Challenges and Opportunities in Joining Advanced High Strength Steels

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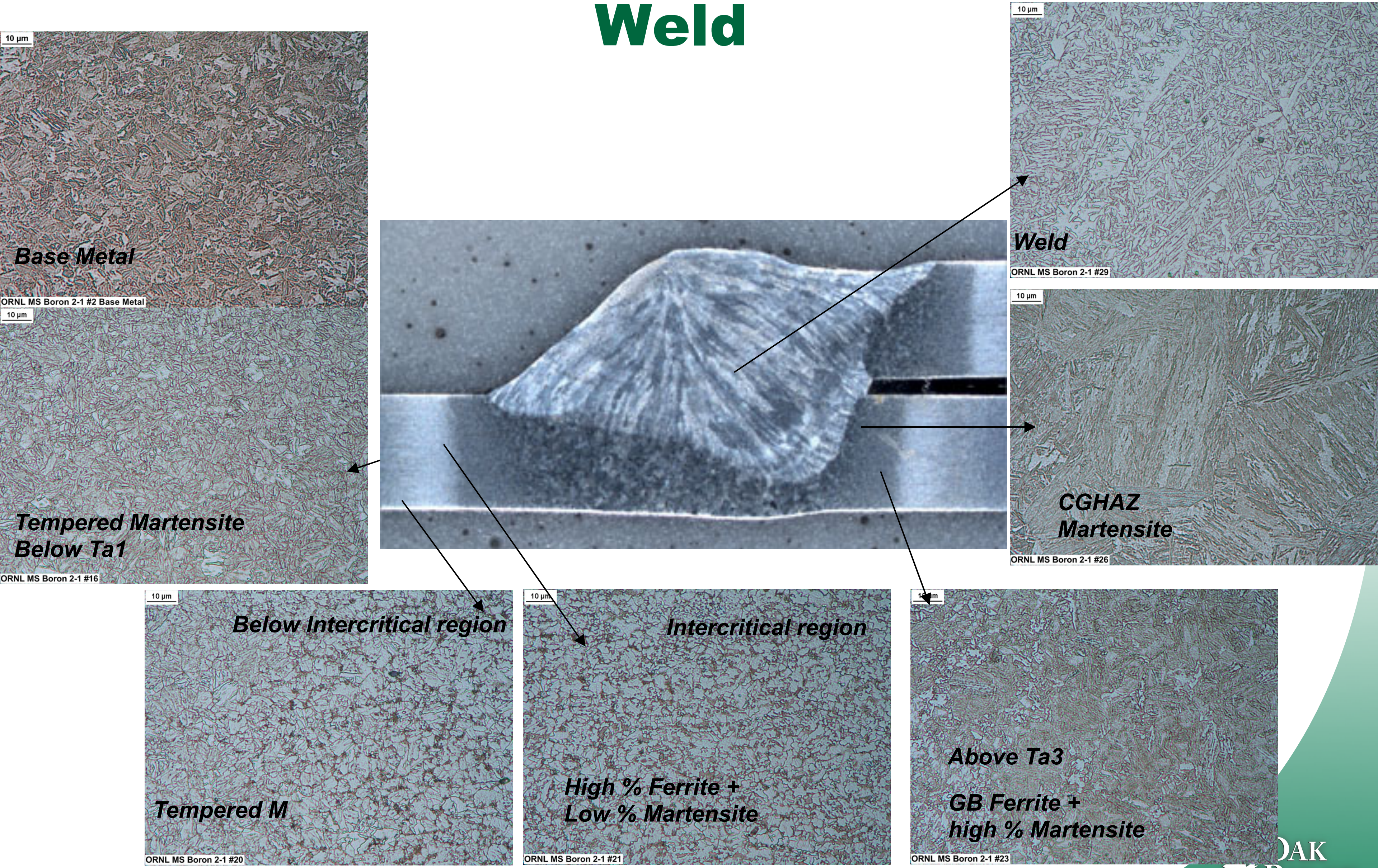
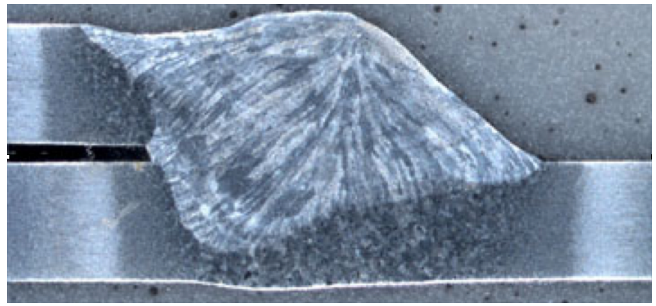
Challenges in Welding of AHSS

- Higher carbon and alloying element contents make AHSS more sensitive to the welding thermal cycle, resulting greater variations of microstructures and properties of weld
- Microstructure and properties can highly depend on welding conditions and steel chemistry
- Welding practices developed for one types of AHSS may not apply to other types
  - Weld quality
  - Weld structural performance (static, fatigue, impact/crash)
- There are wide range of grades and types of AHSS and they continue to evolve

Microstructural Gradient in a Boron Steel Weld

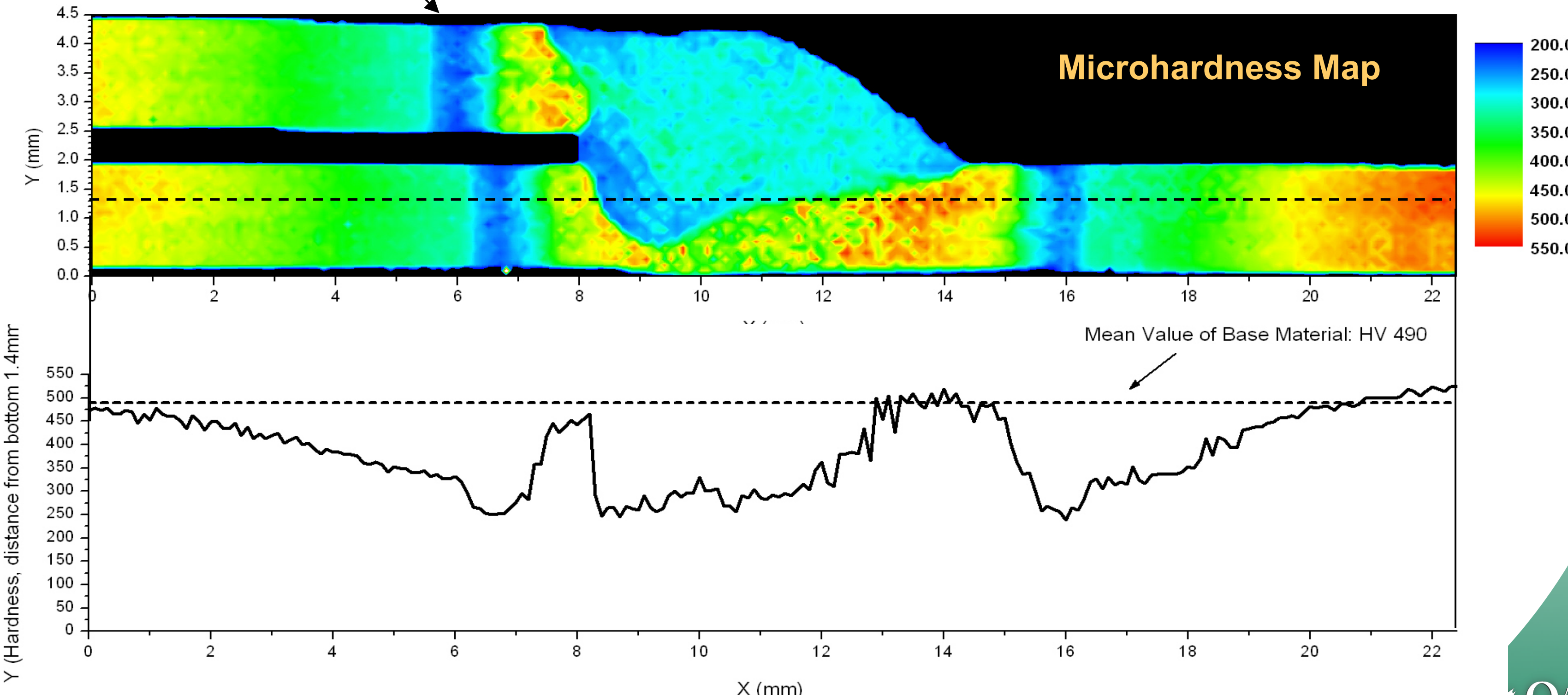


Microhardness Mapping: Local strength variation and HAZ Softening

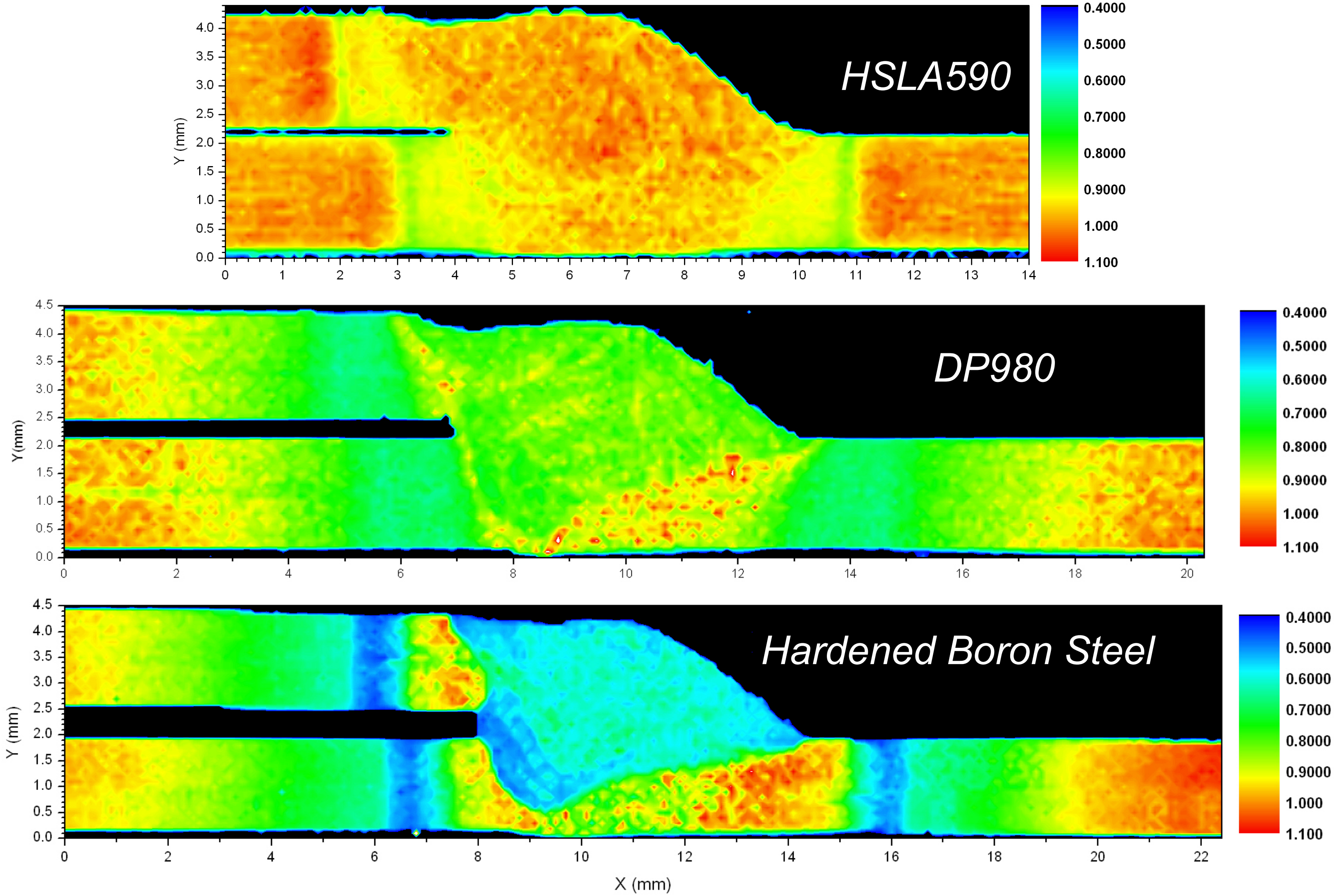


Boron Steel, Hardened

HAZ Softening



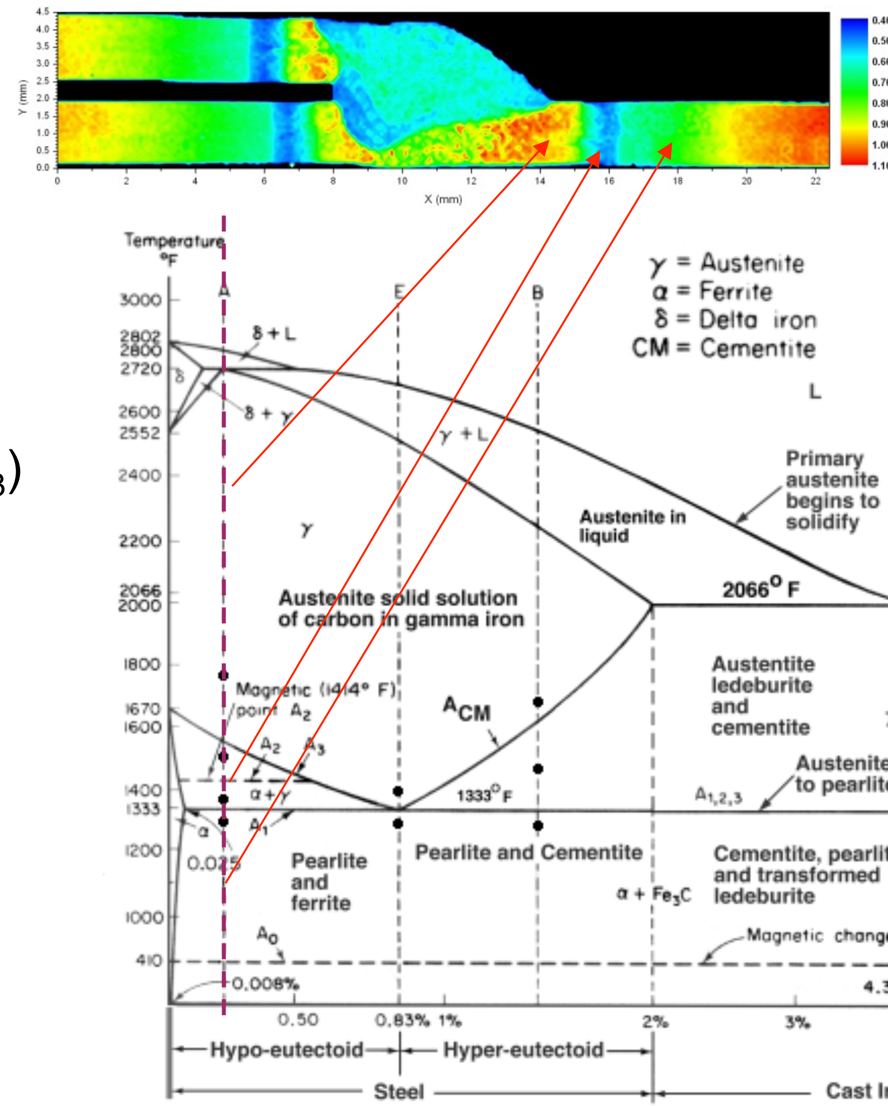
HAZ Softening is More Pronounced in Higher Grade Steels



Normalized Hv with respect to base metal Hv

Mechanism of HAZ Softening of AHSS

- HAZ softening is primarily related to the intercritical region
- Supercritical region (above T_{A3})
  - Single austenite phase region
  - On-cooling, austenite decomposition to low temperature phases depends on hardenability (composition) of steel and cooling rate
- Intercritical region (between T_{A1} and T_{A3})
  - Co-existence of ferrite and austenite
  - Austenite decomposes
  - Ferrite will remain on cooling
- Below T_{A1}
  - Tempering of martiniste/bainite
- Extent of HAZ soften depending on the initial base metal microstructure & hardness, steel chemistry and welding thermal cycle



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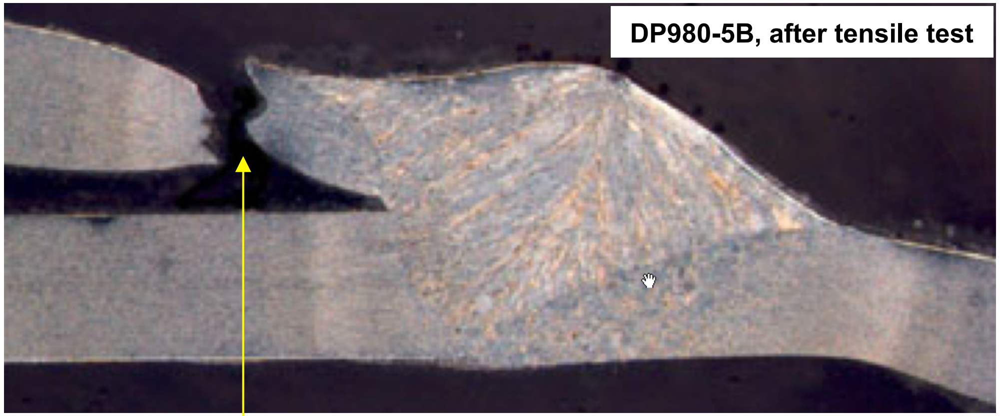
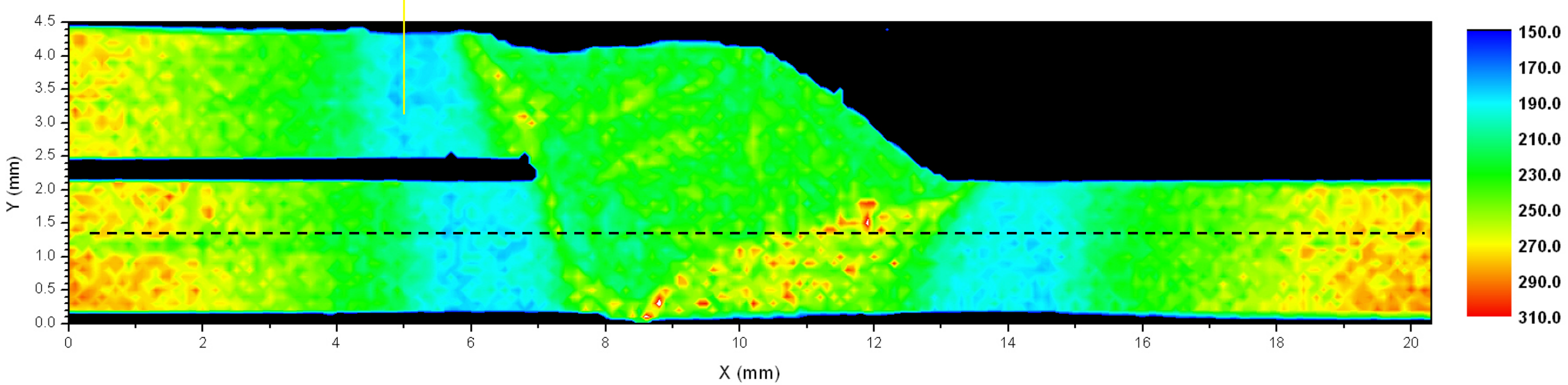
Static Tensile Failure Location Correlates to HAZ Softening Region

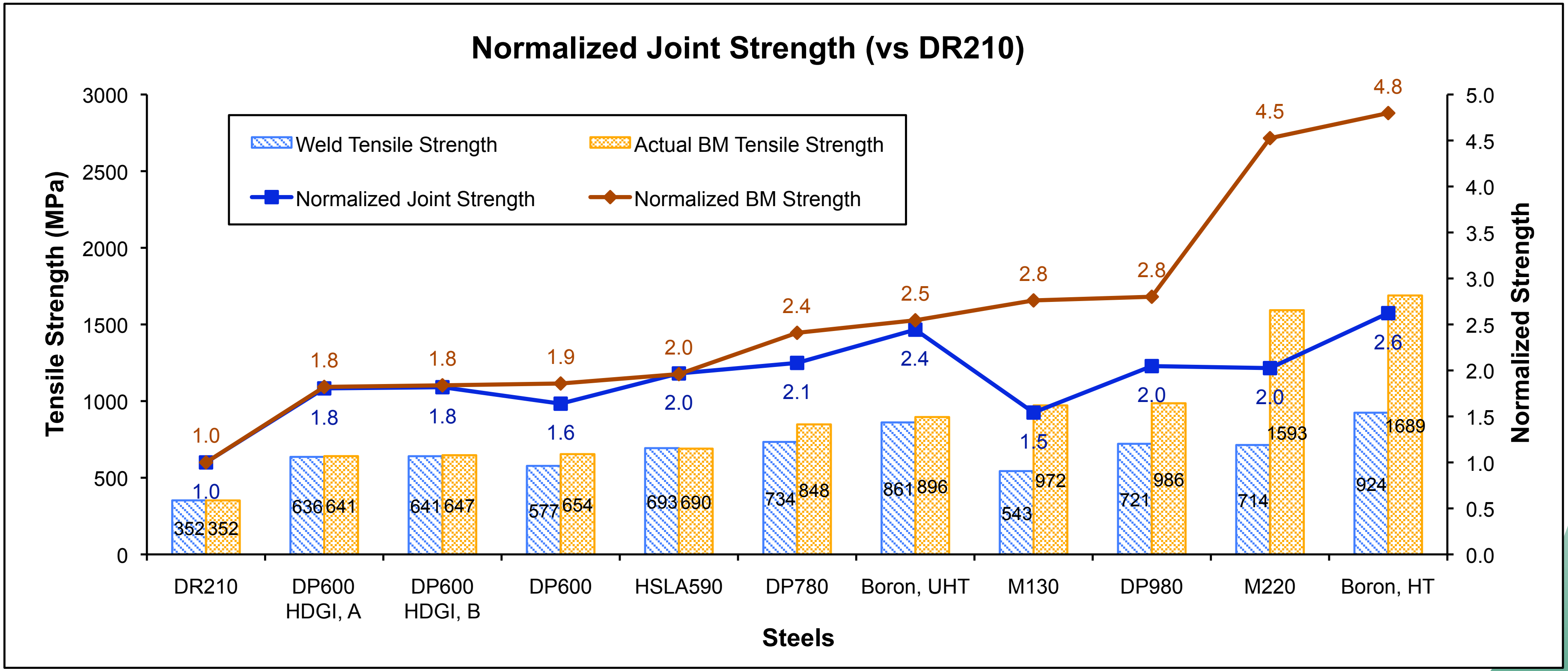


(DP980)



Static Joint Strength of GEN 1 AHSS

- AHSS has higher weld strength (static and impact) than mild steel, though with a deduction compared to base steel



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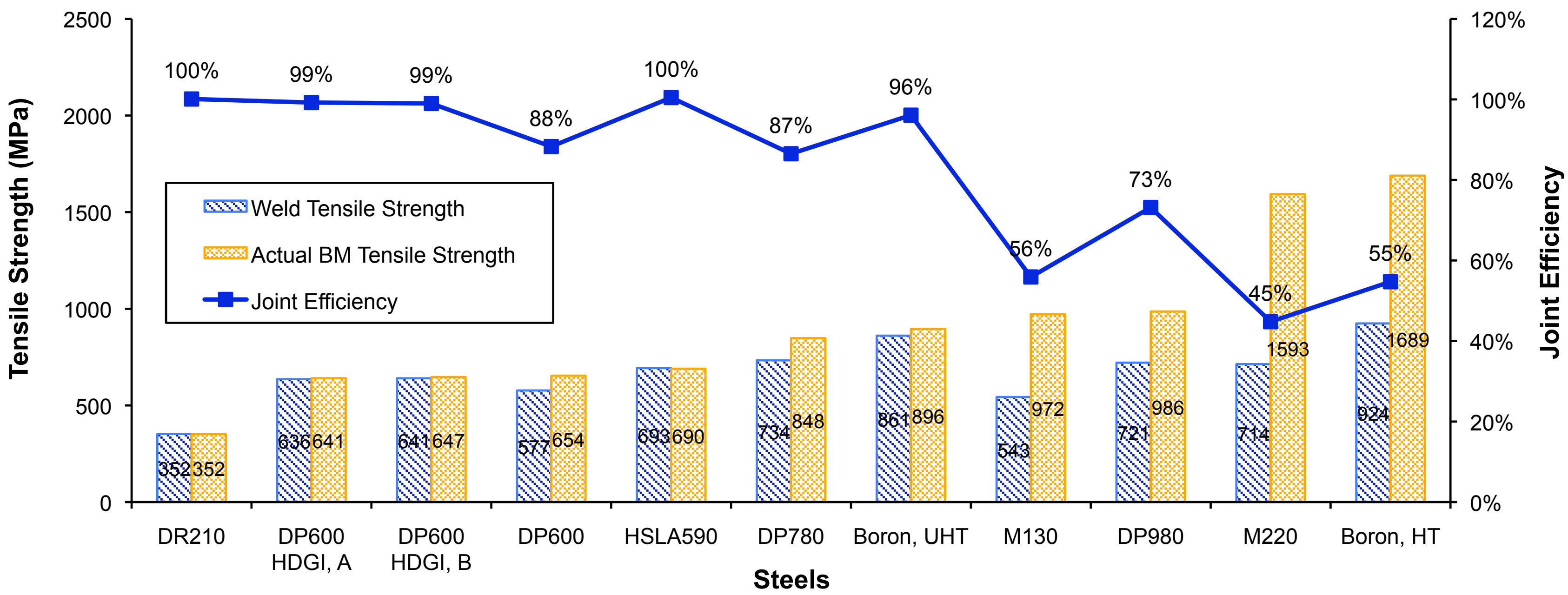
Joint Efficiency: A Practical Design Index

- Joint efficiency is proposed to quantify the reduced weld strength for design
- Cross weld tensile strength generally increases, as base metal strength increases



Joint efficiency = weld strength/BM strength

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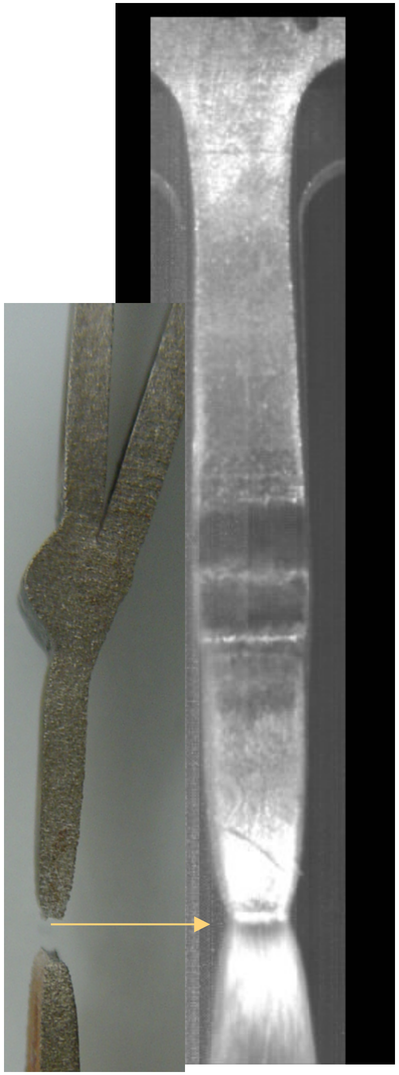
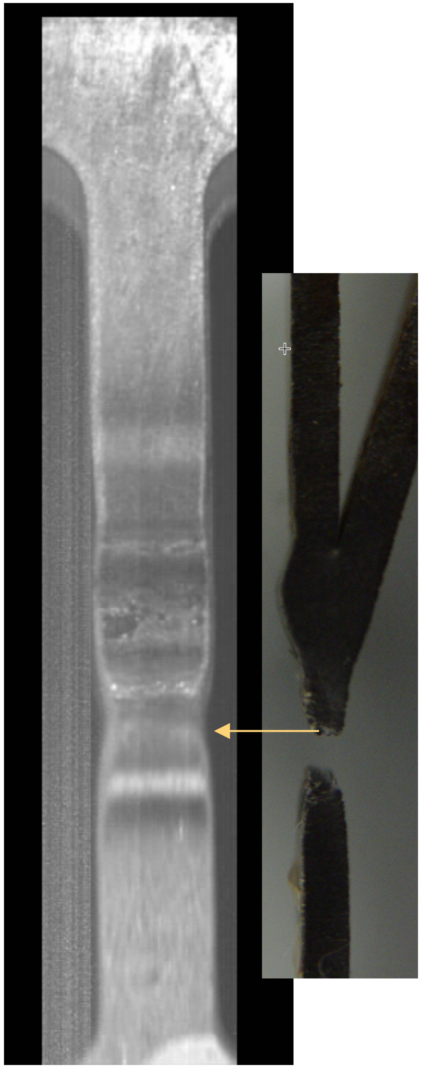
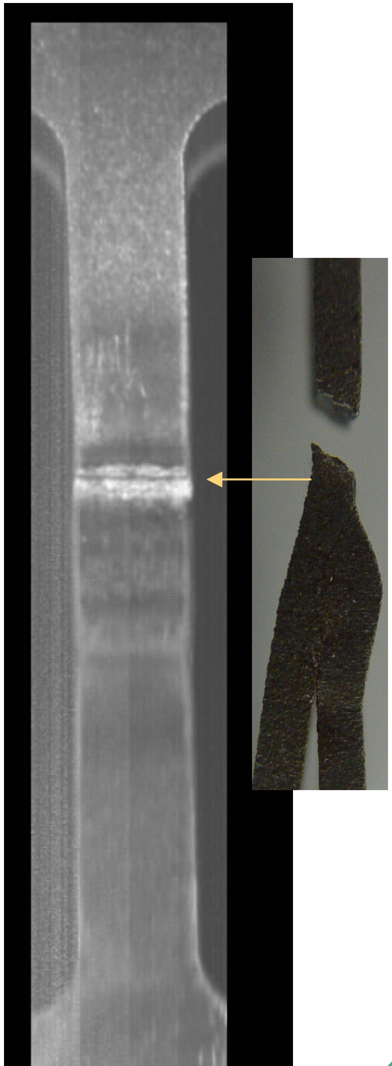
HAZ Softening Influences Impact Behavior of AHSS Weld (5 to 25 mph)



DR210

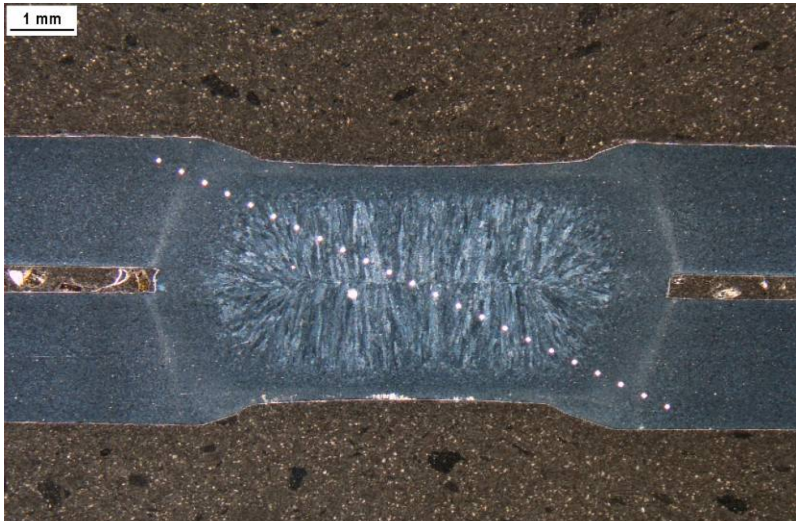


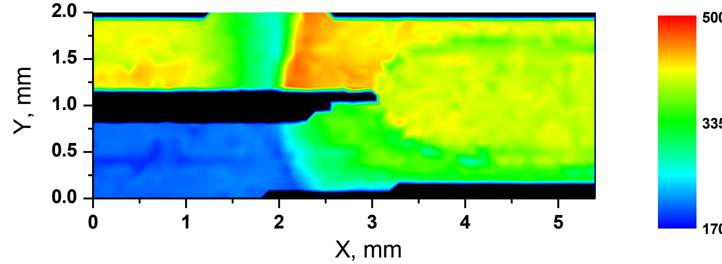
DP780

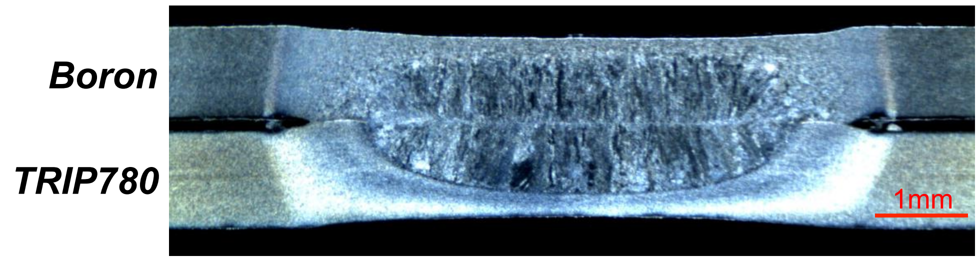


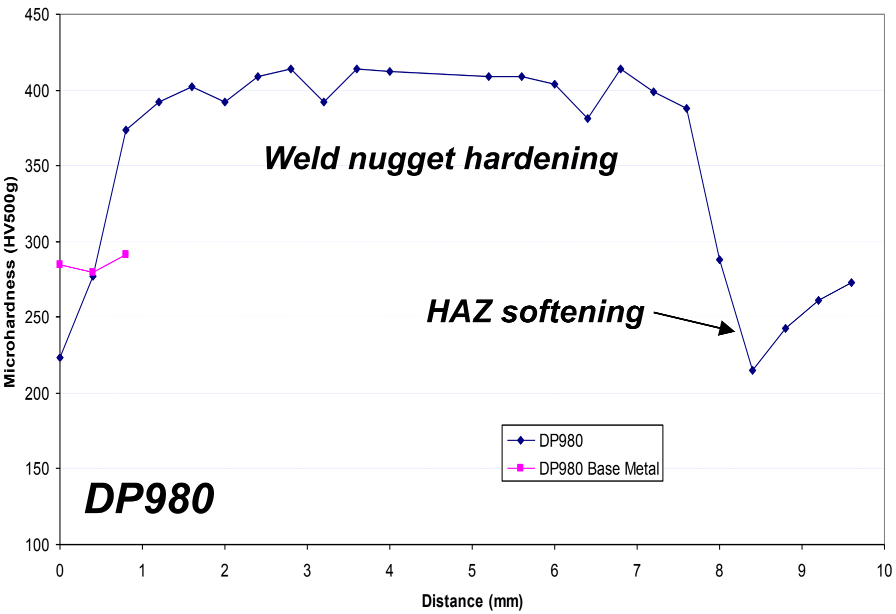
Boron Steel

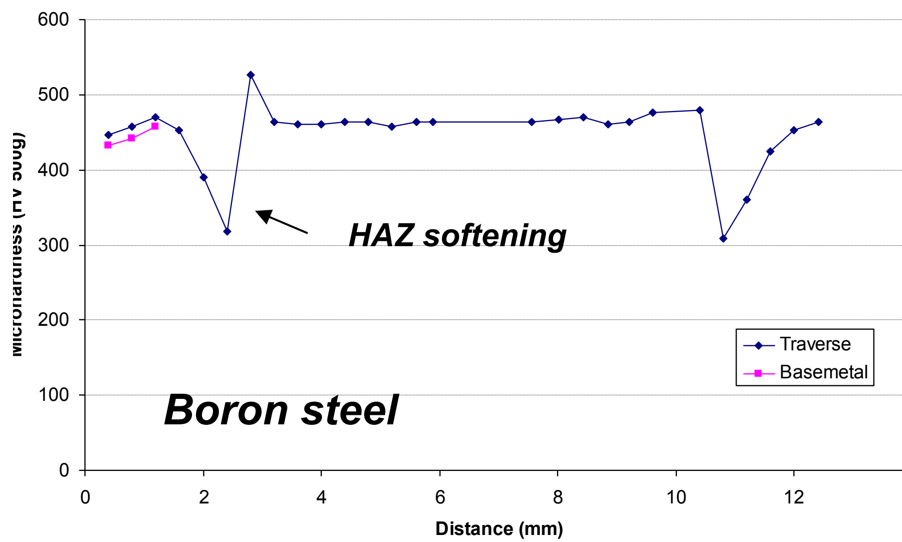
HAZ Softening in Resistance Spot Weld of AHSS



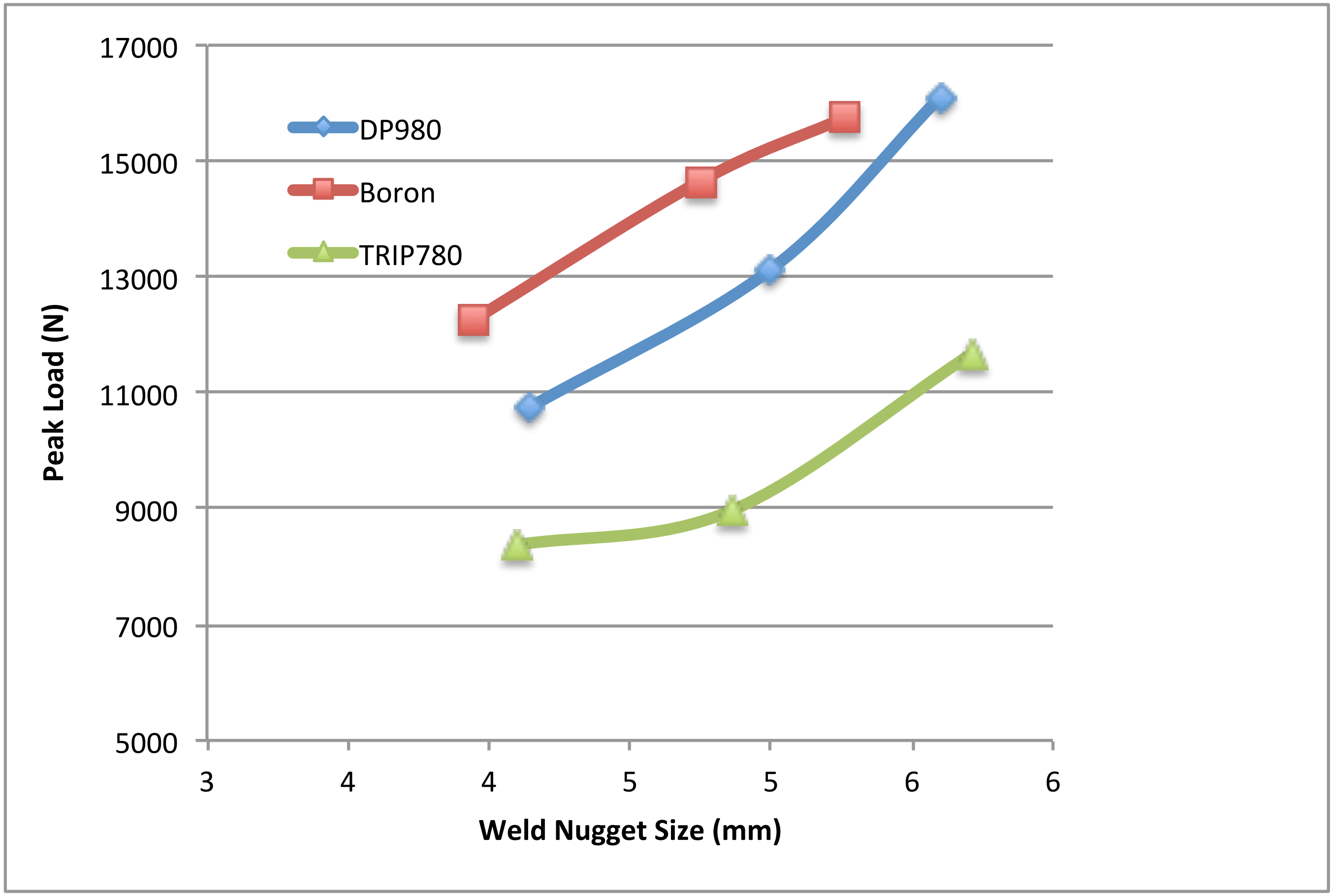






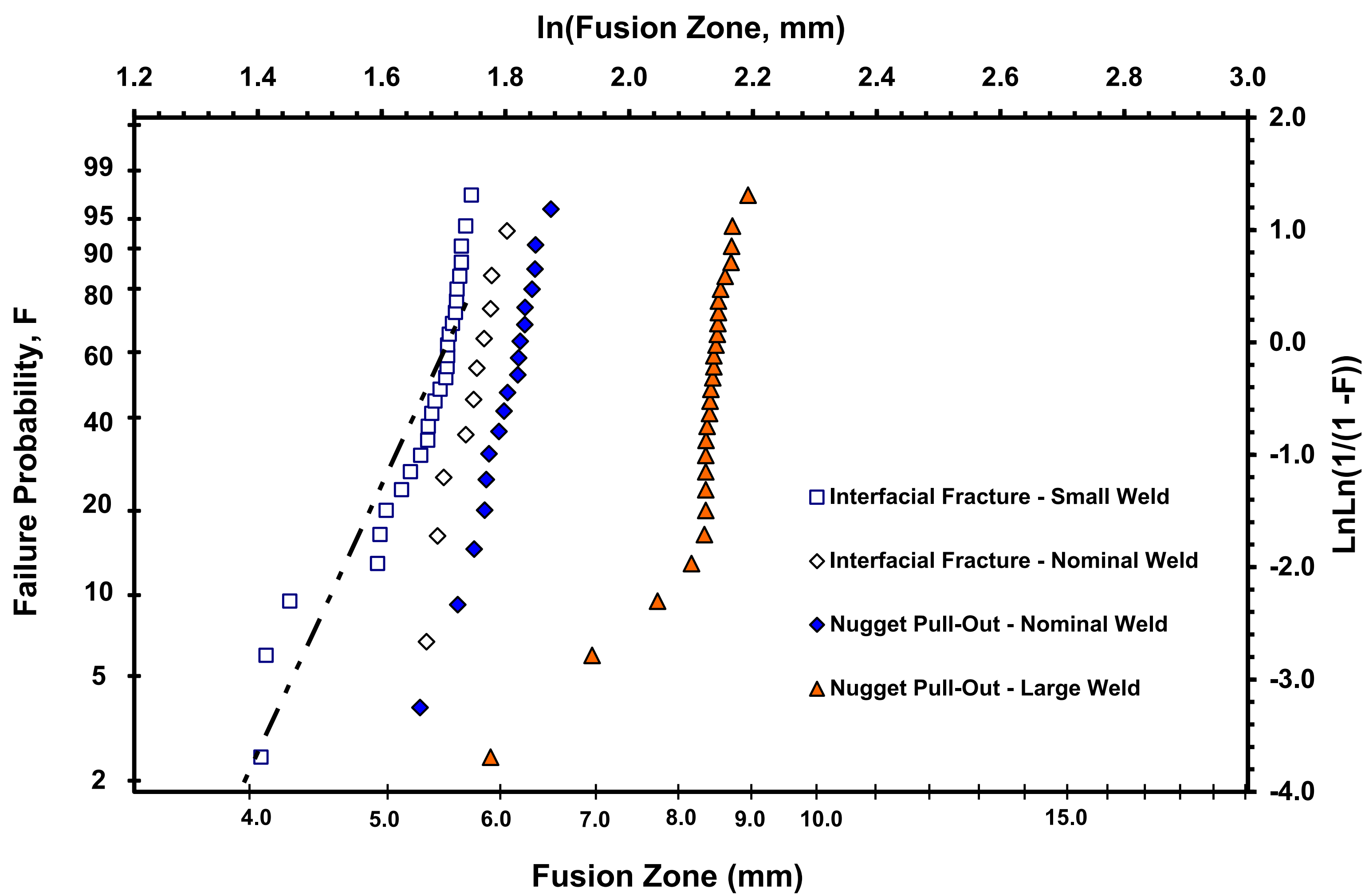


Effect of Weld Nugget Size on Joint Strength



Lap shear, 1-mm nominal thickness

Failure Mode as Function of Fusion Zone Size - DP800 Cross Tension



Resistance Spot Welds

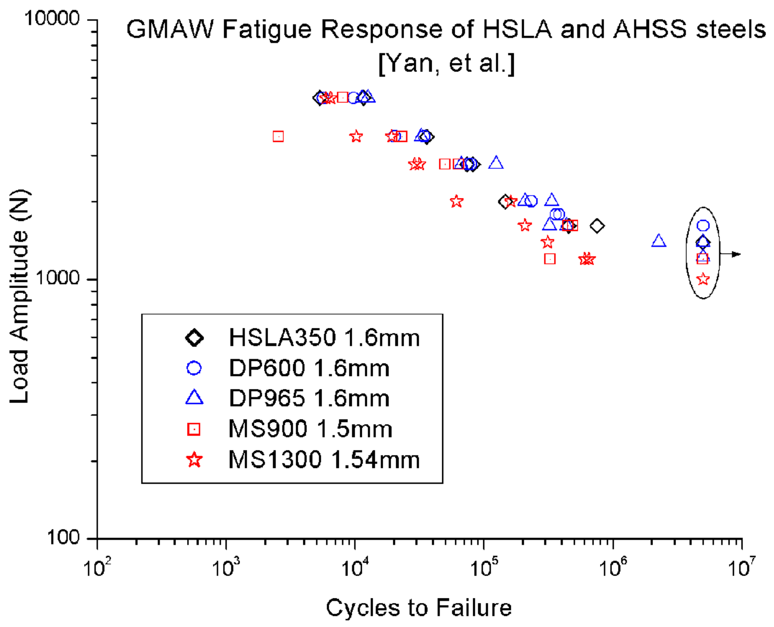
- Failure mode changes from interfacial to button pull-out as the weld nugget reaches a critical size
- Static strength and energy absorption of a spot weld strongly depends on the nugget size

Fatigue of AHSS Welds

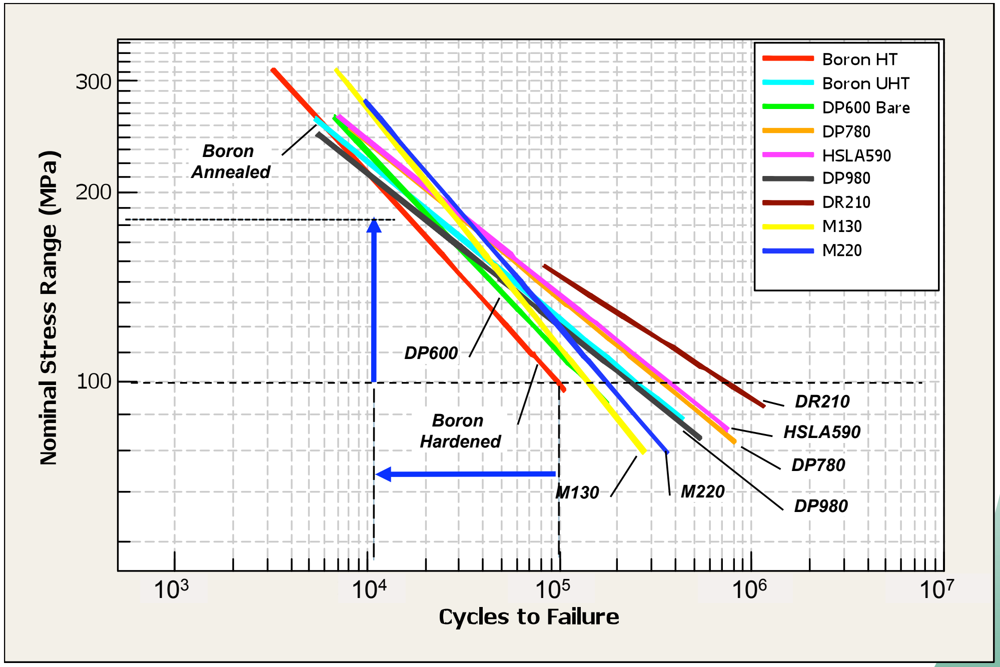
- Recent studies by A/SP, DOE Lightweight Materials Program and others have shown that, unlike the base metal case, welds of AHSS do not exhibit appreciable increase in fatigue strength (i.e. weld fatigue strength is insensitive to the steel type and grades of current AHSS).
- Down-gaging of AHSS for light-weighing would result in increase in applied stresses in the weld region, and potentially shorten the fatigue life and durability of body structures.
- Fatigue performance of welded joints is a critical element in durability because the likeliest fatigue failure location are often at welds
- Therefore, the use of AHSS for light-weighing must be accomplished by approaches to improve the fatigue performance of the weld joint (John Bonnen and R.M. Iyengar, 2006, Int. Auto. Body Congress).

Fatigue strength of AHSS weld is insensitive to steel types and grades

- GMAW fillet welds are shown; spot welds are similar

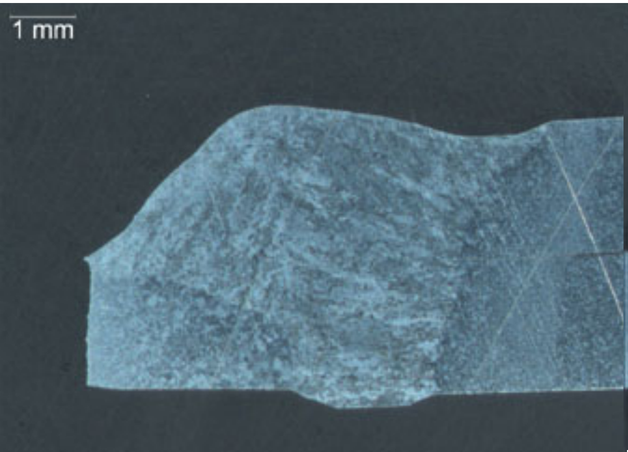


Yan et al (SAE 2005)

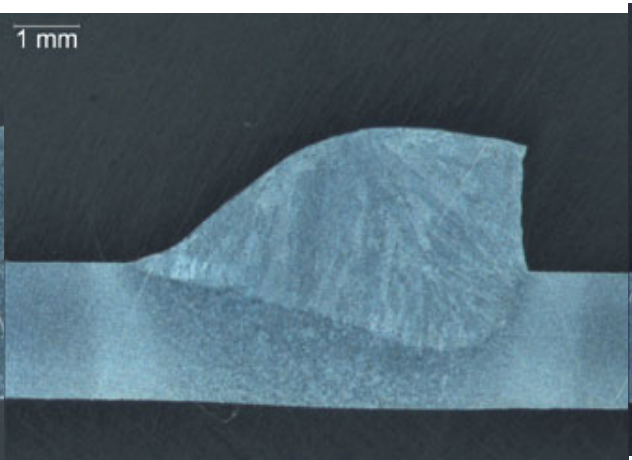


Feng et al (SAE 2009)

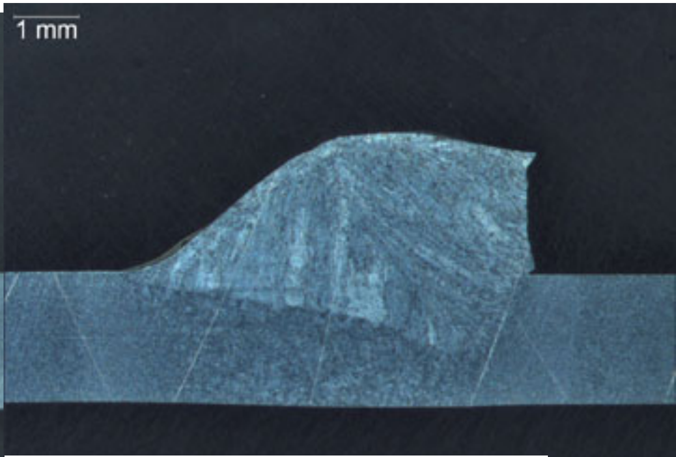
Fatigue Failure at Weld Root or Toe, Away from HAZ Softening Region



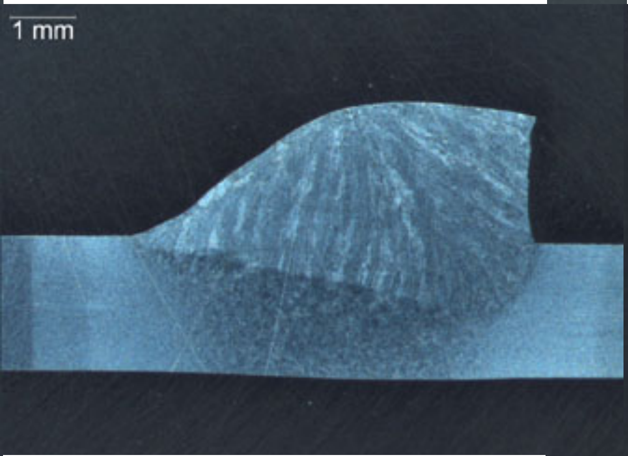
2.0 mm DR210 uncoated-fatigue tested, 1,164,447 cycles at 1200/120 lbs



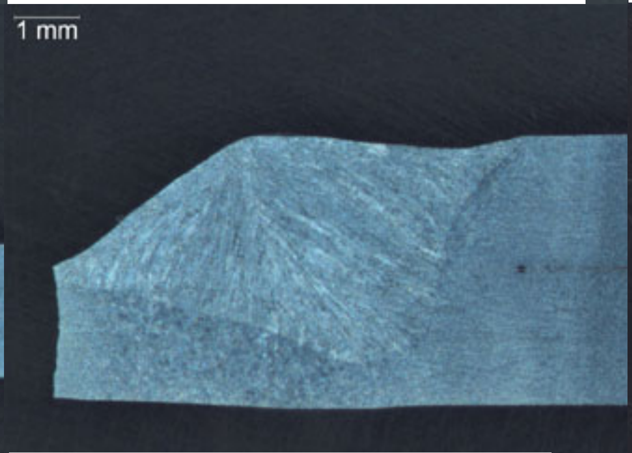
2.0 mm HSLA590 uncoated-fatigue tested, 749,637 cycles at 1200/120 lbs



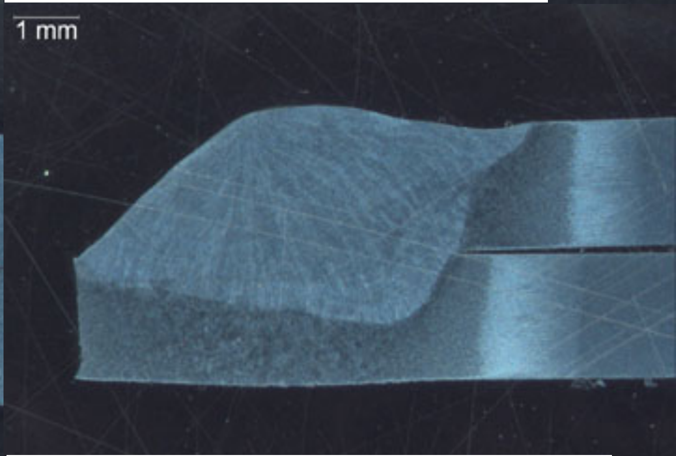
2.0 mm DP600 uncoated-fatigue tested, 177,810 cycles at 1200/120 lbs



2.0 mm DP780 uncoated-fatigue tested, 819,203 cycles at 1200/120 lbs



2.0 mm DP980 uncoated-fatigue tested, 543,481 cycles at 1200/120 lbs

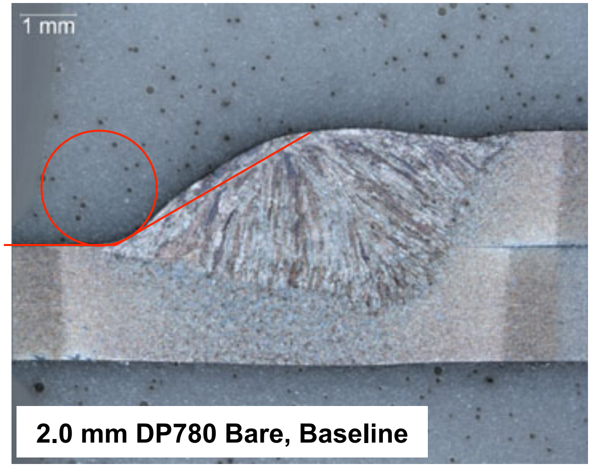


2.0 mm Boron heat treated uncoated-fatigue tested, 106,413 cycles at 1200/120 lbs

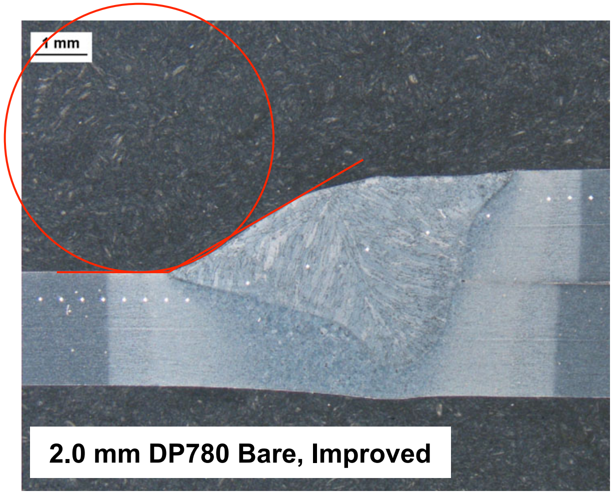
Factors Governing Weld Fatigue Strength

- Stress concentration due to weld geometry and weld surface quality/discontinuity
  - SCF = 6-9 from FEM analysis for lap joint under tensile loading
- High tensile residual stresses at the weld toe and other critical locations
- Weld microstructure change (limited knowledge)
  - HAZ softening has minimal influence

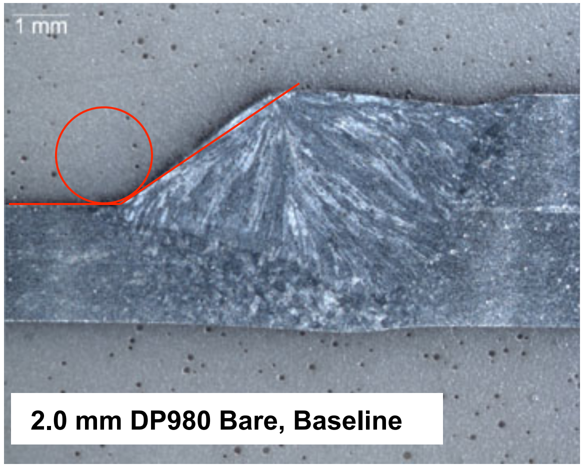
Improve Weld Profile to Reduce Stress Concentration



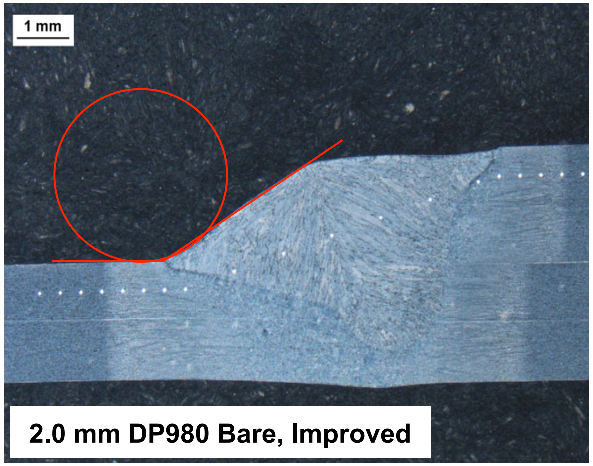
2.0 mm DP780 Bare, Baseline



2.0 mm DP780 Bare, Improved

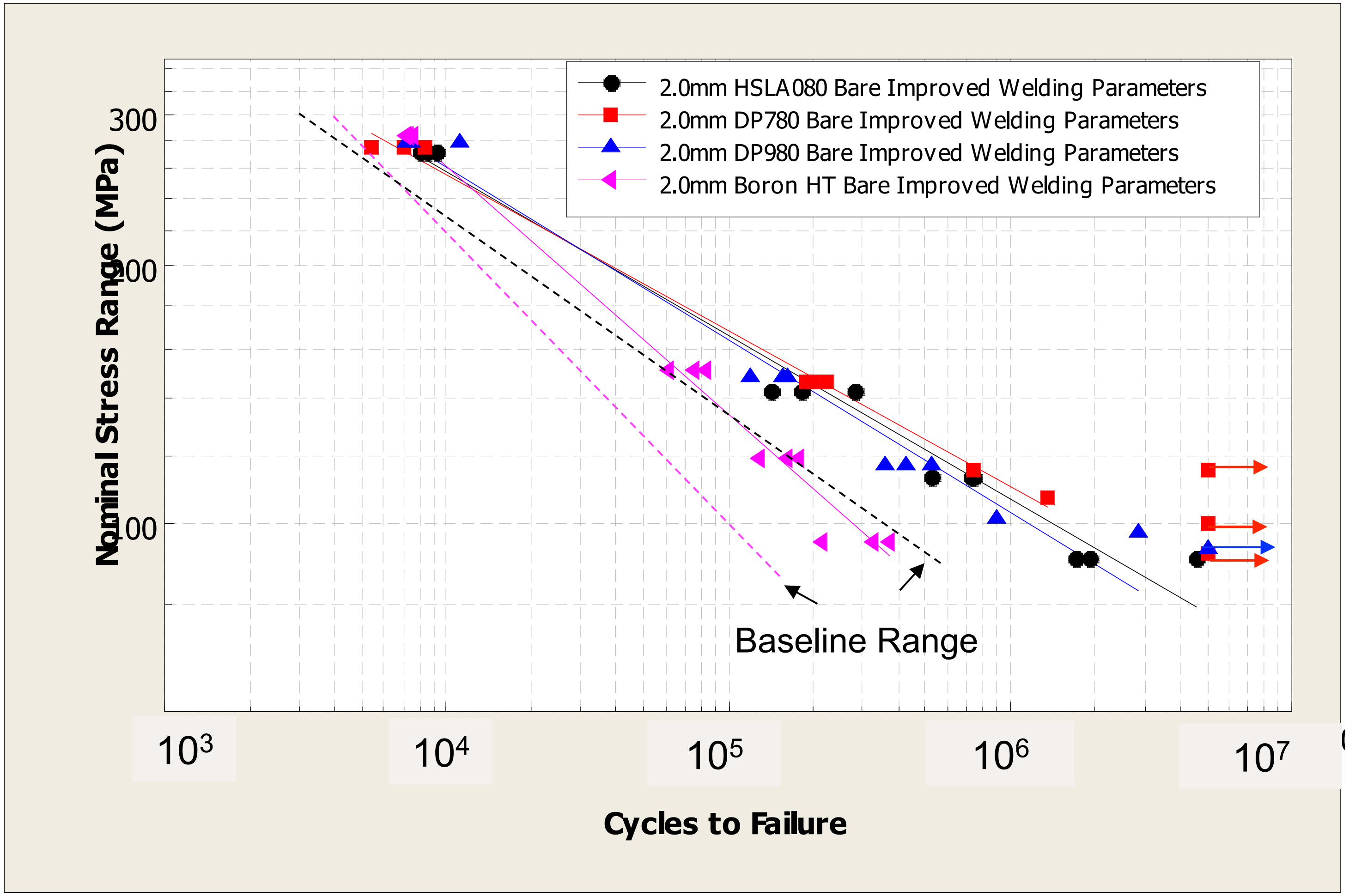


2.0 mm DP980 Bare, Baseline



2.0 mm DP980 Bare, Improved

Fatigue Life Comparison

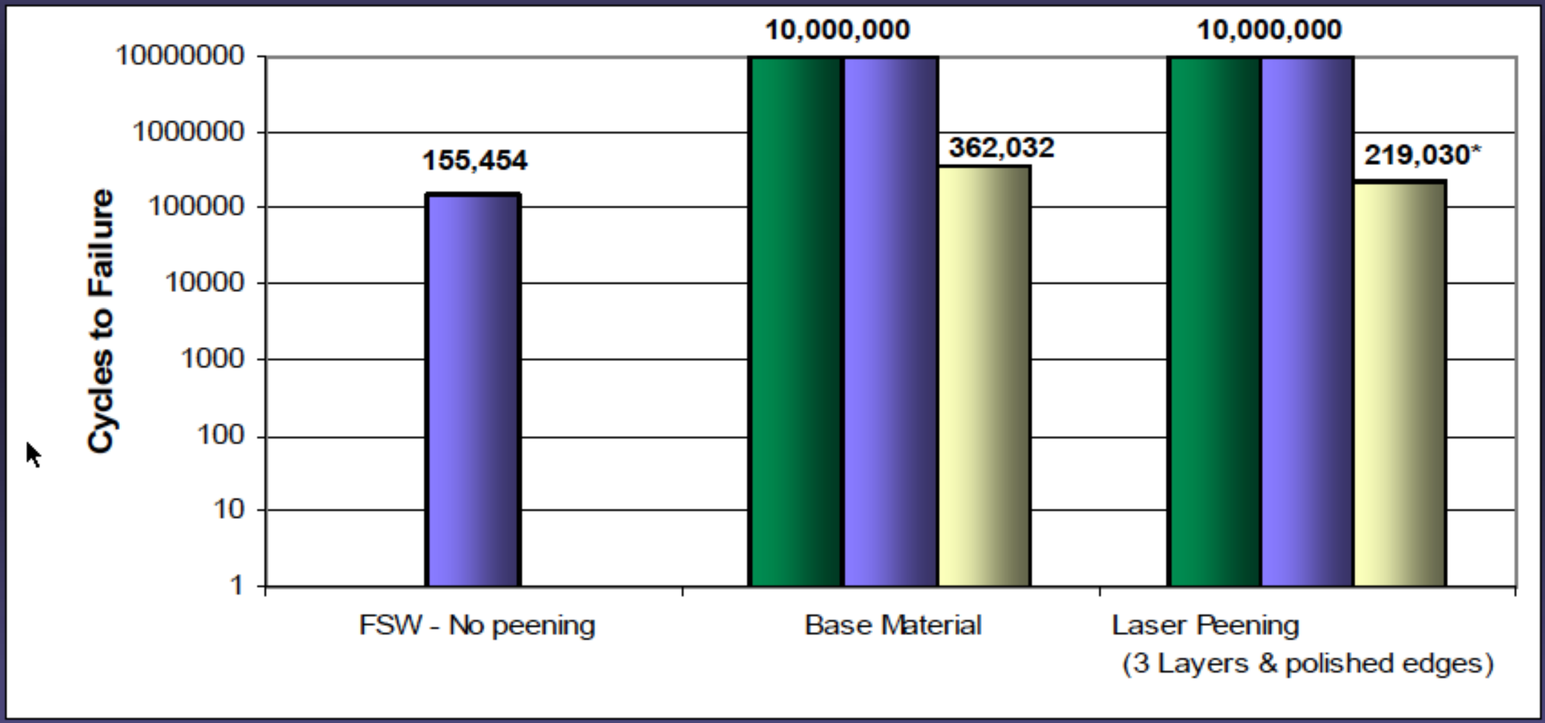


Improve Weld Fatigue Life through Surface Residual Stress Control

- Post-weld surface residual stress modification
  - Principle: by means of surface plastic deformation
  - Laser shot peening, Sand blasting/peening, Low plasticity burnishing
- In-process residual stress control
  - Principle: control and alter the "normal" thermal expansion/contraction sequence of welding
    - In-process proactive thermomechanical management
    - Special weld filler metal by means of low-temperature phase transformation
- Others
  - Post-weld heat treatment
  - Mechanical stretching

Fatigue Life Improvement by Surface Residual Stress Modification

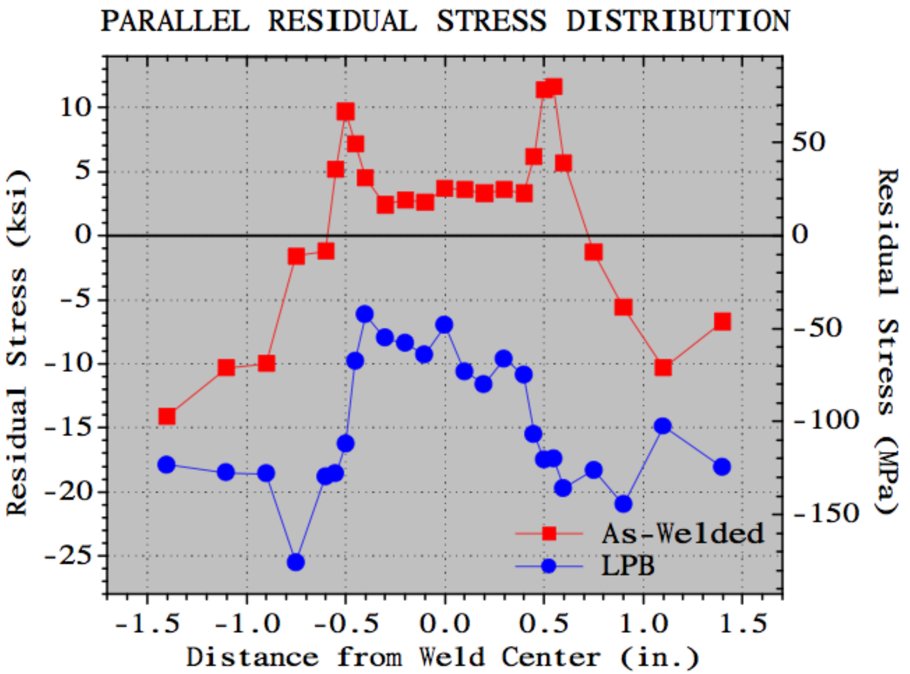
- Example: Laser shock peening of friction stir weld of Al7075 for aerospace applications (NASA, Hatamleh, et al 2006)

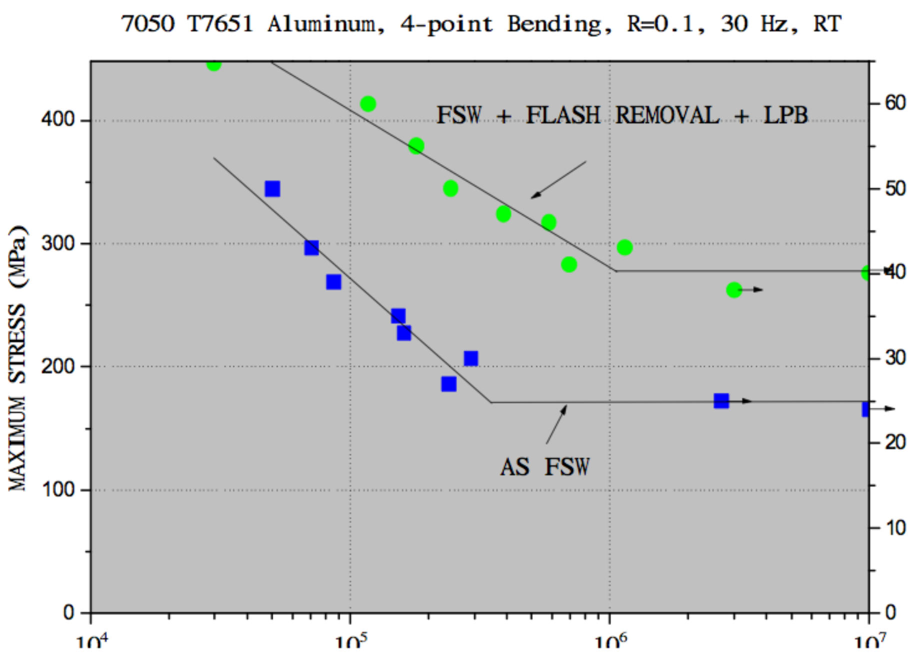


* Broke in the parent material away from the weld and peening zone

Benefit of Compressive Surface Residual Stress

- Low Plasticity Burnishing (Hornbach et al)





Work in Japan Demonstrating the Effectiveness of LTPT on fatigue life)
(Ohta et al, Welding in the World, 2000)

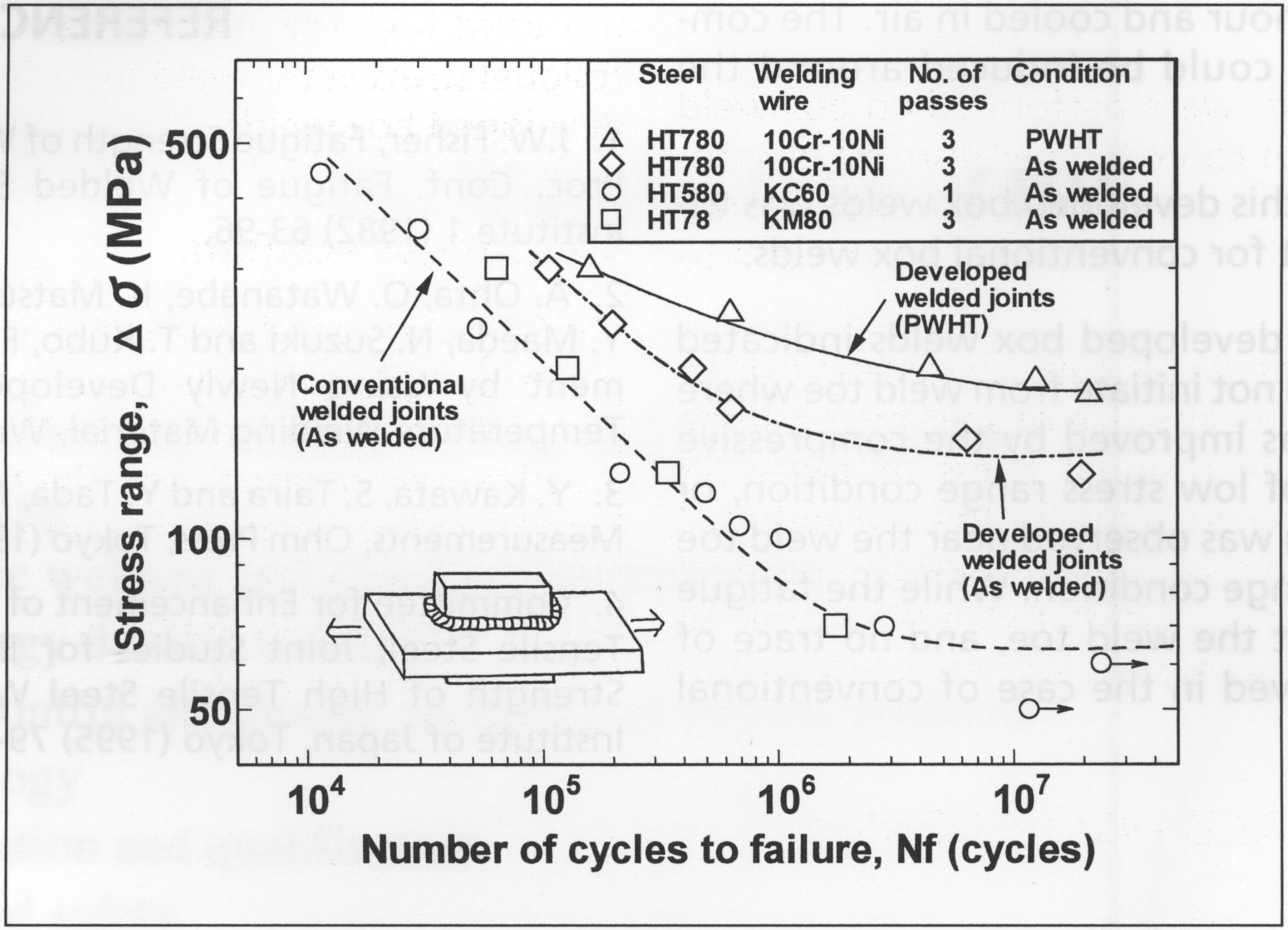
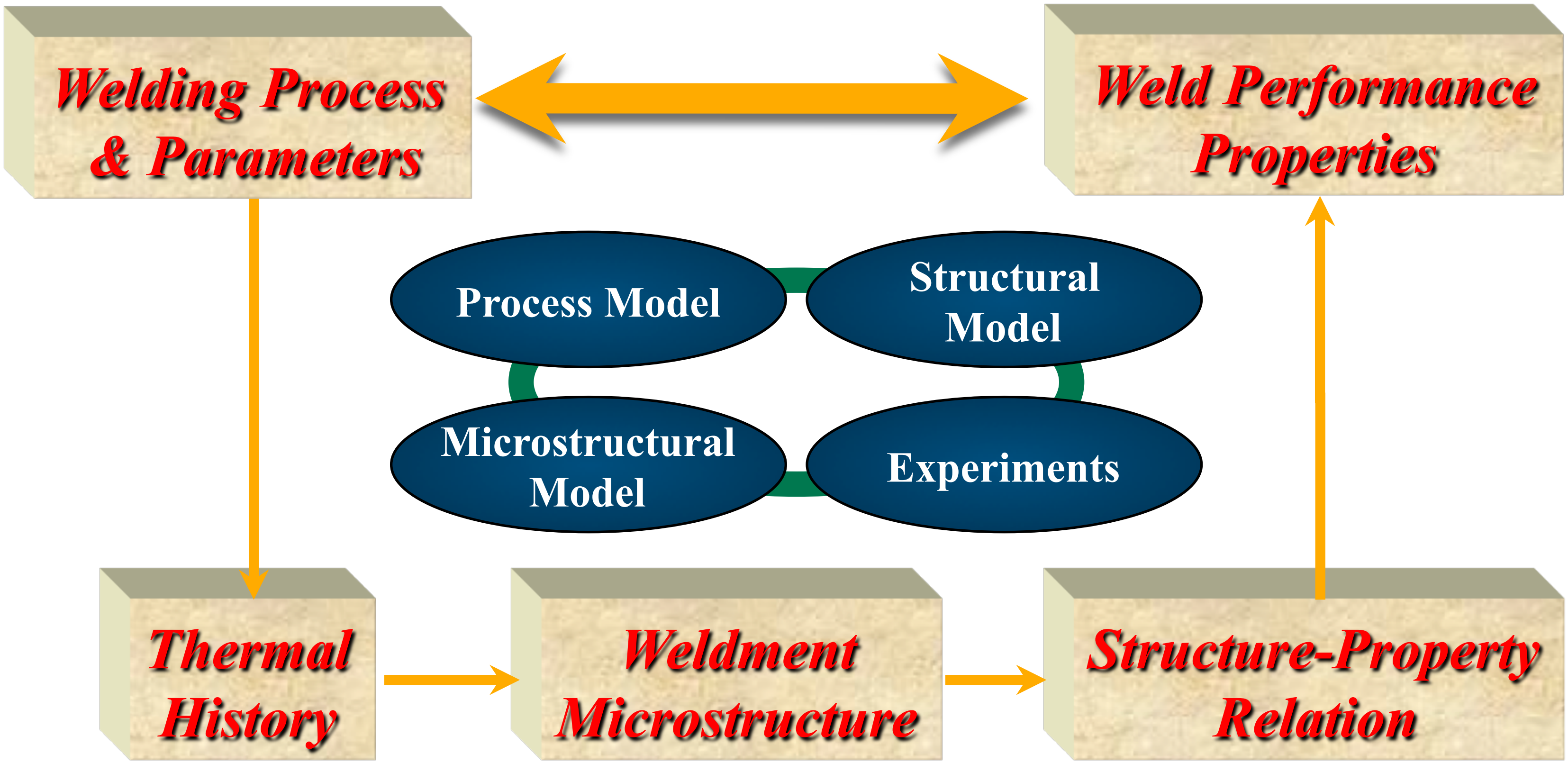


Fig. 6. S-N diagram of box welded joints.

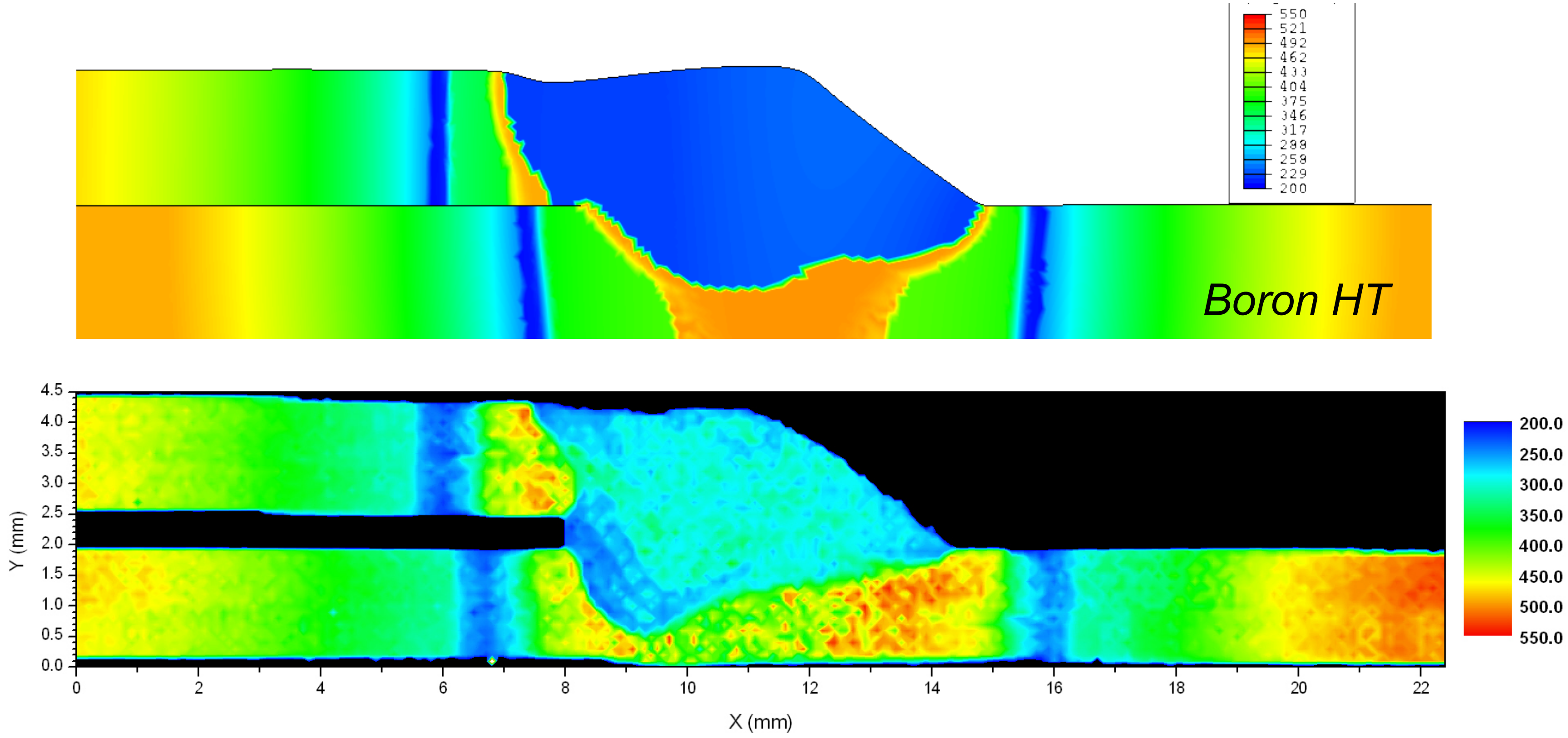
Integrated Model to Predict Welding Effects on AHSS Microstructure & Performance



- Choose appropriate individual models for each physical process, and integrate them
- Generally adopted for many welding processes
- Many individual models are already available

Integrated thermal-metallurgical-mechanical modeling of AHSS welds

- Capable of predicting HAZ softening and other microstructural changes



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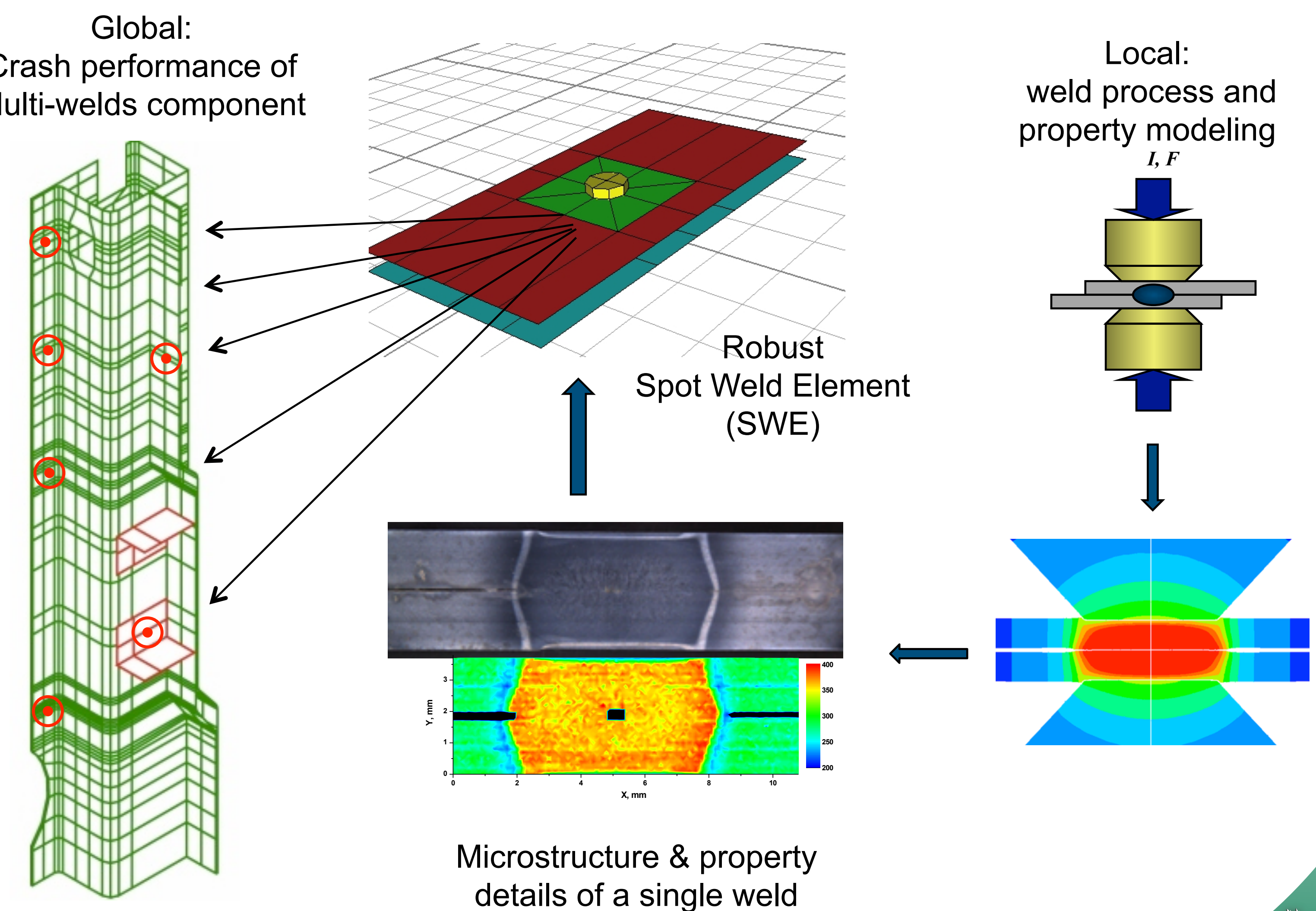
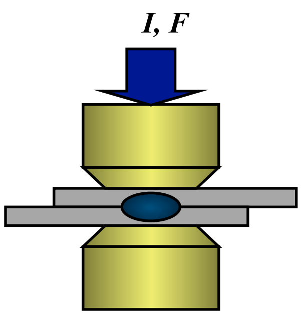
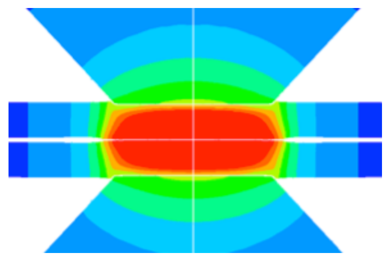
Resistance Spot Welding: Process to Crash Performance

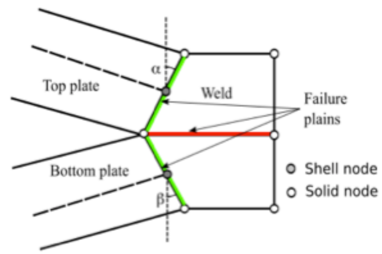


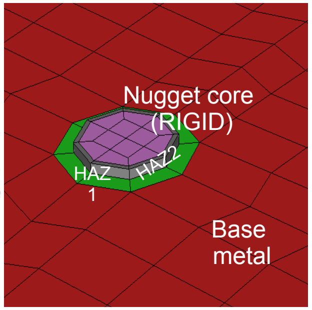
Resistance Spot Welding: Process to Crash Performance

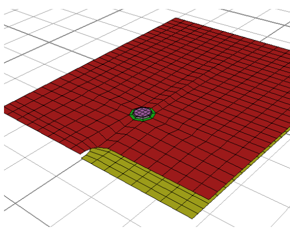
- *Incrementally coupled electric-thermal-mechanical-metallurgical model to predict weld microstructure and properties as function of steel chemistry and welding conditions.*
- *Special spot weld element formulation incorporating effect of weld properties and weld geometry allowing for robust crash simulations of welded structures*

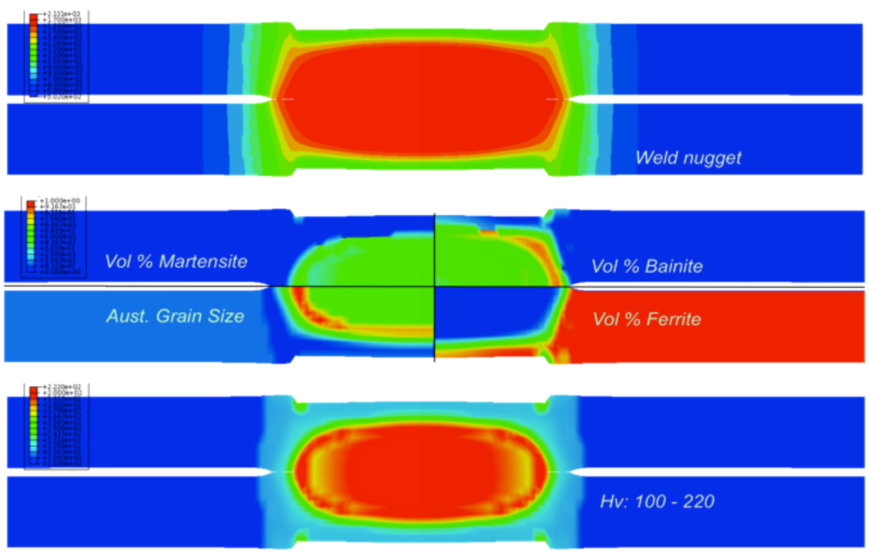


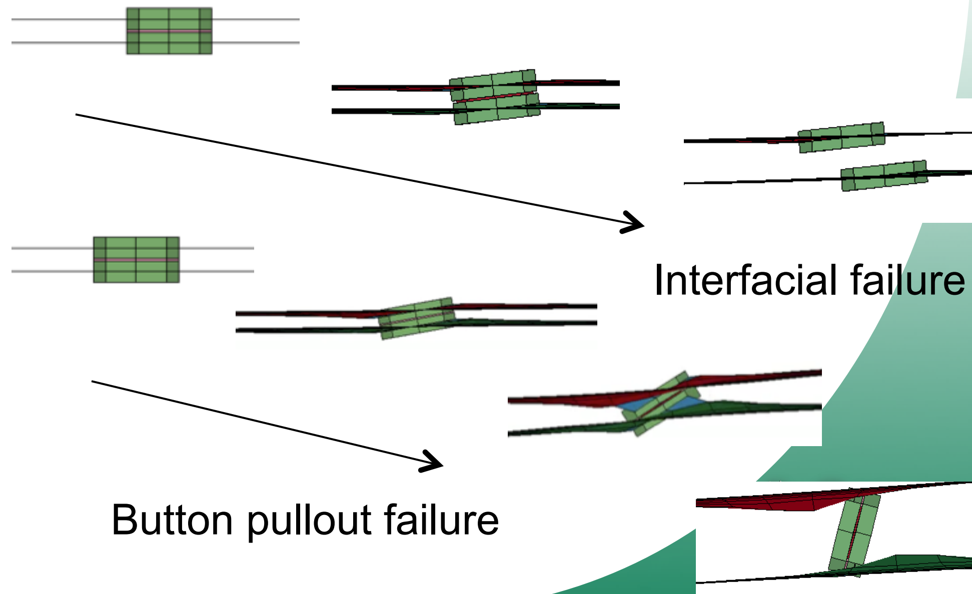






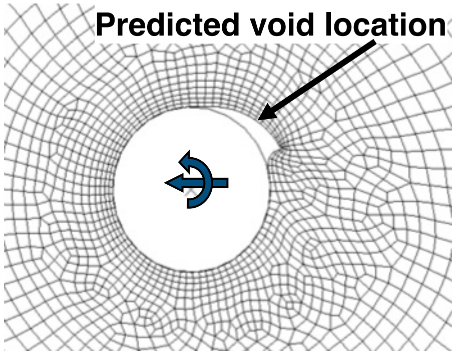


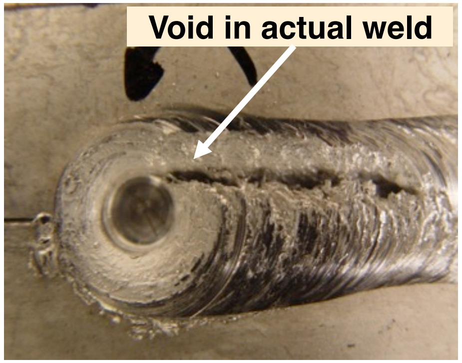




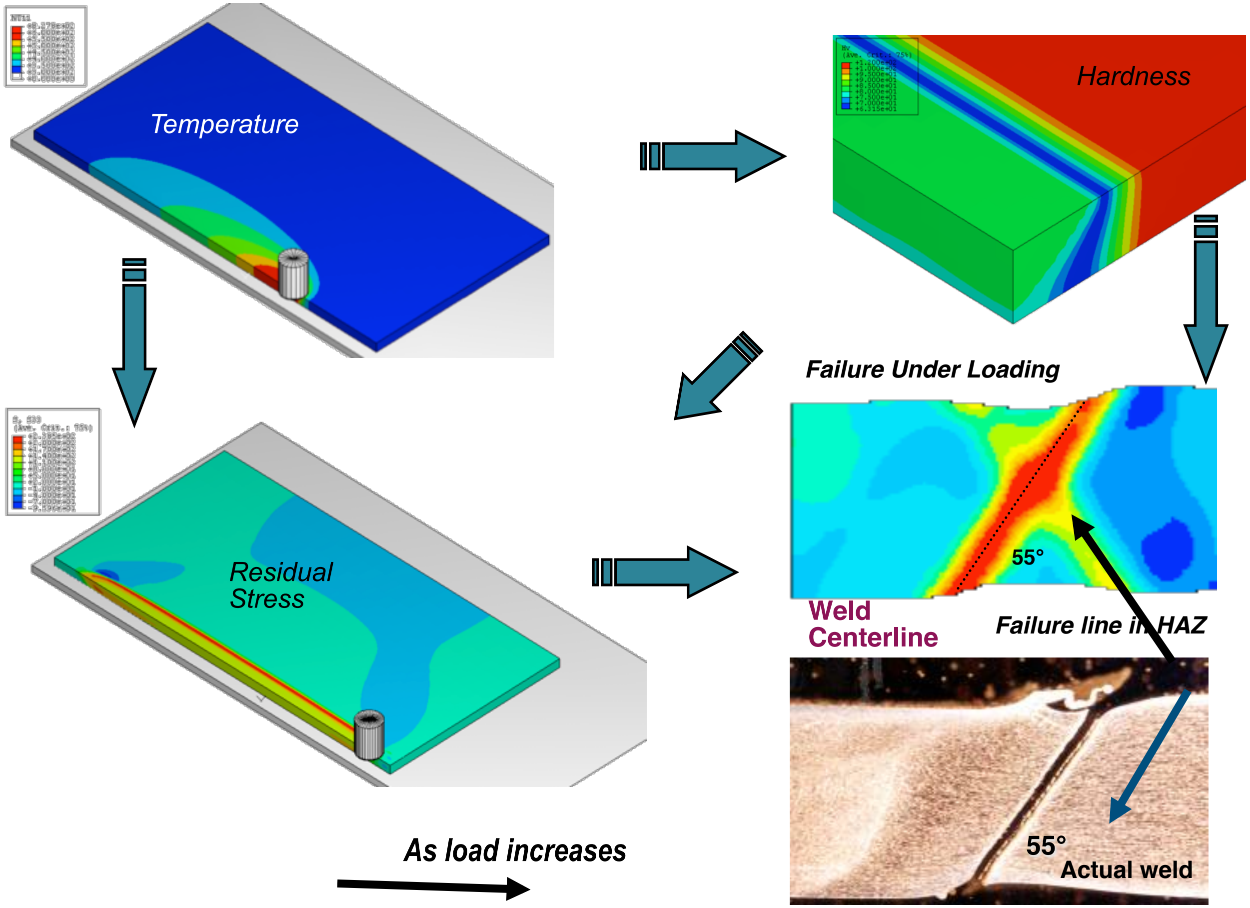
Integrated Model for FSW of Al Alloys

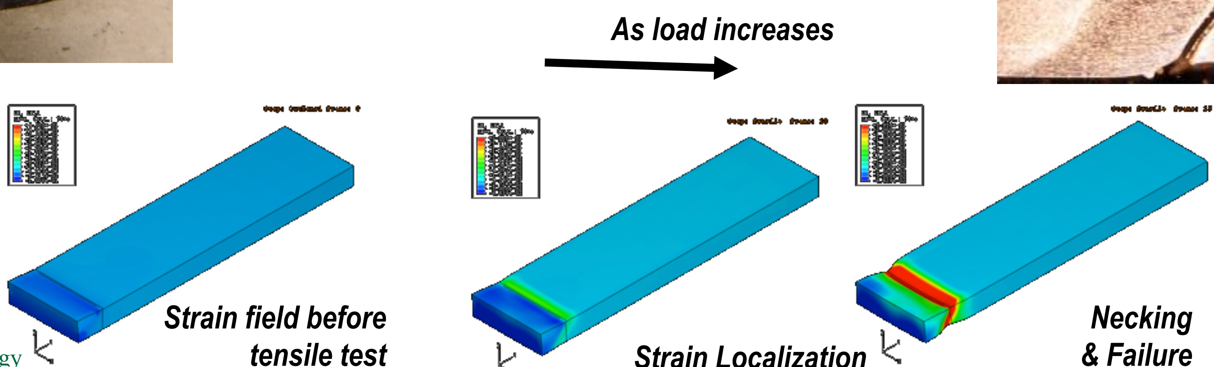
Arbitrary Lagrangian-Eulerian (ALE) finite element mode predicts weld defect formation under conditions.





Integrated multi-physics simulations provide realistic prediction of failure and insights to the performance of Al 6061 friction stir welds





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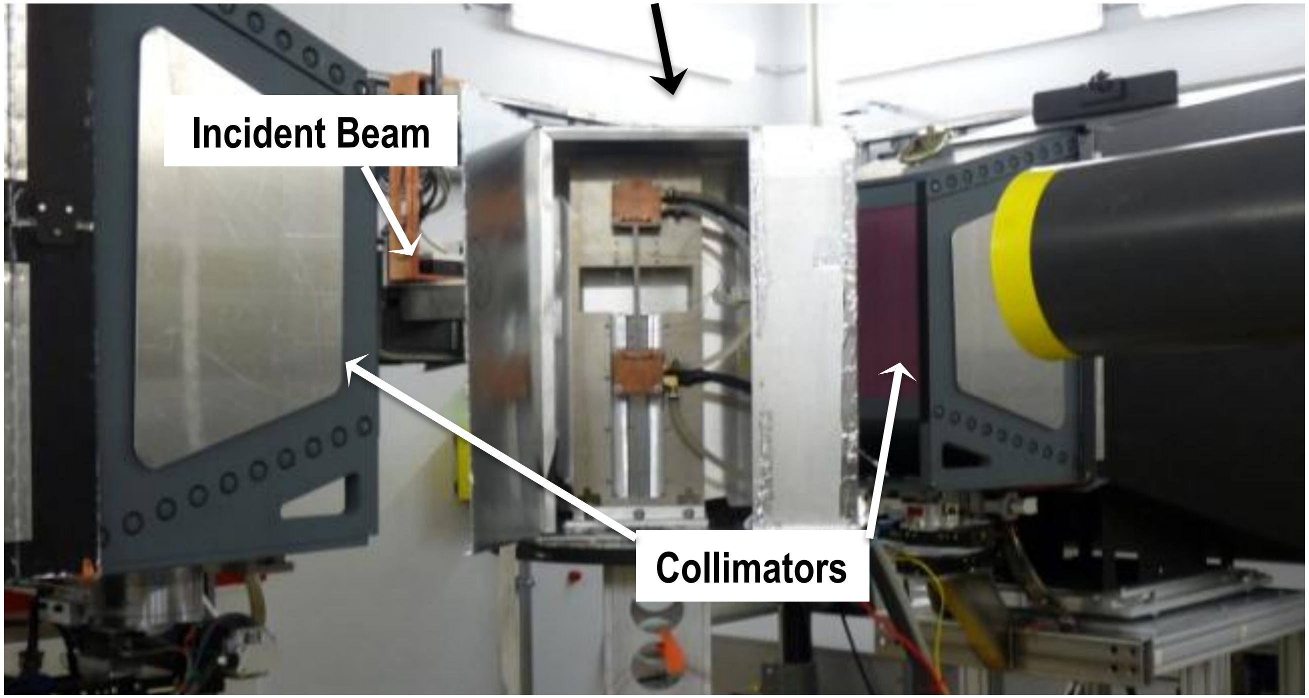
Weld modeling

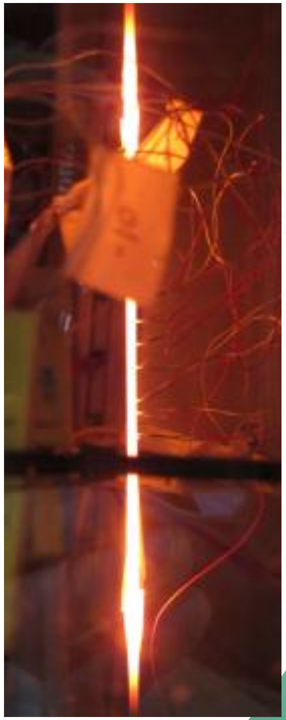
- Considerable progress in developing integrated weld process and performance modeling in the past decades or so
- Some remaining issues
  - More fundamental understanding and accurate prediction of non-equilibrium phase transformation processes during welding
  - More accurate failure/fracture prediction under complex microstructure gradient in the weld region

In-Situ Neutron Experiment Study of Non-Equilibrium Steel Phase Transformation Relevant to Welding

Programmable thermo-mechanical device



Heated Sample

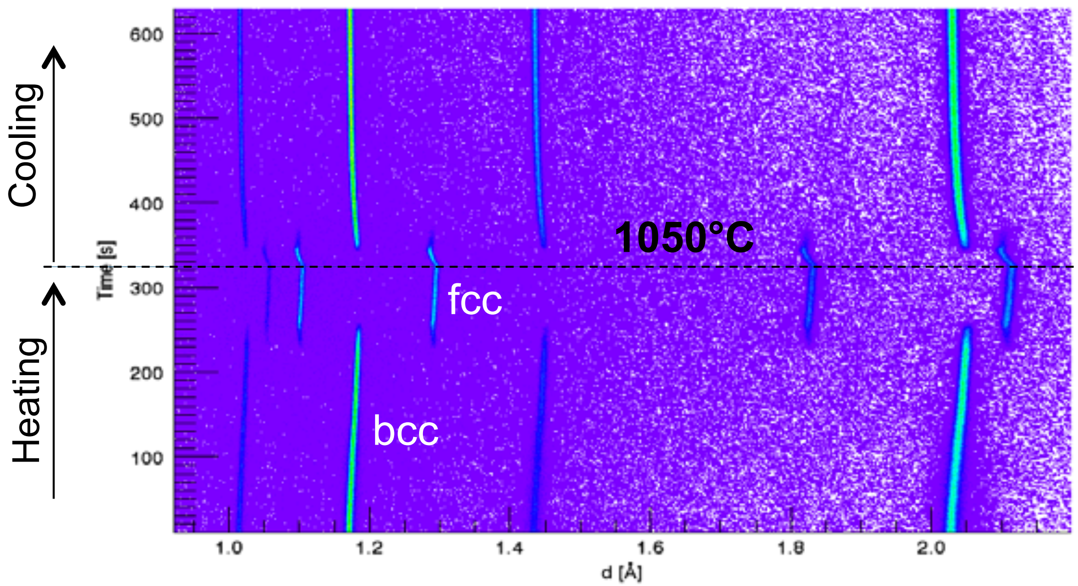


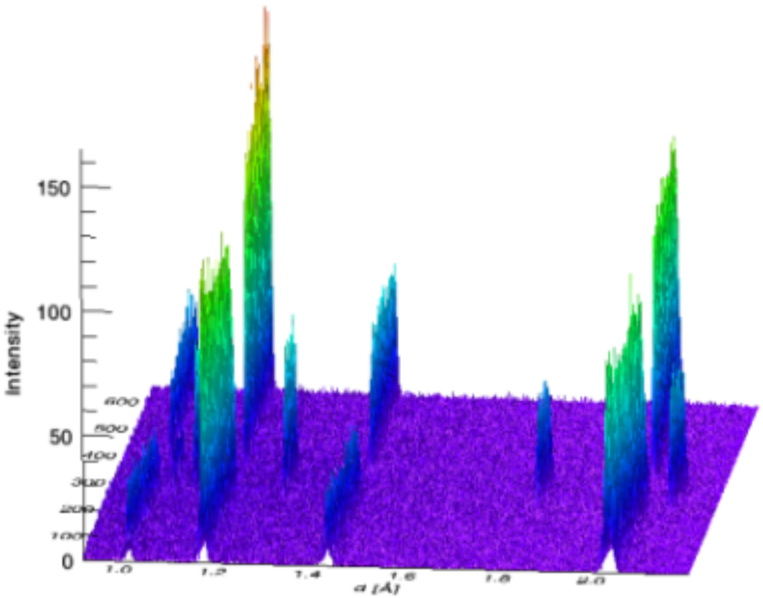
Fast resistive heating of high strength steel in a controlled atmosphere box at SNS VULCAN

DP980 Complete heating and cooling cycle

Significant Achievement: Direct measurement with 1 sec time resolution (@ 3C/s). A first for such type of in-situ neutron experiment.

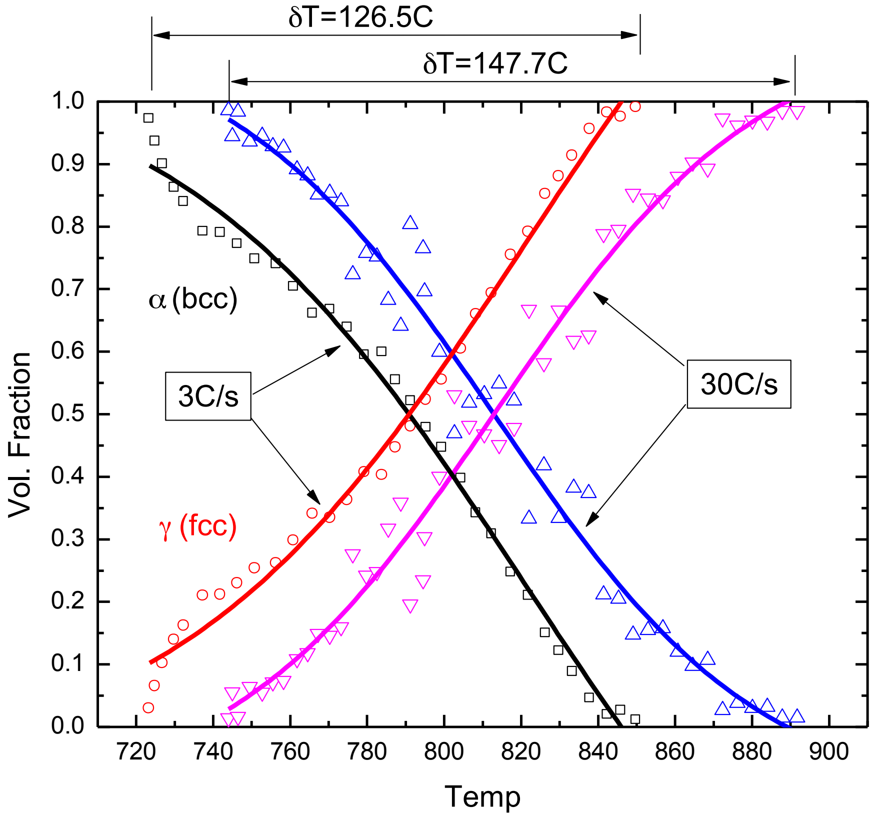
Sample was heated up to 1050°C at 3°C/s, and then cooled down in argon gas atmosphere to room temperature.





No retained austenite (fcc) after heating.

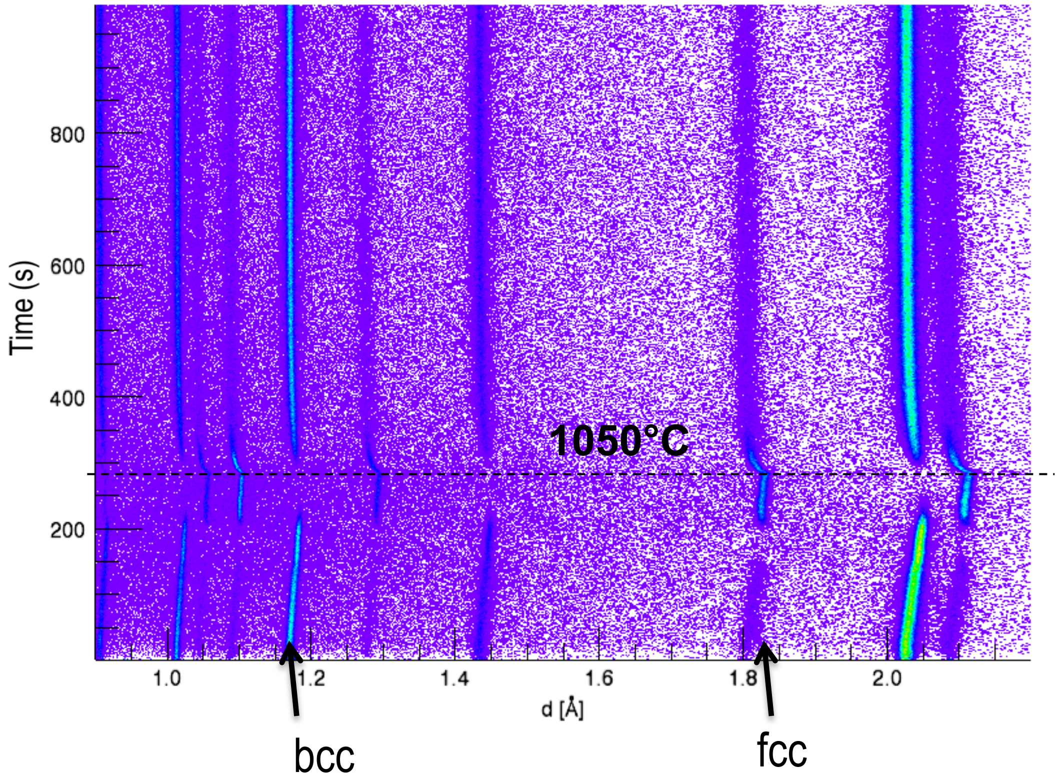
Effect of Heating Rate on Phase Transformation in DP980

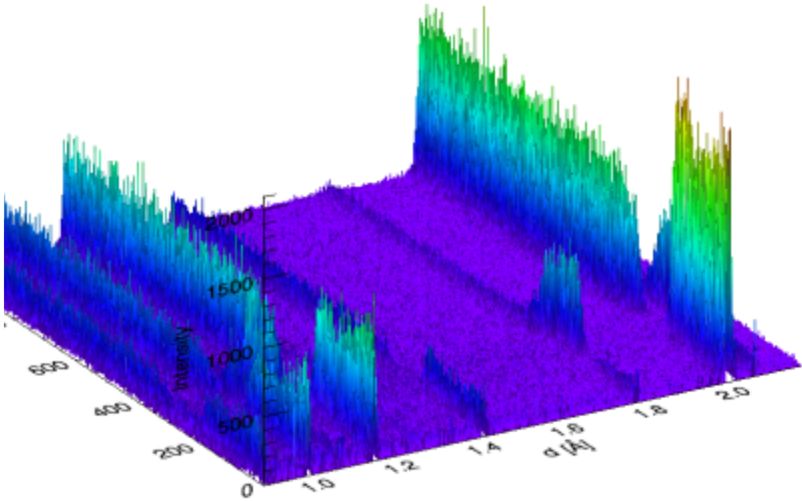


Two-step phase transformation at 3°C/s.

Q&P Steel (3C/s heating, complete thermal cycle)

Observation of *Retained Austenite after heating cycle*





Joining AHSS with Other Materials

	FBJ	SPR	FSSW	Ultrasonic
Material Combination				
Steel to Al	yes	yes	coated steel	coated steel
Steel to Mg	yes	difficult	TBD	TBD
Steel Grade	All AHSS	up to DP780	All AHSS	All AHSS
Material Stacks	2T, 3T	2T, 3T	2T	2T
Surface Requirement	no restriction	no restriction	Zn coating	Zn coating
Bonding Mechanism	Metallurgical + Mechnical	Mechanical	Brazing or Metallurgical + Mechanical	Brazing, or metallurgical
Lap shear strength (N)				
Steel to Al	6300 - 8100	5000 - 5500	2500 - 3500	~3000
Steel to Mg	~5400	cracking	TBD	TBD
Z load (N)	~ 9000	20,000 or higher	TBD	Low
Process Time (sec)	1.5 - 2	< 1	<4	~2
Weld bonding	Feasible	yes	Difficult	Difficult
Comsumable Bit	Yes	Yes		
Cost	SPR comparable	low		
Nonconsumerable Tool			Yes	Yes
Cost			Low (tool steel)	High (specialty alloy)
Machine cost	comparable	comparable	comparable	Potentially high (high power)

Summary: Joining of AHSS

- Challenges and Opportunities
  - Fundamental understanding and predictive capability to quantify the effects of welding and service loading on the structural performance of welded AHSS auto-body parts;
  - Design guidelines and weld performance data to assist rapid structure design and prototyping, CAE model for weld structure performance design;
  - Welding techniques and practices to improve structural performance of AHSS welded auto body components