Dynamic Considerations in Prediction of Fracture of Ultra High-Strength Steel During Crash

Presenter: Michael Worswick, uWaterloo

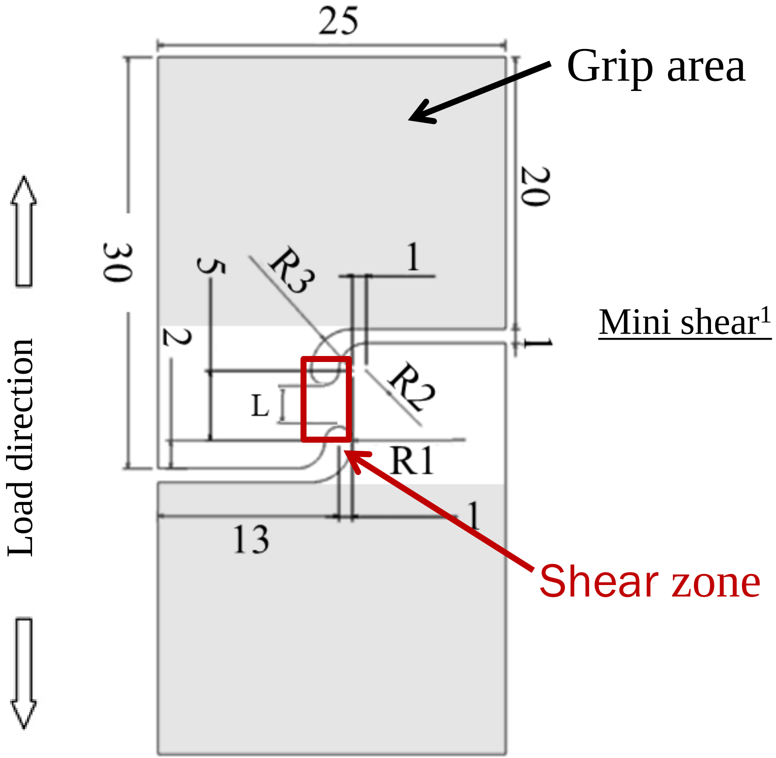
Co-Authors

A. Abedini, M. Nemcko, T. Rahmaan, N. Pathak,
C. O’Keefe, C. Tolton, A. Zhumagulov,
C. Butcher, M. Worswick
uWaterloo
S. Malcolm, J. Dykeman, *Honda R&D Americas*
C. Yau, *Promatek Research Centre*

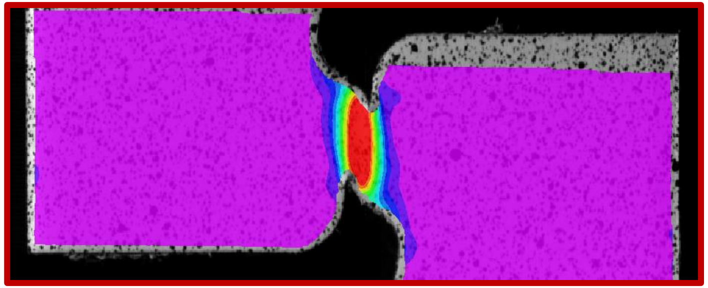
Overview

- High strain rate response of automotive alloys (tensile + shear characterization):
  - DP980 (SMDI), DP600
  - Fully quenched Usibor® 1500-AS, Ductibor® 500-AS
- Effect of strain rate on fracture?
  - Shear conditions (zero triaxiality)
  - Positive triaxiality conditions
- Weld failure characterization – “*spot weld groups*”

Shear Testing



Mini shear[1]



- Achieves shear strains easily on the order of unity with relatively constant triaxiality of zero**
- Appropriate for high rate testing in Hopkinson bar or high speed hydraulics (1-1000/s)

*J. Peirs, P. Verleysen, W. Van Paepegem, J. Degrieck, International Journal of Impact Engineering, **38**, 406-415, 2011.

Abedini, A., Butcher, C., Worswick, M.J., *Journal of Experimental Mechanics*, **57 (1), 75–88, 2017.

Dynamic Fracture

Issue today lies in the majority of fracture characterization for crash CAE being done at quasi-static rates…

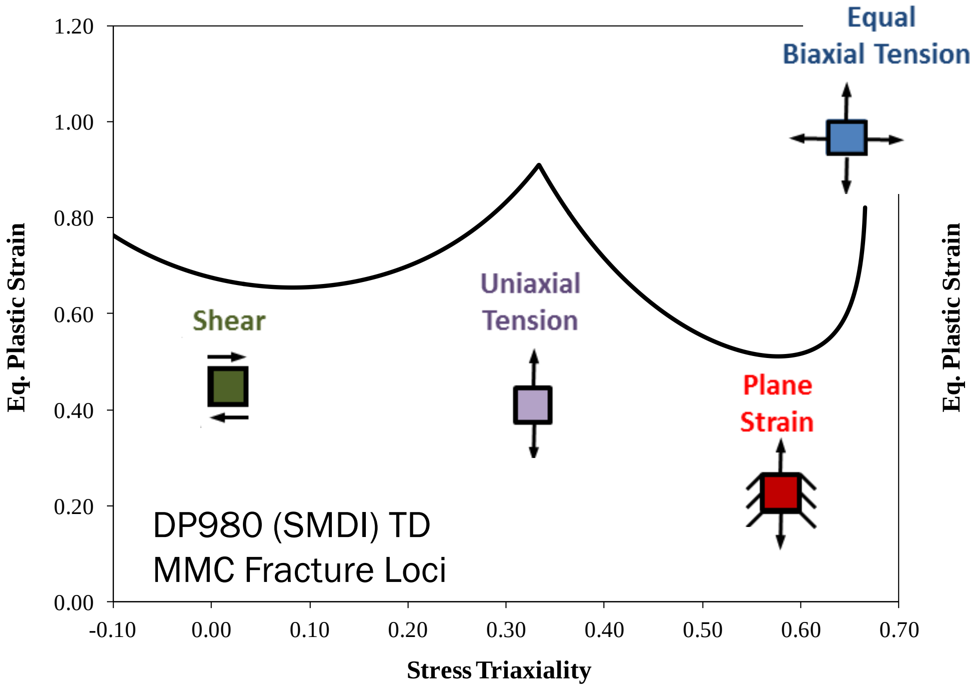
Potential sources of rate effects:

- Elevated strain rates
- Temperature increase through adiabatic heating (~90% of plastic work converted to heat) *
- Inertial effects

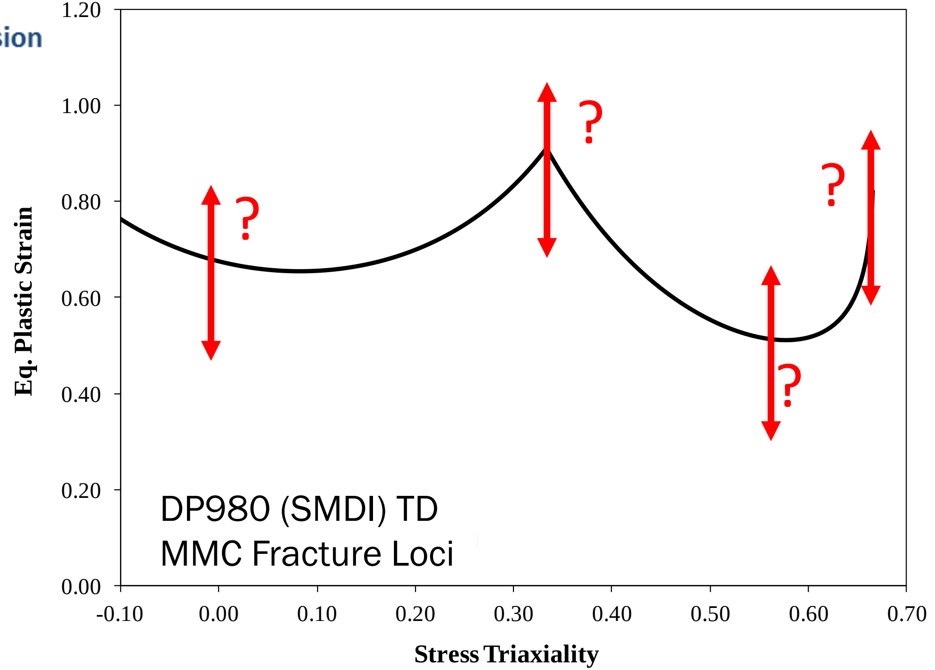
** Temperature increase also important for constitutive behaviour and not commonly considered in today's crash CAE…*

Dynamic Fracture

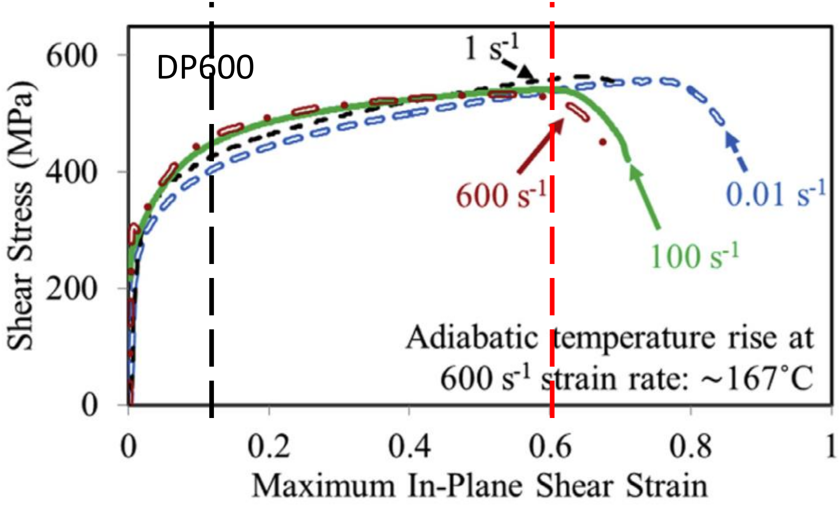
Quasi-static loading

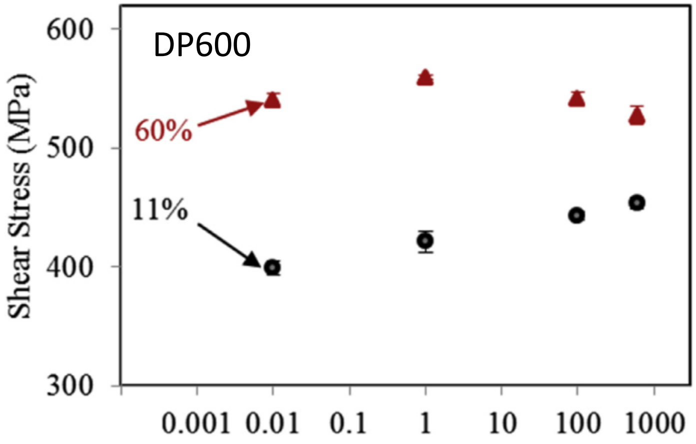


Effect of dynamic loading on failure strain?



Rate Effects – Shear (DP600)

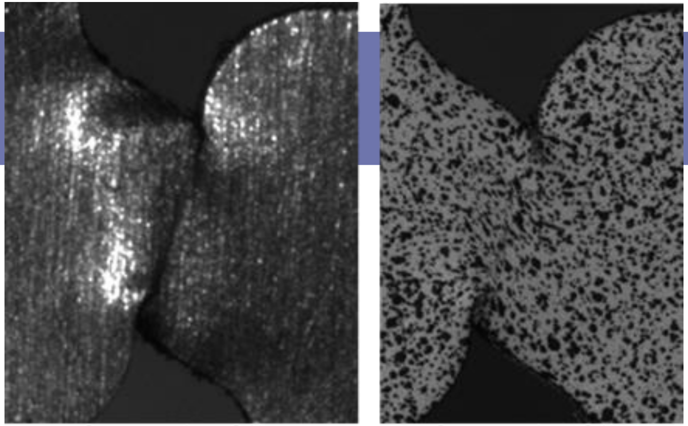




- Rate sensitivity is initially positive, but becomes negative at large strains
- Promotes earlier localization under shear loading*

*Rahmaan, T., Abedini, A., Butcher, C., Pathak, N., Worswick, M.J., *International Journal of Impact Engineering,* **108,** 303-321, 2017.

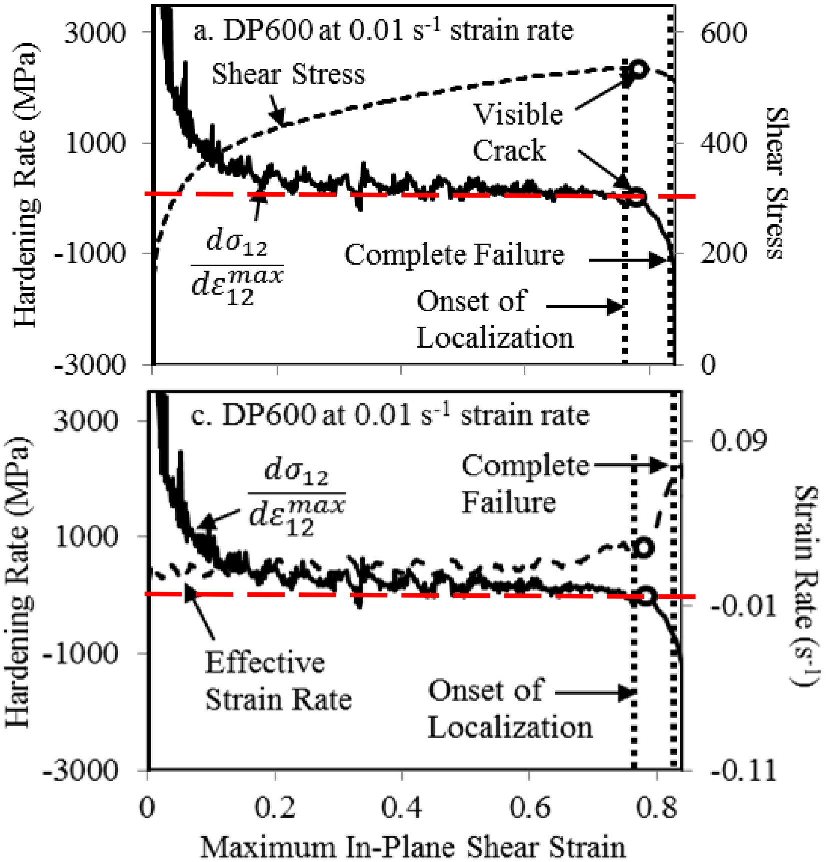
Onset of Shear Localization



After complete failure
Specimen without speckle

After complete failure
Specimen with speckle

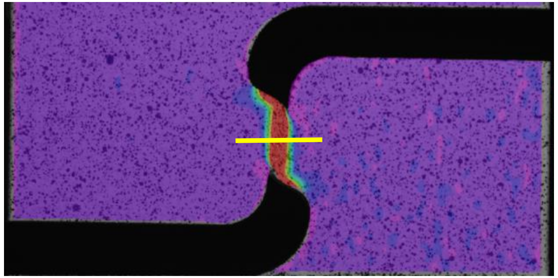
- Onset of shear cracking is determined as the point where the hardening rate is exhausted[1]
- Repeatable and eliminates the need to detect fracture based on visible cracking[2]



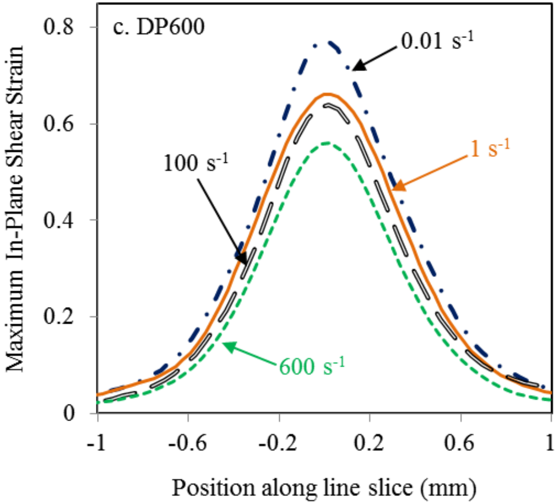
[1]Zener and Hollomon, Journal of Applied Physics, **15,** 22-32, 1944.

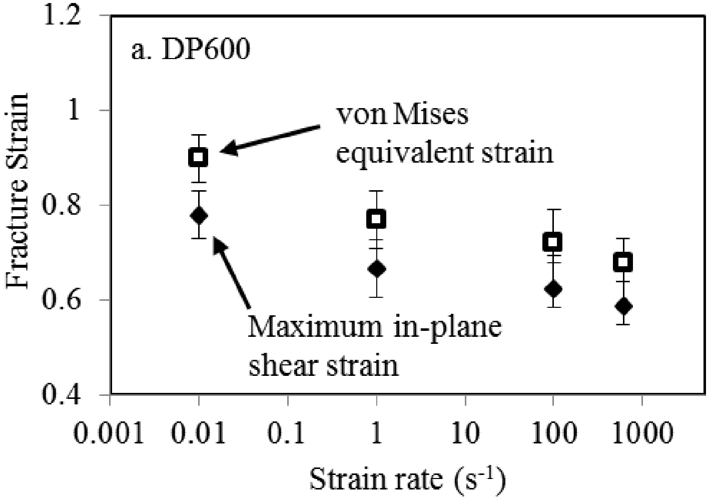
[2]Rahmaan, T., Abedini, A., Butcher, C., Pathak, N., Worswick, M.J., *International Journal of Impact Engineering,* **108,** 303-321, 2017.

Effect of strain rate on failure strain

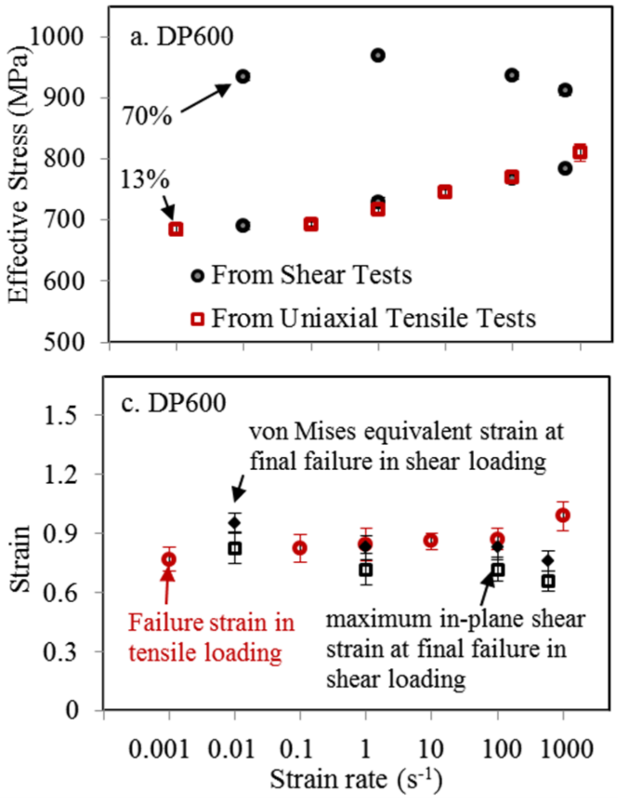


Earlier localization at higher strain rates due to thermal instability promotes lower fracture strain (DIC measurements)





Failure in Uniaxial Tension versus Shear – Rate Effect



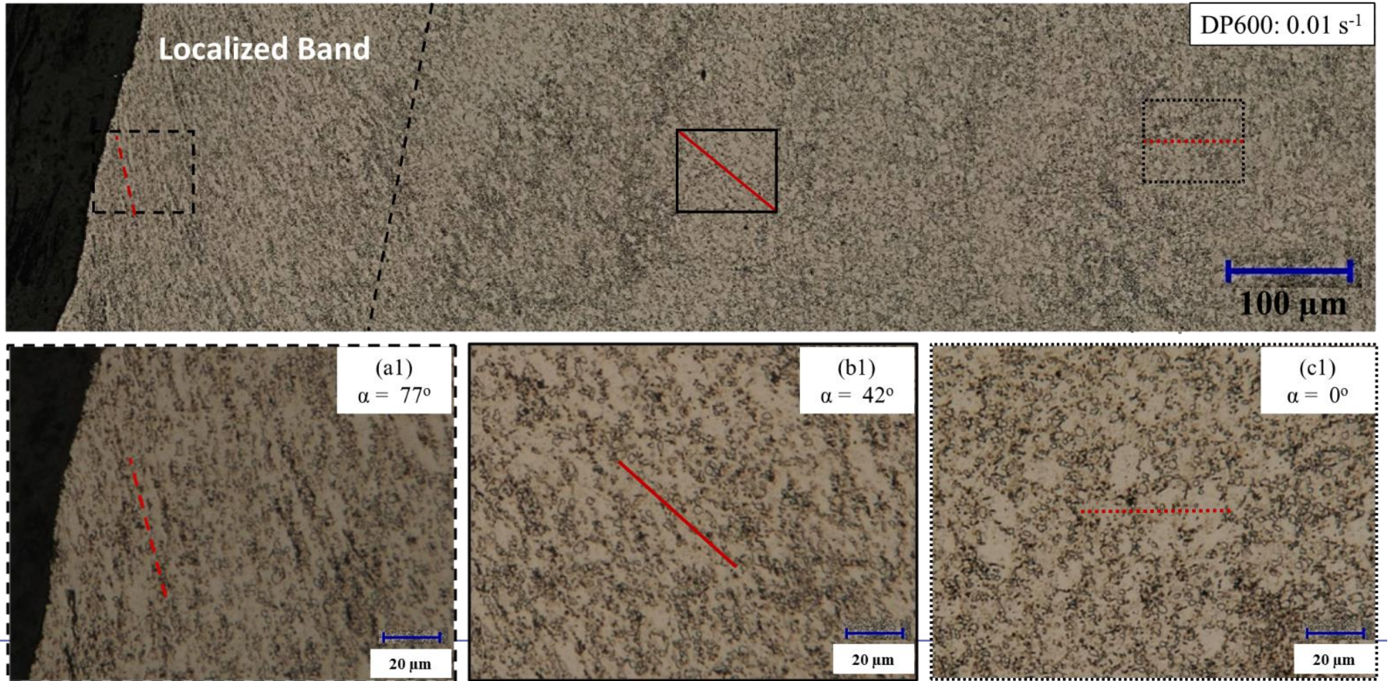
In tension, positive rate sensitivity promotes higher failure strains as strain rate increases.

In shear, thermal localization reduces failure strain (as measured using DIC) with increasing strain rate.

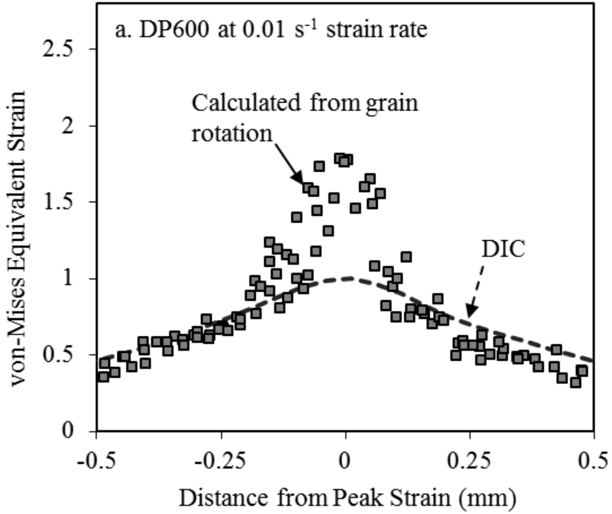
Local Strains at Failure

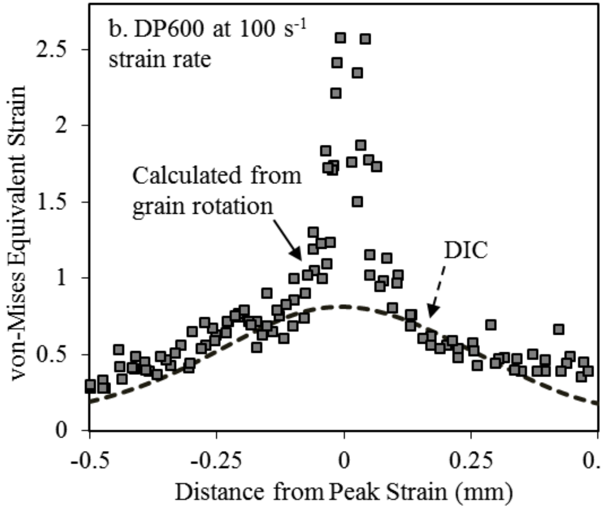
- At microstructural level, gain rotation can be used to estimate the local shear strains within the shear band (gives shear angle, α)

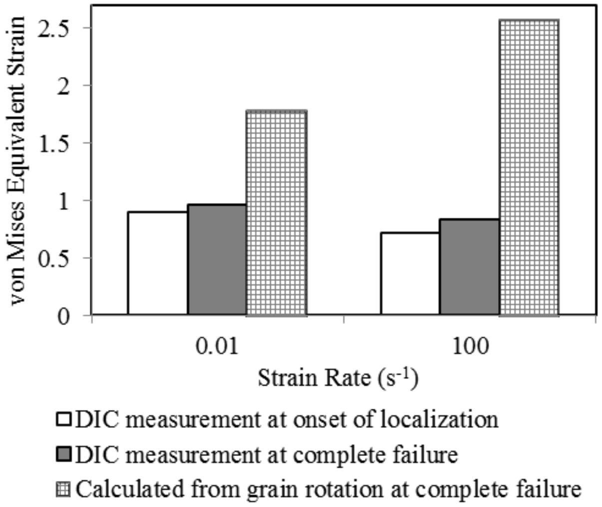
$$\varepsilon_{eq}^{VM} = \frac{2}{\sqrt{3}}\varepsilon_1 = \frac{2}{\sqrt{3}}\sinh^{-1}\left({}^{\gamma}/_{2}\right) \qquad \gamma = \tan(\alpha)$$

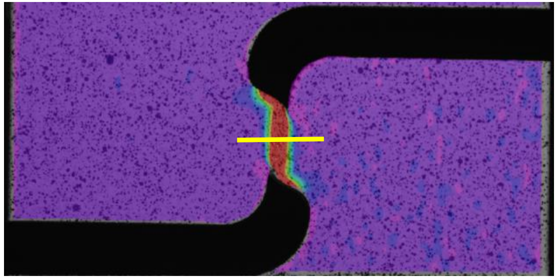


Local Strains at Failure



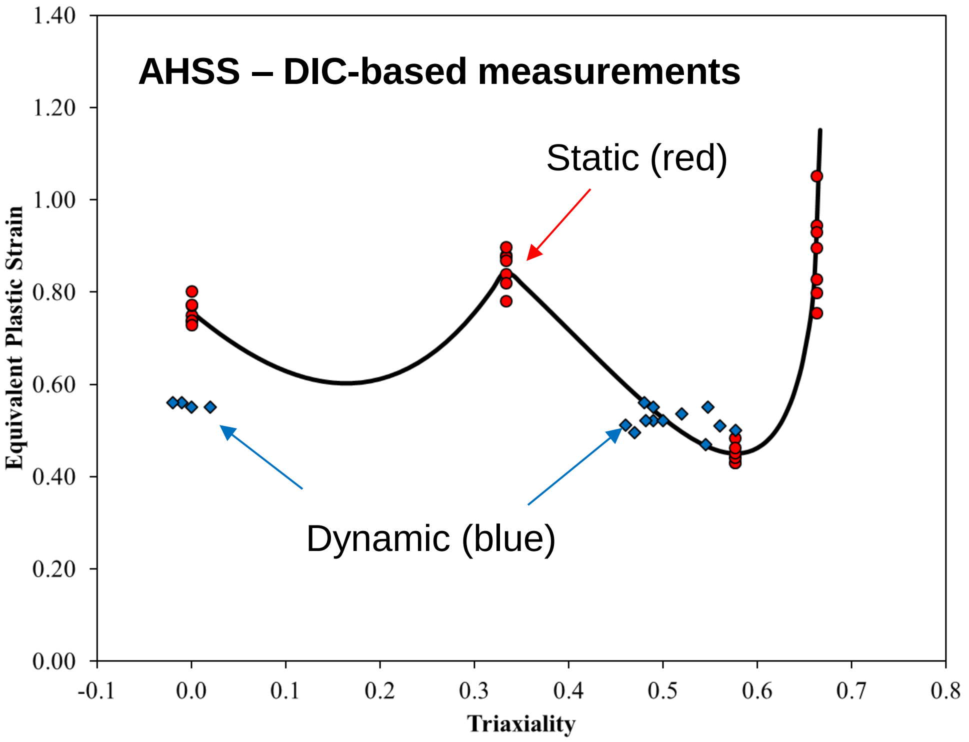






Sharper strain localization and higher peak strains using the grain-level strain measurement as compared to DIC measurements.

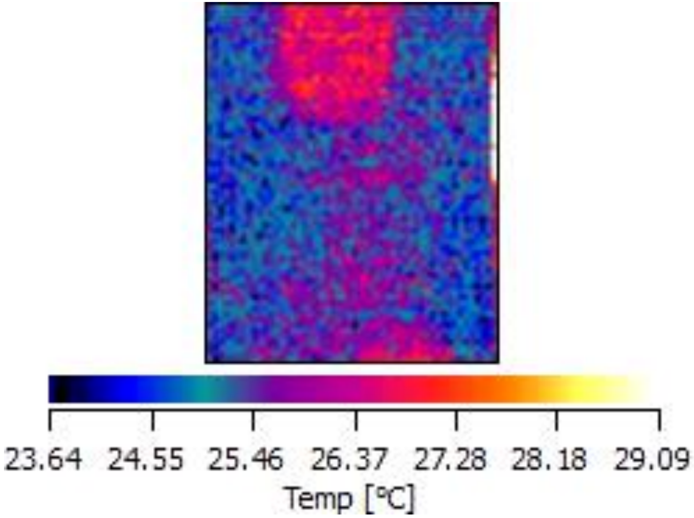
Implications for crash CAE



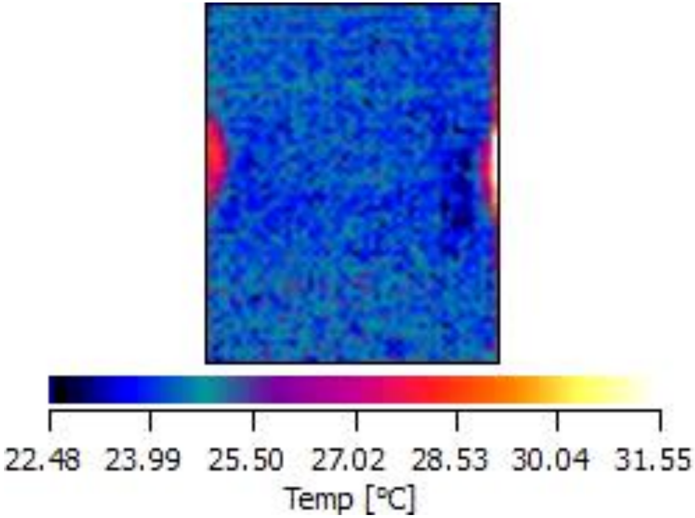
- Given the coarse meshes necessitated in vehicle CAE, failure strains should be measured using a length scale on the order of the element size
- DIC virtual strain gauge length: 0.3 mm) versus 3-5 mm element size
- For these materials, shear strain to failure ***input to FEA decreases*** with strain rate!
- Less impact on positive triaxiality regime, however, confounding results exist in the literature

High Speed Thermography

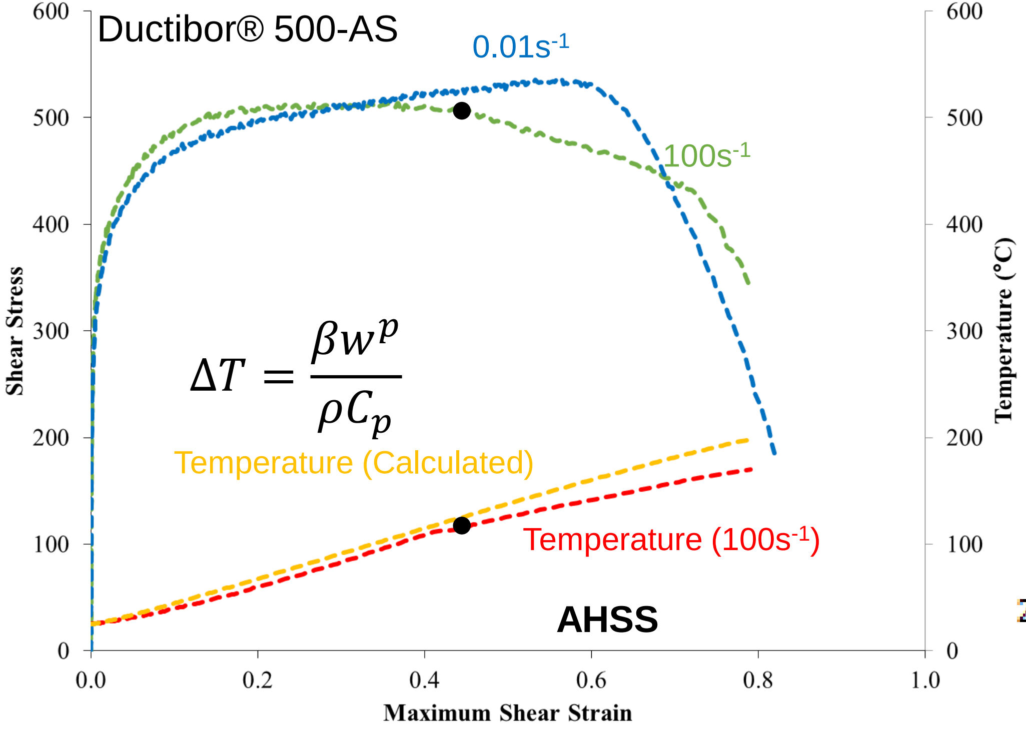
Ductibor® 500-AS: Shear
(T_{peak} ~234 C)



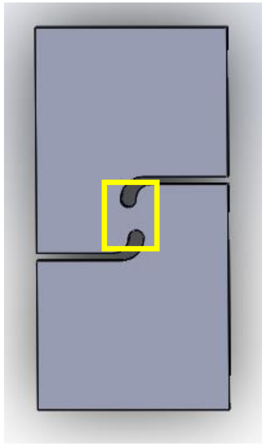
Ductibor® 500-AS: Notched Tension
(T_{peak} ~230 C)

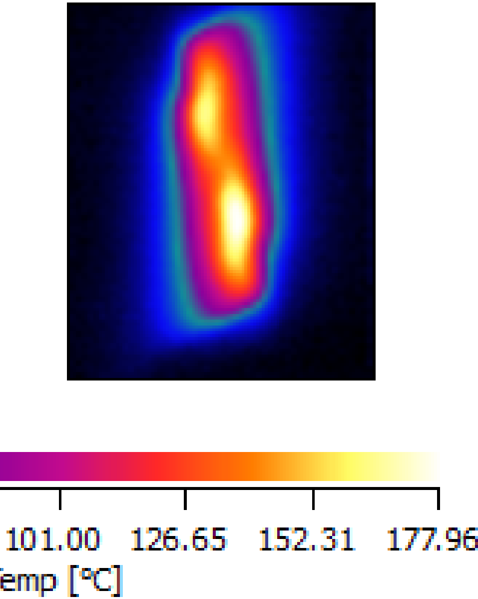


Thermal Softening in Shear (Ductibor® 500-AS)

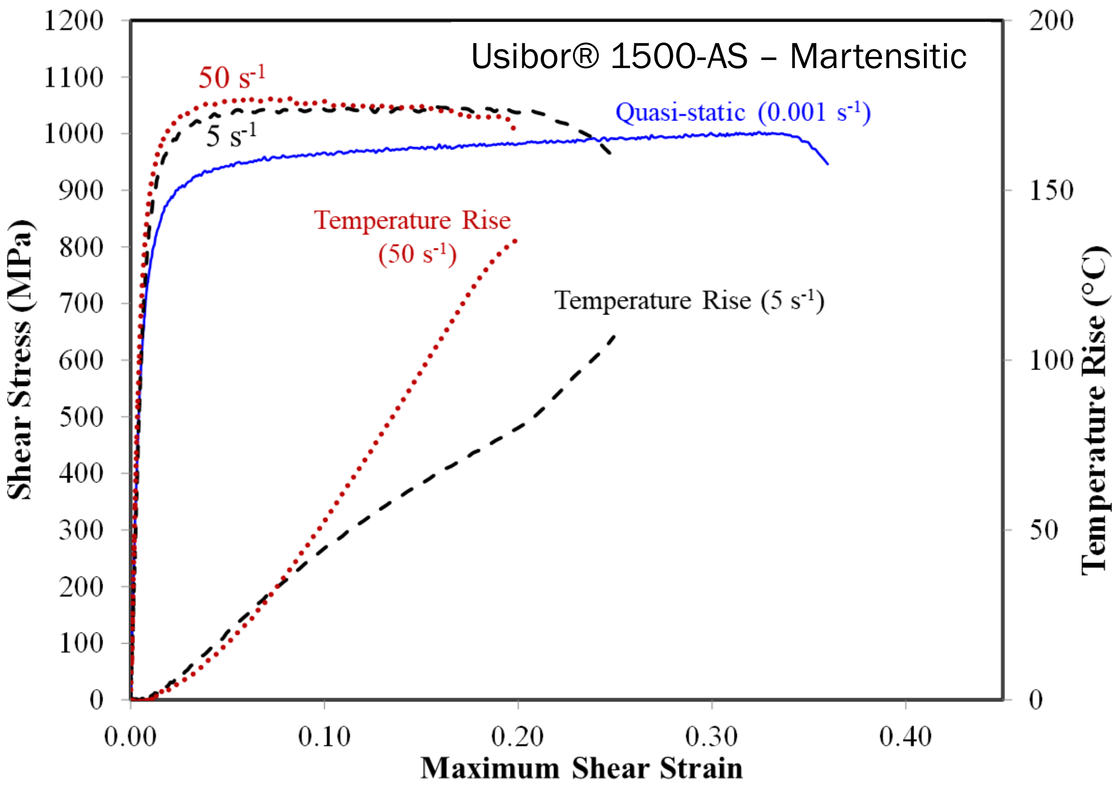


$$\Delta T = \frac{\beta w^p}{\rho C_p}$$





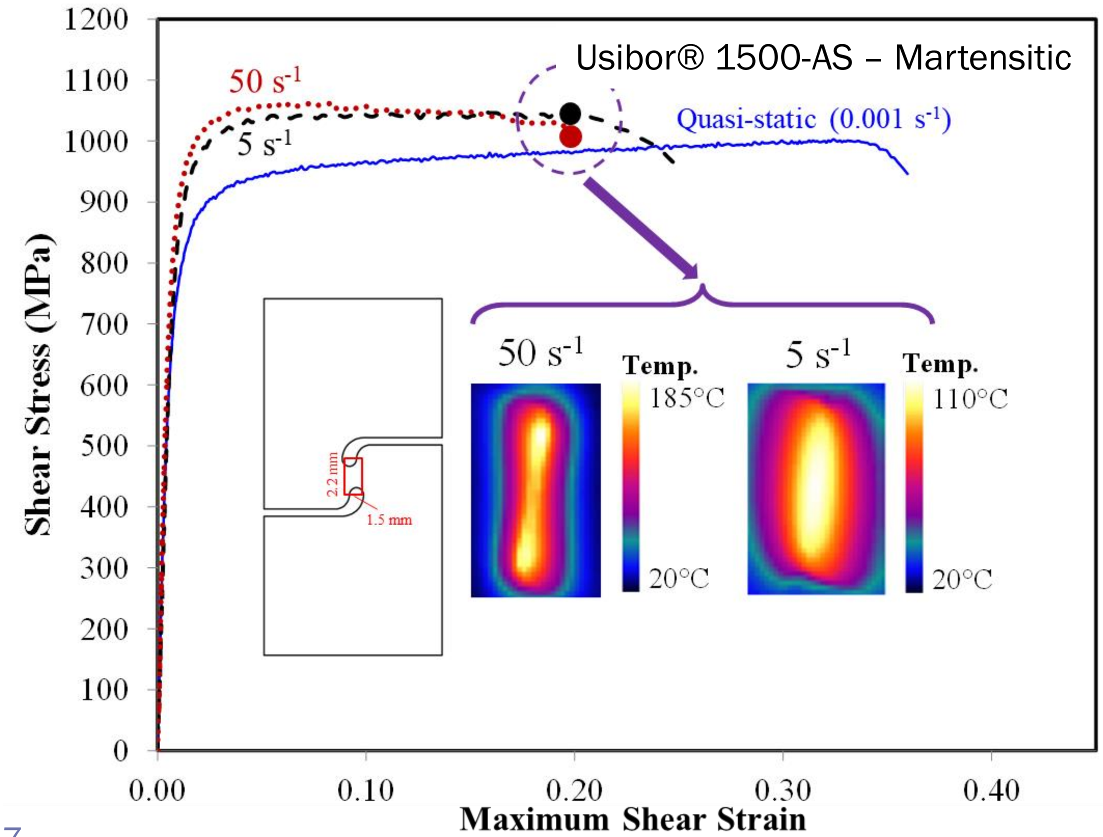
Shear Response: Martensitic Condition



Fully-quenched Usibor® 1500-AS condition – primarily martensitic Microstructure

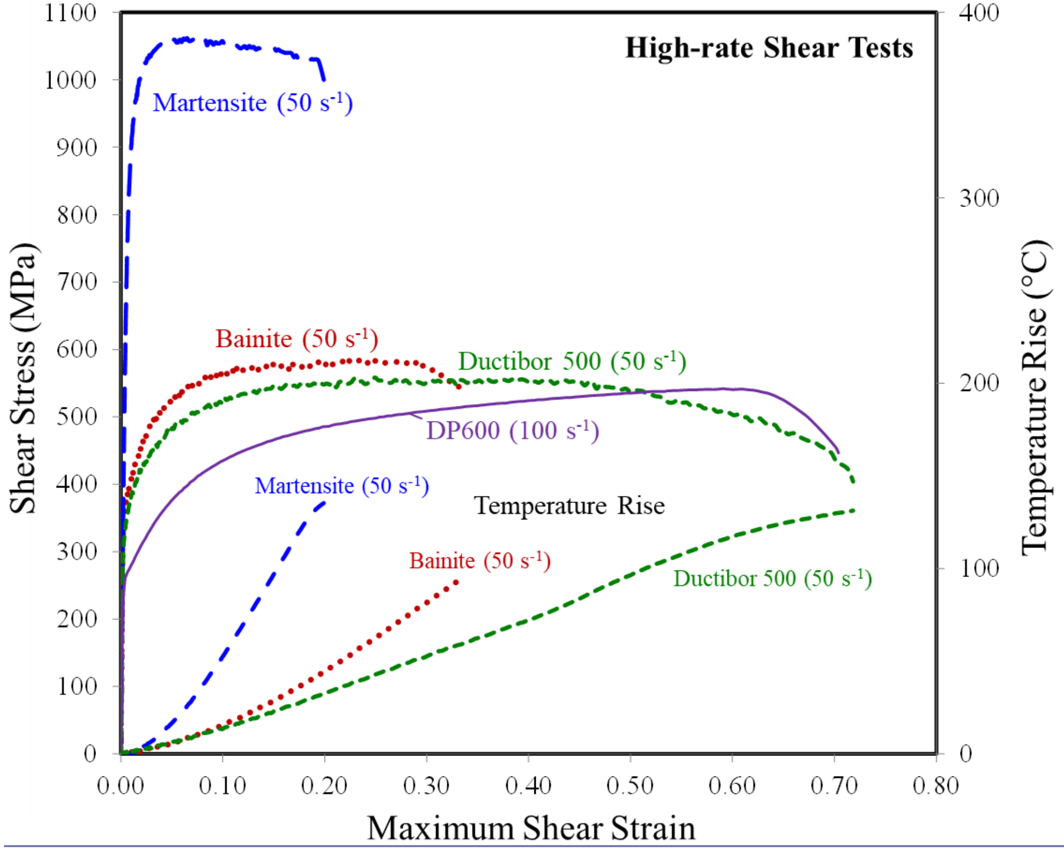
- Lower strains to failure
- Higher heat generation rates

Shear Response: Martensitic Condition



Thermal localization at lower strains due to higher internal work rate and low work hardening rate

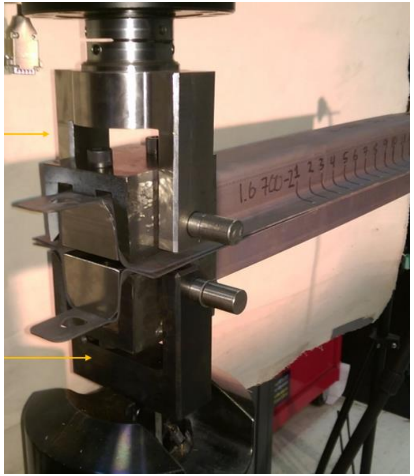
Effect of strength on onset of localization



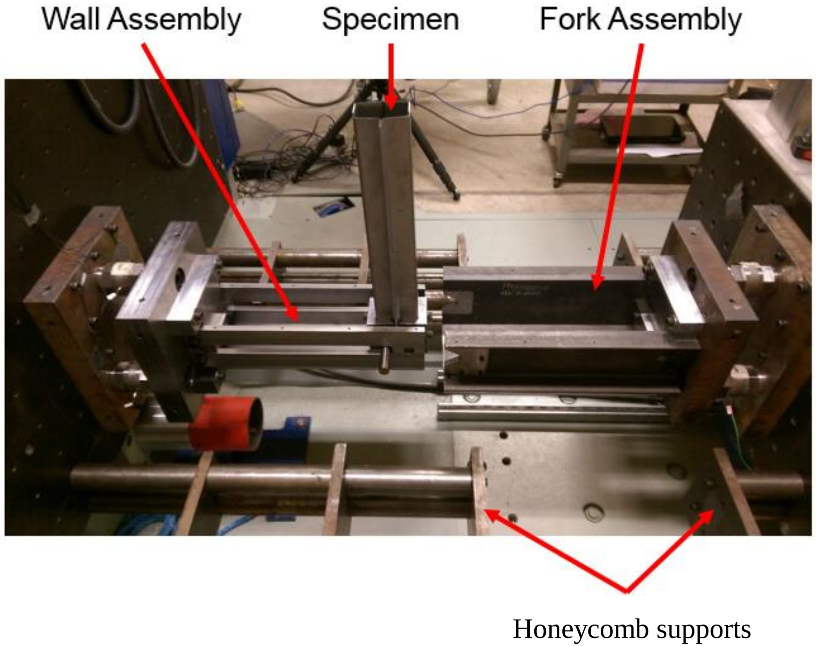
- Earlier localization, narrower thermal field for the higher strength conditions
- Thermal localization enhanced for higher strength alloys
- The strong work hardening of the DP600 is clearly beneficial

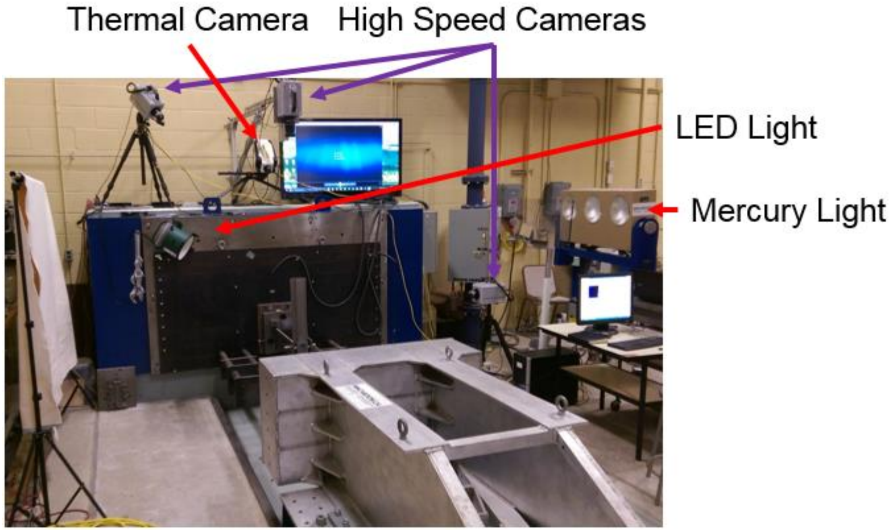
Characterization of failure in spot weld groups

- Interaction between nugget, HAZ and parent metal strength (single weld)
- Test method for weld group testing (Mode I Caiman)



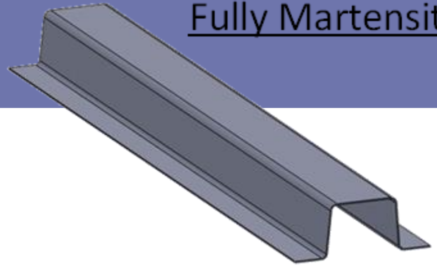
MODE I DYNAMIC (1.6MM)



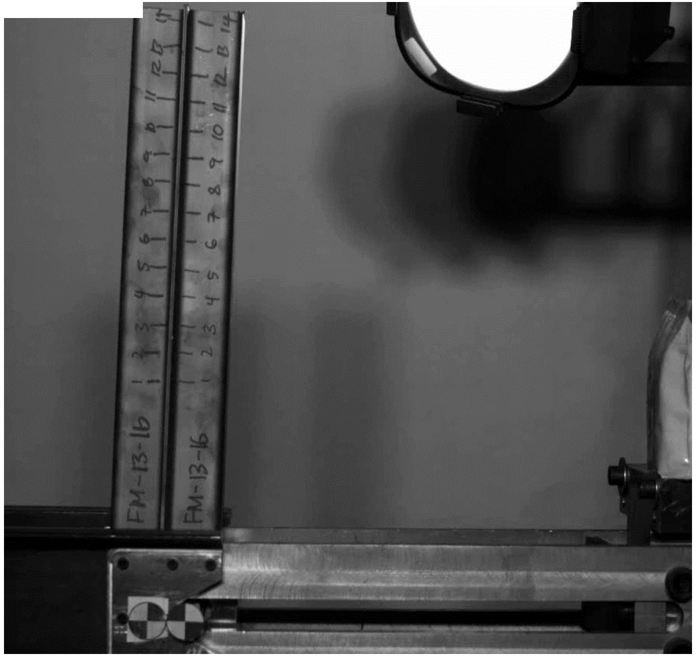


DYNAMIC SIDE VIEW

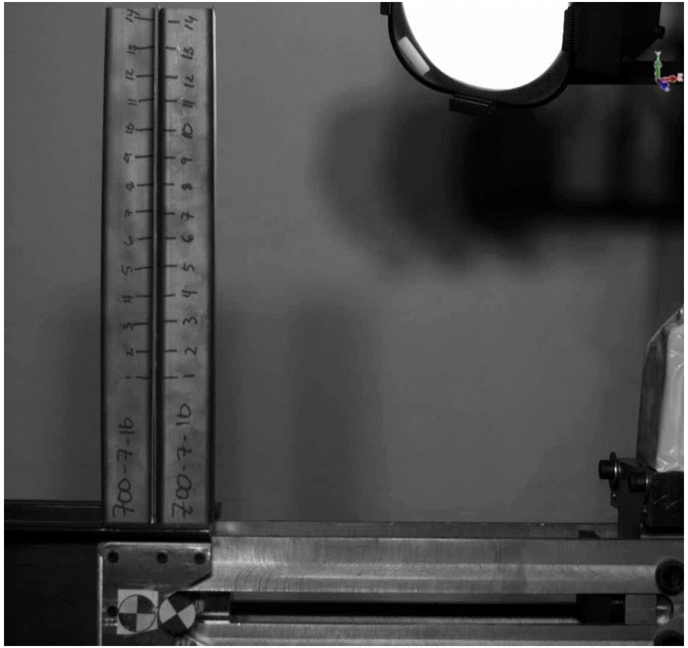
Fully Martensitic

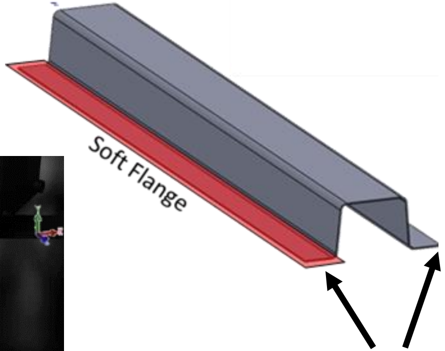


1.6mm 25°C



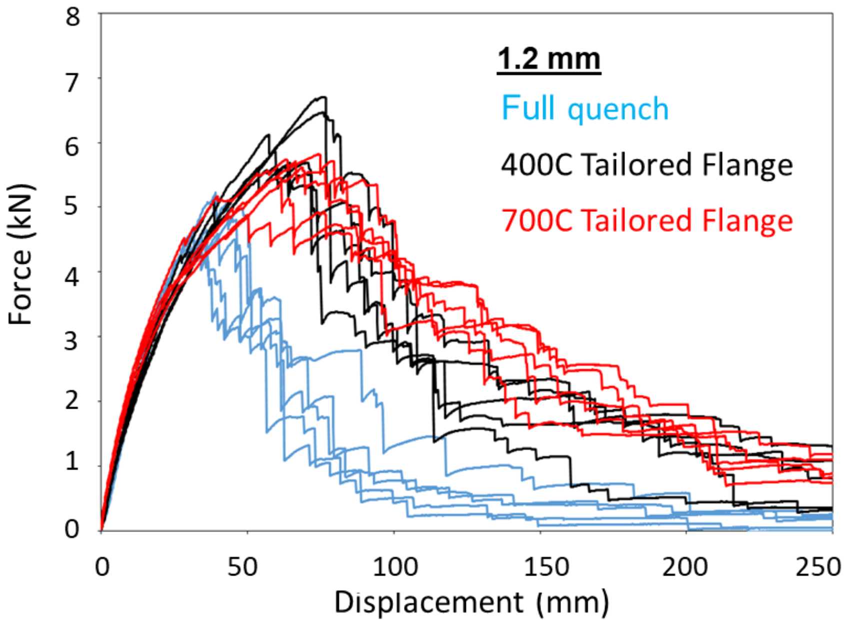
1.6mm 700°C

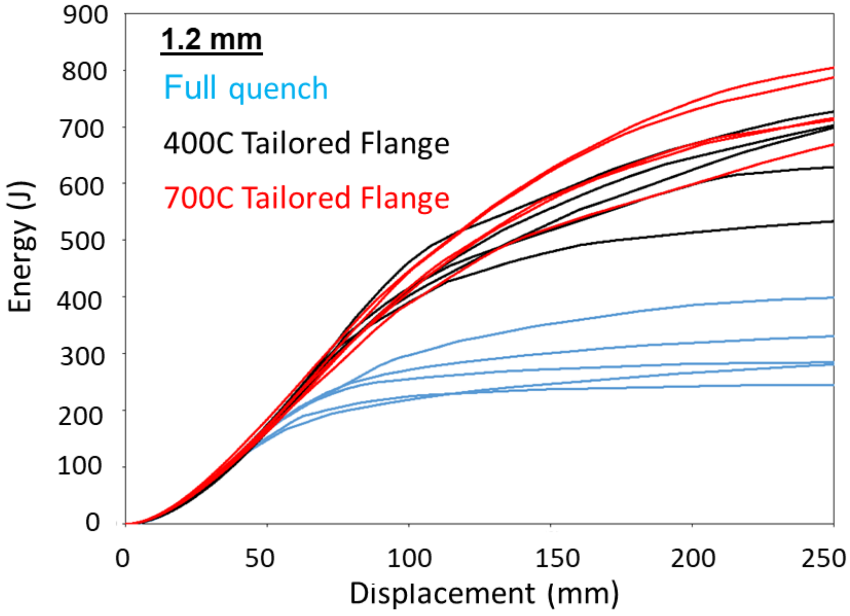




400 or 700 °C die temperature in flange regions

Mode 1 Quasi-Static





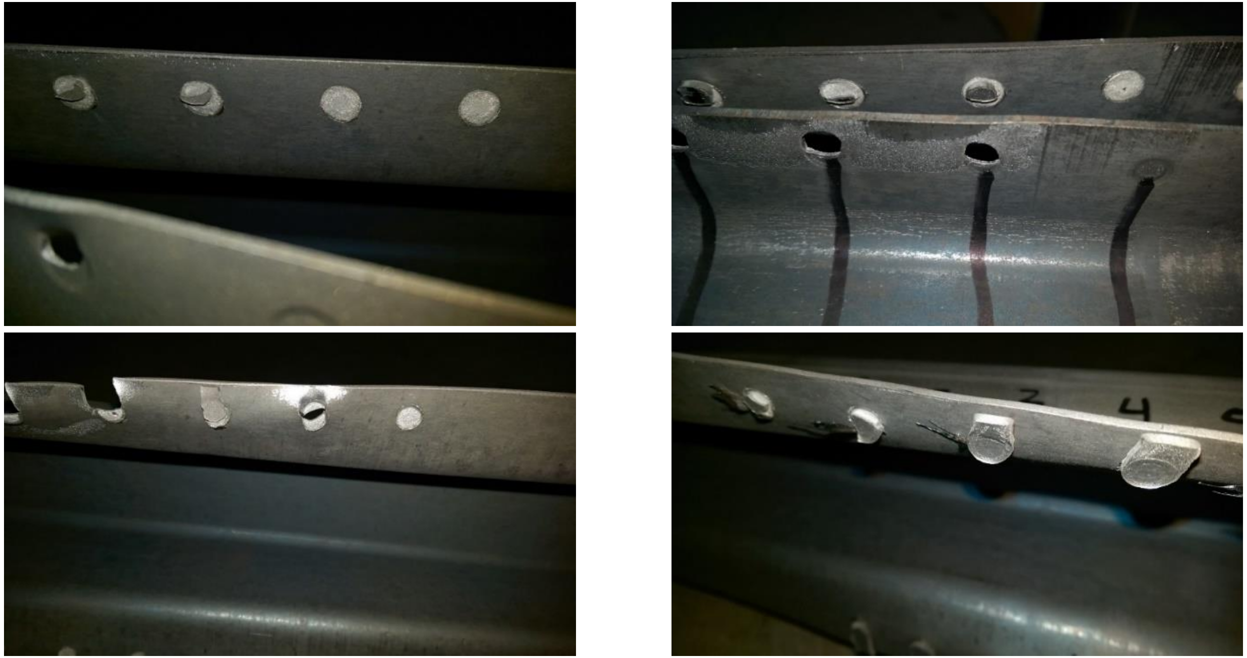
Mode 1 Dynamic

Weld Failure Surface (1.6 mm)

Dynamic | Quasi-static

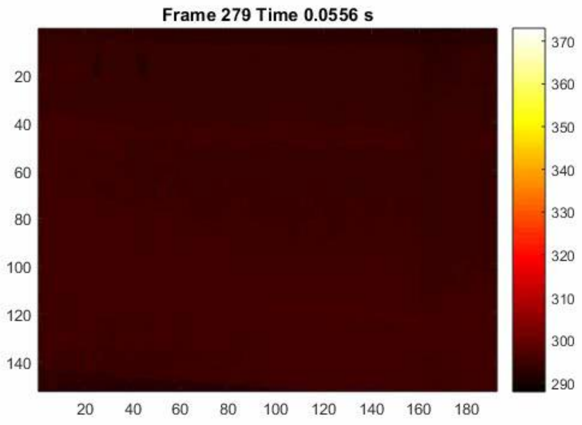
25°C

700°C



DYNAMIC THERMOGRAPHY

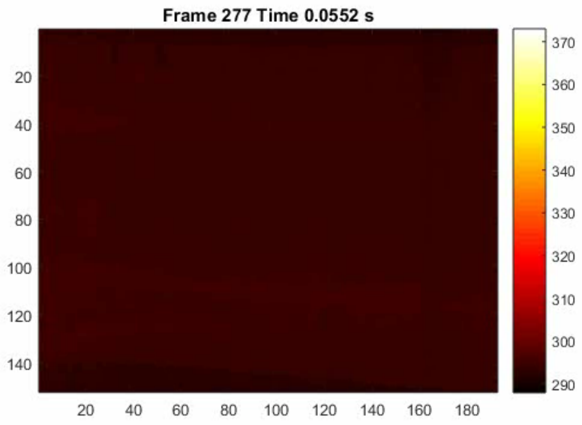
1.6 mm, 25°C



370 K

290 K

1.6 mm, 700°C

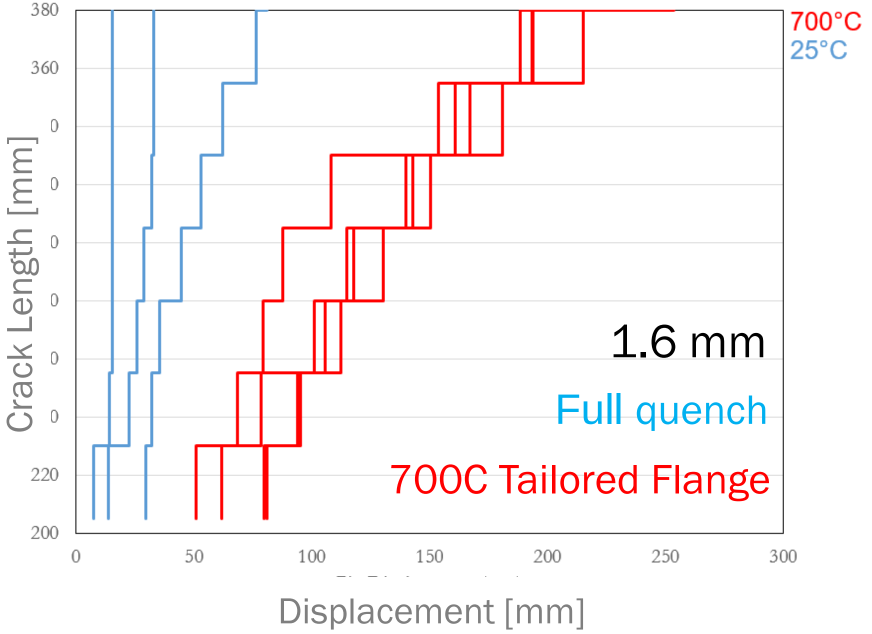


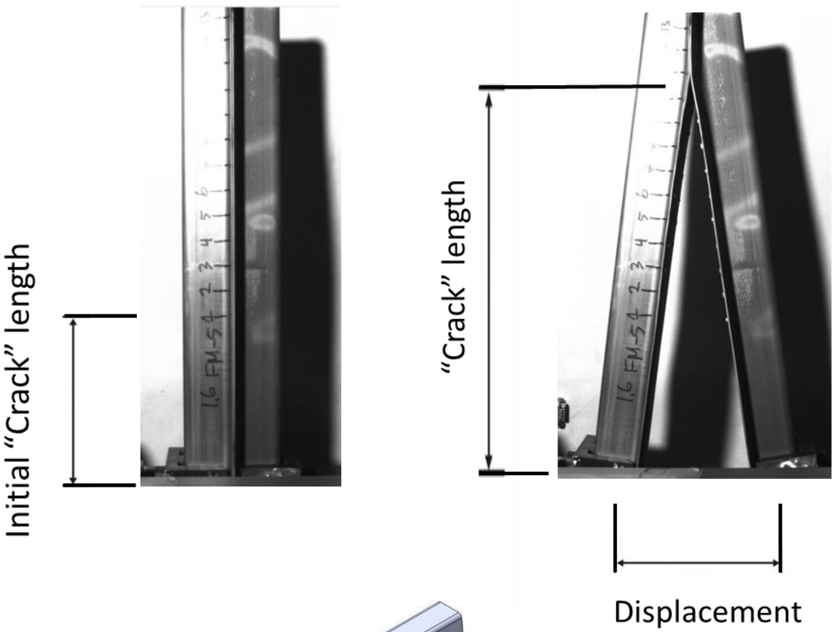
370 K

290 K

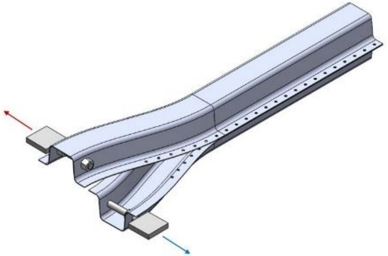
Softer flanges (high flange die temperature) contribute more towards energy dissipation

Mode 1 Quasi-Static





- Key data for CAE validation
- Weld assessment tool for AHSS and UHSS
- Shear version of the "Caiman"



Acknowledgements

HONDA
The Power of Dreams

MAGNA
COSMA INTERNATIONAL

ArcelorMittal

Steel
Market Development
Institute

NSERC
CRSNG

Ontario
Research Fund

Canada Research Chairs
www.chairs-chaires.gc.ca

INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

For More Information

Michael Worswick
University of Waterloo
michael.worswick@.uwaterloo.ca

Cliff Butcher
University of Waterloo
cbutcher@uwaterloo.ca