GREAT DESIGNS IN STEEL

FORMABILITY AND FRACTURE CHARACTERIZATION OF DP980 AND 3RD GEN STEELS

A collaborative project between Honda Research Americas, SMDI, Bowman, and the University of Waterloo

University of Waterloo:
Cliff Butcher

Honda Research Americas:
Jim Dykeman & Skye Malcolm

Bowman Precision Tooling
Neil Parker & Jamie Bowman

PROJECT TEAM

Steel Marketing Development:	Hesham Ezzat, John Catteral
Bowman Precision Tooling:	Neil Parker, Jamie Bowman
Honda Research of Americas:	Jim Dykeman, Skye Malcolm
ArcelorMittal:	Tim Lim, Steve Lynes
AK Steel:	Kavesary Raghavan
Nucor:	Dean Kanelos, Andy Thompson
Algoma Steel:	Kashif Rehman
University of Waterloo:	Jacqueline Noder, PhD Student
	Edward Gutierrez, MASc Student
	Amir Zhumagulov , Research Associate

PROJECT GOALS

1. Characterize properties of 3rd GEN 980 and 1180 MPa steels provided by the Steel Marketing Development Institute (*Blind Study*)

2. Apply optimized fracture testing methodology established for Advanced High Strength Steels (GDIS 2017 and GDIS 2018) to 3rd GEN Steels

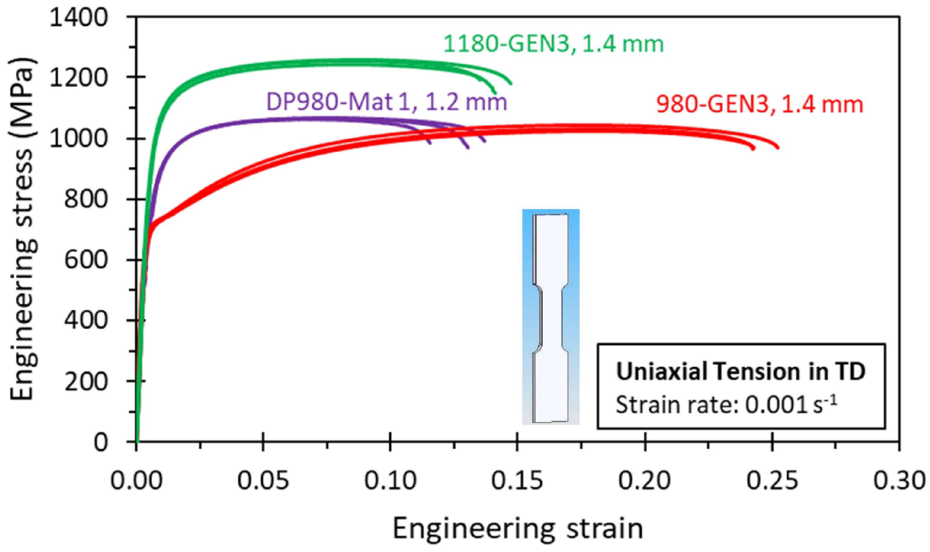
3. Focus upon formability and fracture characterization of 3rd GEN Steels to integrate into CAE toolkit from forming-to-crash (GDIS 2019)

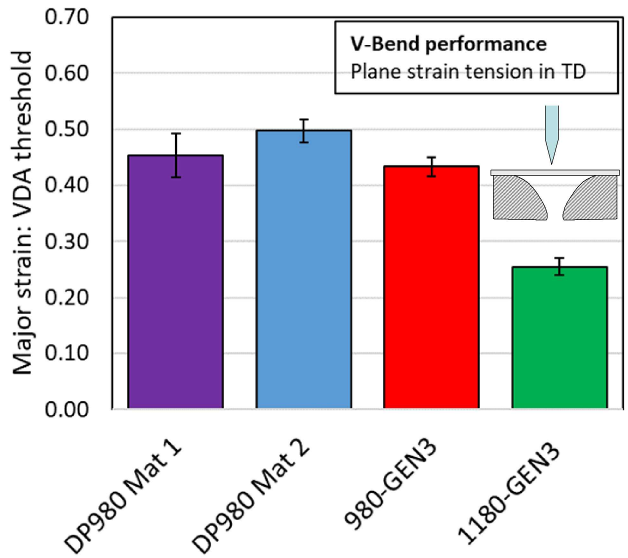
4. Design forming process of full-size B-pillar for mid-size SUV using CAE toolkit with Bowman Precision Tooling and Honda R&D (GDIS 2020)

5. Perform dynamic B-pillar impact tests to evaluate CAE toolkit and methodology to design 3rd Gen. steel components from concept to crash the formed B-Pillar (GDIS 2020)

MATERIAL PERFORMANCE

- Superior tensile performance of 3rd GEN Steels compared to "optimized" DP980
- 980 3rd GEN. has comparable v-bend performance with 2x the uniform elongation as DP980 optimized for local formability

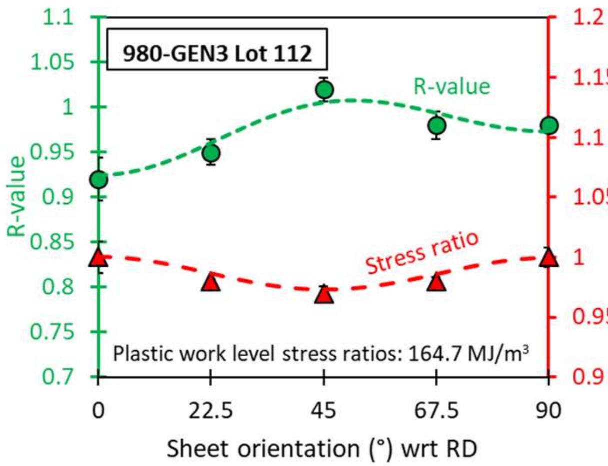


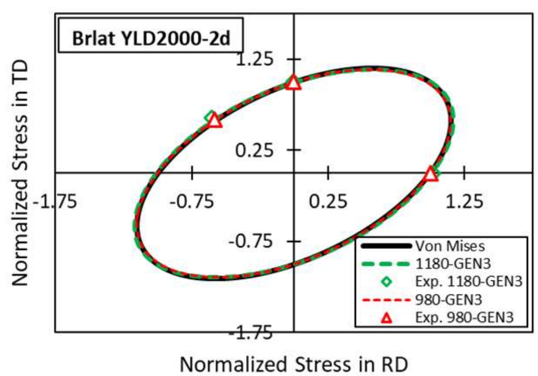


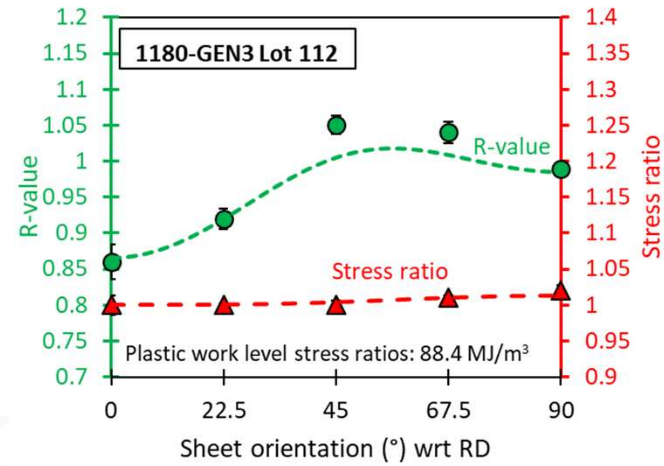
CONSTITUTIVE CHARACTERIZATION: ANISOTROPY

Rather mild anisotropy in both 3rd GEN steels → Calibrated Yld2000 model

980-3rd Gen Lot 112	R_0	$R_{22.5}$	R_{45}	$R_{67.5}$	R_{90}	R_b
	0.92	0.95	1.02	0.98	0.98	1.00
	σ_0/σ_0	$\sigma_{22.5}/\sigma_0$	σ_{45}/σ_0	$\sigma_{67.5}/\sigma_0$	σ_{90}/σ_0	τ_{12}/σ_0
	1.00	0.98	0.97	0.98	1.00	0.586
1180 3rd Gen Lot 111	R_0	$R_{22.5}$	R_{45}	$R_{67.5}$	R_{90}	R_b
	0.86	0.92	1.05	1.04	0.99	0.92
	σ_0/σ_0	$\sigma_{22.5}/\sigma_0$	σ_{45}/σ_0	$\sigma_{67.5}/\sigma_0$	σ_{90}/σ_0	τ_{12}/σ_0
	1.00	1.00	1.00	1.01	1.02	0.605

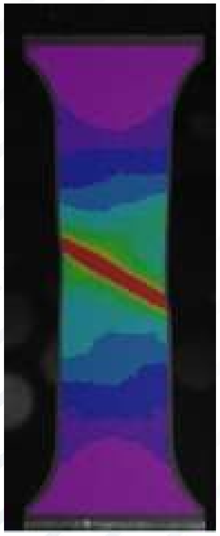




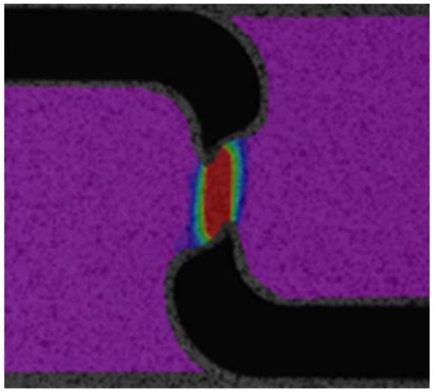


CONSTITUTIVE CHARACTERIZATION: *ISOTROPIC HARDENING*

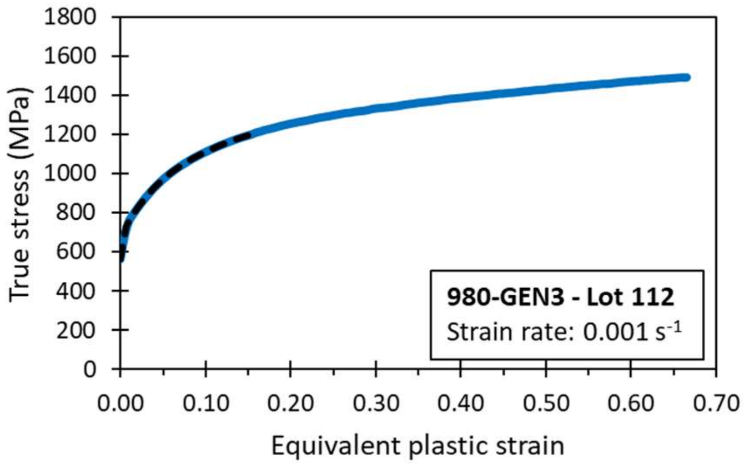
- Isotropic hardening response obtained using tensile & shear tests
- Methodology in Rahmaan *et al.* (2017) and refined in Noder & Butcher (2019)
- Kinematic hardening characterization in-progress for springback simulations



Tensile Test until UTS



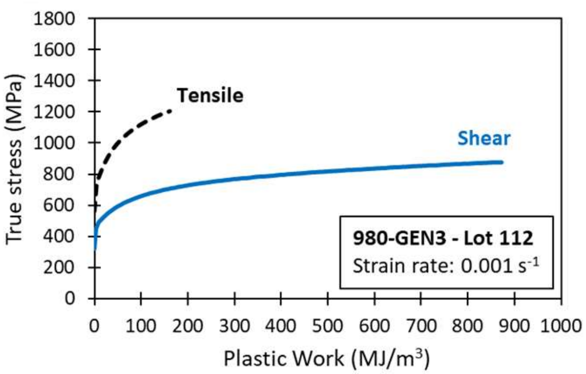
Simple Shear After Tensile UTS

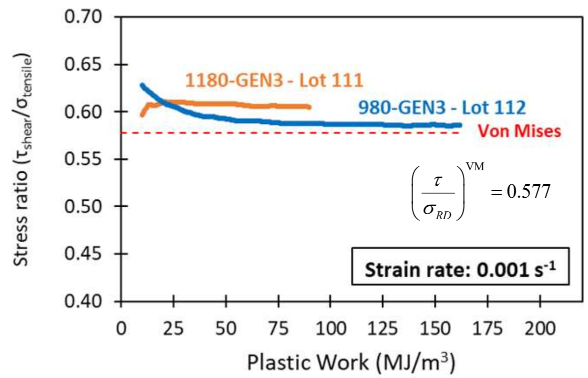


Rahmaan, T., Abedini, A., Butcher, C., Pathak, N., Worswick, M. J., (2017). Investigation into the shear stress, localization and fracture behaviour of DP600 and AA5182-O sheet metal alloys under elevated strain rates, International Journal of Impact Engineering, 108, 303-321.
Noder, J., Butcher, C., (2019). An Investigation into the Influence of the Constitutive Model on the Prediction of In-Plane Formability and Process Corrections for Nakazima and Marciniak Tests, submitted to International Journal of Mechanical Sciences.

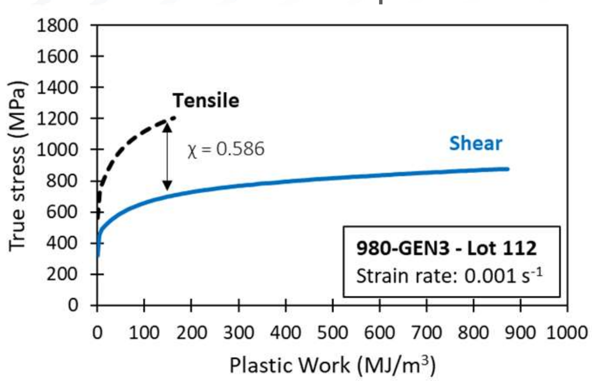
CONSTITUTIVE CHARACTERIZATION: *TENSILE & SHEAR TESTS*

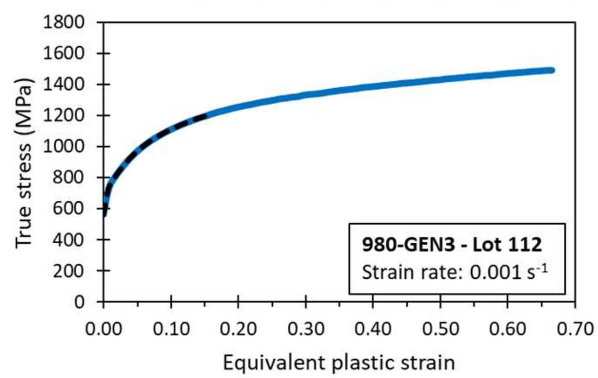
Step 1: Convert tensile and shear tests to Stress vs. Plastic work and obtain shear-to-tensile ratio





Step 2: Convert shear stress post tensile UTS, deconstruct work to equivalent plastic strain & fit model





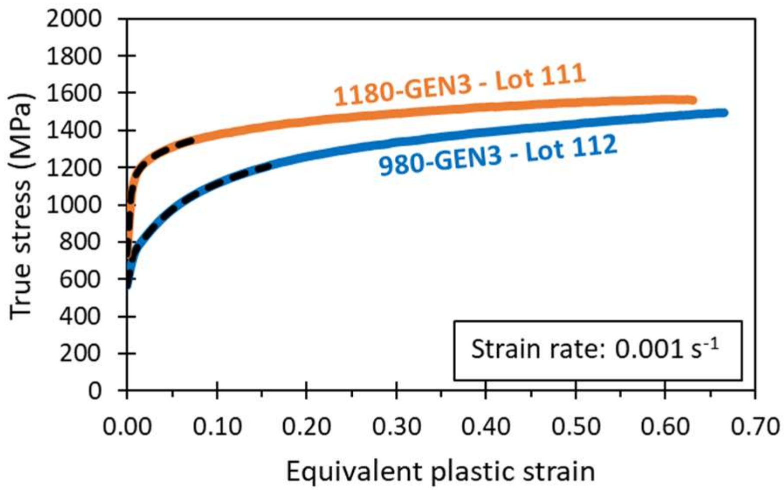
Rahmaan, T., Abedini, A., Butcher, C., Pathak, N., Worswick, M. J., (2017). Investigation into the shear stress, localization and fracture behaviour of DP600 and AA5182-O sheet metal alloys under elevated strain rates, International Journal of Impact Engineering, 108, 303-321.

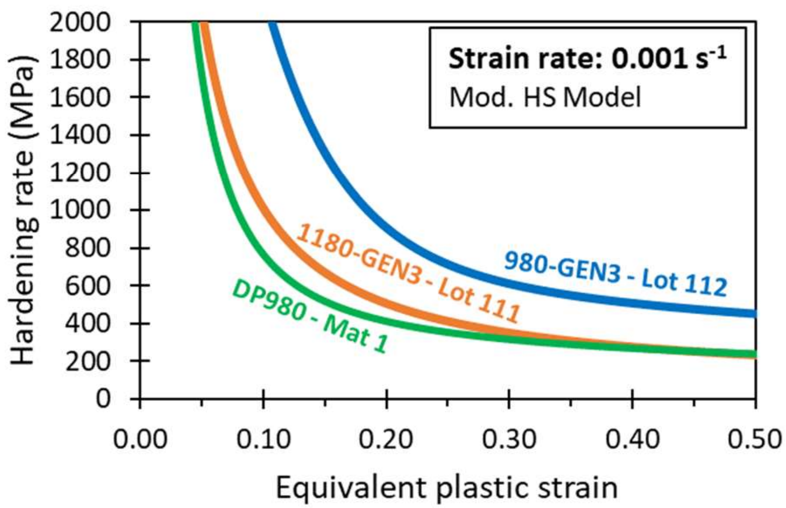
Noder, J., Butcher, C., (2019). An Investigation into the Influence of the Constitutive Model on the Prediction of In-Plane Formability and Process Corrections for Nakazima and Marciniak Tests, submitted to International Journal of Mechanical Sciences.

CONSTITUTIVE CHARACTERIZATION: *TENSILE & SHEAR TESTS*

Hardening response obtained until large strains without inverse FEA

Method assumes anisotropy does not evolve past the tensile UTS

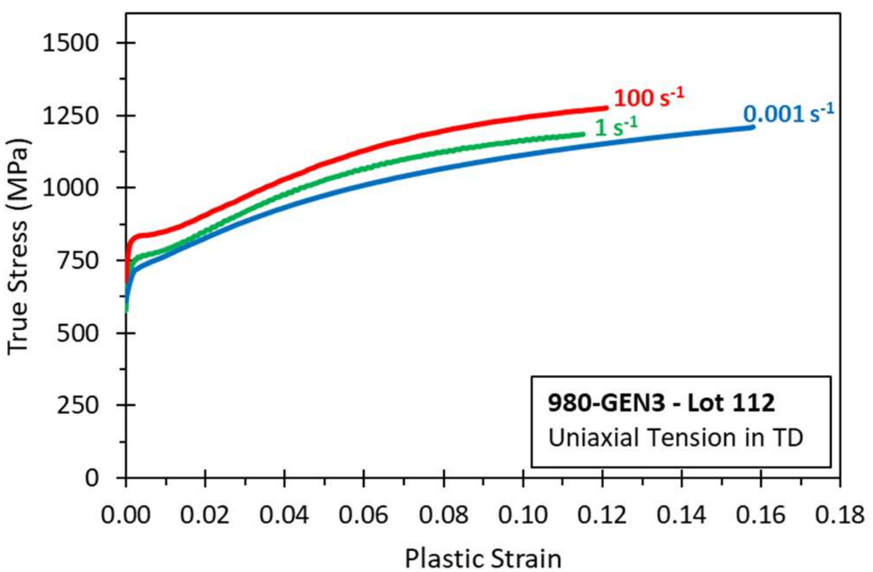


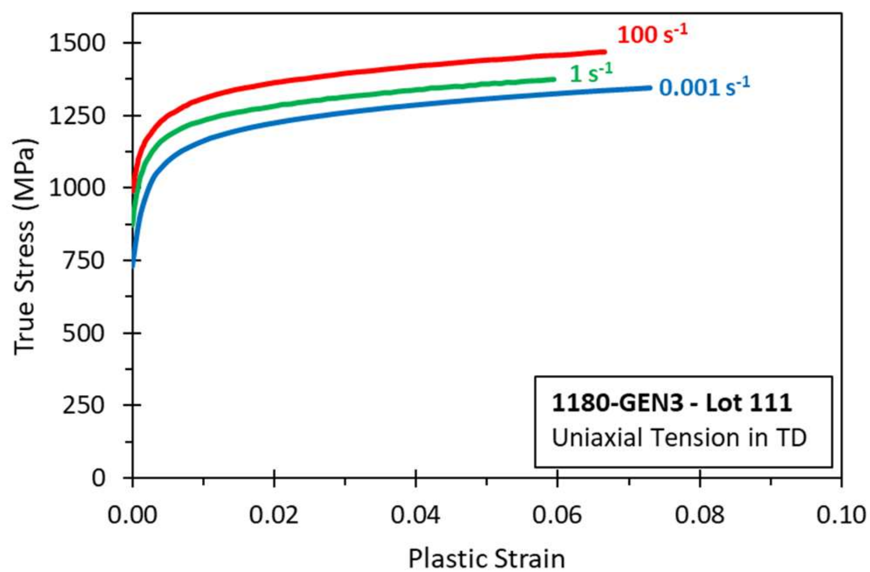


Relatively simple to select and calibrate a hardening model, uncertainty with extrapolation is reduced

CONSTITUTIVE CHARACTERIZATION: *ELEVATED STRAIN RATES*

Hardening response of 980 & 1180 evaluated at 0.001/s, 1/s and 100/s



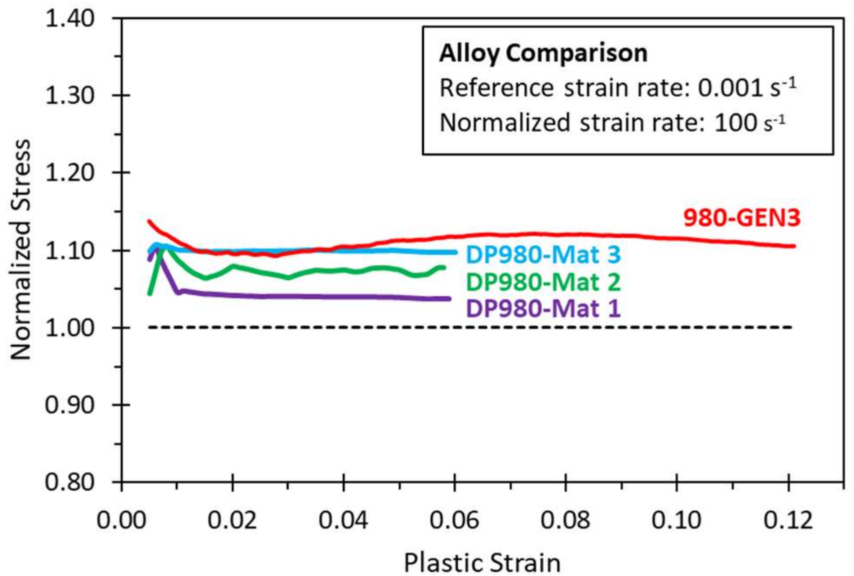


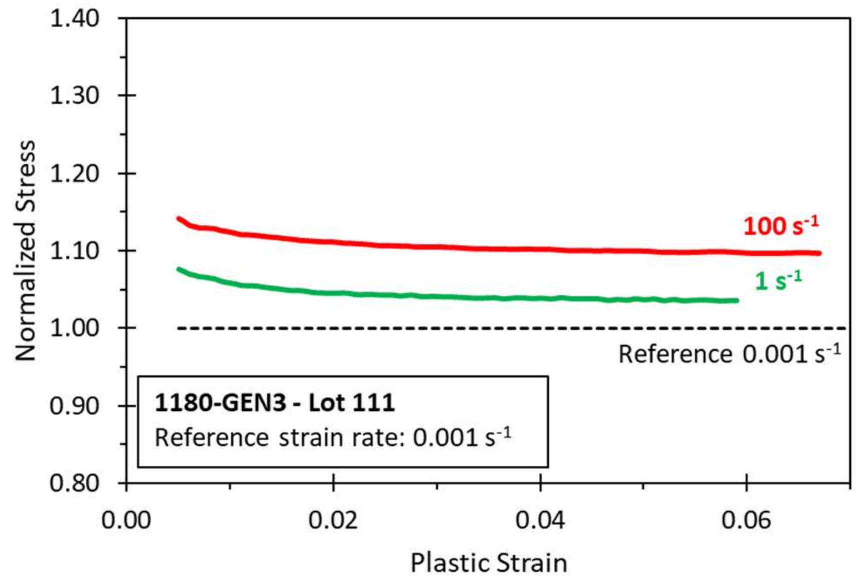
Positive rate-sensitivity: Appreciable non-linear hardening with strain rate in 980 3rd GEN

CONSTITUTIVE CHARACTERIZATION: *ELEVATED STRAIN RATES*

Strain rate effects are appreciable at strain-rates for forming operations: *Improves Formability*

980 3rd GEN has 5% higher flow stress at 1/s and is 10% higher at 100/s





FORMABILITY CHARACTERIZATION

- B-Pillar design is influenced by material limitations
  → Accurate formability characterization is required

- Bowman Precision Tooling in charge of B-Pillar design, machining of the die set, and forming trials
  → AutoForm software was used to identify critical sections in the B-Pillar
  → Material cards and FLCs created by UWaterloo to finalize the design

BOWMAN PRECISION TOOLING

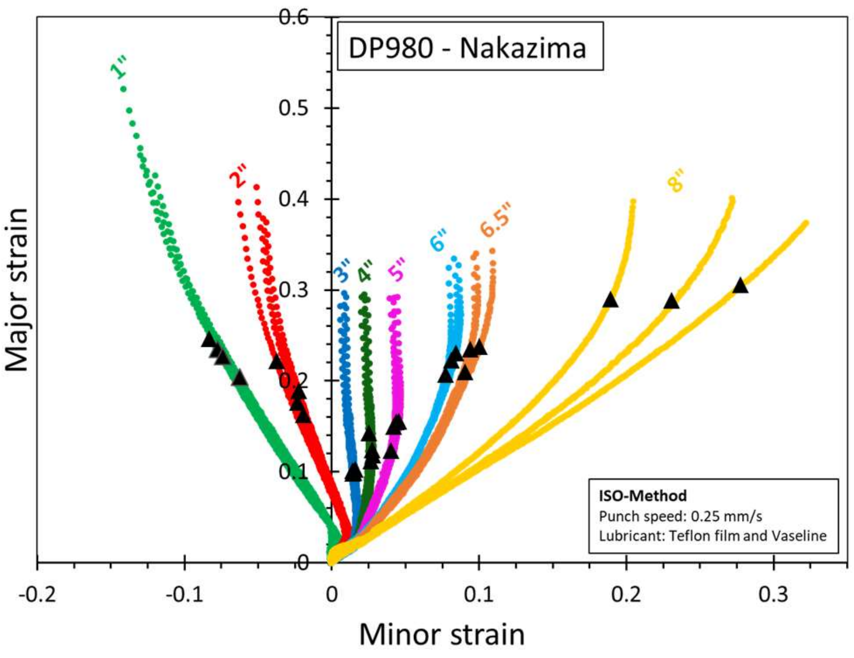
FORMABILITY CHARACTERIZATION

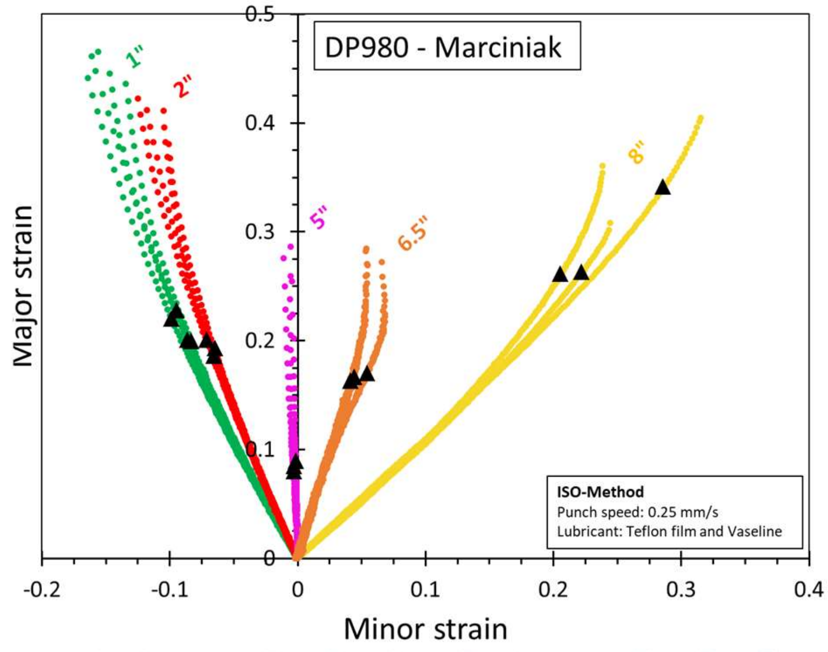
Nakazima dome tests: *Out-of-Plane Stretching*

→ Higher limiting strains and non-linear strain path

Marciniak tests: *In-plane deformation*

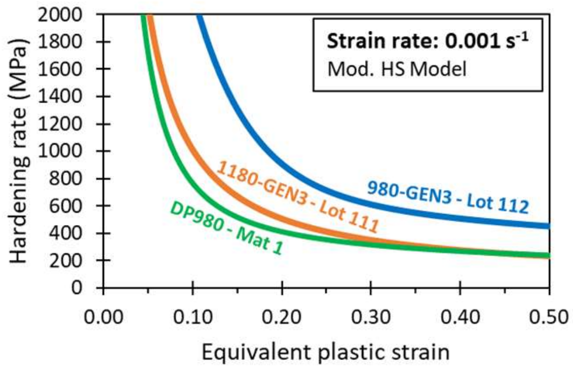
→ Approximately linear strain path & consistent with theoretical models for FLC

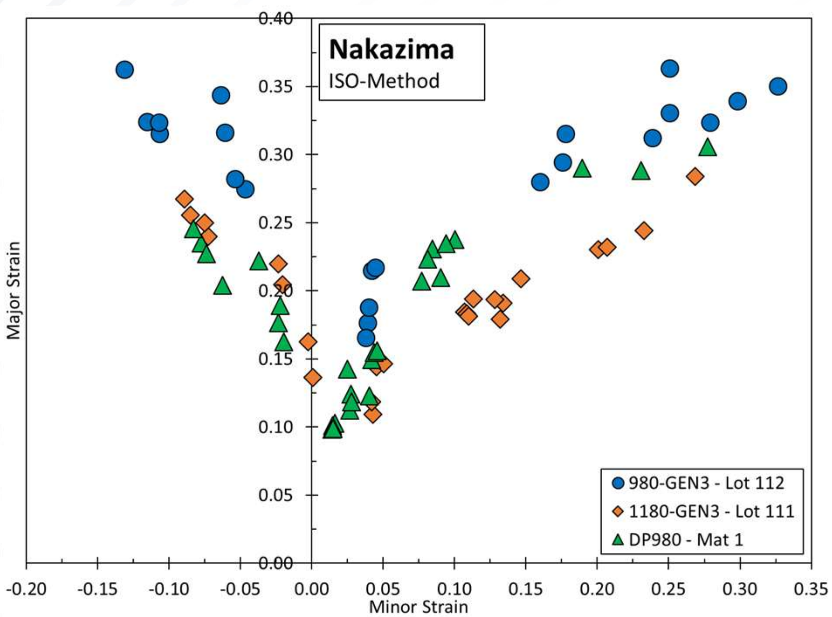


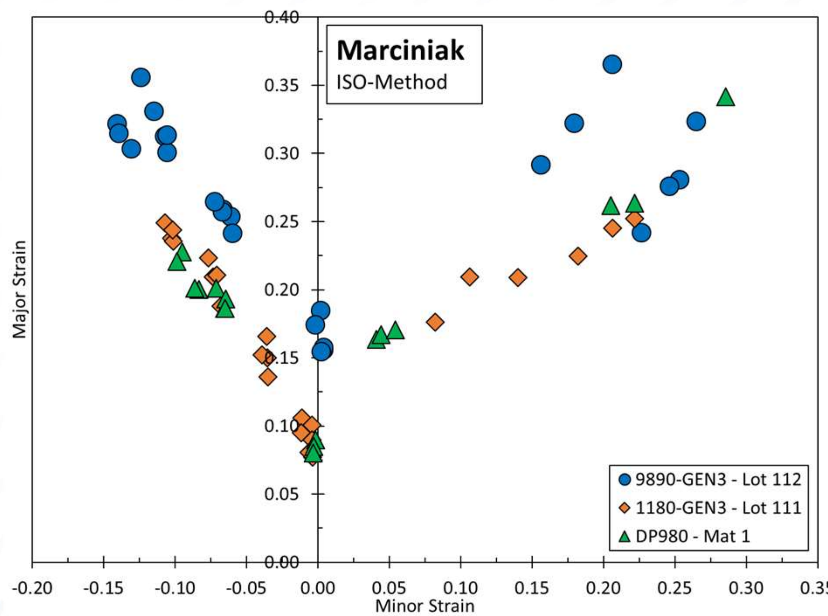


FORMABILITY COMPARISON

- Same conclusions for Nakazima & Marciniak FLCs:
  - → Superior formability of 980 3rd GEN. vs. DP980
  - → Similar FLC for DP980 and 1180 3rd GEN.







FORMABILITY: NAKAZIMA VS. MARCINIAK FLC

Which Forming Limit Curve to use?

Nakazima FLC has "process effects" of *bending, non-linear strain paths* and *tool contact* that alter the limit strains

Nakazima tests are generally preferred for simplicity of testing

Inconsistent to use Nakazima FLC data without compensating for process effects

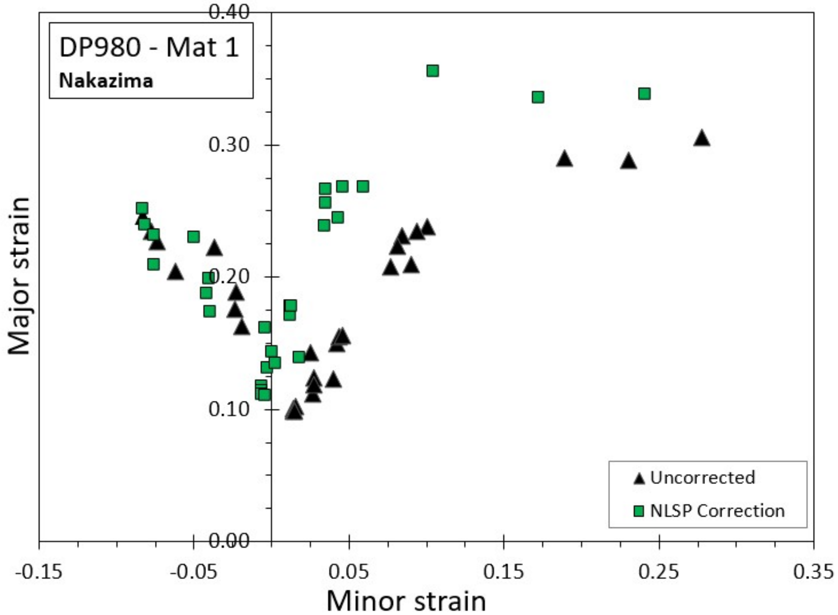
Adopted methodology of Min et al. (2016) to correct the FLC data of DP980 and 3rd GEN. steels

Min, J., Stoughton, T. B., Carsley, J. E., Lin, J., (2016). Compensation for process-dependent effects in the determination of localized necking limits, International Journal of Mechanical Sciences, 117, 115-134.

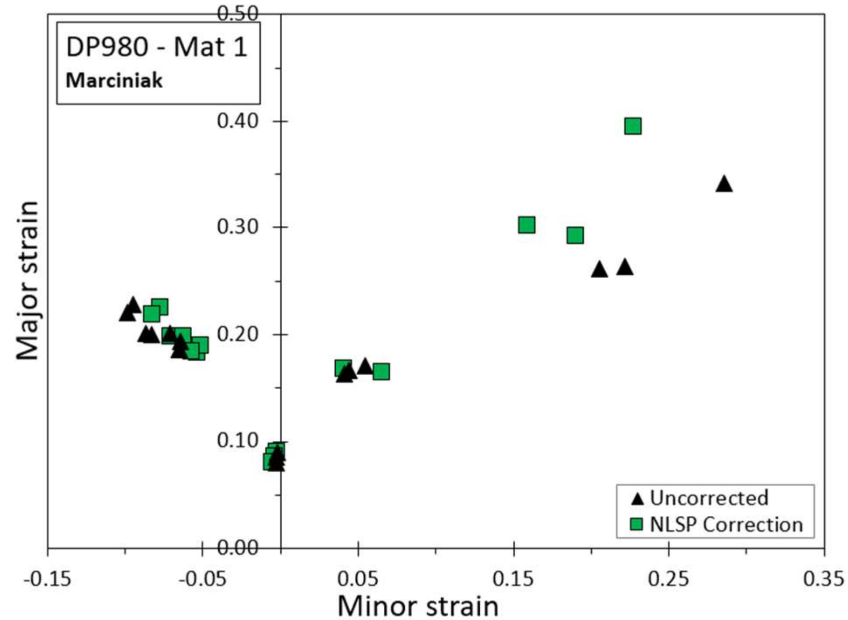
FLC PROCESS CORRECTIONS

- Details of correction methodology provided in Min *et al.* (2016, IJMS)
- Applied for DP980 and 3rd GEN.

Apply Non-linear Strain Path (NLSP) Corrections for DP980 (1.2 mm)



Significant correction for NSLP in Nakazima tests

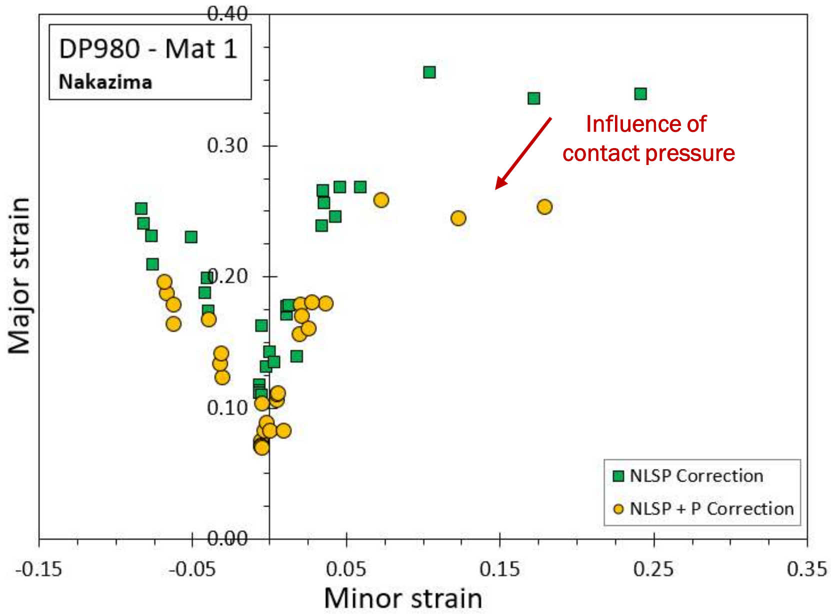


Minor NSLP effects in Marciniak. Largest in Biaxial Stretching

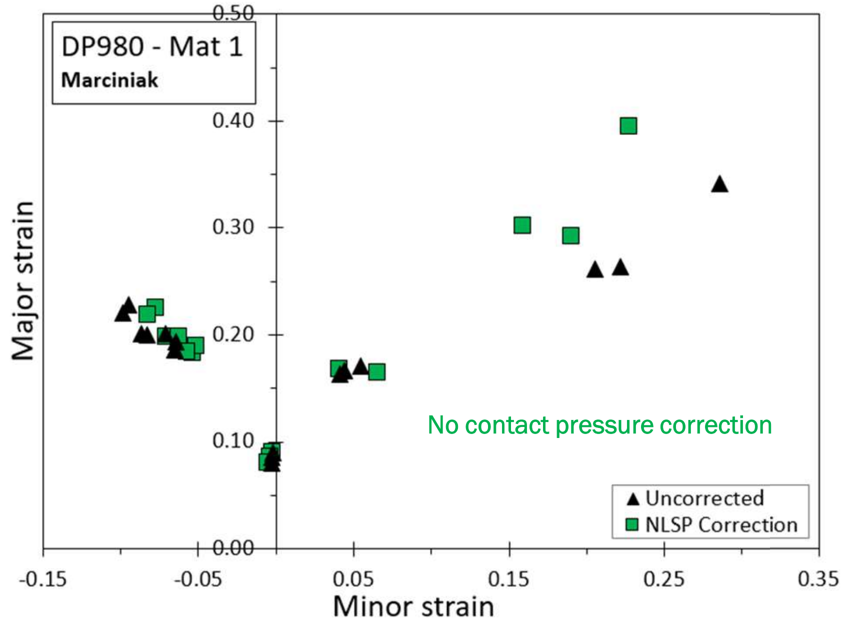
Min, J., Stoughton, T. B., Carsley, J. E., Lin, J., (2016). Compensation for process-dependent effects in the determination of localized necking limits, International Journal of Mechanical Sciences, 117, 115-134.

FLC PROCESS CORRECTIONS: *TOOL CONTACT*

- Stress-based mapping strategy for 3D and Plane Stress forming limits used to remove influence of contact stress



Significant contact pressure adjustment



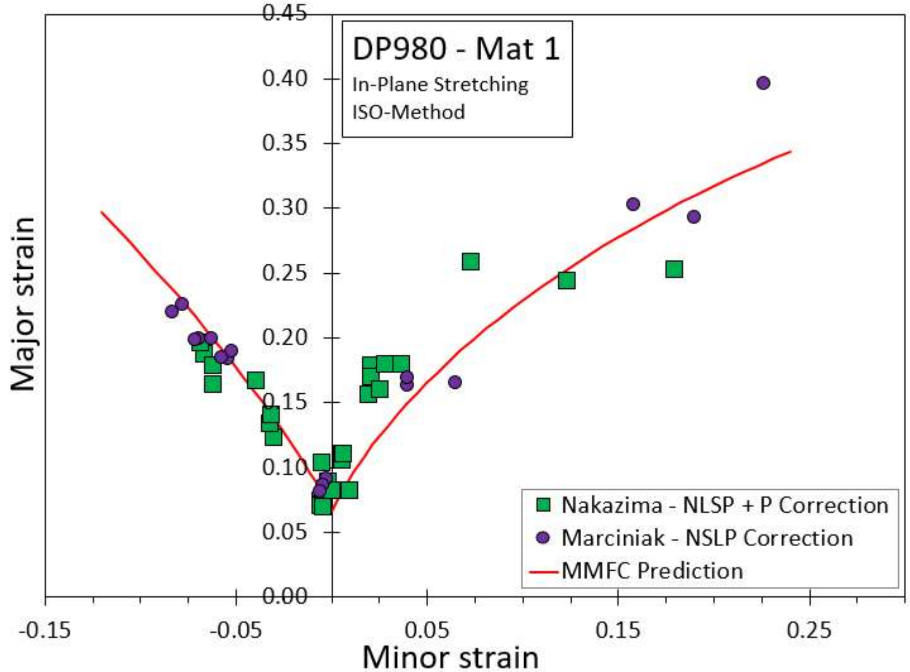
No contact pressure correction for Marciniak

Min, J., Stoughton, T. B., Carsley, J. E., Lin, J., (2016). Compensation for process-dependent effects in the determination of localized necking limits, International Journal of Mechanical Sciences, 117, 115-134.

FLC & ANALYTICAL PREDICTION: DP980

Corrected Nakazima FLC in good agreement with Marciniak

Analytical prediction of FLC using Modified Maximum Force Criterion of Hora et al. (2013) in very good agreement: *Only requires yield surface & hardening model*

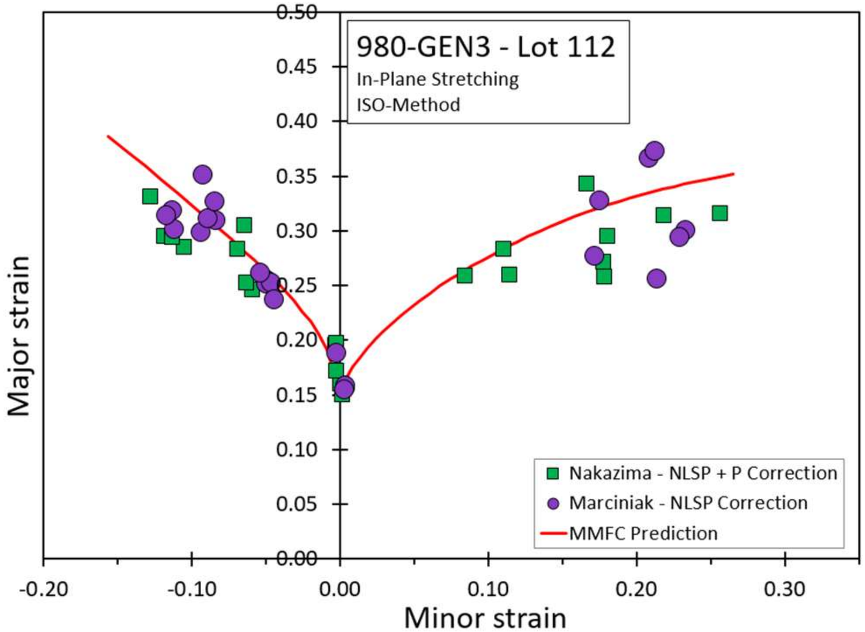


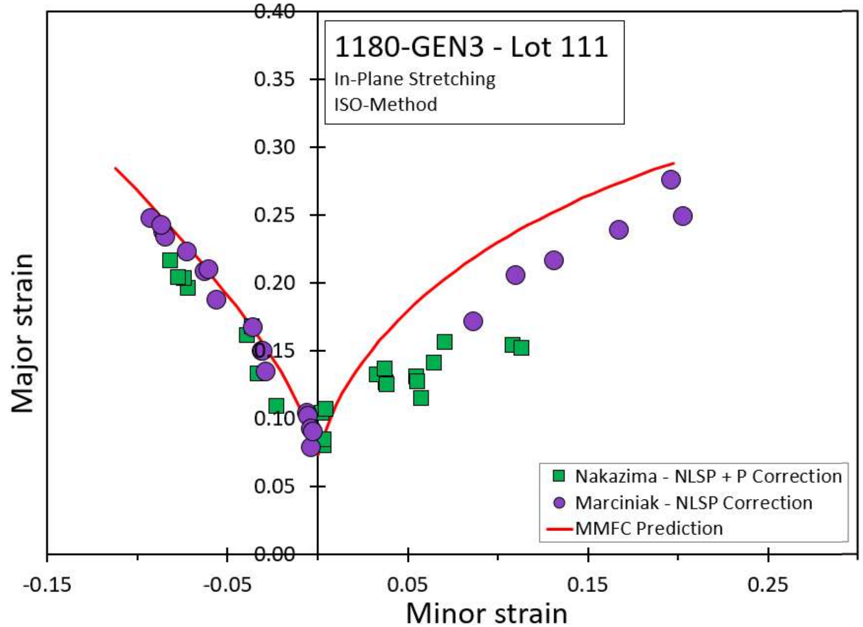
Hora, P., Tong. L., Berisha, B., (2013). Modified maximum force criterion, a model for the theoretical prediction of forming limit curves, International Journal of Material Forming, 6, 267-279.

FLC & ANALYTICAL PREDICTION: 3RD GEN. STEEL

Corrected Nakazima FLCs for 3rd GEN. also in good agreement with Marciniak

Simple MMFC model with isotropic assumption can predict the FLCs with only hardening data. *No calibration parameters*

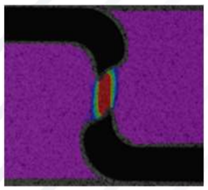




INDUSTRIAL STRATEGY FOR PLANE STRESS FRACTURE CHARACTERIZATION

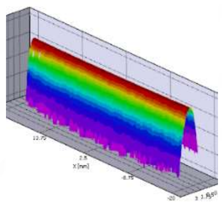
Fracture characterization and CAE application to rail sections detailed in GDIS 2017 & 2018

1. Perform 4 Plane Stress Characterization Tests

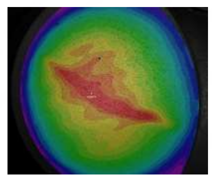


Shear

Conical
Hole Expansion



V-Bend
(VDA238-100)

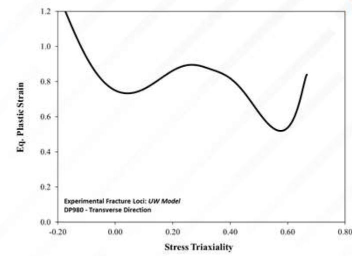


Biaxial Dome
(R = 5 mm)

2. Experimental Fracture Locus

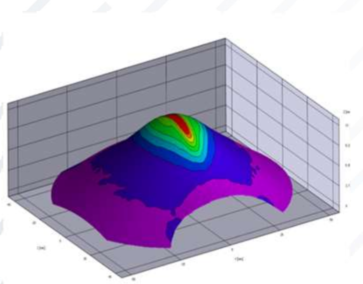
- Assume failure locus form & calibrate with 4 points

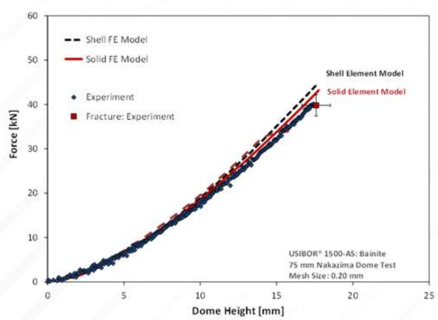
$$\varepsilon_f^{\exp} = \varepsilon^{UW}\left(T, a_{1-4}\right) \longrightarrow$$



Physically meaningful
fracture locus: *Not an FE construct*

3. Plane Stress Models with Various Mesh Sizes



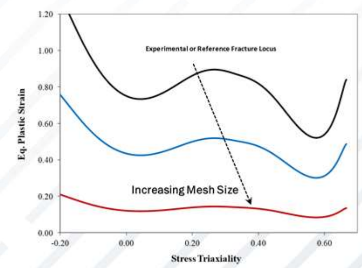


4. Regularize Exp. Fracture Locus for CAE

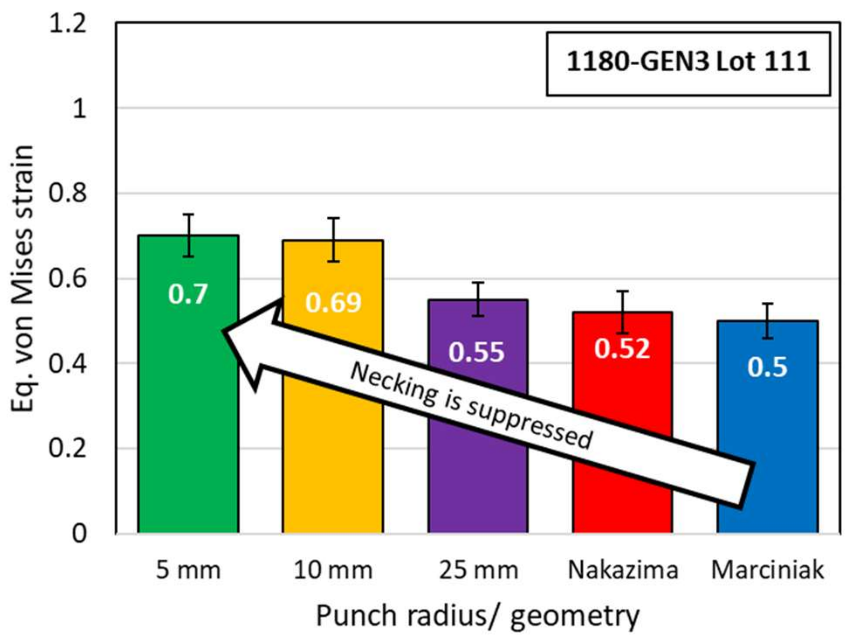
- Assume damage model & scale locus with mesh size, R:

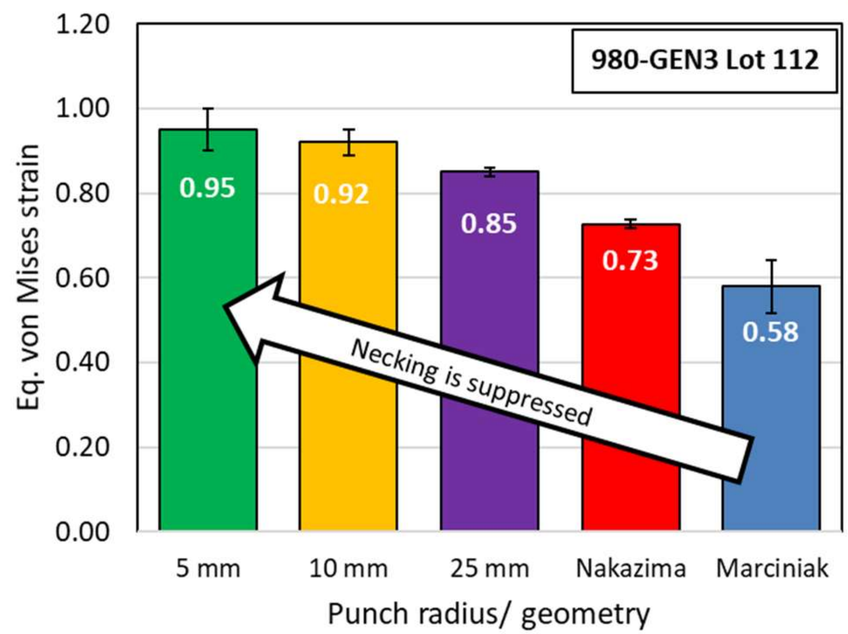
$$D = \frac{d\varepsilon^p}{\varepsilon_f\left(T\right)} \quad + \quad \longrightarrow$$

$$\varepsilon_f^{CAE}\left(R, \varepsilon_f^{\exp}\right) = R \cdot \varepsilon^{\exp}\left(T, a_i\right)$$



FRACTURE CHARACTERIZATION: BIAXIAL STRETCHING

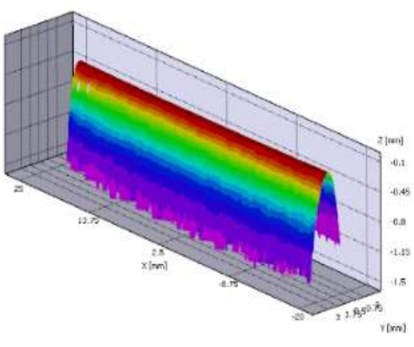




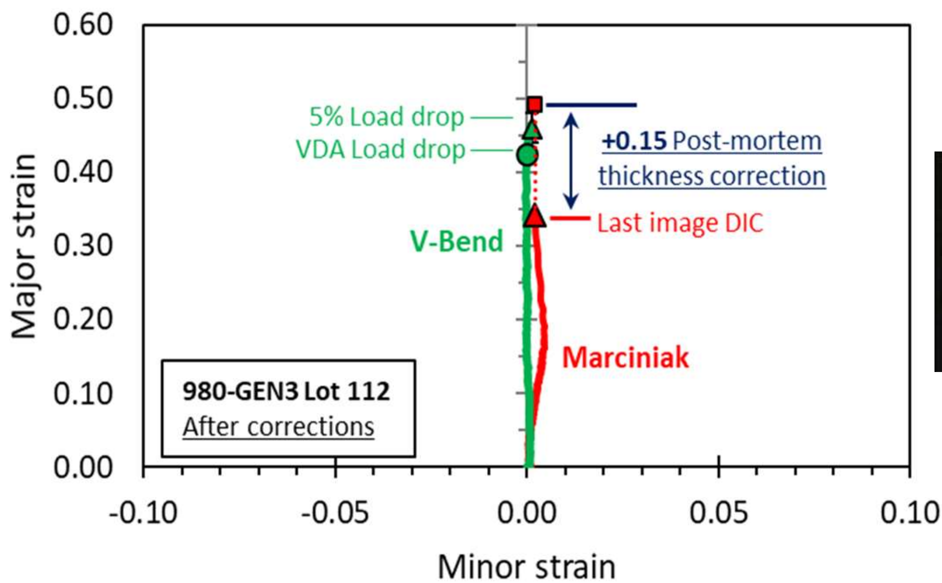
- Smaller punch radii suppress necking and thus give higher failure strains
- Marciniak is best for formability, not for fracture

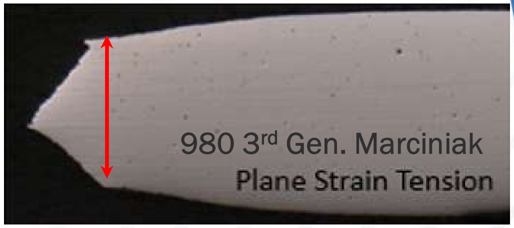
FRACTURE COUPON SELECTION: PLANE STRAIN

- Marciniak, Nakazima or notch tests could be used for plane strain but have strain localization: *Not plane stress until fracture and NLSP*
- DIC often underestimates fracture strain for coupons with localization
- VDA bend test with DIC avoids necking and provides linear path



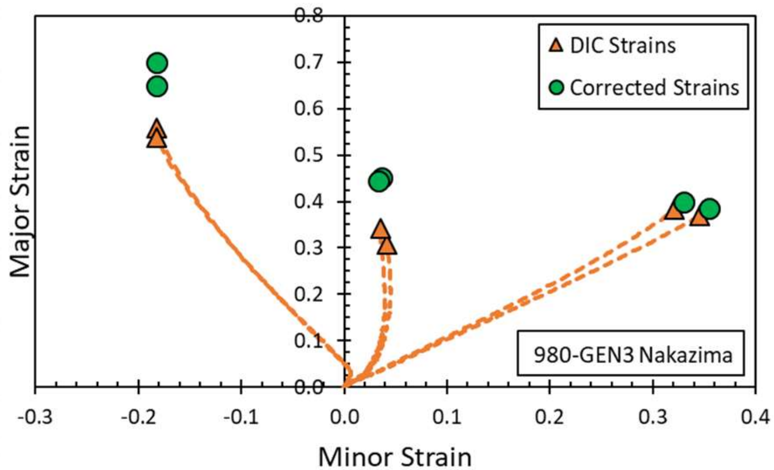
V-Bend test with DIC

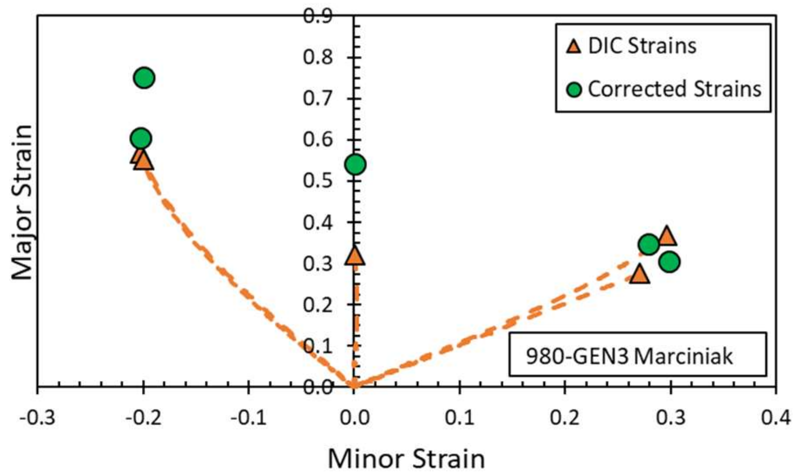




POST-MORTEM CORRECTIONS 980 3RD GEN.

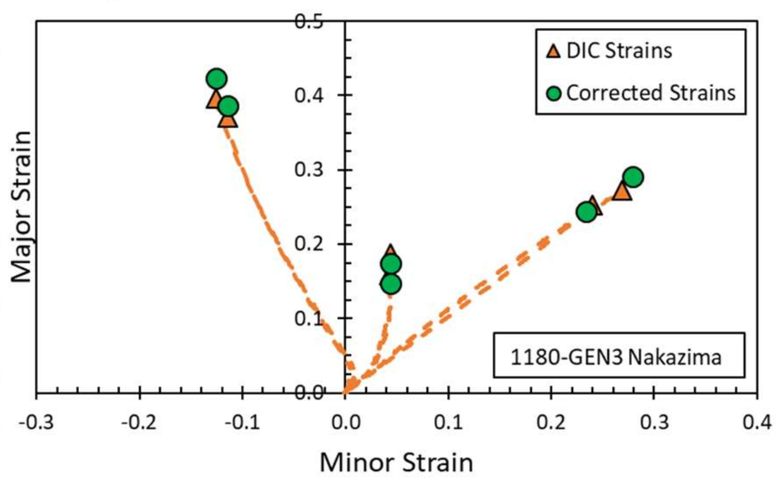
Non-linear strain path and underestimation of failure strains with DIC for necking-based fracture

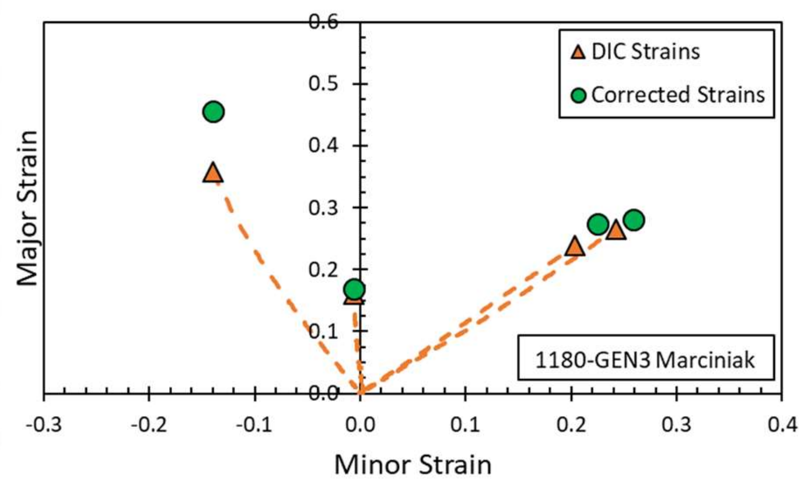




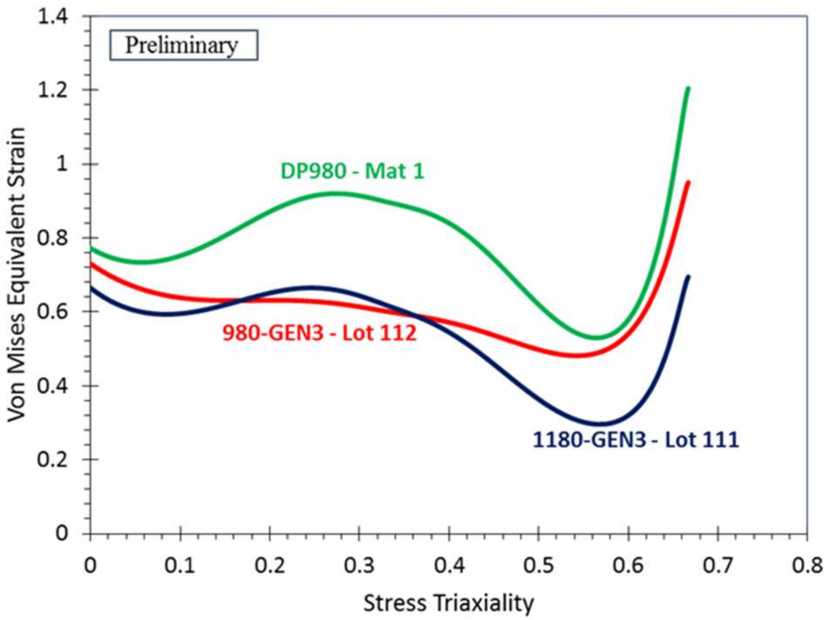
POST-MORTEM CORRECTIONS 1180 3RD GEN

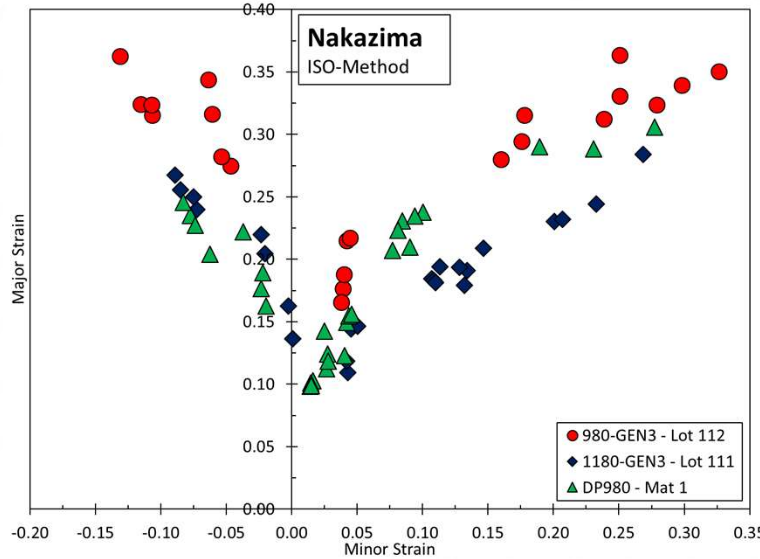
Reduced necking of 1180-3rd GEN from plane strain to biaxial stretching





FRACTURE CHARACTERIZATION





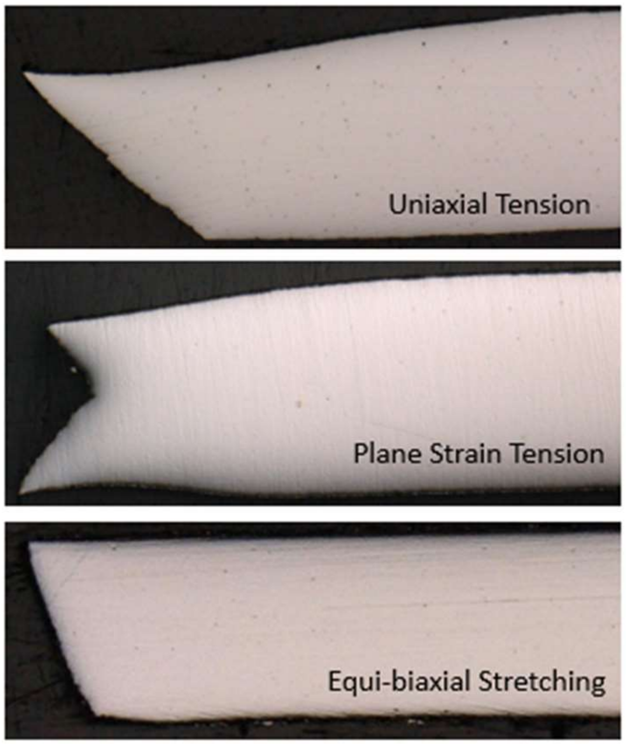
- DP980 and 1180 3rd Gen. have similar FLCs (global formability) but very different local formability

→ Trade-offs between formability (need high FLC) and crash performance (want high fracture strain)

FRACTURE IN FORMABILITY TESTS: 980 3^{RD} GEN.

Ductile-type fracture with necking in formability tests of 980 3^{rd} GEN.

Nakazima tests

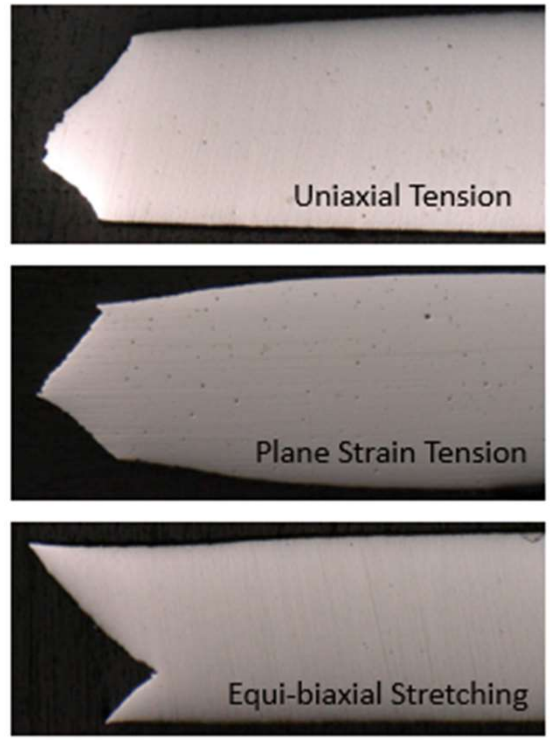


Necking

Necking

No Necking

Marciniak tests



Necking

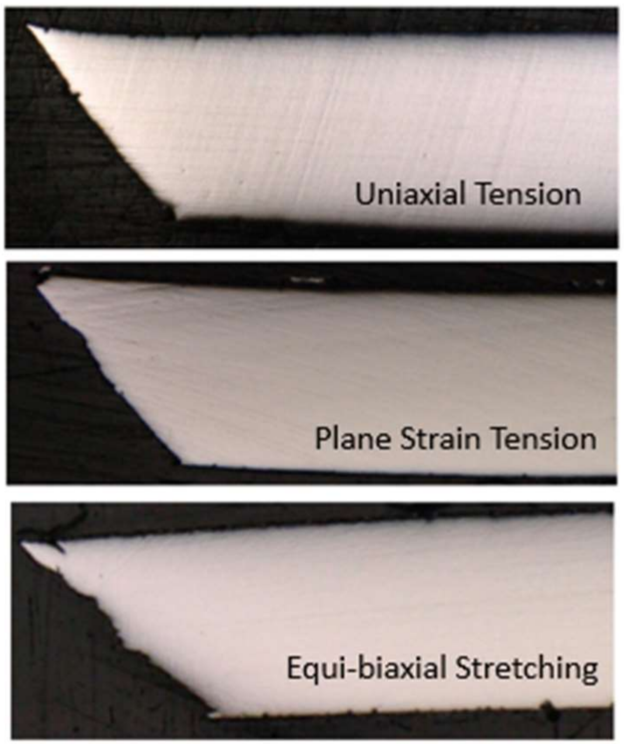
Necking

No Necking

FRACTURE IN FORMABILITY TESTS: 1180 3RD GEN.

1180 3rd GEN is showing marginal necking and through-thickness shear fracture

Nakazima tests

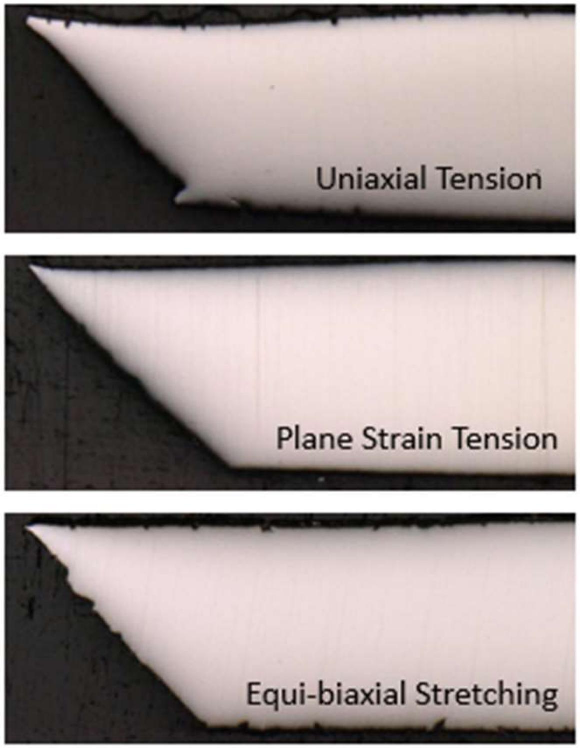


Minor Necking

No Necking

No Necking

Marciniak tests



Minor Necking

No Necking

No Necking

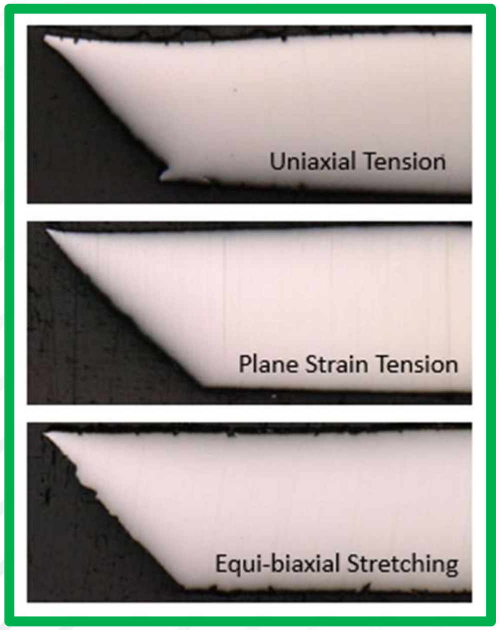
REVISITED FLC FOR 1180 3RD GEN.

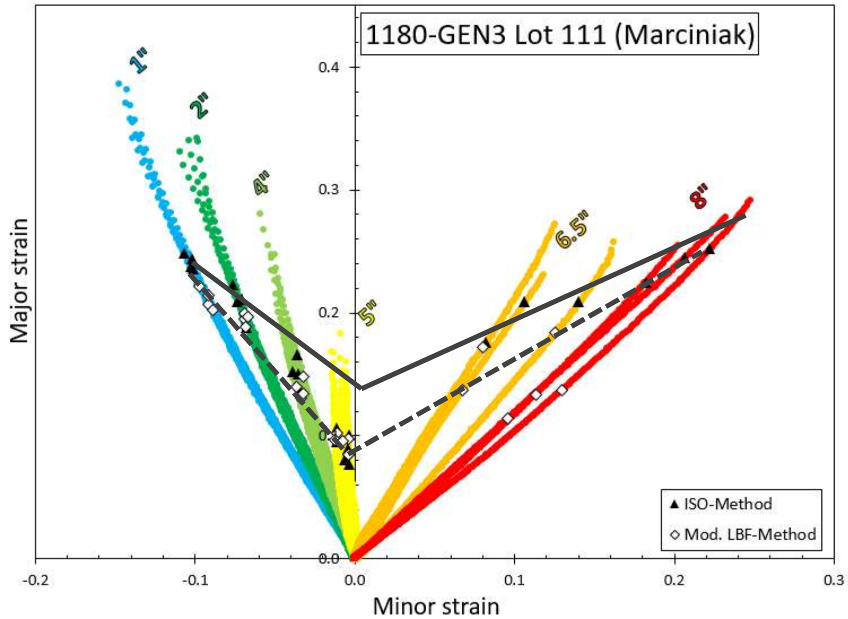
ISO-method and time-dependent (LBF) limit strains are not realistic for stretch side

Through-thickness shear fracture without necking from plane strain to biaxial stretching

Stretch-side of 1180 3rd GEN. FLC is conservative: Fracture limits are effective limit strain

Marciniak tests





OUTLOOK & FUTURE WORK

High-rate constitutive model to large strains and fracture locus for two 3rd GEN steels have been developed

Next steps:

- Transfer from coupon level testing to a structural component (B-Pillar)
- Experimental characterization for kinematic hardening to study springback
- B-pillar impact tests and CAE simulations from forming-to-crash

ACKNOWLEDGEMENTS

GDIS

BOWMAN
PRECISION TOOLING

HONDA
The Power of Dreams

UNIVERSITY OF
WATERLOO

AK Steel

Steel
Market Development
Institute

NUCOR®

ALGOMA
STEEL INC.

ArcelorMittal

FOR MORE INFORMATION

Cliff Butcher
University of Waterloo
cbutcher@uwaterloo.ca

Jim Dykeman
Honda Research America
Jdykeman@oh.hra.com

Jamie Bowman
Bowman Precision Tooling
jamie@jpbowmantool.com

GREAT DESIGNS IN STEEL

Presentations will be available for download on SMDI's website on Wednesday, May 22