GREAT DESIGNS IN STEEL

UNIQUE FORMABILITY CHARACTERISTICS OF THE LASER WELDED BLANK (LWB) OF 3RD GEN AHSS

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BACKGROUND

- The formability of LWB is greatly influenced by:
  - Base metal conditions - thickness ratio and strength ratio.
  - Weld conditions - weld orientation, location, soft-zone, heat affected zone (HAZ), and hardness variation.
- Designers should be able to predict the reduced formability and unique behavior of LWB during forming.
- The objective of the study is to develop prediction capability for base metal necking and weld fracture with the selected LWB materials with the GEN3 steel and advanced high-strength steel (AHSS).

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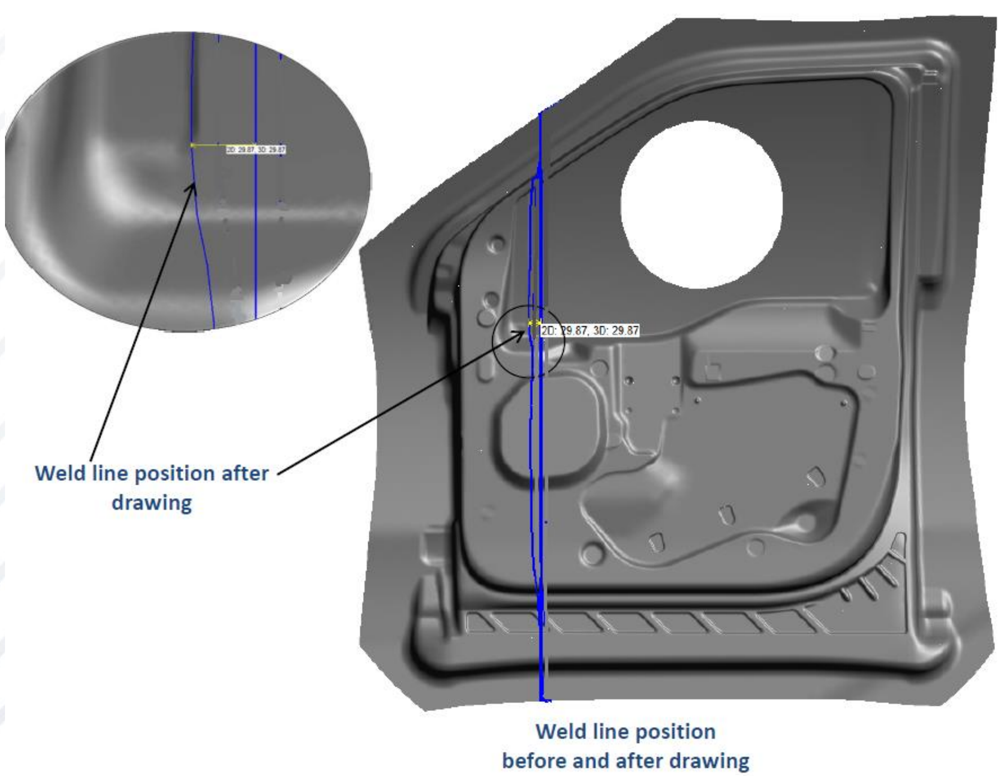
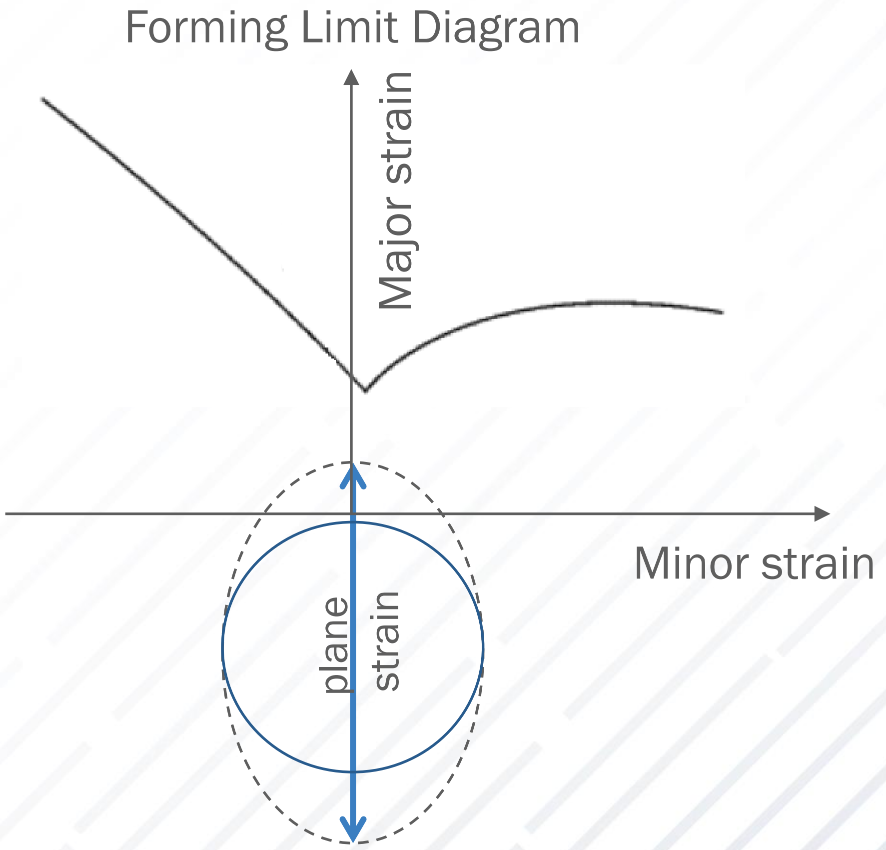
FORMABILITY OF THE LWB

- Non-uniform strain distribution in the panel
  - ✓ More strain in the thinner or weaker base metal
  - ✓ The weld seam moves toward the thick or stronger section.
  - ✓ The material adjacent to the weld experiences a near plane strain condition.

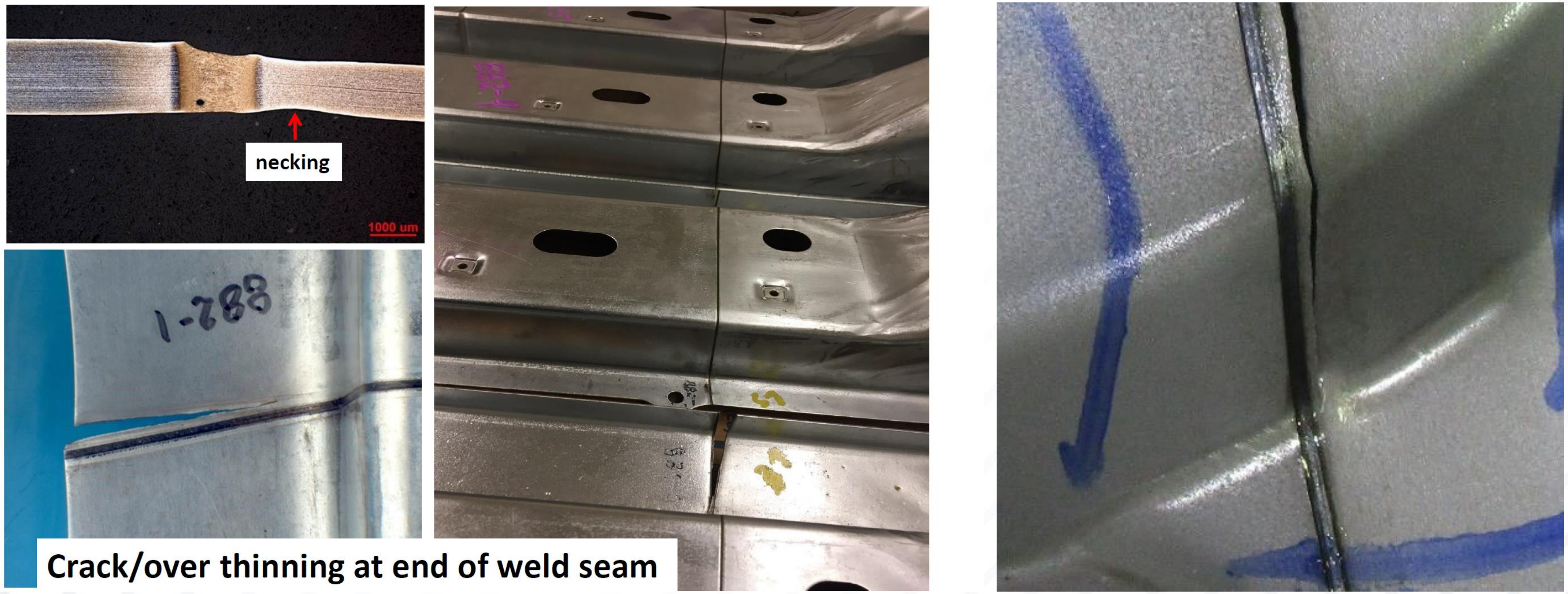




PROBLEMS OBSERVED IN THE PRODUCTION

Necking failure (Type 1) occurs on a thinner or weaker base metal.

Example: Cross Member, DP590, 1.6 + 1.3 mm thickness

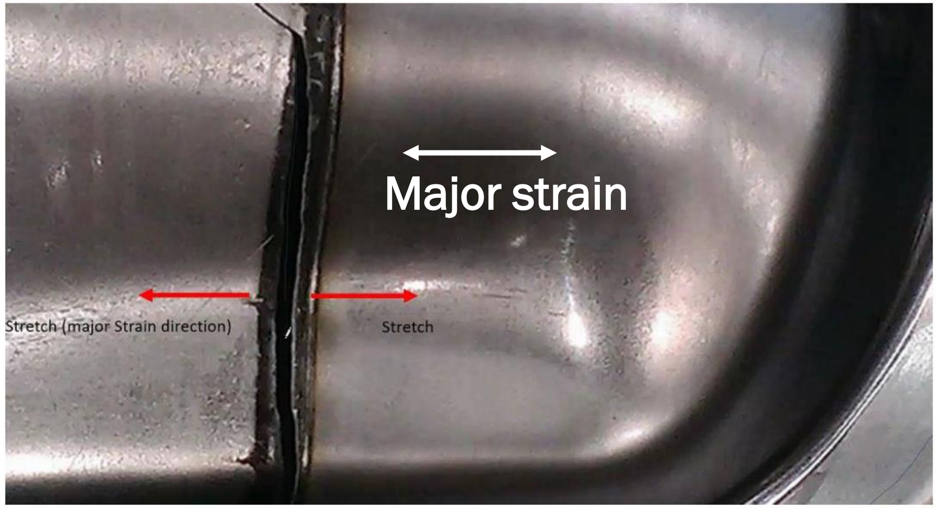


Crack/over thinning at end of weld seam

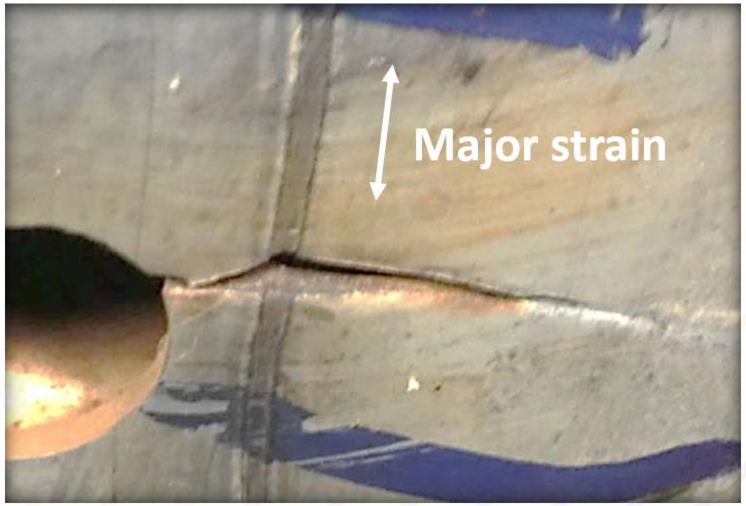
(Courtesy of ASME)

PROBLEMS OBSERVED IN THE PRODUCTION

- Fracture (Type 2) are often observed on the weld or HAZ.
- A steel weld seam is 2~3x stronger than base metal.
- A steel base metal is about 3~6x more ductile than the weld seam.
- Weld fracturing orientation changes depending on the major strain direction.



Weld fracture parallel to the weld seam

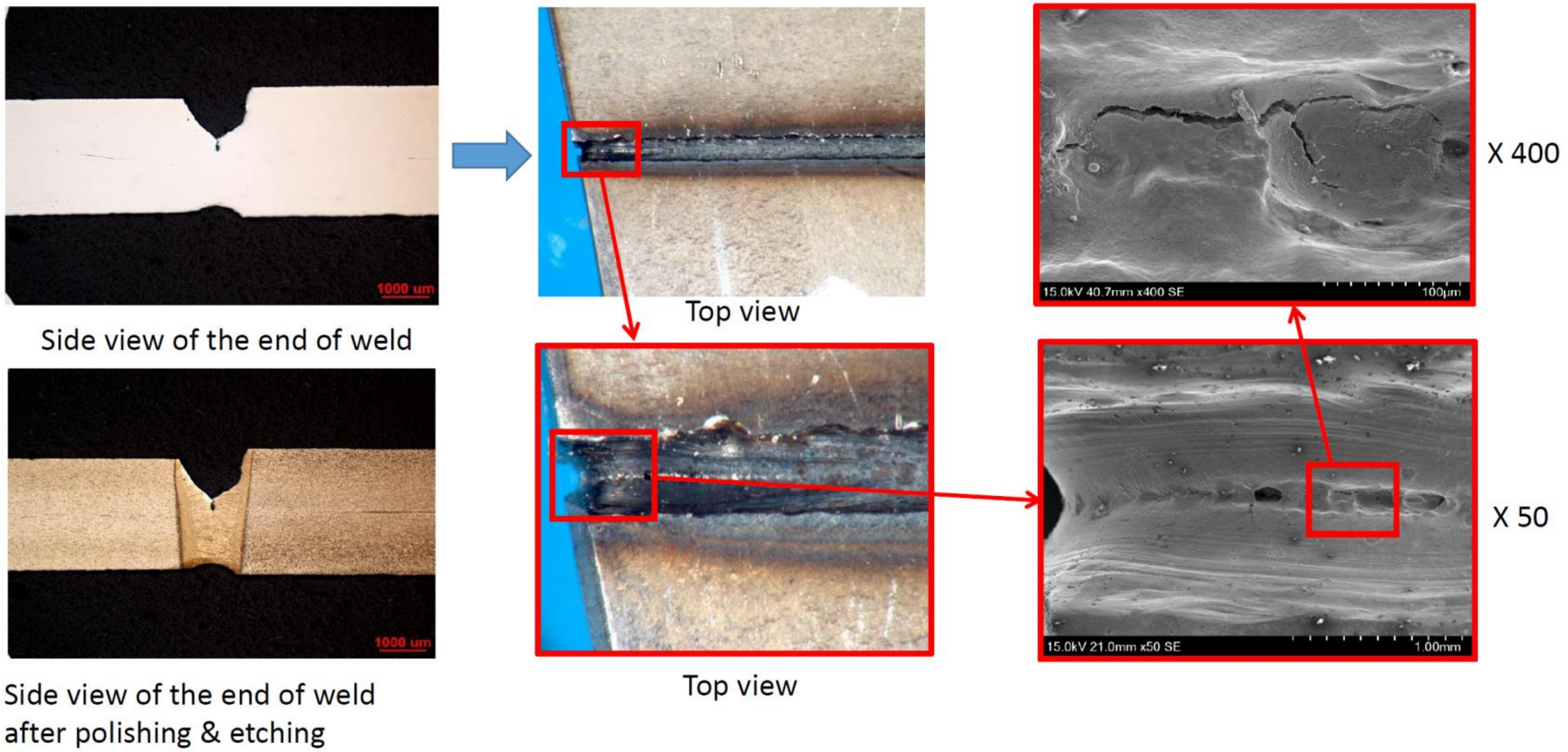


Weld fracture perpendicular to the weld seam

PROBLEMS OBSERVED IN THE PRODUCTION

Edge cracking (Type 3) can be initiated due to the poor weld quality.

Left hand front rail is splitting at laser weld seam ends during forming.
Welding end has more severe defects of (1) Deep concavity, (2) Pores, (3) Microcracks.



(Courtesy of ASME)

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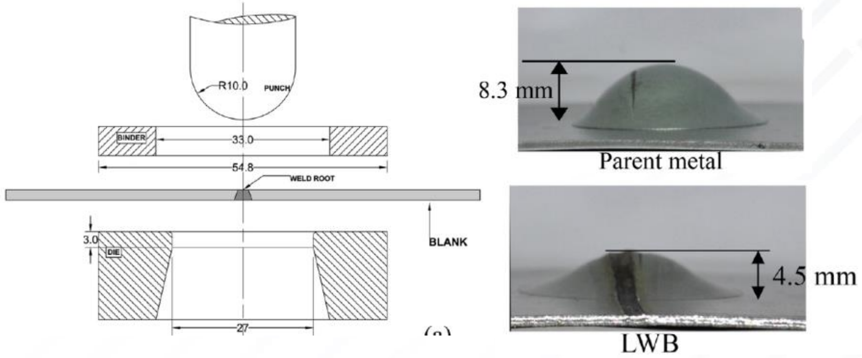
FRACTURE TYPES IN FORMING OF THE LWB

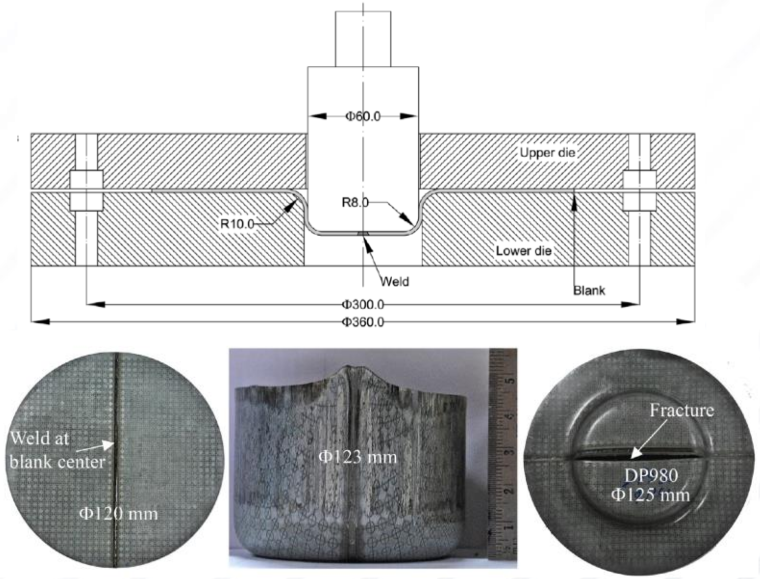
1. Type 1 - Necking fracture at either thinner or weaker base metal
   - Predictable with the forming limit diagram (FLD) and other available criteria
   - Modeling on the weld seam and HAZ can influence on the necking prediction.
2. Type 2 - Cracks on the weld seam or HAZ
   - Challenging to predict using any conventional failure criteria since the weld shape variation and any pre-existing defects within the weld are difficult to measure.
   - Experimentally measured strain and thinning with digital image correlation (DIC) are useful to quantify the strain limit of the weld, soft zone, and HAZ.
3. Type 3 - Edge cracking initiated at the end of the weld
   - Difficult to predict without accurately measuring the lack of penetration or mismatch edge gap between base metals.
   - For the good weld seam, the strain limit for edge cracking can be experimentally quantified with DIC.

HOW TO CHARACTERIZE THE FORMABILITY OF THE LWB

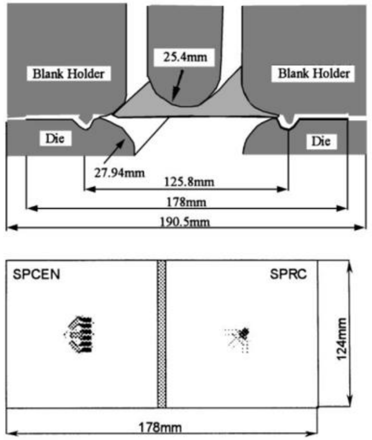
1. Uniaxial Tensile Testing
2. Limiting Dome Height (LDH) testing
3. Nakajima Testing for FLD
4. Marciniak Testing for FLD
5. Erichsen Cup Testing
6. Round Cup Draw Testing
7. Stretch Bend Testing



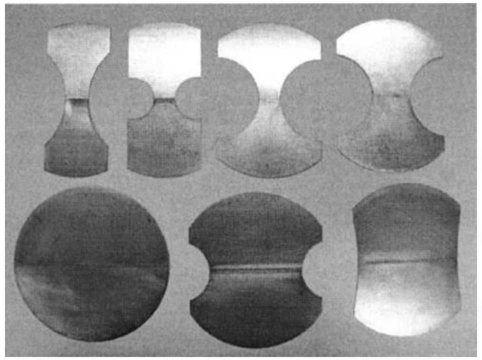
[Erichsen Cup Testing, Bandyopadhyay et al., 2016]



[Round Cup Draw Testing, Bandyopadhyay et al., 2016]



[Stretch-bend test, Zhao et al., 2001]



[LWB samples for FLD testing, Chan et al., 2005]

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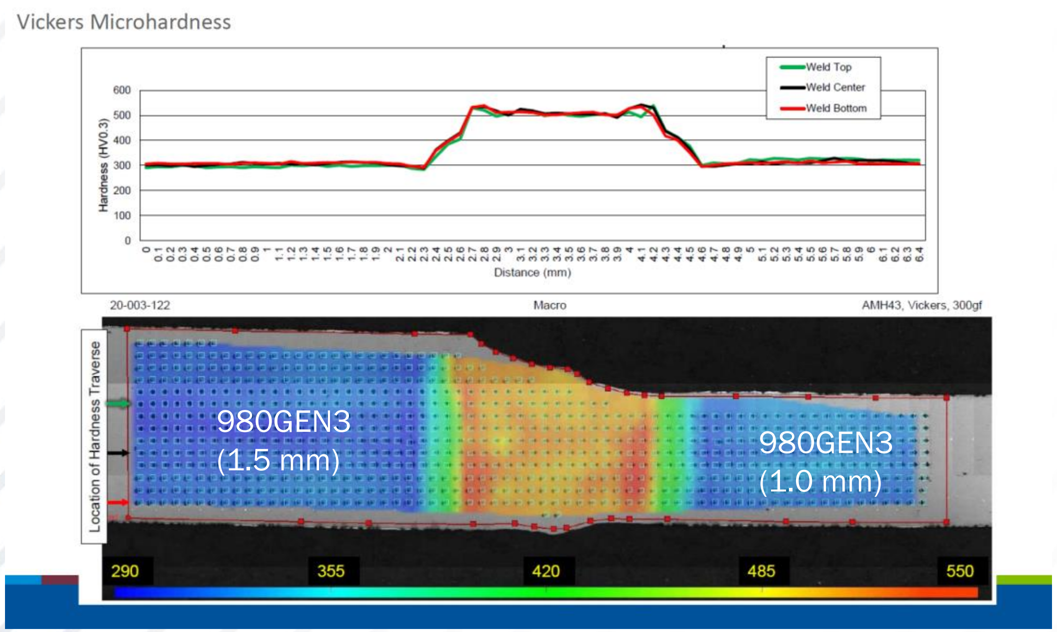
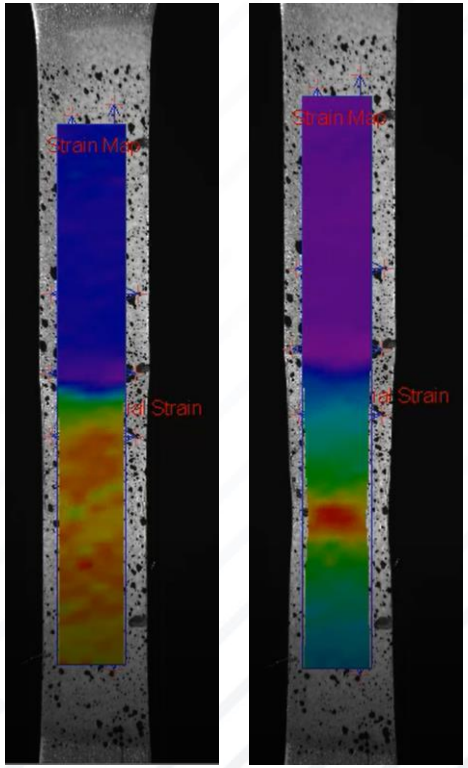
FORMABILITY - SAME STRENGTH AND DIFFERENT GAUGE LWB

1. The blank material is homogeneous except weld.
2. Thickness variation exists between the base metals and weld seam.
3. The weld zone material is about 60% ~100% harder than the base high strength.
4. The necking should occur at a thinner base metal.

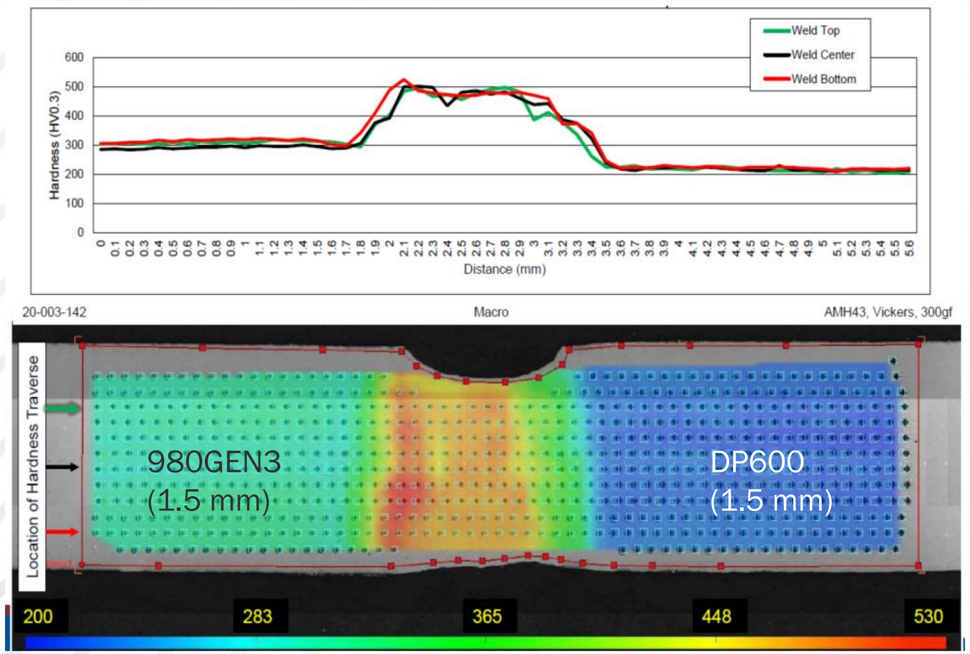


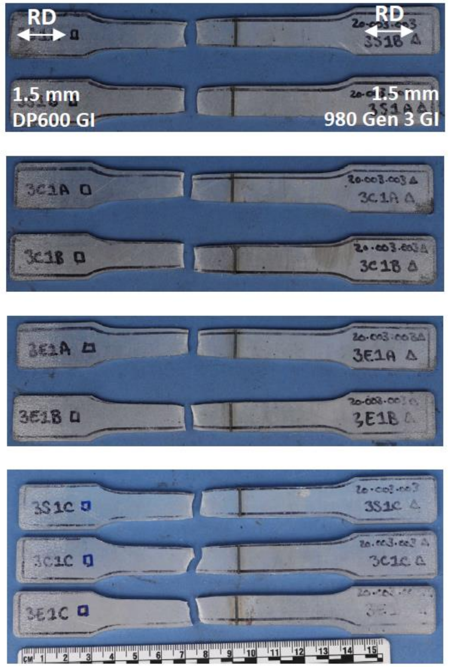


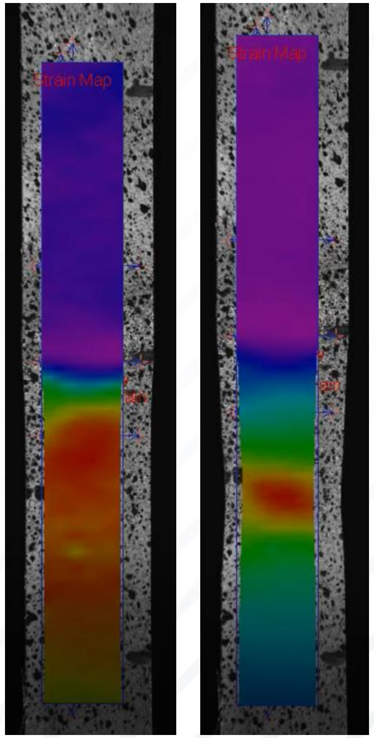
Major strains before and after necking

FORMABILITY - DIFFERENT STRENGTH AND SAME GAUGE LWB

1. The blank material is heterogeneous including weld.
2. A weld concavity can be formed when the weld pool shrinks within the weld.
3. The weld zone material is about 60% ~ 150% harder than the base high strength metals.
4. The necking should occur at a weaker base metal.







Major strains before and after necking

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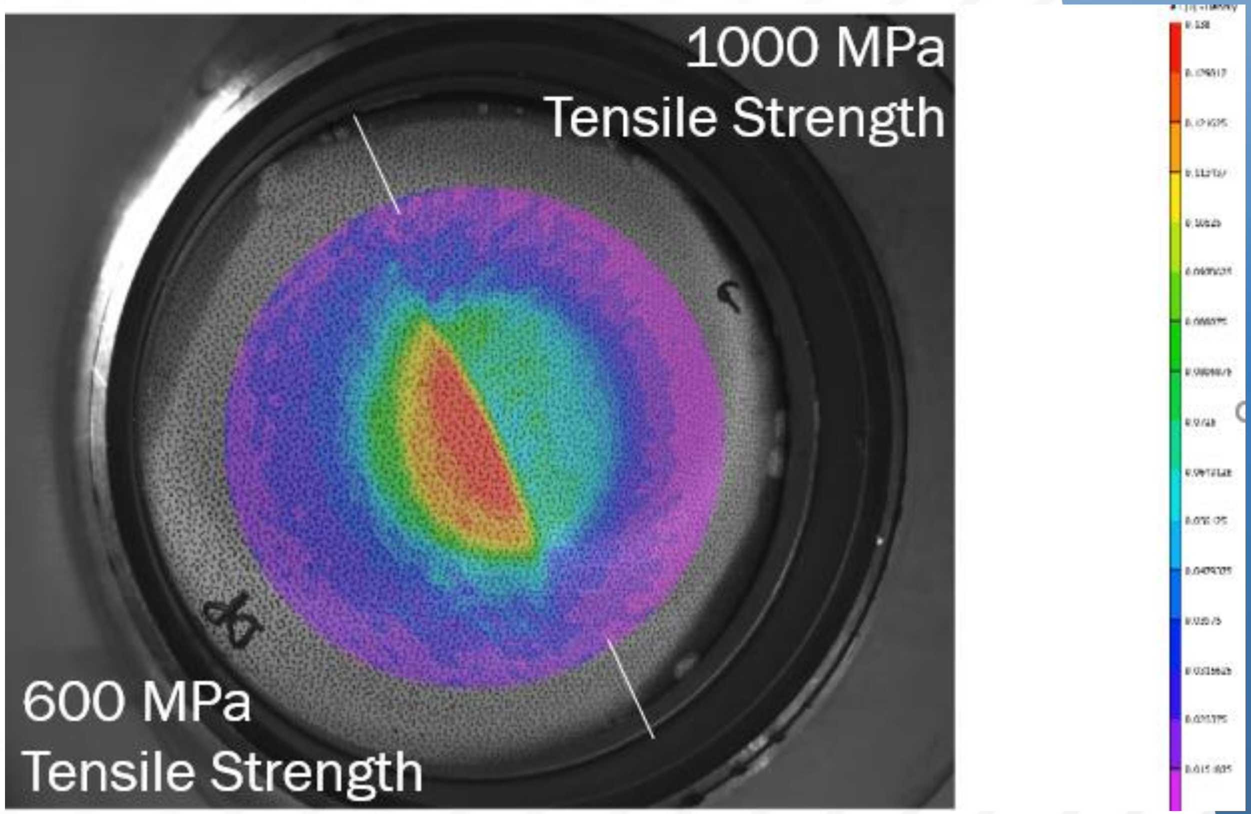
FORMABILITY - DIFFERENT STRENGTH AND SAME GAUGE LWB

- The biaxial bulge test of a DP600 to 980GEN3 laser welded blank demonstrates the similar effect.
- The fracture occurs adjacent to the weld in the weaker parent metal.

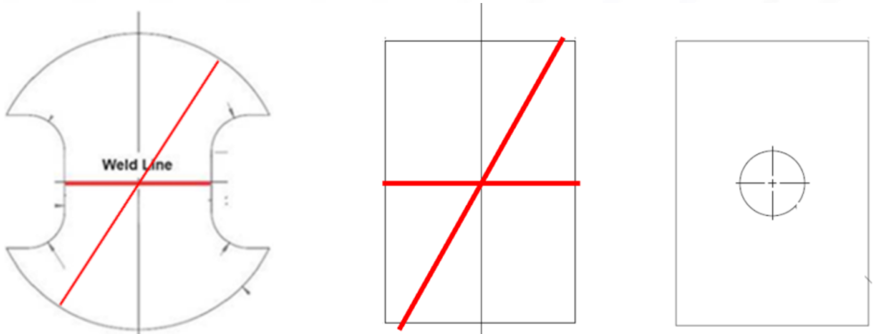


TESTING ON PLANE STRAIN CONDITION

- EWI tested the plane strain condition using the Nakajima and Marciniak tooling for the following materials with DIC (10 images/second):
  - **LWB of 980GEN3 (1.5 mm) and 980GEN3 (1.5 mm)**
  - **LWB of 980GEN3 (1.5 mm) and 980GEN3 (1.0 mm)**
- Test matrix:

Materials	Nakajima testing with the parallel weld orientation	Nakajima testing with the 60-degree weld	Marciniak testing with the parallel weld orientation	Marciniak testing with the 60-degree weld
980GEN3 (1.5 mm) and 980GEN3 (1.5 mm)	3	3	3	3
980GEN3 (1.5 mm) and 980GEN3 (1.0 mm)	3	3	3	3

- Sample shapes:

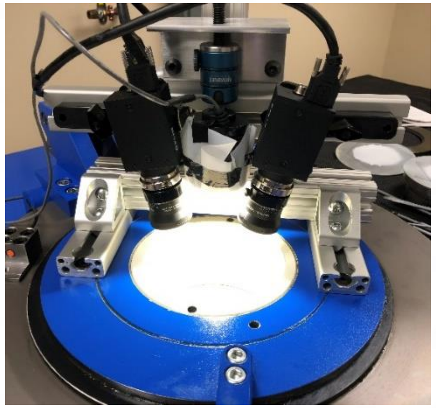


Nakajima blank with 2 weld orientations **Marciniak blank with 2 weld orientations** **Marciniak carrier blank**

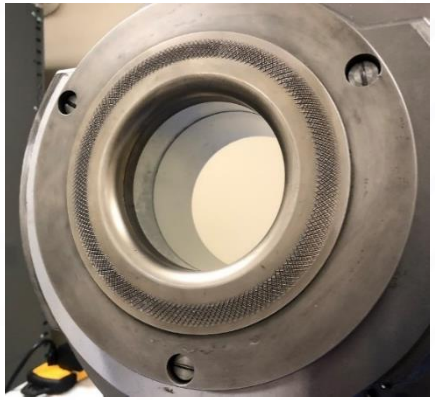
EXPERIMENTAL SETUP AT EWI

- Nakajima and Marciniak test tools based on ISO 12004.

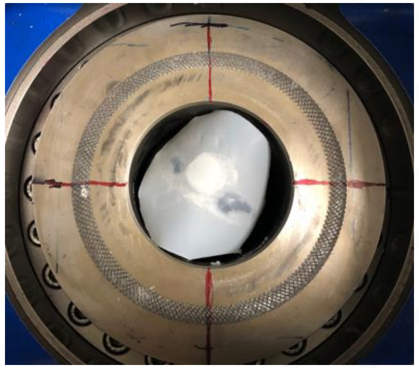
Erichsen Universal Sheet Metal Testing machine at EWI



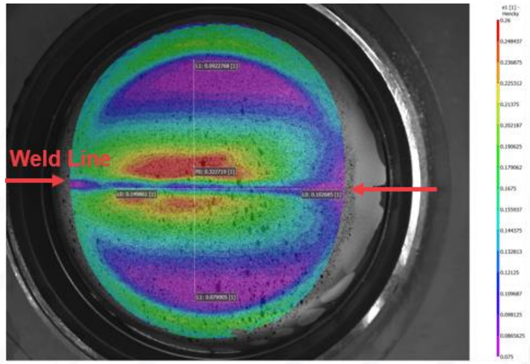
DIC cameras



Upper Die



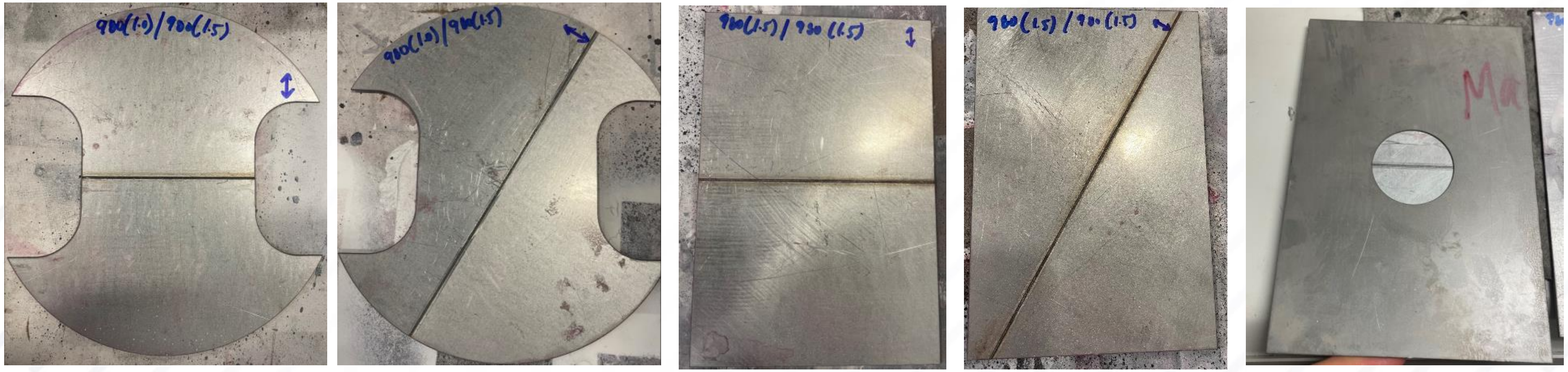
Teflon lubrication on punch



DIC Data

SAMPLE ANALYSIS

- The following analysis is completed for one representative case from the test matrix.
  - Full field strain measurements up to fracture using DIC
  - Necking point determined using the linear best fit method
  - Load-displacement data
  - Data exported from DIC to determine the plane strain condition



Examples of samples left to right: Nakajima 0 degree, Nakajima 60 degree, Marciniak 0 degree, Marciniak 60 degree, Marciniak carrier blank (BH340, 0.75 mm)

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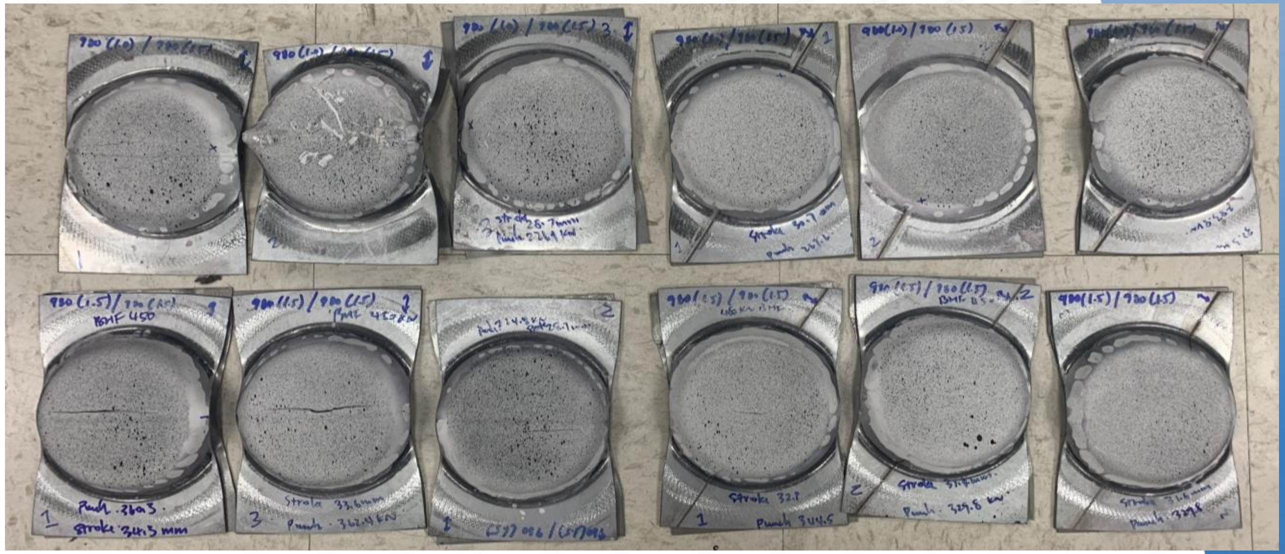
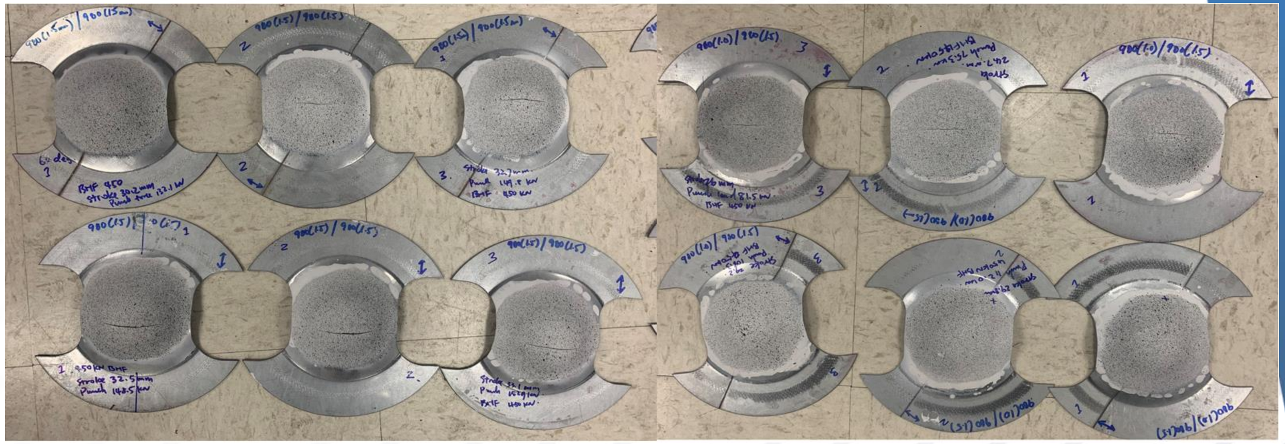
SAMPLE ANALYSIS

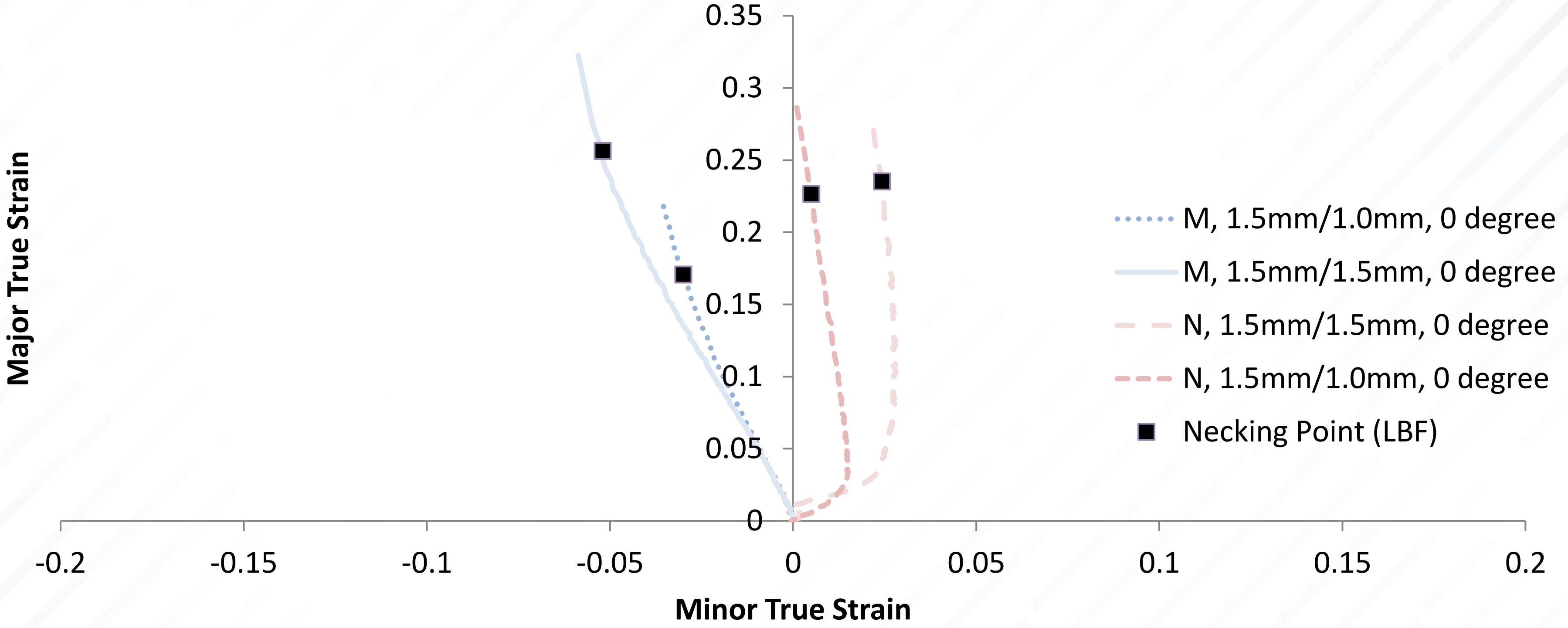
Regardless of the thickness combinations and test tooling,

- The most 0-degree weld samples showed “base metal necking fracture.”
- The most 60-degree weld samples showed “weld fracture.”
- *This implies the weld fracture can be initiated before base metal necking if the major strain direction is close to the weld seam direction.*





STRAIN PATH AND NECKING POINT DATA: 0 DEGREE



Linear Best Fit Method		
SAMPLE ID	e1	e2
M, 1.5 mm/1.5 mm, 0 degree	0.256	-0.052
M, 1.5 mm/1.0 mm, 0 degree	0.171	-0.030
N, 1.5 mm/1.5 mm, 0 degree	0.235	0.024
N, 1.5 mm/1.0 mm, 0 degree	0.226	0.005

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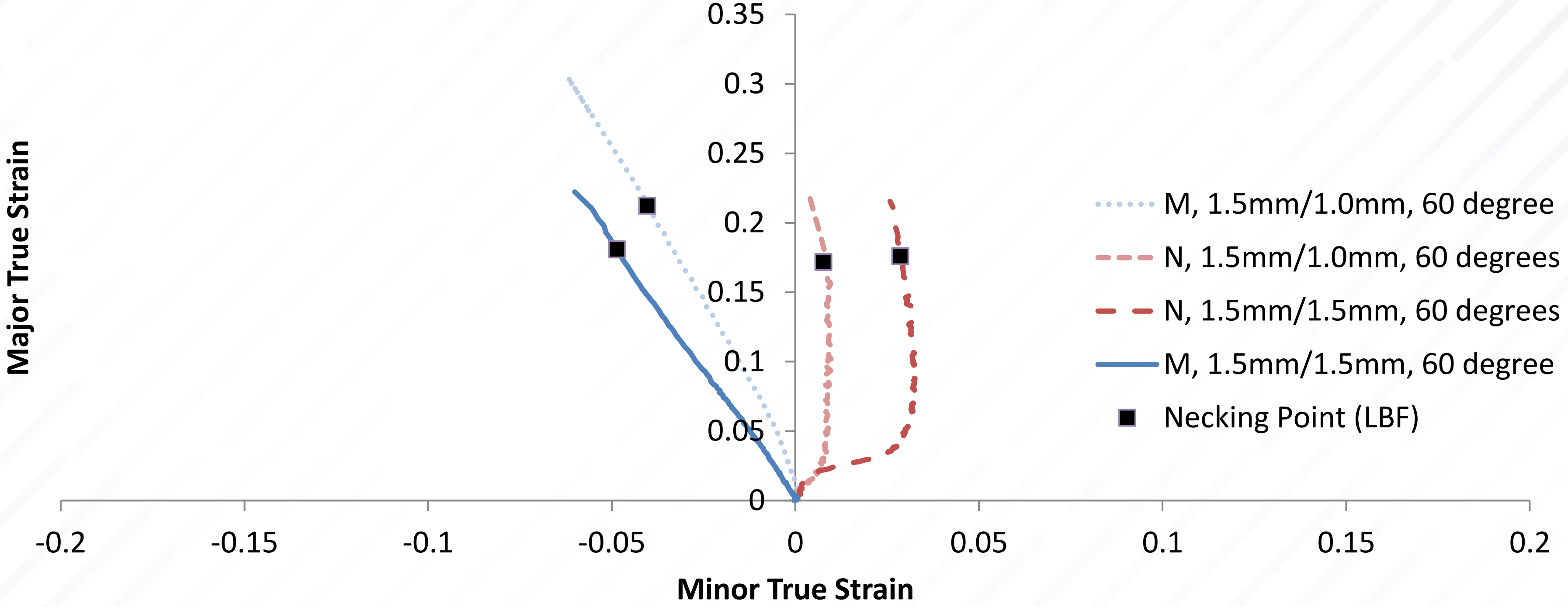
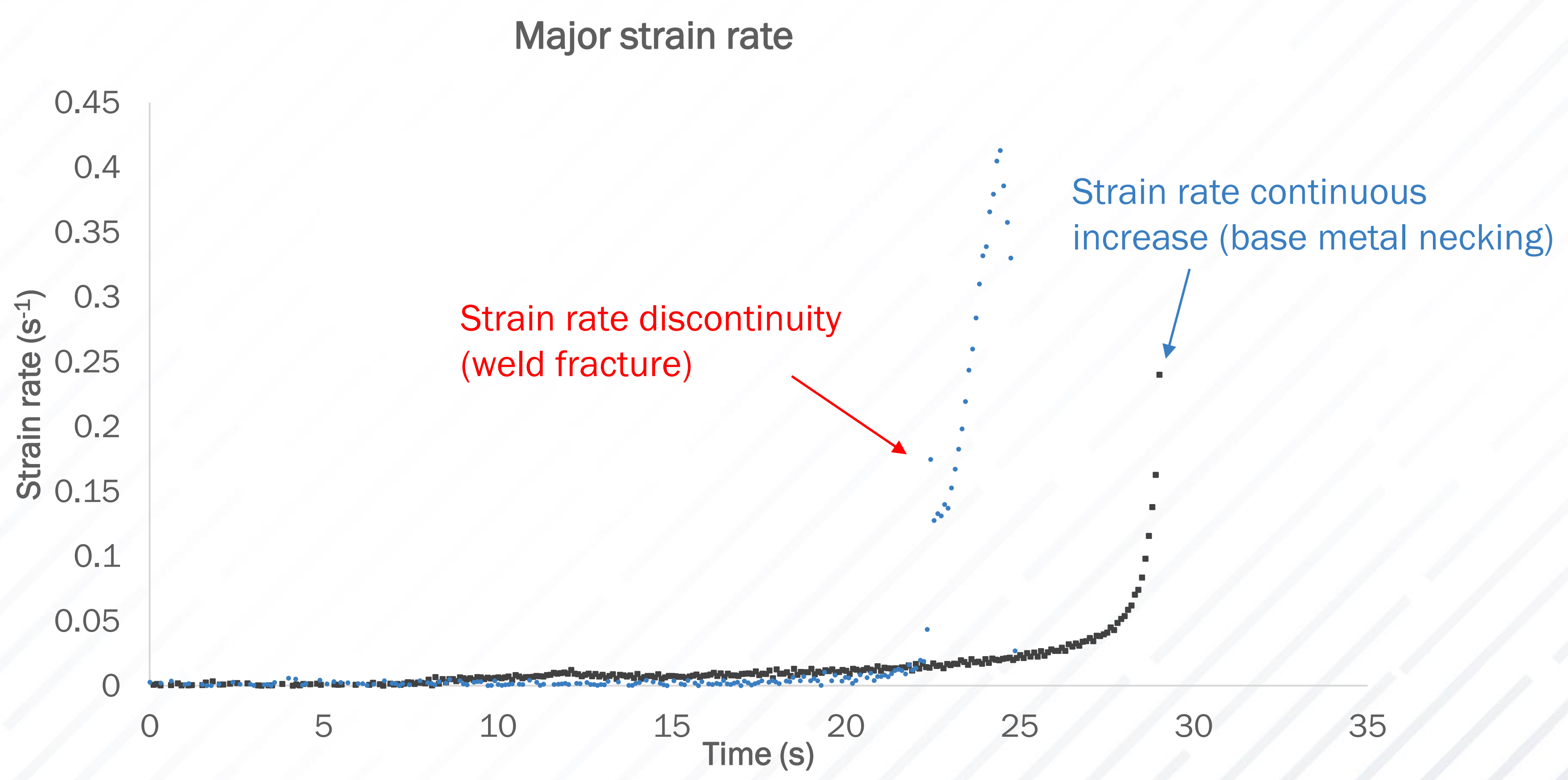
STRAIN PATH AND NECKING POINT DATA: 60 DEGREE



Linear Best Fit Method		
SAMPLE ID	e1	e2
M, 1.5 mm/1.0 mm, 60 degree	0.212	-0.040
M, 1.5 mm/1.5 mm, 60 degree	0.181	-0.048
N, 1.5 mm/1.0 mm, 60 degrees	0.172	0.008
N, 1.5 mm/1.5 mm, 60 degrees	0.176	0.029

STRAIN RATE DATA FOR WELD FRACTURE VS. BASE METAL NECKING

- Distinguishable strain rate trends were captured with DIC during the test.



HOW TO MODEL THE LWB USING FEM SOFTWARE

1. 3D Shell model with no weld
   - Simple but over-constrained B.C. for weld
2. 3D Shell model with weld properties
   - Practical but need the weld/HAZ properties
3. Hybrid shell-solid model with weld properties
   - More accurate to consider the weld behavior, but simulation cost increases
4. 3D Solid model with weld properties
   - Numerically most accurate, but impractical in sheet metal forming simulations

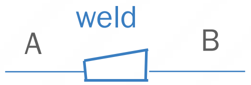
#1

AutoForm,
Dyna,
PAM-STAMP

#2

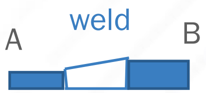
AutoForm,
Dyna,
PAM-STAMP

#3

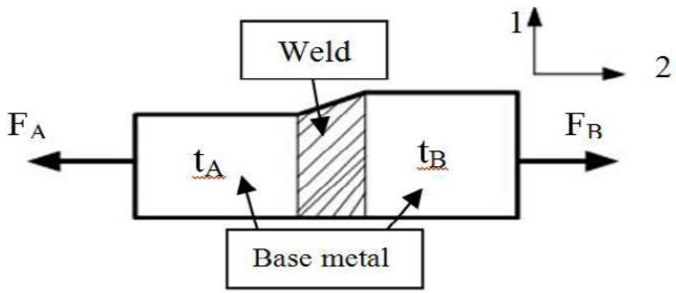


Dyna

#4



Dyna,
PAM-STAMP



Geometry of the LWB

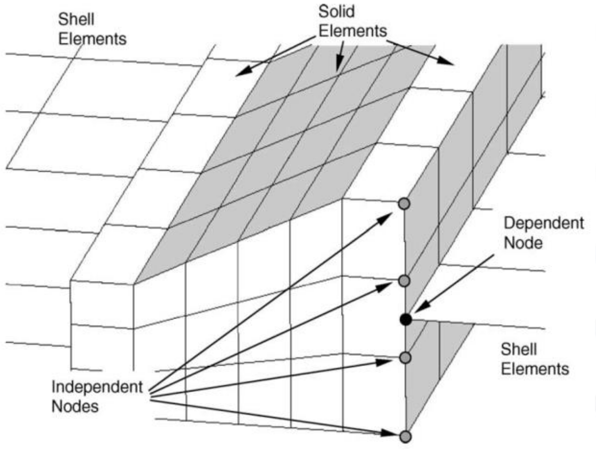


Fig. 1. Schematic diagram of the interpolation constraint available in LS-DYNA.

[Raymond et al., 2003]

EFFECTS OF THE MESH MODEL FOR SIMULATION RESULTS

- A commercial finite element analysis (FEA) software, PAM-STAMP, was applied to simulate the LWB model.

	Description of the mesh models
Case 1	Shell model for base metal (no weld)
Case 2	Shell models for base metal and weld
Case 3	Solid models for base metal and weld

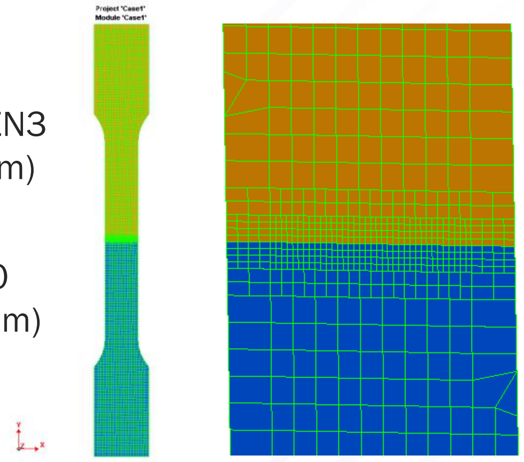
Case 1: Shell element, weld line modeled as constraint

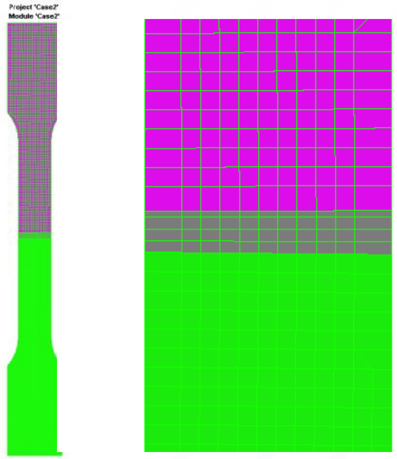
Case 2: Shell element, weld line modeled as a material zone

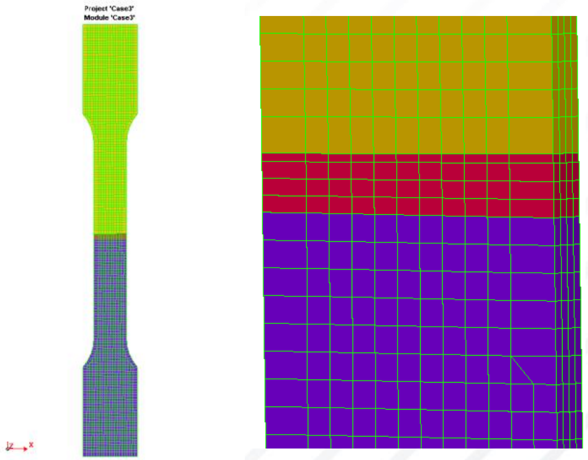
Case 3: Solid element, weld line modeled as a material zone

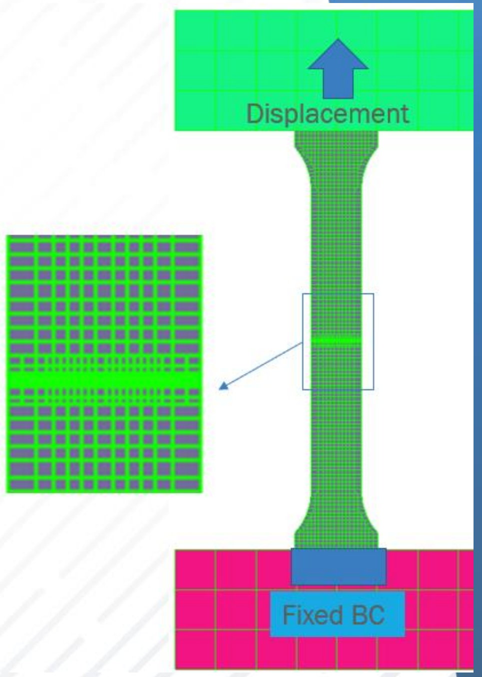
980GEN3 (1.5 mm)

DP780 (1.5 mm)









Four elements for a 1-mm weld seam

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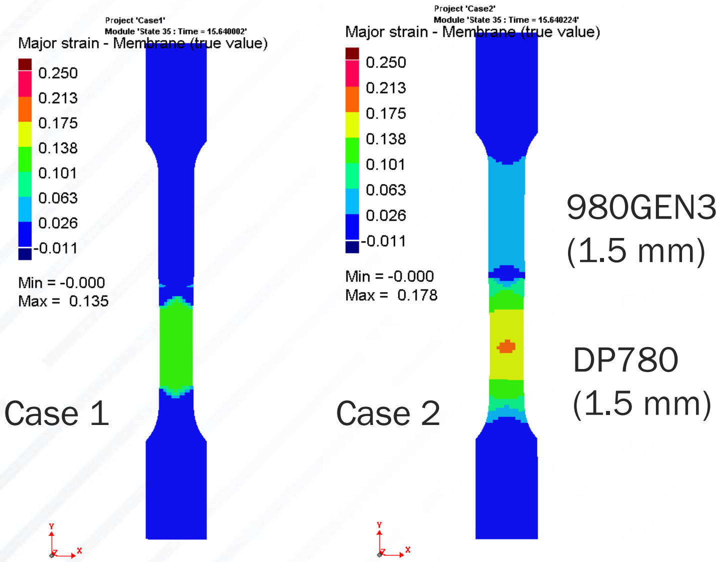
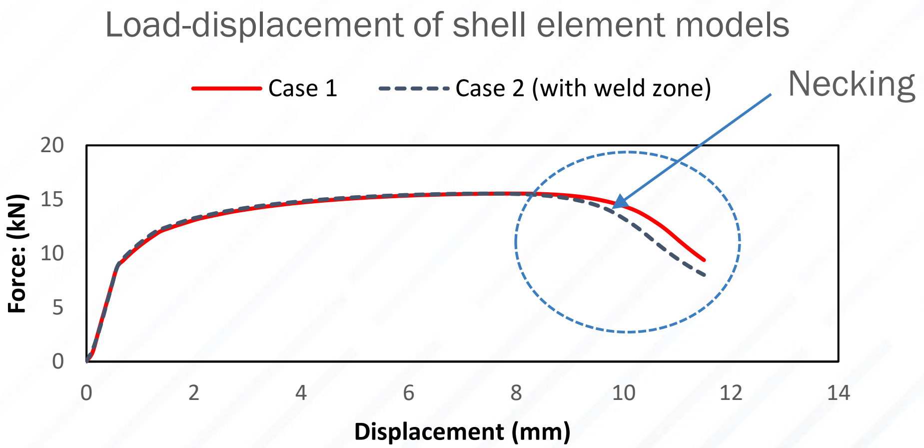
SIMULATION RESULTS

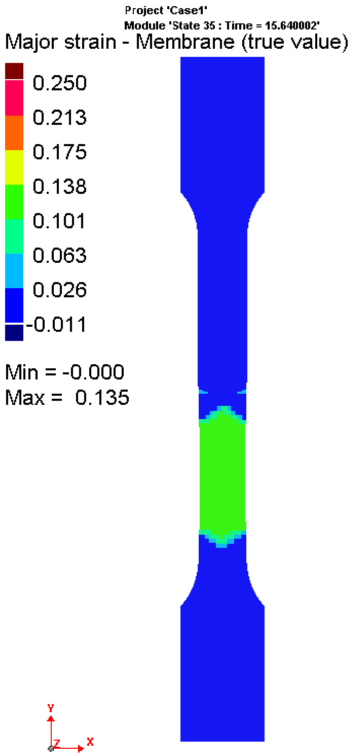
- Load displacement curve of Case 1 and Case 2 are very close to each other until passing the maximum load.
- The necking behavior is the main difference of the two models.



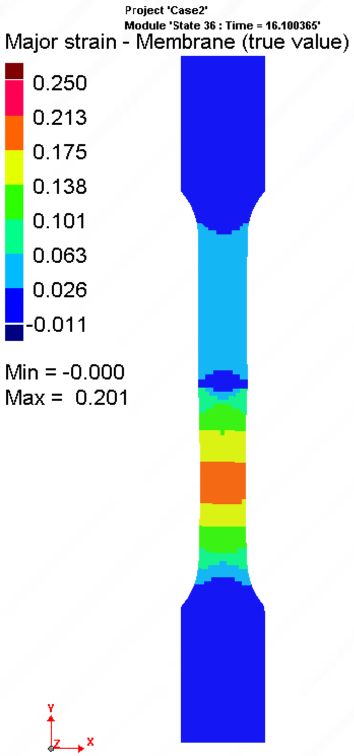
Major strains at 7.5-mm displacement



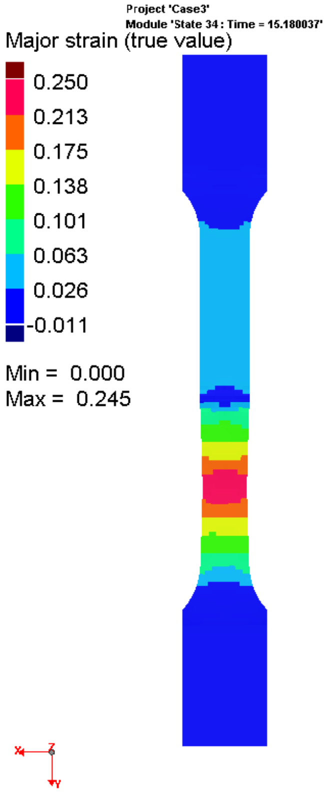
MAJOR STRAIN DISTRIBUTION WHEN NECKING



Case 1: Shell element without weld property



Case 2: Shell element with weld property



Case 3: Solid element with weld property

- Cases 2 and 3 predicts higher major strain (~0.2) at the necking area compared to Case 1 (~0.1).

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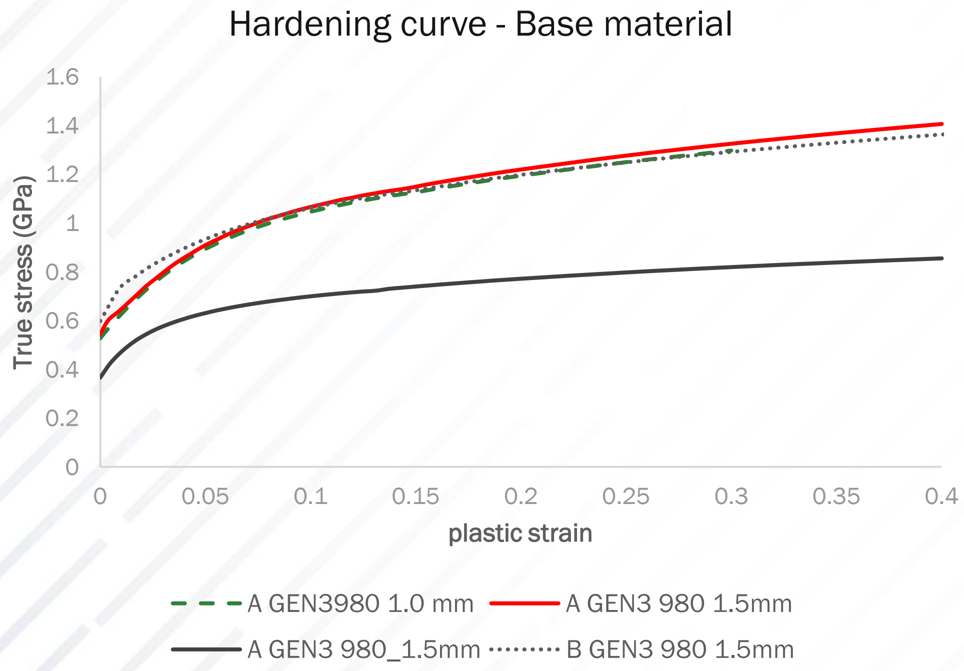
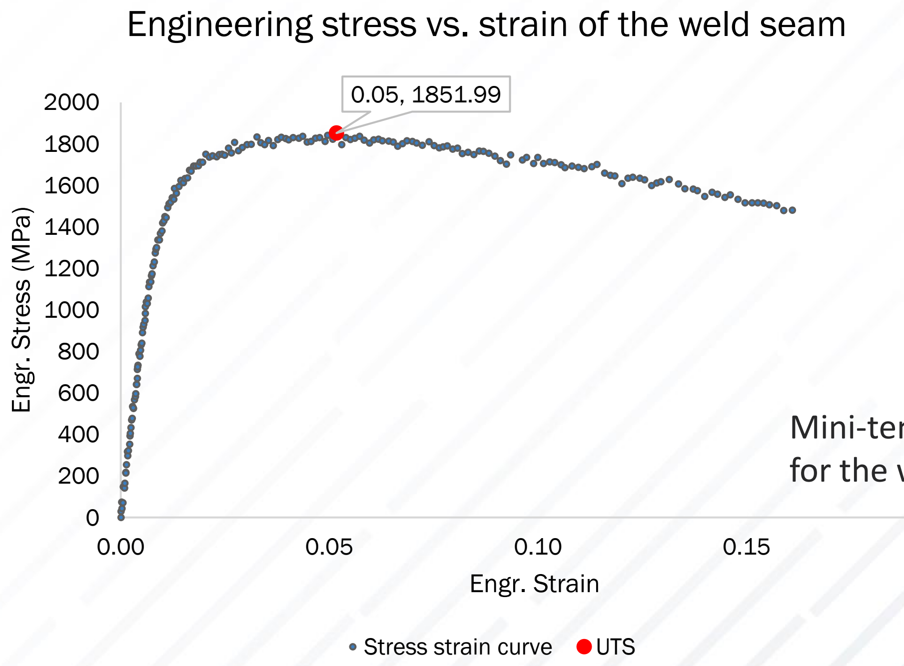
MATERIAL HARDENING MODELS FOR BASE METAL AND WELD SEAM

- Tensile data of base metal were used to establish the base material model.
- The hardening curve was obtained from the mini-tensile test for the weld seam.





Mini-tensile testing for the weld seam

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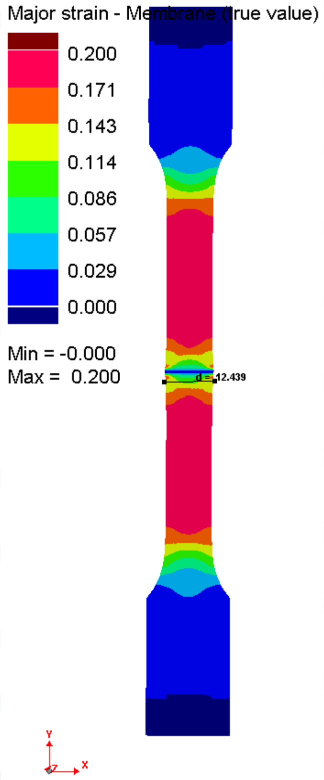
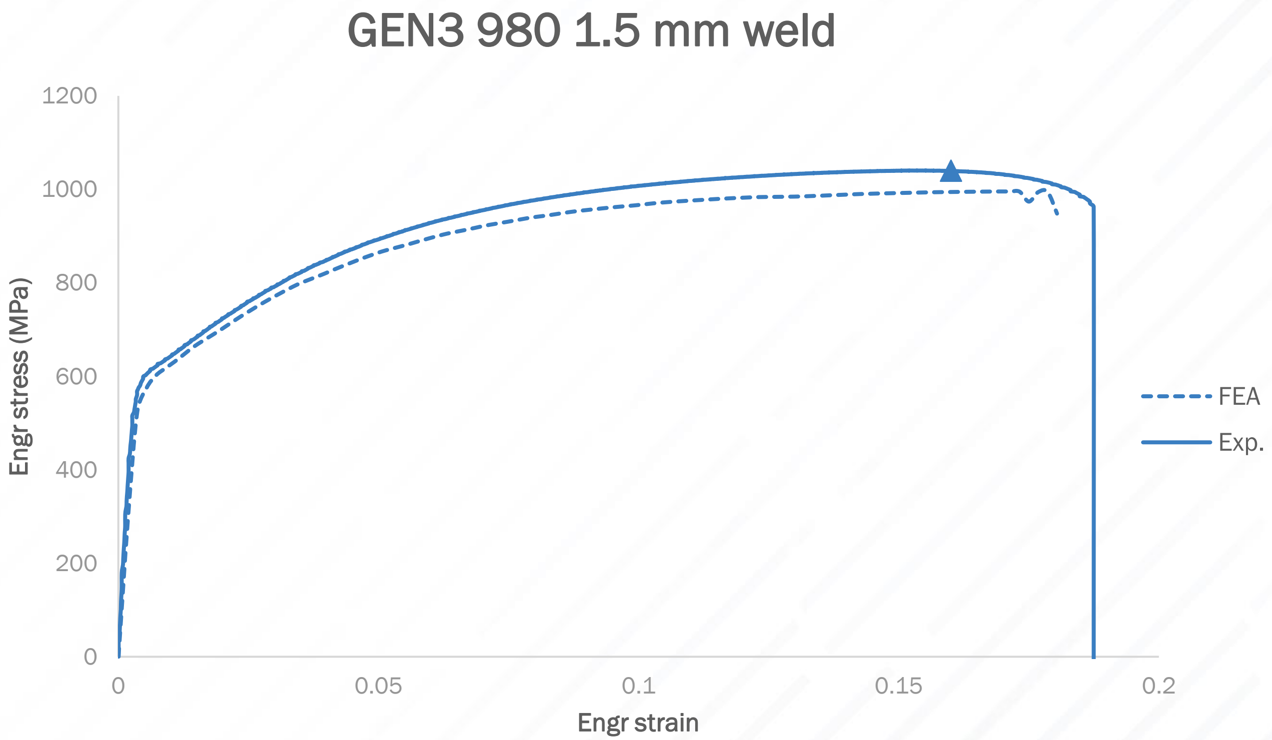
RESULT – 980GEN3 1.5 MM – 980GEN3 1.5 MM

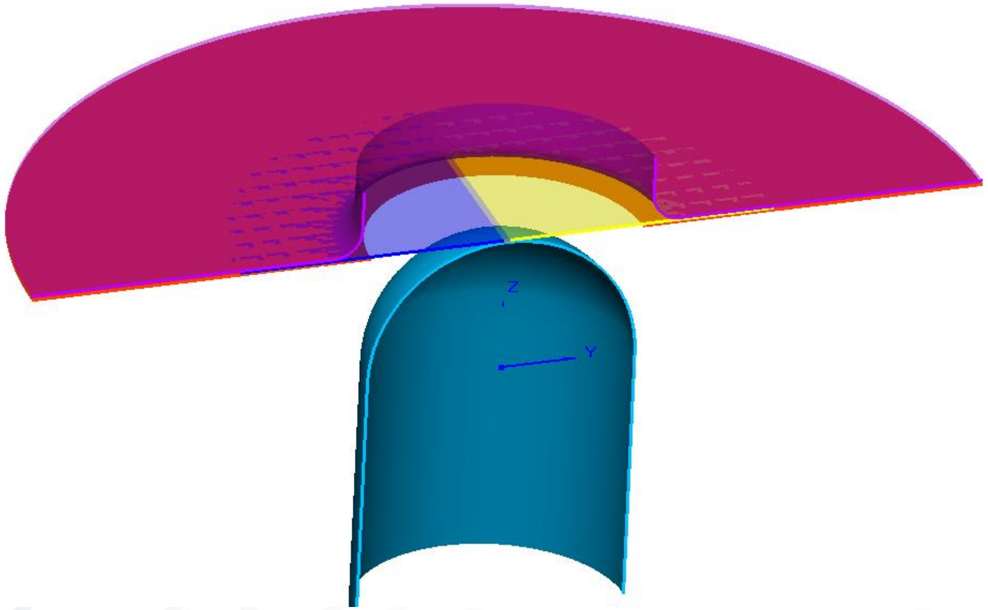




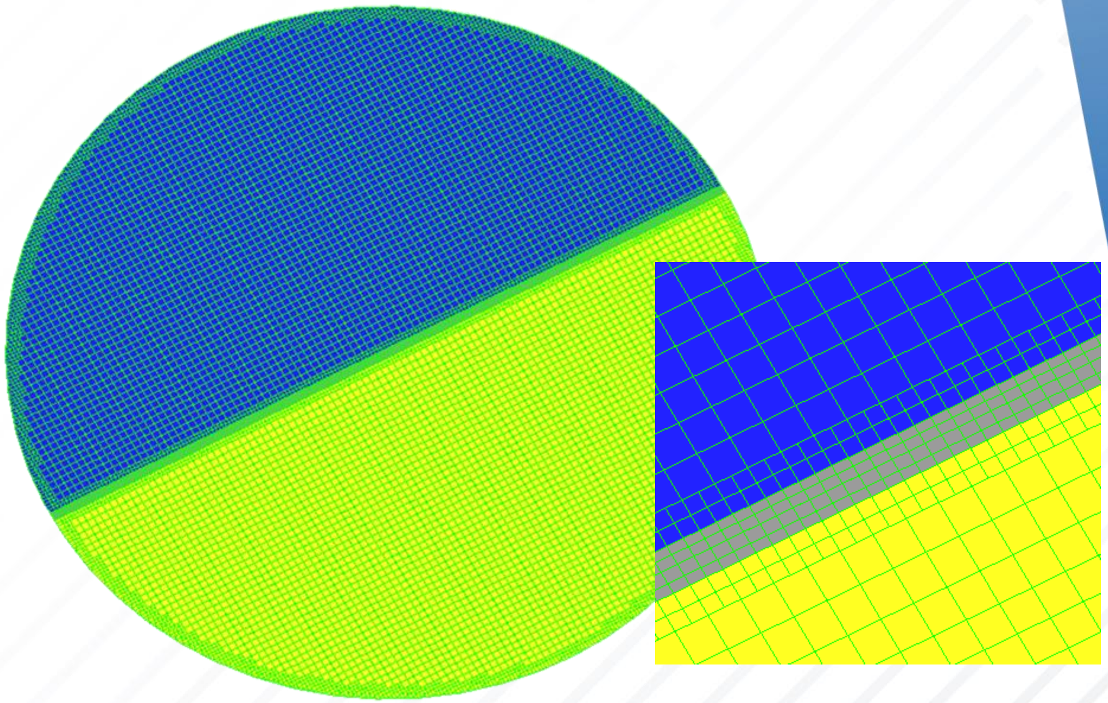
Local max major strain on the base metal: 0.220
Max major strain on the weld: 0.012

FEA SETUP

- The weld line was simulated by defining a small material zone (in grey).
- Blank holder force is sufficient so that the material is stretched with no draw-in.

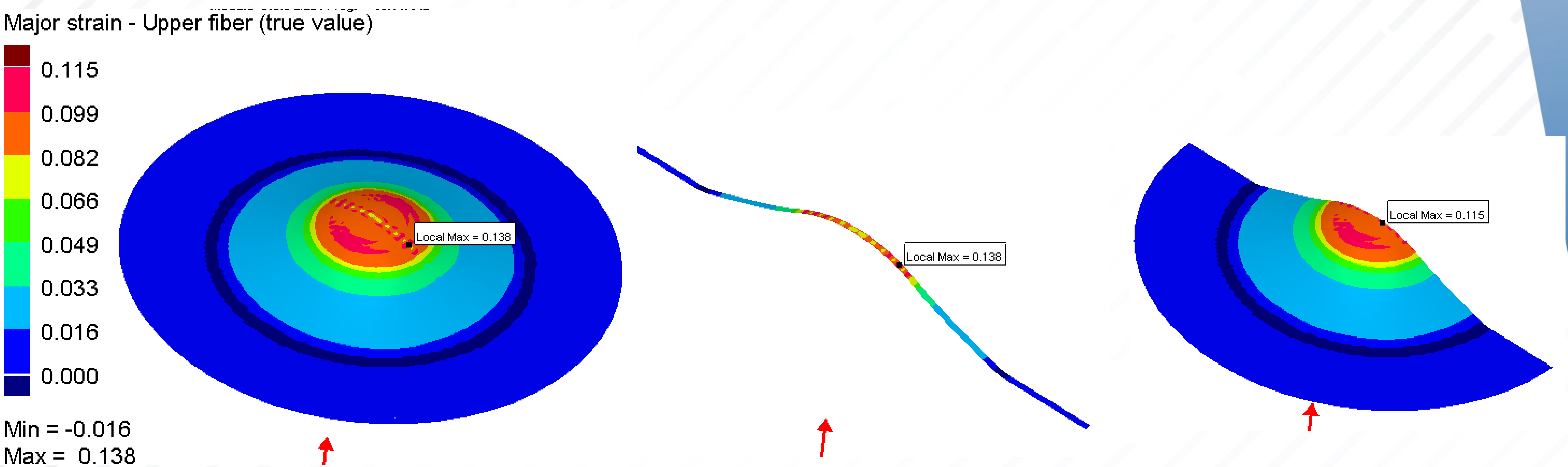


Model sectioned in half to show tooling setup



Mesh and weld line setup

COMPARISON OF SIMULATION WITH EXPERIMENT



	Stroke	Fracture location	Major strain on the weld zone	Major strain on base metal
Experiment	19.85	Weld	0.12	N/A
FE Prediction	19.87	N/A	0.138	0.115

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CONCLUSIONS

- Important to consider weld seam properties of the LWB of AHSS and GEN3 steel for the automotive structure designs
- Weld seam deforms only in one weld line direction. Whenever possible, the weld seam should not be placed in high strain areas and parallel to the major strain direction.
- To fully characterize the formability limit of the LWB, three standard testing methods (i.e., uniaxial, plane-strain, and equi-biaxial tension tests) with DIC capability are very useful.
- Present finite element modeling (FEM) software is capable to model the LWB accurately with reliable material data.
- Useful to develop beneficial practices for the automotive and steel industry to characterize and predict the formability of the LWB with GEN3 and AHSS.

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FOR MORE INFORMATION

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