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

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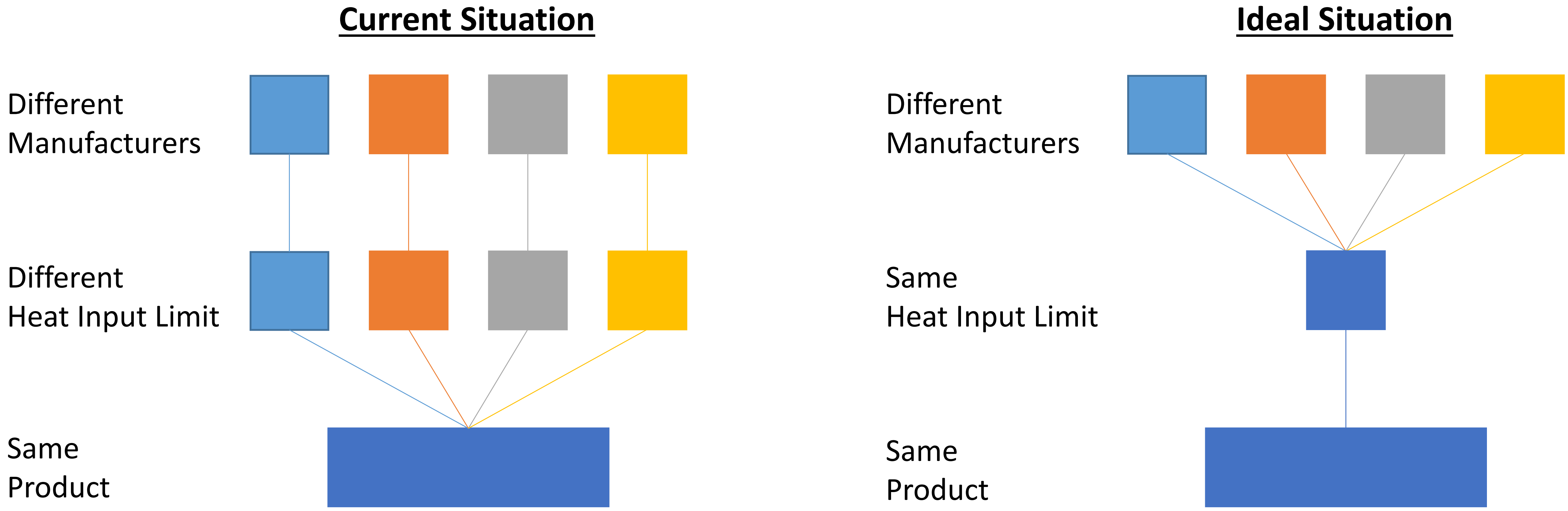
Problem Statement

- 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*

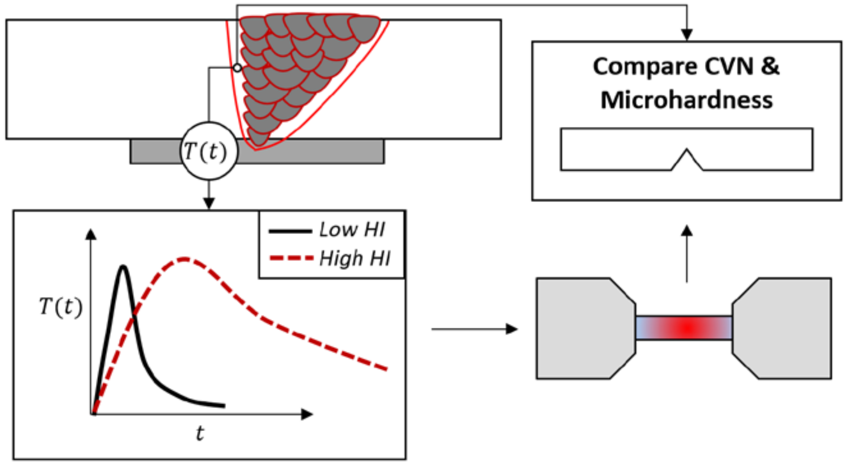
- **Task 1**: Build database of 8 welds: thin/thick plates (12.7, 50.8 mm); low/high heat input (~50 kJ/in , ~100 kJ/in) and bounding alloys (HSLA-65, DH-36). Measure heat affected zone (HAZ) toughness, microstructure, thermal cycle.

- **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 – Selected and Procured Materials

Material Selection

- ***Goal:*** *Identify two candidate alloys from S-1 material list with following requirements*

  <u>Top Priorities</u>

  1. Are available in plate format in a thin (0.5”) and thick (2.0”) condition
  2. Have toughness requirements in base material at both thicknesses
  3. Will display qualitatively different microstructural (toughness) response in CGHAZ to high heat input/low heat input welding conditions.
     1. **Carbon content** controls maximum attainable hardness
     2. **Carbon equivalent** (and microalloying elements) affect hardenability

  <u>Secondary Priorities</u>

  4. Toughness requirements are different for two alloys
  5. Yield strengths are different for two alloys

Material Selection

Result: Built candidate S-1 grouped material database with 10 alloys

1. Maximum allowable Carbon
2. Carbon equivalent (CE), assuming value of max carbon and mid-point on all others

$$CE = \%C + \frac{\%Mn+\%Si}{6} + \frac{\%Cr+\%Mo+\%V}{5} + \frac{\%Cu+\%Ni}{15}$$

3. Grain refining/microalloying elements that are required
4. Condition of supply and/or required heat treatment
5. Yield strength and CVN Test Requirements

	ASTM131 Grade D **[1]**	ASTM131 Grade AH-36 **[1]**	ASTM131 Grade DH-36 **[1]**	ASTM131 Grade EH-36 **[1]**	ABS Grade D **[2]**	ABS Grade AH-36 **[2]**	ABS Grade DH-36 **[2]**	ASTM709 50W-Grade A **[3]**	ASTM709 50W-Grade B **[3]**	ASTM945 Grade 65 **[4]**
Max C, %	0.21	0.18	0.18	0.18	0.21	0.18	0.18	0.19	0.20	0.10
CE	0.35	0.45	0.45	0.45	0.35	0.45	0.45	0.54	0.52	0.40
Min Microalloying	Al (over 25 mm)	≥ 0.015 Al, ≥ 0.02 Nb; ≥ 0.05 V			Al (over 25 mm)	> 0.015 Al, ≥ 0.02 Nb; ≥ 0.05 V	> 0.015 Al, ≥ 0.02 Nb; ≥ 0.05 V	≥ 0.02 V; ≥0.4 Cr; ≥ 0.25 Cu	≥ 0.01 V; ≥0.4 Cr; ≥ 0.25 Cu	≥ 0.007 Ti
Condition or HT	>35 mm, N, CR, or TMCP	N, CR, TMCP, or QT as specified			>35 mm, N, CR, or TMCP	> 20 mm, various	> 12.5 mm, various	--	--	> 32 mm, QT
Yield Point, min, ksi	34	51	51	51	34	51	51	50	50	65
CVN (Test Temp; Energy)	-20 °C/14 ft-lb	0 °C/17 ft-lb	-20 °C/17 ft-lb	-40 °C/17 ft-lb	-20 °C/14 ft-lb	0 °C/17 ft-lb	-20 °C/17 ft-lb	-12 °C/25 ft-lb	-12 °C/25 ft-lb	-40 °C/70 ft-lb

[1] ASTM A131/A131M-19, Standard Specification for Structural Steel for Ships, ASTM 2019. **[2]** Rules for materials and Welding, Part 2, ABS, 2020. **[3]** ASTM A709/A709M-18, Standard Specification for Structural Steel for Bridges, ASTM 2018. **[4]** ASTM A945/A945M-16, Standard Specification for High-Strength Low-Alloy Structural Steel Plate with Low Carbon and Restricted Sulfur for Improved Weldability, Formability, and Toughness, ASTM 2016.

Material Selection

Analysis 1: Hydrogen cracking susceptibility

1. Use AWS D1.1 methodology to map maximum attainable hardness/hardenability [5]
2. **ABS Grade-D** is essentially a plain carbon steel with fine grain practice (Al)
3. **HSLA-65** (ASTM A945-Grade 65) is low carbon, low carbon equivalent material
4. While ASTM A709-Grade 50 W has highest CE, it is a weathering grade.

	ABS Grade D **[2]**	ABS Grade DH-36 **[2]**	ASTM945 Grade 65 **[4]**
Max C, %	0.21	0.18	0.10
CE	0.35	0.45	0.40
Min Microalloying	Al (over 25 mm)	> 0.015 Al, ≥ 0.02 Nb; ≥ 0.05 V	≥ 0.007 Ti
Condition or HT	>35 mm, N, CR, or TMCP	> 12.5 mm, various	> 32 mm, QT
Yield Point, min, ksi	34	51	65
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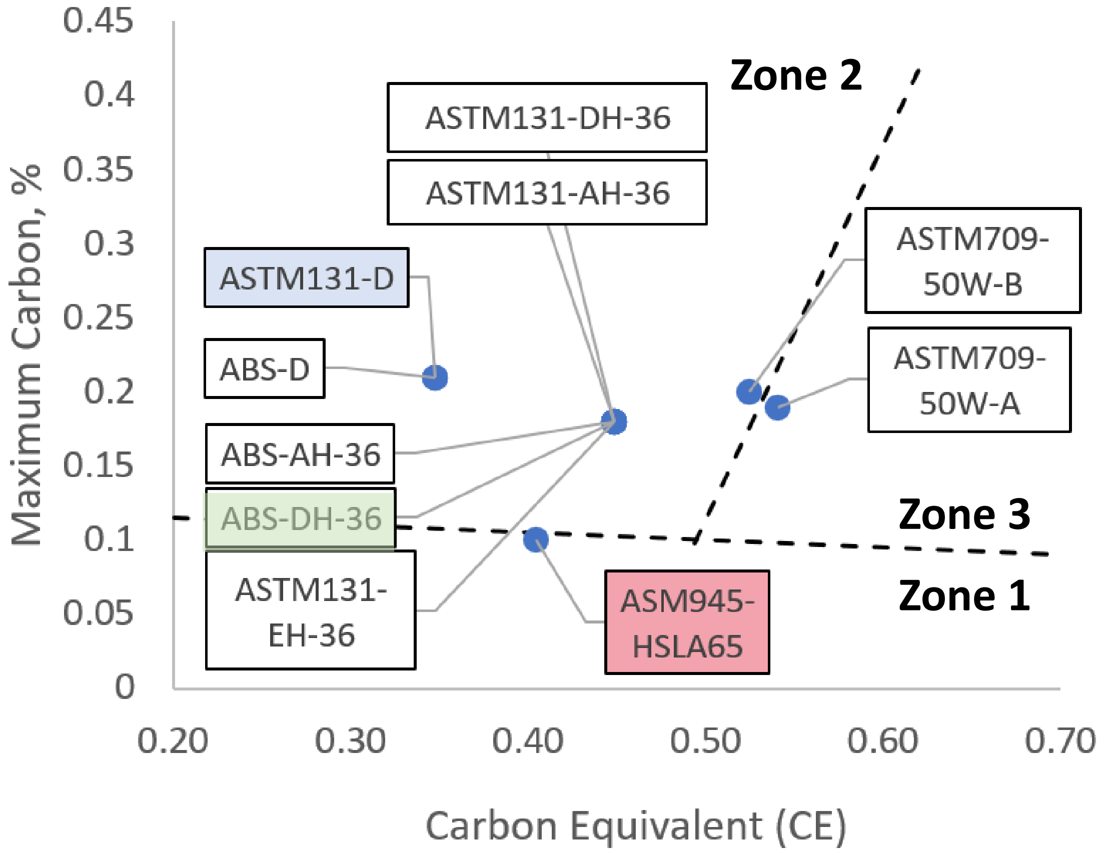

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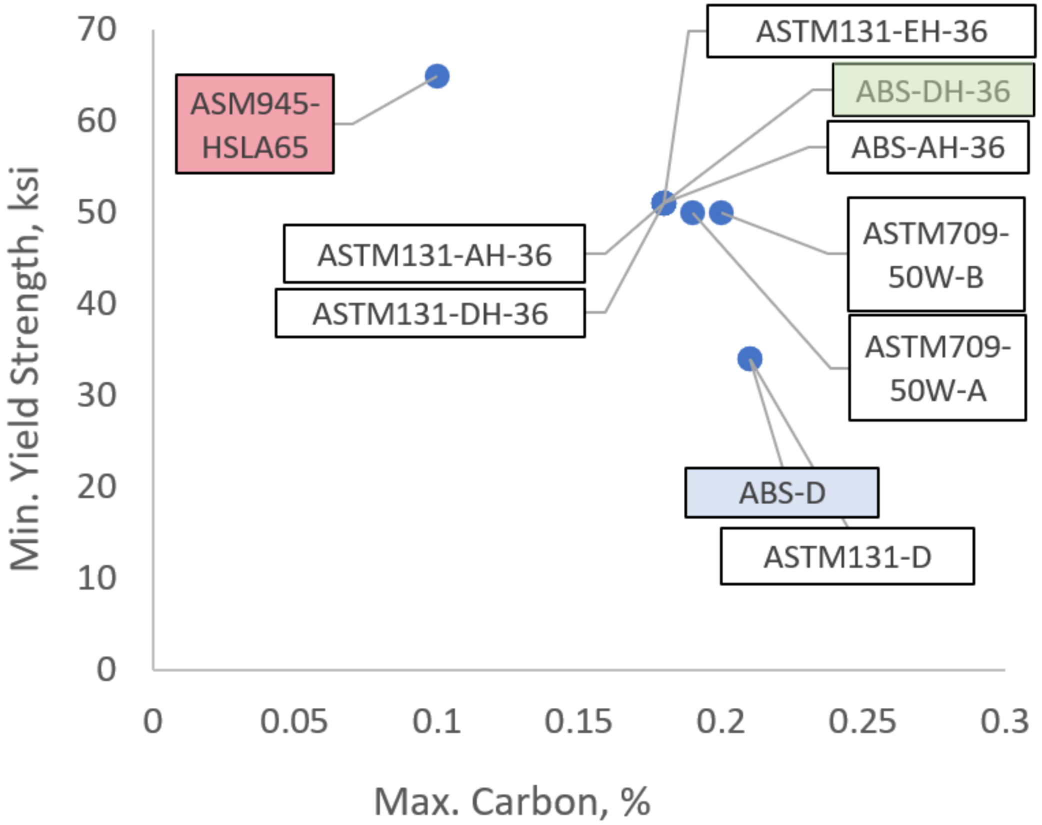
Material Selection

Analysis 2: Compare yield strength to max carbon content

1. Grain size/microstructure control versus alloying of strengthening
2. **HSLA-65** vs **ABS Grade D**: approximately double the strength at half the (max) carbon
3. **DH-36** is mid-point between ABS-D and HSLA-65



	ABS Grade D **[2]**	ABS Grade DH-36 **[2]**	ASTM945 Grade 65 **[4]**
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Material Selection

Analysis 3: Compare toughness requirements

1. **HSLA-65** has highest toughness requirements in base plate (-40 °C/70 ft-lb). TechPub248 states: *"HSLA-65 HAZ tests shall meet a toughness of 30 ft-lbs minimum at -20 °F" (-29 °C) [5].*

2. **ABS Grade D** has lower toughness requirements in base plate (-20 °C/14 ft-lb). TechPub248 states: *"Weld tests shall be evaluated to the requirements of the filler metal specification. Base metal and HAZ impact tests shall be evaluated to the requirements of the applicable base metal specification or per 4-5.2.4.2, as applicable" [6].*

	ABS Grade D **[2]**	ABS Grade DH-36 **[2]**	ASTM945 Grade 65 **[4]**
Max C, %	0.21	0.18	0.10
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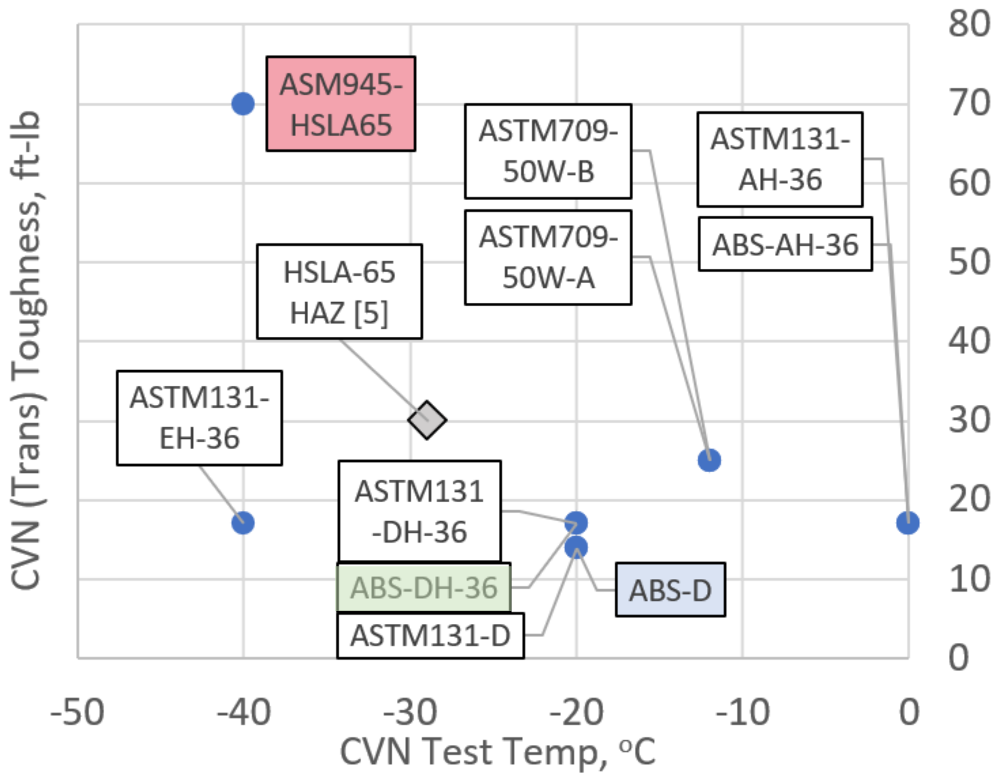
CVN (Test Temp; Energy)	-20 °C/14 ft-lb	-20 °C/17 ft-lb	-40 °C/70 ft-lb



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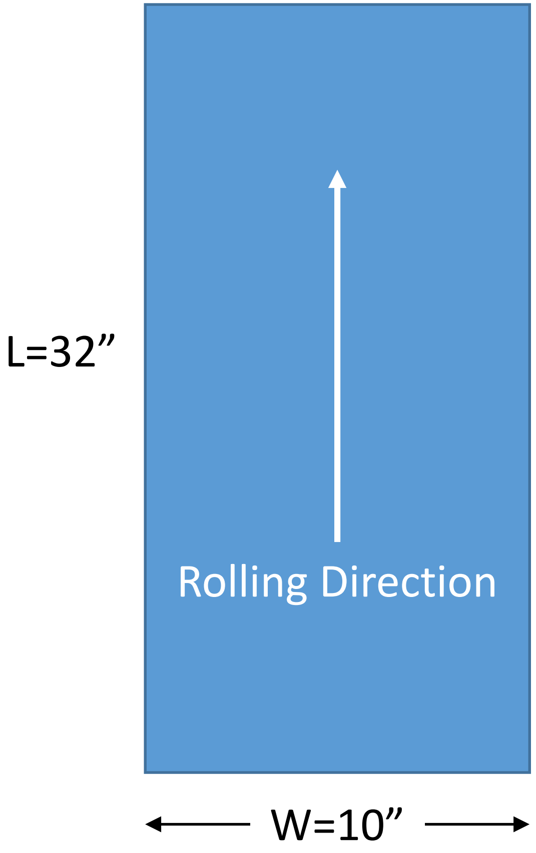
Material Selection

The following materials have been procured/ordered



Status	Material	Plate ID (Ingalls/**LETU**)	Thickness [in]	Plate Size	Quantity
At LETU	**ASTM A945 Grade 65 (HSLA 65)** [1]	QI 128 (2” HSLA 65): **I**	2.0	32” x10”	16
At LETU	**ASTM A945 Grade 65 (HSLA 65)** [1]	QI 032 (½” HSLA 65): **H**	0.5	32” x10”	16
Ordered	**ABS Grade D** [2] (or ASTM A131 Grade D, [3])	WJ 128 (2” Grade D): **J**	2.0	32” x10”	16
At LETU	**ABS Grade DH-36** [2] (or ASTM A131 Grade DH-36, [3])	WM 128 (2” DH-36): **L**	2	32” x10”	8
At LETU	**ABS Grade DH-36** [2] (or ASTM A131 Grade DH-36, [3])	WM 032 (½” DH-36): **K**	0.5	32” x10”	24

[1] ASTM A945/A945M-16, Standard Specification for High-Strength Low-Alloy Structural Steel Plate with Low Carbon and Restricted Sulfur for Improved Weldability, Formability, and Toughness, ASTM 2016.
[2] Rules for materials and Welding, Part 2, ABS, 2020. **[3]** ASTM A131/A131M-19, Standard Specification for Structural Steel for Ships, ASTM 2019.

Result #2 – Prototyped welding procedures

Weld Design

Joint Design and GMA weld procedure summary

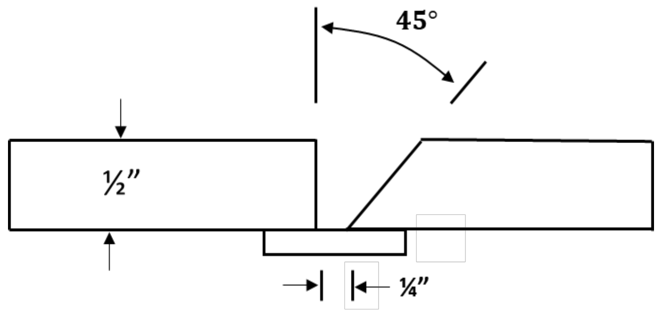


Figure 1: 0.5 in Joint Design

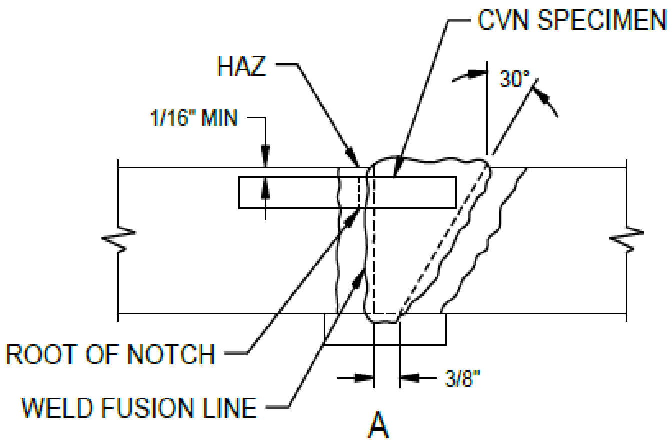


Figure 2: 2 in Joint Design

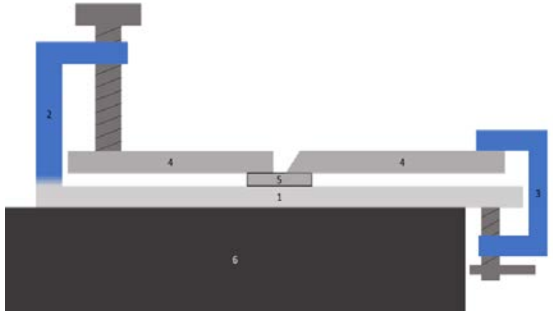


Figure 3: Joint Fit Up

Table 1: Weld Details

Shielding Gas	Ar-O_2 98-2
Wire	AWS ER70S-3 [1]
Wire diameter	0.045”

Table 2: Weld Parameters

	Voltage (V)	Current (A)	TS (ipm)	HI (kJ/in)
Low	28	240	8	50
High	30	300	6	90

[1] Lincoln SuperArc L-50®, Q1 Lot 15791962

Weld Procedure: Slow Cooling Rate

1/2" welding procedure has been optimized for CVN samples and good quality has been achieved

Table 1: Weld Parameters

	V	A	TS (ipm)	HI (kJ/in)	Distance to Weld (mm)	$\Delta t_{8/5}$ (sec)
Root	23.9	220	6	52.58	8	13.5
F1&2	28, 28	262, 271	6, 6	73.4, 75.9	9, 15	27, N/A
C	24	191	16	17.2	10	N/A

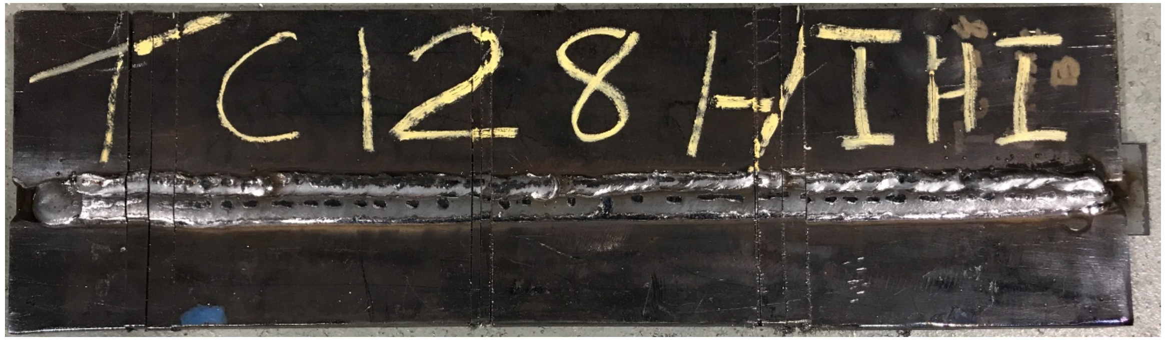
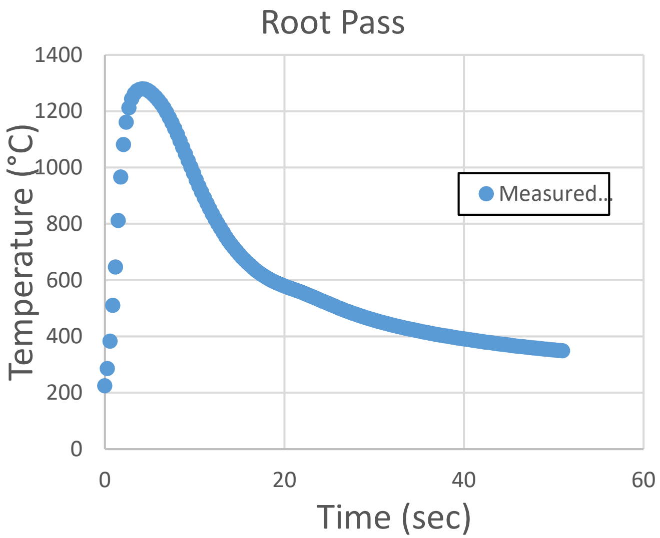


Figure 1: TC128 Weld



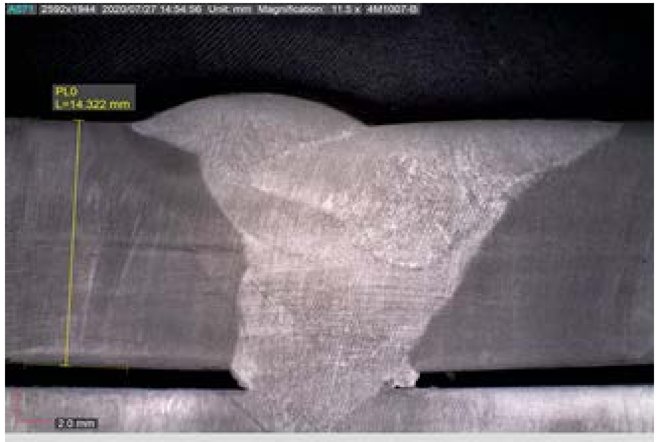


Figure 2: Weld Cross Section
(200714_NSRP_T_E9-16in_M-5_C2)

Figure 3: Weld Cross Section w/ TC
(200714_NSRP_T_E9-16in_M-2.5_TC2.5)

Weld Procedure: Fast Cooling Rate

2” welds show good overall quality. *Future work to modify procedure to remove remaining discontinuities and improve thermal cycle measurement*

Table 1: Weld Parameters

	V	A	TS (ipm)	HI (kJ/in)	Distance to Heat Source (mm)	Dt8-5 (sec)
F	28	240	8	50	15	N/A

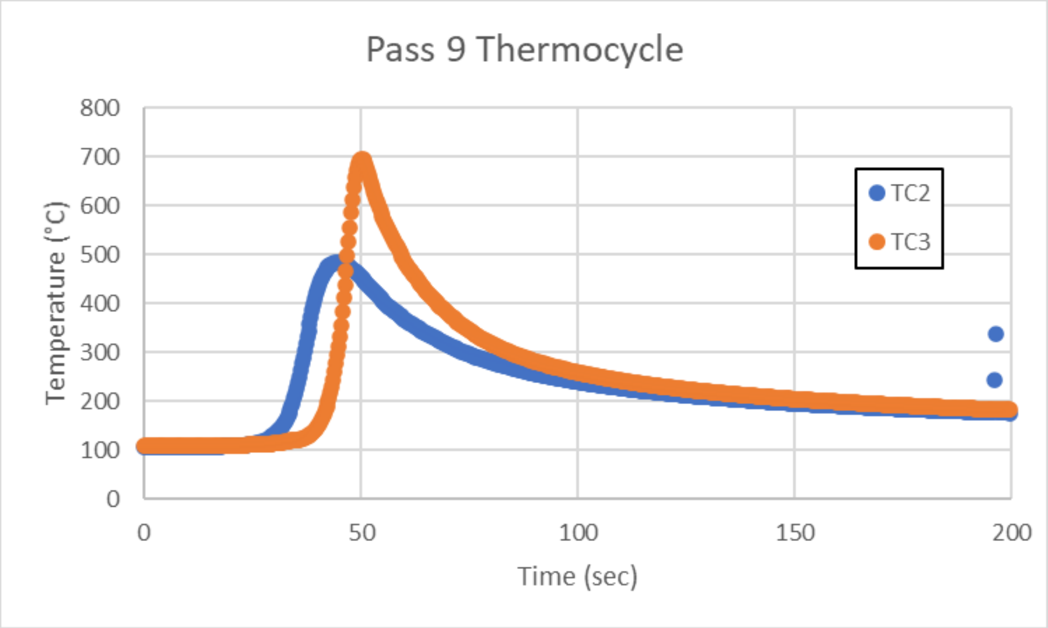


Figure 1: Weld Cross Section

(200827_NSRP_T_F2in_M1-1)

Result #3 – Prototyped simulative HAZ test

Simulated HAZ Procedure: Process Control

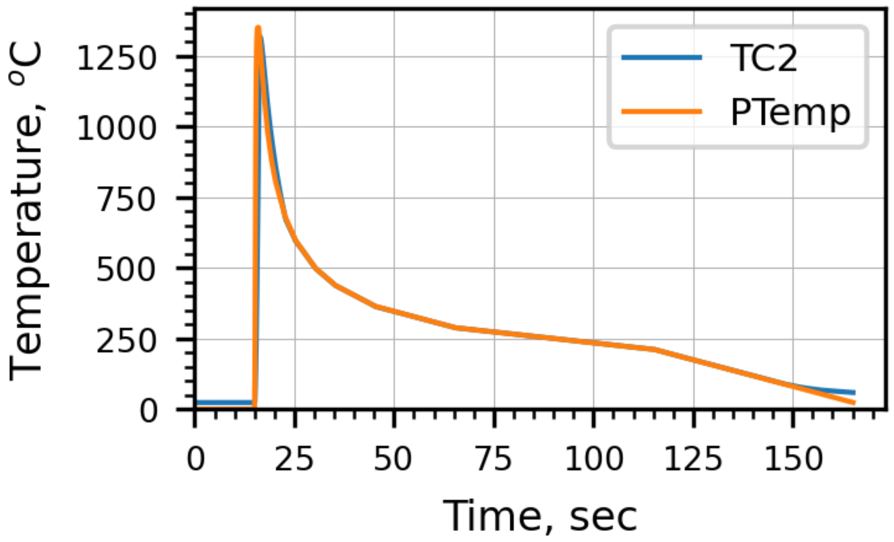
- **Result:** *Developed test parameters to reproducibly run slow cooling rate condition (T_p=1350 °C; $\Delta t_{8/5}$=60s). 5 consecutive trials successfully completed.*

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

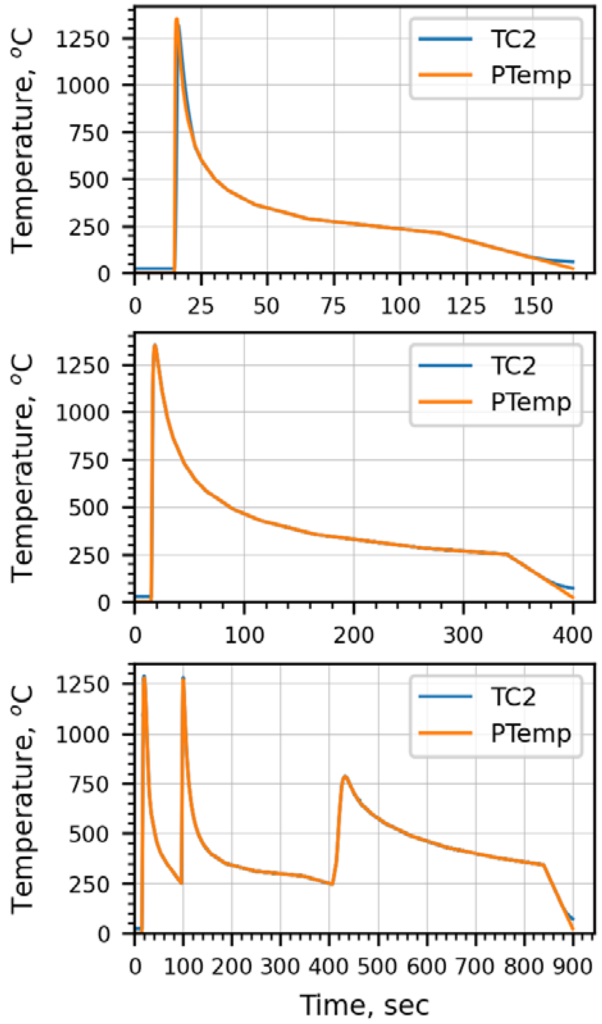
Simulated HAZ Procedure: CGHAZ Comparison

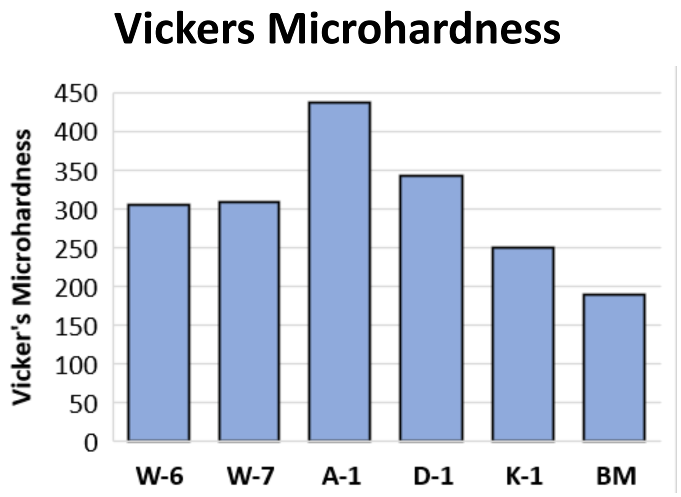
- **Results:** 3 different HAZ thermal cycles simulated; properties compared to weld results
- Multipass thermal cycles significantly change properties.
- **Q3 work focused on thermal cycle measurement and prediction**

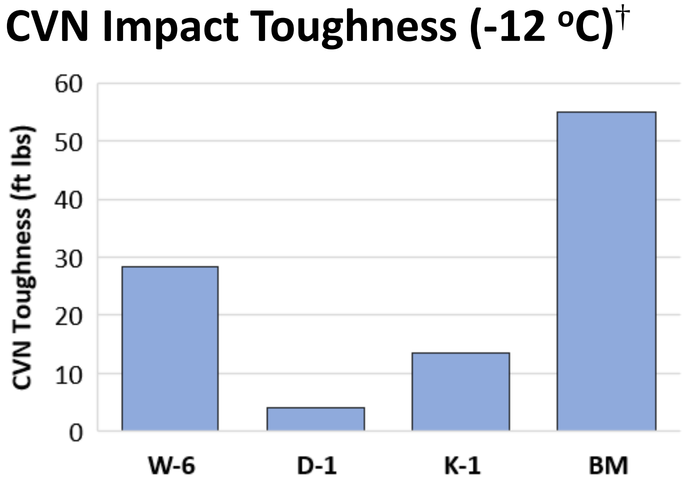
<u>A-1</u> ($T_p = 1317$ °C; $\Delta t_{8/5} = 9.1\ s$)
Single Pass; Fast HAZ CR

<u>D-1</u> ($T_p = 1352$ °C; $\Delta t_{8/5} = 47\ s$)
Single Pass; Slow HAZ CR

<u>K-1</u> ($T_p / \Delta t_{8/5}$)
C_1: 1286 °C/13.4 s
C_2: 1279.1 °C/20.9 s
C_3: 786.5 °C/124.5 s
Multi Pass; Mixed HAZ CR
C_1, C_3 <u>measured</u> in W6
C_2, predicted





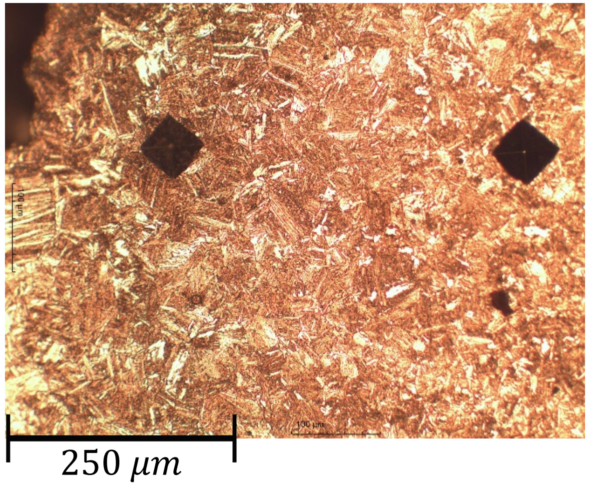


†Bath temperature between -10 °C and -14 °C

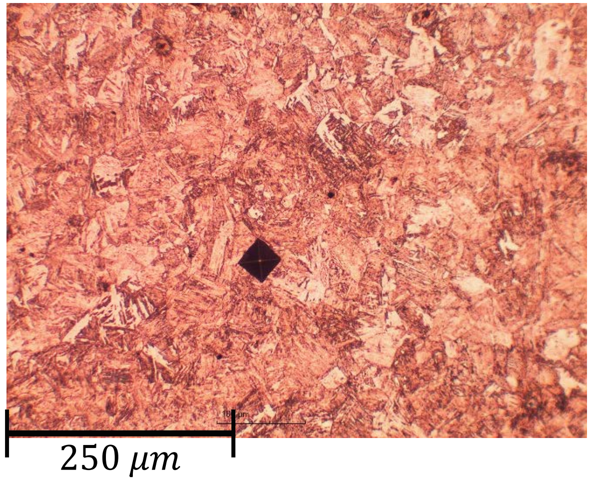
***Prototype weld/HAZ simulations in TC128B steel (CE=0.53; C=0.23 wt%)*

Simulated HAZ Procedure: CGHAZ Comparison

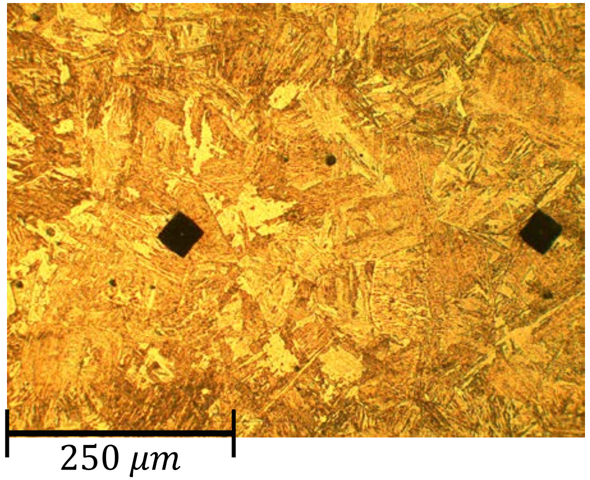
- **Microscopy for weld and simulated CGHAZ**
  - ***Welds***: *Gradient microstructure; smaller grain size*
  - ***Simulated:*** *More uniform microstructures; larger grain size in* ***A-1*** *and* ***D-1*****.** Refined microstructure in ***K*** sample



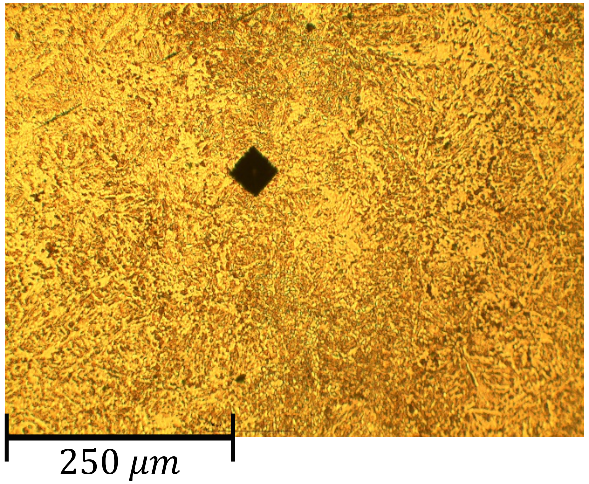
W-6 (74.6 kJ) Weld Sample 200x (1000 gf)



A-1_1317_9.2 Simulated Sample 200x (500 gf)



D-1_1352_47 Simulated Sample 200x (500 gf)



K Simulated Sample 200x (500 gf)

C_1: 1286 °C/13.4 s
C_2: 1279.1 °C/20.9 s
C_3: 786.5 °C/124.5 s

***Prototype weld/HAZ simulations in TC128B steel (CE=0.53; C=0.23 wt%)*

Summary: Prototyped weld/test procedures

Q1 and Q2 Progress

- **Selected/Procured materials** (DH-36 and HSLA-65, 0.5” and 2”); ordered Grade D (2”)
- **Developed GMA welding procedures** at slow cooling rate (75 kJ/in in 9/16” TC128-Grade B) and fast cooling rate (50 kJ/in weld in 2” (HPS Grade 50W) with in-situ T(t) obtained
- **Prototyped simulative HAZ test:** Demonstrated closed-loop validation protocol with direct toughness/ microstructure comparison of simulated HAZ to real weld

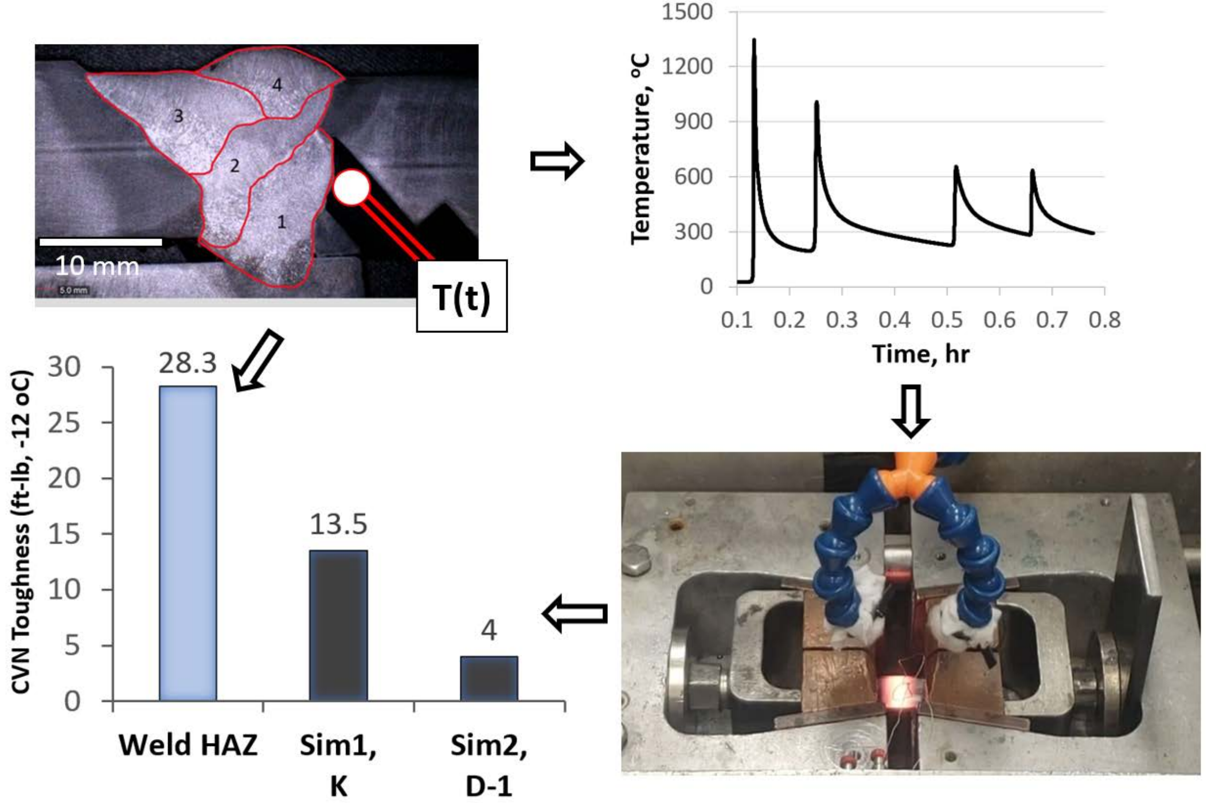


Figure 1: Closed loop validation *compares welding to physical simulation directly*

Project Benefits

Physical simulation provides:

- **Reduced variation**: thermal cycles, microstructures, and CVN toughness are reproducible. Avoids weld metal interference with measurement of HAZ toughness

- **Simplicity**: Systematically investigate relationship of weld thermal cycle to toughness for any combination of material thickness, welding heat input, and number of weld passes.

- **Streamlined PQR development** in S-1 series carbon steels with toughness requirements through simulative testing to find maximum heat inputs

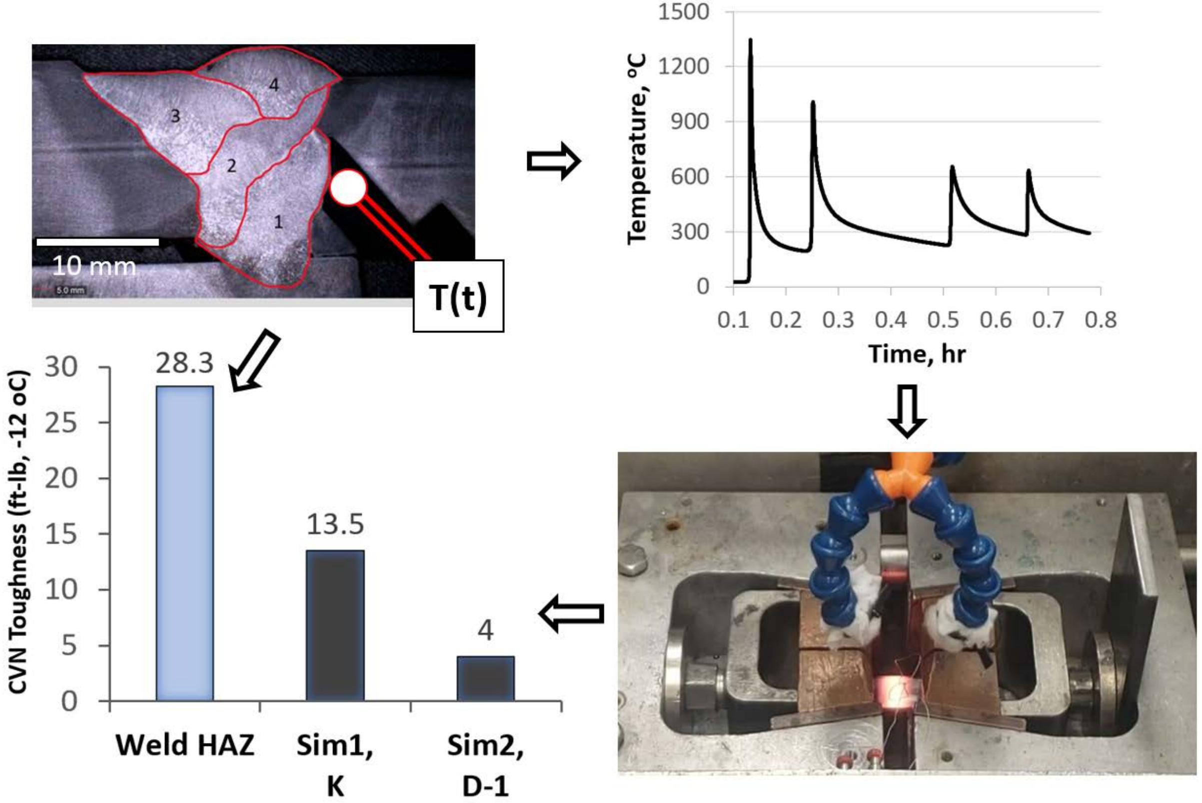


Figure 1: Closed loop validation *compares welding to physical simulation directly*

Next Steps

- **Execute four welding experiments**: 1/2″ 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)

- **Reproduce weld experiment data with simulative HAZ test**
  - Implement thermal cycle calculation protocol that reproduces welding thermal cycle
  - Develop Gleeble simulation protocol that reproduces HAZ weld properties (toughness, microhardness, and qualitative microscopy)

Questions?

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