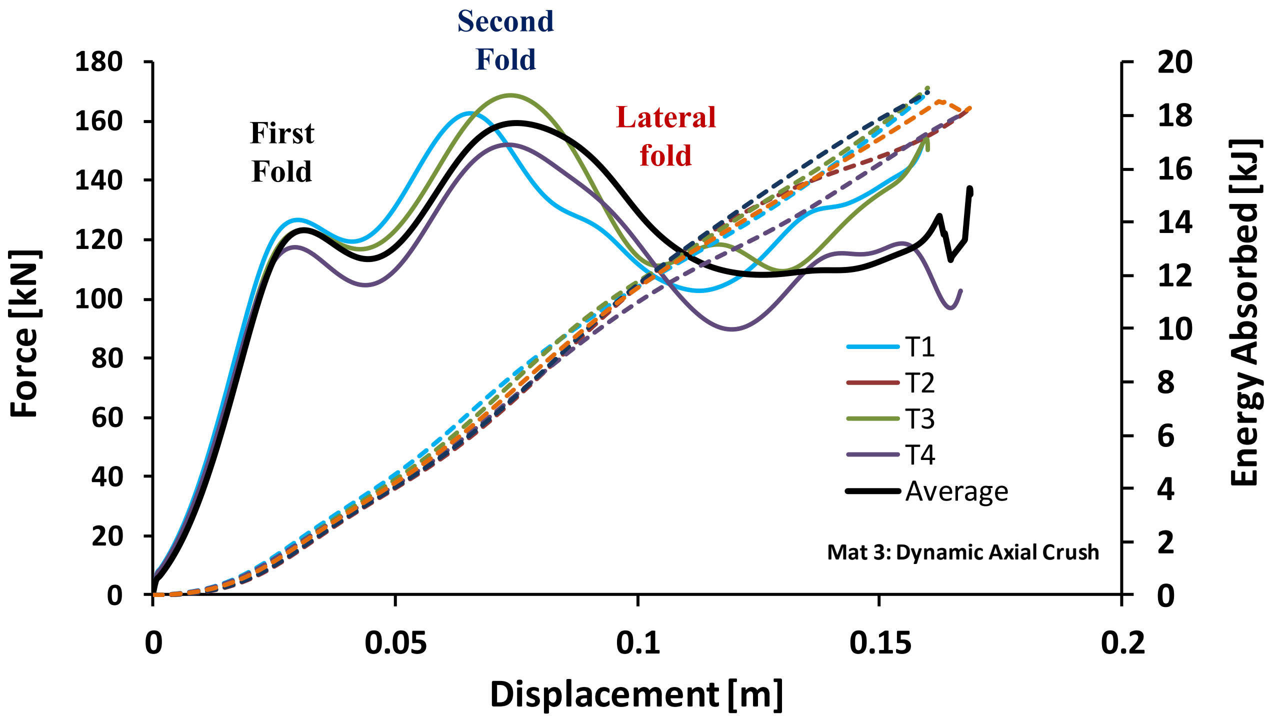
Material #1: t = 1.2 mm

Dynamic Axial Crush Test: Material 3



Material #3: t = 1.4 mm

Dynamic Axial Crush Test: Material 3



Dynamic Axial Crush Test Results

Material #1: $t = 1.2$ mm

Material #2: $t = 1.6$ mm

Material #3: $t = 1.4$ mm

Relatively Good Performance for 3 Grades

Repeatable Energy Absorption

Material 3 had highest spot weld strength and strain rate sensitivity

Conclusions

Efficient and Accurate Experimental Methodologies Established for Characterization of AHSS

1. Method to experimentally obtain hardening to large strains and strain rates
2. New FLD detection algorithm: Curvature-based
3. Optical V-Bend developed: Ideal plane strain test
4. Four tests required to efficiently obtain fracture locus for a material

As with FLD's, Use 4 Industrially Friendly Tests to Construct Fracture Locus to Compare Material Performance → Accounts for Edge Condition

New model to use four tests for rapid FE model implementation → Next GDIS

For More Information

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