NSRP | National Shipbuilding Research Program

Program Update

Welding

Virtual Panel Meeting

July 30, 2020

GoToWebinar

Welding Technology Virtual Panel Meeting

Time	Presentation	Speaker
1:00 pm	Opening Remarks & NSRP Program Update	Paul Hebert, Panel Chair Ryan Schneider, NSRP / ATI
1:15 pm	Panel Project Presentation – High Penetration Dynamic Buried Arc Welding	Nick Kapustka, EWI
1:45 pm	Panel Project Presentation – High Deposition Robotic Arc Additive Manufacturing Process Development	Mike Carney, EWI
2:15 pm	Panel Project Presentation – Miniature Torch Speed Sensor Based Adaptive Manual Arc Welding	Yu Ming Zhang, University of Kentucky
2:45 pm	Potential Panel Project	Megan Brinker, TruQC
3:05 pm	Potential Panel Project	Jonathan Roberts, Ingalls
3:25 pm	Potential Panel Project	Dennis Harwig, EWI
3:45 pm	Final Remarks	Paul Hebert, Panel Chair
4:00 pm	**End**	

NSRP Mission

NSRP Mission

The mission of the National Shipbuilding Research Program is to reduce the total ownership cost and improve the capabilities of both United States Government and U. S.-flag commercial ships.

The Program accomplishes this mission by providing a collaborative framework to manage, focus, develop and share research & development, and leverage best practices in shipbuilding and ship repair.

NSRP Collaboration

Anti-Trust Rules

Anti-Trust Rules

- Regarding your company's and/or your competitor's **product & services**:
  - Do not discuss current or future prices.
  - Do not discuss any increase or decrease in price.
  - Do not discuss pricing procedures.
  - Do not discuss standardizing or stabilizing prices.
  - Do not discuss controlling sales or allocating markets for any product.
  - Do not discuss future design or marketing strategies.

Anti-Trust Rules

- Regarding your company's and/or your competitors' selection of their **supplier companies**:
    - Do not discuss refusing to deal with a company because of its pricing or distribution practices.
    - Do not discuss strategies or plans to award business to remove business from a specific company.

- Regarding your company's and/or competitors' **trade secrets**:
    - Do not discuss trade secrets or confidential information of your company or any other participant.

Program Overview

Organization

Executive Control Board

Executive Director and Staff

Extended Team

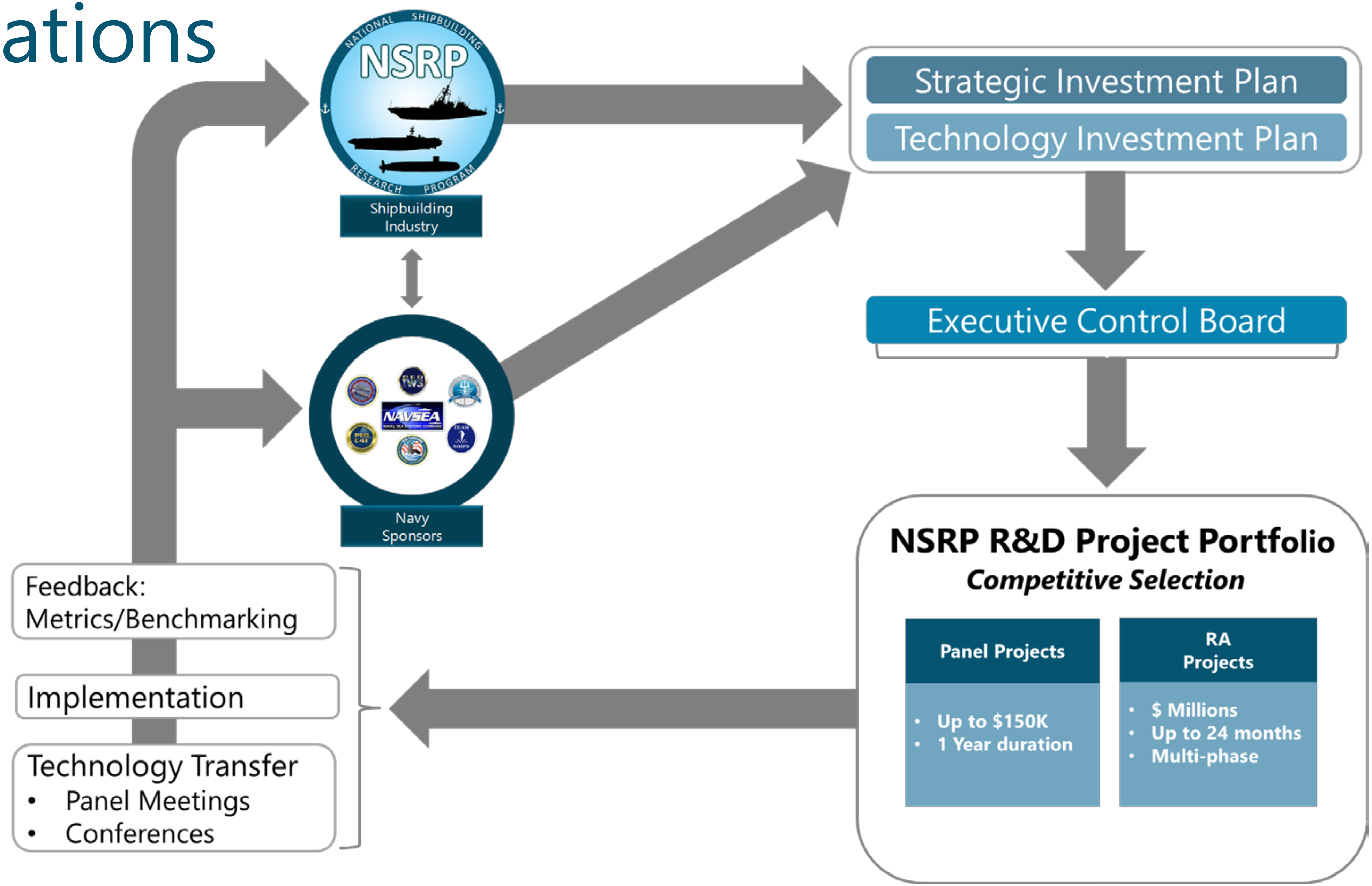
Major Initiatives

- Ship Design & Material Technologies
- Ship Production Technologies
- Business Processes & Information Technologies
- Infrastructure & Support

Panels

- Ship Design & Material Technologies
- Ship Warfare Systems Integration
- Electrical Technologies
- Planning, Production Processes & Facilities
- Surface Preparation & Coatings
- Welding Technology
- Business Technologies
- Digital Shipbuilding Committee
- Environmental, Health, and Safety
- Workforce Development

Operations


NATIONAL SHIPBUILDING RESEARCH PROGRAM
NSRP
Shipbuilding Industry
NAVSEA
Navy Sponsors
Strategic Investment Plan
Technology Investment Plan
Executive Control Board
NSRP R&D Project Portfolio
Competitive Selection
Panel Projects
• Up to $150K
• 1 Year duration
RA Projects
• $ Millions
• Up to 24 months
• Multi-phase
Feedback: Metrics/Benchmarking
Implementation
Technology Transfer
• Panel Meetings
• Conferences

Leadership and Management

Executive Control Board

Executive Director and Staff

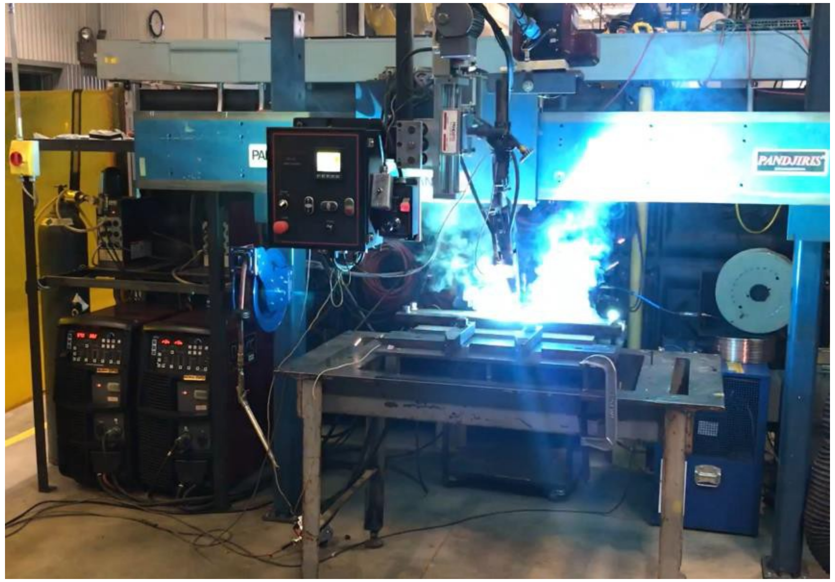
Extended Team

Major Initiatives

Panels

Navy Sponsors

Questions?



High Penetration Dynamic Buried Arc Welding

NSRP Project Number 2019-375 Task 003

EWI Project Number 58244GTH

Welding Technology Panel Meeting

July 30, 2020

Acknowledgements

- This project was funded by the National Shipbuilding Research Program – Advanced Shipbuilding Enterprise.
- Ingalls Shipbuilding provided the ½-in. DH 36 steel plate and 3/8-in. EH 36 steel plate for this project.
- OTC DAIHEN provided the buried arc GMAW system used for this project.

Project Team

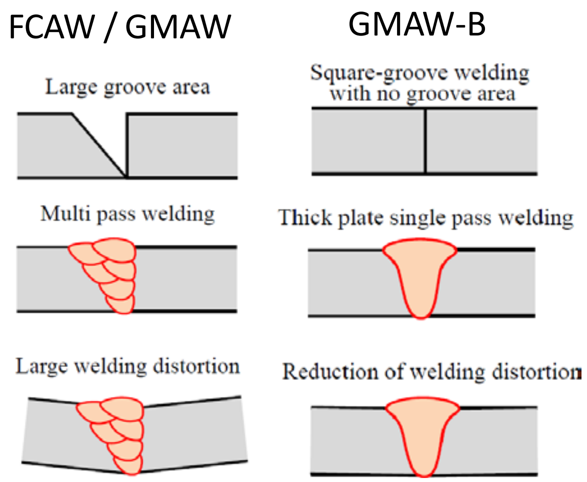
- EWI (prime)
  - Nick Kapustka (PI), Katie Hardin (PM), Steve Manring (Eng. Support)
- Participants
  - Kevin Roossinck (Ingalls)
  - Cody Whitely (NASSCO)
  - Jeff Farren (NSWCCD)
  - Ken Johnson (Vigor)
- NSRP Program Technical Representative (PTR)
  - Jonathan Roberts (Ingalls)
- NSRP Technical Representative
  - Mark Smitherman (ATI)
- Supporters
  - Nick Evans (GD-BIW)

Overview

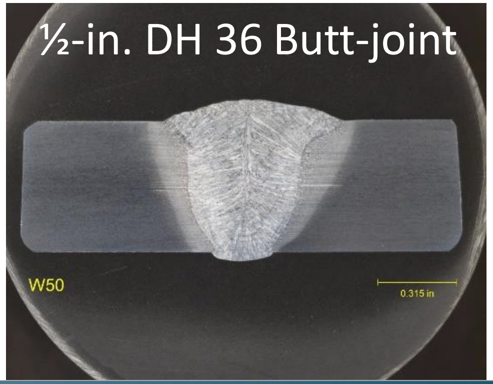
- Introduction
- Objectives
- Approach
- Application selection
- Results
- Conclusions

Introduction 1 of 2

- Shipyards have historically used submerged arc welding (SAW), flux cored arc welding (FCAW), and gas metal arc welding (GMAW) to fabricate butt-joints in thick steel plate.
- For butt-joints in ½-in. or thicker steel plate
  - Joint preparation is common.
  - Two-sided welding is common.
    - Plate flipping
    - Back gouging
  - SAW commonly uses two or more passes.
  - FCAW/GMAW typically require five or more passes.

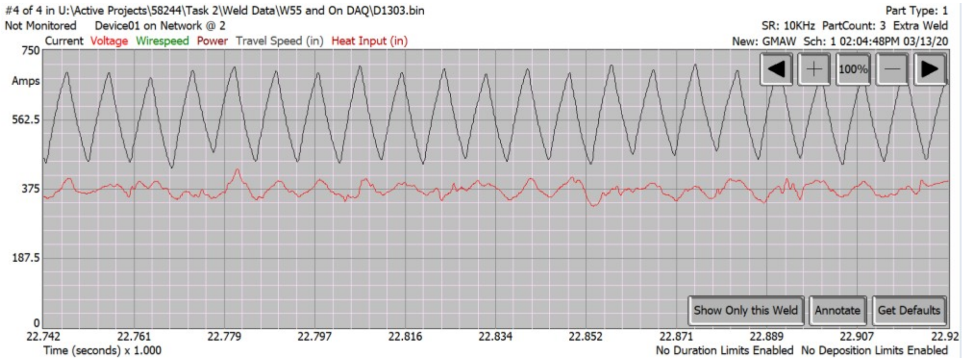


- OTC DAIHEN has a GMAW variant that is designed for buried arc welding of thick steel plate.
  - Single-sided, single-pass welds in up to ¾-in. thick steel
  - Joint preparation can be reduced or eliminated.
  - Plate flipping and back gouging can be eliminated.



Introduction

- GMAW-B has been promoted in the past, but erratic behavior and difficulty “tuning" the process have limited its applications.
- OTC DAIHEN has made improvements to the entire spectrum of this technology, which makes GMAW-B a potential high productivity, high-quality method for joining thick steel plates.
- GMAW-B is in the early stages of commercialization, so process and business case data are needed to support potential implementation in the U.S. shipbuilding industry.



Objective

- Identify GMAW-B procedures that can produce satisfactory thick plate welds in Navy and/or ABS steels that consistently meet the nondestructive evaluation (NDE) and mechanical testing requirements, while reducing weld times.

Approach 1 of 2

- Task 1 – Project Initiation and Kick-off Meeting (Complete)
  - Setup GMAW-B system at EWI
  - Project kick-off telecom
    - Identify up to two applications for evaluation
    - Discuss tests for evaluation of procedures for each application
  - Consult with NSWCCD and shipyard team members to identify tests for evaluating procedures for each application

- Task 2 – Identification of Buried Arc Parameter Sets (Complete)
  - Develop buried arc GMAW procedures for each application
  - Produce weldments for each application using the developed procedures
    - Evaluate with procedure qualification tests for legacy processes
    - Additional tests identified by the project team
  - Document productivity, heat input, and other data to support business case

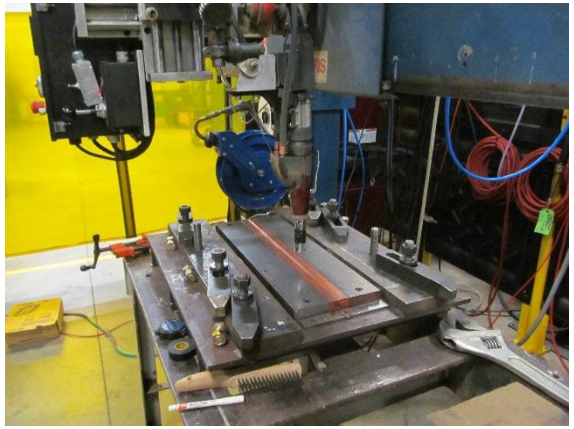
Approach

- Task 3 – Demonstration and Implementation (Complete)
  - Demonstrate the GMAW-B process and corresponding best developed procedures for the selected applications for the project team members at EWI

- Task 4 – Technology Transfer and Reporting (In-Process)
  - Project briefings at NSRP Welding Technology Panel meetings
  - Quarterly project progress reports
  - Final written report

Buried Arc System Setup

- OTC Daihen GMAW-B system
  - "Welbee DPS" power sources (2)
    - Programs designed for 0.052-in. Ø and 0.062-in. Ø steel wire, CO_2 shielding gas, and steel base material
  - Servo wire feed controllers (2)
  - Push wire feeder
  - Pull wire feeder
  - Heavy duty torch, 2.5 m
- Pandjiris side beam
- ArcAgent™ DAQ
- Water chiller

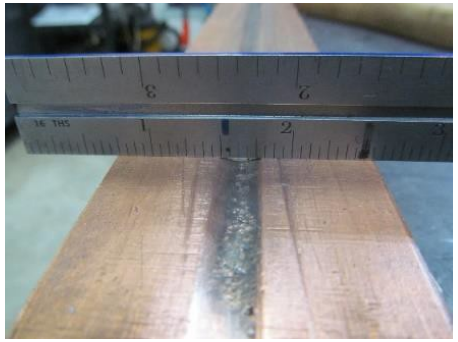


Candidate Applications

- Target implementation opportunities
  - Panel line welding
  - Gantry system welding

- #1 – Butt-joint in ½-in. thick DH 36 steel plate
  - Several joint designs screened

- #2 – Butt-joint in 3/8-in. thick EH36 steel plate
  - Square groove Butt-joint
- Constants
  - Flat (1G) position
  - ER70S-3 filler wire (preferred)
  - 100% CO_2 shielding gas
  - Copper backing bar



Qualification Requirements – Navy Work 1 of 2

- Tests required for evaluating GMAW-B procedures for both applications have been discussed with NSWCCD.
  - GMAW-B will likely be viewed as a GMAW process variant.
  - The selected joint designs don't comply with MIL-STD-22D, so special approval may be required.

- Actual procedure qualification requirements need to be determined in the future through discussions with NSWCCD and NAVSEA.

- Requirements specified in NAVSEA Tech Pub 248 for qualifying procedures of legacy processes will likely apply in addition to any other NAVSEA specified requirements.
  - Nondestructive evaluation
    - Visual testing, magnetic particle testing, radiographic testing, ultrasonic testing
  - Mechanical testing
    - Tensile specimens (2), face bend specimens (2), root bend specimens (2)

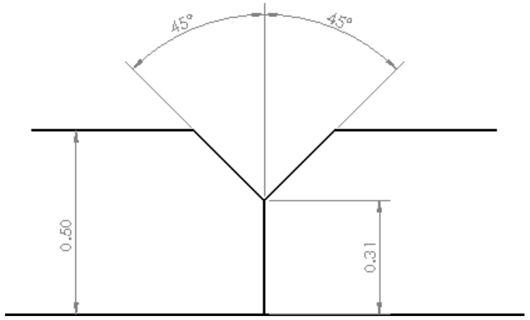
Qualification Requirements – Navy Work

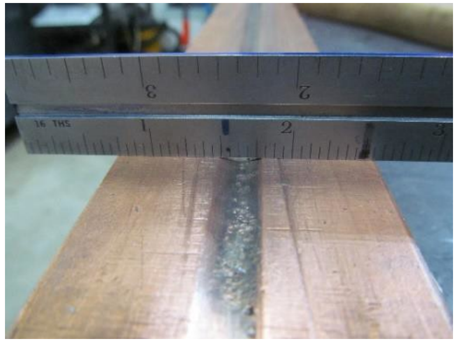
- Impact testing for S-1 materials using legacy processes
  - Not required when base material thickness is less then ½ in. per both Tech Pub 248 revisions
  - Not required for S-1 materials per Tech Pub 248 1995 Revision
  - Not required for S-1 materials when heat input is 109 kJ/in. or less per Tech Pub 248 2019 Revision

- Impact testing performed per project team's request
  - Five weld metal CVN specimens
  - Three heat affected zone (HAZ) CVN specimens
  - Three base metal CVN specimens

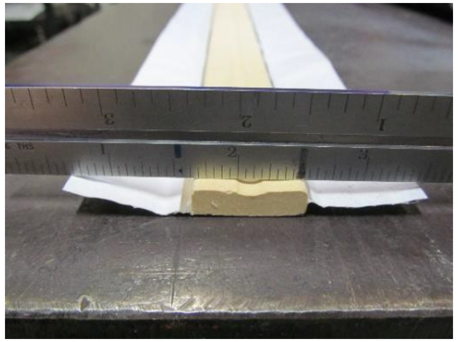
Welds W49 to W52 – ½-in. DH 36 Plate

- Goals
  - Determine NDE and mechanical test results
  - Evaluate effects of backing type
  - Evaluate effects of wire type/source
- Approach
  - Joint prep with shallow groove
  - Filler wires
    - 1/16-in. Ø ER70S-3 (W51, W52)
    - 1/16-in. Ø ER70S-G (W49, W50)
  - Backing
    - Copper backing (W50, W52)
    - Ceramic backing (W49, W51)
  - No root opening
- Evaluation
  - NDE: VT, MT, RT, UT
  - Mechanical testing of W50





0.034-in. Deep, 0.31-in. Wide

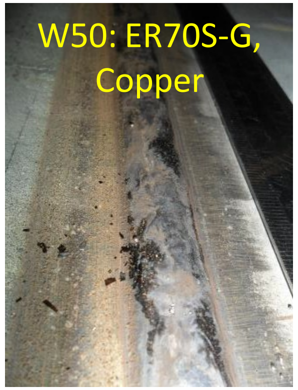


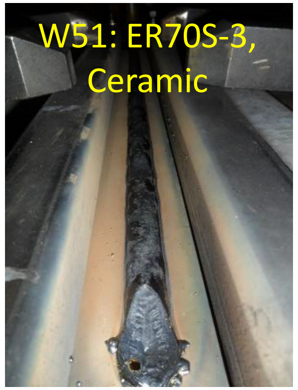
0.050-in. Deep, 0.20-in. Wide

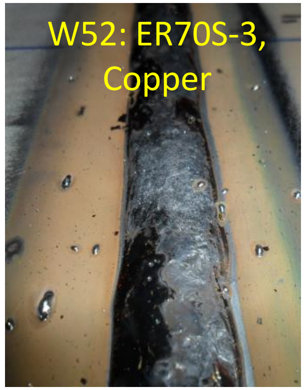
Power Source Parameters (Main)						
Travel Speed (ipm)	CTWD (in)	Travel Angle (deg)	Main		Buried Arc Char. (-20 to +20)	Arc Control (-10 to +10)
			Current (A)	Trim (-30 to +30)		
18.0	5/8	10° Push	508	-10	0	0

Welds W49 to W52 – NDE

- All welds met the Class 1 NDE requirements of MIL-STD-2035.
  - Reinforcement ≤ 3/32 in. in the as-welded condition
- ER70S-G wire provided better stability and profile compared to the ER70S-3 wire.
  - W49, W50, W51
    - Met VT requirements in as-welded condition
  - W52 (ER70S-3)
    - Arc instability between 18 and 21 in. from the start which resulted in overlap in the reinforcement
    - Reinforcement removed from 18 in. to the end prior to NDE by grinding



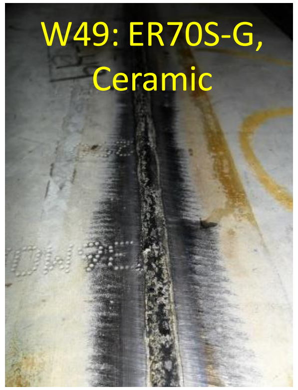


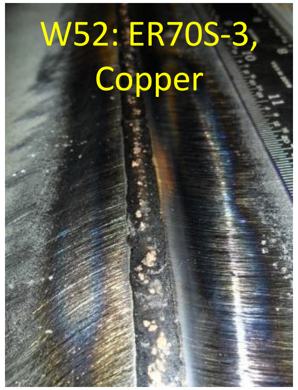


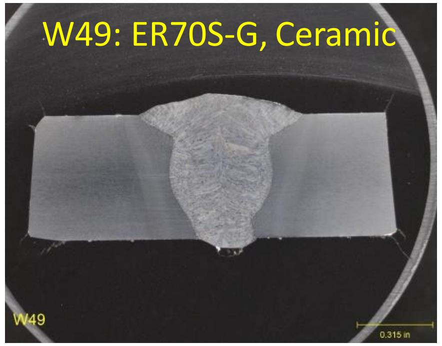
Weld ID	Wire	Backing	Visual Testing		Magnetic Particle Testing		Ultrasonic Testing	Radiographic Testing
			Weld Side (Pass/Fail)	Root Side (Pass/Fail)	Weld Side (Pass/Fail)	Root Side (Pass/Fail)	(Pass/Fail)	(Pass/Fail)
W49	ER70S-G	Ceramic	Pass	Pass	Pass	Pass	Pass	Pass
W50	ER70S-G	Copper	Pass	Pass	Pass	Pass	Pass	Pass
W51	ER70S-3	Ceramic	Pass	Pass	Pass	Pass	Pass	Pass
W52	ER70S-3	Copper	Pass	Pass	Pass	Pass	Pass	Pass

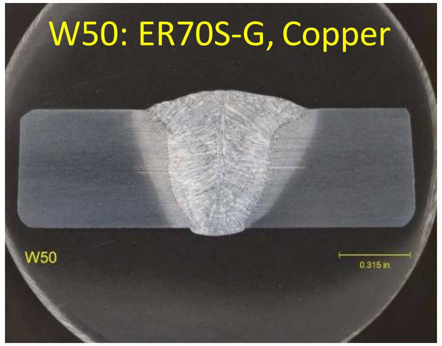
Welds W49 to W52 – Backing Evaluation

- Welds made with identical procedures and both copper and ceramic backing met all NDE requirements.
- Ceramic backing resulted in smoother toes on the underside of the weld.
  - Effect of root opening on backing type needs to be determined.









Weld W50 – Tensile & Bend Testing

- Tensile test specimens met the property requirements for ER70S-3 wire and DH 36 plate.
  - Tensile test specimens broke in the base material.

Specification	Ultimate Tensile Strength	0.2% Yield Strength	Elongation
AWS A5.18 (ER70S-3 Wire)	70-ksi Min.	58-ksi Min.	22% Min.
ABS Rules (DH 36 Plate)	71- to 90-ksi	51-ksi Min.	20% Min.
T1	79.0-ksi	66.0-ksi	31.7%
T2	80.1-ksi	66.8-ksi	35.9%

- Bend test specimens passed with no visual defects.
  - Tested with a mandrel Ø of 1.5 in. to impose 20% elongation

Weld W50 – Weld Metal CVN Results

- AWS A5.18 Table 4 impact test requirements for ER70S-3 wire
  - Test temperature: -20°C
  - Min. average impact strength of middle three specimens: 27-J
- Weld metal CVN specimens met the filler wire impact test requirements.
  - All five values are above 27-J.
  - Average impact strength is 67-J.

Notched Bar Impact Test, ASTM E23

Specimen Type: A (V-Notch) **Test Date:** 2/21/2020 **Released By:** Steve O'Mara

Specimen ID (N/A)	Notch Location (N/A)	Notch Orientation (N/A)	W (mm)	D (mm)	Test Temperature (C)	Abs. Energy (J)	Lateral Expansion (mm)	Shear Area (%)	Condition (N/A)
WM1	WCL	T-L	9.99 0.393 (in)	10.00 0.394 (in)	-20.0 -4 (F)	33.0 24 (ft-lb)	0.66 0.026 (in)	10	As Received
WM2	WCL	T-L	9.99 0.393 (in)	10.00 0.394 (in)	-20.0 -4 (F)	76.0 56 (ft-lb)	1.23 0.048 (in)	38	As Received
WM3	WCL	T-L	9.99 0.393 (in)	10.00 0.394 (in)	-20.0 -4 (F)	59.0 44 (ft-lb)	1.00 0.039 (in)	26	As Received
WM4	WCL	T-L	9.99 0.393 (in)	10.00 0.394 (in)	-20.0 -4 (F)	74.0 55 (ft-lb)	1.18 0.046 (in)	43	As Received
WM5	WCL	T-L	9.99 0.393 (in)	10.00 0.394 (in)	-20.0 -4 (F)	69.0 51 (ft-lb)	1.12 0.044 (in)	26	As Received

Weld W50 – HAZ/BM CVN Results

- ABS Rules impact test requirements for DH 36 base material.
  - Test temperature: -20°C
  - Minimum average impact strength: 34-J, 24-J
- HAZ CVN specimens met the base metal requirements.
  - All three values are well above 34-J.
  - Average impact strength is 317-J.
- Base material (BM) meets base material requirements.
  - All three values are well above 34-J.
  - Average impact strength is 285-J.

HAZ CVNs

Notched Bar Impact Test, ASTM E23

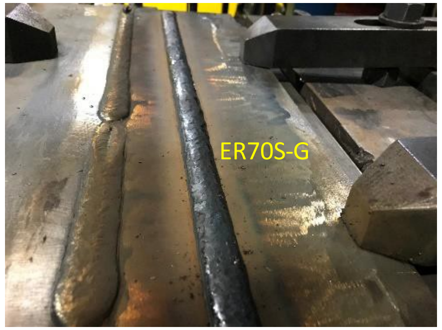
Specimen Type: A (V-Notch) **Test Date:** 2/21/2020 **Released By:** Steve O'Mara

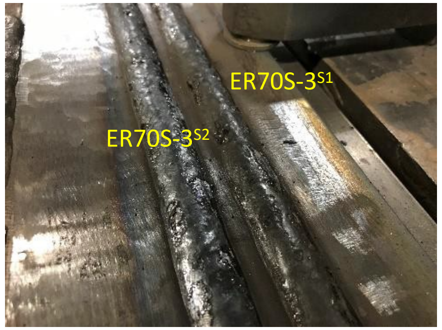
Base Material CVNs

Specimen ID (N/A)	Notch Location (N/A)	Notch Orientation (N/A)	W (mm)	D (mm)	Test Temperature (C)	Abs. Energy (J)	Lateral Expansion (mm)	Shear Area (%)	Condition (N/A)
BM1	Base	T-L	9.99 0.393 (in)	10.00 0.394 (in)	-20.0 -4 (F)	315.0 232 (ft-lb)	2.47 0.097 (in)	100	As Received
BM2	Base	T-L	9.99 0.393 (in)	10.00 0.394 (in)	-20.0 -4 (F)	291.0 215 (ft-lb)	1.81 0.071 (in)	100	As Received
BM3	Base	T-L	9.99 0.393 (in)	10.00 0.394 (in)	-20.0 -4 (F)	250.0 184 (ft-lb)	2.49 0.098 (in)	100	As Received
HAZ1	HAZ	T-L	9.99 0.393 (in)	10.00 0.394 (in)	-20.0 -4 (F)	190.0 140 (ft-lb)	2.08 0.082 (in)	52	As Received
HAZ2	HAZ	T-L	9.99 0.393 (in)	10.00 0.394 (in)	-20.0 -4 (F)	380.0 280 (ft-lb)	2.57 0.101 (in)	100	As Received
HAZ3	HAZ	T-L	9.99 0.393 (in)	10.00 0.394 (in)	-20.0 -4 (F)	382.0 282 (ft-lb)	2.63 0.104 (in)	100	As Received

Wire Selection Trials – ½-in. DH 36

- GMAW-B is of interest for both NAVSEA and ABS applications.
  - ER70S-G cannot be used for NAVSEA applications and is not preferred for ABS applications.
  - Domestically supplied MIL70S-3 wire or ER70S-3 wire is needed.
- Second domestic source of 1/16-in. ER70S-3* wire was acquired to compare to ER70S-G wire and first source of ER70S-3* wire.
- Bead-on-plate trial data
  - Parameters of W49 – W52
  - Visual observation
  - High speed data acquisition of current and voltage waveforms (10 kHz)



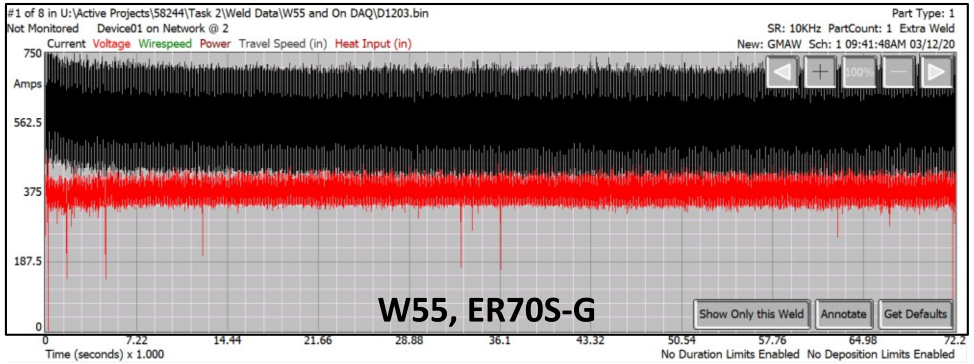


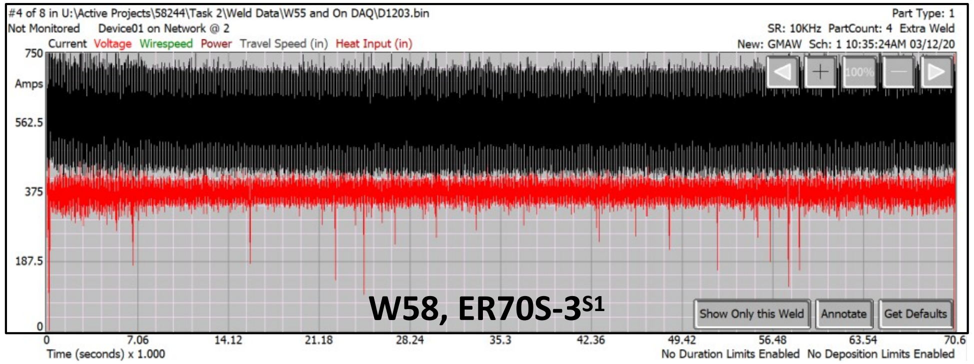
Weld ID	Wire Type	Duration (sec)	≈ Length (in)	Data Acquisition (10-kHz Sampling Freq.) Avg. Current (A)	Avg. Voltage (V)	Power (W)	Heat Input (kJ/in.)
W55	ER70S-G	72.2	21.3	566	37.3	21,184	70.6
W58	ER70S-3S1	70.6	20.6	569	37.2	21,238	70.8
W59	ER70S-3S2	73.1	21.3	555	37.6	20,971	69.9

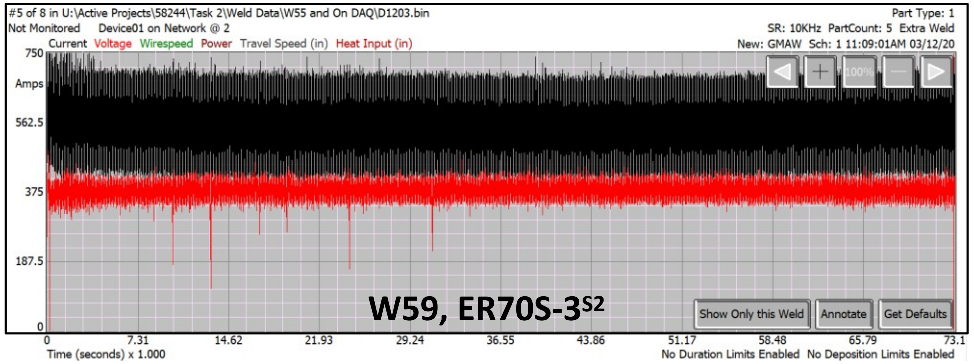
* First source of ER70S-3 wire designated ER70S-3S1, Second source or ER70S-3 wire designated ER70S-3S2

Wire Selection Trials – ½-in. DH 36 2 of 2

- Process stability – visual
  - Welds with ER70S-3^{S2} and ER70S-G wires have excellent process stability.
  - Weld with ER70S-3^{S1} wire had much less process stability.
- I and V waveforms
  - Welds made with ER70S-3^{S2} and ER70S-G wires appear more stable than weld made with ER70S-3^{S1} wire.

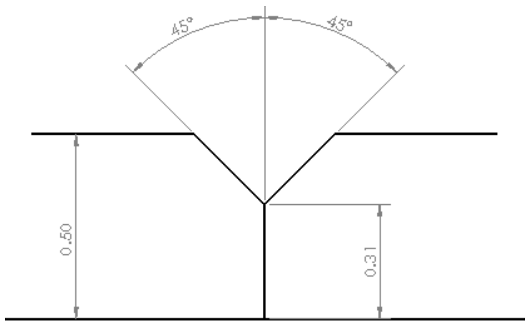


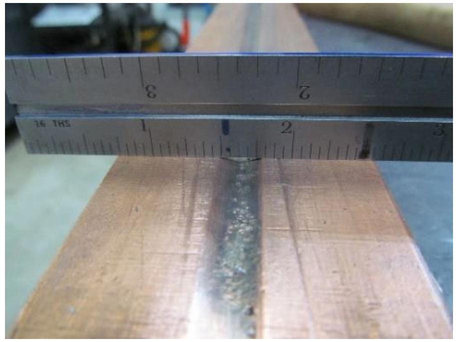




Weld W65 – ½-in. DH 36 Plate

- Goals
  - Verify NDE requirements can be met when ER70S-3 wire is used
  - Calculate heat input (10-kHz freq.)
  - Video
- Approach
  - ER70S-3[S2] wire, 1/16 in. Ø
  - Parameters of W49 – W52
  - Copper backing bar
  - No root opening
- Evaluation
  - NDE: VT, MT, RT, UT
  - Heat input calculated



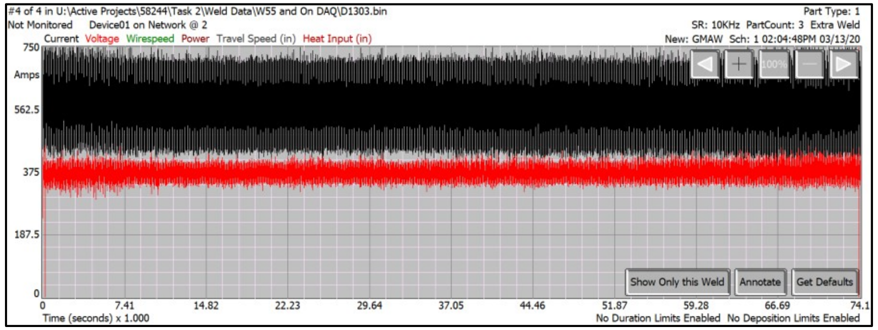


0.034-in. Deep, 0.31-in. Wide

Power Source Parameters (Main)						
Travel Speed (ipm)	CTWD (in)	Travel Angle (deg)	Main		Buried Arc Char. (-20 to +20)	Arc Control (-10 to +10)
			Current (A)	Trim (-30 to +30)		
18.0	5/8	10° Push	508	-10	0	0

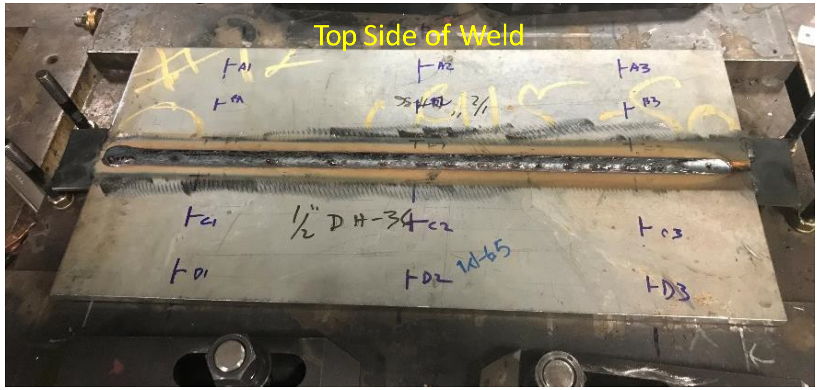
Weld W65 – Video & Waveforms

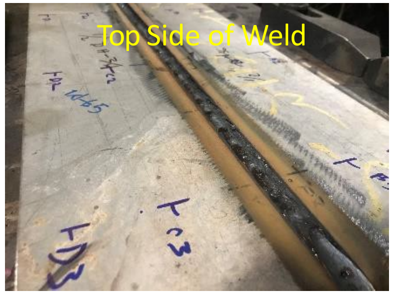
- Video available upon request
- Excellent process stability
- Heat input = 71.1 kJ/in.

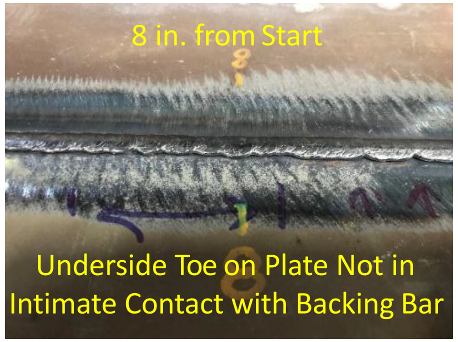


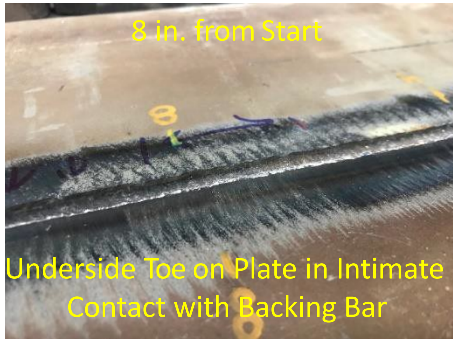
Weld W65 – NDE

- W65 meets the Class 1 VT, MT, RT, and UT requirements
  - One of two plates was not in intimate contact with the backing bar which resulted in rollover on the underside.
    - Underside reinforcement removed prior to NDE.
  - Lesson learned
    - Plates need to be in intimate contact with the copper backing.



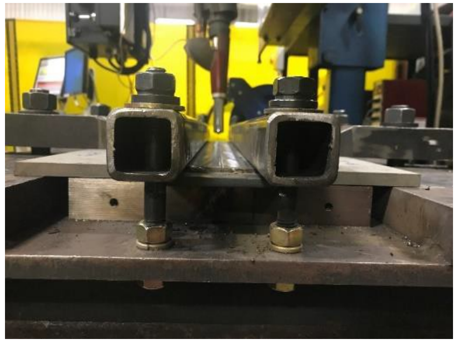


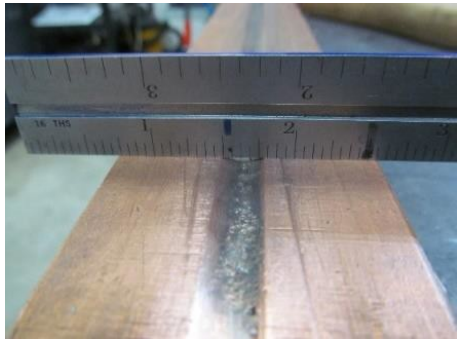




Weld W64 – 3/8-in. EH 36 Plate

- Goals
  - Determine NDE and mechanical test results
  - Calculate heat input
  - Video
- Approach
  - Square butt-joint
  - ER70S-3[S2] wire, 1/16-in. Ø
  - Copper backing bar
  - No root opening
- Evaluation
  - NDE: VT, PT, MT, RT, UT
  - Mechanical testing
  - Heat input calculated

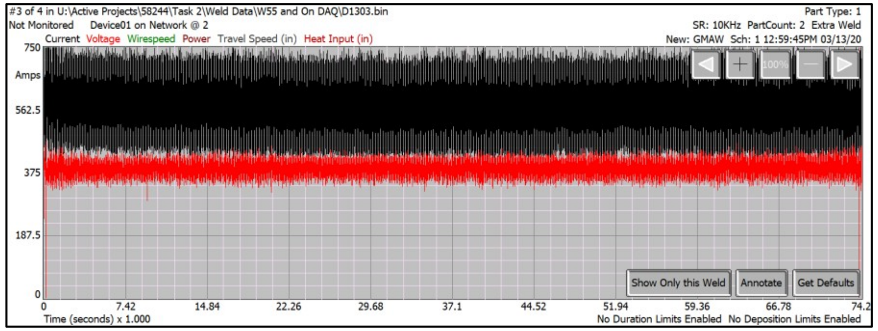


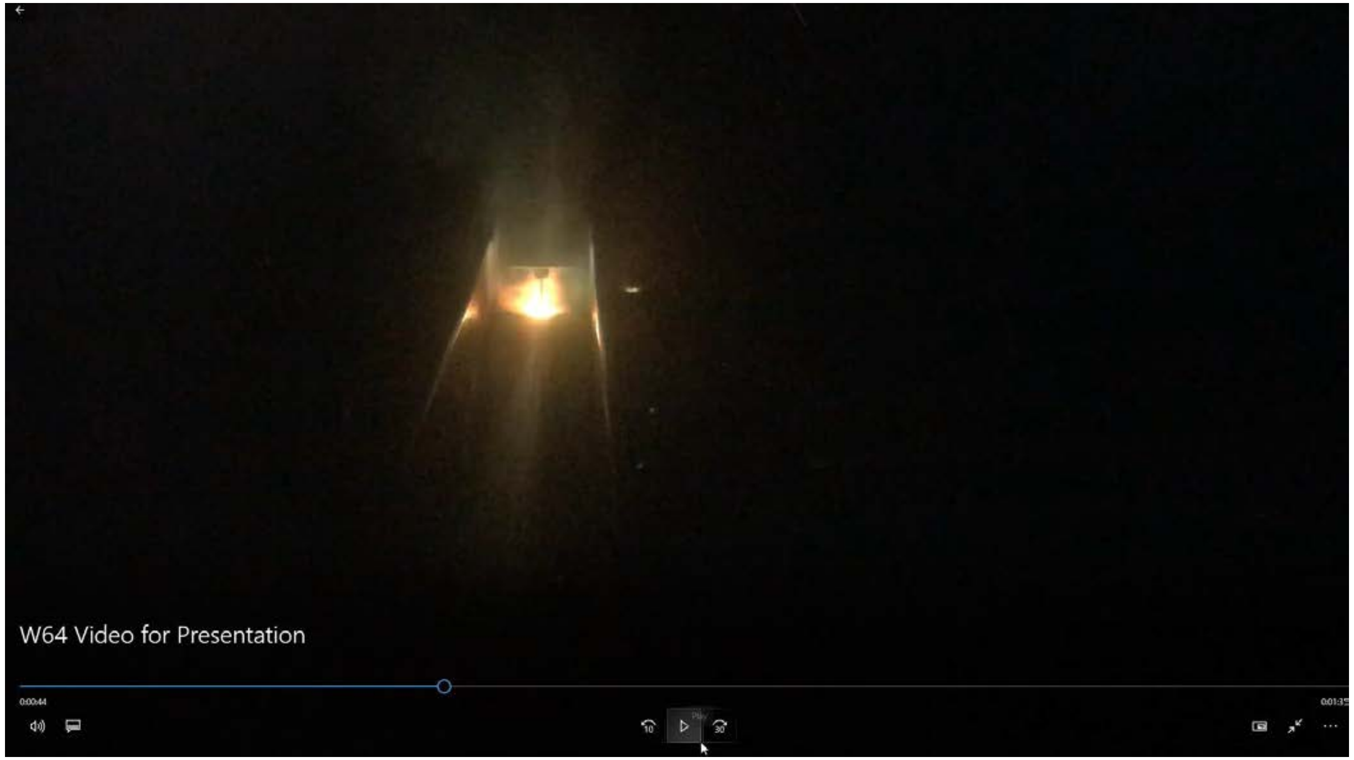


Power Source Parameters (Main)						
Travel Speed (ipm)	CTWD (in)	Travel Angle (deg)	Main		Buried Arc Char. (-20 to +20)	Arc Control (-10 to +10)
			Current (A)	Trim (-30 to +30)		
18.0	5/8	10° Push	529	-10	0	0

Weld W64 – Video & Waveforms

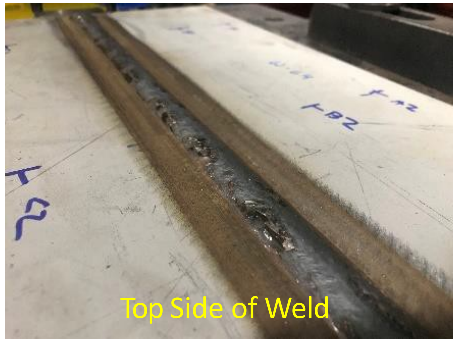
- Video available upon request
- Excellent process stability
- Heat input = 74.2 kJ/in.

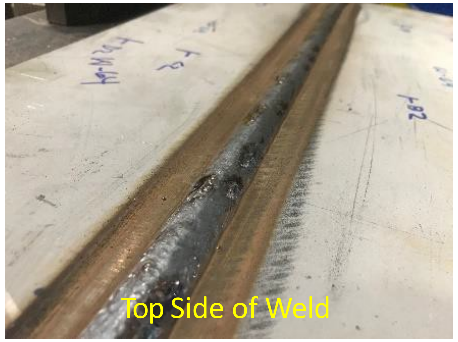




Weld W64 – NDE

- Excellent weld and underside profiles
- W64 meets the Class 1 VT, MT, RT, and UT requirements.
  - VT acceptance is contingent on weld cap reinforcement being reduced from 1/8 to 3/32 in.


Top Side of Weld

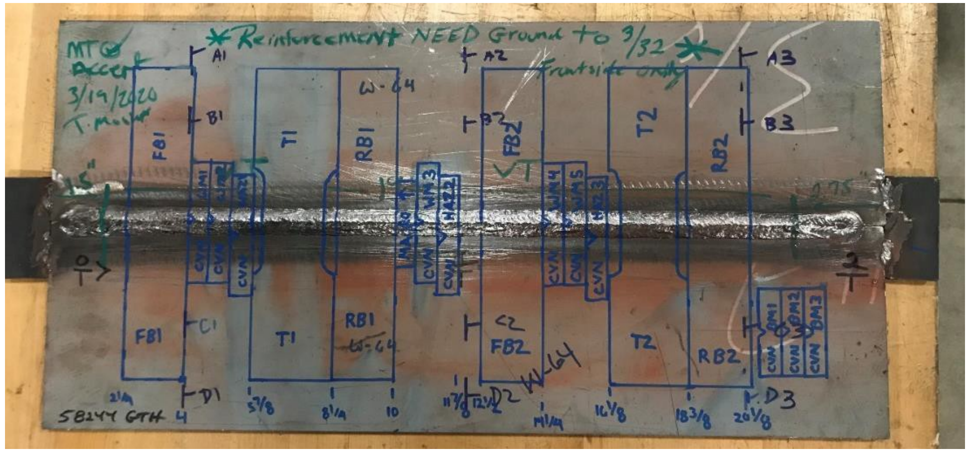

Top Side of Weld


Underside of Weld


Underside of Weld

Weld W64 – Destructive Testing

- Mechanical testing was performed in accordance with Tech Pub 248
  - Specimen layout was performed in accordance with Figure 2
    - Tensile (2)
    - Face bend (2)
    - Root bend (2)
    - Weld metal CVN (5)
    - HAZ CVN (3)
    - Base metal CVN (3)
  - ¾ Size CVN specimens



Weld W64 – Tensile and Bend Testing

- Tensile test specimens met the property requirements for ER70S-3 wire and EH 36 plate.

Specification	Ultimate Tensile Strength	0.2% Yield Strength	Elongation
AWS A5.18 (ER70S-3 Wire)	70-ksi Min.	58-ksi Min.	22% Min.
ABS Rules (EH36 Plate)	71- to 90-ksi	51-ksi Min.	20% Min.
T1	83.5-ksi	65.0-ksi	31.5%
T2	82.9-ksi	61.7-ksi	29.4%

- Bend test specimens passed with no visual defects.
  - Tested using a 1.5-in. Ø mandrel to impose 20% elongation

Weld W64 – Weld Metal CVN Results

- AWS A5.18 Table 4 impact test requirements for ER70S-3 wire.
  - Test temperature: -20°C
  - Min. average impact strength of middle three specimens: 20-J (3/4-size)
- Weld metal CVN specimens did not meet the filler metal CVN requirements.
  - Average impact strength = 14-J
  - Impact testing is not required for procedure qualification of S-1 materials with thickness < ½ in.

Notched Bar Impact Test, ASTM E23

Specimen Type: A (V-Notch) **Test Date:** 4/8/2020 **Released By:** Steve O'Mara

Specimen ID (N/A)	Notch Location (N/A)	Notch Orientation (N/A)	W (mm)	D (mm)	Test Temperature (C)	Abs. Energy (J)	Lateral Expansion (mm)	Shear Area (%)	Condition (N/A)
WM1	WCL	T-L	7.50 0.295 (in)	10.00 0.394 (in)	-20.0 -4 (F)	12.0 9 (ft-lb)	0.35 0.014 (in)	38	As Received
WM2	WCL	T-L	7.50 0.295 (in)	10.00 0.394 (in)	-20.0 -4 (F)	22.0 16 (ft-lb)	0.63 0.025 (in)	48	As Received
WM3	WCL	T-L	7.49 0.295 (in)	10.00 0.394 (in)	-20.0 -4 (F)	12.0 9 (ft-lb)	0.39 0.015 (in)	35	As Received
WM4	WCL	T-L	7.49 0.295 (in)	10.00 0.394 (in)	-20.0 -4 (F)	18.0 13 (ft-lb)	0.49 0.019 (in)	40	As Received
WM5	WCL	T-L	7.50 0.295 (in)	10.00 0.394 (in)	-20.0 -4 (F)	7.0 5 (ft-lb)	0.18 0.007 (in)	30	As Received

Weld W64 – HAZ/BM CVN Results

- ABS Rules impact test requirements for EH 36 base material.
  - Test temperature: -40°C
  - Minimum average impact strength for ¾ size specimens: 26-J, 18-J
- HAZ CVN specimens met the base material requirements.
  - All three values are above 26-J.
  - Average impact strength is 72-J.
- Base material CVN specimens met the base material requirements.
  - All three values are well above the 26-J.
  - Average impact strength is 108-J.

HAZ CVNs

Notched Bar Impact Test, ASTM E23

Specimen Type: A (V-Notch) **Test Date:** 4/8/2020 **Released By:** Steve O'Mara

Base Metal CVNs

Specimen ID (N/A)	Notch Location (N/A)	Notch Orientation (N/A)	W (mm)	D (mm)	Test Temperature (C)	Abs. Energy (J)	Lateral Expansion (mm)	Shear Area (%)	Condition (N/A)
HAZ1	HAZ	T-L	7.49 0.295 (in)	10.00 0.394 (in)	-40.0 -40 (F)	44.0 32 (ft-lb)	0.99 0.039 (in)	81	As Received
HAZ2	HAZ	T-L	7.49 0.295 (in)	9.99 0.393 (in)	-40.0 -40 (F)	69.0 51 (ft-lb)	1.43 0.056 (in)	92	As Received
HAZ3	HAZ	T-L	7.49 0.295 (in)	10.00 0.394 (in)	-40.0 -40 (F)	103.0 76 (ft-lb)	2.07 0.081 (in)	89	As Received
BM1	Base	T-L	7.50 0.295 (in)	9.98 0.393 (in)	-40.0 -40 (F)	83.0 61 (ft-lb)	1.81 0.071 (in)	82	As Received
BM2	Base	T-L	7.50 0.295 (in)	9.98 0.393 (in)	-40.0 -40 (F)	132.0 97 (ft-lb)	2.51 0.099 (in)	100	As Received
BM3	Base	T-L	7.50 0.295 (in)	9.98 0.393 (in)	-40.0 -40 (F)	110.0 81 (ft-lb)	2.18 0.086 (in)	88	As Received

Heat Input & Productivity Comparison with a Legacy Process

- Legacy process used at one shipyard is single wire SAW, two-sided procedure.
- Benefits of buried arc GMAW:
  - Plate flipping can be eliminated.
  - Arc-on-time per foot can be reduced.
  - Total heat input can be reduced which may result in lower distortion.
  - Back-gouging can be eliminated for plates ½-in. thick and above.
  - Flux is eliminated.

3/8-in. EH 36 Steel Plate								
Process	Joint Prep	Pass 1		Pass 2		Additional Processes	Total Arc-on-Time per Foot of Weld	Total Heat Input
		Travel Speed	Heat Input	Travel Speed	Heat Input			
SAW	Square Groove	32-ipm	30.9-kJ/in.	32-ipm	55.8-kJ/in.	Plate Flipping	1.50-min.	86.7-kJ/in.
GMAW-B (W64)		18-ipm	74.2-kJ/in.	N/A	N/A	None	1.33-min.	74.2-kJ/in.
						% Change	11% Reduction	14% Reduction

½-in. DH 36 Steel Plate								
Process	Joint Prep	Pass 1		Pass 2		Additional Processes	Total Arc-on-Time per Foot of Weld	Total Heat Input
		Travel Speed	Heat Input	Travel Speed	Heat Input			
SAW	Square Groove	25-ipm	58.8-kJ/in.	25-ipm	82.1-kJ/in.	Plate Flipping Back-gouging	1.92-min.	140.1-kJ/in.
GMAW-B (W65)	Shallow Bevel*	18-ipm	71.1-kJ/in.	N/A	N/A	Plate Bevel	1.33-min.	71.1-kJ/in.
						% Change	31% Reduction	49% Reduction

Heat Input & Productivity Comparison with a Legacy Process

- Legacy process used at one shipyard is single wire SAW, two-sided procedure.
- Benefits of buried arc GMAW:
  - Plate flipping can be eliminated.
  - Arc-on-time per foot can be reduced.
  - Total heat input can be reduced which may result in lower distortion.
  - Back-gouging can be eliminated for plates ½-in. thick and above.
  - Flux is eliminated.

3/8-in. EH 36 Steel Plate								
Process	Joint Prep	Pass 1		Additional Processes	Pass 2		Total Arc-on-Time per Foot of Weld	Total Heat Input
		Travel Speed	Heat Input		Travel Speed	Heat Input		
SAW	Square Groove	32-ipm	30.9-kJ/in.	Plate Flipping	32-ipm	55.8-kJ/in.	1.50-min.	86.7-kJ/in.
GMAW-B (W64)		18-ipm	74.2-kJ/in.	None	N/A	N/A	1.33-min.	74.2-kJ/in.
						% Change	11% Reduction	14% Reduction

½-in. DH 36 Steel Plate								
Process	Joint Prep	Pass 1		Additional Processes	Pass 2		Total Arc-on-Time per Foot of Weld	Total Heat Input
		Travel Speed	Heat Input		Travel Speed	Heat Input		
SAW	Square Groove	25-ipm	58.8-kJ/in.	Plate Flipping Back-Gouging	25-ipm	82.1-kJ/in.	1.92-min.	140.1-kJ/in.
GMAW-B (W65)	Shallow Bevel*	18-ipm	71.1-kJ/in.	Plate Bevel	N/A	N/A	1.33-min.	71.1-kJ/in.
						% Change	31% Reduction	49% Reduction

Summary

- Buried arc GMAW procedures were developed for producing single pass welds in ½-in. DH 36 steel plate.
  - Weldments made with ER70S-G and two ER70S-3 wire met Class 1 NDE requirements.
  - Weldment produced with ER70S-G wire met the mechanical testing requirements for procedure qualification of legacy processes. Impact testing was also performed.
    - Weld metal CVNs met the impact testing requirements for ER70S-3 wire.
    - HAZ and base metal CVNs met the requirements for DH 36 steel plate.
  - Suitability for use with both copper backing and ceramic backing was shown.

- Buried arc GMAW procedures were developed for producing single pass welds in 3/8-in. EH 36 steel plate.
  - Weldment produced with the developed procedures and ER70S-3 wire met the NDE and mechanical testing requirements for procedure qualification of legacy processes. Impact testing was also performed using ¾ size specimens.
    - Weld metal CVNs did not meet the requirements for ER70S-3 wire.
    - HAZ and base metal CVNs met the requirements for EH 36 steel plate.
  - Feasibility of root opening tolerance of 0.04 to 0.16 in. was demonstrated with similar procedures.

Questions

High Deposition Robotic Arc Additive Manufacturing Process Development

NSRP Project Number 2019-375 Task 002

Welding Technology Panel Meeting

July 30, 2019

Acknowledgments

• This project was funded by the National Shipbuilding Research Program – Advanced Shipbuilding Enterprise

Introduction

- Shipyards need a faster way to deposit weld material used in directed energy deposition (DED) additive manufacturing (AM) applications
- For gas metal arc (GMA) AM, high melting rate waveforms (lbs/amp) are desired to minimize heat input while maximizing deposition rate (lbs/hr)
- Tandem GMAW (T-GMAW), offers 200% to 300% improvement in speed and deposition rate compared to conventional single electrode GMAW for welding applications
- T-GMAW provides improvements by using two electrodes in close proximity.
- This project is focused on developing high deposition robotic T-GMA AM technology for a candidate material (such as stainless steel) that is selected by the project team.

Project Team

- EWI (prime)
  - Michael Carney (PI), Katie Hardin (PM), Dennis Harwig (STA)
- Austal (participant)
  - Shawn Wilber
- NSWCCD (participant)
  - Susan Hovanec
- NSRP Project Manager
  - Frances Pearce (ATI)
- NSRP Program Technical Representative (PTR)
  - Ken Johnson (Vigor Shipyards)

Objectives

The project goal is to develop high deposition robotic T-GMA AM process technology and establish process metrics for building large shapes and features on candidate material applications. The project objectives were:

1. Identify a candidate application and select a material for high deposition GMA AM technology development.
2. Evaluate high deposition GMA waveforms for maximum melting rate (lbs/amp) to minimize total heat input for building bulk shapes and controlling features (near net shape).
3. Develop high deposition GMA AM procedure models for the candidate material to control edge and layer features for building single-pass per layer walls and multiple pass per layer blocks.
4. Build prototype process qualifications for the selected application to establish structural properties and process-feature-property relationships.
5. Provide high deposition GMA AM process metrics for the selected application as an alternative to conventional shipbuilding processes.

Approach (1 of 2)

- Task 1 – Project Initiation and Kick-off Meeting:
  - Issue subcontracts to participants **(Complete)**
  - Project kick-off meeting **(Complete)**
  - Finalize the project plan **(Complete)**
- Task 2 – Evaluate T-GMA Waveforms for Maximum Melting Rate and Quality:
  - Setup a robotic T-GMA system **(Complete)**
  - Select up to four candidate waveforms for evaluation **(Complete)**
  - Develop T-GMA procedures for single bead and multi-pass deposits with the goal of maximizing productivity (single layer) **(Complete)**
  - Produce a single pass bead and a multi-pass deposit using the best developed procedures for each candidate waveform **(Complete)**
  - Summarize results in PowerPoint and present results to the project team **(Complete)**

Approach (2 of 2)

- Task 3 – Develop Robotic T-GMA AM Procedures for Shape Deposition: **(Complete)**
  - For each waveform, develop procedures for both single pass per layer walls and multi-pass per layer bulk shapes using waveforms from Task 2.
  - For each waveform, produce an 18-in. long build that is 1- to 2-in. tall using the developed procedures
- Task 4 – T-GMA AM Property Evaluation: **(Complete)**
  - Based on guidance from NSWCCD, EWI will fabricate standard qualification builds for both high deposition T-GMA waveforms and corresponding procedures developed in Task 3.
  - Evaluate qualification builds using radiographic testing and ultrasonic testing
  - Prepare and test property specimens (tensile, bend, metallographic) from the builds using the qualification scheme of the pending Navy Technical Publication
- Task 5 – Technology Transfer and Reporting: **(Complete)**
  - Project briefings at NSRP Welding Technology Panel meetings
  - Quarterly project progress reports
  - Final written report

Application 1 – Lincoln HyperFill™ Overview

- Twin-wire GMAW solution
- Designed for semiautomatic and automatic applications
- Deposition rates above 18 lbs/hr (24+ lbs/hr robotically)
- Ease-of-use (one power supply/feeder)
- Not direction dependent

- Equipment
  - S700 Powerwave
  - Autodrive 19
  - Flex Cool 35
  - R-30iB Plus Robot Controller
  - Arcmate 100iC 8L Robot

LINCOLN ELECTRIC

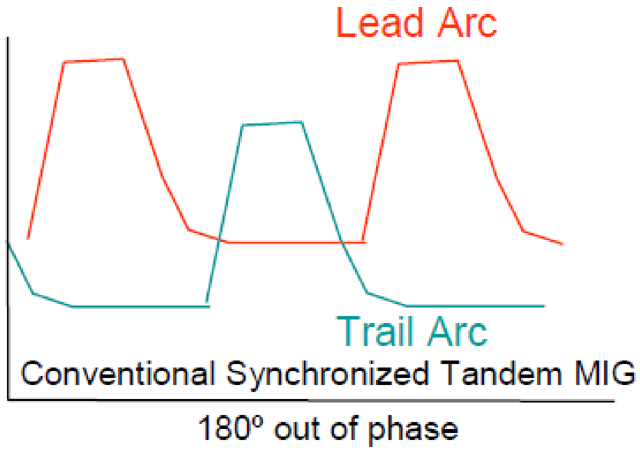
Application 1 – Lincoln HyperFill™ Results

Trial No.	Process	Wire Feed Speed (in./min.)	Travel Speed (in./min.)	WFS/TS Ratio	Avg. Volts (V)	Avg. Amps (A)	Dep. Rate (lb./hr.)	Heat input (kJ./in.)
1	Hyperfill	277	9.16	60	25.29	296.3	14.97	49.08
2	Hyperfill	277	18.46	30	25.18	280.4	14.97	22.96
3	Hyperfill	375	25	30	28.72	368.3	20.27	25.39
4	Hyperfill	465	31	30	32.26	460.1	25.13	28.73

Application 2 – Pulse Tandem Overview

- Two-wire GMAW solution
- Designed for automatic applications
- Deposition rates of 16 to 40 lb/hr
- Complex system (two power supplies/feeders)
- Direction dependent

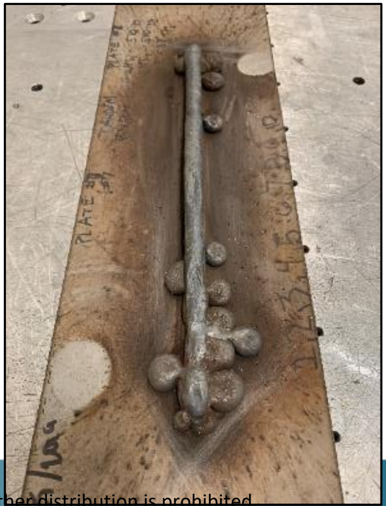
- Equipment
  - (2) S700 Powerwave
  - (2) Autodrive 19 Tandem Controller
  - (2) 4R220 Auto Drive
  - Flex Cool 35
  - R-30iA Plus Robot Controller
  - Arcmate 120iC Robot



Application 2 – Pulse Tandem Results

Trial No.	Process	Wire Feed Speed (in./min.)	Travel Speed (in./min.)	WFS/TS Ratio	Avg. Volts (V)	Avg. Amps (A)	Dep. Rate (lb./hr.)	Heat input (kJ./in.)
5	Tandem P-P	390/360	25	30	25.76	214.1	20.26	26.47
6	Tandem P-P	480/450	31	30	27.28	244.4	25.13	25.81
7	Tandem P-P	570/540	37	30	28.97	277.3	29.99	26.06

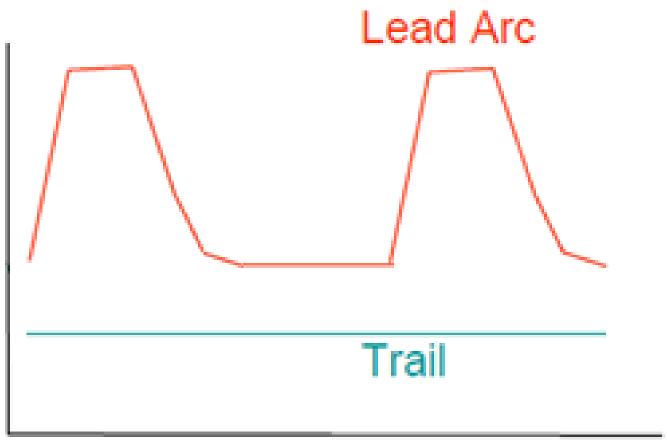




Application 3 – Hotwire Tandem Overview

- Two-wire GMAW solution with reduced heat input up to 40%
- Designed for automatic applications
- Deposition rates of 16 to 40 lb/hr
- Complex system (two power supplies/feeders)
- Direction dependent

- Equipment
  - (2) S700 Powerwave
  - (2) Autodrive 19 Tandem Controller
  - (2) 4R220 Auto Drive
  - Flex Cool 35
  - R-30iA Plus Robot Controller
  - Arcmate 120iC Robot



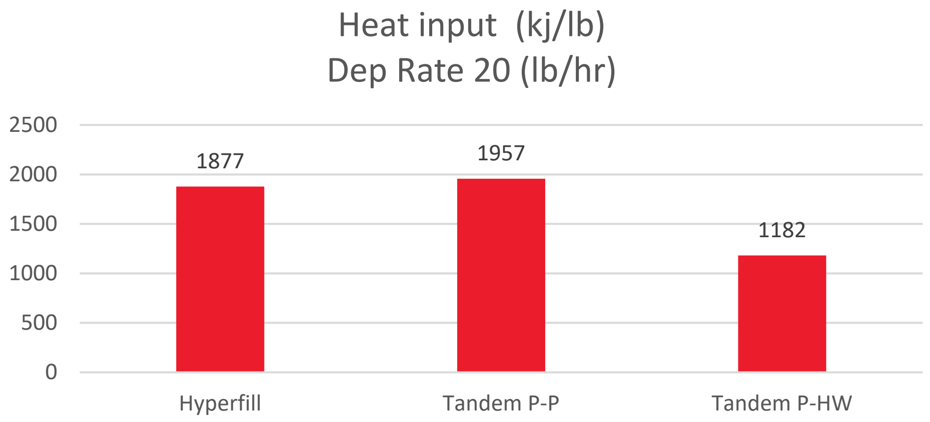
LINCOLN ELECTRIC

Application 3 – Hotwire Tandem® Results

Trial No.	Process	Wire Feed Speed (in./min.)	Travel Speed (in./min.)	WFS/TS Ratio	Avg. Volts (V)	Avg. Amps (A)	Dep. Rate (lb./hr.)	Heat input (kJ./in.)
8	Tandem P-HW	480	16	60	18.28	248.6	25.13	15.02
9	Tandem P-HW	570	37	30	19.35	290.42	29.99	27.49
10	Tandem P-HW	390	25	30	17.4	198.7	20.53	25.44

Application Down Selection

Process	Maximum Deposition Rate Achieved (lbs/hr)	Power Efficiency at 20 lbs/hr (kJ/lb)	CTWD Sensitive?	Ease-of-use?	Direction Dependent?
Hyperfill	25	1877	No	Yes	No
Tandem P-P	30	1957	Yes	No	Yes
Tandem P-HW	30	1182	Yes	No	Yes

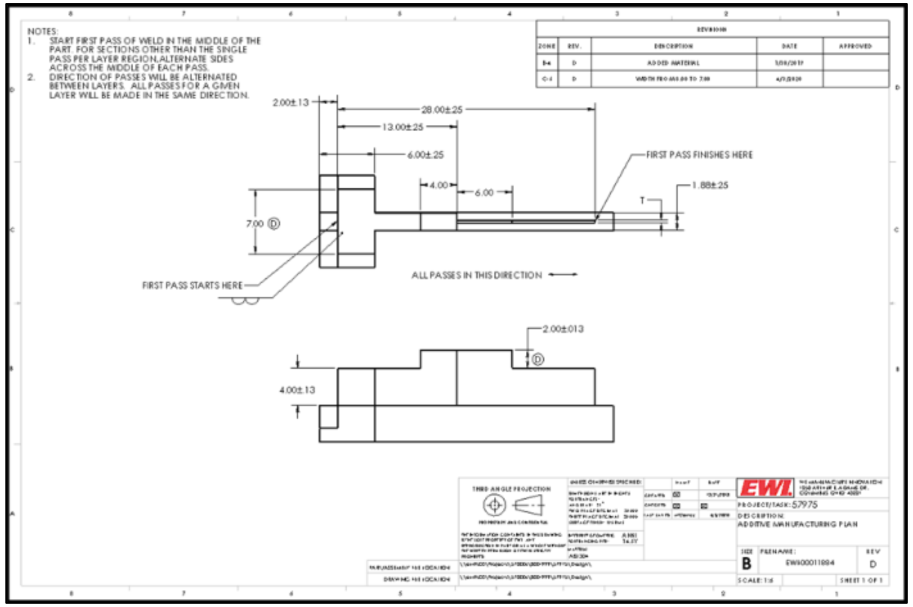


HyperFill™ was selected

Approach – Application Selection

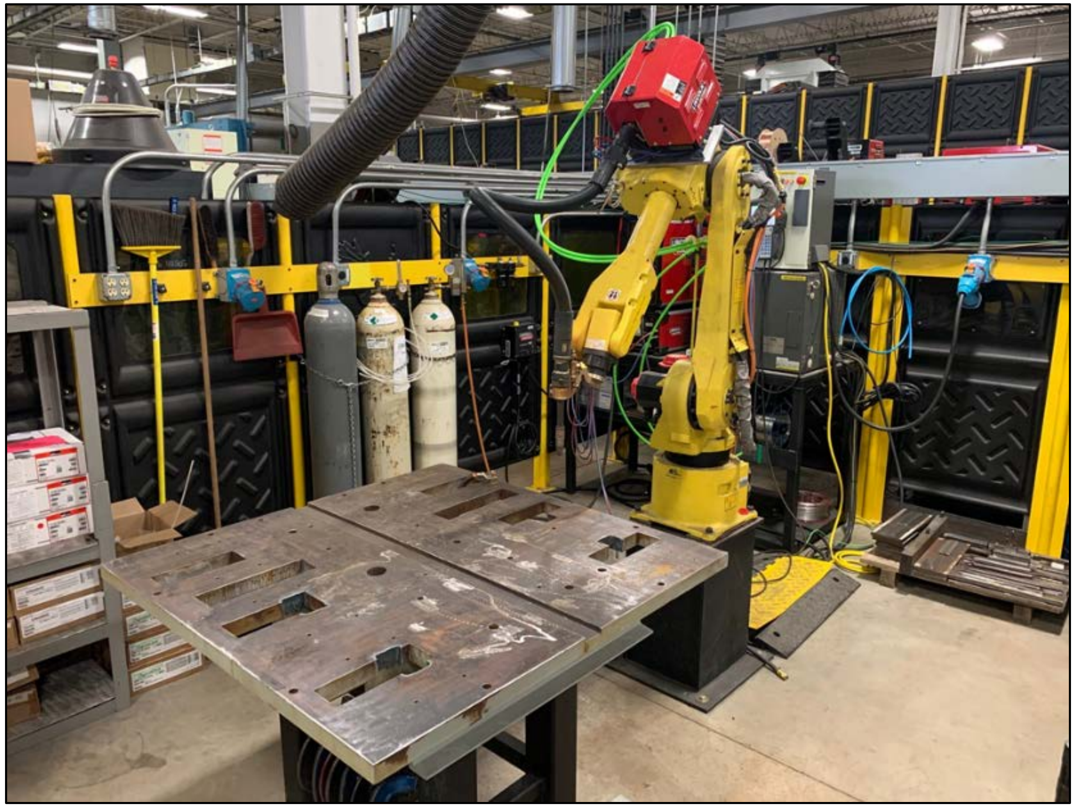
SS-IBP Stainless Steel

- GMA-P (pulse gas metal arc) DED – Stainless Steel (SS), Single Sided, Nonintegrated Build Platform (SS-NIBP)
  - UNS C30403 QQ-S-763F Build Platform
  - ER308LSi Welding Electrode
    - 0.040-in. diameter
  - 99% Argon 1% CO_2 Shielding Gas
- Designed standard qualification build (SQB)
  - Thick 4-in. build platform to control distortion
  - Property specimens in x-, y-, and z-direction
  - Wall and block features in each build



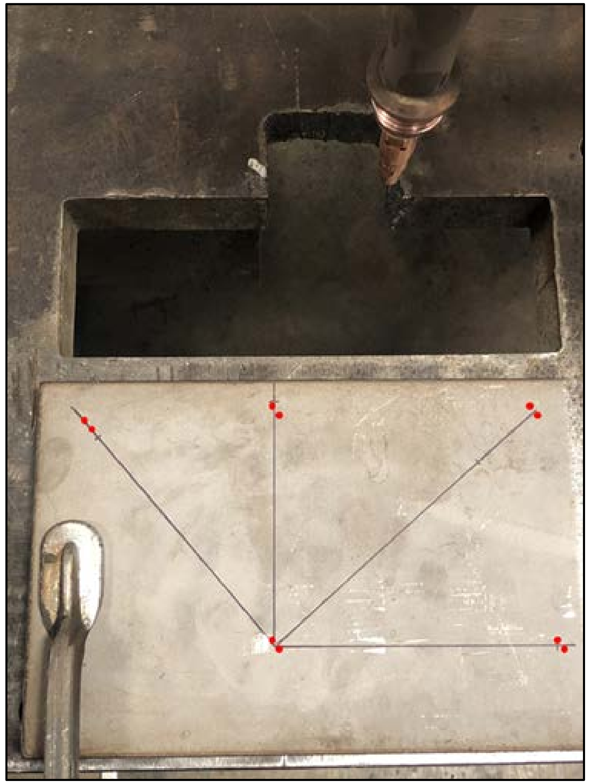
Cell Setup

- Fanuc robot system
  - Arc Mate 120iBe 6-axis robot
  - R-30iA controller
- Lincoln GMA System
  - Power Wave s500/s700 power source
  - AutoDrive 4R220 wire feeder
  - MagnumPro torch
- Cooling system
  - Vortec Frost Free Guns connected to an air supply and solenoid
  - Oil filters are in the air supply lines
- Infrared (IR) temperature sensor
  - Keyence FT-H40K infrared sensor



Directionality Study

- Set wire-to-wire orientation
- Ran four trials 45-degrees from each other
- No noticeable difference
- Process is omni-directional



Contract to Work Distance (CTWD) Study

- Additive Manufacturing Procedures Specification (AMPS) was set to a CTWD = 5/8 in.
- Ran trials at the following distances:
  - 3/8 in. - Stable
  - ½ in. - Stable
  - 1 in. - Stable
  - 1.5 in. - Unstable
  - 2 in. - Unstable

½ in.

1.5 in.

3/8 in.

1 in.

2 in.

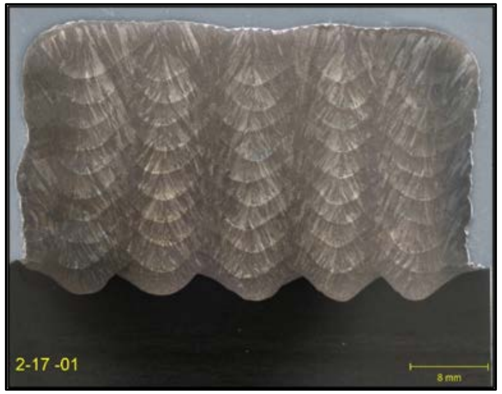
Approach – Standard Qualification Build & Test/Qualification Scheme (ref 1)

- Standard Qualification Build
  - (x, y, z) Block & (x, z) wall features
  - Integrated or nonintegrated build platform
  - Single or double sided
- Nondestructive Evaluation (NDE) (radiographic testing (RT) & ultrasonic testing (UT))
  - Post build machined
  - RT wall/UT block section features
- Property specimen matrix
  - Evaluate tensile, bend, impact etc. based on materials
  - x --, y --, z direction; evaluate anisotropy with height and scale
- Forms
  - (AMPS) and AM Procedure Qualification Record PQR

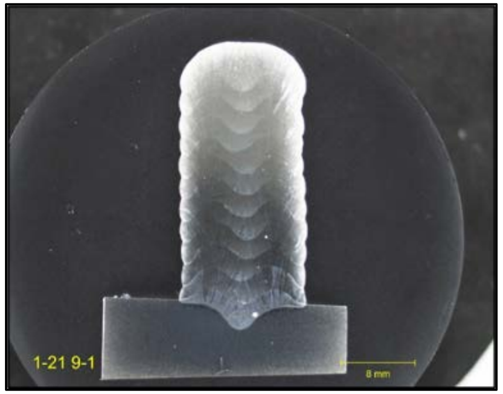
REF 1 -D.D Harwig,, W. Mohr,, S. Hovanec, J. Rettaliata, R. Hayleck., E Handler, and J.Farren, "Tech Pub Qualification Scheme Development for Arc Directed Energy Deposition Additive Manufacturing", In Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium (GVSETS), NDIA, Novi, MI, Aug. 13-15, 2019.

Qualification Build Matrix

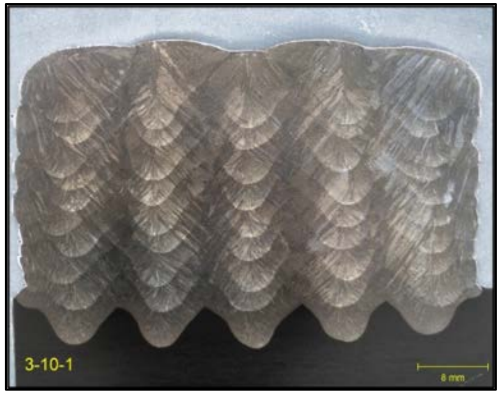
- Build matrix included two bead sizes and two pre-heat/inter-pass temperature combinations:
  - Small bead (wire feed speed/travel speed (WFS/TS) = 35) and pre-heat/inter-pass (0/350°F) temperature (15 Lbs/Hr)
  - Large bead (WFS/TS = 42) and pre-heat / inter-pass (0/350°F) temperature (23 Lbs/Hr)
- Final bead conditions:
  - Small bead – Multi bead: 35 WFS/TS (15 Lbs/Hr)
  - Small bead – Single bead: 35 WFS/TS (15 Lbs/Hr)
  - Large bead – Multi bead: 42 WFS/TS (23 Lbs/Hr)
  - Large bead – Single bead: 32 WFS/TS (17 Lbs/Hr)



Multi Bead
35 WFS/TS



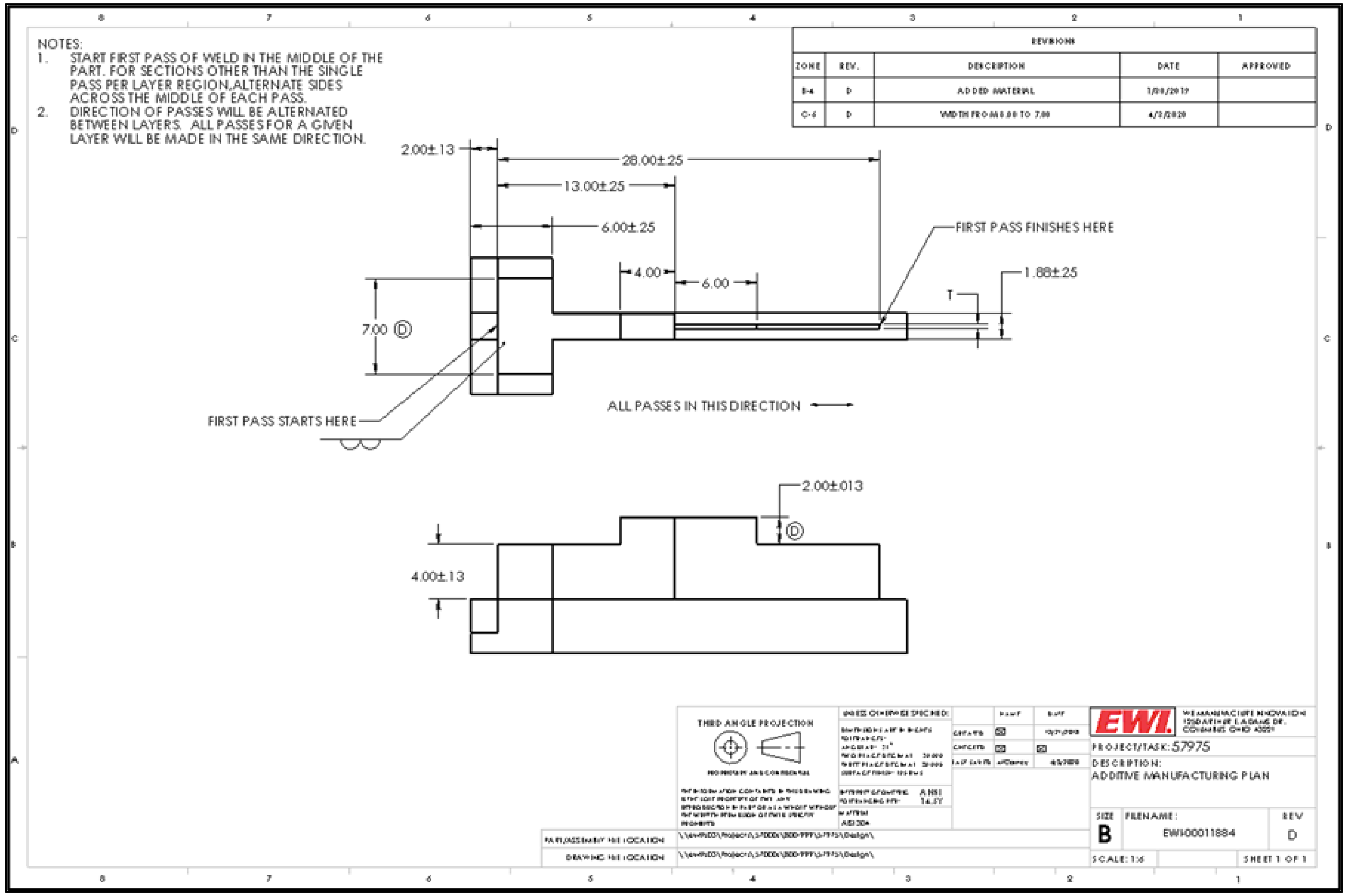
Single Bead
35 WFS/TS



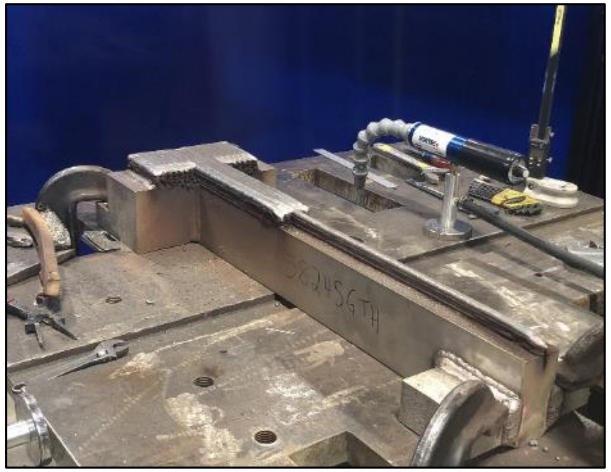
Multi Bead
42 WFS/TS

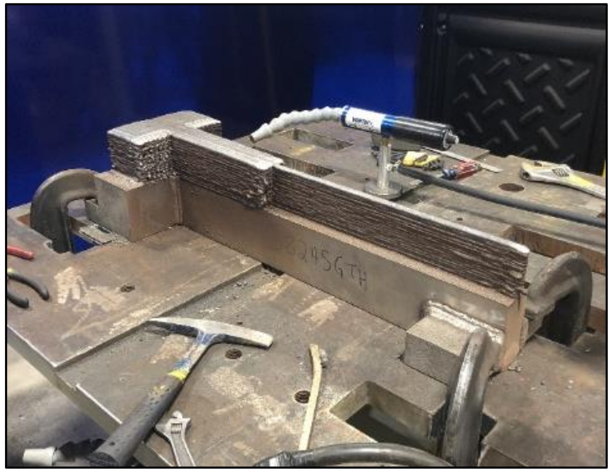
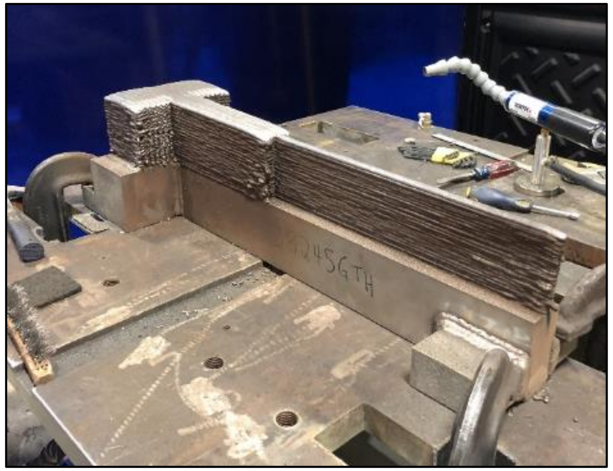
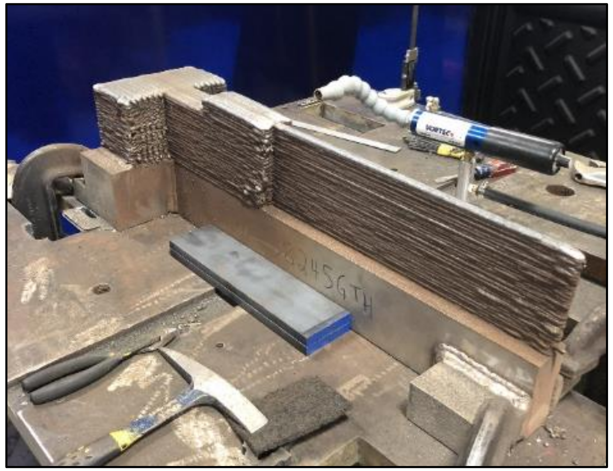
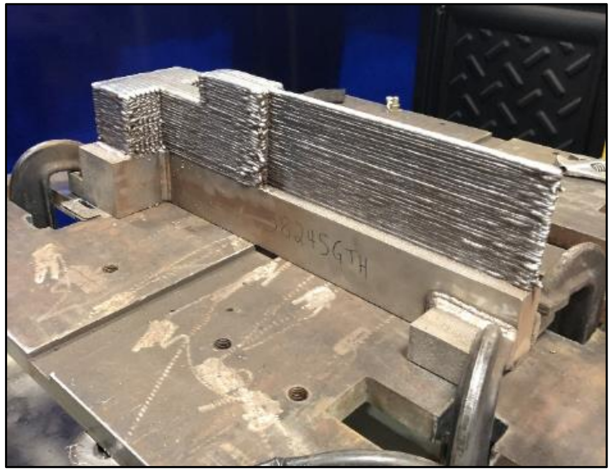
Single Bead
32 WFS/TS

Build

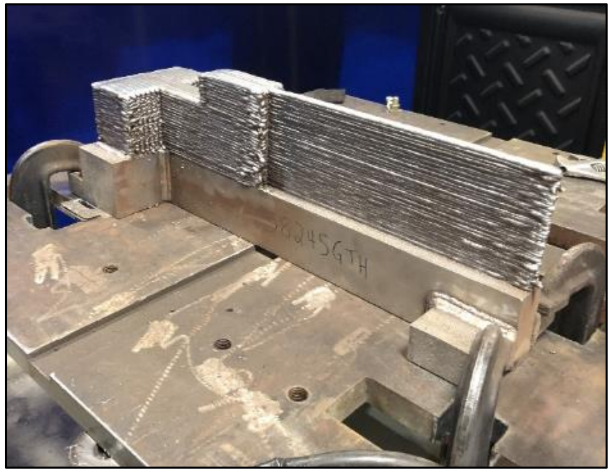

NOTES:
1. START FIRST PASS OF WELD IN THE MIDDLE OF THE PART. FOR SECTIONS OTHER THAN THE SINGLE PASS PER LAYER REGION, ALTERNATE SIDES ACROSS THE MIDDLE OF EACH PASS.
2. DIRECTION OF PASSES WILL BE ALTERNATED BETWEEN LAYERS. ALL PASSES FOR A GIVEN LAYER WILL BE MADE IN THE SAME DIRECTION.
2.00±.13
28.00±.25
13.00±.25
6.00±.25
FIRST PASS FINISHES HERE
4.00
6.00
T
1.88±.25
7.00 D
FIRST PASS STARTS HERE
ALL PASSES IN THIS DIRECTION
2.00±.013
D
4.00±.13
REVISIONS
ZONE REV. DESCRIPTION DATE APPROVED
D ADDED MATERIAL
D WIDTH FROM 6.00 TO 7.00
THIRD ANGLE PROJECTION
EWI
PROJECT/TASK: 57975
DESCRIPTION:
ADDITIVE MANUFACTURING PLAN
SIZE B
FILENAME: EWI-00011884
REV D
SCALE: 1:6
SHEET 1 OF 1

Build #1 – 1-in. Increments

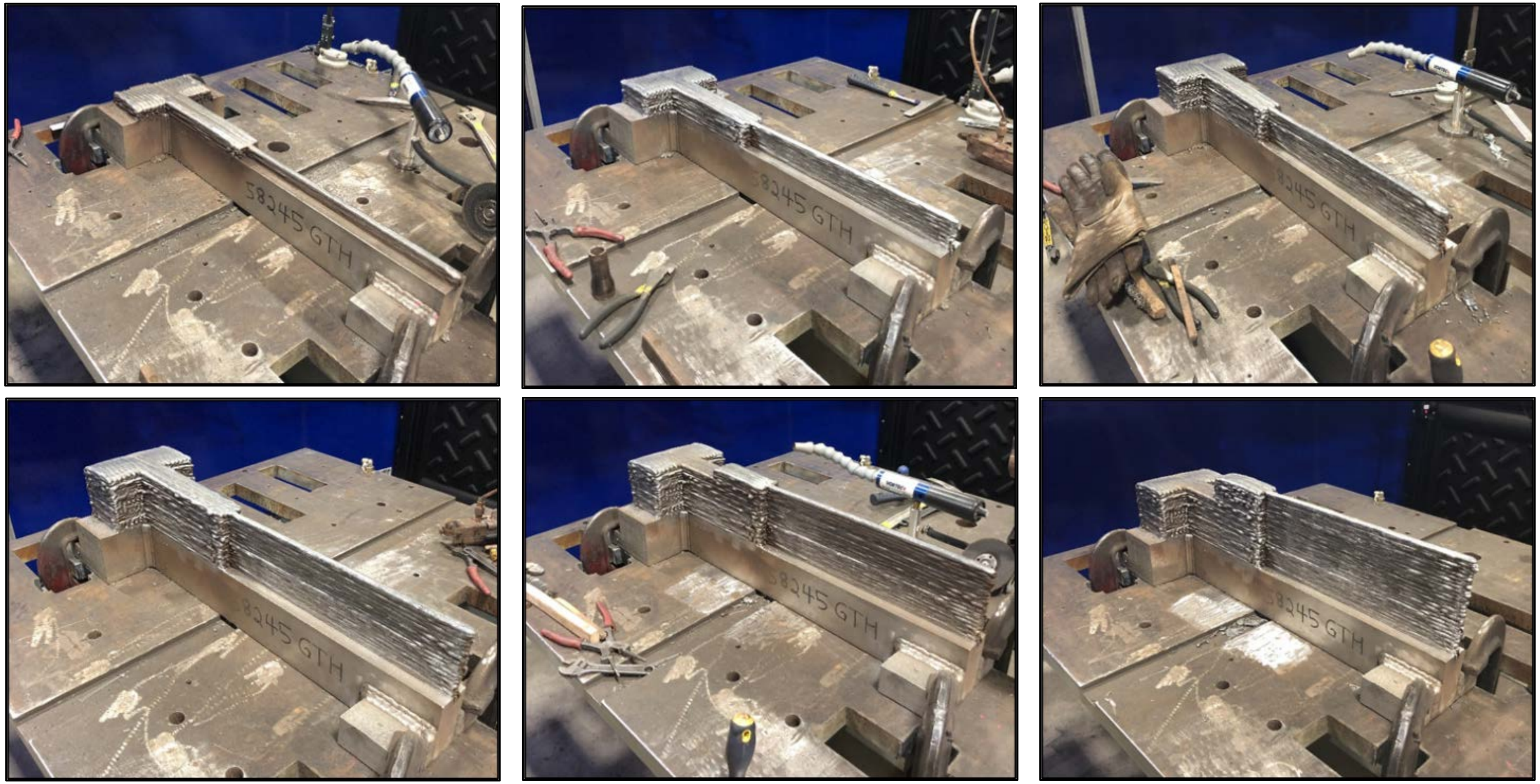


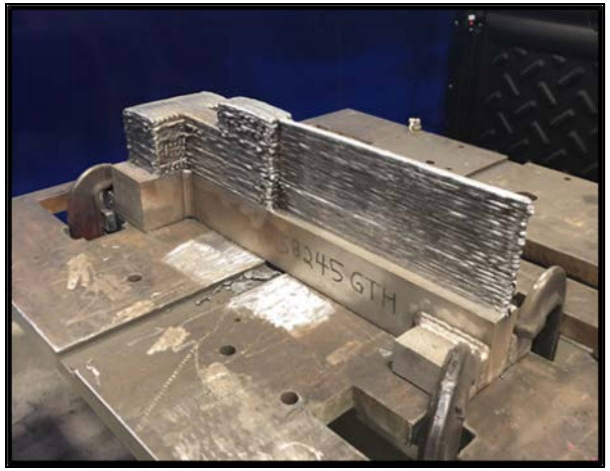
Build #1 – As Built



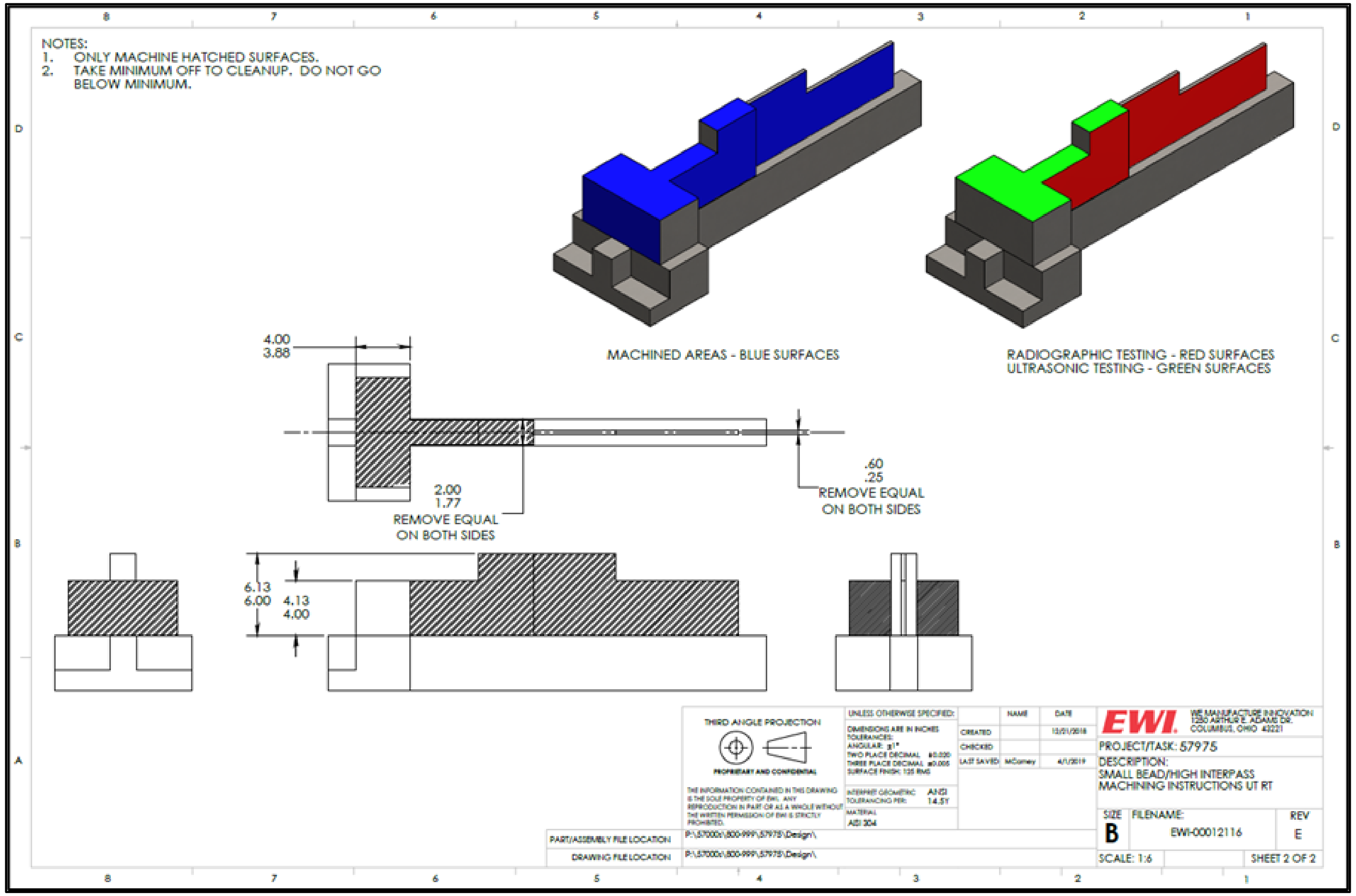
Build #2 – 1-in. Increments



Build #2 – As Built

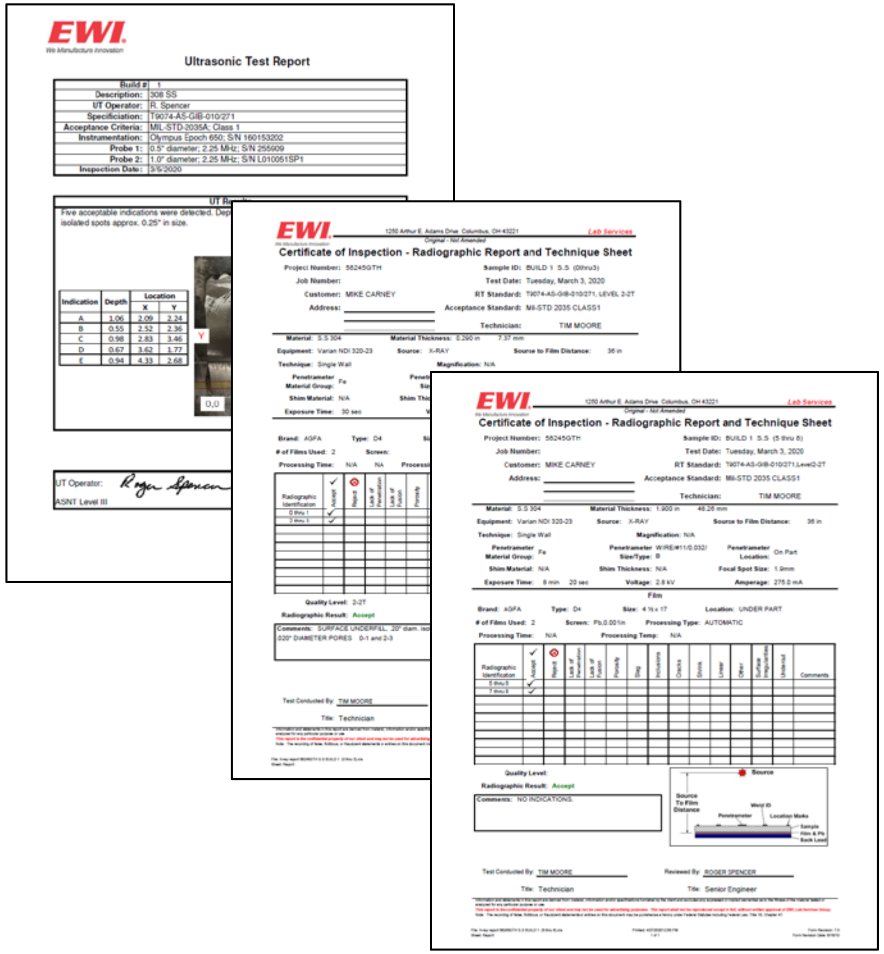


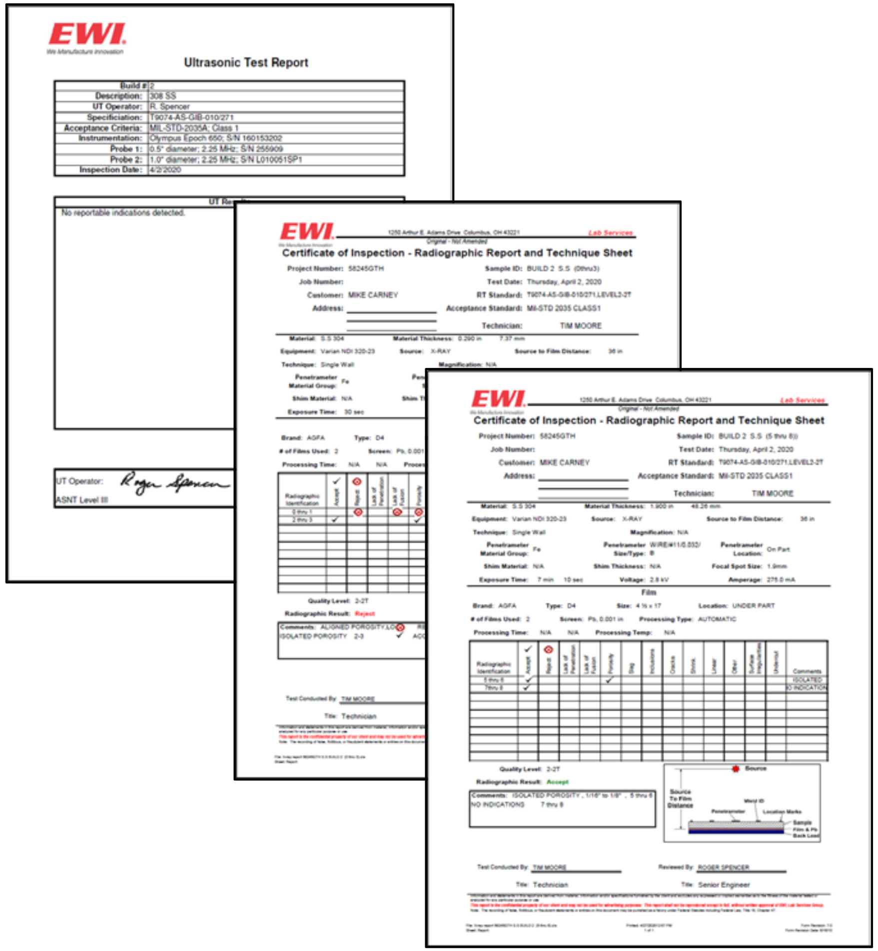
Machining/RT & UT



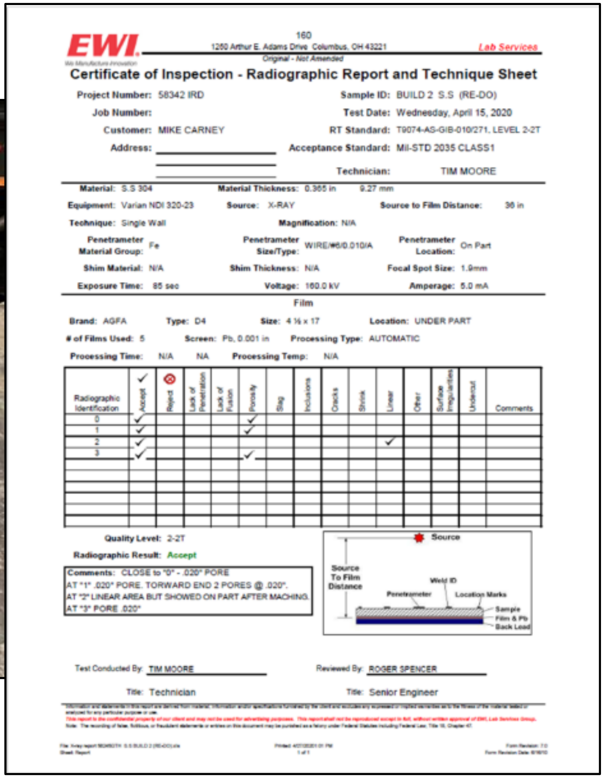
Build #1 After Machining

Build NDE Reports





Build #2 Repeat Single Wall



EWI
We Manufacture Innovation

160
1250 Arthur E. Adams Drive Columbus, OH 43221
Lab Services
Original - Not Amended

Certificate of Inspection - Radiographic Report and Technique Sheet

Project Number: 58342 IRD
Sample ID: BUILD 2 S.S (RE-DO)
Job Number:
Test Date: Wednesday, April 15, 2020
Customer: MIKE CARNEY
RT Standard: T9074-AS-GIB-010/271, LEVEL 2-2T
Address:
Acceptance Standard: Mil-STD 2035 CLASS1
Technician: TIM MOORE

Material: S.S 304
Material Thickness: 0.365 in 9.27 mm
Equipment: Varian NDI 320-23
Source: X-RAY
Source to Film Distance: 36 in
Technique: Single Wall
Magnification: N/A
Penetrameter Material Group: Fe
Penetrameter Size/Type: WIRE/#6/0.010/A
Penetrameter Location: On Part
Shim Material: N/A
Shim Thickness: N/A
Focal Spot Size: 1.9mm
Exposure Time: 85 sec
Voltage: 160.0 kV
Amperage: 5.0 mA

Film

Brand: AGFA
Type: D4
Size: 4 ½ x 17
Location: UNDER PART
# of Films Used: 5
Screen: Pb, 0.001 in
Processing Type: AUTOMATIC
Processing Time: N/A NA
Processing Temp: N/A

Radiographic Identification	Accept	Reject	Lack of Penetration	Lack of Fusion	Porosity	Slag	Inclusions	Cracks	Shrink	Linear	Other	Surface Irregularities	Undercut	Comments
0	✓				✓									
1	✓				✓									
2	✓									✓				
3	✓				✓									

Quality Level: 2-2T
Radiographic Result: Accept

Comments: CLOSE to "0" - .020" PORE
AT "1" .020" PORE. TORWARD END 2 PORES @ .020".
AT "2" LINEAR AREA BUT SHOWED ON PART AFTER MACHING.
AT "3" PORE .020"

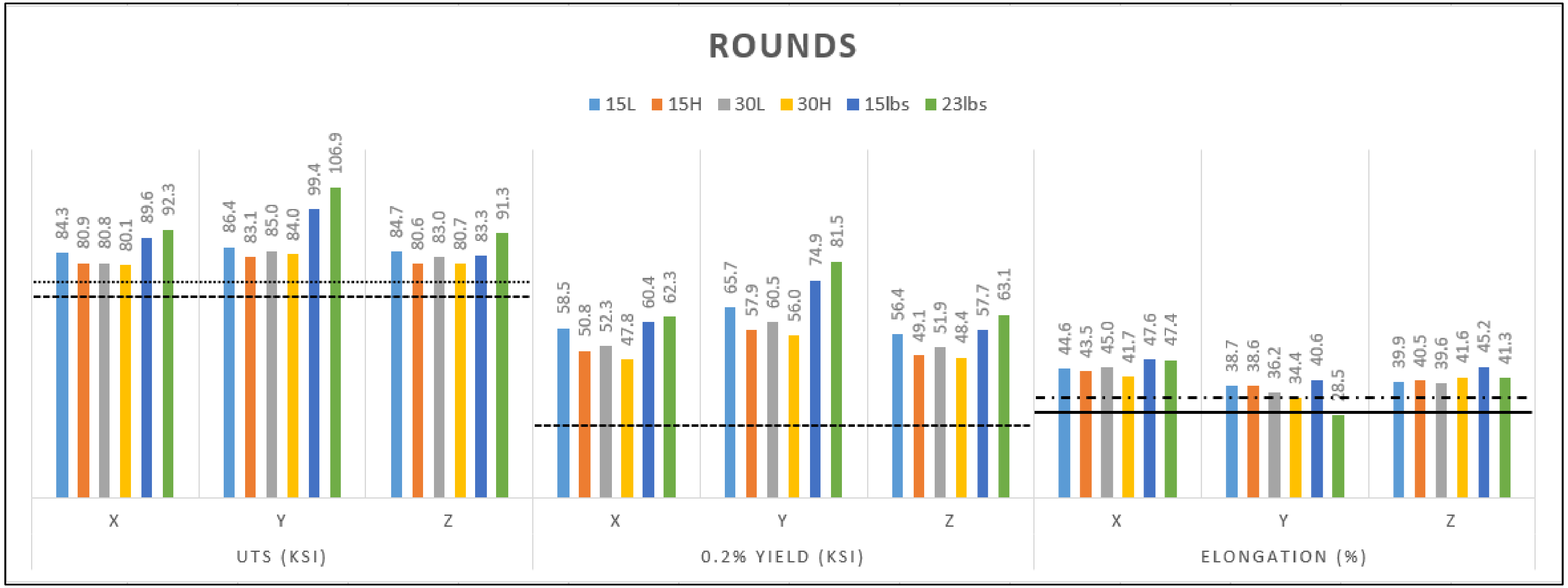
Test Conducted By: TIM MOORE
Reviewed By: ROGER SPENCER
Title: Technician
Title: Senior Engineer

Data

[redacted]		Round (0.5-inch dia.)								
		UTS (ksi)			0.2% Yield (ksi)			Elongation (%)		
		x	y	z	x	y	z	x	y	z
Single Wire GMAW	15L	84.3	86.4	84.7	58.5	65.7	56.4	44.6	38.7	39.9
	15H	80.9	83.1	80.6	50.8	57.9	49.1	43.5	38.6	40.5
	30L	80.8	85.0	83.0	52.3	60.5	51.9	45.0	36.2	39.6
	30H	80.1	84.0	80.7	47.8	56.0	48.4	41.7	34.4	41.6
Twin Wire GMAW	15lbs	**89.6**	**99.4**	**83.3**	**60.4**	**74.9**	**57.7**	**47.6**	**40.6**	**45.2**
	23lbs	**92.3**	**106.9**	**91.3**	**62.3**	**81.5**	**63.1**	**47.4**	**28.5**	**41.3**

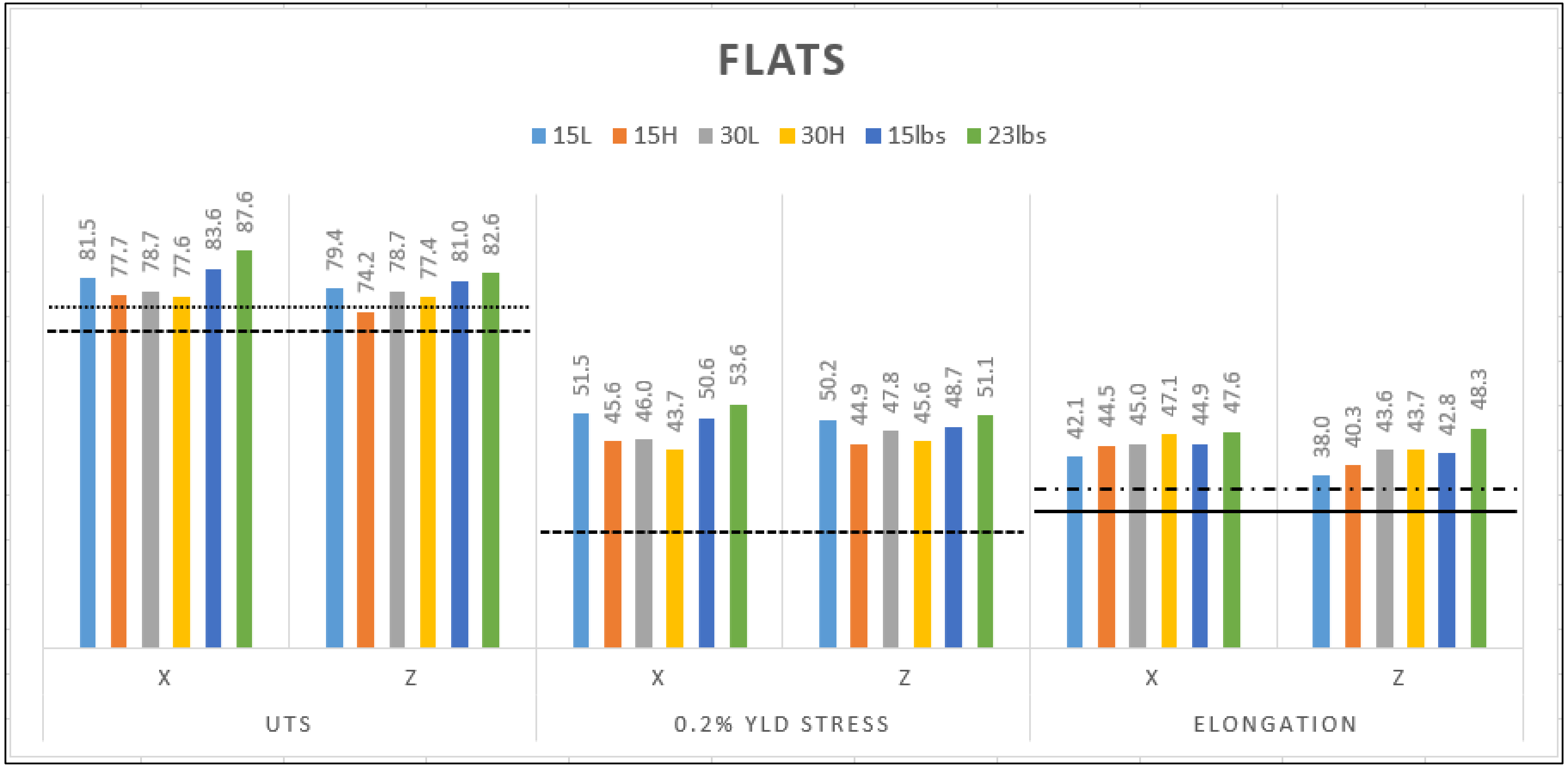
[redacted]		Flats					
		UTS		0.2% Yld Stress		Elongation	
		x	z	x	z	x	z
Single Wire GMAW	15L	81.5	79.4	51.5	50.2	42.1	38.0
	15H	77.7	74.2	45.6	44.9	44.5	40.3
	30L	78.7	78.7	46.0	47.8	45.0	43.6
	30H	77.6	77.4	43.7	45.6	47.1	43.7
Twin Wire GMAW	15lbs	**83.6**	**81.0**	**50.6**	**48.7**	**44.9**	**42.8**
	23lbs	**87.6**	**82.6**	**53.6**	**51.1**	**47.6**	**48.3**

Graph



ROUNDS
15L 15H 30L 30H 15lbs 23lbs
84.3 80.9 80.8 80.1 89.6 92.3
86.4 83.1 85.0 84.0 99.4 106.9
84.7 80.6 83.0 80.7 83.3 91.3
58.5 50.8 52.3 47.8 60.4 62.3
65.7 57.9 60.5 56.0 74.9 81.5
56.4 49.1 51.9 48.4 57.7 63.1
44.6 43.5 45.0 41.7 47.6 47.4
38.7 38.6 36.2 34.4 40.6 28.5
39.9 40.5 39.6 41.6 45.2 41.3
X Y Z X Y Z X Y Z
UTS (KSI)
0.2% YIELD (KSI)
ELONGATION (%)

Graph



FLATS
15L
15H
30L
30H
15lbs
23lbs
81.5
77.7
78.7
77.6
83.6
87.6
79.4
74.2
78.7
77.4
81.0
82.6
51.5
45.6
46.0
43.7
50.6
53.6
50.2
44.9
47.8
45.6
48.7
51.1
42.1
44.5
45.0
47.1
44.9
47.6
38.0
40.3
43.6
43.7
42.8
48.3
X
Z
UTS
X
Z
0.2% YLD STRESS
X
Z
ELONGATION

Productivity Metrics

		WFS (IPM)	# Wire	TS (IPM)	Wire Dia (in)	Deposition (lb/hr)	WFS/TS	Deposition Increase Over Max GMAW-P (%)
GMAW-P	**LOW**	305	1	20	0.045	8.41	15.25	
GMAW-P	**HIGH**	250	1	8	0.045	6.89	31.25	
GMAW-TW	**LOW**	350	2	20	0.04	15.25	35	181%
GMAW-TW	**HIGH**	525	2	25	0.04	22.88	42	272%

Conclusions

- Twin Wire (TW) -GMAW shows promise for high deposition DED builds.
  - Based on puddle size, the minimum wall achieved was 0.47 in.
- Compared to tandem GMAW, TW-GMAW offers the following benefits:
  - Omni-directional
  - Good tolerance to CTWD variation
  - Deposition 2X-3X single wire GMA-P
- SQB properties were equal or better than GMA-P properties in most cases.
  - Exceeded AWS 5.9 requirements for ER308L

Next Steps/Schedule - Recommendations

Next Steps/Schedule:

- Submit Final Report
  - Project end date is July 31, 2020

Recommendations:

- Based on this investigation, the Twin Wire GMA-P process should be considered for large-scale DED build and other welding applications.
  - Arc DED
  - Fillet welds
  - Groove welds
  - Hybrid Laser

Questions?