GREAT DESIGNS IN STEEL

TWENTY YEARS

IN-SITU FAILURE ANALYSIS AND MESO-SCALE DAMAGE MODELING OF SPOT WELD FAILURE: PULLOUT VS. INTERFACIAL

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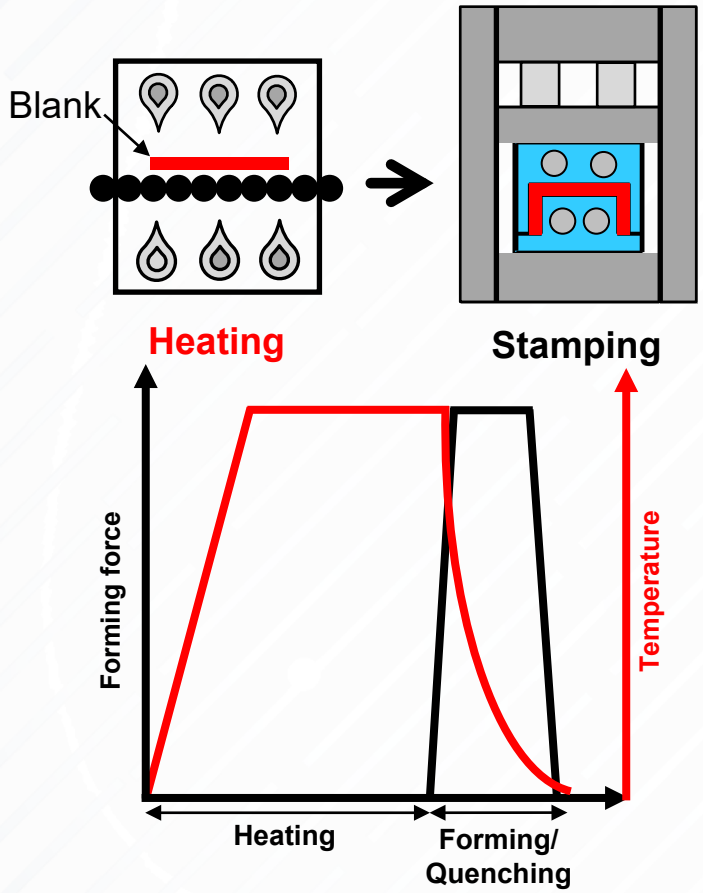
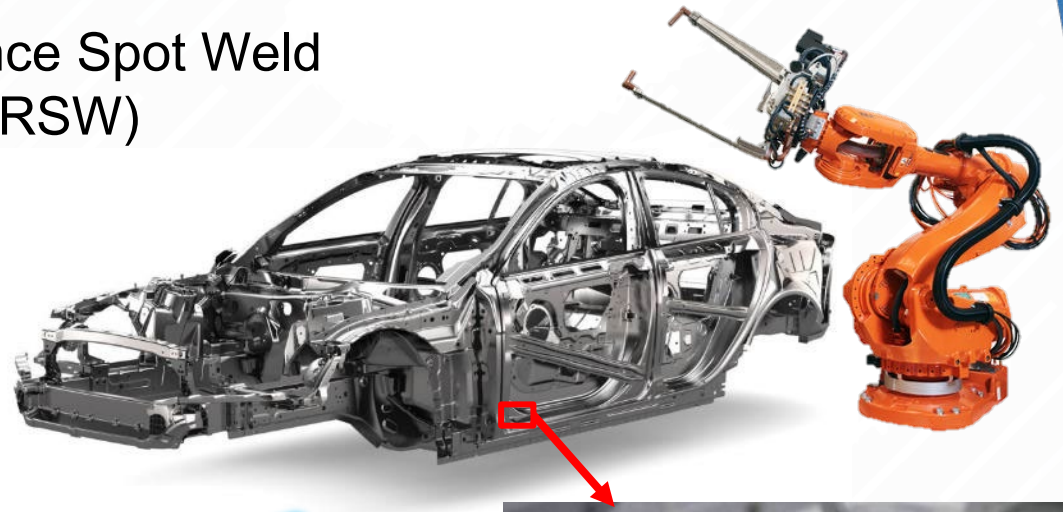
AUTOMOTIVE MATERIALS AND PROCESSES

Improved Crash Performance → Hot-stamped "Press Hardened" → Structural Integrity, Safety Performance ← Joint Quality



Resistance Spot Weld (RSW)

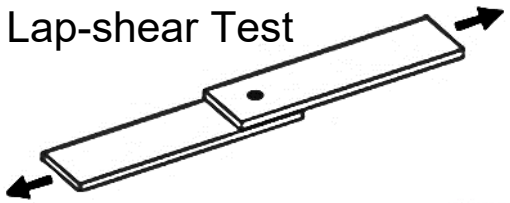


2000-6000 Spot welds

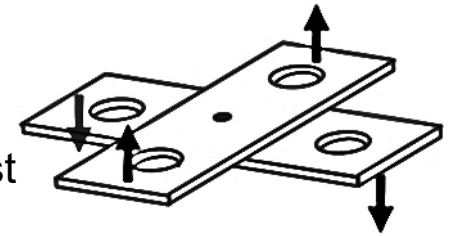
ASSESSMENT OF MECHANICAL PROPERTIES

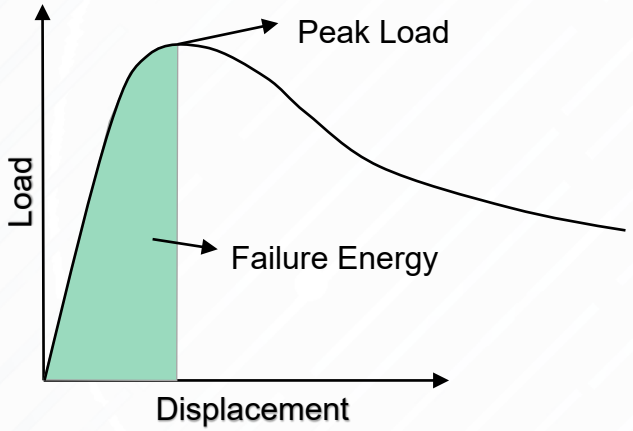
Mechanical Properties and Failure Analysis

Lap-shear Test



Cross-tension Test

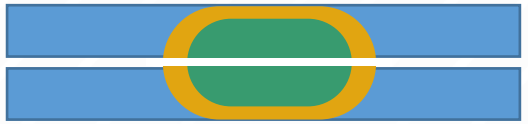




Failure Modes

Pull-out Failure (PF)

Weld nugget detachment



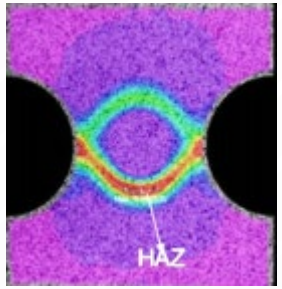
Interfacial Failure (IF)

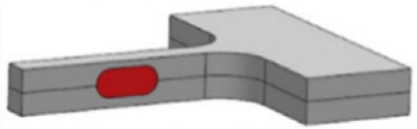
Weld cracking along the faying surfaces

Limited Information from Typical Experiments

Failure Occurs in an Enclosed Space

- Interrupted tests
- Surface DIC measurement
- Miniaturized samples





Post-Failure Analysis

Ghassemi-Armaki H, Biro E, Sadagopan S. Advanced Characterization of HAZ Softening of AHSS for Crash Modeling. ISIJ Int 2017;57:1451–60.
Ma et al. Measurement of local material properties and failure analysis of resistance spot welds of advanced high-strength steel sheets. Mater Des 2021;201

MICROSTRUCTURE OF THE SPOT WELDS

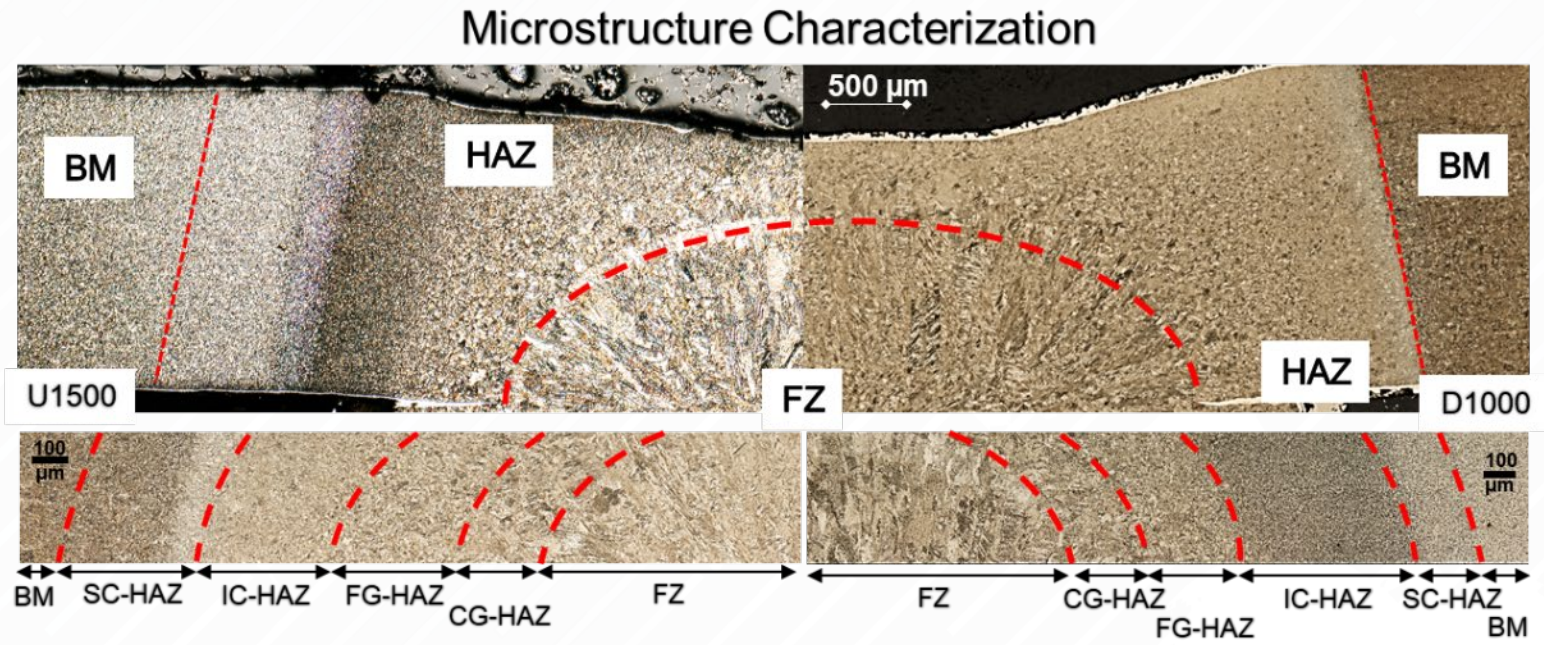
Materials:
Usibor®1500-AS (PHS1500)
Ductibor®1000-AS (PHS1000)
1.6 mm thick

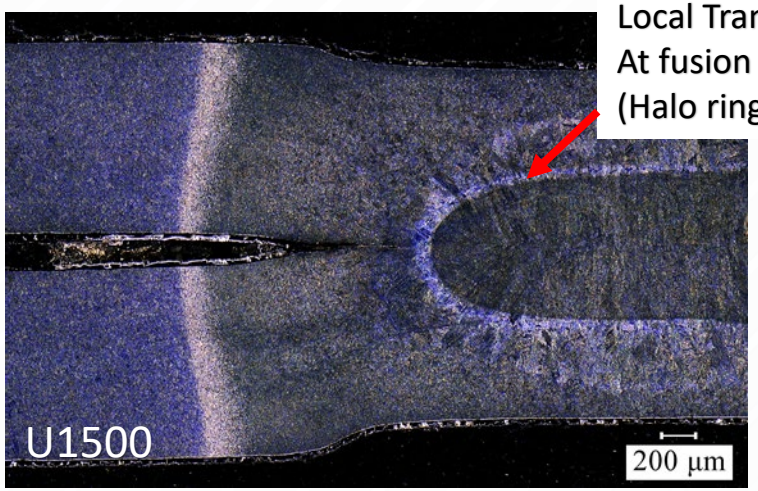
Hot-stamped from 930°C, 6 min using RT flat dies

RSW Parameters:

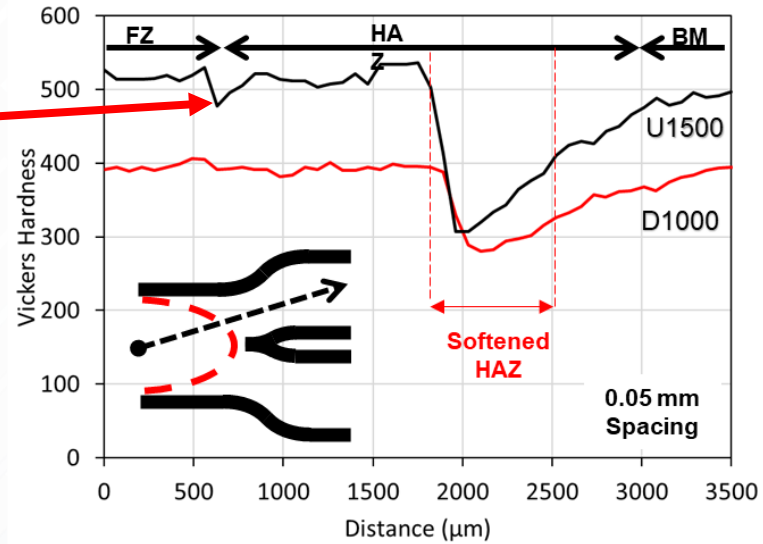
MFDC welder
6mm B-type cap
1 Pulse
500 ms
8.5 kA
3.5 kN
Similar Joints

Average weld size:
5.9±0.1 mm





Local Transient Softening
At fusion boundary
(Halo ring)



FAILURE CHARACTERIZATION

Lap-shear (Shear Loading)

PHS1500

Mode 2 Partial thickness fracture with button pull

PHS1000

Mode 7 Interfacial Fracture

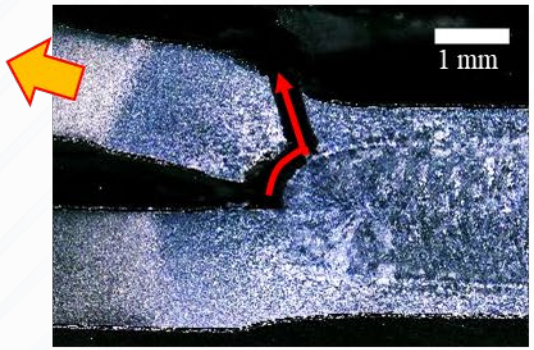
Cross-tension (Normal Loading)

PHS1500

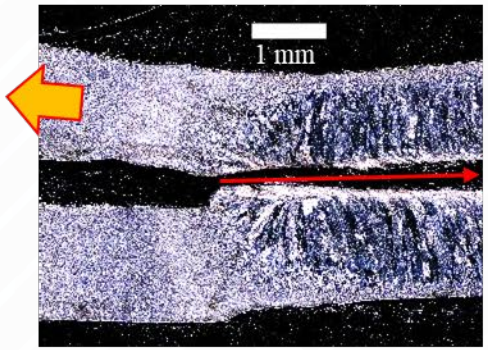
Mode 2 Partial thickness fracture with button pull

PHS1000

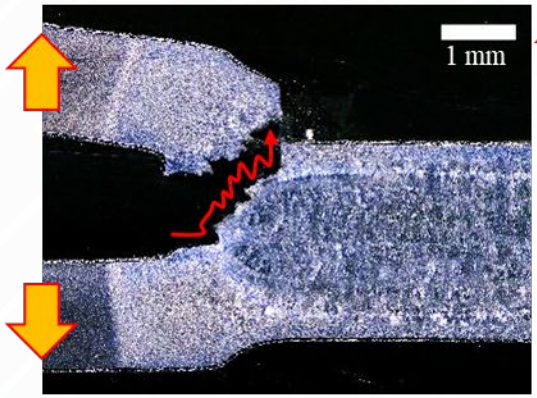
Mode 1 Button-pull



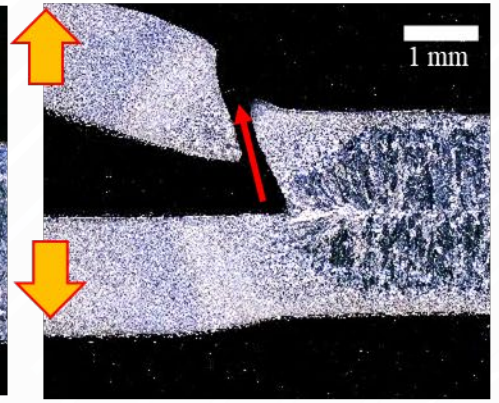
Failure along the halo ring Partial thickness failure



Failure along the faying surface of the sheets



Failure along a path through the thickness

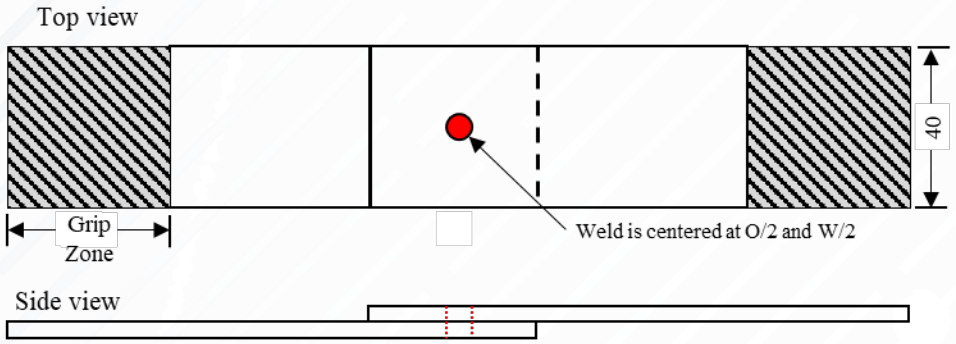


Failure through the thickness parallel to the loading direction

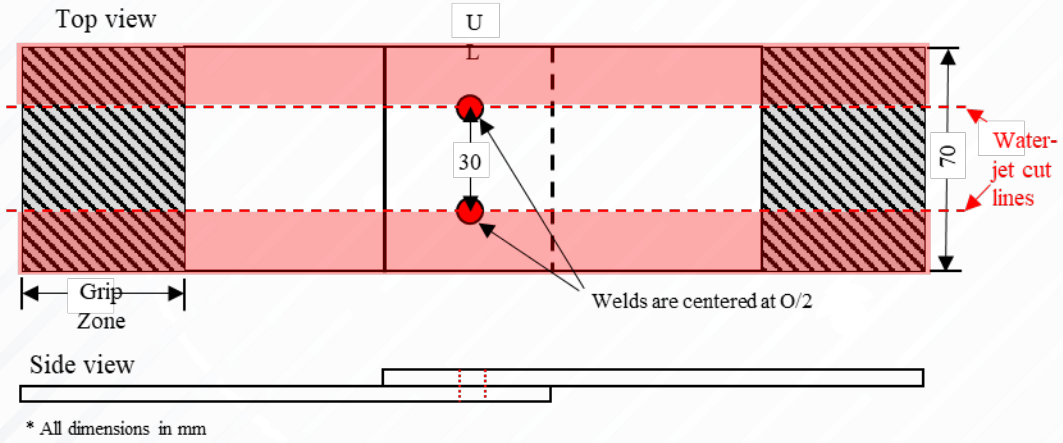
MODIFIED TESTING COUPONS FOR *IN-SITU* FAILURE CHARACTERIZATION

Lap-shear (Shear Loading)

Standard lap-shear sample



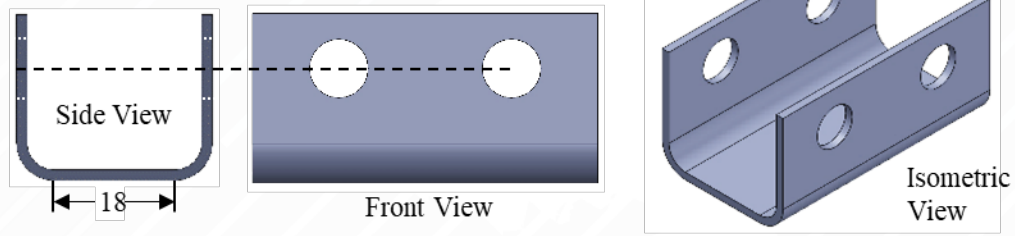
Modified Double-Half (DHW) weld lap-shear sample



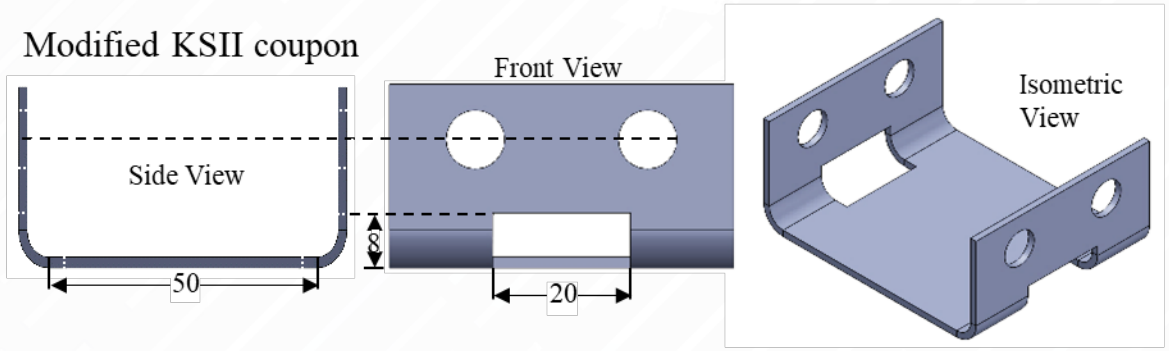
* All dimensions in mm

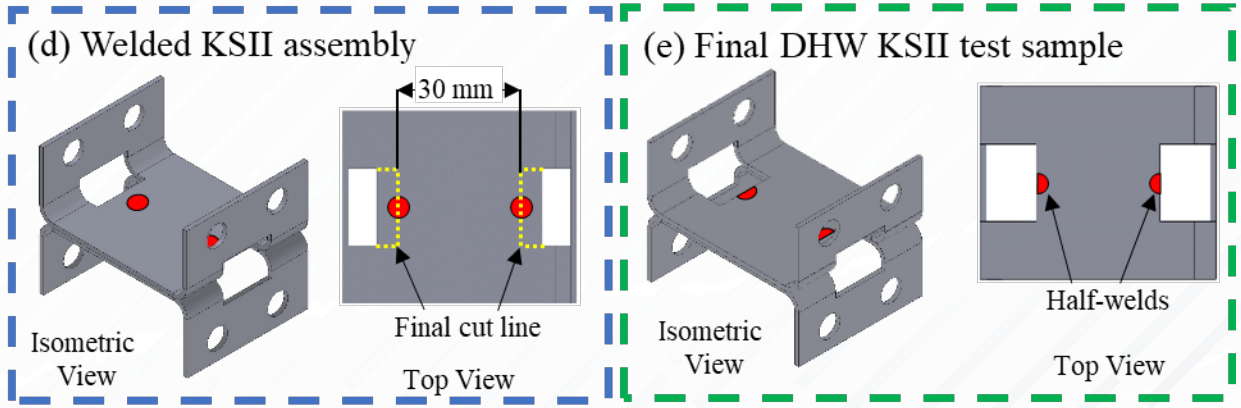
Cross-tension (Normal Loading)

Conventional KSII coupon

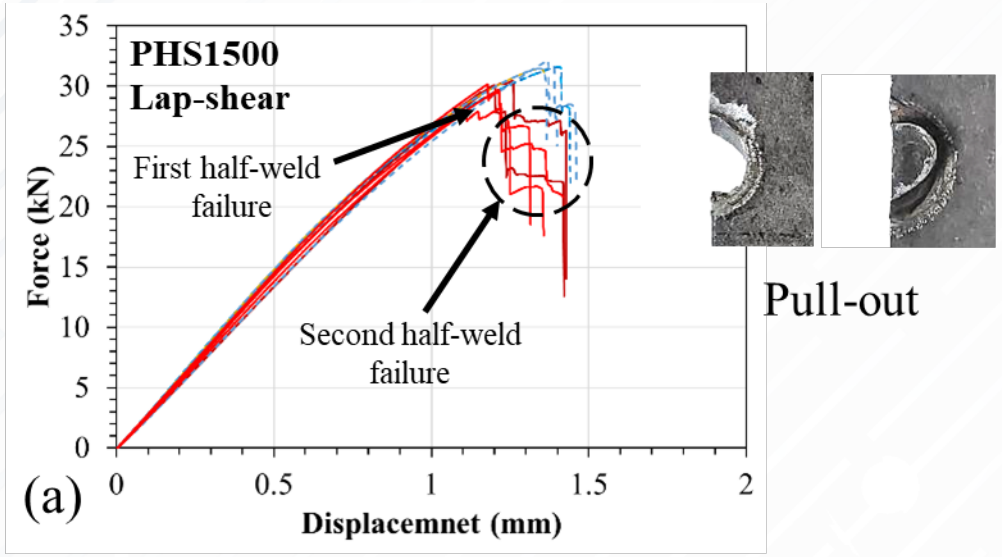


Modified KSII coupon

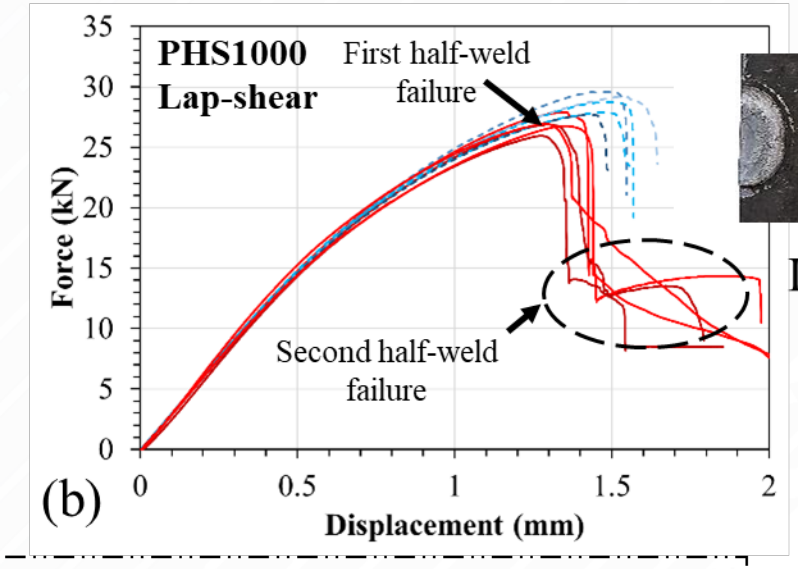




LOAD-DISPLACEMENT RESPONSE FOR THE DHW TESTS

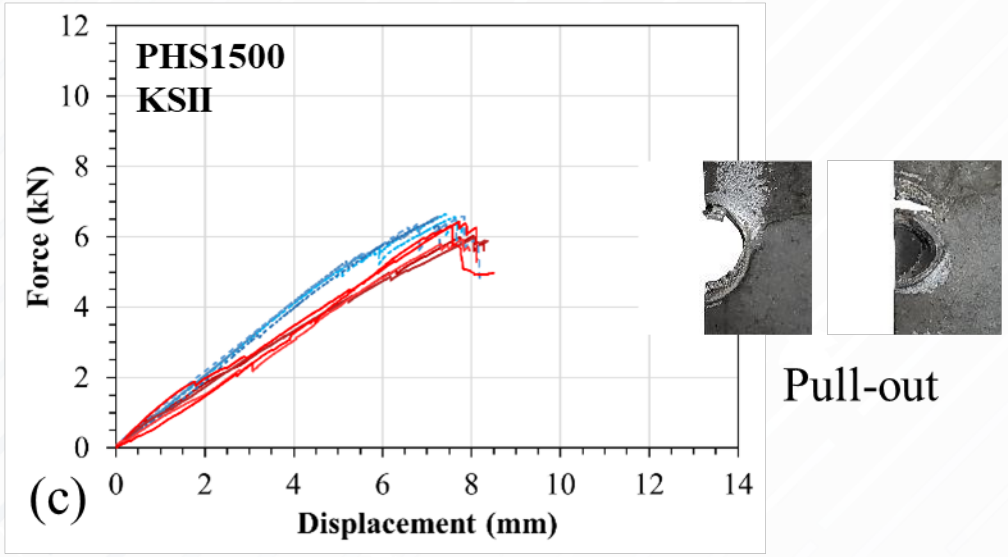


Pull-out

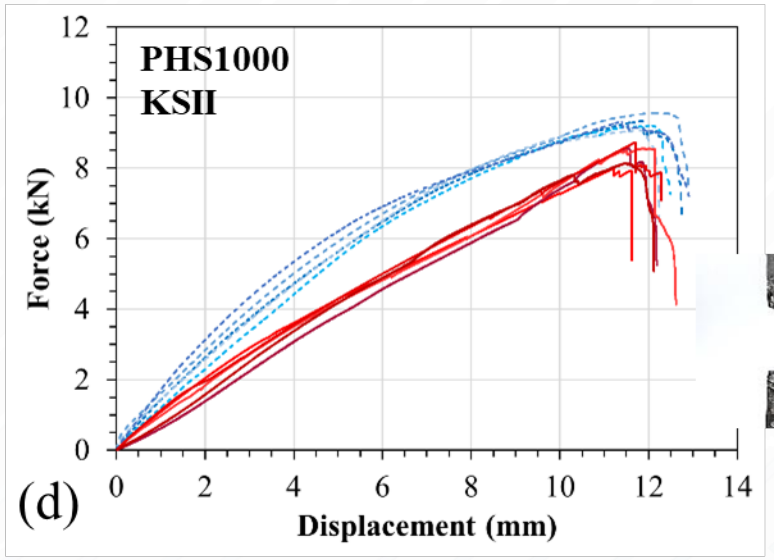


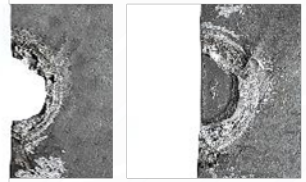
Interfacial

Dashed ■ ■ ■ ■ Standard/Reference Tests Solid ▬ Modified DHW Tests



Pull-out



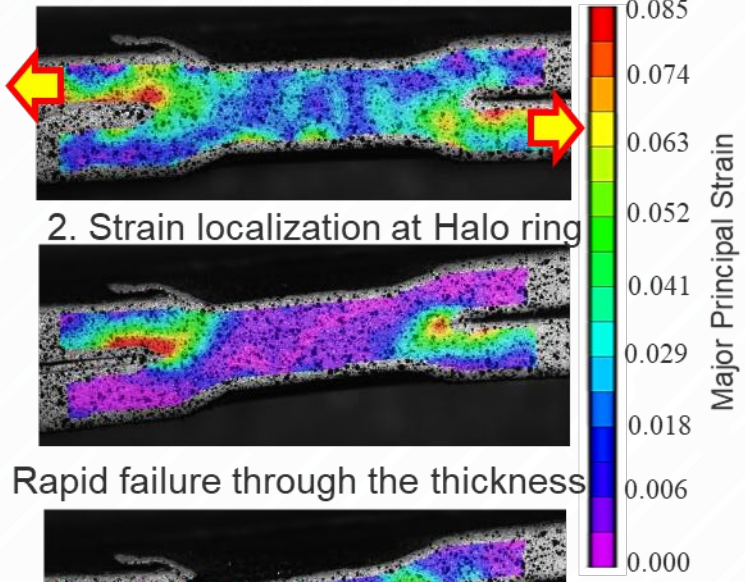


Pull-out

DHW TEST RESULTS (SHEAR LOADING)

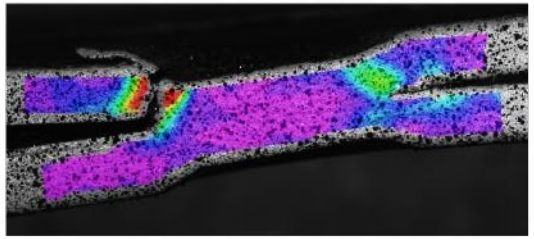
PHS1500

1. Initial localization at weld notch

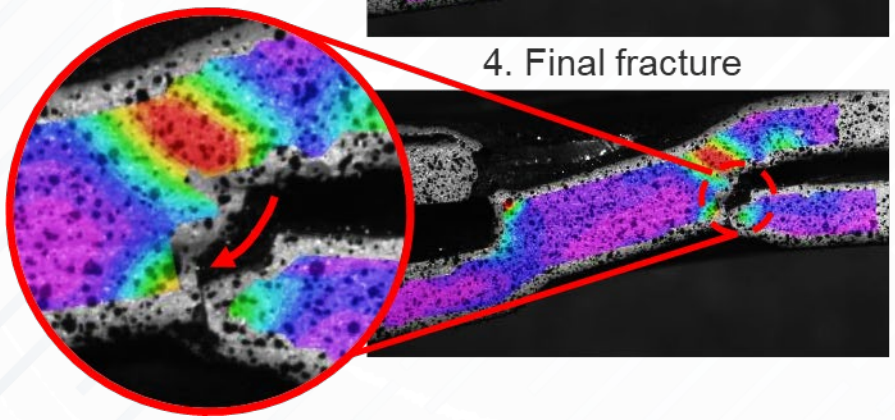


2. Strain localization at Halo ring

3. Rapid failure through the thickness

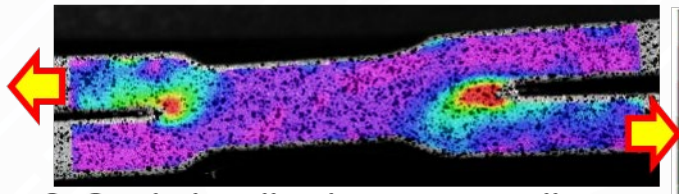


4. Final fracture

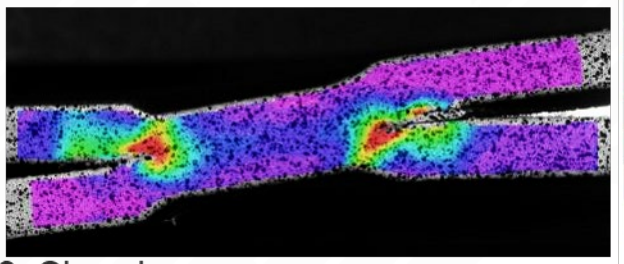


PHS1000

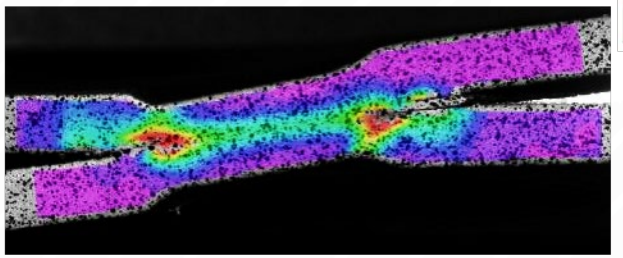
1. Initial localization at weld notch



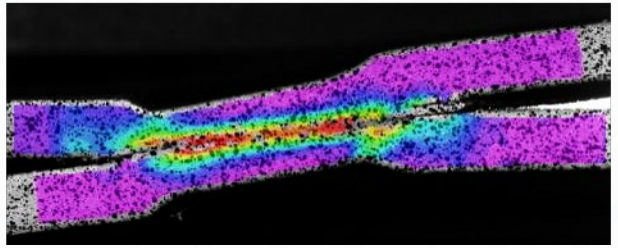
2. Strain localization at center line



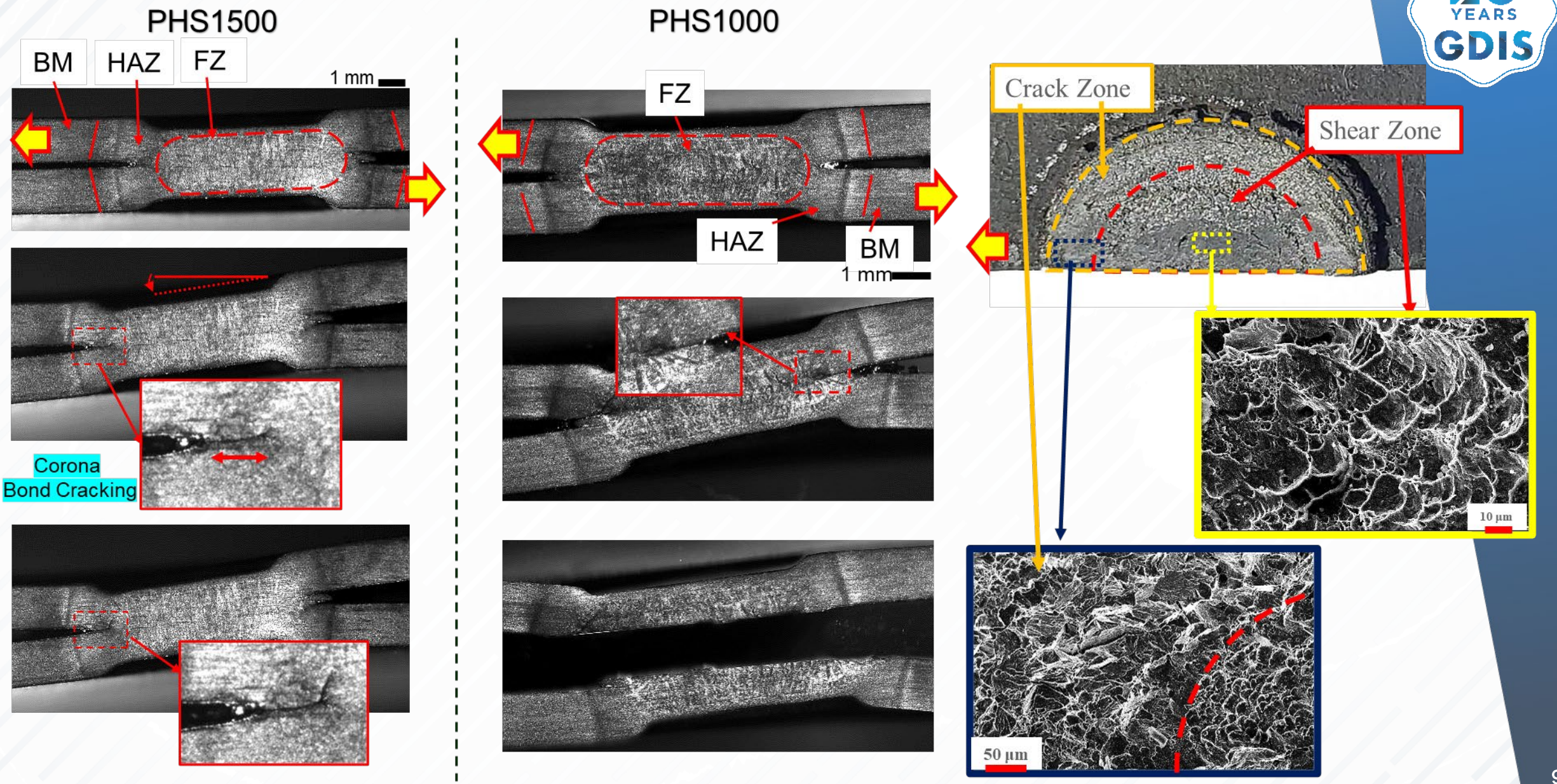
3. Shearing



4. Fracture at shear band



DHW TEST RESULTS (SHEAR LOADING) – MACRO-ETCHING TECHNIQUE

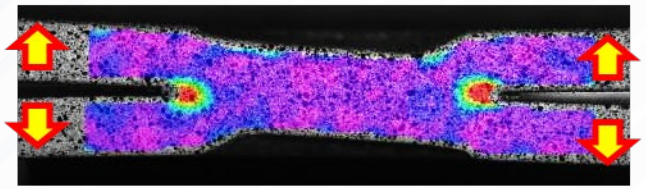


DHW TEST RESULTS (NORMAL LOADING)

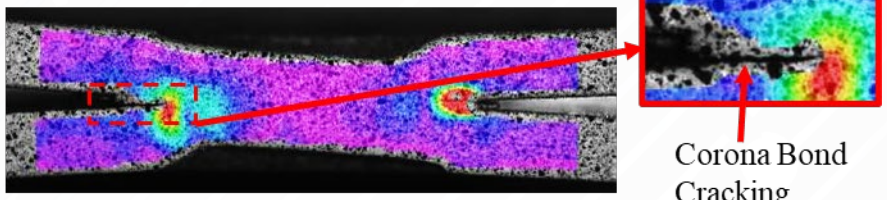
PHS1500

e1 Strain
0.057
0.050
0.043
0.035
0.028
0.021
0.013
0.006
0.000

(1) Initial localization at the weld notch

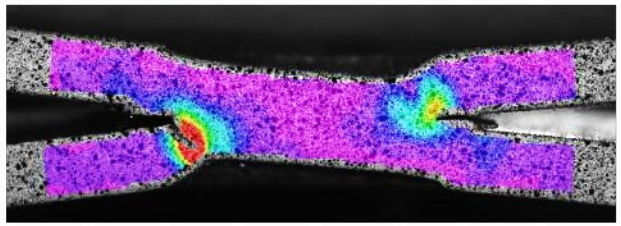


(2) Corona debonding and notch opening

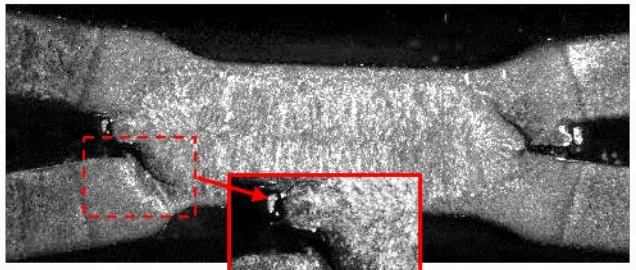


Corona Bond Cracking

(3) Strain localization at Halo ring



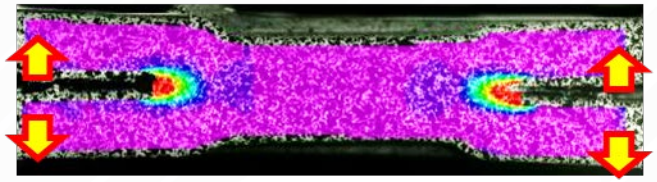
(4) Final Fracture (Macro-etched sample)



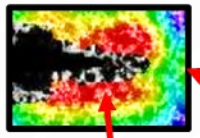
Cracking along the halo ring

PHS1000

(1) Initial localization at the weld notch

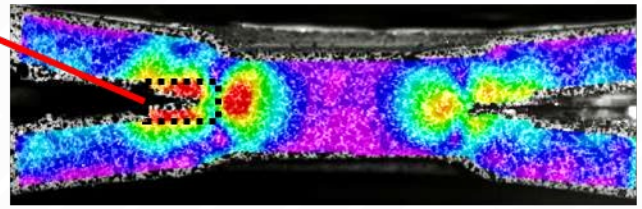


e1 Strain
0.100
0.087
0.075
0.063
0.050
0.038
0.025
0.013
0.000

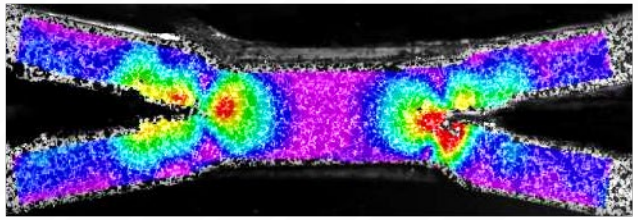


Corona Bond Cracking

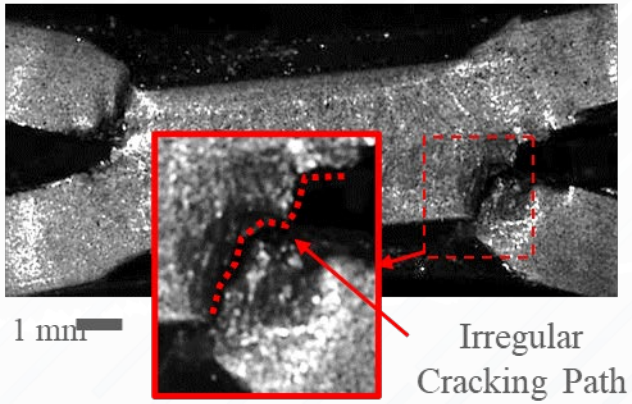
(2) Corona debonding and notch opening



(3) Cracking parallel to loading direction

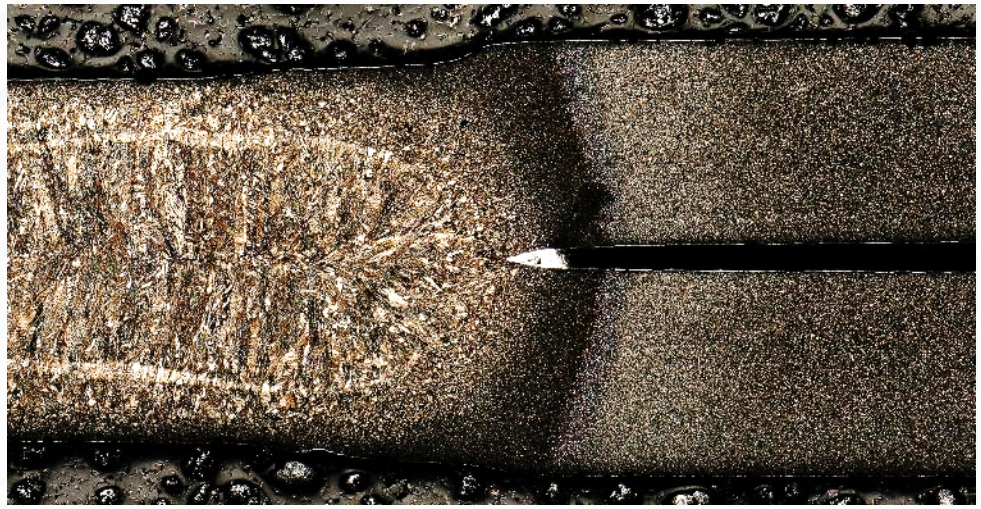


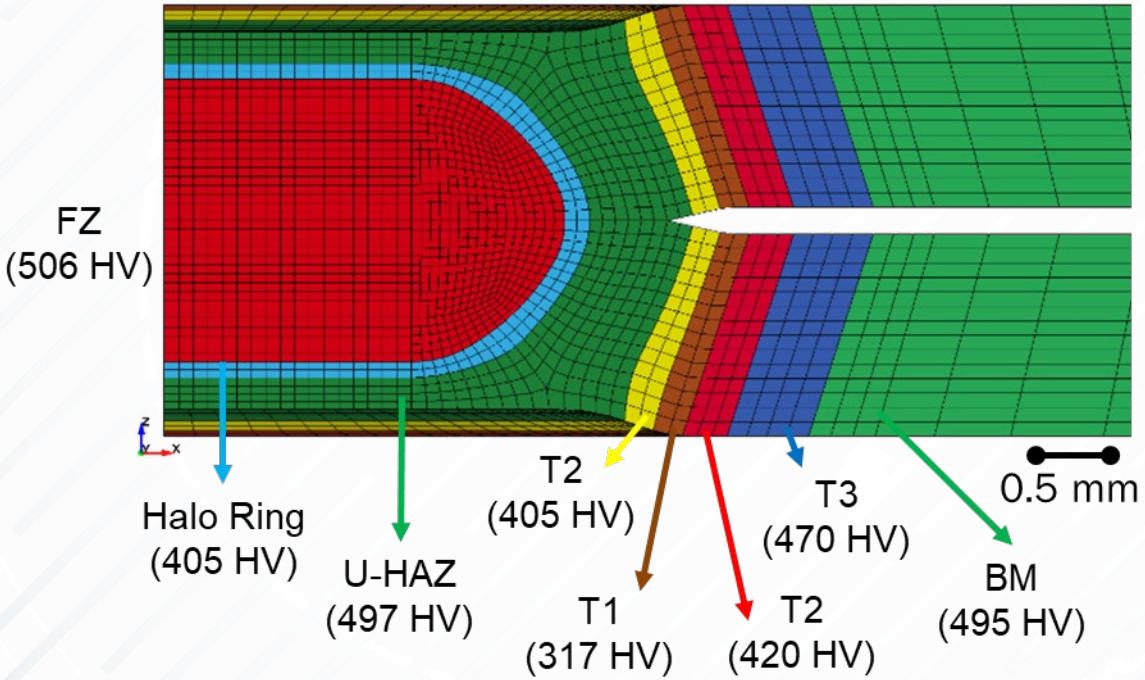
(4) Final fracture (Macro-etched sample)

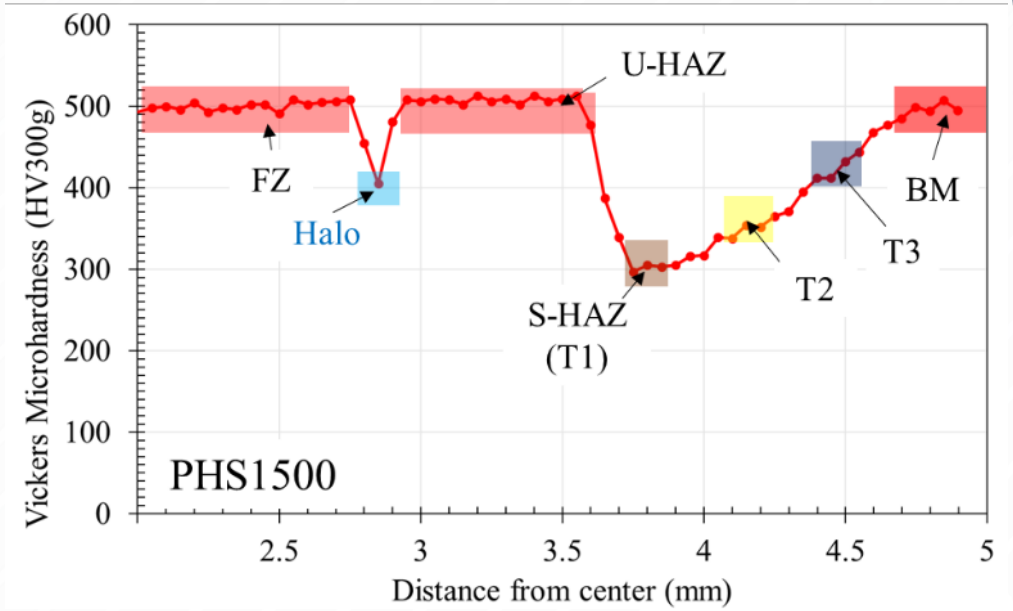


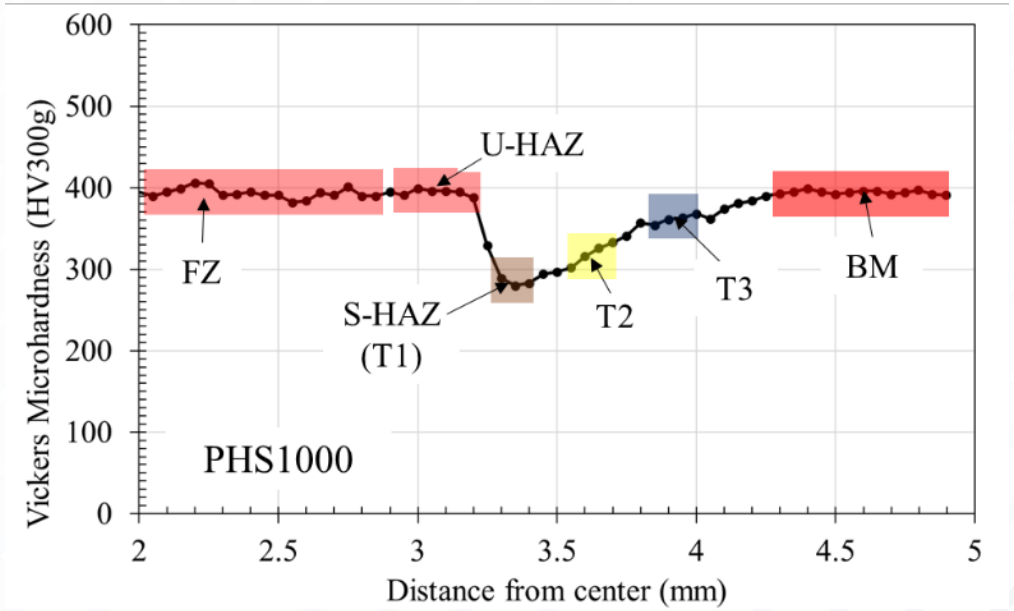
Irregular Cracking Path

MICROSTRUCTURE/MICROHARDNESS-BASED MESO-SCALE MODELING APPROACH



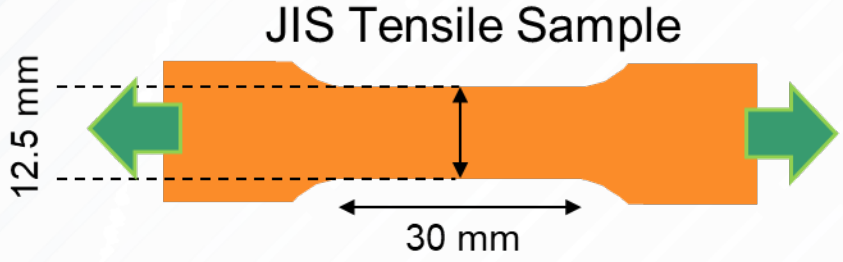


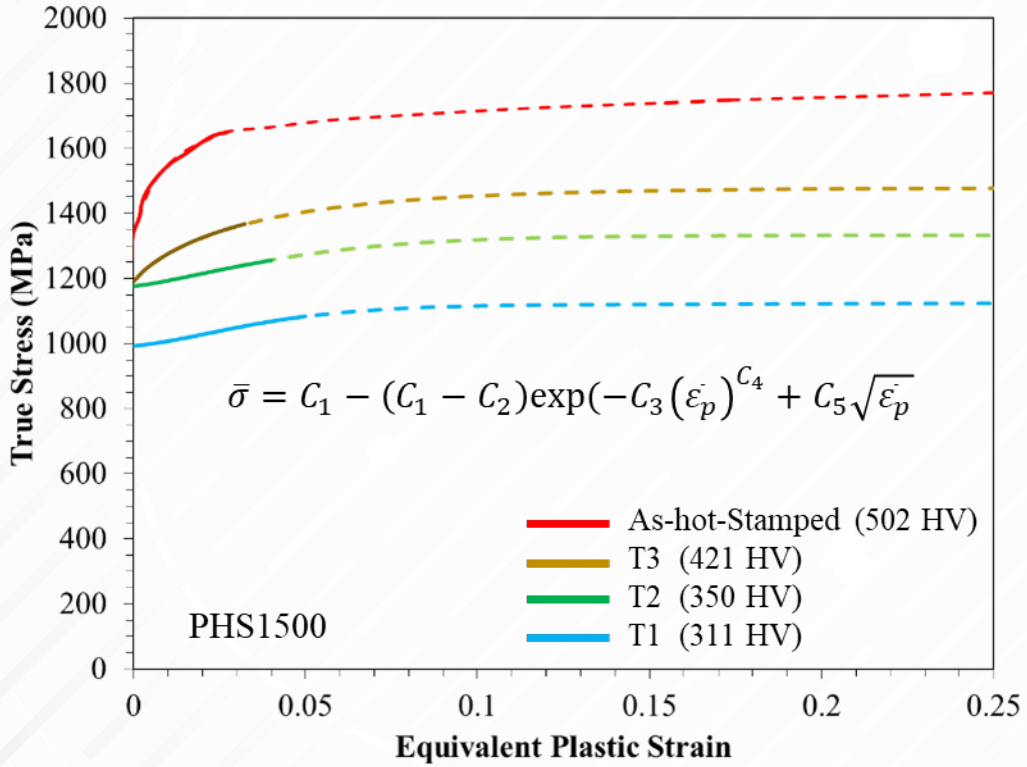




CONSTITUTIVE AND FRACTURE CHARACTERIZATION OF WELD REGIONS

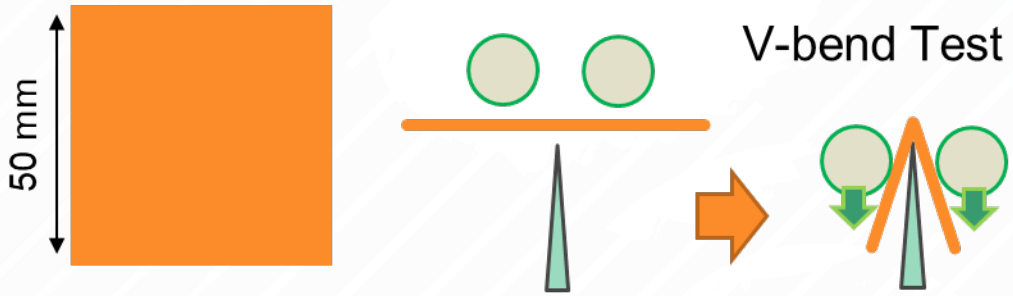
Constitutive Behavior

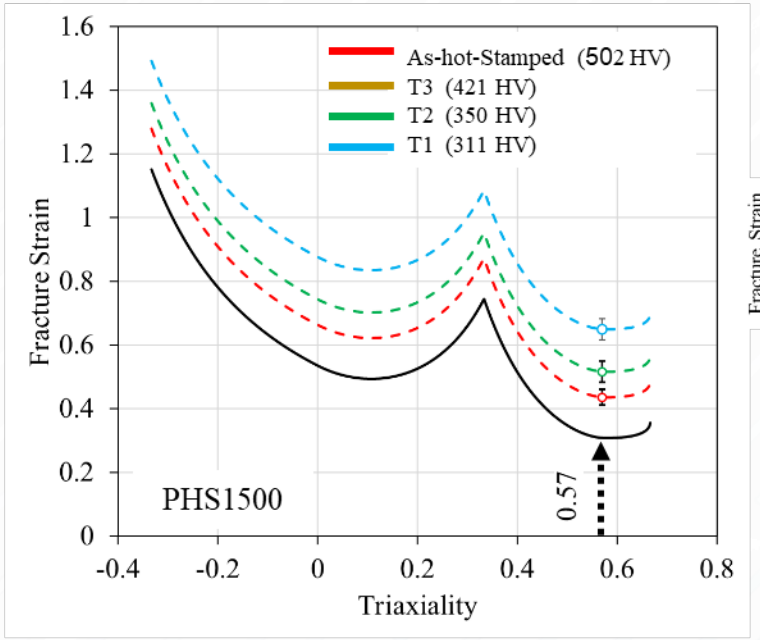


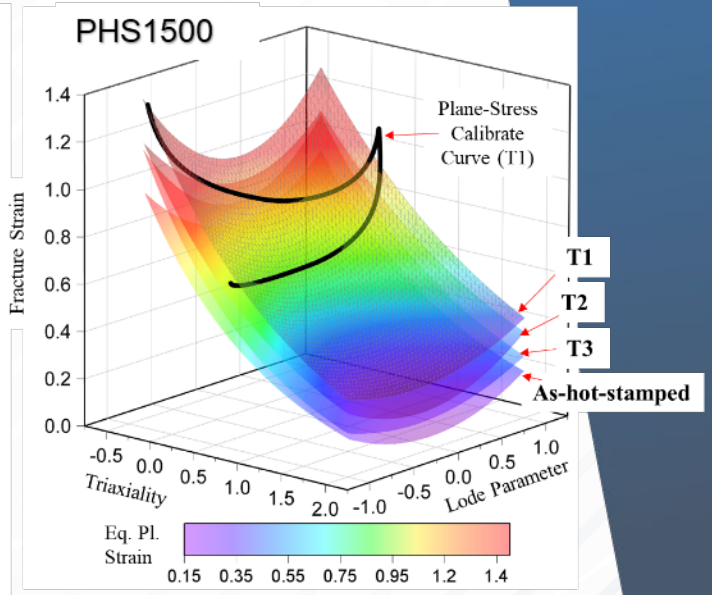


Fracture Strain

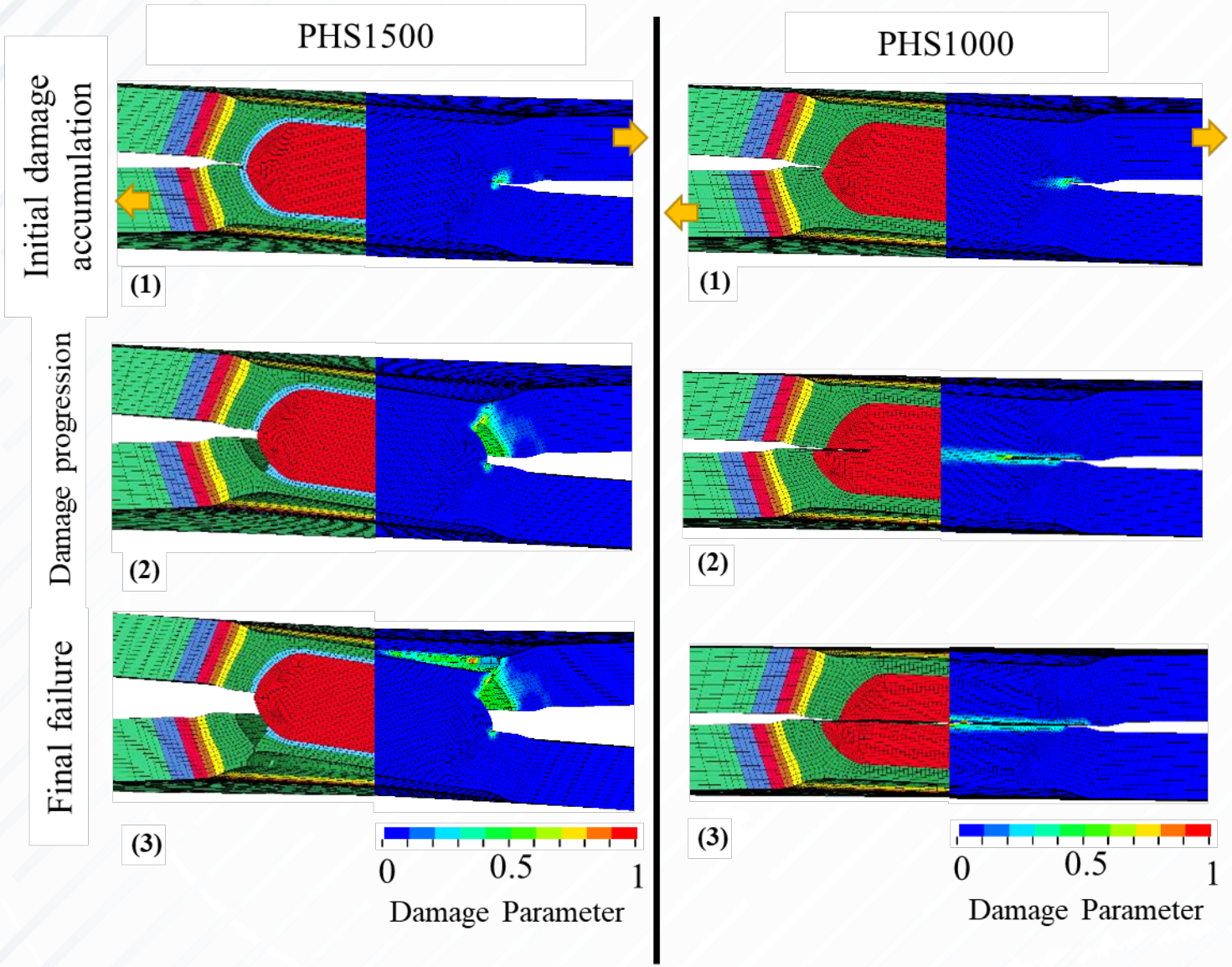
- Strain at fracture for plane strain condition

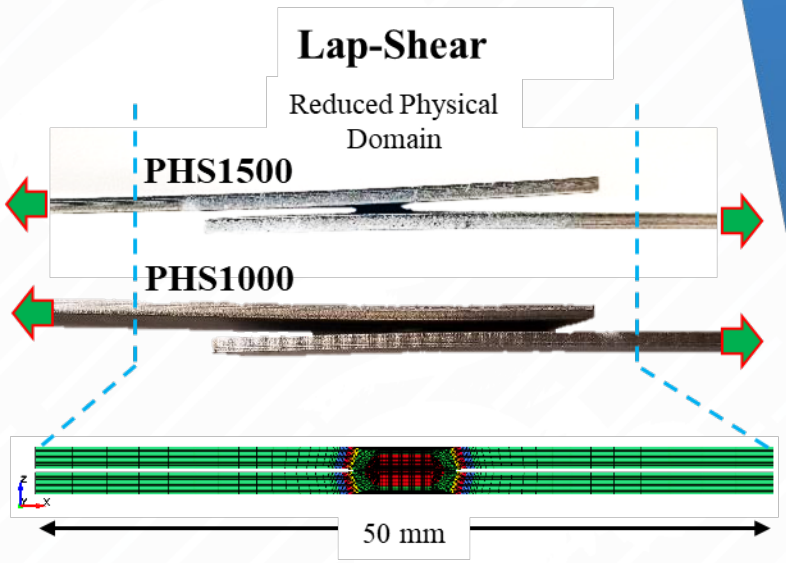






MESO-SCALE FAILURE PREDICTION (SHEAR LOADING)

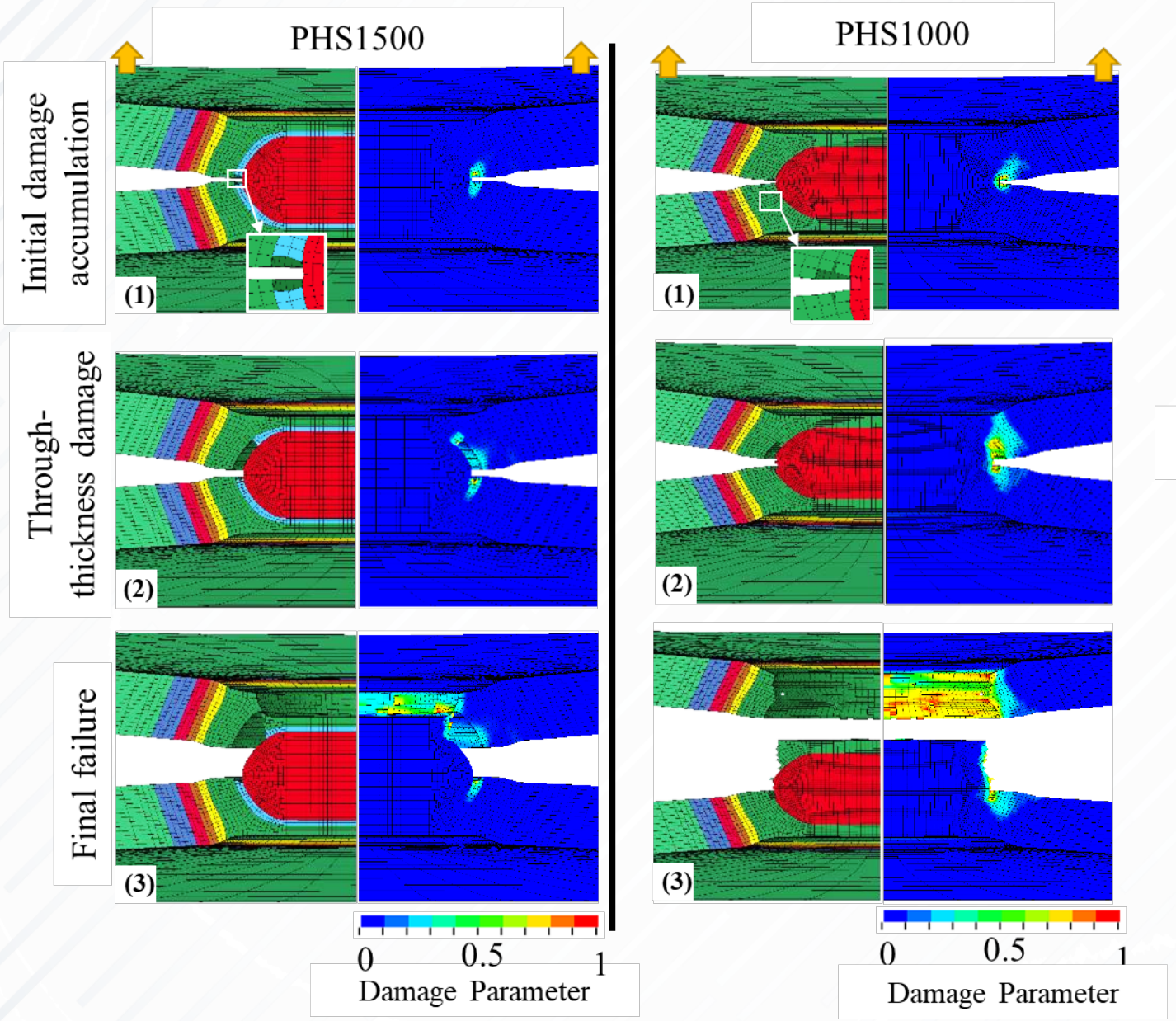


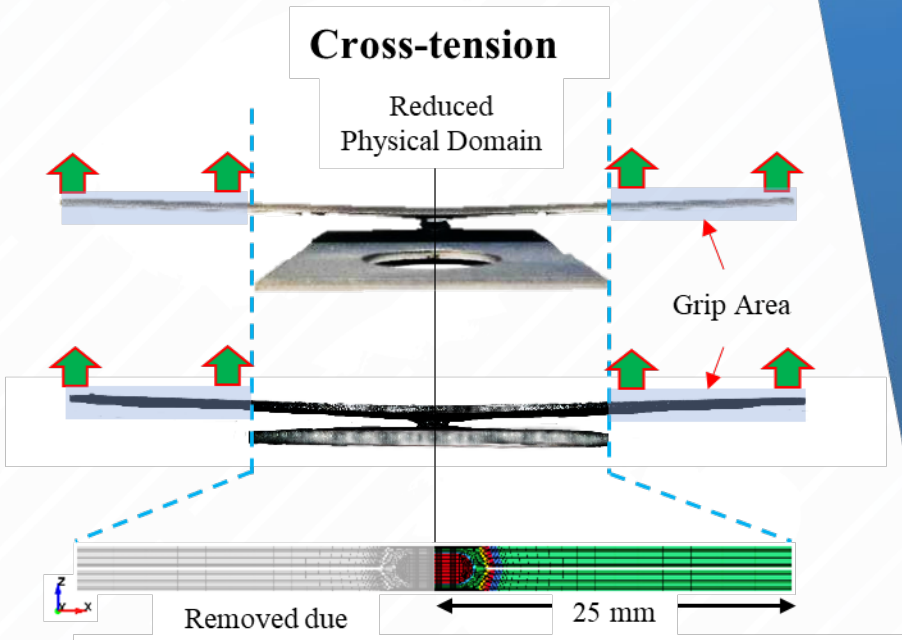


Half-symmetry Model
Average element size in weld area : 0.06 mm

Single point integration
Test velocity: 10 mm/min

MESO-SCALE FAILURE PREDICTION (NORMAL LOADING)

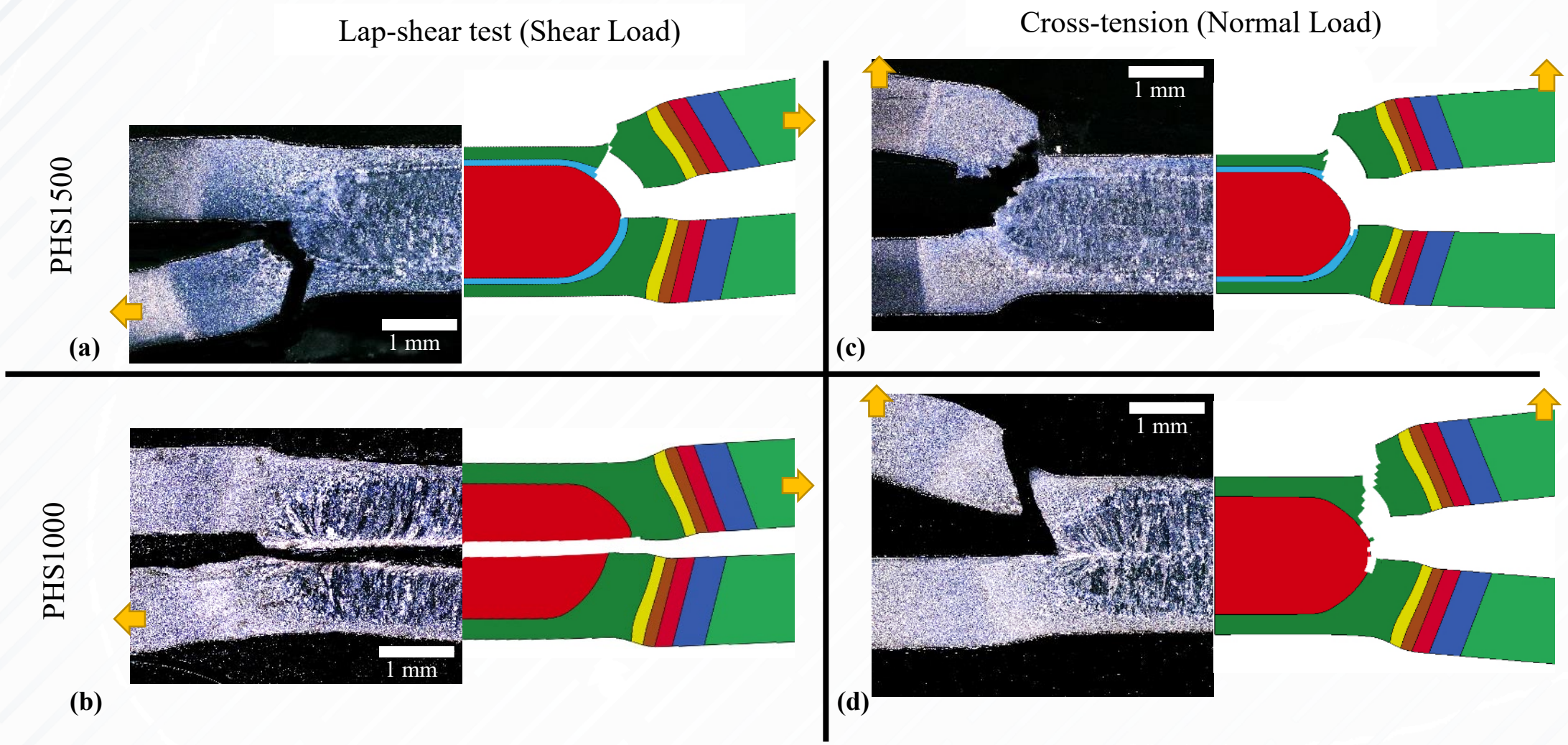




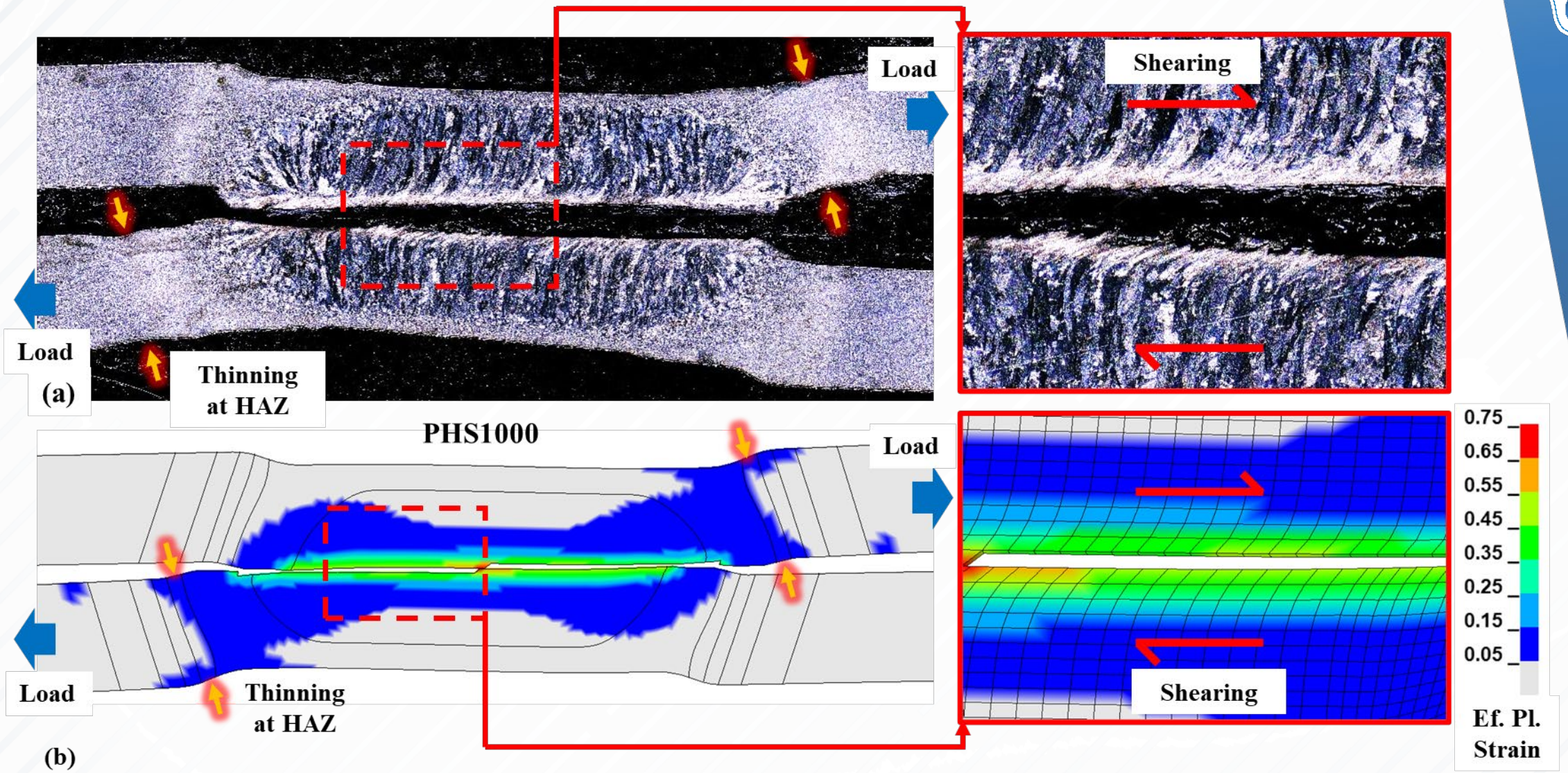
Quarter-symmetry Model
Average element size in weld area : 0.06 mm

Single point integration
Test velocity: 10 mm/min

MESO-SCALE FAILURE PREDICTION: PREDICTION VS. EXPERIMENT

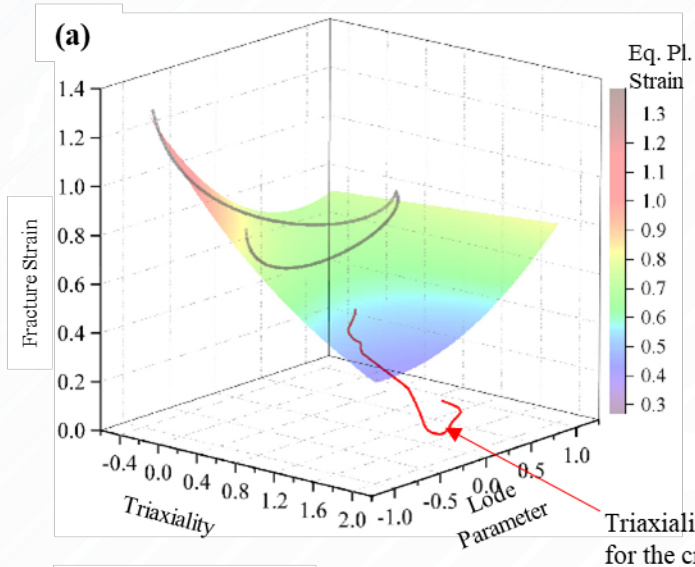


INTERFACIAL FAILURE MECHANISM

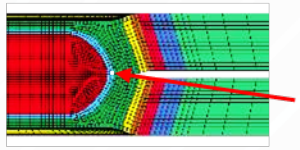


INTERFACIAL FAILURE MECHANISM

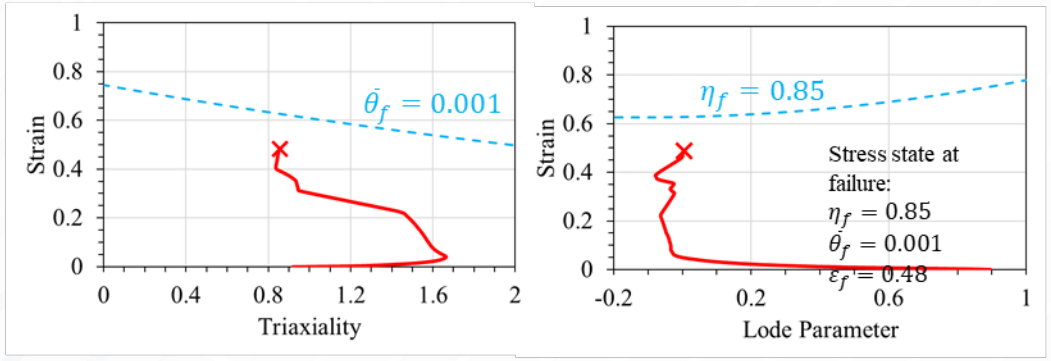
Pull-out Failure



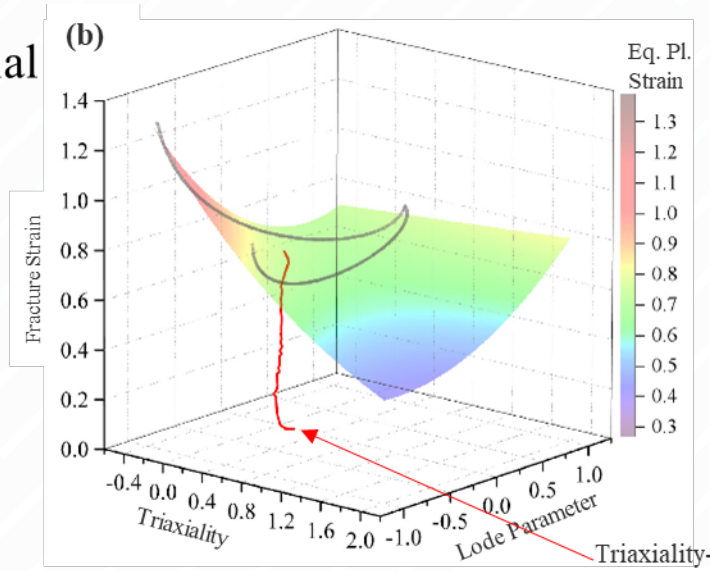
Triaxiality-Lode history for the critical element:
PHS1500
Lap-shear test



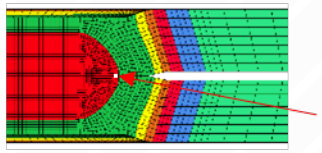
Critical element at the weld notch (the halo ring)



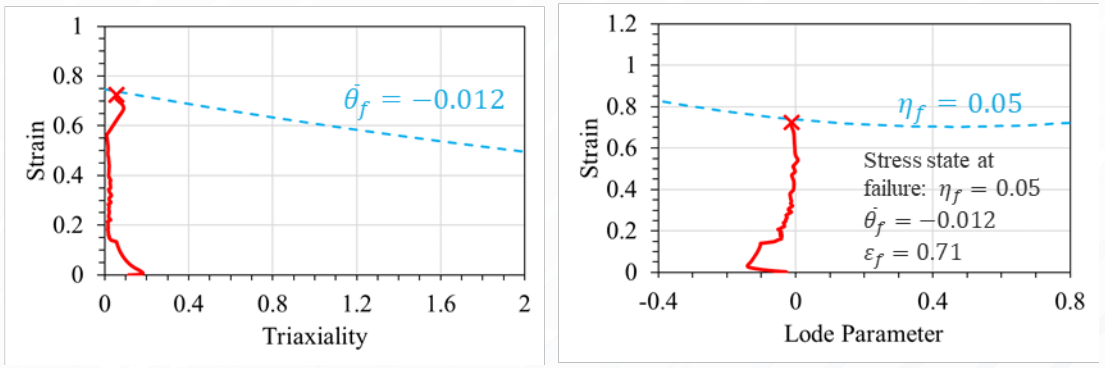
Interfacial Failure



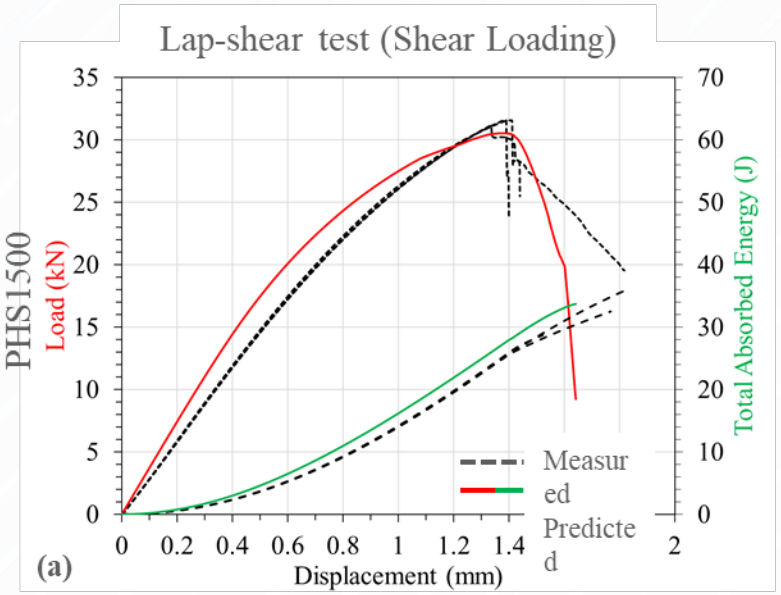
Triaxiality-Lode history for the critical element:
PHS1000
Lap-shear test

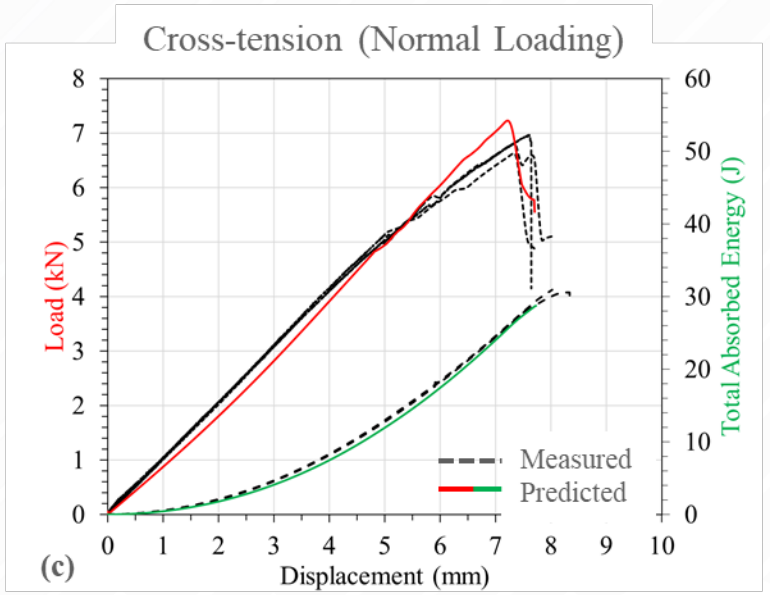


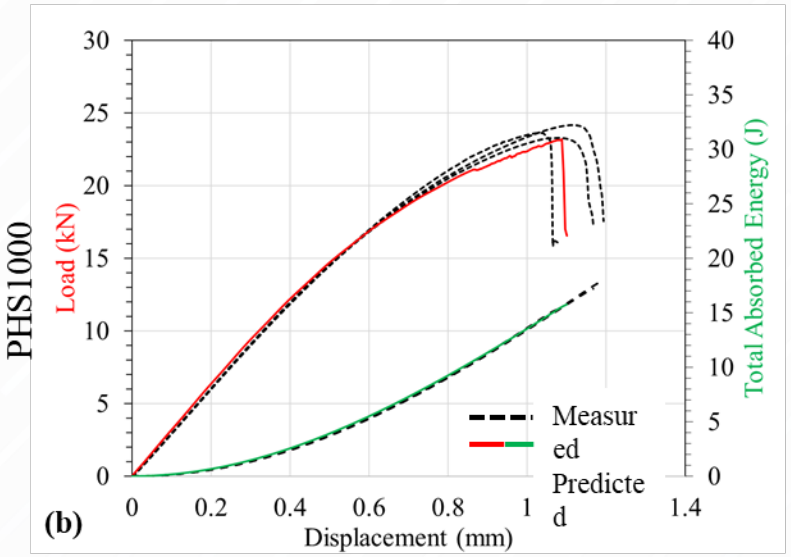
Critical element at the weld centerline (the FZ)

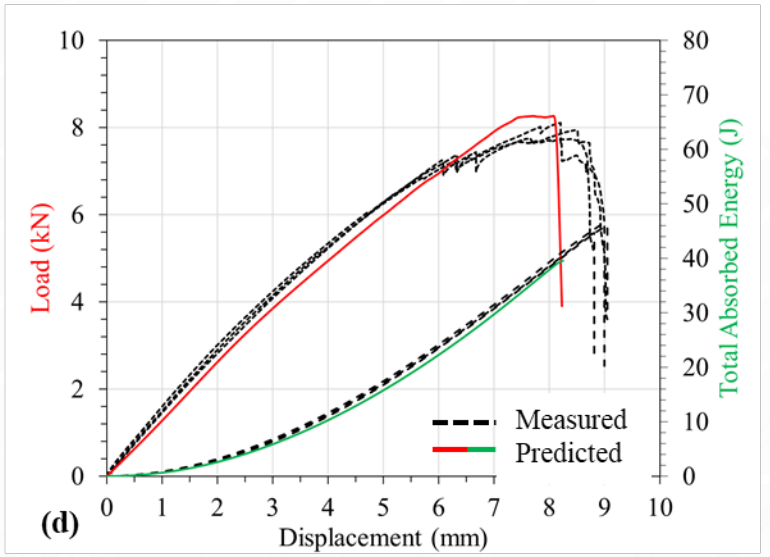


LOAD-DISPLACEMENT PREDICTION









CONCLUSIONS

- The Double-Half Weld (DHW) testing technique coupled with DIC can be used to perform *in-situ* failure characterization on the spot welds in different materials and loading conditions. In this work the shear-dominant mechanism of interfacial failure for PHS1000 steel was observed for the first time.

- Based on the microstructural observations, the local material properties of the weld regions affect the location and mode of failure. In the presence of the transient softened zone, the PHS1500 material tends to fail at the fusion boundary.

- Microhardness/microstructure relationship can be used to develop a discretized meso-scale model with the local material properties assigned to each subregion based on the actual shape and microstructure/microhardness of subregions.

- The developed meso-scale models provide accurate prediction of spot weld failure mode, failure path, and global load-displacement response of the weld coupons as well as information on failure mechanism and state of stress for critical elements which are quite influential in spot weld failure behavior.

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