First Generation Advanced High-Strength Steels Deformation Fundamentals

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Overview

Timeline

- Start: Oct. 2009
- End: Dec. 2011
- 100% Completed with reduced scope

Budget

- Total funding:
  - DOE direct $300K (reduced from original $814K)
  - Industry:
    - Auto
    - Steel

Barriers

- Lack of fundamental understandings on the driving forces for localized forming fracture for AHSS
- Lack of appropriate set of material properties requirements to ensure localized formability of AHSS

Partners

- Chrysler, Ford, GM
- 4 steel companies
  - US, Asia, Europe
- CSM, POSTECH

Project Objectives

- Gain fundamental understandings of the local deformation mechanisms for higher strength AHSS
- Develop quantitative understandings on key mechanical properties and microstructure features influencing the local formability of higher strength AHSS
- Identify material acceptance criteria and develop associated (industry-wide) screening tests for material qualification
- Reduce the launch time and promote wider applications of AHSS on vehicle bodies

Different in-die behaviors of two commercial DP980 steels

Deliverables (FY11-12)

- Examination on relationship between local formability of DP980 steels and their various material properties (completed)
- Metallographic analyses and 3-D microstructure books of DP980 steels (completed)
- Quantification/examination of microstructural features of DP980 steels based on image processing tool (completed)
- Hardness disparity of the constituent phases of DP980 steels based on nano-indentation test (completed)

Technical Approaches

- Acquire different DP980 materials from various suppliers
- Perform chemical composition analyses, microstructural analyses and various mechanical tests: in-plane tension, HET, B-Pillar in-die stamping, to obtain the mechanical properties for the various DP980 materials
- Develop image analyses tools to quantify the grain size, volume fraction, grain orientation, aspect ratio…
- Perform nano-indentation tests to determine the strength disparity of the constituent phases
- Perform microstructure-based finite element analyses to gain to fundamental understandings on the key material features to withstand localized deformation
- Derive a theoretical microstructure-to-properties correlations based on the results

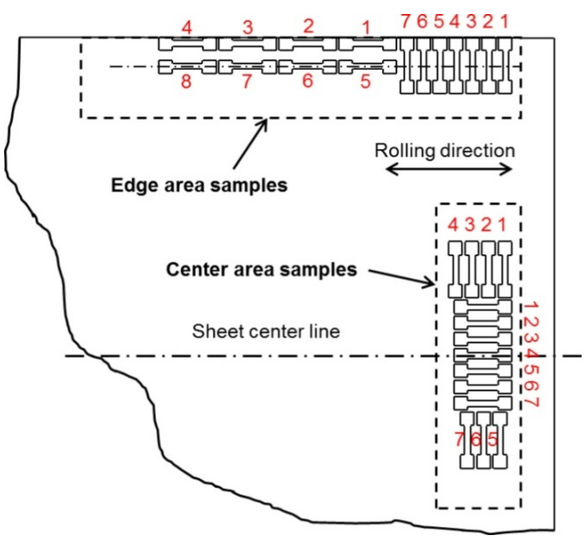
Technical Accomplishments
-- Chemical Composition Analyses

- Acquired 8 different type of DP980 sheet steels from 4 different suppliers (labeled with generic designations (A to H))
- Surface coating was removed before test
- Used ICP-AES and ASTM E1019-11

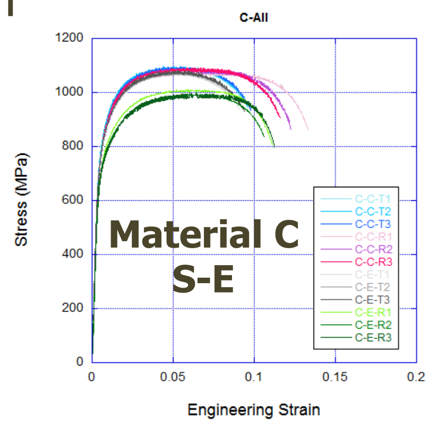
DP980 (t)	C (1.0)	D (1.2)	H (1.0)	G (1.4)	F (1.4)	A (2.0)	B (1.7)	E (2.0)
Al	0.05	0.05	0.03	0.04	0.04	0.03	0.04	0.03
C	0.11	0.12	0.15	0.08	0.10	0.09	0.09	0.09
Cr	0.26	0.25	0.32	0.47	0.47	0.02	0.20	0.46
Cu	0.01	0.01	0.04	<0.01	<0.01	0.07	0.01	<0.01
Mn	2.38	2.47	1.93	2.08	2.09	2.13	2.16	2.10
Mo	0.20	0.36	0.01	0.28	0.28	0.07	0.27	0.29
Ni	0.01	<0.01	0.04	0.01	0.01	0.01	0.01	0.01
P	0.008	0.014	0.010	0.008	0.007	0.007	0.008	0.008
S	0.003	0.004	<0.001	0.003	0.002	0.002	0.001	0.001
Si	0.08	0.03	0.64	0.18	0.18	0.57	0.31	0.33
Ti	0.04	<0.01	0.13	0.03	0.03	0.02	0.02	0.05
B	0.008	0.010	<0.002	0.008	0.008	0.003	0.008	0.008
Ca	<0.004	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Nb	0.031	0.002	0.003	0.017	0.017	0.009	0.015	0.036
V	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zn	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01
N	0.008	0.009	0.005	0.004	0.004	0.006	0.005	0.006

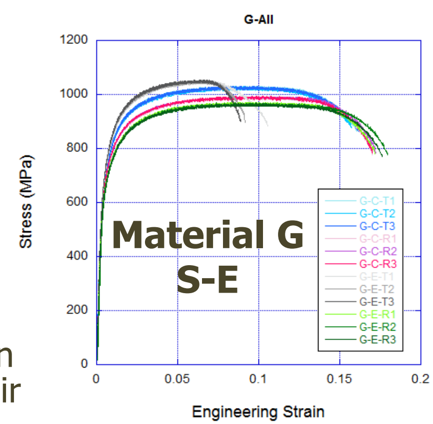
Technical Accomplishments -- Tensile Test

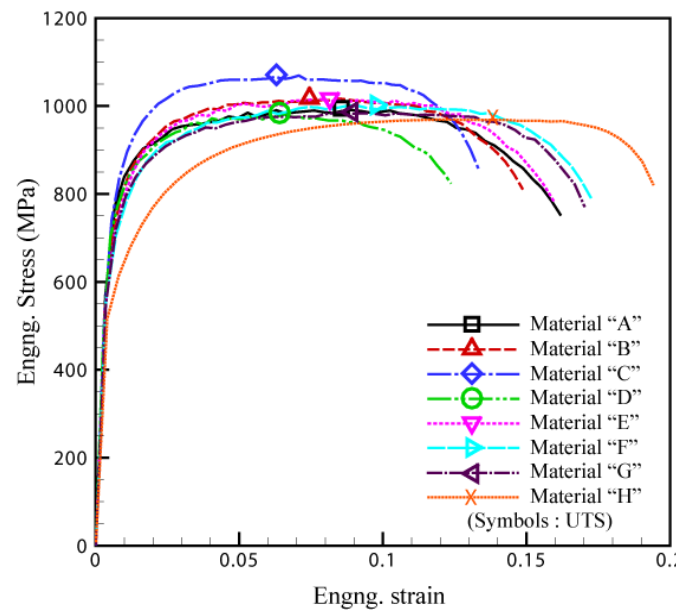
- Tested ASTM E8 sub-size samples with $\dot{\varepsilon} = 10^{-4}$/sec
- Samples were cut by EDM from center and edge areas along rolling and transverse directions
- 3 tests for each condition



Sample Locations







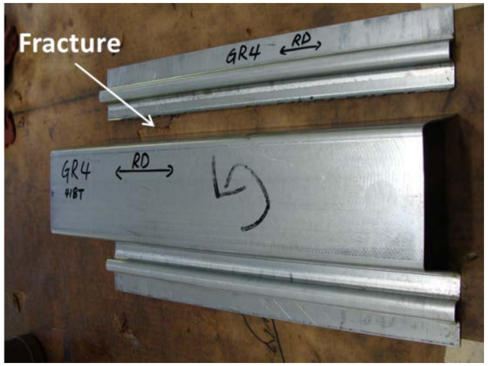
Comparison of S-E curves of DP980(Center/Rolling Dir.)

- S-E curves depend on sample location and loading direction
- DP980 steels show large discrepancy in their performances possibly due to their different microstructural features

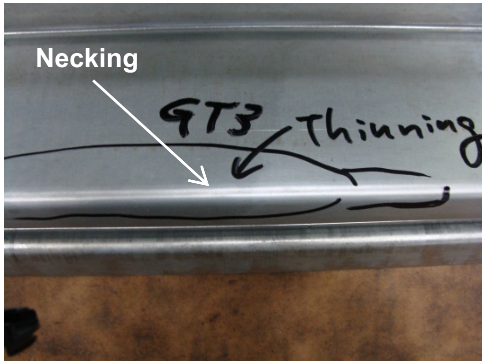
Technical Accomplishments
-- Straight Channel Forming (1)

- 5 materials (C,D,F,G,H) were selected due to the allowable thickness limit of the forming die
- Square blanks (450mmX450mm) were formed using a straight rail die
- Lubricant was applied on the blank surface before forming
- Forming test was done both along the rolling and transverse directions

Successful forming



Fractured



Necking failure

Technical Accomplishments -- Straight Channel Forming Test (2)

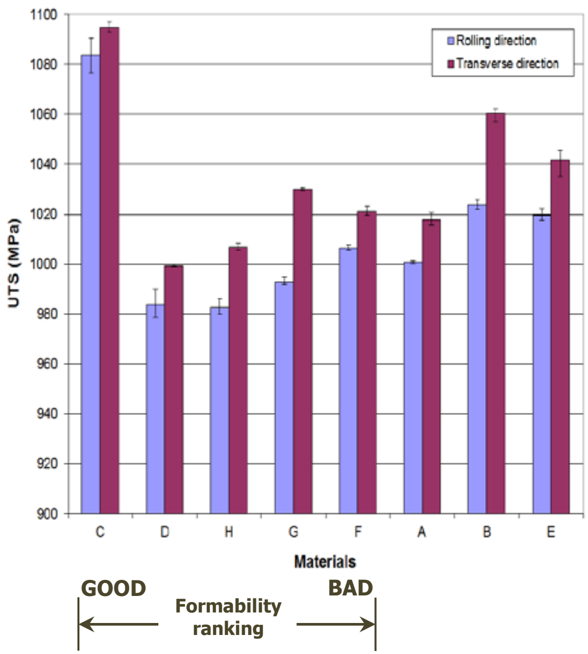
- Forming test results

DP980 Thickness (mm)	Rolling Direction			Trans. Direction		
	No. of Trials	No. of Success	Success rate (%)	No. of Trials	No. of Success	Success rate (%)
C (1.0)	3	3	100	3	3	100
D (1.2)	4	3	75	3	3	100
F (1.4)	2	0	0	2	0	0
G (1.4)	4	2	50	3	1	33
H (1.0)	6	3	50	4	3	75

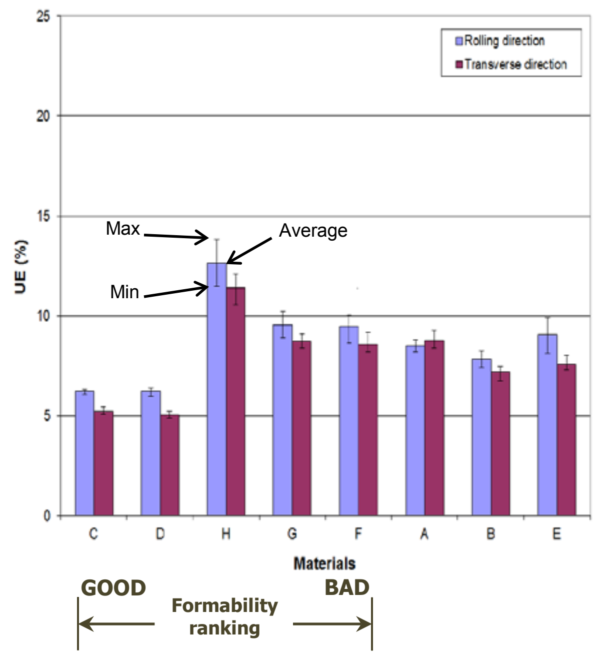
- Ranking of formability: **C > D > H > G > F**

Technical Accomplishments
-- Local Formability and Tensile Test Results

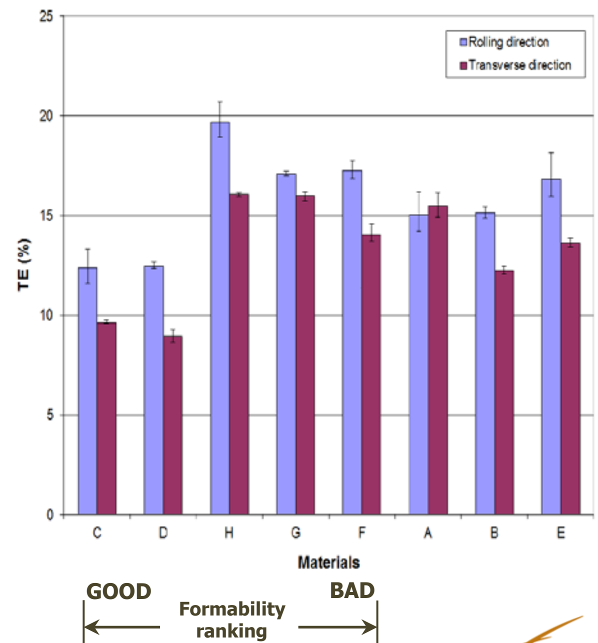
- Some tensile properties (i.e., UTS, uniform elongation, total elongation) obtained from the center area samples were compared with formability ranking
- Clear correlation is not observed between tensile properties and local formability



UTS vs formability ranking



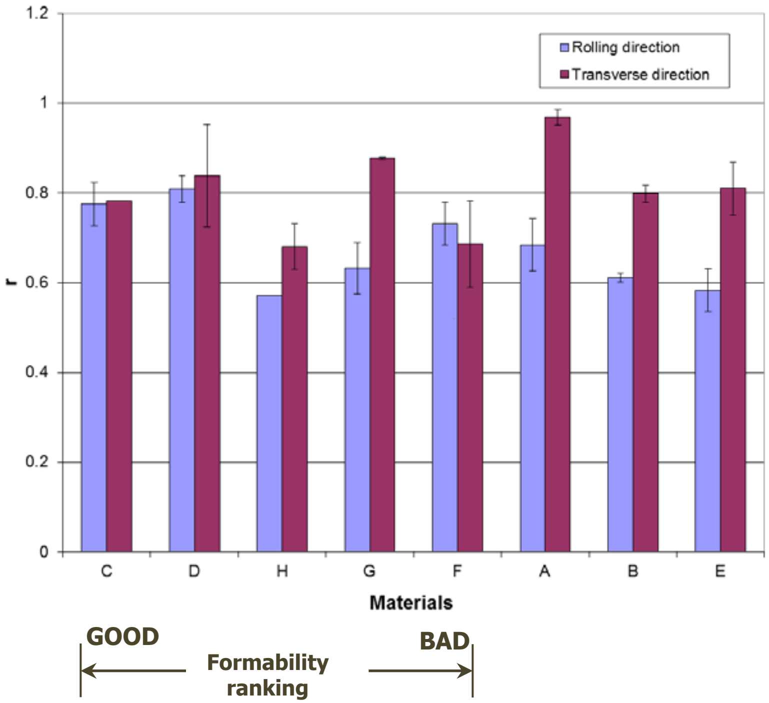
Uniform elongation vs formability ranking



Total elongation vs formability ranking

Technical Accomplishments -- Local Formability and Plastic Strain Ratio (r-value)

- Represents the resistance to thinning ($r = \varepsilon_w / \varepsilon_t$)
- Used ASTM E8 sub-size specimen and followed the manual procedure in ASTM E517
- 2 tests were done for each conditions

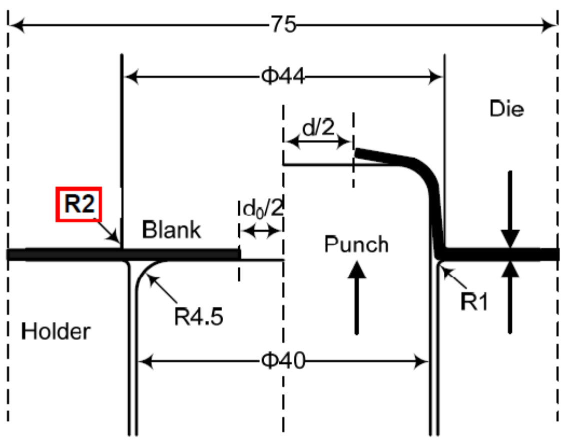


- It 'appears' that higher r-value is helpful to get better formability

R-value in formability ranking

Technical Accomplishments
-- Hole Expansion Test (1)

- Used square samples (75mmX75mm) with 12mm diameter hole
- Punch Dia.:40mm; Punch speed: 20mm/min; Die holding force: 100kN
- 2~3 tests were done for each material
- Different hole machining methods are examined (EDM, punching and laser-cutting)



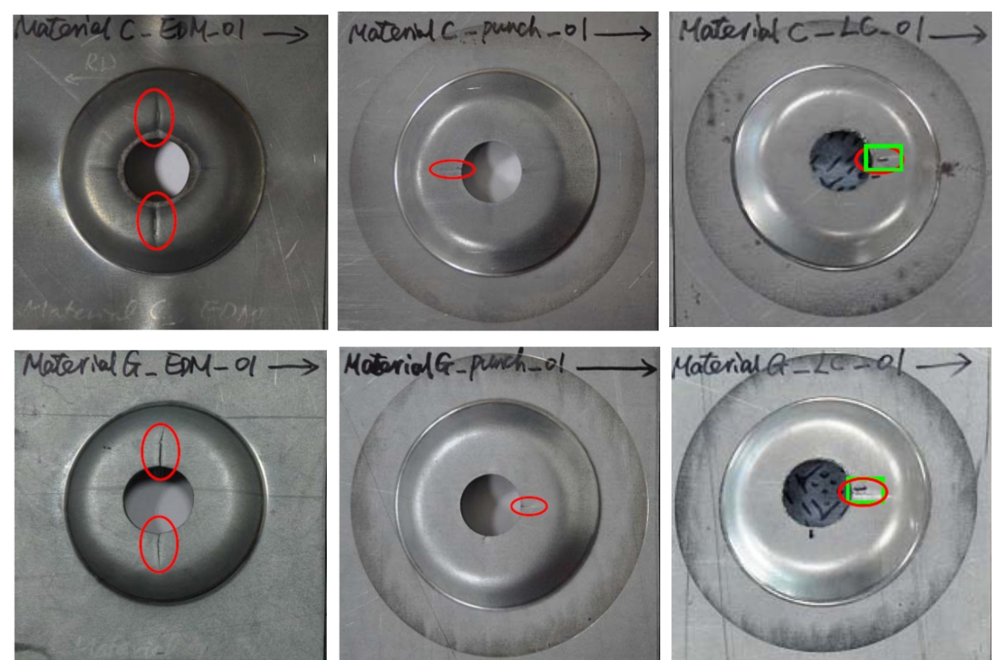
Schematic of HET

$$HER = \frac{d - d_0}{d_0} \times 100\%$$

EDM hole | Punch hole | Laser cut hole

Mat "C"

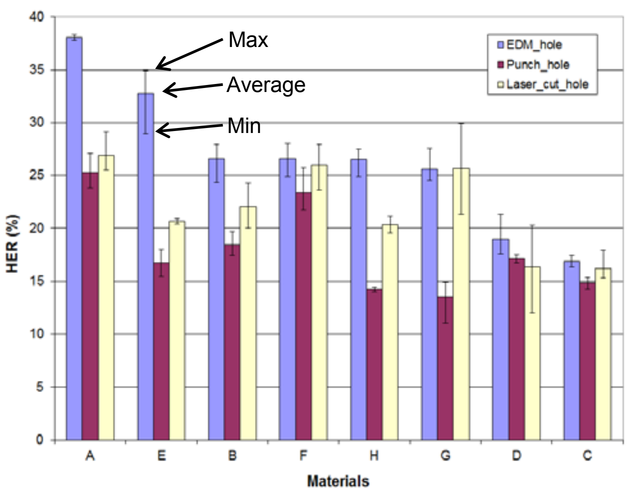
Mat "G"



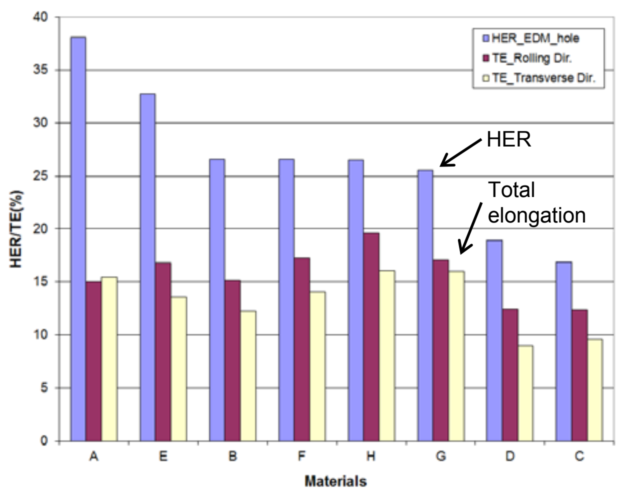
Failed samples

Technical Accomplishments
-- Hole Expansion Test (2)

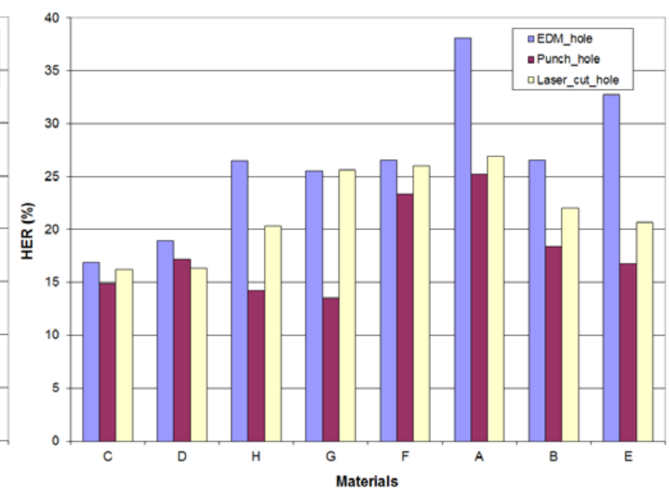
- Correlation is not observed among the three different hole machining methods
- HER does not necessarily correlate with total elongation (Thick plates appear to have higher HER)
- Clear correlation is not observed between HER and formability for the three machining methods



Comparison of HER for different hole preparation methods



Comparison of HER of EDM sample with total elongation

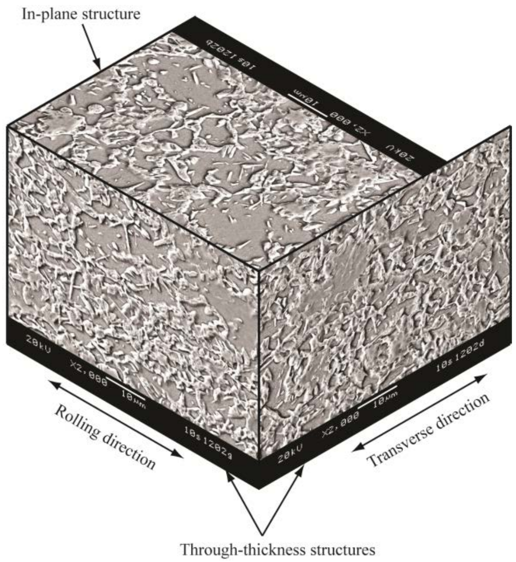


GOOD Formability ranking BAD

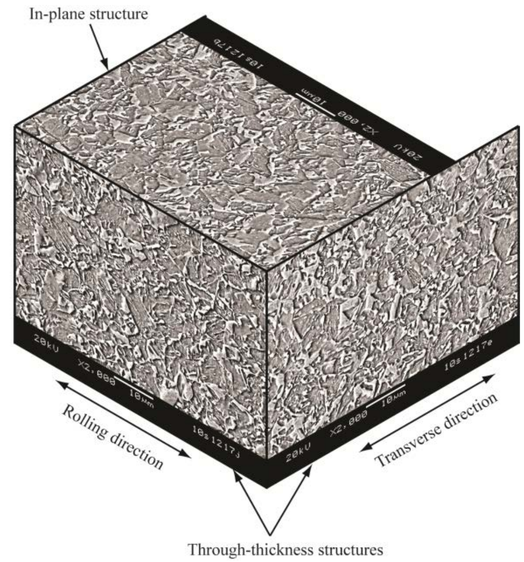
HER in formability ranking

Technical Accomplishments
-- Microstructure Analysis (1) - SEM

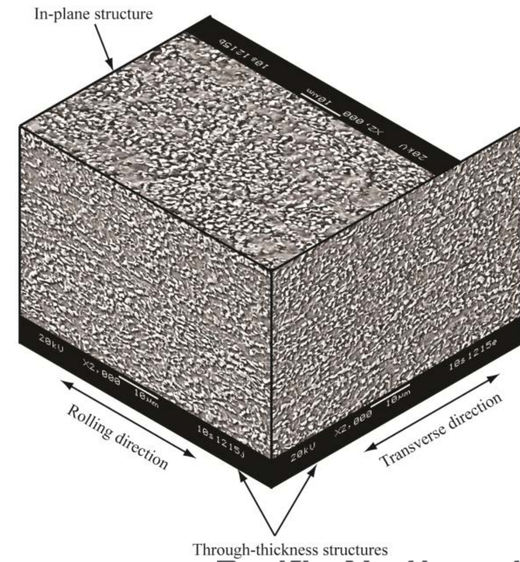
- In-plane/through-thickness SEM pictures were obtained from surface and mid-thickness regions along rolling and transverse directions for center and edge areas
- Materials have different microstructures such as different size/shape of martensite grains and different distribution feature of martensite
- Different microstructural features were expected to induce different local formability → Image analysis



Material A



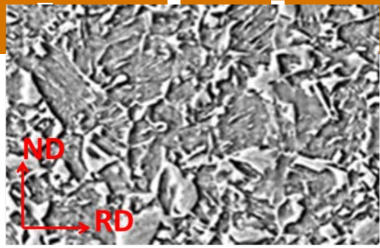
Material D



Material H

*See SAE 2012-01-0042 for microstructures of other DP980

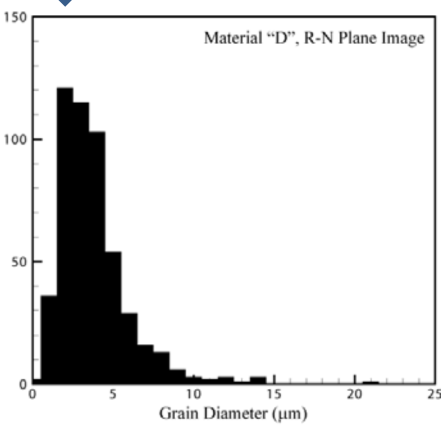
Technical Accomplishments
-- Microstructure Analysis (2) – Image Analyses



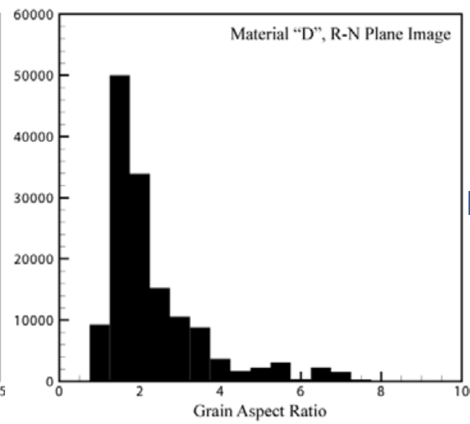
SEM of material D

Binary image after image process

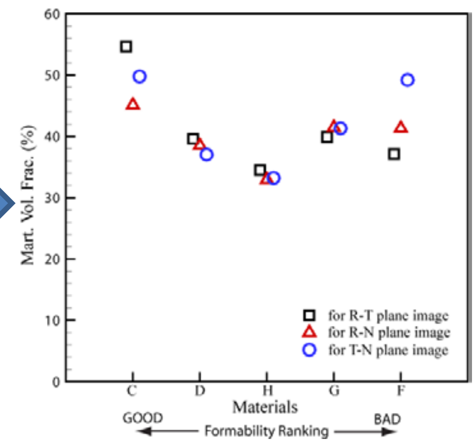
- Image processing tools are adopted to quantify several different microstructural features (i.e., volume fraction, average grain size/aspect ratio, average grain eccentricity, grain orientation etc.)
- Obtained quantity of microstructural features were compared with material's formability/ductility ranking
- Feasible correlations and trends between material microstructural features and its local formability could not be reasoned yet from the results of image analysis



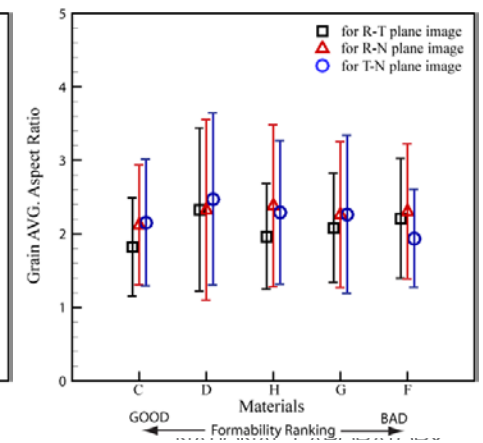
Histogram of martensite grain size



Histogram of martensite grain aspect ratio

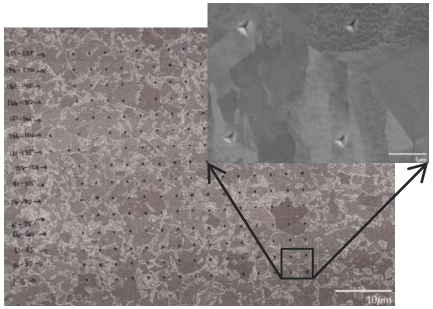


Martensite volume fraction in formability ranking

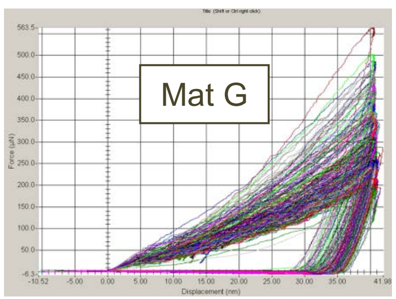


Martensite avg. grain aspect ratio in formability ranking

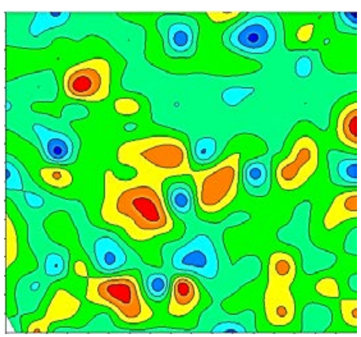
Technical Accomplishments -- Nano-Indentation Test



Grid of indents

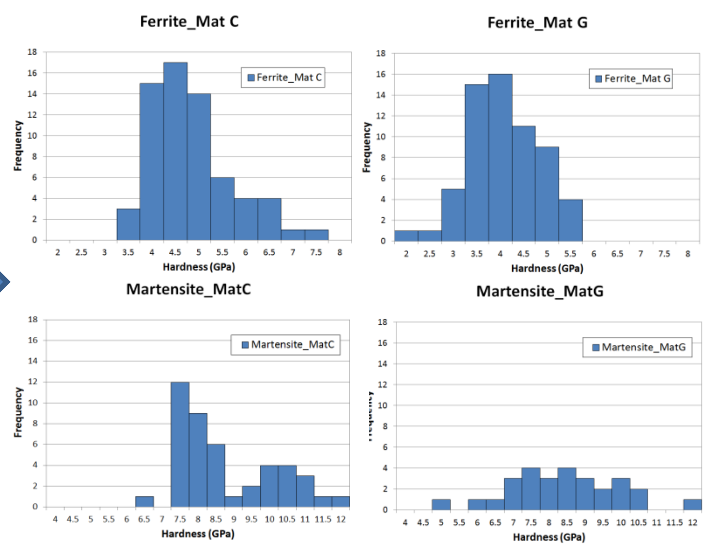


Load-displacement curves

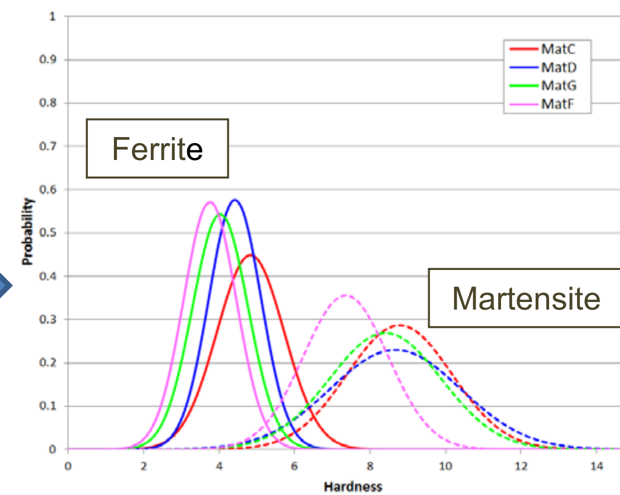


Hardness contour

- Nano-indentation test was performed with 4 materials (C,D,F,G)
- Micro hardness was measured for ferrite/martensite phases and grain boundary
- Generally, $H_{ferrite} < H_{GB} < H_{mart}$
- Variation of H_{mart} are bi-modal or larger as compared to those of $H_{ferrite}$
- Hardness of ferrite/martensite phases and/or their differences have possible correlation with the macroscopic properties (i.e., ductility, local formability)→ Need further investigation



Histograms of ferrite/martensite for Mat C and G



Hardness distribution

Summary

- Eight different DP980 steels have been examined with different tests to establish the fundamental understandings on key mechanical properties and the microstructure features influencing the local formability of AHSS:
  - Chemical, microstructural, in-plane mechanical, hole expansion, straight channel forming
- Macroscopically measured in-plane mechanical properties of these steels do not correlate with their local formability
- Clear correlations between the microstructural features and the localized deformation capability could not be established yet:
  - Image analysis was adopted for the SEM pictures of DP980 steels in order to quantify their various microstructural features
  - Nano-indentation test was adopted to measure the constituents' hardness and their strength difference

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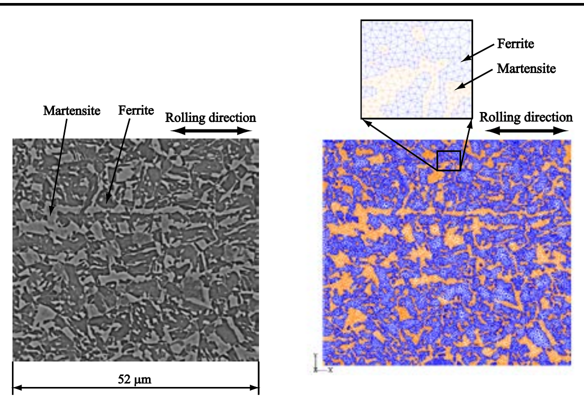
Collaborations

- Chrysler, Ford, GM (Industry)
  - Served as project steering committee
  - Provided valuable suggestions on project initial scope and reduced scope
  - Provided access to straight channel forming facility
- Steel Suppliers (Industry)
  - Donated eight different types of DP980 steels (4 steel suppliers from Europe, Asia and North America)
- POSTECH (Academic)
  - Collaborated on investigation of the influence of hole machining methods on HER of DP980 steels
- Colorado School of Mines (Academic)
  - Collaborating on the measurement of strength disparity of the constituent phases of DP980 steels

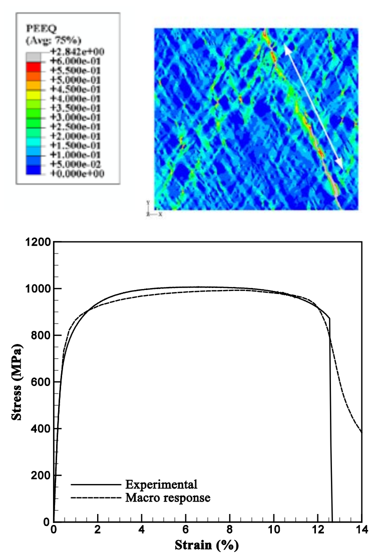
Proposed Future Work

- Examine the effects of damage (i.e., edge crack) from shear cutting on HER and local formability
- Perform further microstructural analysis for wider area to examine the martensite distribution features (i.e., homogeneity)
- Perform microstructure-based finite element analysis for the DP980 steels to examine the effects of the constituents' hardness and their difference on the ductility and local formability
- Consider the effects of strain rate and adiabatic heating in the forming analysis

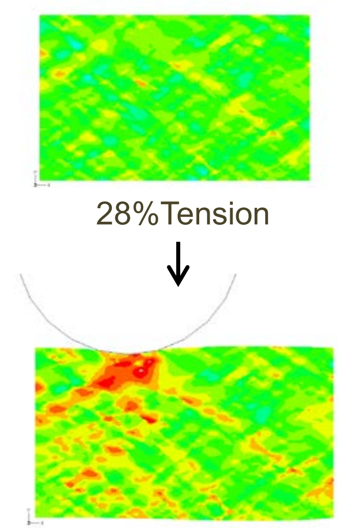


Actual structure of DP980

Finite element modeling



Uniaxial Tension

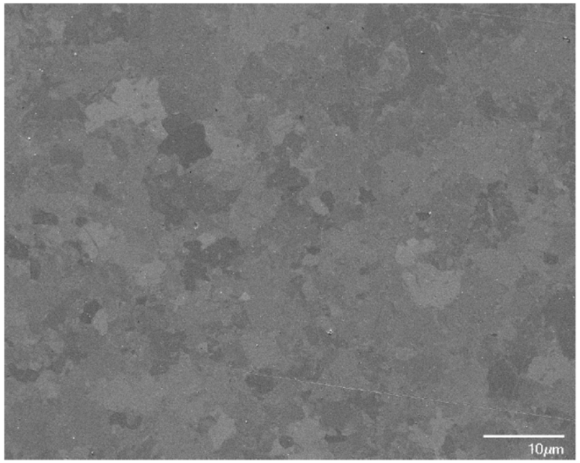


32%Tension and Indent

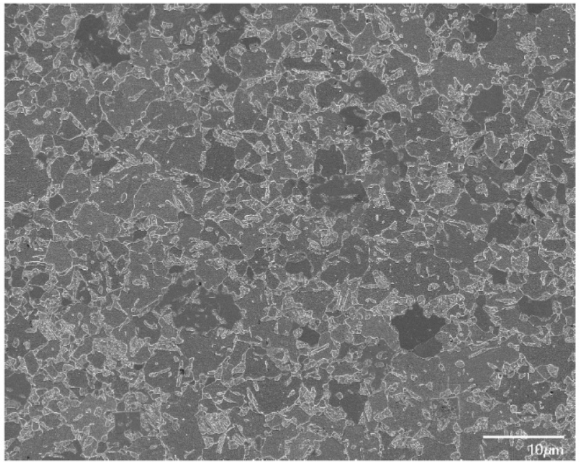
Technical Back-up Slides

Nano-Indentation Test

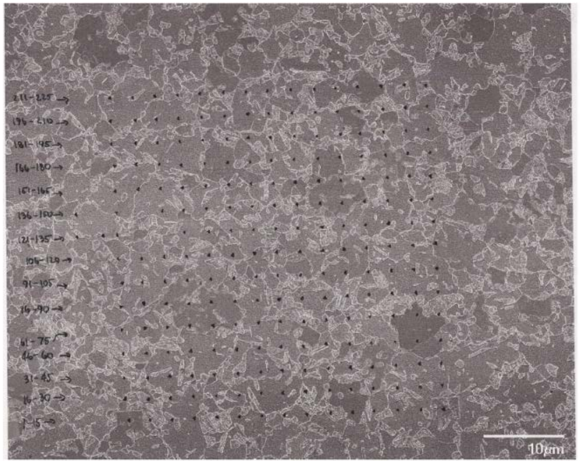
- 225 indents were performed on a smooth surface, etched with colloidal silica (3um by 3um apart, indent depth ~35nm) → Transparency was used to mark indent locations
- Surface was etched with nital → Most of indents were eaten away
- Marked transparency was overlaid on etched surface to decide which phase the indent hit



Indents on the smooth surface

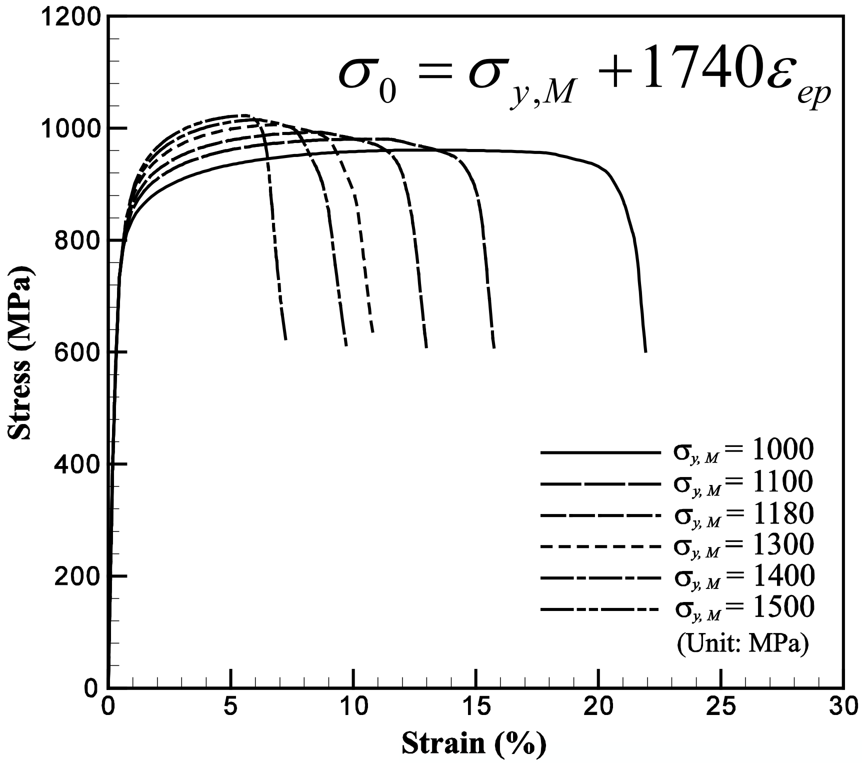


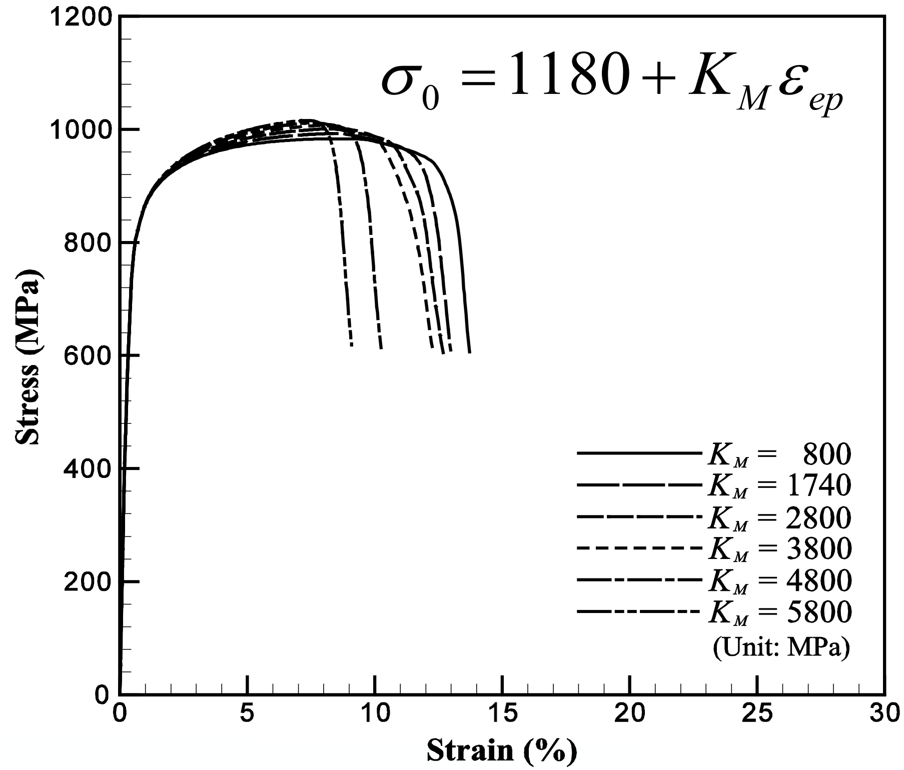
Surface after nital etching

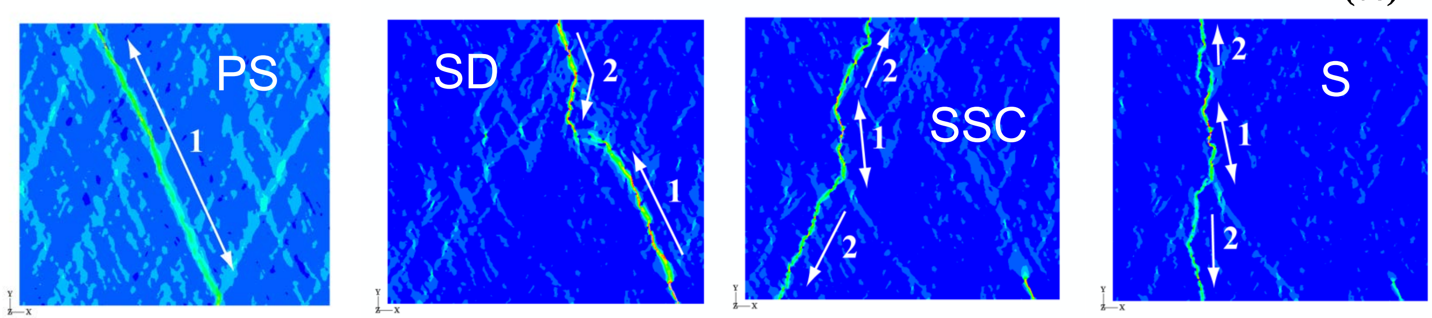


Overlaid transparency on etched surface

Effects of Martensite Mechanical Properties on Tensile Behavior of DP980







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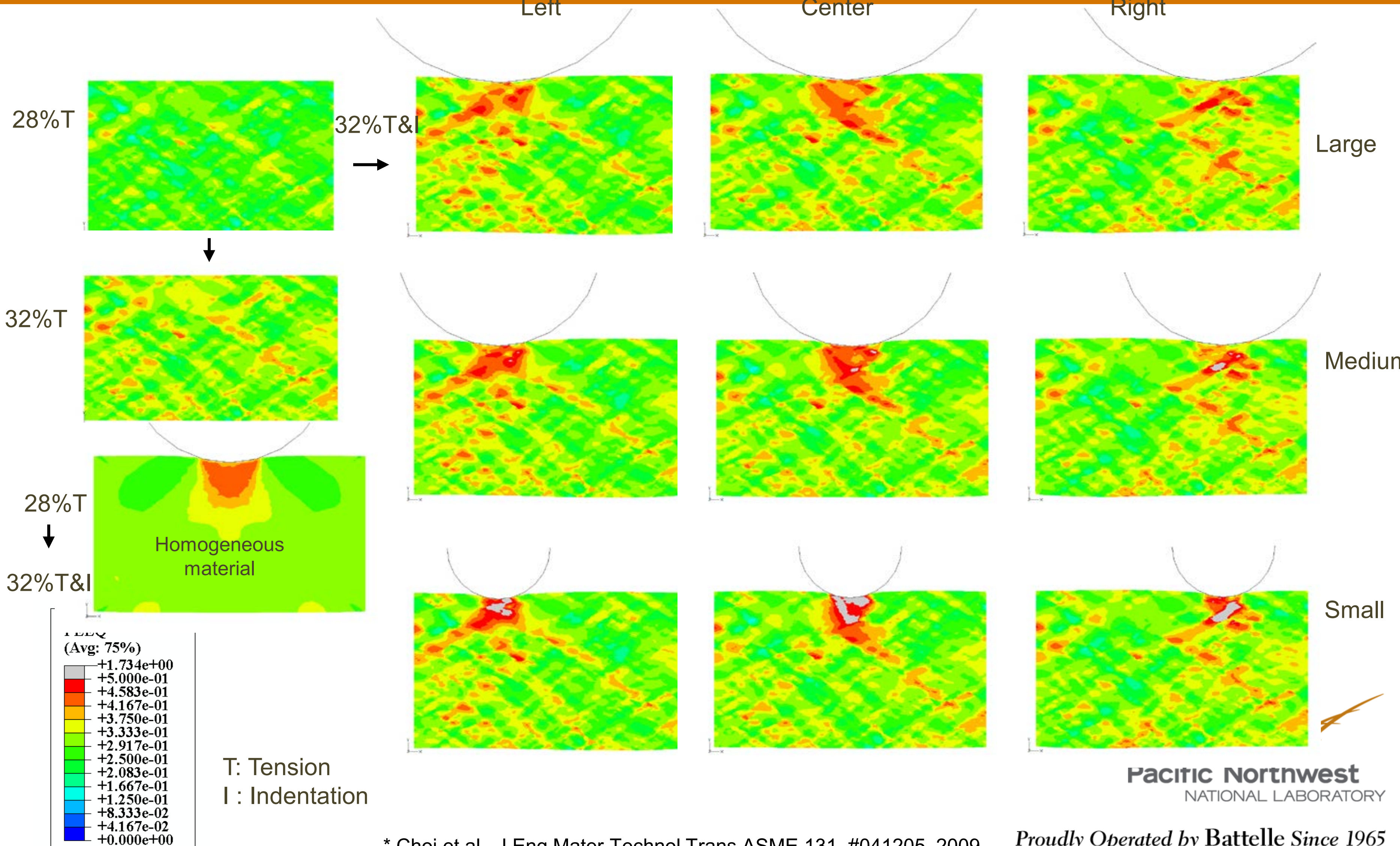
Operated by Battelle Since 1965

* Choi et al., MMTA 40, pp. 796-809, 2009.

Effects of Indenter Radius and Indentation Location



T: Tension
I : Indentation

* Choi et al., J Eng Mater Technol Trans ASME 131, #041205, 2009.