GREAT DESIGNS IN STEEL

EFFECTS OF AHSS GAUGE AND PUNCH RADIUS IN THREE-POINT BENDING

Kenneth Cheong

University of Waterloo, Research Associate

AUTO/STEEL PARTNERSHIP PROJECT TEAM MEMBERS

GDIS

JPC Project Mentor: D. Kanelos, Nucor Steel

Project Leader: R. Kaminiski, Nucor Steel and J. Singh, FCA US LLC

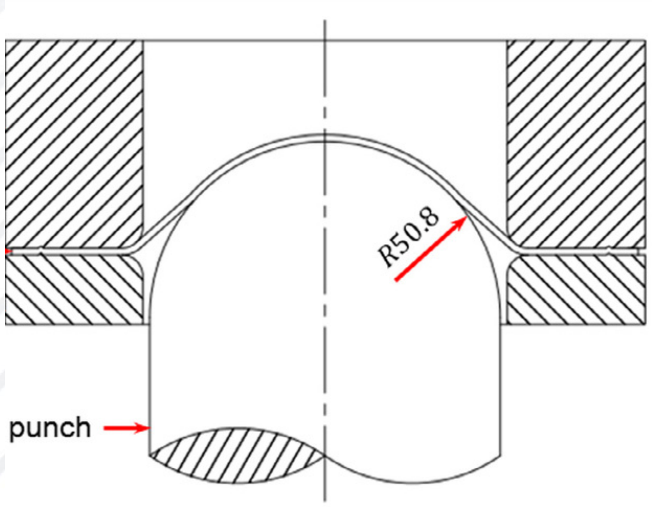
Project Manager: J. Smith, Auto/Steel Partnership

Project Team Members:

- C. Butcher, University of Waterloo
- D. Baker, General Motors
- E. S. Batt, ArcelorMittal
- J. Bickham, ArcelorMittal
- J. J. Coryell, General Motors
- J. J. Fitzpartrick, ArcelorMittal
- M. P. Hammerl, AK Steel
- M. M. Huang, ArcelorMittal
- S. Liu, ArcelorMittal
- P. Makrygiannis, AK Steel
- N. Ramisetti, ArcelorMittal
- D. S. Ruhno, Ford Motor
- A. Thompson, Nucor Steel
- S. Wolf, ArcelorMittal
- W. Wu, General Motors
- J. Catterall, AISI
- M. Davenport, Auto/Steel Partnership
- W. Dillingham, Auto/Steel Partnership
- E. McCarty, Auto/Steel Partnership
- M. White, Auto/Steel Partnership

MOTIVATION

- AHSS characterization has focused on in-plane stretching (tensile test, FLC tests) → *Global Formability*
- *Local formability* in bending operations or crash components is not well predicted by stretch-based test metrics

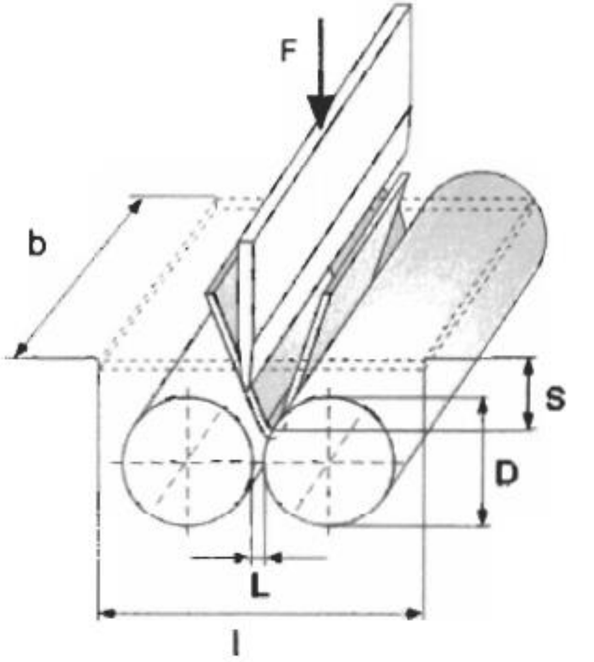


Stretch-based forming limit test

?

Energy-absorbing crush member [1]

Mimic folding behavior

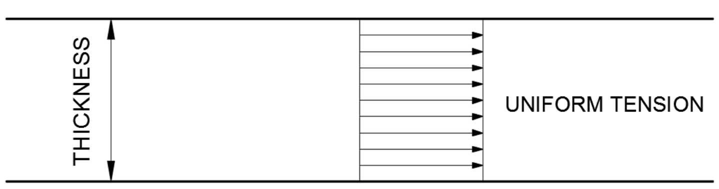


VDA 238-100 tight radius bend test

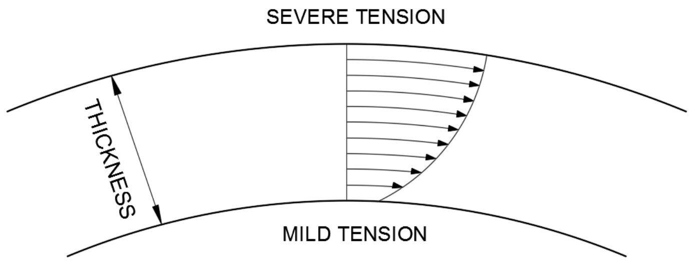
[1] Abedrabbo, N., Mayer, R., Thompson, A., Salisbury, C., Worswick. M., van Riemsdijk, I., (2009). Crash response of advanced high-strength steel tubes: Experiment and model, International Journal of Impact Engineering 36, 1044-1057.

EFFECT OF BENDING

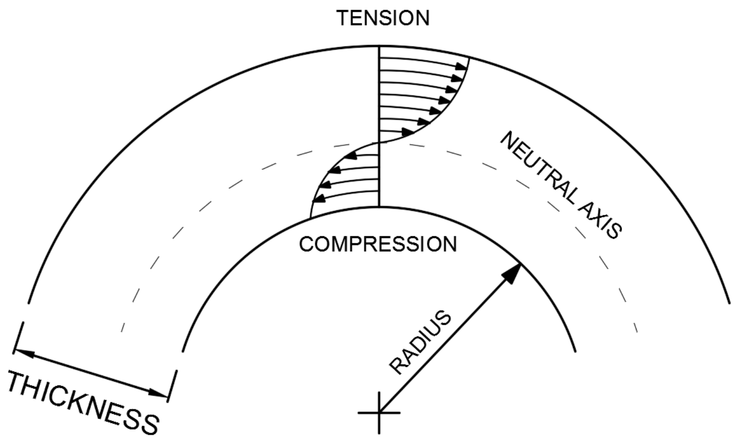
In-Plane Tension
(Necking mode)



Stretching + Bending
(Necking mode)



Severe Bending
(Fracture without Necking)

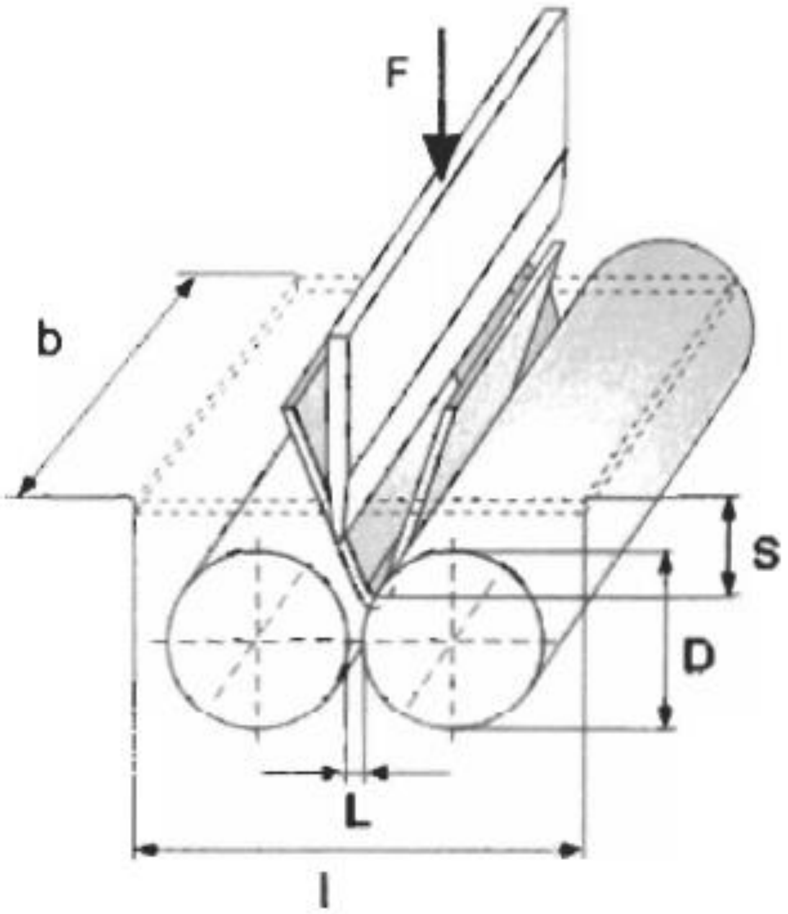


- The relative severity of tensile and bending will influence the failure mode
- Under severe bending, cracking occurs at/near the convex surface <u>**without necking**</u> where the tensile stresses are highest

VDA 238-100 BEND TEST

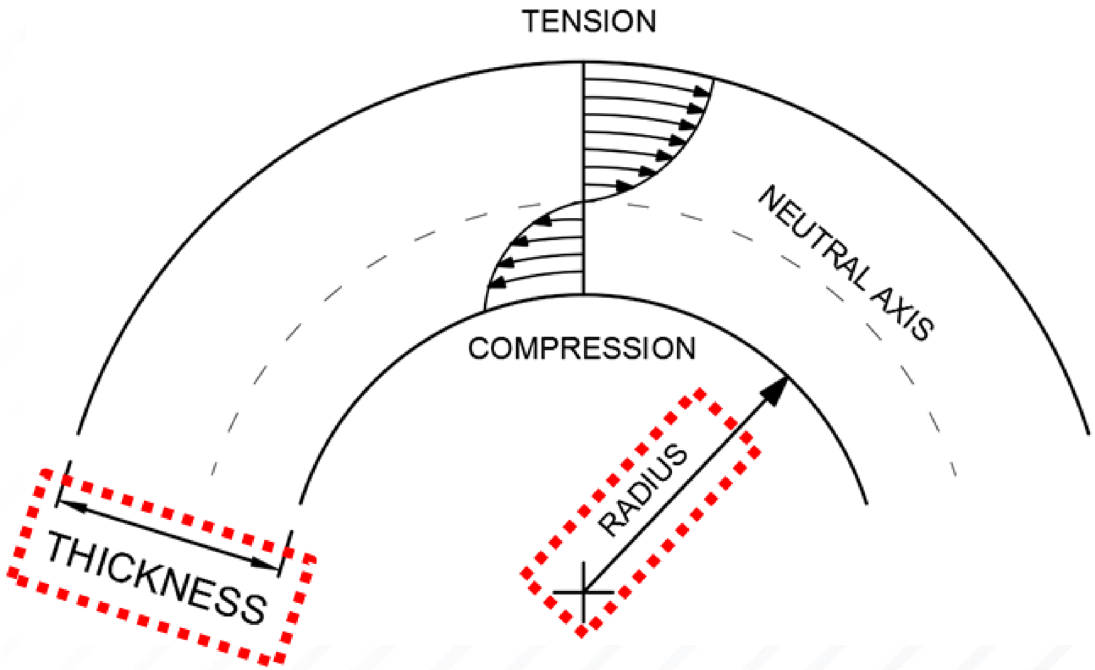
- **VDA 238-100** is becoming a well-known test specification
  - Provides tight radius three-point bending in plane strain condition
  - Bend angle can be estimated by provided correlation based on the punch displacement
- Existing challenges of the VDA bend test
  - No independent metric exists for material characterization
  - **Bend angle is valid for ranking or comparing materials but is not applicable to CAE simulation purpose**

    → *Bend angle varies with punch radius and sheet thickness*



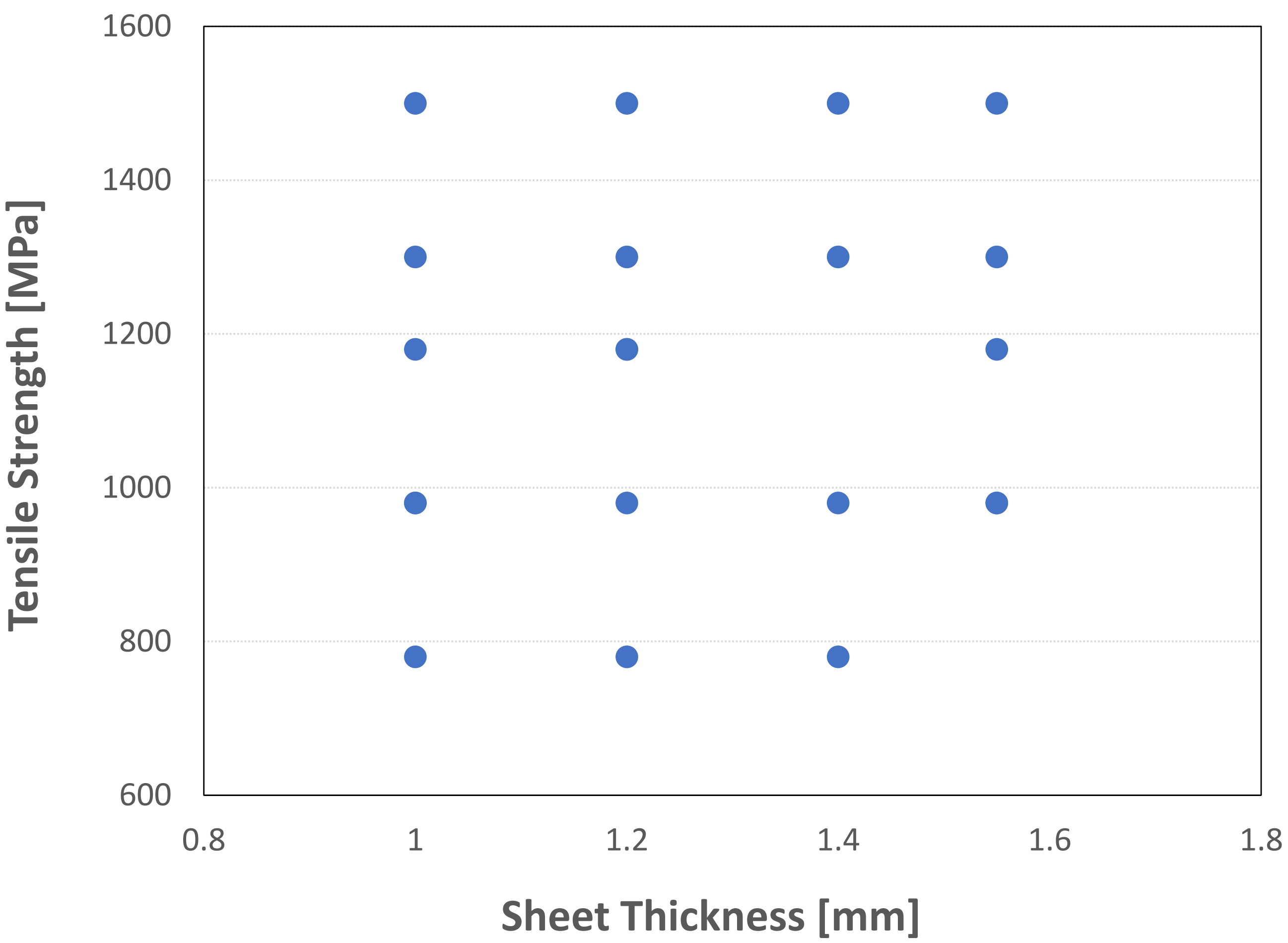
PROJECT SCOPE

- The primary objective of this project is *to investigate the influence of bend test parameters for AHSS*
- Three parameters were studied
  - Material Strength
  - Bend Radius
  - Sheet Thickness
- Metrics to evaluate the test
  - Bend angle at the VDA load threshold
  - Fracture strain on the convex side
- **Bend severity can combine the radius and thickness effect in the bend test as there is no superimposed stretching**



$$\text{Bend Severity} = \frac{\textit{Sheet Thickness}}{\textit{Bend Radius}}$$

RANGE OF MATERIAL CONDITIONS



Material considered in this project

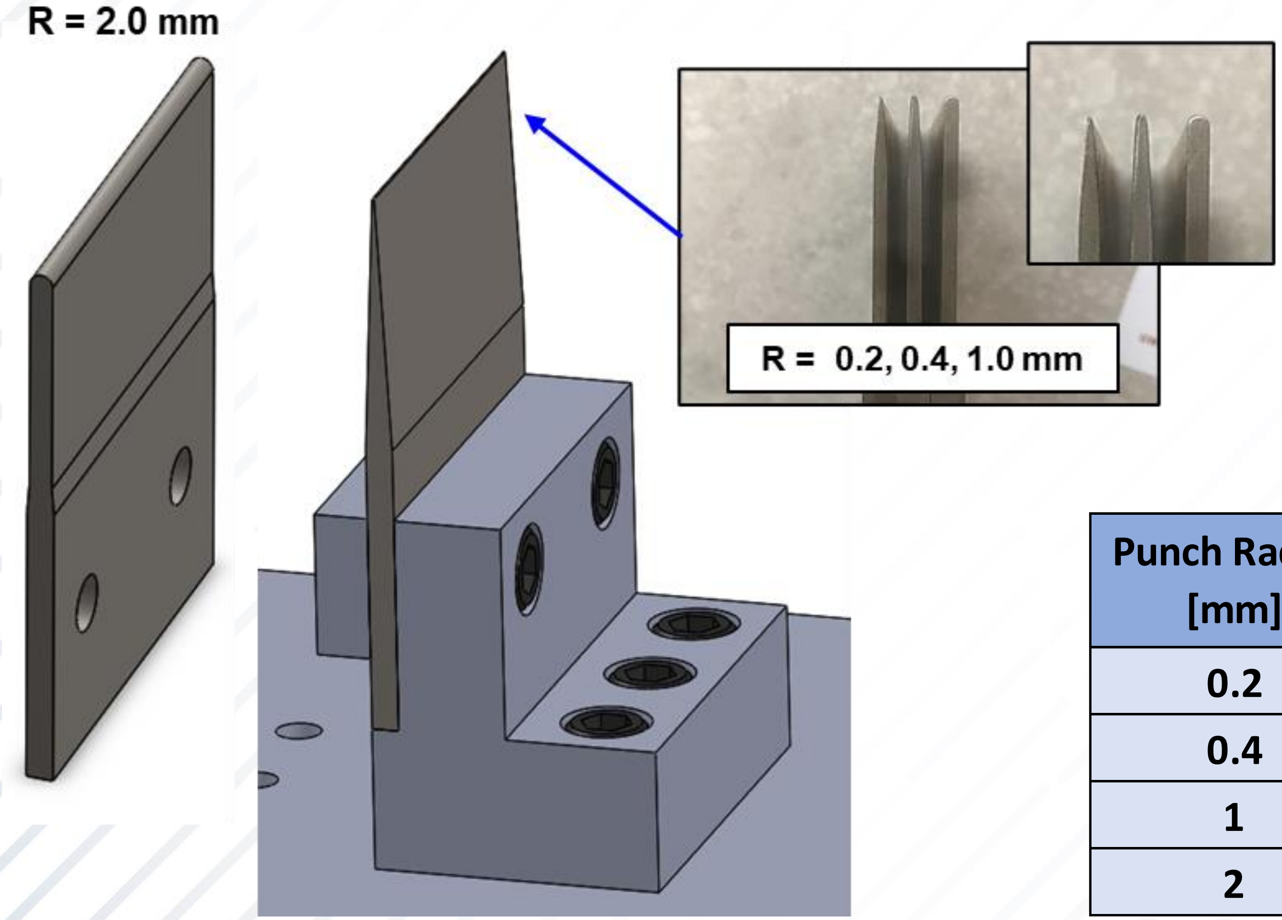
- Yield Strength: 420 ~ 1200 MPa
- Tensile Strength: 780 ~ 1500 MPa
- Thickness: 1 ~ 1.6 mm

Material	Yield Str.	Tensile Str.
CR420Y780T-DP	420	780
CR700Y980T-MP	700	980
CR600Y980T-RA-HE-GI	600	980
CR850Y1180T-RA-SE	850	1180
CR875Y1180T-MP	875	1180
CR950Y1300T-PHS	950	1300
CR1200Y1500T-MS	1200	1500

Two 3rd Gen: 980 and 1180 with RA designation

RANGE OF BEND SEVERITY

Punch Layout



- Fracture behavior is expected to be affected by the bend severity, t_o/R_p

  (t_o = Initial sheet thickness, R_p = Punch radius)

- *83 total test conditions*

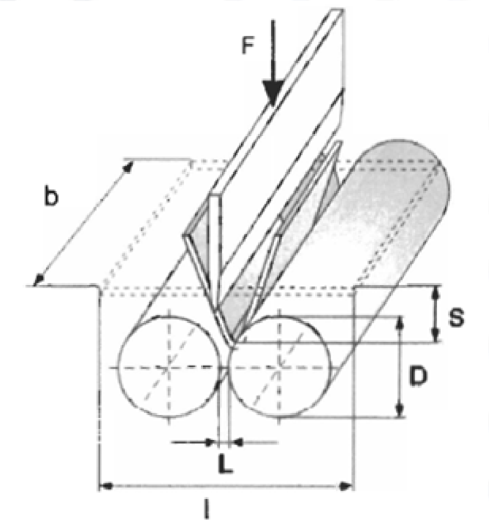
Bend Severity Chart

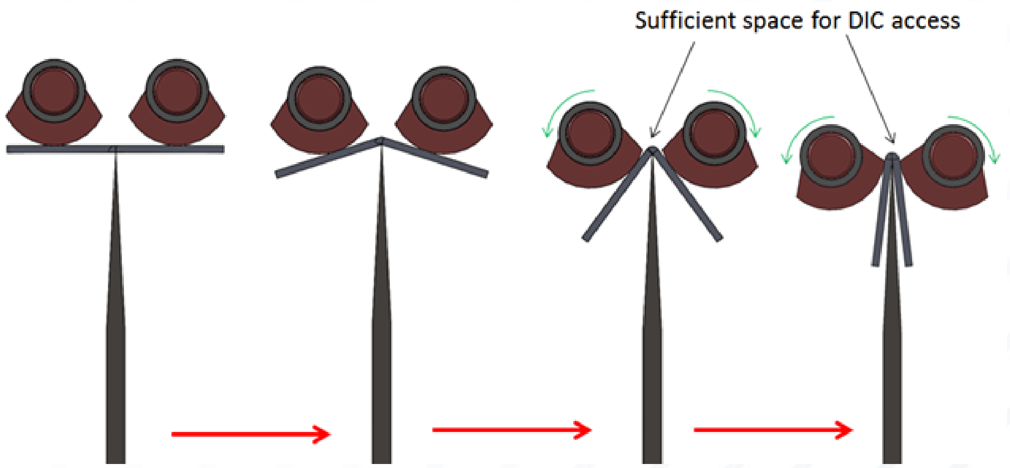
Punch Radius [mm]	Sheet Thickness [mm]				
	1	**1.2**	**1.4**	**1.5**	**1.6**
0.2	5.00	6.00	7.00	7.50	8.00
0.4	2.50	3.00	3.50	3.75	4.00
1	1.00	1.20	1.40	1.50	1.60
2	0.50	0.60	0.70	0.75	0.80

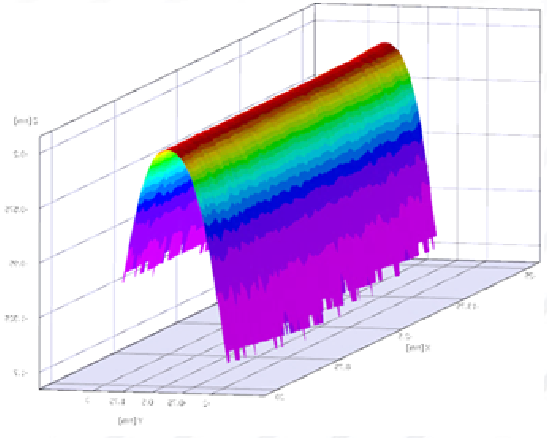
V-Bend Test Frame & Parameters

VDA 238-100 BEND TEST

- UW developed an inverted VDA test frame to enable DIC of the bending process
  - → *Measure strain at convex layer where tensile strains are highest*
  - → *Virtual Strain Gauge Length (VSGL) ≈ 0.5 mm*
- *The plane strain fracture limit is expected to be a material property while the bend angle varies with test parameters*



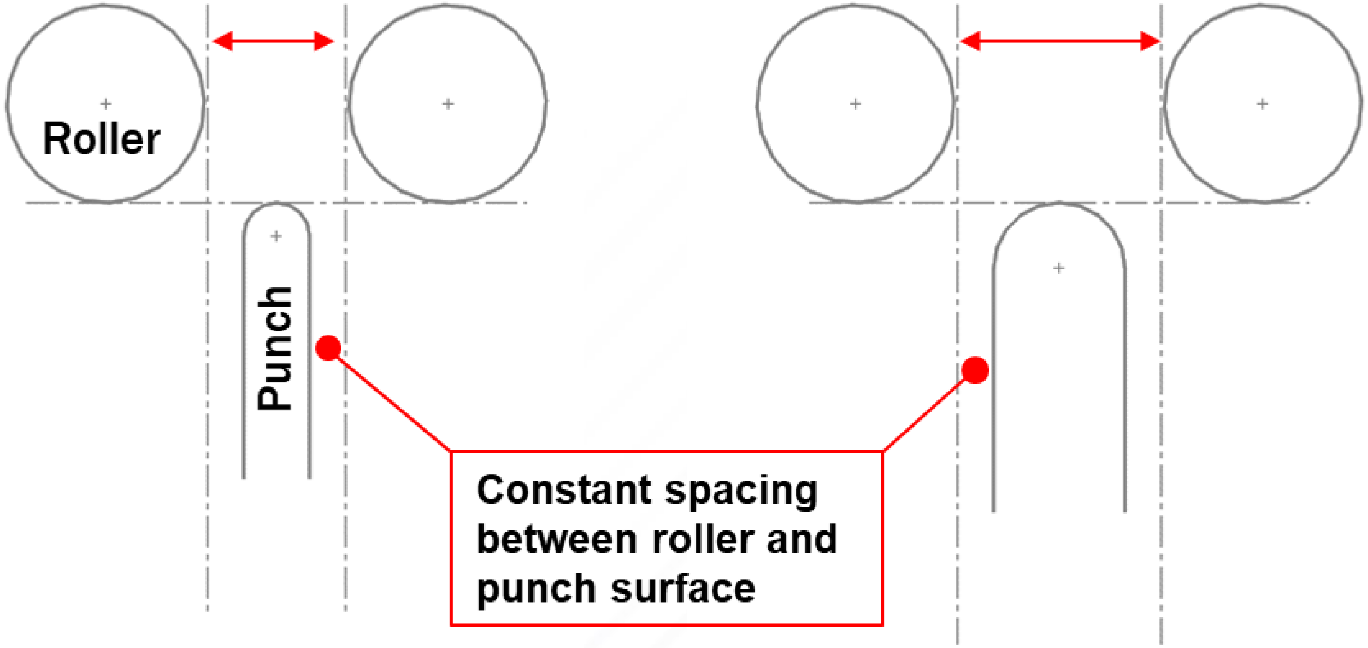


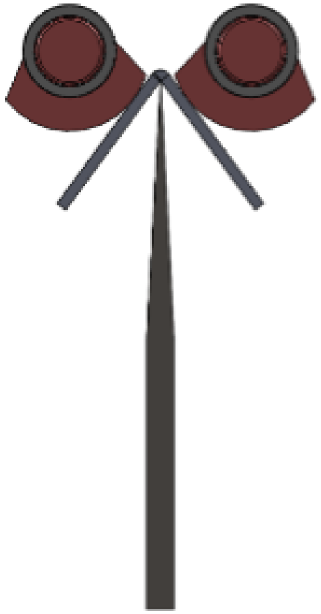


SETTING OF THE ROLLER GAP

- VDA 238-100 suggested gap: 2 x sheet thickness, in case of steel, + 0.5 mm
- Punch radius/thickness were not considered in setting VDA roller gap

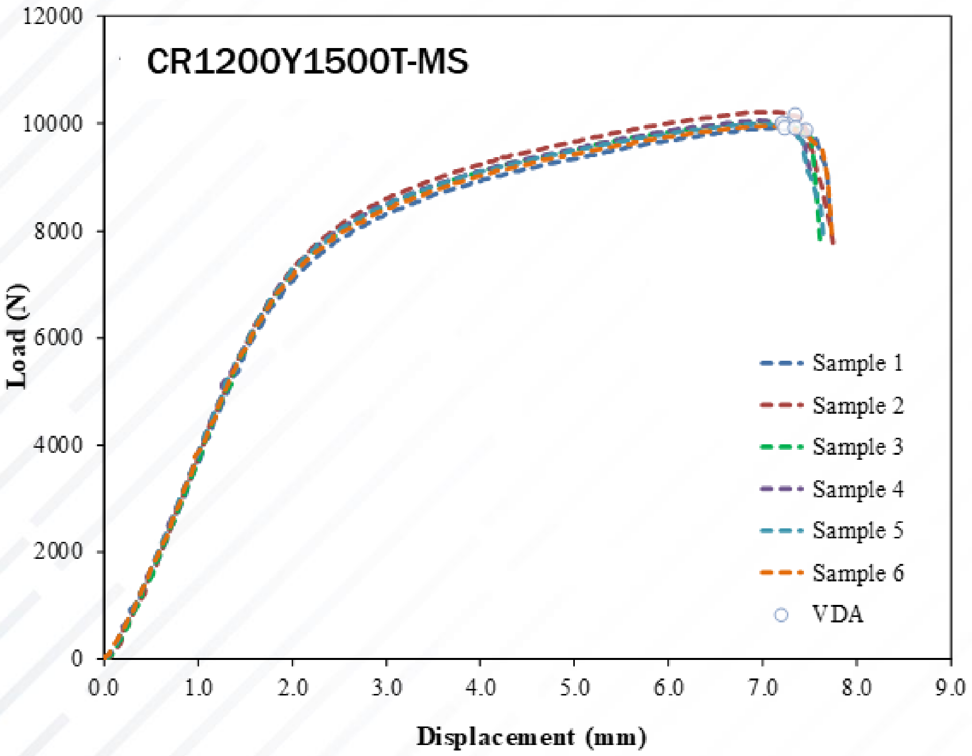
Modification of Gap: Gap = 2*(thickness) + 0.5 mm + 2*(R_p – 0.2 mm)



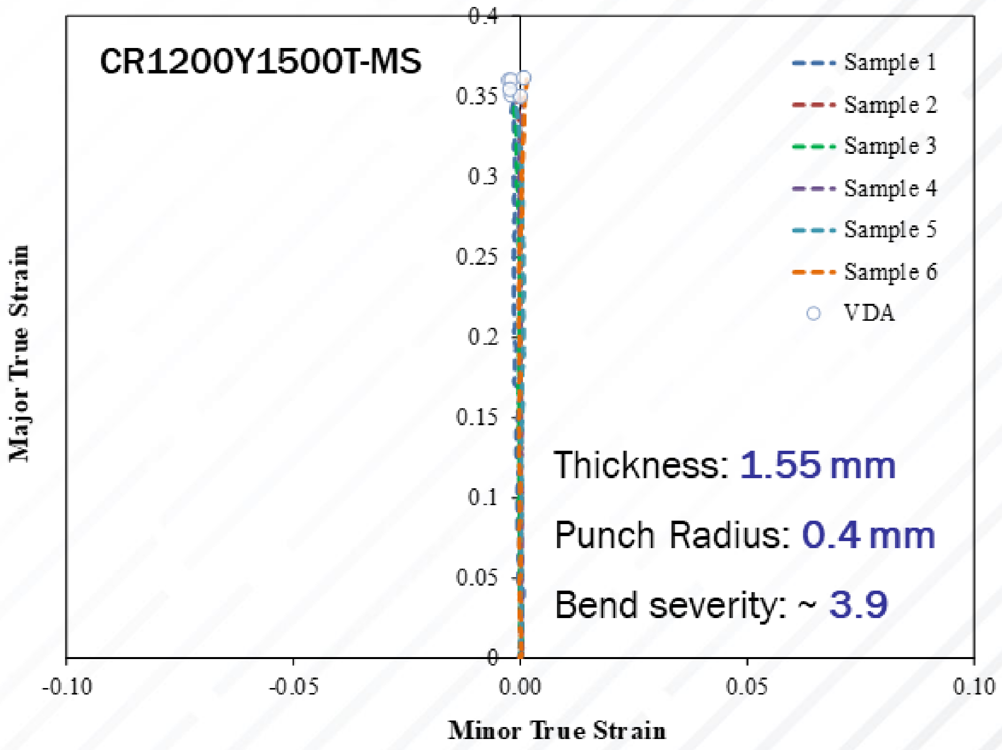


V-BEND TEST RESULT EXAMPLE

Load Curve



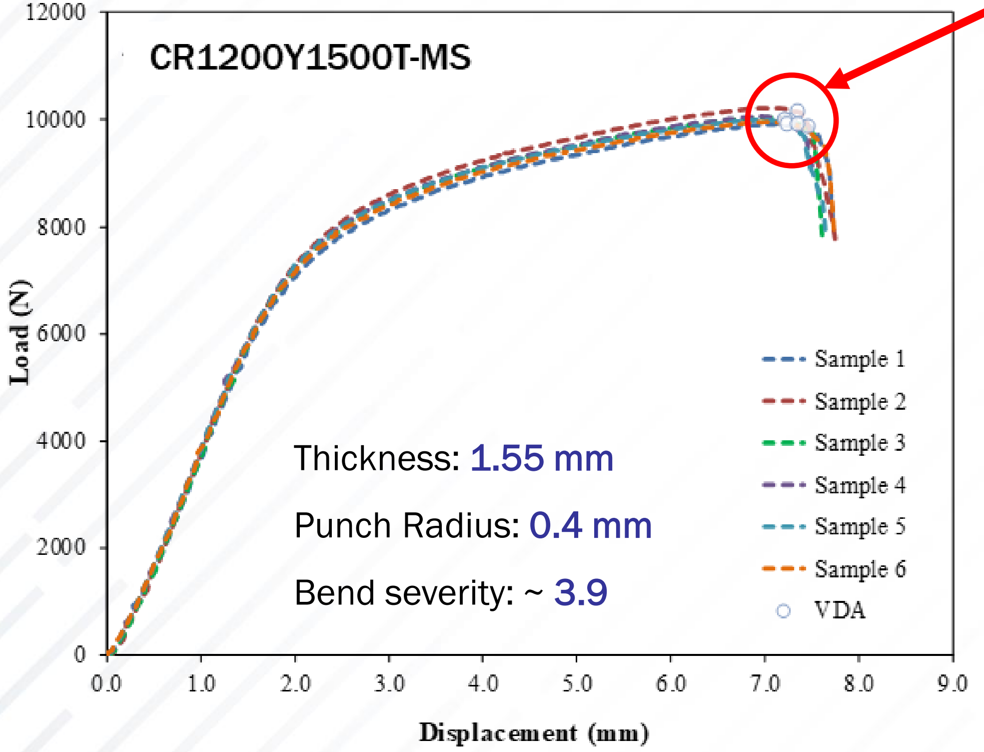
Strain Path



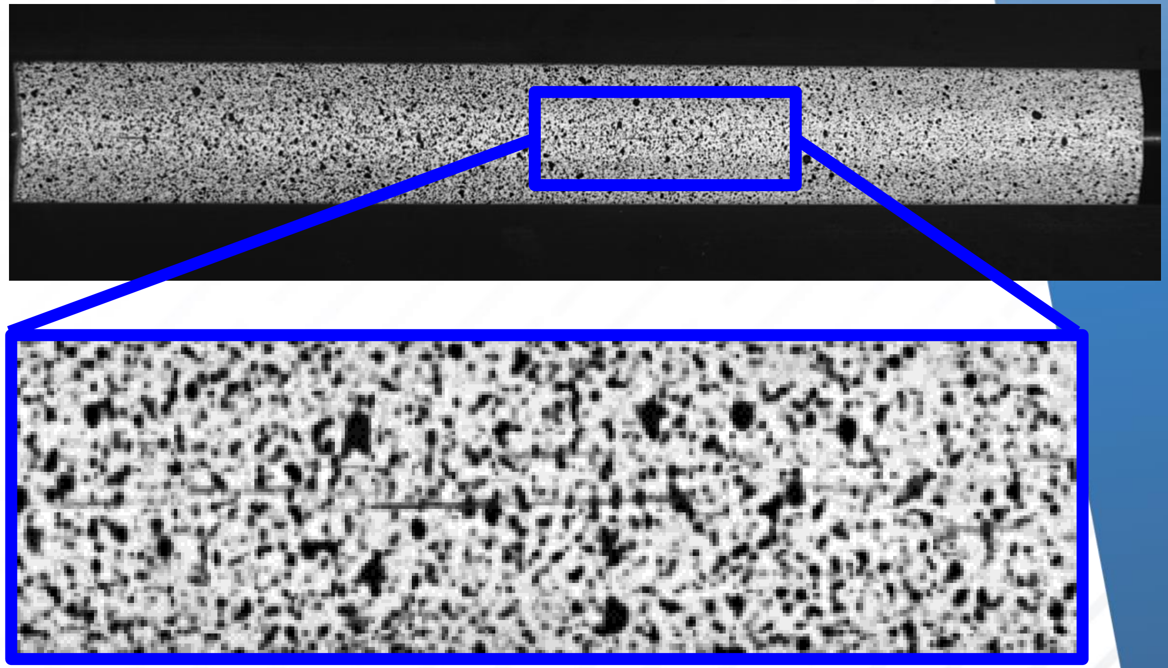
- VDA 238-100 defines fracture based on the peak load location (can give false positive)
- For most AHSS in this project, this corresponds to the initiation of hairline cracks

V-BEND TEST RESULT EXAMPLE

Load Curve

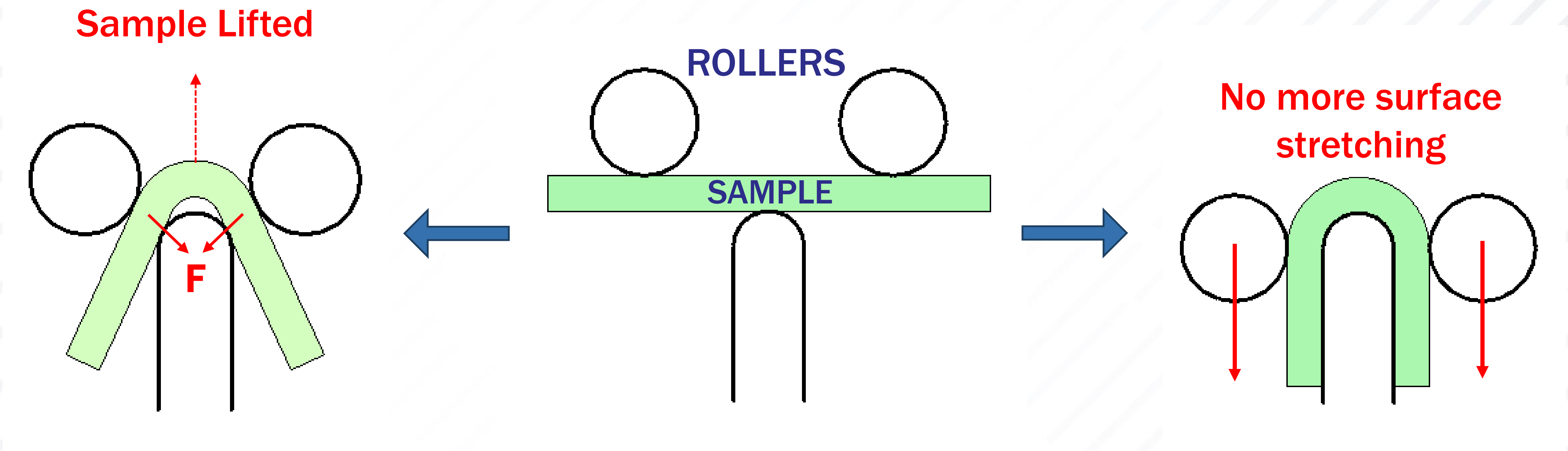


VDA load threshold: 60 N load drop from the peak load



- VDA 238-100 defines fracture based on the peak load location (can give false positive)
- For most AHSS in this project, this corresponds to the initiation of hairline cracks

VDA BEND TEST LIMITATIONS



Punch tip lift-off

- Punch lift-off changes the effective bend radius and can alter the load response used to detect failure

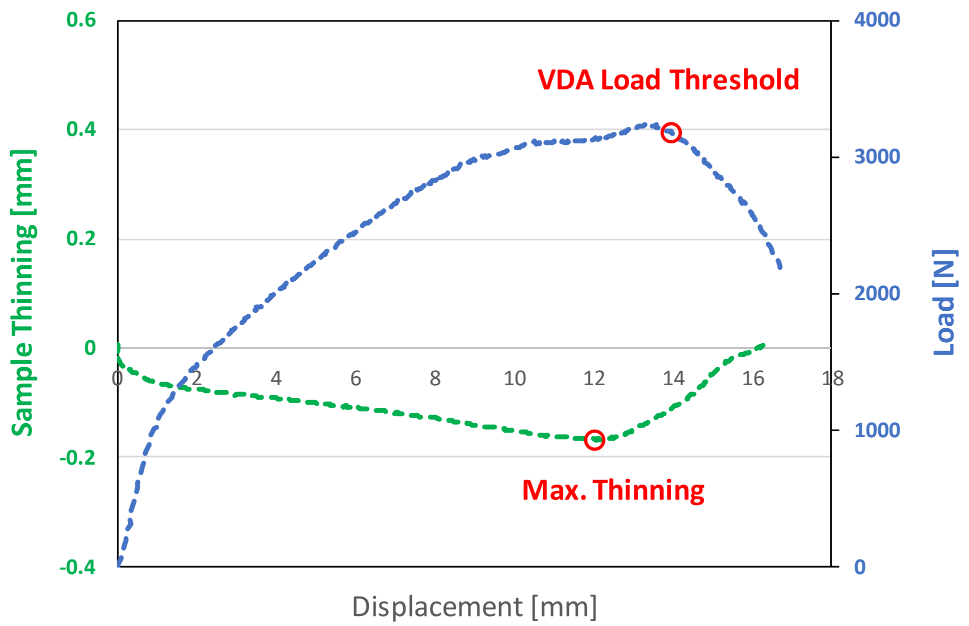
Sample folding over

- Ductile material can be folded over around the punch
- Load will still drop due to the loss of roller contact

→ **False positive for load-based analysis (VDA)**

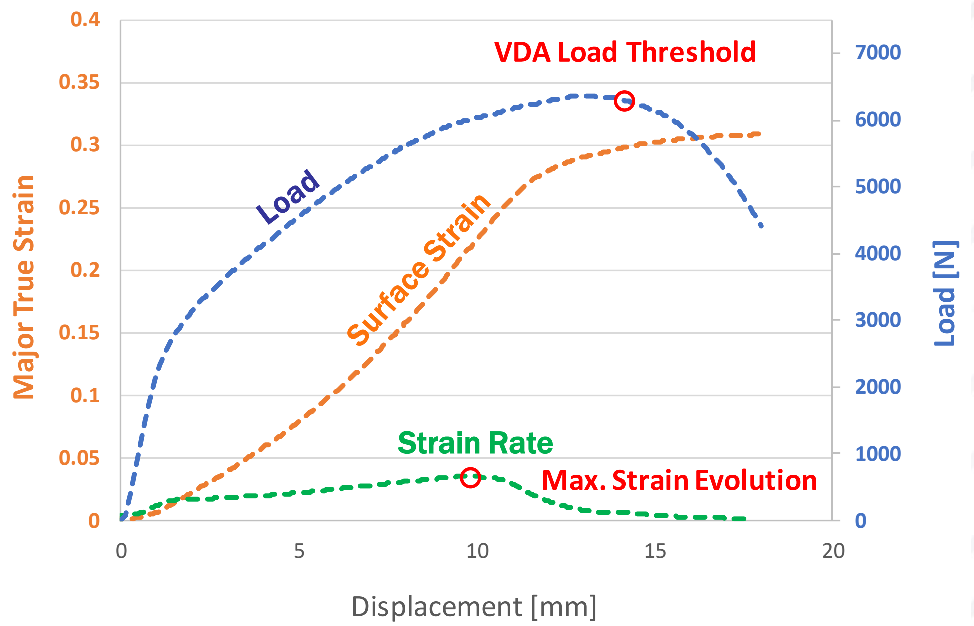
VDA BEND TEST VALIDATION

Punch Tip Lift-Off



- The cross-section thins during severe bending which can be tracked from DIC Z-displacement
- Punch tip lift-off detected when the Z-displacement reverses

Material Fold Over

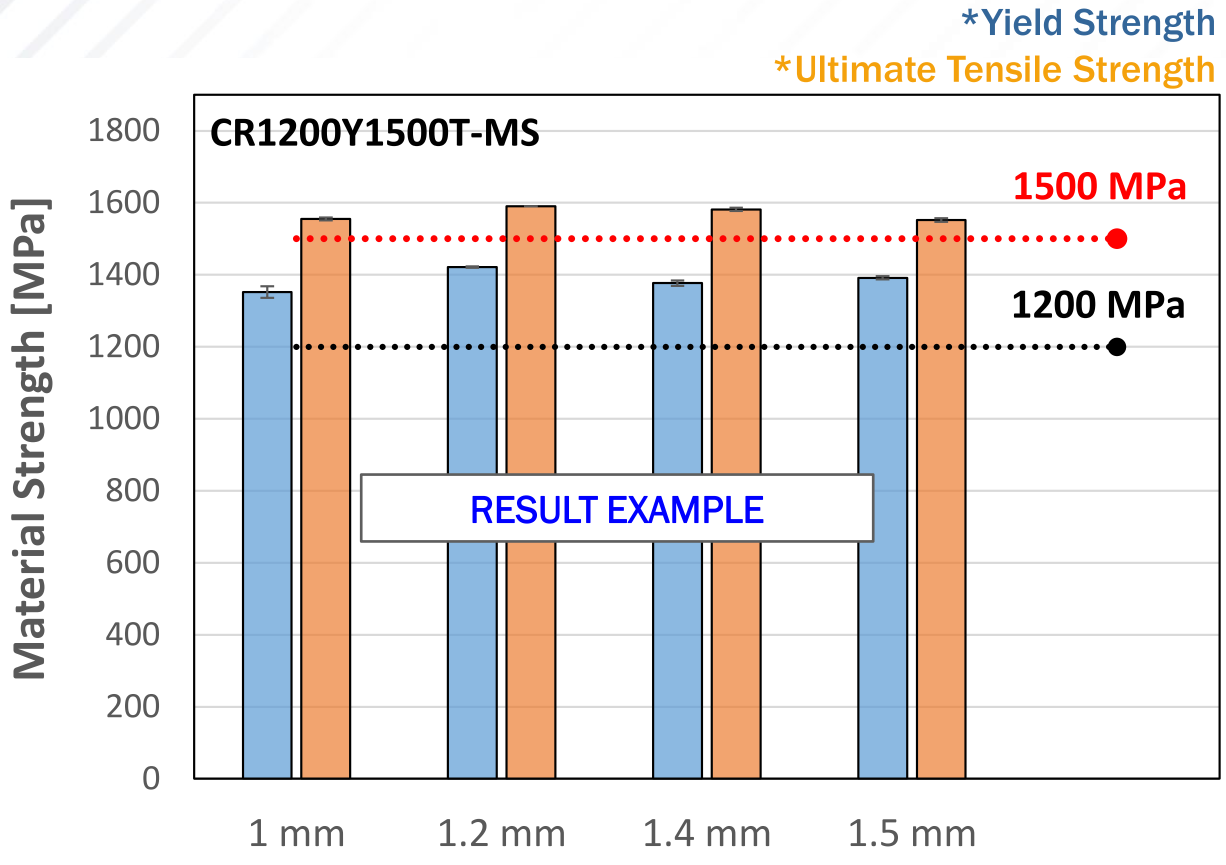


- Smooth load drop and stagnation of surface strain indicate the material folding over without fracture
- Reduction of strain rate detects folding over and removes VDA false positive

Effect of Test Parameter

Material Strength | *Sheet Thickness* | *Bend Radius*

TENSILE STRENGTH VERIFICATION



Material	Nominal		Experimental	
	Yield Str [MPa]	UTS [MPa]	Yield Str [MPa]	UTS [MPa]
CR420Y780T-DP	420	780	519	855
CR600Y980T-RA-HE-GI	600	980	669	1004
CR700Y980T-MP	700	980	751	1063
CR850Y1180T-RA-SE	850	1180	911	1244
CR875Y1180T-MP	875	1180	898	1222
CR950Y1300T-PHS	950	1300	1127	1534
CR1200Y1500T-MS	1200	1500	1385	1570

* All materials met or exceeded the target mechanical properties

- Material strength of each lot was verified by uniaxial tensile tests analyzed with stereo DIC
- Tensile mechanical properties were consistent for each grade despite the different thicknesses

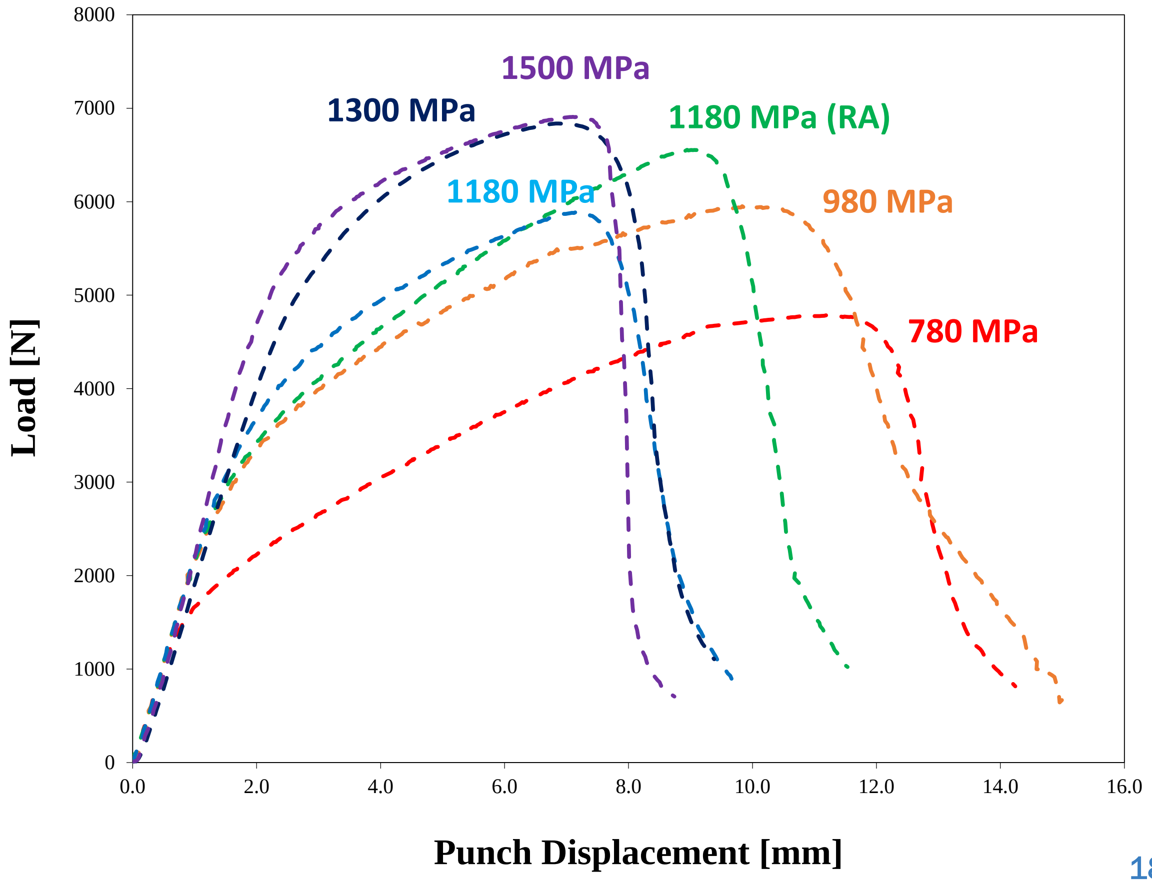
VDA BEND TEST LOAD RESPONSE

- Overall trend agrees with the behavior of yield strength and UTS from the tensile test
- Peak-load location is important in VDA analysis
- Work hardening and local formability are critical factors to describe material bendability

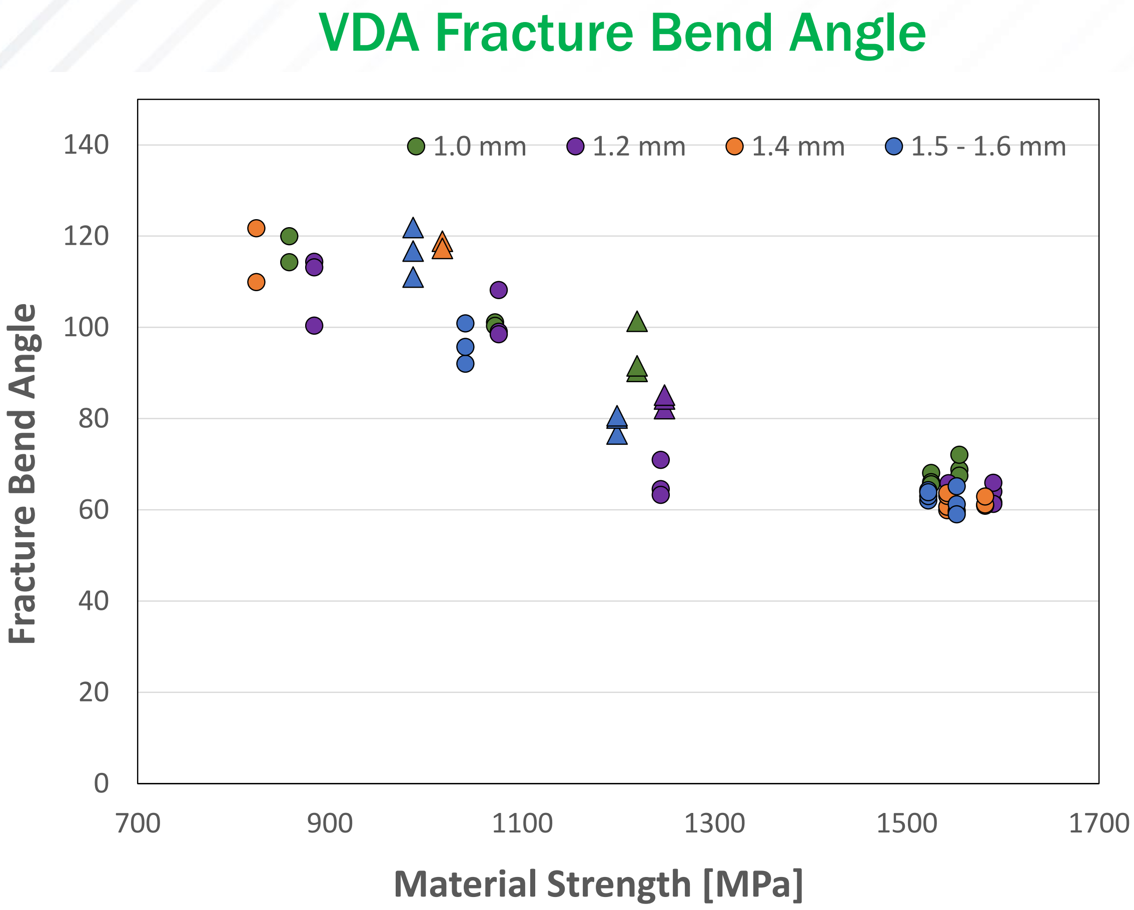
→ 1180-RA converges towards peak load of 1500 MPa steel

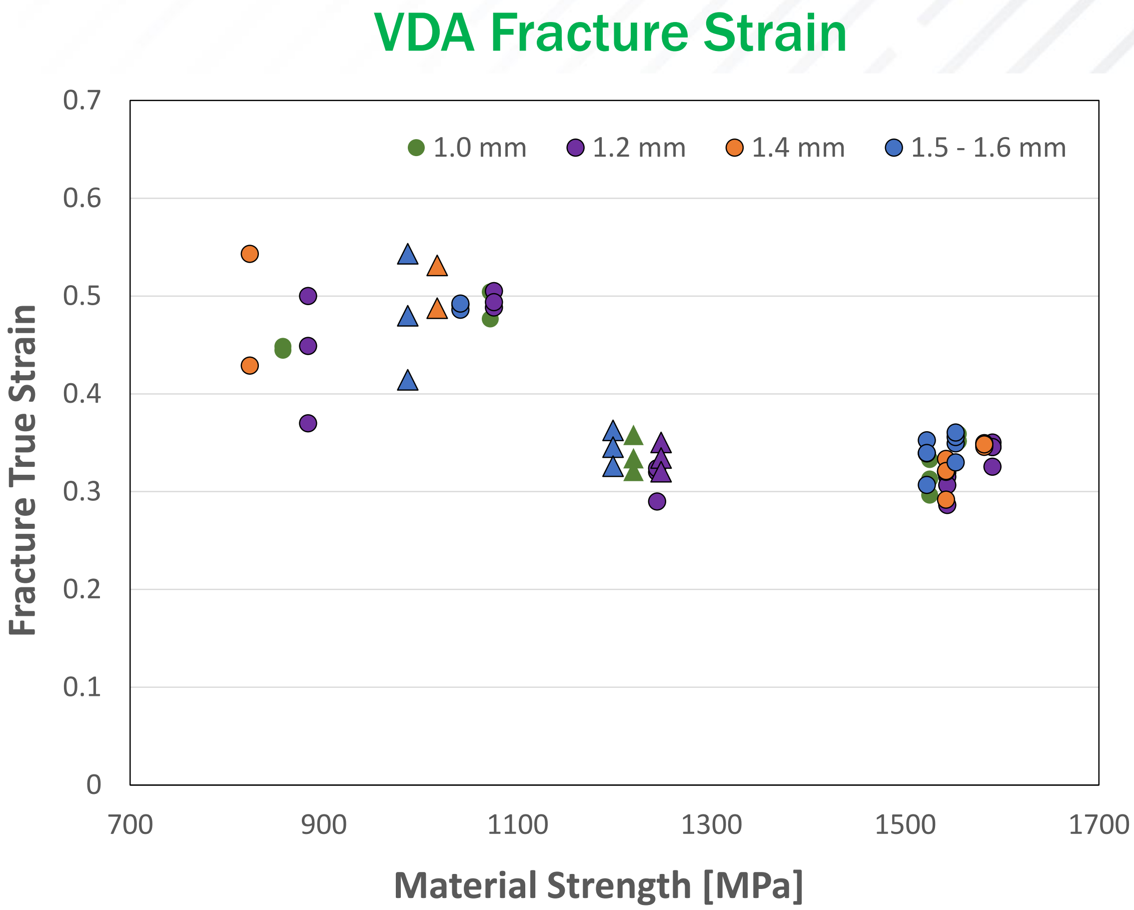
→ Clear difference between **1180-MP** and **1180-RA (3rd Gen)**

Thickness: 1.2 mm (Constant)
Punch Radius: 0.4 mm (Constant)
Material Strength: 780 ~ 1500 MPa



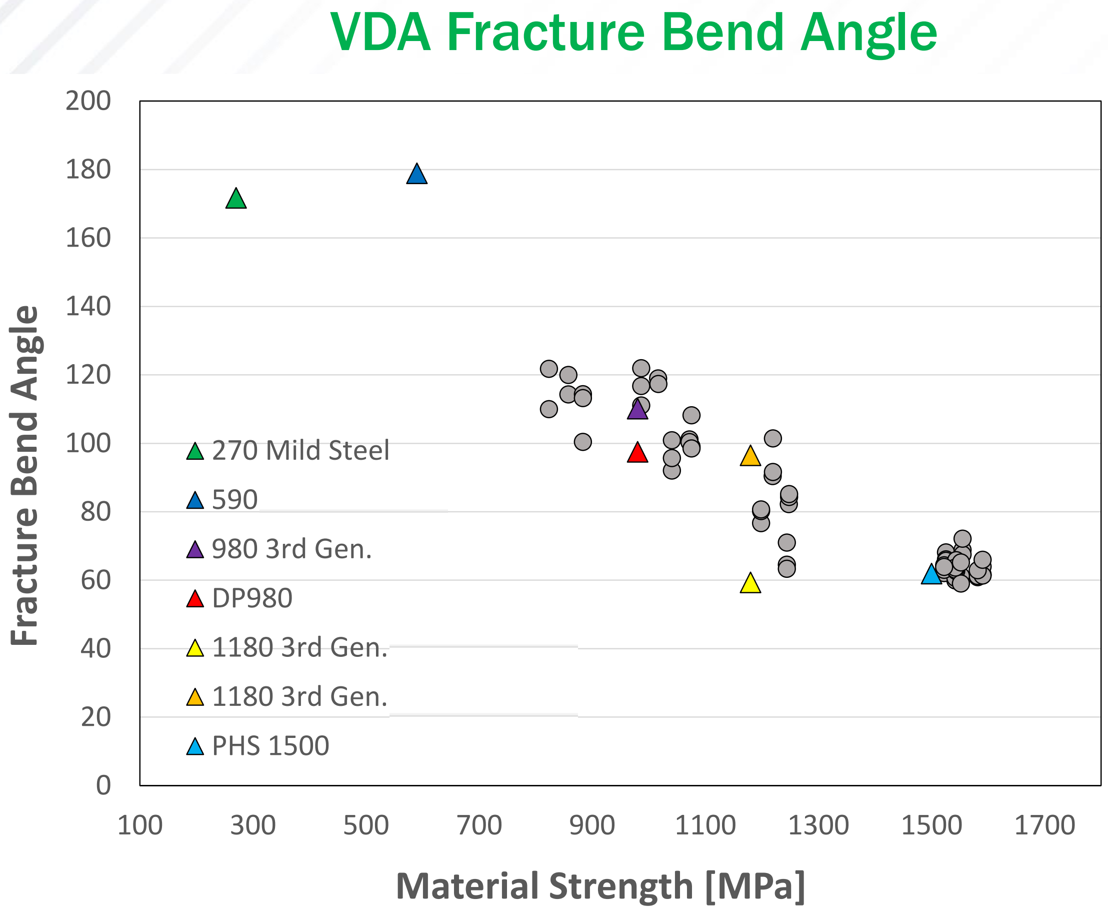
VDA BEND TEST RESULT WITH UTS

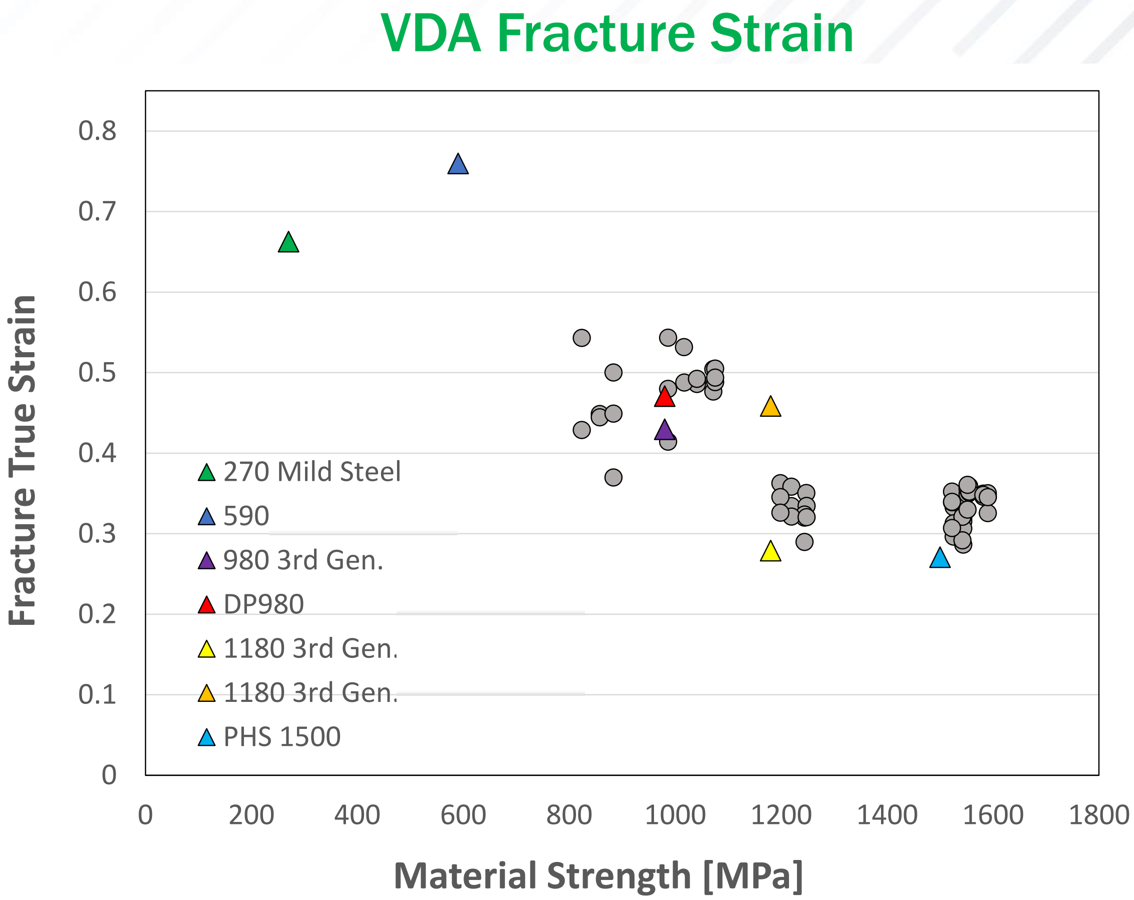




* Each data point represents different test conditions (4 - 6 repeats each)

VDA BEND TEST WITH ADDITIONAL AHSS DATA

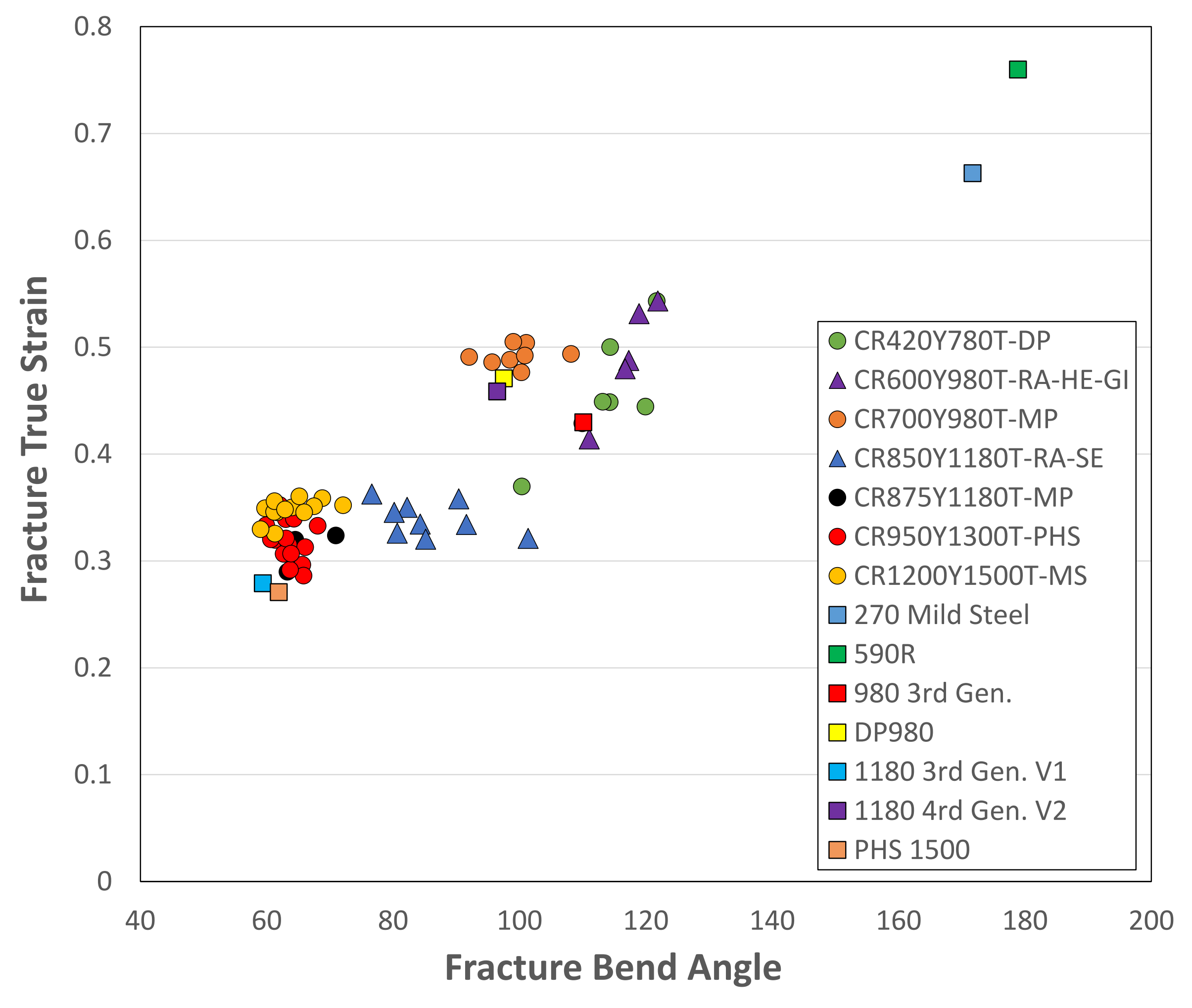




- General trend of fracture vs. strength emerges for AHSS for 780 MPa and higher

Noder, J., Dykeman, J. and Butcher, C., 2020. New Methodologies for Fracture Detection of Automotive Steels in Tight Radius Bending: Application to the VDA 238–100 V-Bend Test. Experimental Mechanics, pp.1-28.

SUMMARY: INFLUENCE OF MATERIAL STRENGTH



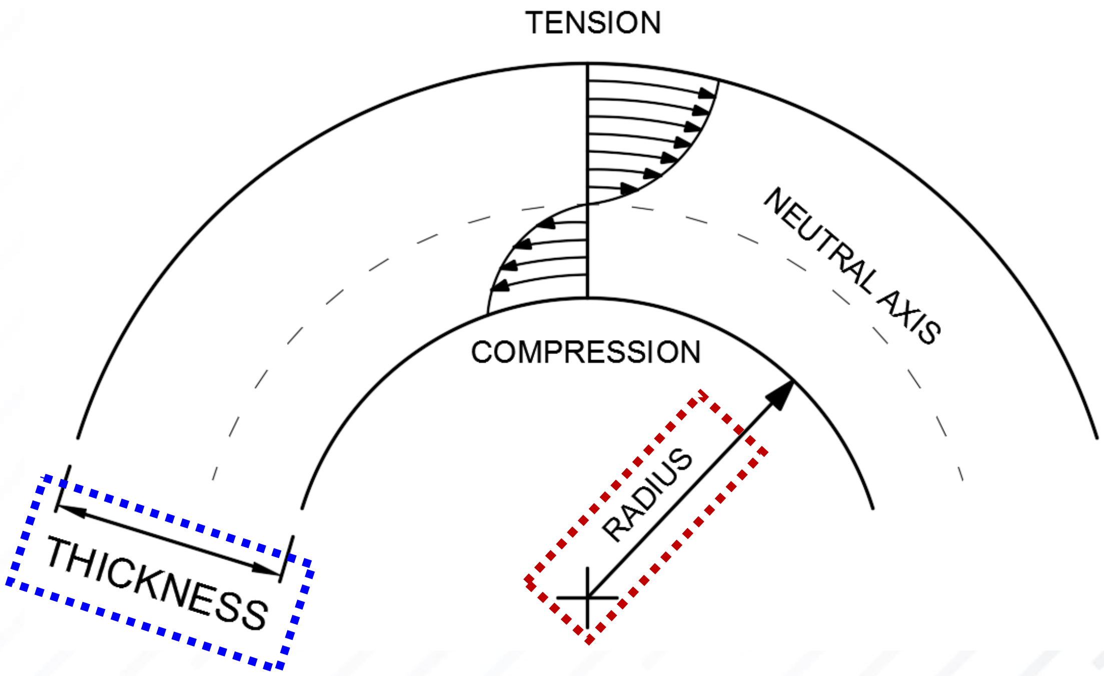
- Material strength only provides a rough guess on the material bending performance
- Work hardening and local formability of material are important factors to determine material bendability

Effect of Test Parameter

Material Strength | Sheet Thickness | Bend Radius

EFFECT OF BEND SEVERITY

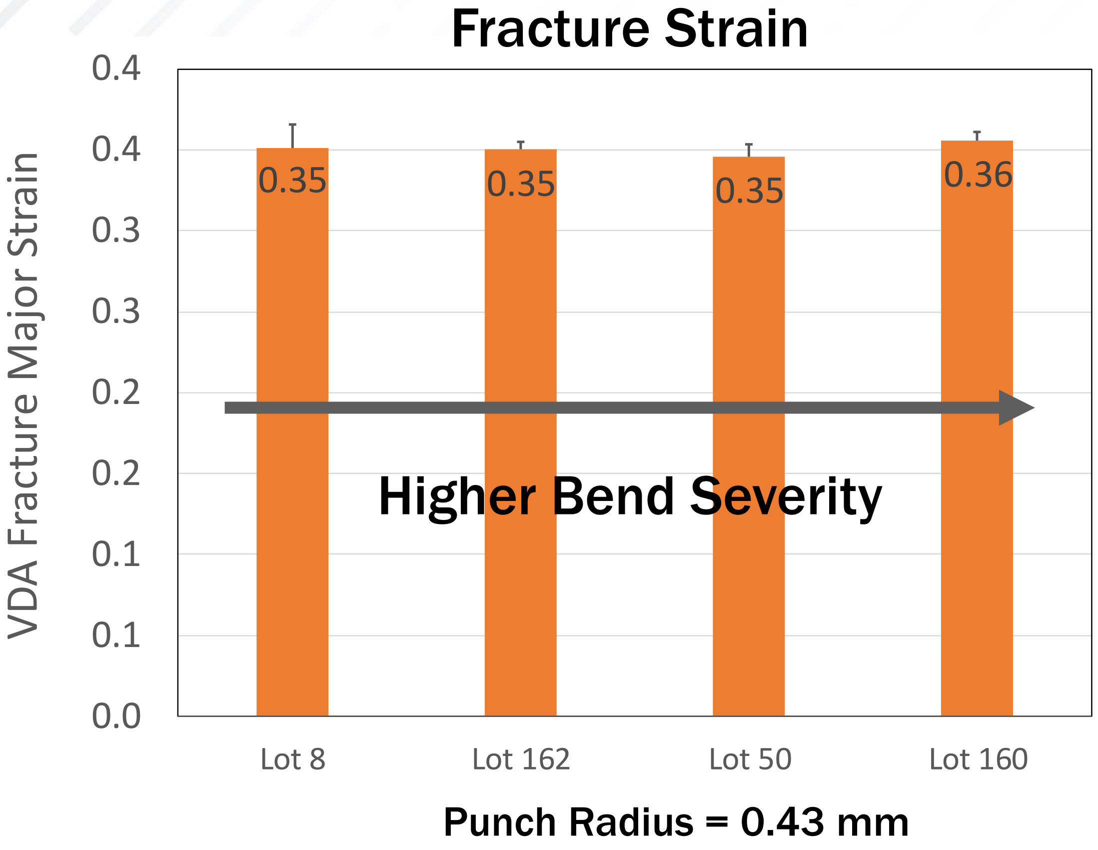
- A strain gradient is generated through the thickness during bending deformation
- Larger sheet thickness results in more severe bending which allows the strain gradient to grow larger on the surface with identical bend angle
- Similarly, sharper bend radius will result in higher surface strain under identical bend angle
- Therefore, fracture bend angle cannot be considered as an independent metric to describe a material performance



$$\text{Bend Severity} = \frac{\textit{Sheet Thickness}}{\textit{Bend Radius}}$$

THICKNESS COMPARISON (CR1200Y1500T-MS)

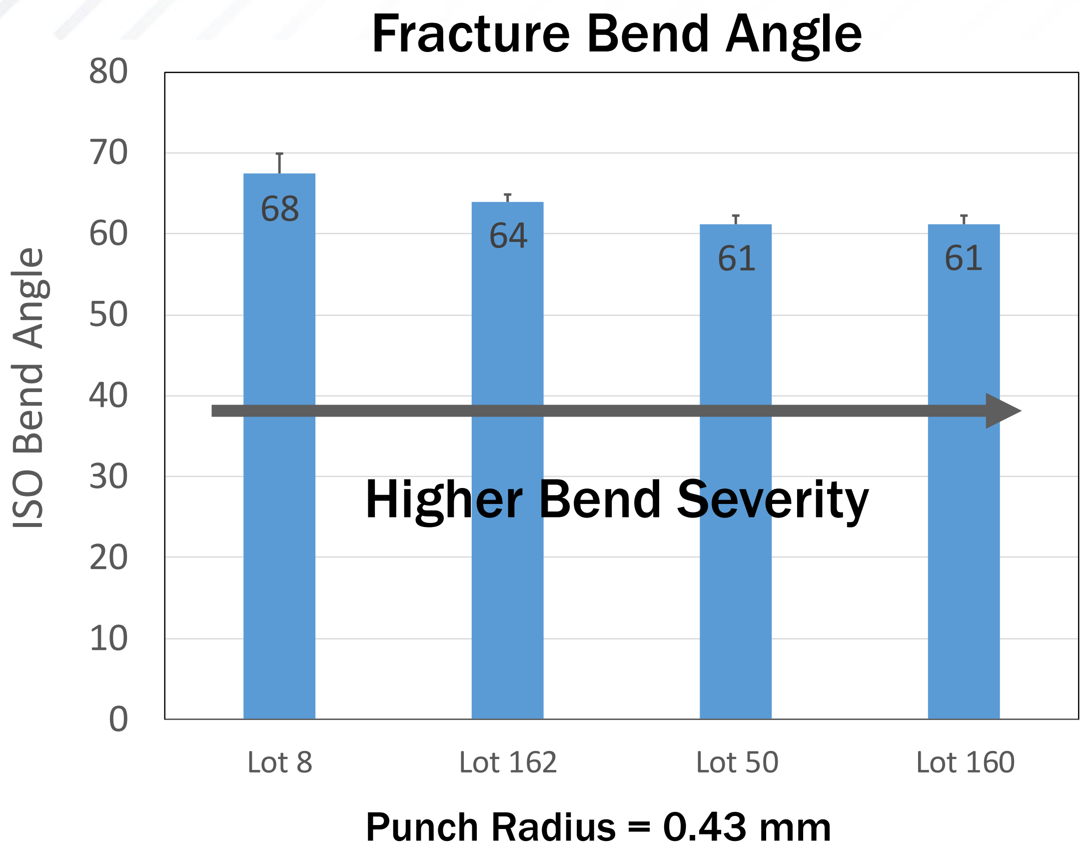
CR1200Y1500T	Lot #8	Lot #162	Lot #50	Lot #160
Thickness:	1	1.2	1.4	1.55



- **Plane strain fracture limit remained approximately constant with varying sheet thickness**
- Similar observations for all AHSS considered in this project
- Unless there is a significant change in the baseline mechanical properties with thickness, *the bending fracture limit for AHSS appears to be insensitive to thickness*

THICKNESS COMPARISON (CR1200Y1500T-MS)

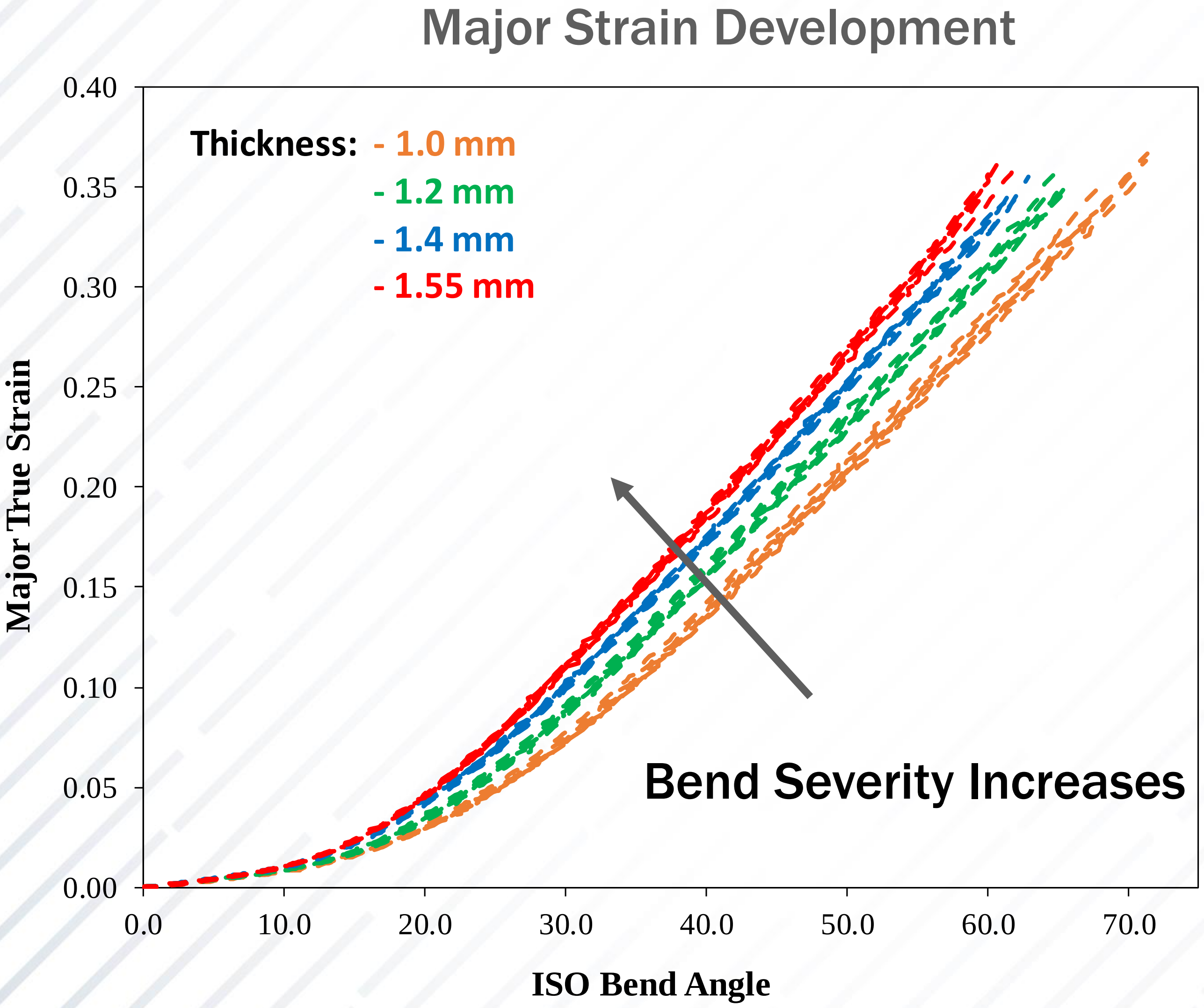
CR1200Y1500T	Lot #8	Lot #162	Lot #50	Lot #160
Thickness:	1	1.2	1.4	1.55



- **Fracture bend angle was observed to decrease as the bend gets more severe**
- Bend angle is dependent on the test condition (e.g. sheet thickness)

→ Fracture bend angle can be used for ranking but only for identical test conditions

THICKNESS COMPARISON (CR1200Y1500T-MS)



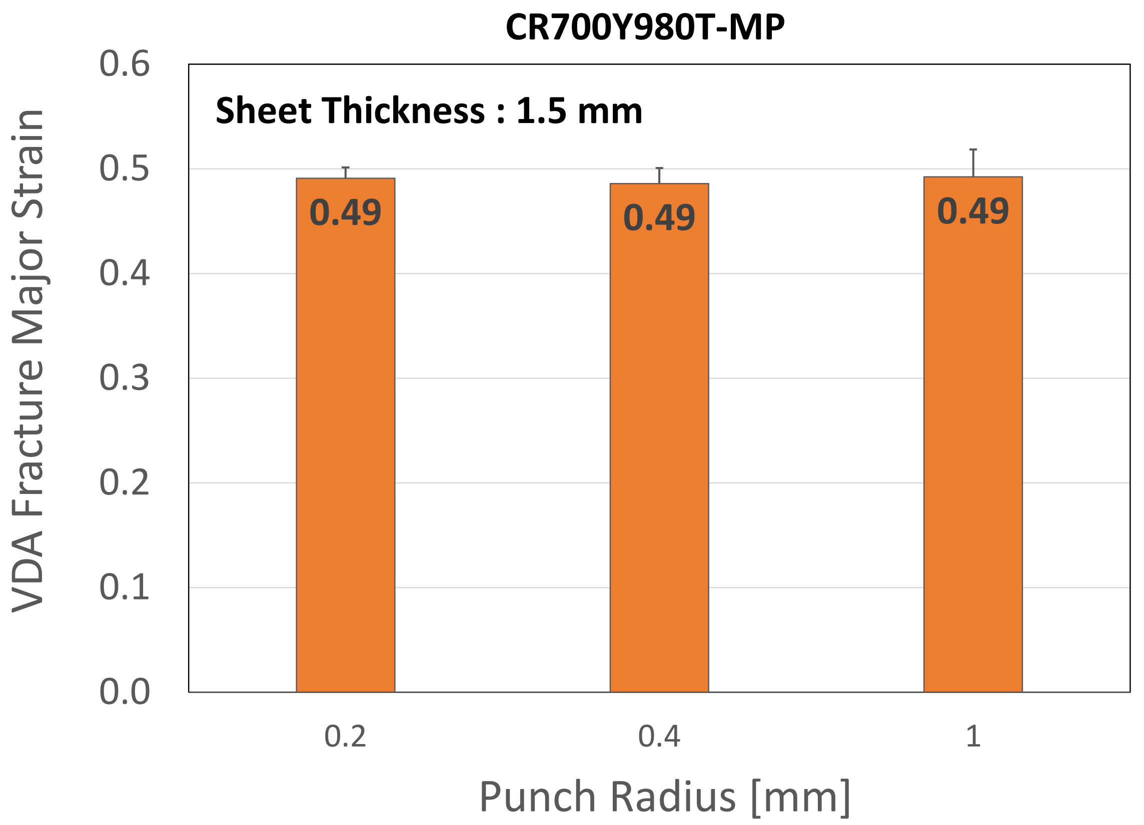
- Plane strain fracture limit remained unchanged with varying sheet thickness
- Development of the surface strain is affected by the bend severity
- Fracture Bend angle is a function of the bending severity, *t/R*

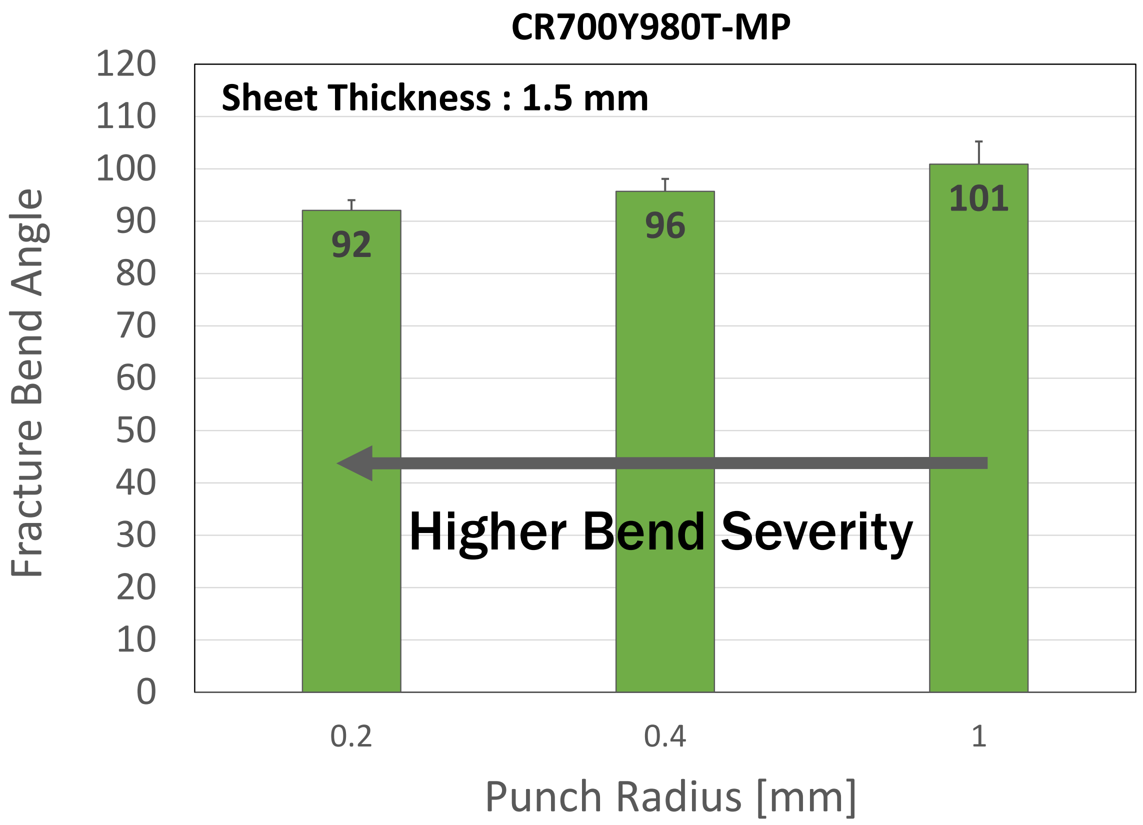
→ Bend angle is only valid for ranking purposes but not ideal to describe material performance

Effect of Test Parameter

Material Strength | *Sheet Thickness* | ***Bend Radius***

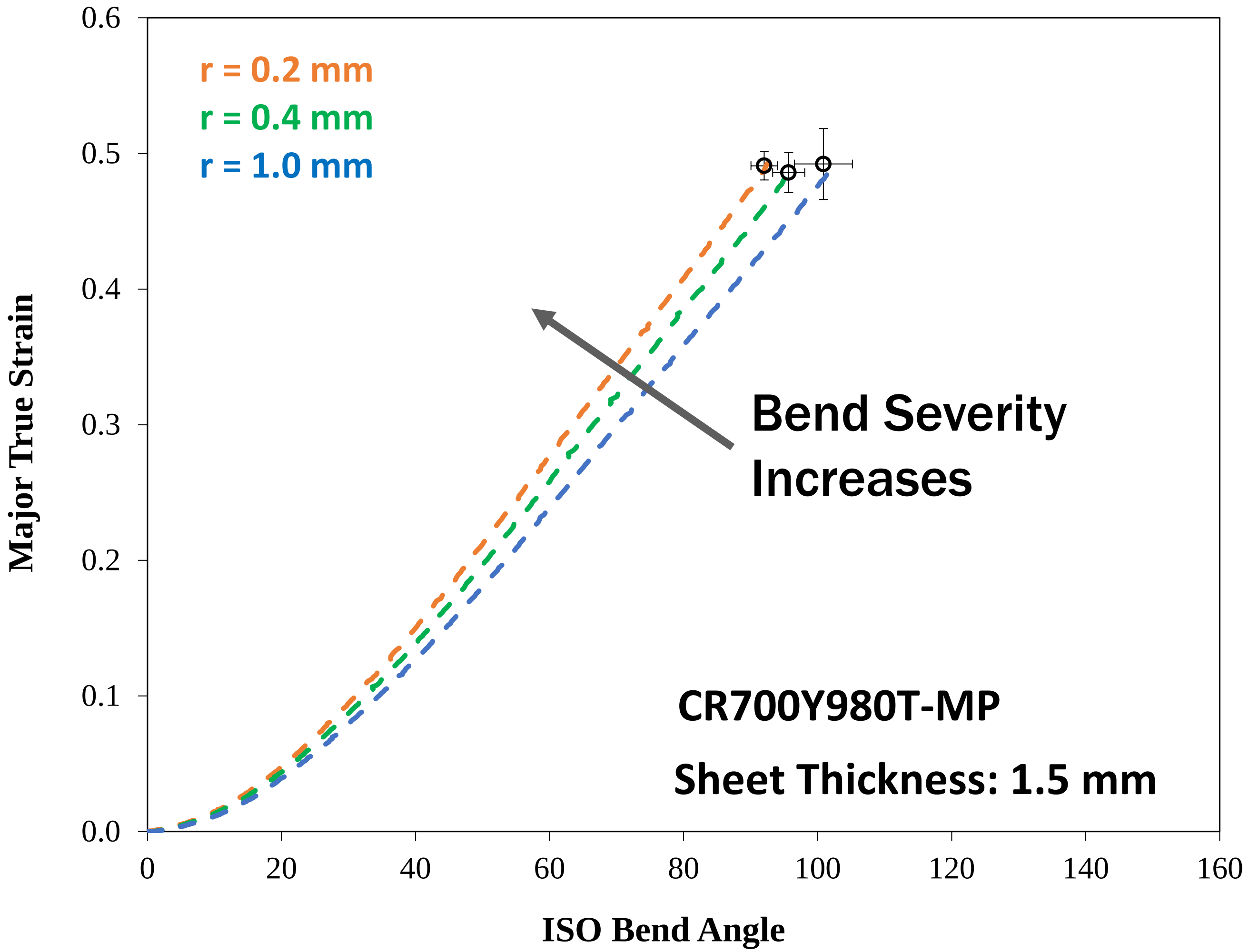
EFFECT OF BEND RADIUS





- Similar behavior was observed: *"constant fracture strain" and "altering fracture bend angle"*
- Larger punch corresponds to the lower bend severity

BEND SEVERITY ON STRAIN DEVELOPMENT

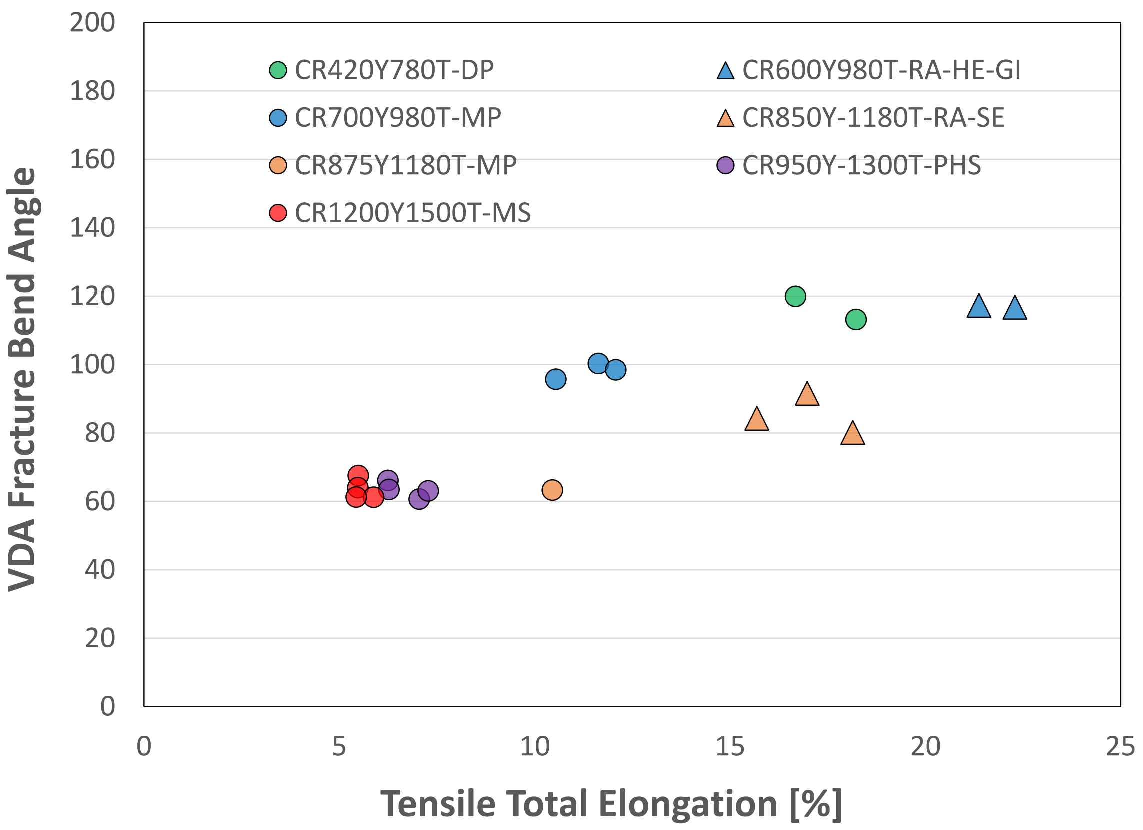


- Similar to the thickness comparison, more severe bending resulted in a steeper strain development
- The impact of the bend severity on strain development is significant
- *Plane strain fracture limit is a material constant, whereas fracture bend angle is dependant on the bend severity*

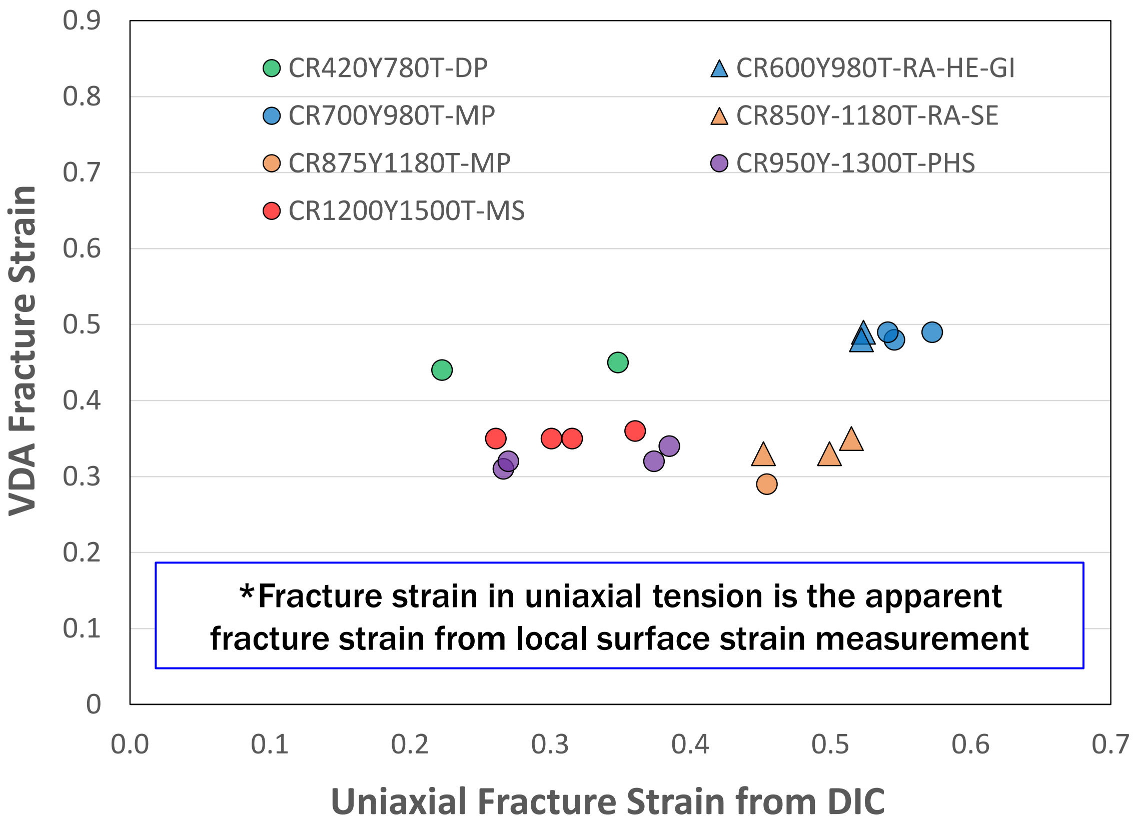
Evaluation of the Bend Performance of AHSS with Tensile Properties

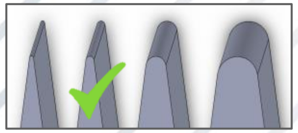
COMPARISON OF BENDING AND TENSILE PROPERTIES

Bend Angle vs. Total Elongation



Bending Fracture vs. Tensile Fracture





Tensile properties do not appear to map over to plane strain bendability

* Each data point represents different test conditions (4 - 6 repeats)

FORMABILITY AND PERFORMANCE INDEX

- Formability Index (F.I.) is a parameter which considers both necking and fracture limit to characterize formability of a material
- In this analysis, True Fracture Strain (TFS) was replaced by the VDA plane strain fracture limit – *"Plane strain F.I. and P.I."*

$$\boldsymbol{Plane\ Strain\ F.I. = \sqrt{\varepsilon_u \cdot TFS}}$$

where: $\boldsymbol{TFS = \varepsilon_{f.VDA}}$ $\boldsymbol{\varepsilon_u = \ln[1 + (UE/100)]}$

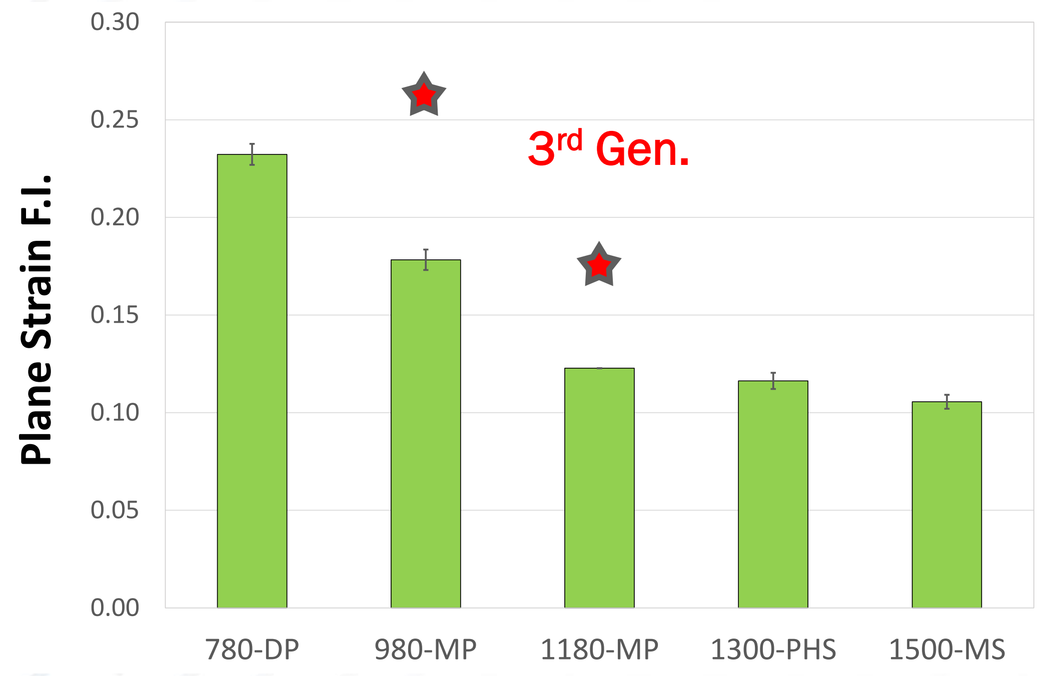
- Performance Index (P.I.) introduces material strength into the concept of formability index

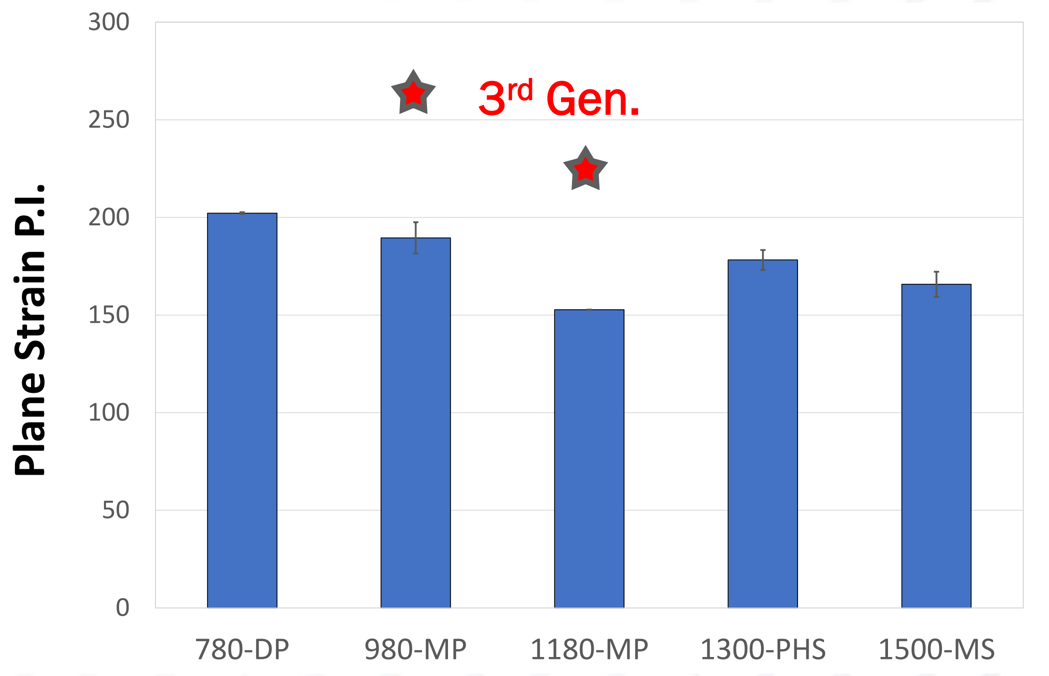
$$\boldsymbol{Plane\ Strain\ P.I. = UTS \cdot F.I. = UTS \cdot \sqrt{\varepsilon_u \cdot TFS}}$$

Hance, B., "Advanced High Strength Steel (AHSS) Performance Levels," *SAE Technical Paper 2018-01-0629*, 2018, doi:10.4271/2018-01-0629.

PLANE STRAIN FORMABILITY & PERFORMANCE INDEX

$$P.I. = UTS \cdot (F.I.) = UTS \cdot \sqrt{\varepsilon_u \cdot TFS}.$$



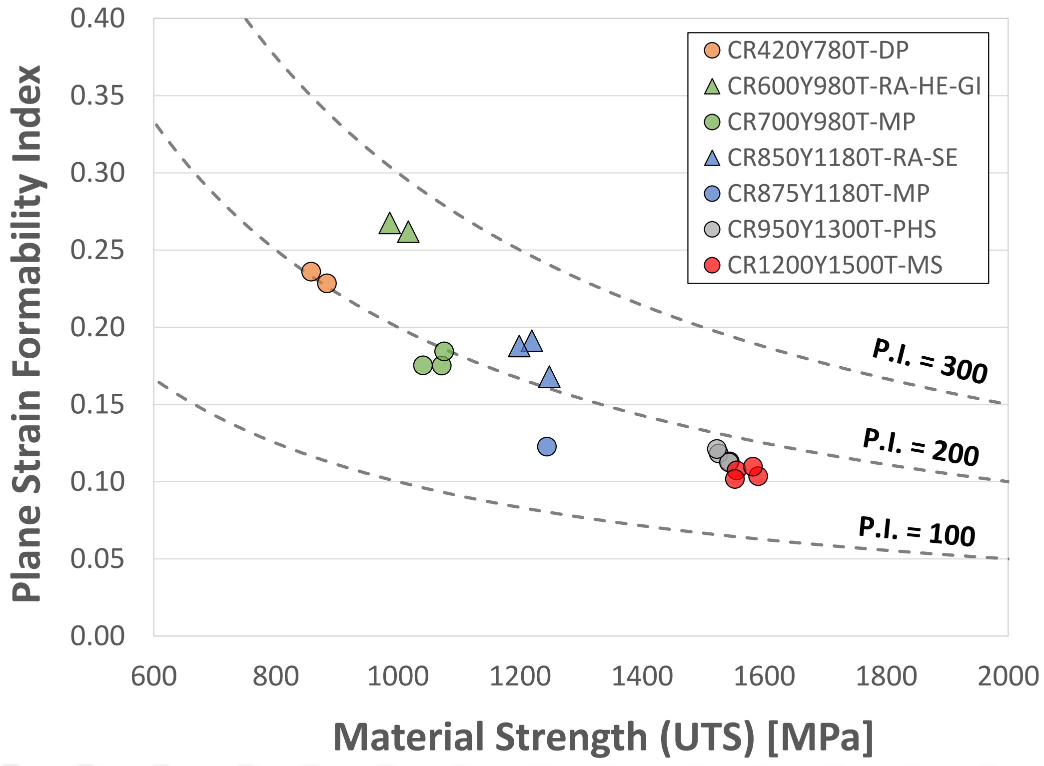


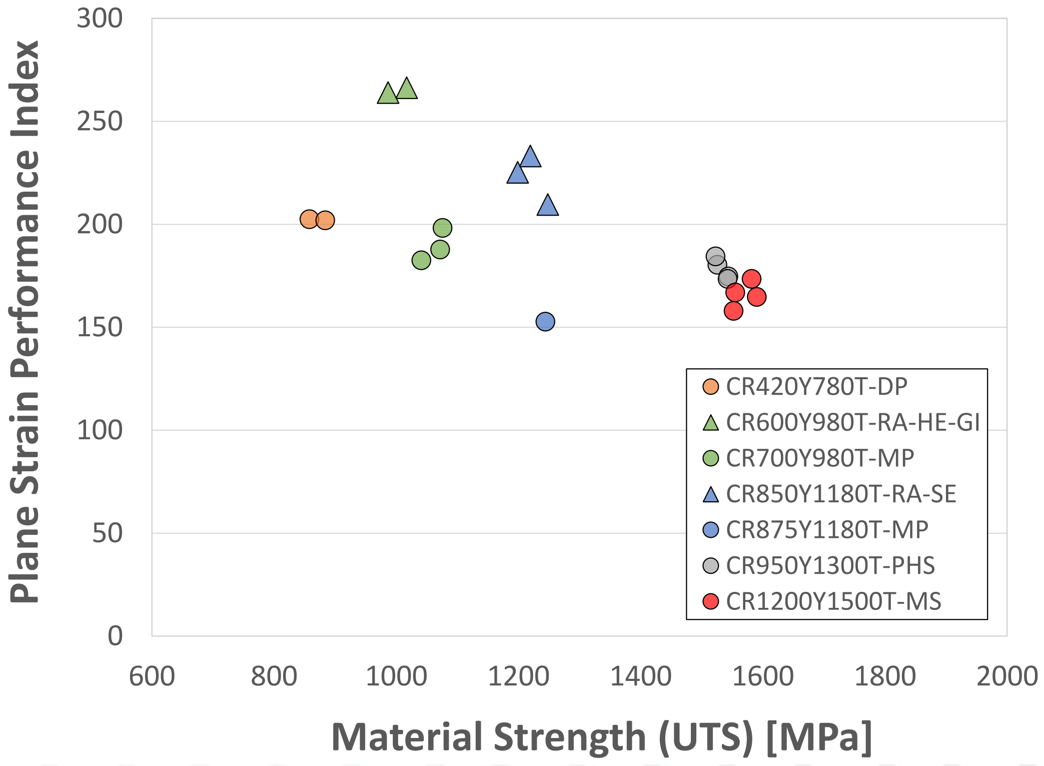
- In general, both F.I. and P.I. showed a similar trend as the mechanical properties
- 3rd Gen materials (red data points) showed superior performance in both indices

PLANE STRAIN FORMABILITY & PERFORMANCE INDEX

$$P.I. = UTS \cdot (F.I.) = UTS \cdot \sqrt{\varepsilon_u \cdot TFS}.$$

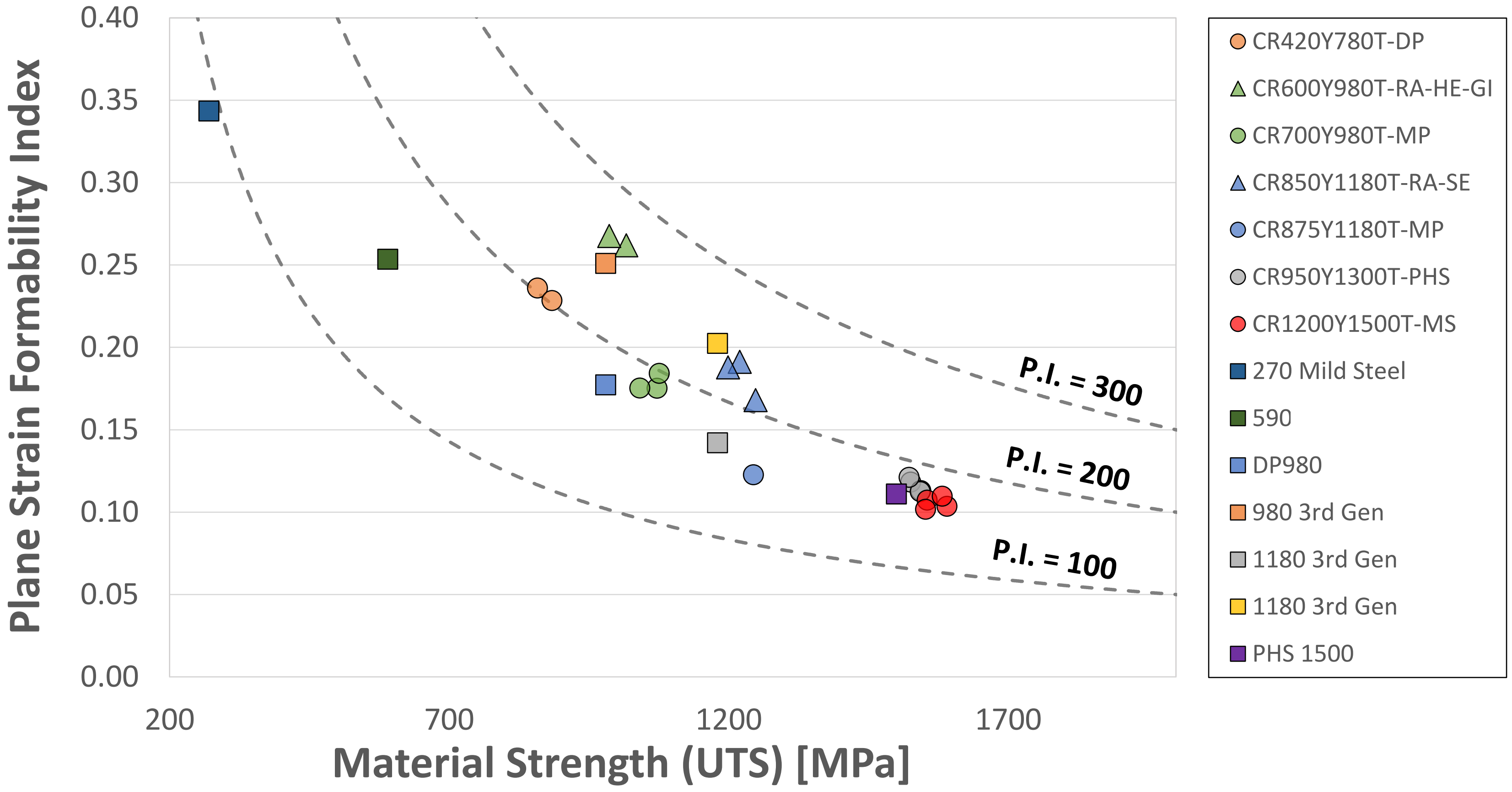
▲ 3rd Gen.





- In general, both F.I. and P.I. showed a similar trend as the mechanical properties
- 3rd Gen materials (triangular data points) showed superior performance in both indices

PS F.I. AND P.I. WITH ADDITIONAL AHSS



- Lower strength grades (270 and 590) showed **high F.I. but low P.I.** – they can tolerate large local strain but will absorb less energy

CONCLUSIONS

- The fracture limit in plane strain bending can be taken as a constant and independent of the bend severity for the AHSS considered
- Fracture limits between AHSS lots were very similar provided the mechanical properties were similar → reduces fracture characterization effort for CAE
- Bend angle is a relative metric, informative for ranking but the plane strain fracture limit should be reported for AHSS
- Tensile mechanical properties do not show a strong correlation with bend performance
- Plane Strain Performance Index shows promise for ranking AHSS and 3rd Gen variants but should include additional evaluations such as structural component testing
- <u>Presented study is restricted to plane strain bending without necking. Results should not be extrapolated to bending under tension (stretch-bending) operations</u>

FOR MORE INFORMATION

Contacts:

Kenneth Cheong, Research Associate
226-505-5232
dwkcheon@uwaterloo.ca

Jugraj Singh, Project Lead
248-512-0029
jugraj.singh@fcagroup.com

Jonathan Smith, Project Manager
248-909-3380
jsmith@steel.org