Validate a Testing Protocol to Establish the Maximum Heat Input for Welding S-1 Series Carbon Steels with Toughness Requirements

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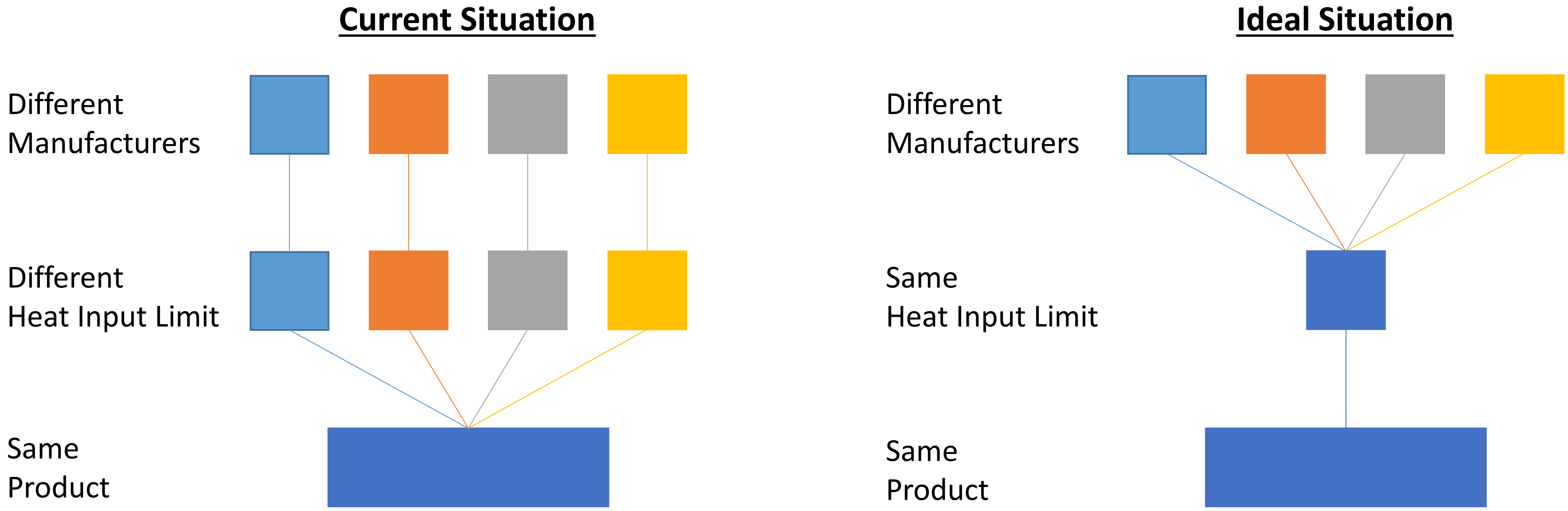
Problem Statement

- S-1 Series carbon steels with minimum toughness requirements are limited to maximum heat input used in qualification for Navy shipbuilding, *leading to excessive procedure qualifications, inconsistency between shipyards, and lower productivity.*



Solution/Approach

- *Develop a physical simulative test method that can be used to determine maximum heat input limits in S-1 Series grouped materials*

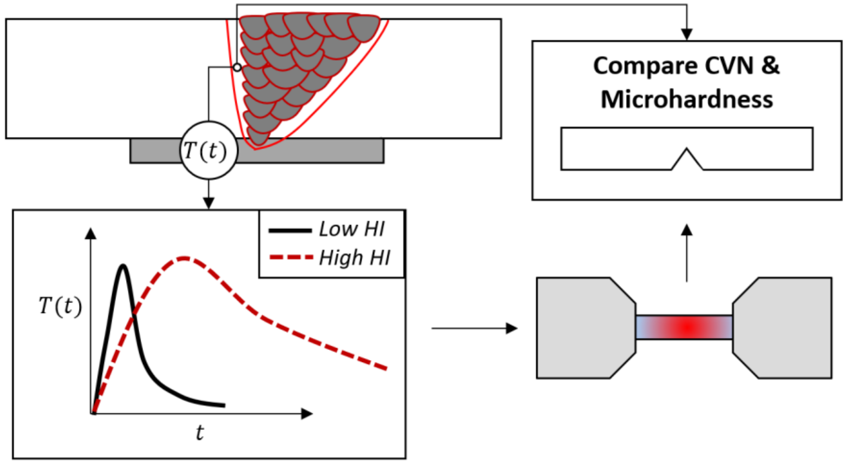
- **Task 1**: Build database of 8 welds: thin/thick plates (12.7, 50.8 mm); low/high heat input (~50 kJ/in , ~100 kJ/in) and bounding alloys (HSLA-65, DH-36). Measure heat affected zone (HAZ) toughness, microstructure, thermal cycle.

- **Task 2:** Develop physical simulation protocol for CVN test blanks that reproduces Task 1 toughness/HAZ thermal cycle relationships for both alloys.

Experiment Matrix

	Thin: 0.5”		Thick: 2.0”	
Low HI: 50 kJ/in	HSLA 65	DH-36	HSLA 65	DH-36
High HI: 100 kJ/in	HSLA 65	DH-36	HSLA 65	DH-36

Closed-Loop Validation



Result #1 – Production ½” plate welds completed (4 of 8)

- **Task 1**: Build database of 8 welds
  - Thin/thick plates (12.7, 50.8 mm); low/high heat input (~50 kJ/in , ~100 kJ/in) and bounding alloys (HSLA-65, DH-36).
  - Measure heat affected zone (HAZ) toughness, microstructure, thermal cycle.

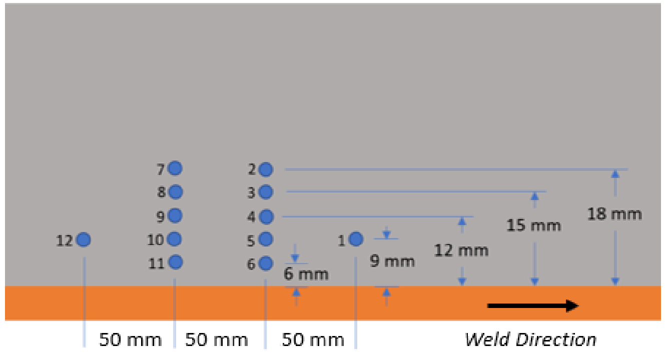
HAZ Thermal Cycles

Production TC Measurement Method (1/2")

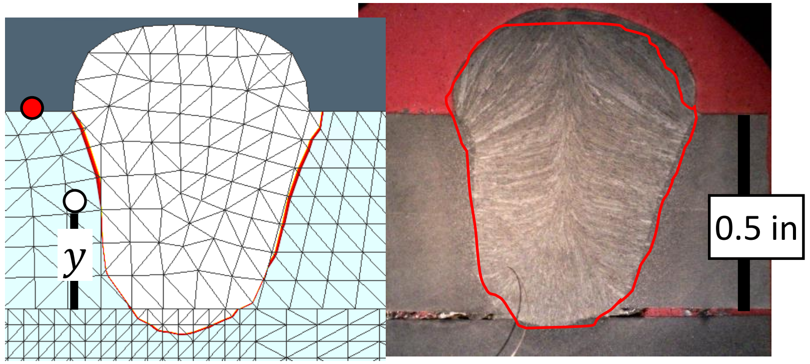
Prototype used TCs installed in HAZ side-wall. *No way to calibrate TCs and concerned about impact on heat flow*

Production welds: *Surface TC measurements and calibration of FEA heat flow model per AWS A9.5 [1].*

1. Weld with surface TCs [1]



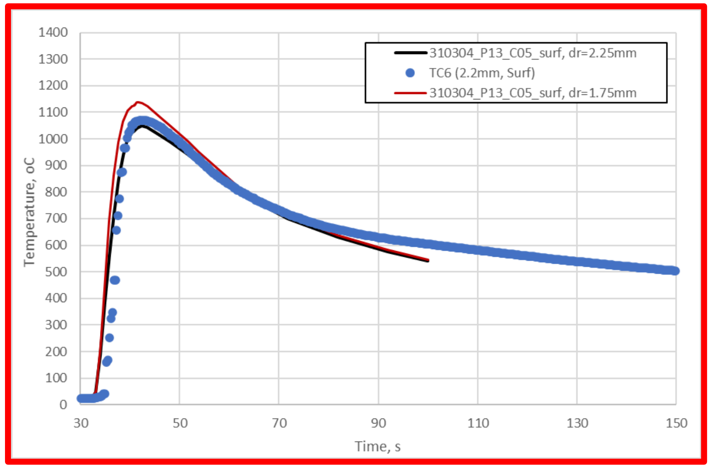
2. FEA Validation: FZ Macro, Surface Gradient/Transient Response



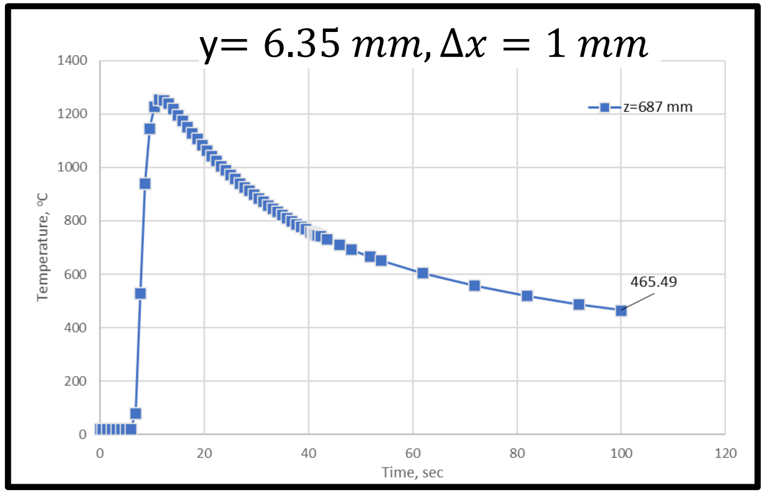
Prototype TC Measurement

Weld Cross Section w/ TC
(200714_NSRP_T_E9-16in_M-2.5_TC2.5)

Surface Calibration



Mid-plane Prediction

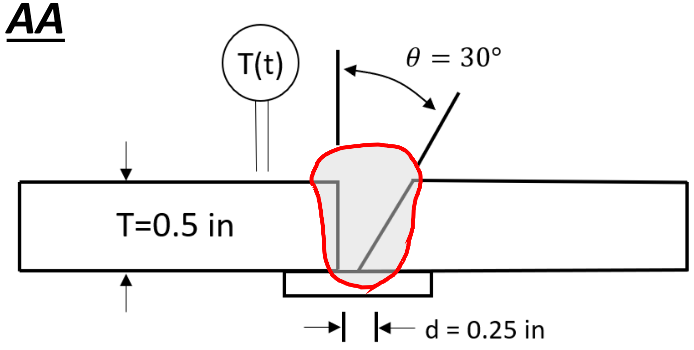


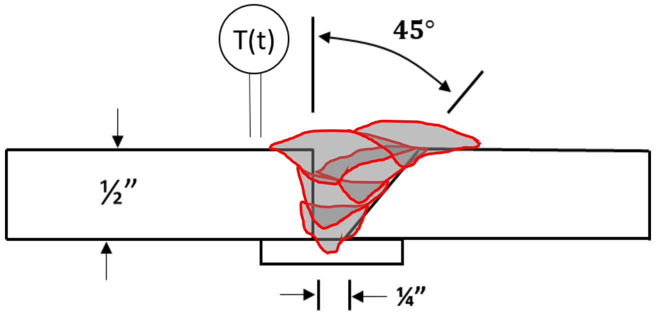
[1] "Guide for Verification and Validation in Computation Weld Mechanics," American Welding Society Standard A9.5, American Welding Society, Doral FL, 2013.

Weld Design: ½" Production Welds

Joint Design and weld procedure summary

AA



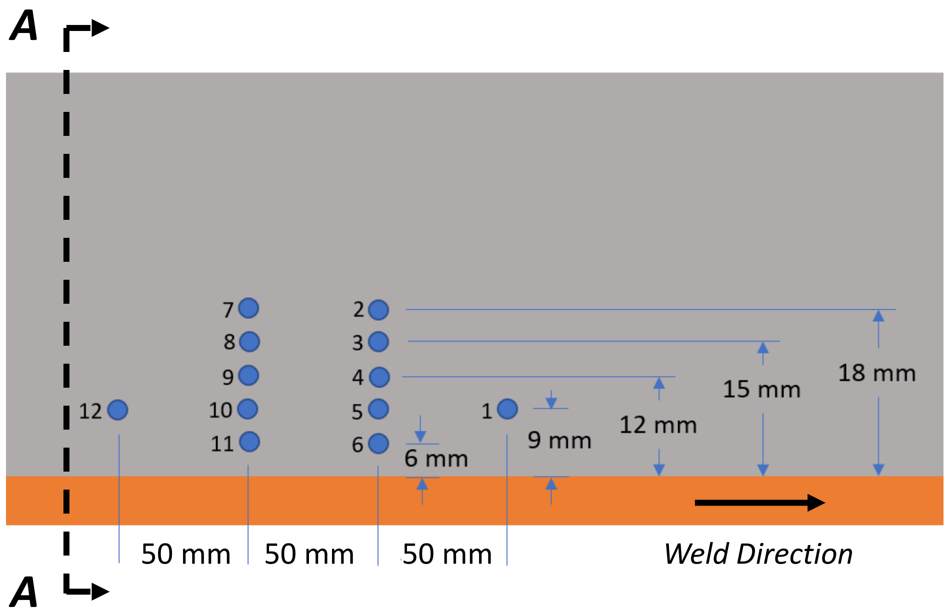


T=0.5 in; SAW-T, 125 kJ/in

T=0.5 in; GMAW-S, 60-70 kJ/in

Process	**Consumable**	**Voltage [V]**	**Current [A]**	**WFS [in/min]**	**Travel Speed (in/min)**	**Heat Input (kJ/in)**
SAW-T	F7A8-EM12K-H8, 1/8" [1]	Lead: 29.4 Trail: 29.4	850 ~790	175	25	125
GMAW-S	Ar-O_2 98-2; ER70S-3, 0.045" [2]	Root: 24 Fill: 28 Cap: 28	230 250 240	--	8 6.7 6.7	41.4 63 60.4

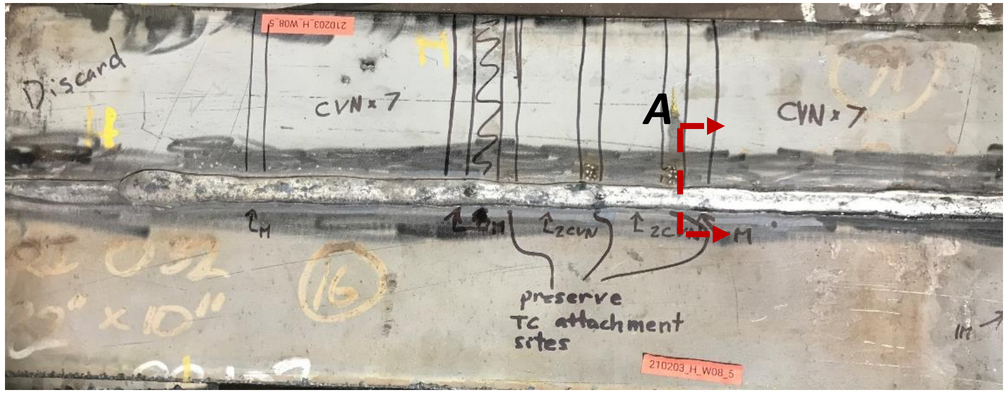
T(t): *12 channels, with grid to measure gradient, transient, and travel speed [3]*



[1] Lincoln LINCOLNWELD® WTX flux and L-61® 1/8" diameter wire.
[2] Lincoln SuperArc L-50®, Q1 Lot 15791962.
[3] "Guide for Verification and Validation in Computation Weld Mechanics," American Welding Society Standard A9.5, American Welding Society, Doral FL, 2013.

Weld Design: ½" Production Welds

HSLA-65, ½" Plate: 125 kJ/in (SAW)



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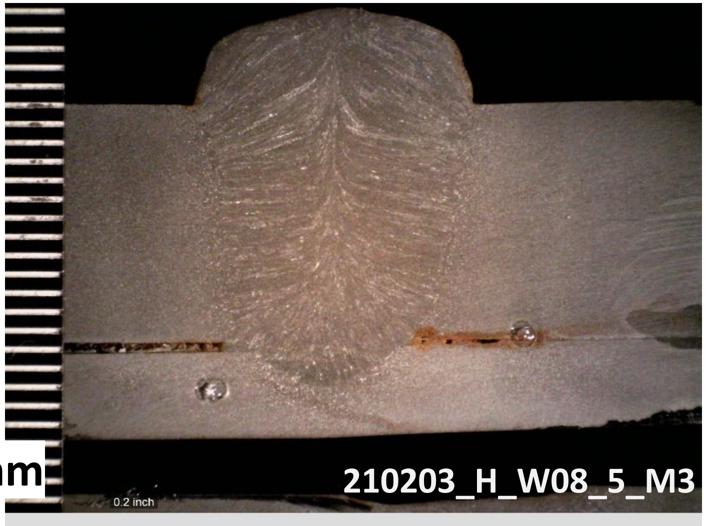

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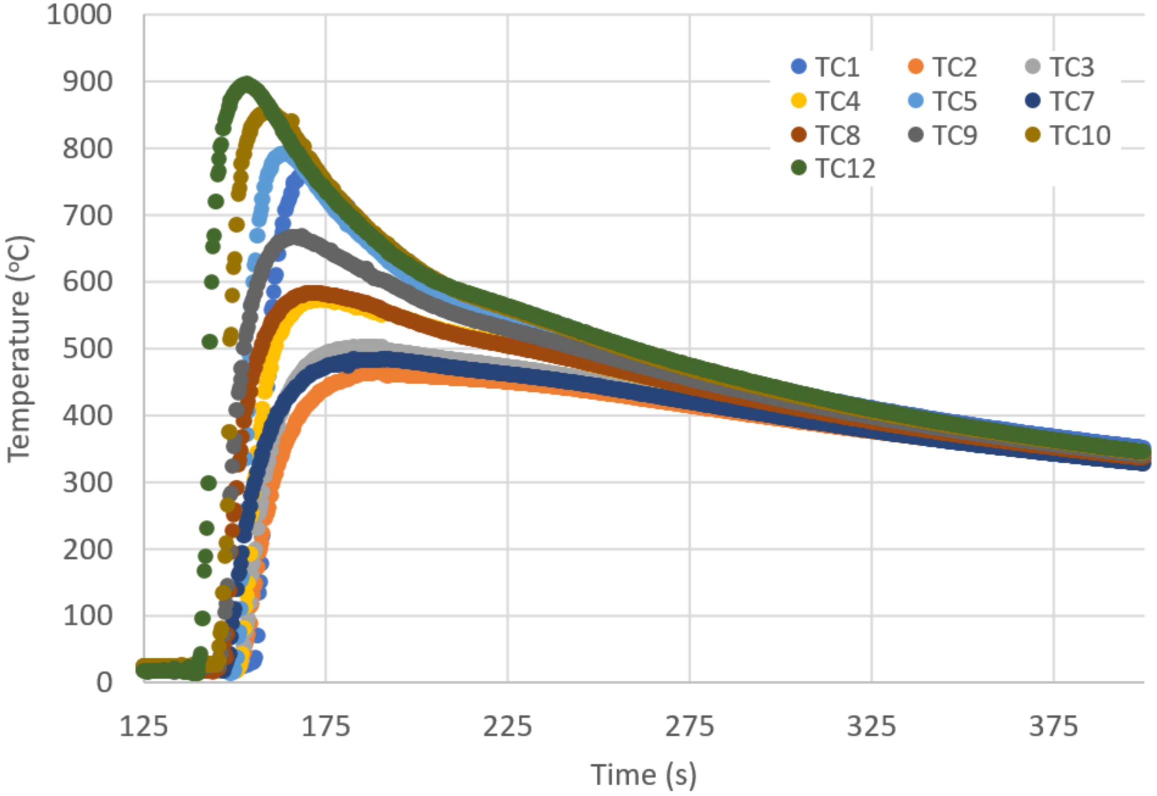

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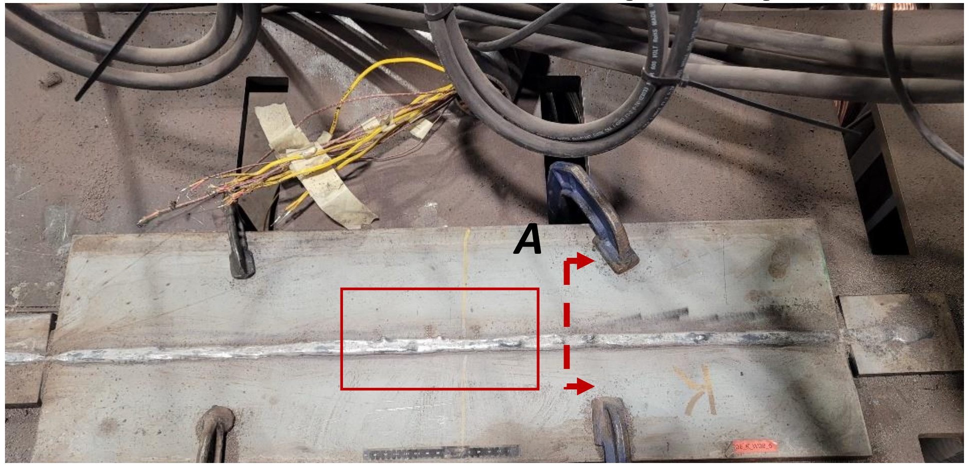
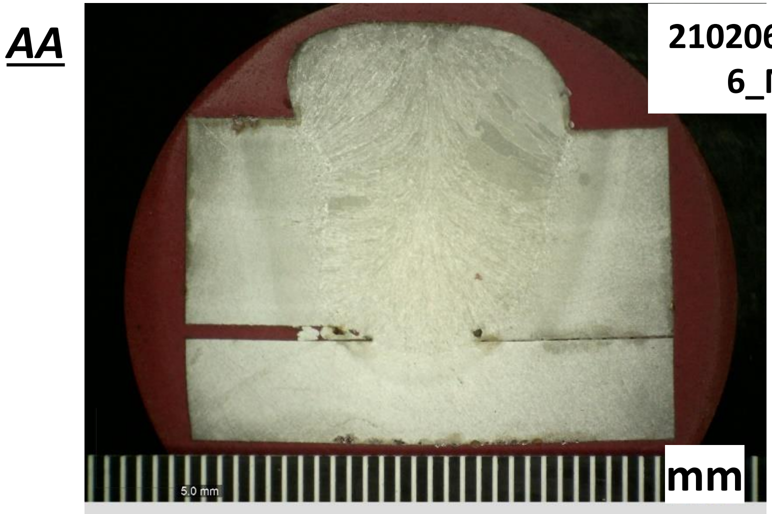
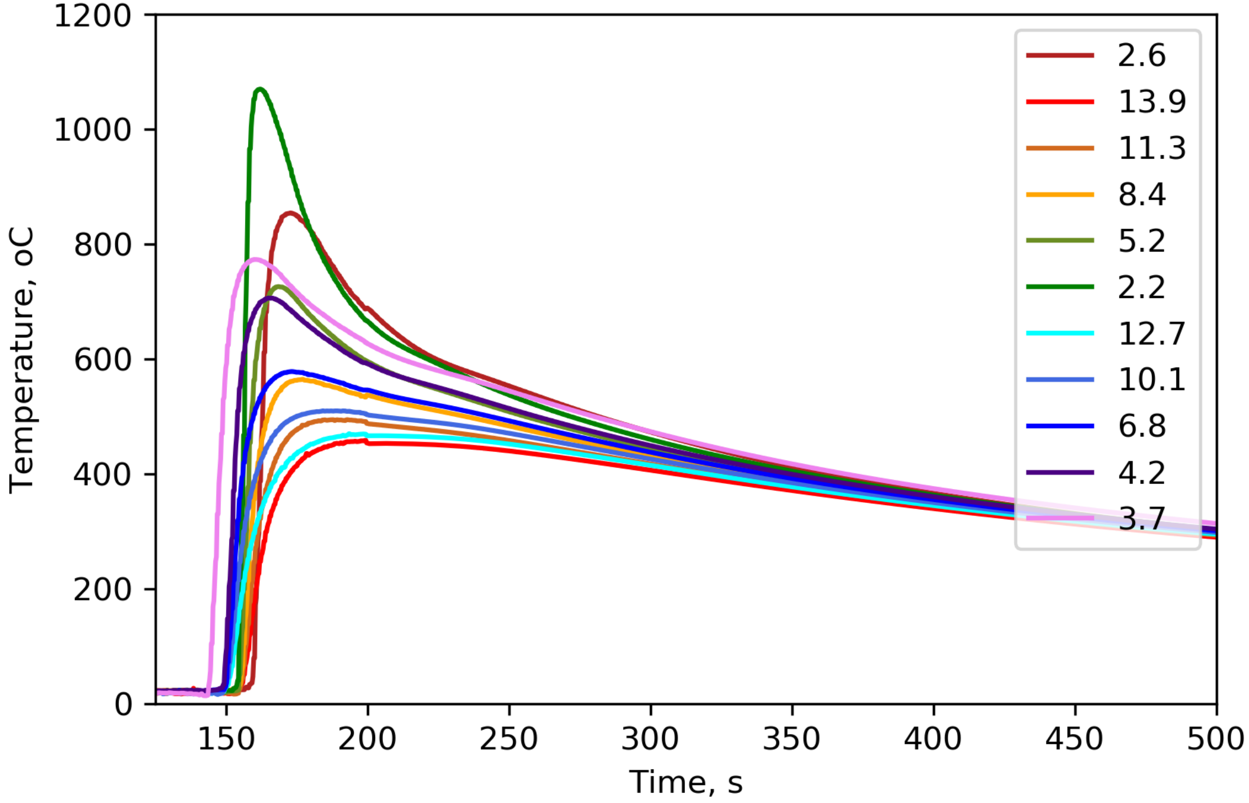
Weld Design: ½" Production Welds

DH-36, ½" Plate: 125 kJ/in (SAW)







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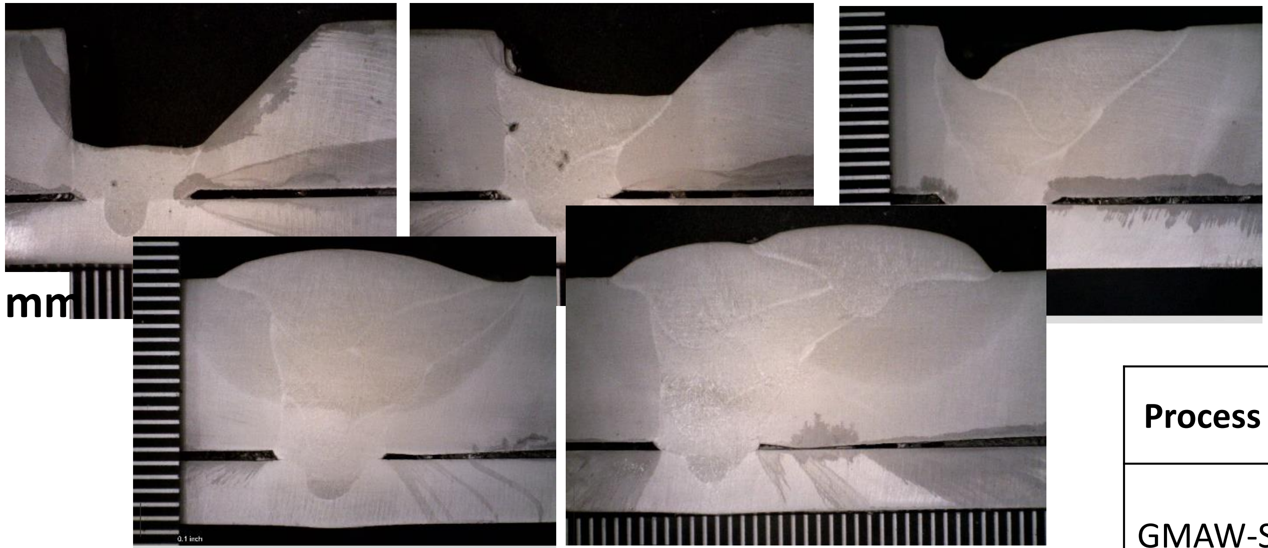
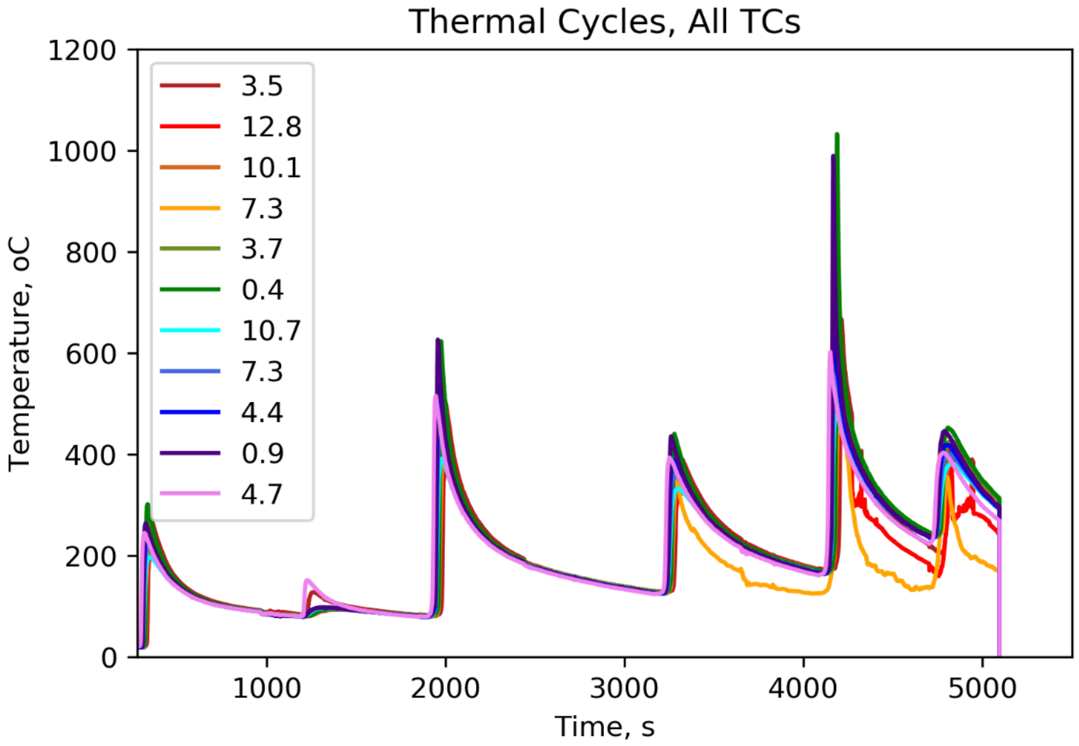
Weld Design: ½" Production Welds

HSLA-65, ½" Plate: 60 kJ/in (GMAW-S)





Process	Consumable	Voltage [V]	Current [A]	WFS [in/min]	Travel Speed (in/min)	Heat Input (kJ/in)
GMAW-S	Ar-O_2 98-2; ER70S-3, 0.045" [2]	Root: 24 Fill: 28 Cap: 28	230 250 240	--	8 6.7 6.7	41.4 63 60.4

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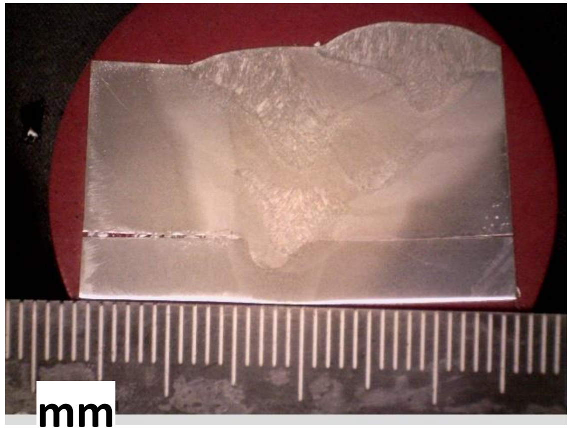
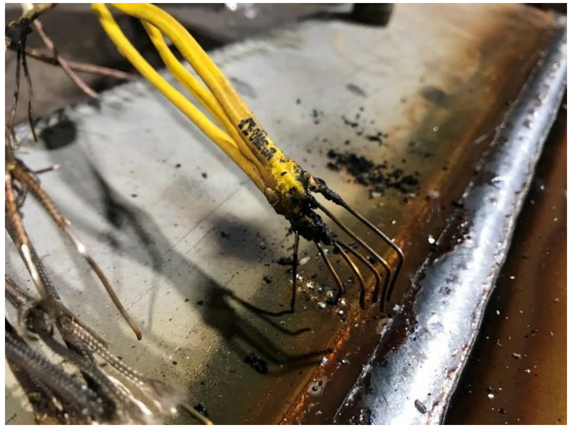
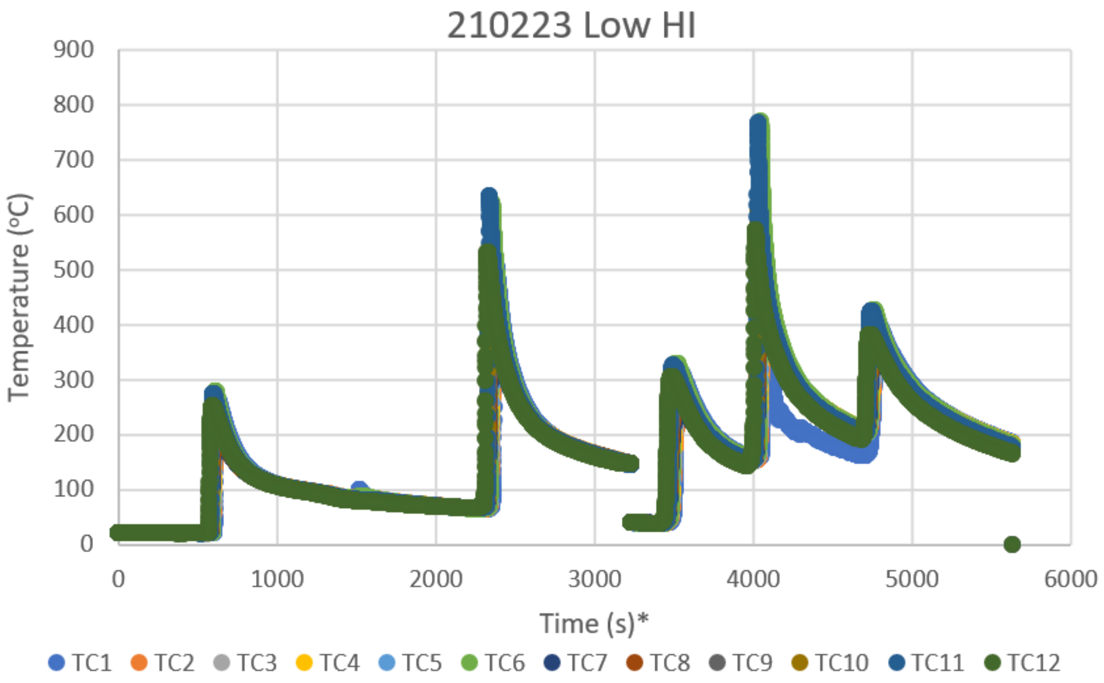
Weld Design: ½" Production Welds

DH-36, ½" Plate: 60 kJ/in (GMAW-S)







**Weld interrupted by tip failure. The torch was cooled, the tip was replaced, and the weld resumed.*

Process	Consumable	Voltage [V]	Current [A]	WFS [in/min]	Travel Speed (in/min)	Heat Input (kJ/in)
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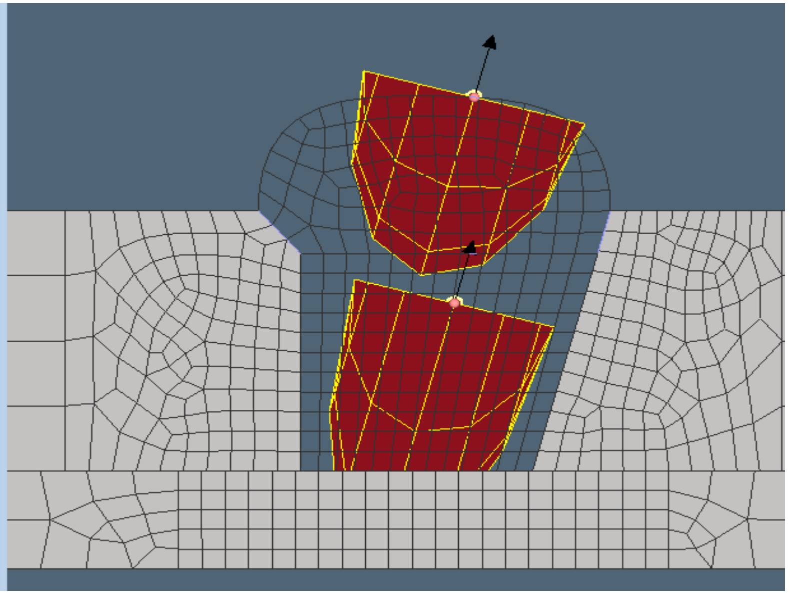
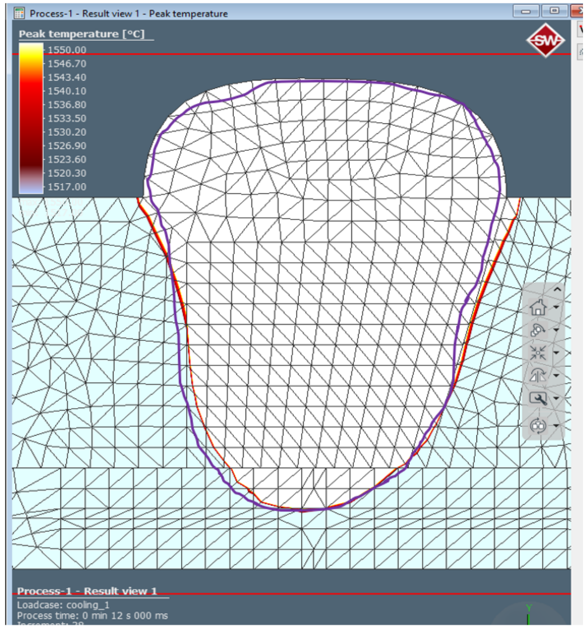
Result #2 – Preliminary FEA Model Developed

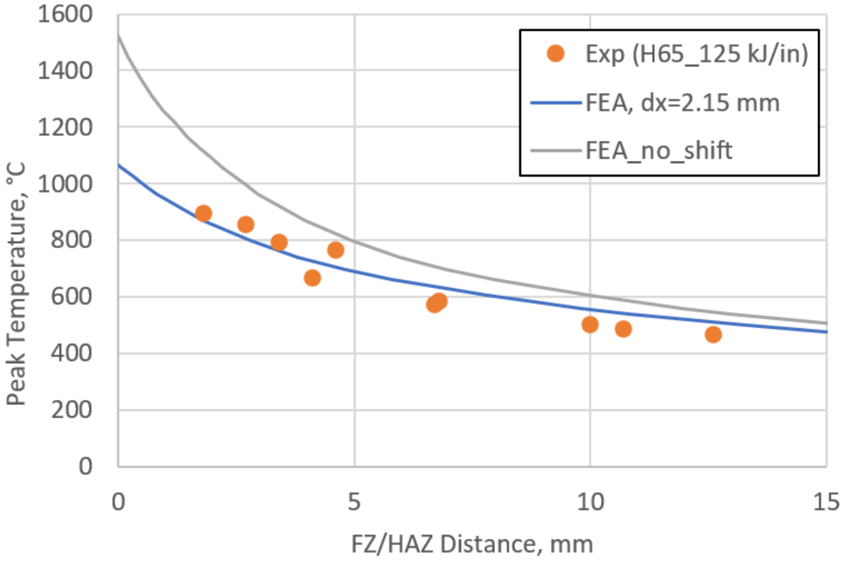
- **Task 1**: Build database of 8 welds
  - Thin/thick plates (12.7, 50.8 mm); low/high heat input (~50 kJ/in , ~100 kJ/in) and bounding alloys (HSLA-65, DH-36).
  - Measure heat affected zone (HAZ) toughness, microstructure, thermal cycle.

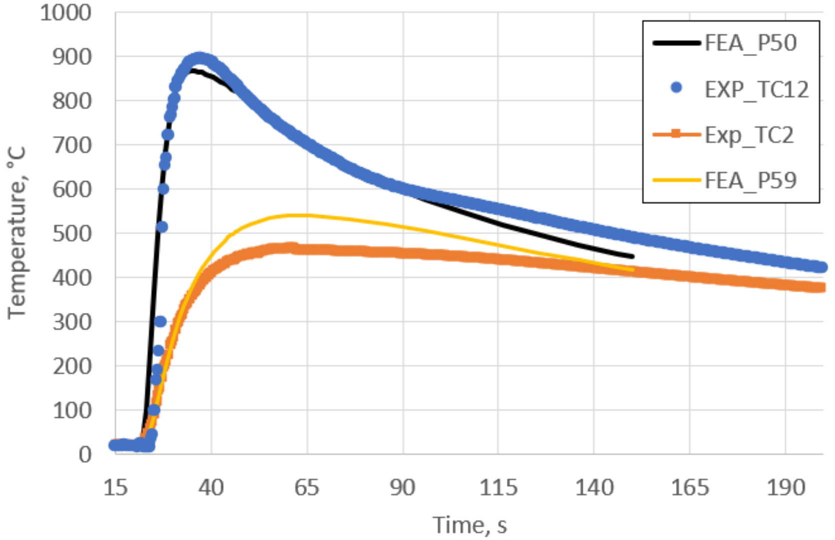
SAW-T FEA Model: Preliminary Results

- *Two Goldak [1], double ellipsoidal heat sources used in Simufact Welding FEA code to model the single-pass, high heat input weld.*
- *Optimized heat source agrees well with FZ geometry*









210319_F02_C19_1mmFZ-9

[1] Goldak et al. A New Finite Element Model for Welding Heat Sources, Metall. Trans. B 15 (1984) 299-305.

Result #3 – Prototyped simulative HAZ test

Simulated HAZ Procedure: Process Control

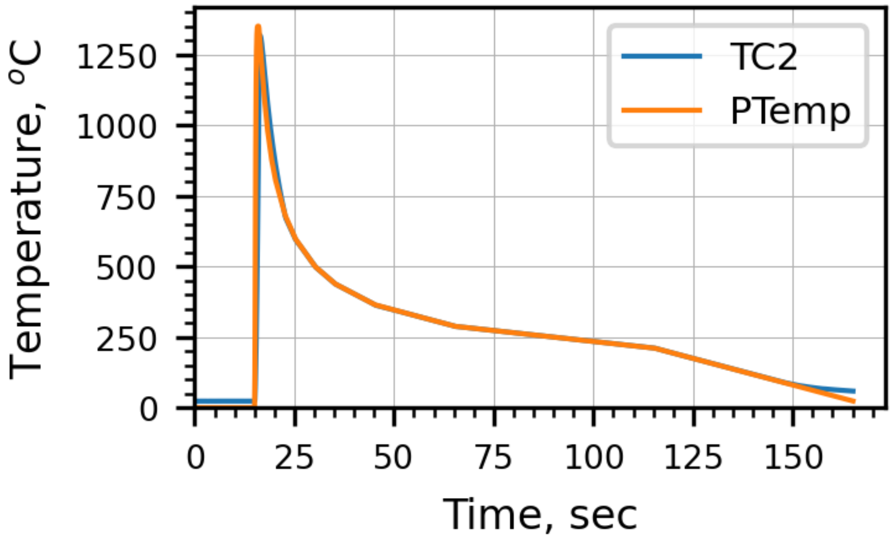
- **Result:** *Developed test parameters to reproducibly run slow cooling rate condition (T_p=1350 °C; $\Delta t_{8/5}$=60s). 5 consecutive trials successfully completed.*

Average of Five Trials

Peak Temperature (°C)	$\Delta t_{8/5}$ (s)	800-500 °C Cooling Rate (°C/s)
1351.1 ± 0.2	60.4 ± 0.1	4.7 ± 0.0

Figure 1: Gleeble 1500 thermomechanical simulator with oversized (11 x 11 mm) CVN blank

Figure 2: Representative thermal cycle to produce simulated CGHAZ in CVN blank. ($T_p = 1317$ °C; $\Delta t_{8/5} = 9.1\ s$)

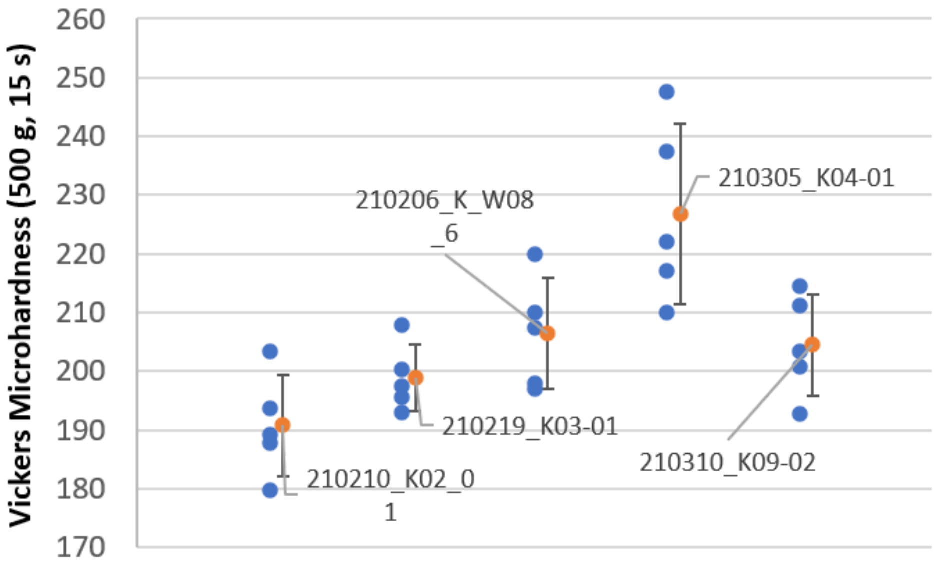


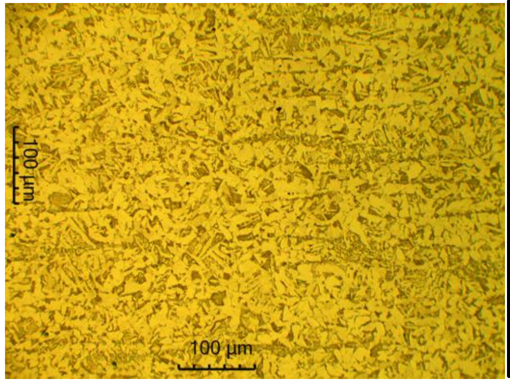
[1] T(t) calculated with Rosenthal, 2D heat flow per Easterling, EQ 1.16. Effective HI = 90 kJ/in

Simulated HAZ vs Weld: CGHAZ in DH-36

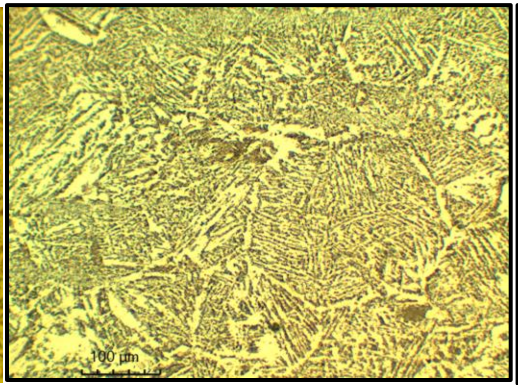
- **DH-36:** FEA *informed* thermal cycle for single-pass SAW (125 kJ/in). ***Good agreement.***

		Hardness [HV, 500 g, 15 s]		Toughness CVN, ft-lbs	
		AVG	STD	AVG	STD
Weld	210206_K_W08_6	206.5	8.5	24.7	15.0
Gleeble	210219_K03-01	198.9	5.8	21.3	11.4

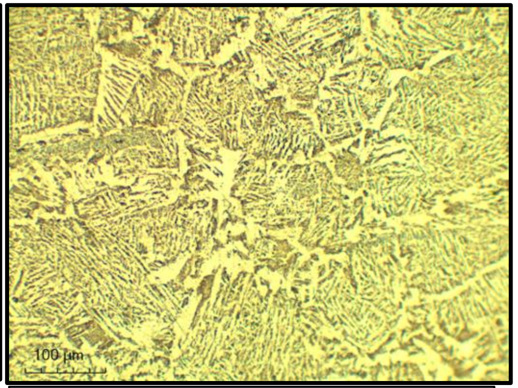




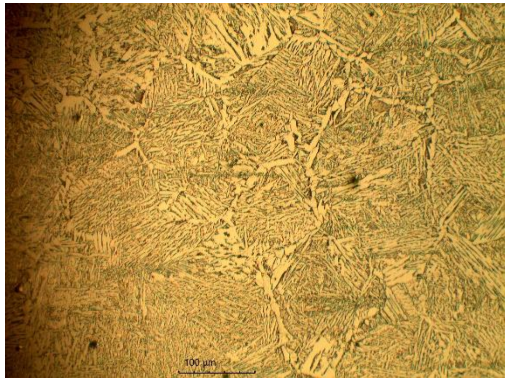
210210_K02_01
$T_p = 1072\ °C; \Delta t_{8/5} = 89.7\ s$



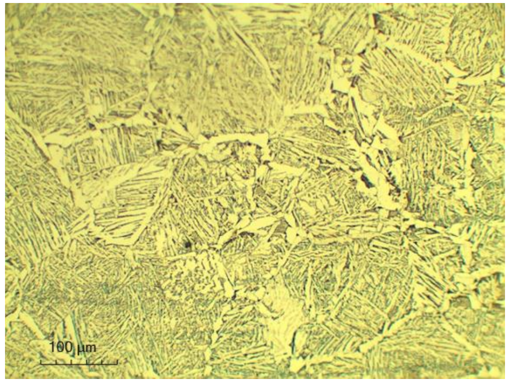
210219_K03-01
$T_p = 1252\ °C; \Delta t_{8/5} = 89.8\ s$



210206_K_W08_6
125 kJ/in SAW-T Weld



210305_K04-01
$T_p = 1261\ °C; \Delta t_{8/5} = 51.3\ s$



210310_K09-02
$T_p = 1315\ °C; \Delta t_{8/5} = 75.4\ s$

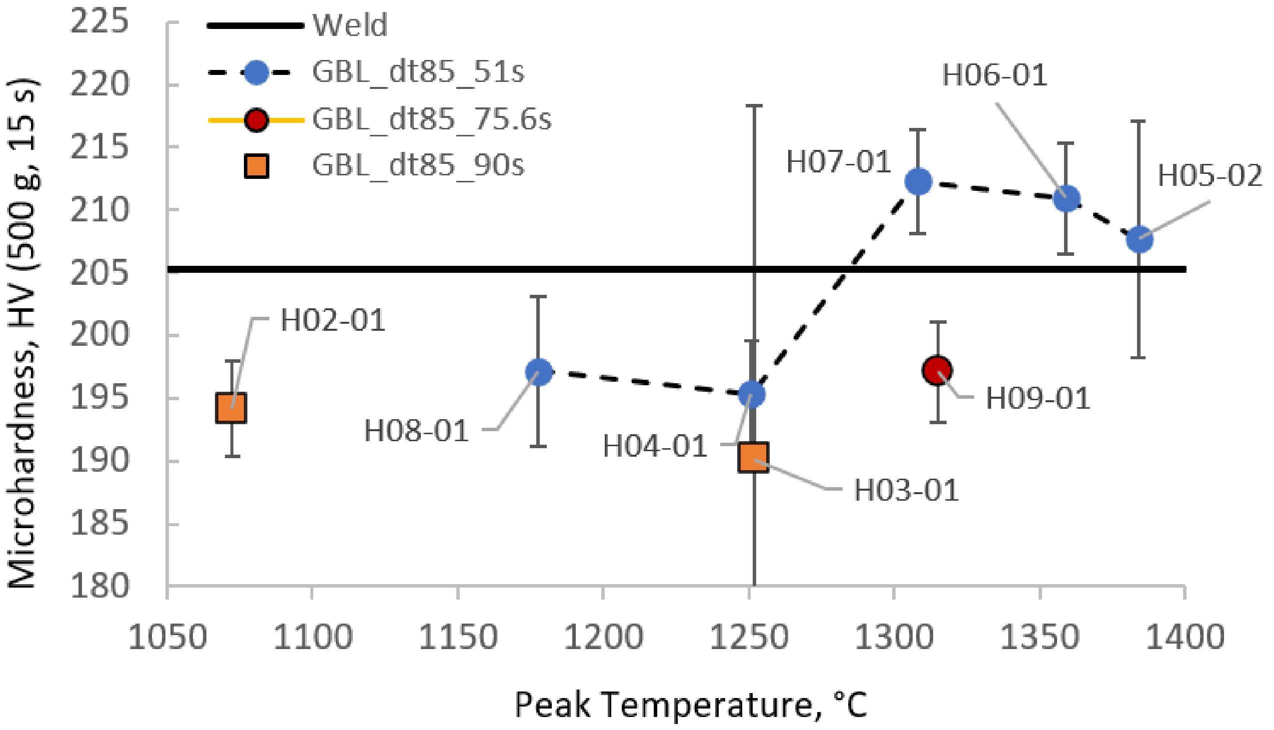
Simulated HAZ vs Weld: CGHAZ in HSLA-65

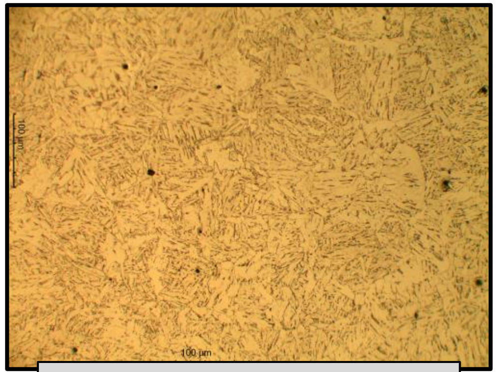
- **HSLA-65:** FEA *informed* thermal cycle for single-pass SAW (125 kJ/in). ***Refinement needed in FEA/Physical Simulation.***

		Hardness [HV, 500 g, 15 s]		Toughness CVN, ft-lbs	
		AVG	STD	AVG	STD
Weld	210203_H W08_5	205.3	5.1	95.8 (73.7)	46.2 (13.5)
Gleeble	210219_K0 3-01	190.1	28.2	19.3	6.4

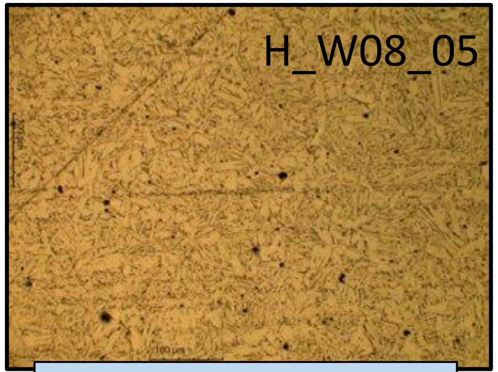
*CVN testing at -40 °C

**Note:* [74,90,163,57]

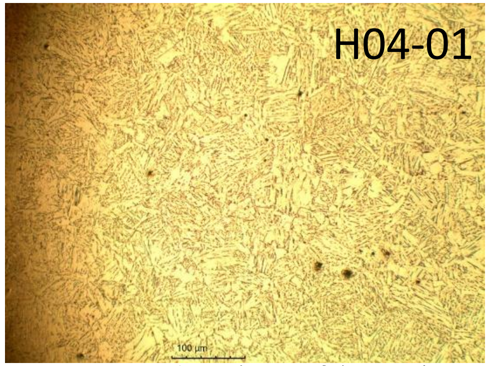




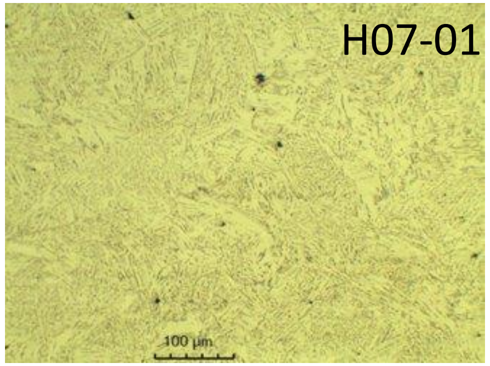
H03-01 (1252 °C/89.7 s)



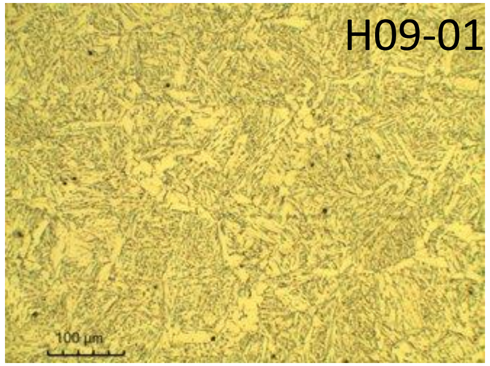
H_W08_05 (SAW-T)



H04-01 (1251 °C/51.2 s)



H07-01 (1308 °C/51.4 s)



H09-01 (1315 °C/75.6 s)

Summary: Prototyped weld/test procedures

Progress to Date

- **Created 4 reference welds for database:** low/high heat input (60 & 125 kJ/in) for HSLA-65 and DH-36 in 0.5 in plate.

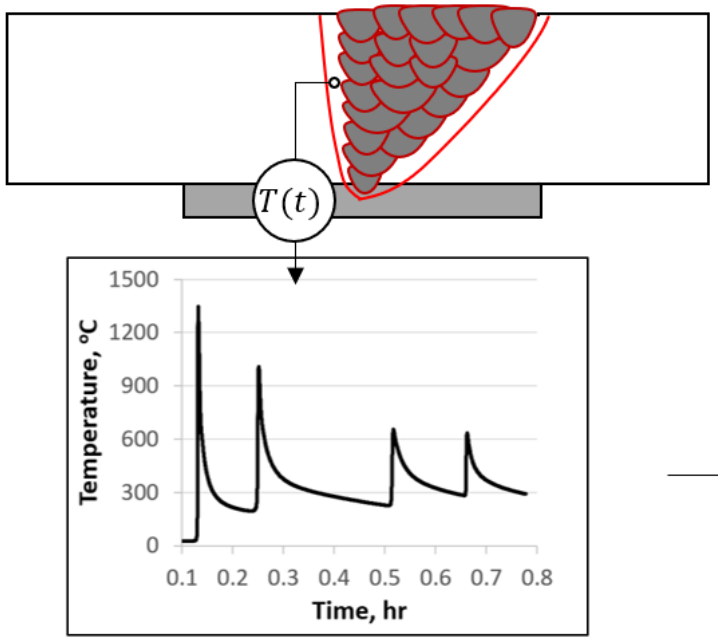
- **Prototyped FEA weld mechanics simulations.** *Validation is on-going.*

- **Demonstrated closed-loop simulative HAZ test:**
  - Prototyped first physical simulations with thermal cycle informed by FEA
  - Demonstrated closed-loop validation protocol with direct toughness/ microstructure comparison of simulated HAZ to real weld
  - Achieved quantitative agreement in DH-36 (125 kJ/in, single pass SAW).
  - Validation is ongoing in HSLA-65.

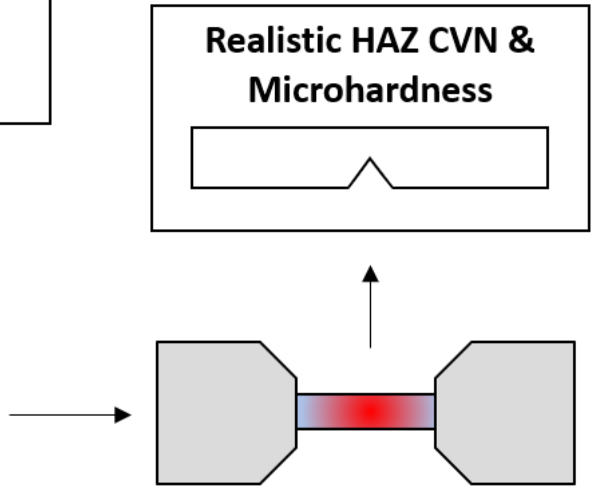
Project Benefits and Long-term Vision

Coupled numerical/physical simulative test method

Finite Element Analysis



Physical Simulation



Identify maximum heat input limit in S-1 Steels

Material	Max Heat Input (worst case)
New Materials	
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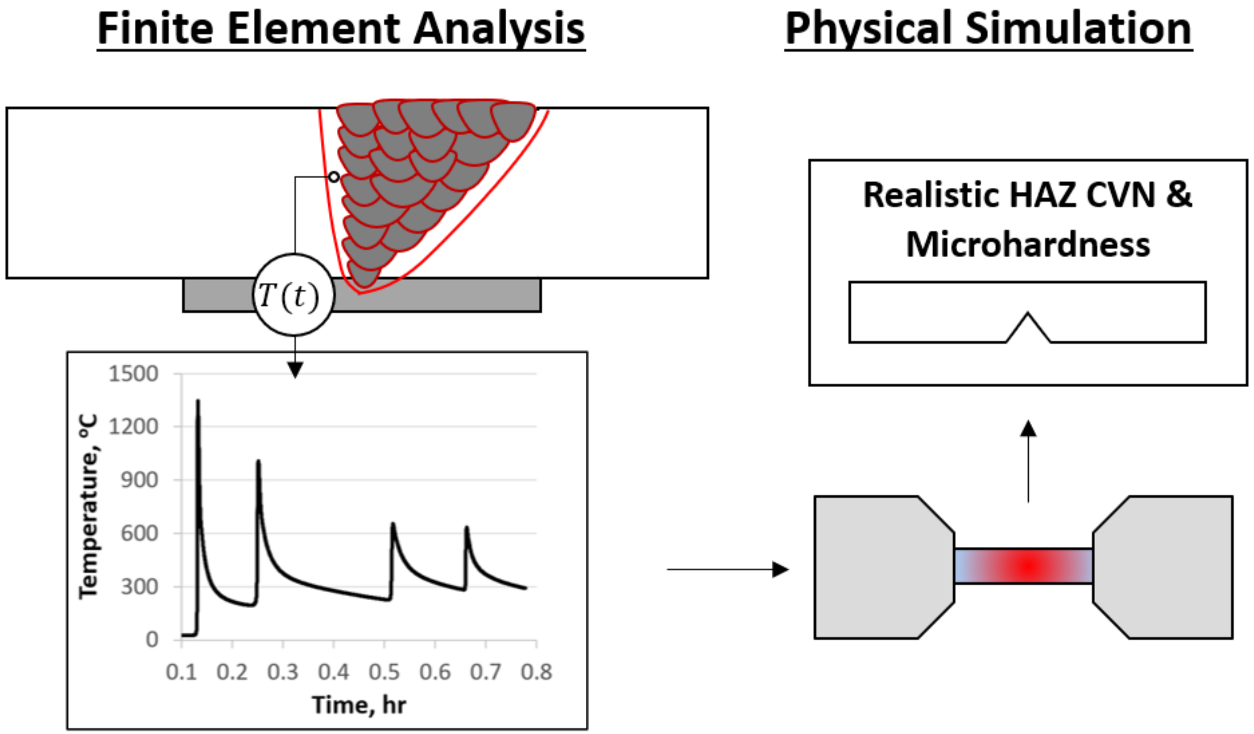
Project Benefits and Long-term Vision

Coupled numerical/physical simulative test method



Benefits:

- **Reduced variation** through reproducible thermal cycles.
- **Systematic**: Relate weld thermal cycle to toughness for representative combinations of material thickness, welding heat input, and number of weld passes.
- **Streamlined PQR development** in S-1 series carbon steels with toughness requirements

Next Steps

- **Validate FEA weld mechanics model**: 1/2″ thick plate (HSLA 65 and DH-36) :
    - Finish validation of single pass SAW FEA model
    - Implement realistic multi-pass GMAW FEA model

- **Execute four welding experiments**: 2″ thick alloy plate (HSLA 65 and DH-36) :
    - Produce four production welds (two alloys; two heat inputs) and measure thermal cycle during welds.
    - Measure weld HAZ properties (toughness, microhardness, and qualitative microscopy)
    - Build computational weld mechanics model for 2″ weldments

- **Reproduce weld experiment data with simulative HAZ test**
    - Continue developing Gleeble simulation protocol that reproduces HAZ weld properties (toughness, microhardness, and qualitative microscopy)

Thanks & Acknowledgments

- **LETU Team**
  - Kaleb Gabbert & Taylor Johnson (Graduate); Sophie Hill, Colton Shambaugh, Brandon Griffith, and Elias Eaton
- **Newport News Shipbuilding**:
  - Greg Pike
- **FEA**
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- **Material Sourcing**
  - Jonathan Roberts (Ingalls)
- **Useful discussions**
  - Lee O'Connell (GDEB)
  - Matthew Sinfield and Daniel Bechetti (NAVSEA, Carderock Division)
  - Dr. Dana Medlin and Dr. Ezequiel Pessoa (LETU)

Questions?

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Backup Slides

Backup #1 – Thermocouple Calibration

Result #1: Thermocouple Validation

- *12 thermocouple channels*
- *TC channels validated with Gleeble: ramp at 350 °C/s to 1355 °C; controlled cooling with* $\Delta t_{8/5} = 27.6$ s. *Error quantified in different ranges*
- *Average of 3.4% error at peak temperature and 0.7% error over 800-500 °C*
- *Developed checks to identify unreliable TC response*

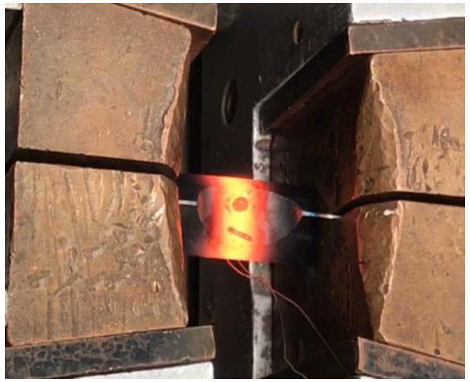

Figure 1: Gleeble TC verified at Cu Melting (1085 °C)

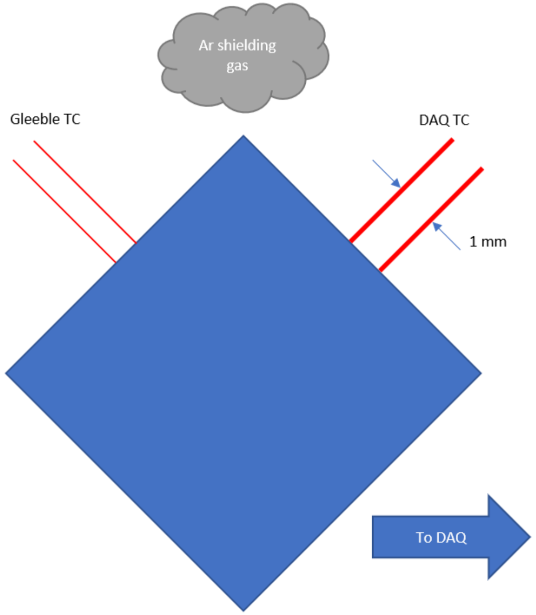

Figure 2: Gleeble TC validation experiment with ramp heating/cooling

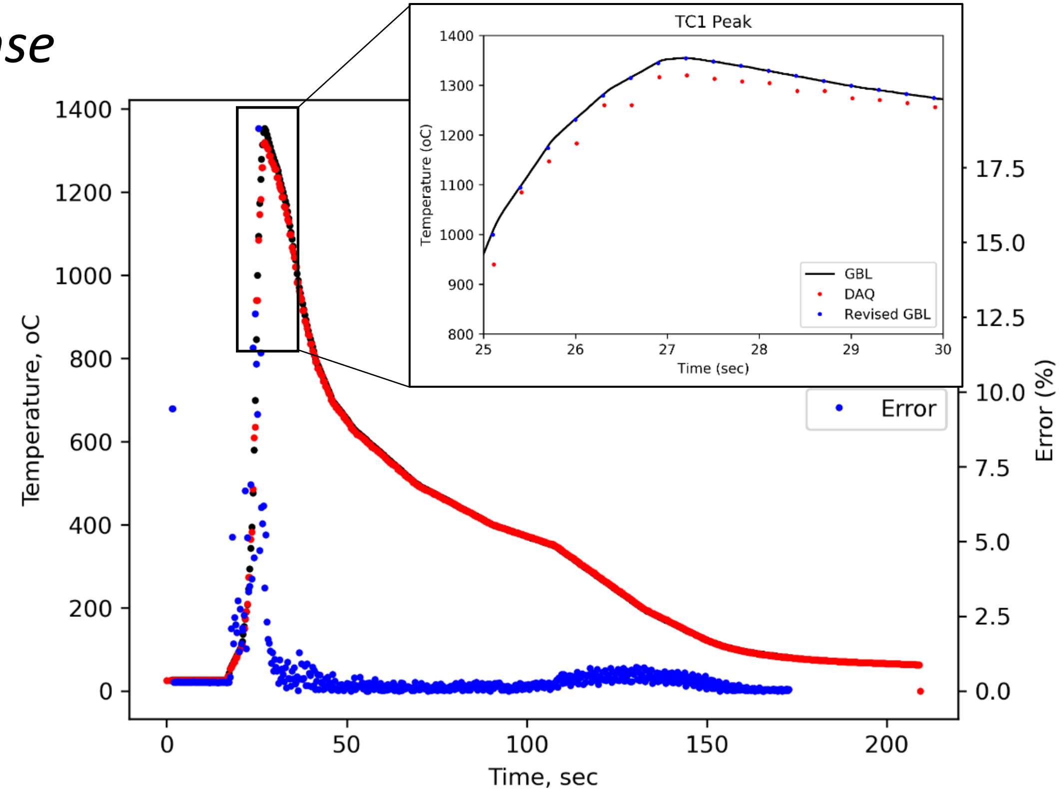

Figure 3: Gleeble TC validation experiment data