EWI
We Manufacture Innovation

1250 Arthur E. Adams Drive, Columbus, Ohio 43221
614.688.5000 • ewi.org

September 27, 2023

Ryan Schneider
ATI Advanced Technology International
315 Sigma Dr
Summerville, SC 29486

**EWI Project No. 59073GTH, "2019-375-009: Next Generation Double Electrode GMAW Process for Precision Fillet Welding"**

Dear Ryan Schneider:

Enclosed is EWI's final report for the above referenced project. Please feel free to contact me at 614.688.5138 if you have any questions or comments regarding this project.

Sincerely,

Michael Carney
Senior Engineer
Arc Welding and Directed Energy Deposition Processes

Enclosure

# 2019-375-009 – Next Generation Double Electrode GMAW Process for Precision Fillet Welding

September 27, 2023

EWI Project No. 59073GTH

Submitted to:
**ATI Advanced Technology International**

EWI
We Manufacture Innovation

Final Report

Project No. 59073GTH

on

# 2019-375-009 – Next Generation Double Electrode GMAW Process for Precision Fillet Welding

to

**ATI Advanced Technology International**

September 27, 2023

**EWI**
1250 Arthur E. Adams Drive
Columbus, OH 43221

# Contents

Page

## Figures

# Executive Summary

Double electrode gas metal arc welding (GMAW) processes, such as tandem and twin, typically provide two to three times the productivity of single electrode GMAW and flux cored arc welding (FCAW) processes. GMAW and FCAW share the same equipment and apparatus and are used in shipbuilding to fabricate panels, units, and ship structures. The former is preferred for high-speed precision fillet welding where metal transfer needs to be controlled, and spatter and slag need to be avoided to minimize rework. The ability to deposit 3- to 4-mm precision fillets continuously on longitudinal and transverse stiffeners can significantly reduce panel distortion and rework. A modern assessment of precision welding processes is needed as the equipment, apparatus, control technology, and consumables continue to advance for shipbuilding applications. This project evaluated next generation double electrode processes for 4-mm fillet welds as this fillet size is more likely to transition into existing shipyard facilities. (The ability to deposit 3-mm fillets requires precision no gap fit-up, clean bright metal surfaces, and highly accurate seam tracking and is an area for future work.) Double electrode processes also offer maximum productivity for both small and large fillets. Many shipyards already use tandem GMAW for larger (5 - 7 mm) fillet welds. Modern double electrode GMAW processes can also provide higher deposition rates, better deposit bead shape and quality, and more robustness than existing shipyard processes. A welding panel project was performed to evaluate next-generation double electrode processes and provide next-step recommendations for technology implementation. The objectives of this panel project were to:

1. Survey industry, screen candidate processes, and select preferred process variants for benchmark feasibility testing.
2. Benchmark advanced double electrode GMAW processes and consumables for high-speed fillet welding.
3. Down select and develop ARCWISE operational windows and bead shape maps for up to three variants. (Target application: 4-mm horizontal fillet welds.) Preferred procedures were identified based on the best combination of acceptable weld geometry (visual weld quality), bead shape cross section (fusion quality) and window size (tolerance to arc length) at the highest travel speed (productivity).
4. Provide technology transfer and demonstration workshop upon project completion.

Based on the evaluation and downselection, the preferred processes were:

- Cloos Tandem Synergy Pro and Fronius TPS/i TWIN offered the highest productivity and quality for 4-mm fillet welds in shipyard production.
- Cloos Tandem Synergy Pro had a lower heat input with a slight loss of productivity versus Fronius TPS/i TWIN.
- Miller's Hercules was able to deposit 3-mm fillet welds but had a small productivity (tolerance) window and is not recommended without further development.

- Lincoln's HyperFill™ was not able to produce repeatable 4-mm fillet welds.
- IPG's LightWELD system proved to be a suitable method for precision tacking joints for 4-mm fillet welding. This process was used to manually make 1-mm fillet tacks which were fully consumed with preferred double electrode procedures. This process uses a well-developed drag torch that forces precision manual travel speed control while providing a light-safe Class 1 enclosure so only protective eyeglasses are required for the welder-fitter.

This project demonstrated that repetitive, high quality 4-mm fillet welds can be applied to shipyard panel fillet welding. Precision tacking and seam tracking technology is required to transition and implement 4-mm precision fillet welding. The LightWELD manual cold wire laser tacking process (Class 1 protected drag torch) is strongly recommended for further development and implementation. Laser profilometers are commercially available for seam tracking to provide a system solution.

# Abbreviated Terms

| | |
|---|---|
| BMD | base metal dilution |
| CMT | cold metal transfer |
| COTS | commercial-off the-shelf |
| CTWD | contract tip to work distance |
| DE GMAW | double electrode gas metal arc welding |
| FCAW | flux cored arc welding |
| GMAW | gas metal arc welding |
| HII | Huntington Ingalls Industries |
| NSWCCD | Naval Surface Warfare Center Carderock Division |
| RWF | reciprocating wire feed |
| WFS/TS | wire feed speed/travel speed |

# 1.0 Introduction

Double electrode gas metal arc welding (GMAW) processes, such as tandem and twin, typically provide two to three times the productivity of single electrode GMAW and flux cored arc welding (FCAW) processes. GMAW and FCAW share the same equipment and apparatus, and are used in shipbuilding to fabricate panels, units, and ship structures. The former is preferred for high-speed precision fillet welding where metal transfer needs to be controlled, and spatter and slag need to be avoided to minimize rework. The ability to deposit 3- to 4-mm precision fillets continuously on longitudinal and transverse stiffeners can significantly reduce panel distortion and rework. A modern assessment of precision welding processes is needed as the equipment, apparatus, control technology, and consumables continue to advance for shipbuilding applications. This project evaluated next generation double electrode processes for 4-mm fillet welds as this fillet size is more likely to transition into existing shipyard facilities. (The ability to deposit 3-mm fillets requires precision no gap fit-up, clean bright metal surfaces, and highly accurate seam tracking and is an area for future work.) Double electrode processes also offer maximum productivity for both small and large fillets. Many shipyards already use tandem GMAW for larger (5 - 7 mm) fillet welds. Modern double electrode GMAW processes can also provide higher deposition rates, better deposit bead shape and quality, and more robustness than existing shipyard processes. A welding panel project was performed to evaluate next generation double electrode processes and to provide recommendations for next-step technology implementation.

# 2.0 Objectives

The objectives of this panel project were to:

1. Survey industry, screen candidate processes, and select preferred process variants for feasibility testing. Candidate processes for feasibility testing include:
   - Twin (i.e., Lincoln HyperFill™)
   - Hot wire tandem (Lincoln)
   - Tandem (Cloos)
   - Adjustable configuration tandem (D&F Specialty Torch)
   - Advanced consumables for tandem (advanced metal core electrodes for high-speed performance)
2. Benchmark advanced double electrode GMAW processes and consumables for high-speed fillet welding.
3. Down select and develop ARCWISE operational windows and bead shape maps for up to three variants.
   - Target application: 4-mm horizontal fillet welds

- Identify preferred procedures based on the best combination of acceptable weld geometry (visual weld quality), bead shape cross-section (fusion quality), and window size (tolerance to arc length) at the highest travel speed (productivity).

4. Provide technology transfer and demonstration workshop upon project completion.

# 3.0 Experimental Procedure

The project team supporting this effort included General Dynamics NASSCO (GD NASSCO), Huntington Ingalls Industries (HII) Ingalls Shipbuilding and Naval Surface Warfare Center Carderock Division (NSWCCD). NSWCCD provided NAVSEA oversight for future requirements development for implementation.

## 3.1 Task 1 – Project Initiation and Kick-off Meeting

A kickoff meeting was held to define the target application and procedure qualification and fabrication requirements, discuss shipyard implementation requirements, and determine process and procedural boundaries.

## 3.2 Task 2 – Survey Suppliers for Next Generation Double Electrode (DE) GMAW Technology

During this task, EWI surveyed welding equipment and consumable suppliers to identify next generation equipment, consumables, and apparatus that could be used to deposit 4-mm and larger fillet welds to support panel line assembly conditions. Equipment suppliers were consulted on recommended setups and parameters for twin, hot wire tandem, tandem, adjustable configuration tandem, and advanced consumables for high-speed precision fillet welding.

## 3.3 Task 3 – Feasibility Testing of Next Generation DE-GMAW Processes

During this task, EWI evaluated candidate double electrode process variants with feasibility tests. For each process combination, a series of constant deposit area (constant wire feed speed/travel speed (WFS/TS) ratio) tests were performed at two arc lengths using the ARCWISE method. This method uses systematic tests to develop operational windows, assess bead shape, and determine preferred parameters and tolerance for weld joint applications. For feasibility tests, all assessments were made using only visual, dimensional, and weld surface quality data. Up to three preferred processes were selected for detailed ARCWISE testing in Task 4. *It should be noted that some of these tests were provided pro-bono from the suppliers who visually controlled arc length on screening tests which is a source for data variation.*

### 3.4 Task 4 – Precision Fillet Weld Operational Windows, Bead Shape Maps, and Productivity Analysis

Systematic ARCWISE tests were performed on up to three process combinations from Task 3. For each process combination, a series of constant deposit area (WFS/TS ratio) tests were performed at two arc lengths. The tests were performed over a full range of travel speeds (for example 0.25 to 2-m/min [10 to 80-ipm]) to determine the minimum speed needed for fusion, the range (tolerance) of acceptable welding conditions, and the maximum speed to process failure. Each test was examined using visual and dimensional methods. Metallographic sections were removed from each test and used to characterize bead shape dimensions and fusion quality.

### 3.5 Task 5 – DE-GMAW Process Benchmarking and Productivity Analysis

This task analyzed all the test data from Task 4. Operational windows were used to determine process tolerance and preferred procedure parameters. The ARCWISE data set included the operational windows and plots that characterize the relationship between voltage, current, and wire feed speed; heat input versus deposition rate; and bead shape relationships. Recommended welding procedures were determined from the operational windows for making precision 4-mm fillets.

### 3.6 Task 6 – Next Generation DE-GMAW Technology Workshop

During this task, a workshop was held to demonstrate the preferred processes and review performance data with U.S. shipyards.

## 4.0 Results

### 4.1 Task 1 – Project Initiation and Kick-off Meeting

The project kickoff meeting was held virtually on November 1, 2022. A representative from each project partner organization attended. Process comparison conditions were gathered from the shipyards over the few weeks following this meeting.

- Material thickness
    - 4- to 5-mm
    - Sand blasted/de-scaled
- DH/EH36 Grade
- ER70S-6
- Fit-up
    - 0 to 1.5-mm (1/16-in.) gap
- Shielding gas
    - Typical – FCAW: 94% Argon (Ar)/6% Carbon dioxide ($CO_2$)

- Panel Lines – 100% $CO_2$
- Tack size
  - Leg size – 3-mm target
  - Length – 1 in.

Figure 1 shows an example of an ARCWISE bead shape map.

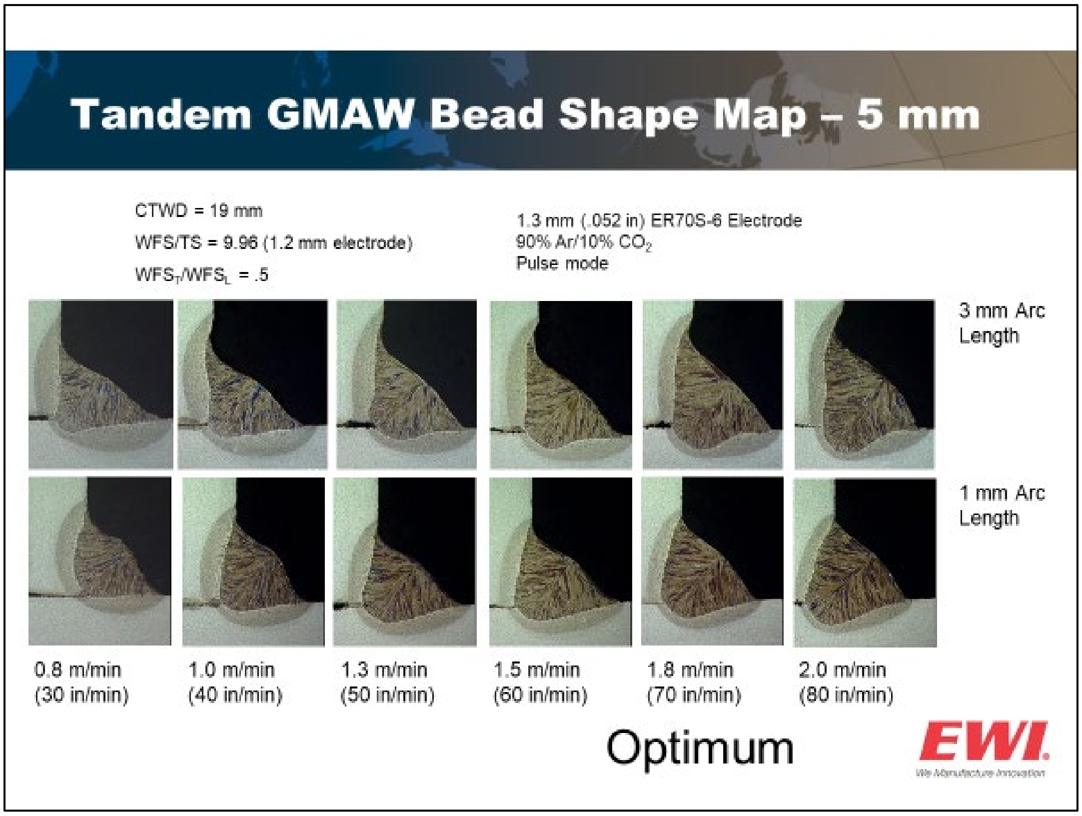



**Figure 1. ARCWISE Bead Shape Map Example**

## 4.2 Task 2 – Survey Suppliers for Next Generation Double Electrode (DE) GMAW Technology

During this task, EWI consulted equipment suppliers on recommended setups and parameters for twin, hot wire tandem, adjustable configuration tandem, and advanced consumables for high-speed precision fillet welding. An initial market survey was performed, as shown in Figure 2:

| COMPANY | TECHNOLOGY | NOTES |
|---|---|---|
| LINCOLN ELECTRIC | HyperFill™ | 24-lbs./hr. |
| Miller | Hercules™ | 30-lbs./hr. |
| Fronius | TPS/i TWIN | 35-lbs./hr. |
| CLOOS | Tandem Synergy Pro | 35-lbs./hr. |
| ESAB | Not Applicable | Not Applicable |
| OTC DAIHEN Inc. | SyncroFeed | 18-lbs./hr. |
| SELECT ARC INC. | Consumables | High Speed Electrodes |
| HOBART FILLER METALS | Consumables | High Speed Electrodes |
| ABICOR BINZEL | SpinArc | Rotating Wire |
| D/F MIG TIG | Tandem Torch | Configurable Tandem |

**Figure 2. Market Survey Results**

Specifics from each supplier are detailed below.

#### 4.2.1 Lincoln HyperFill™

HyperFill™ is a twin wire process (two wires passing through a single electrically common contact tip) GMAW solution that is designed for semi-automatic and automatic applications. Twin wire processes are not new and are widely used in submerged arc welding applications. For HyperFill™, Lincoln has optimized the waveforms for specific consumable applications to maximize metal transfer stability. This process uses one power supply, one feeder, and passes through a single dual bore contact tip. The close wire spacing makes the process omni-directional (not directionally dependent). The process reduces equipment investment costs and complexity and requires the special torch, drive rolls, and dual wire spool holders. Figure 3 shows the Lincoln HyperFill™ twin torch and contact tip (left) and the work cell setup at EWI (right). Deposition rates are stated above 18 lb/hr (24+ lb/hr robotically), which is shown in Figure 4 versus typical GMAW.

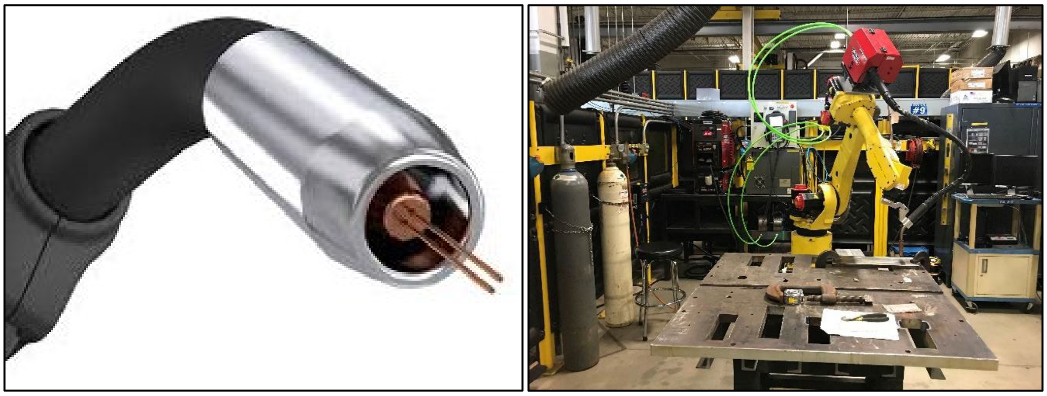


**Figure 3. Lincoln HyperFill$^{TM}$ ,left,[(1)] and EWI's Lincoln HyperFill$^{TM}$ laboratory setup, right**

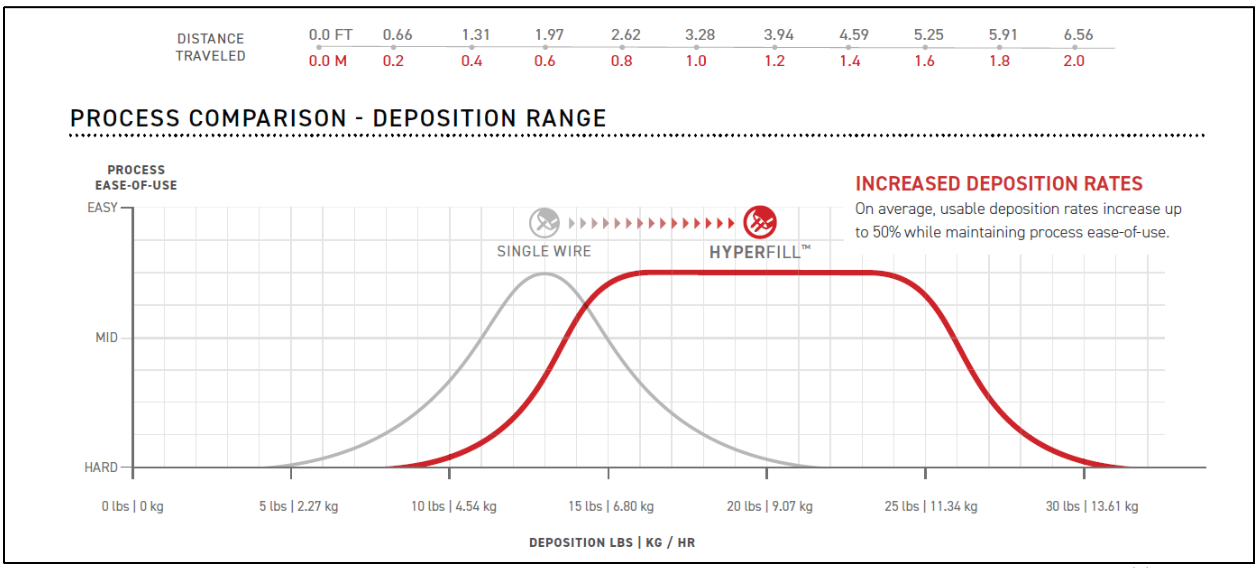



**Figure 4. Process Comparison – Deposition Range for Lincoln HyperFill$^{TM}$ [(1)]**

### 4.2.2 Miller Hercules$^{TM}$

Miller Hercules$^{TM}$ is a modified single wire (wire is conditioned (pre-heated) before passing through a single contact tip) GMAW solution that is designed for semiautomatic and automatic applications as shown in Figure 5. The process uses two power supplies, one feeder, and passes through a single contact tip and is shown in Figure 6. This makes the process omni-directional and very easy to use. Deposition rates are stated above 30.5 lb/hr robotically. Per Miller, this process requires a custom wire (FabCOR®) tailored to the Hercules$^{TM}$ process.

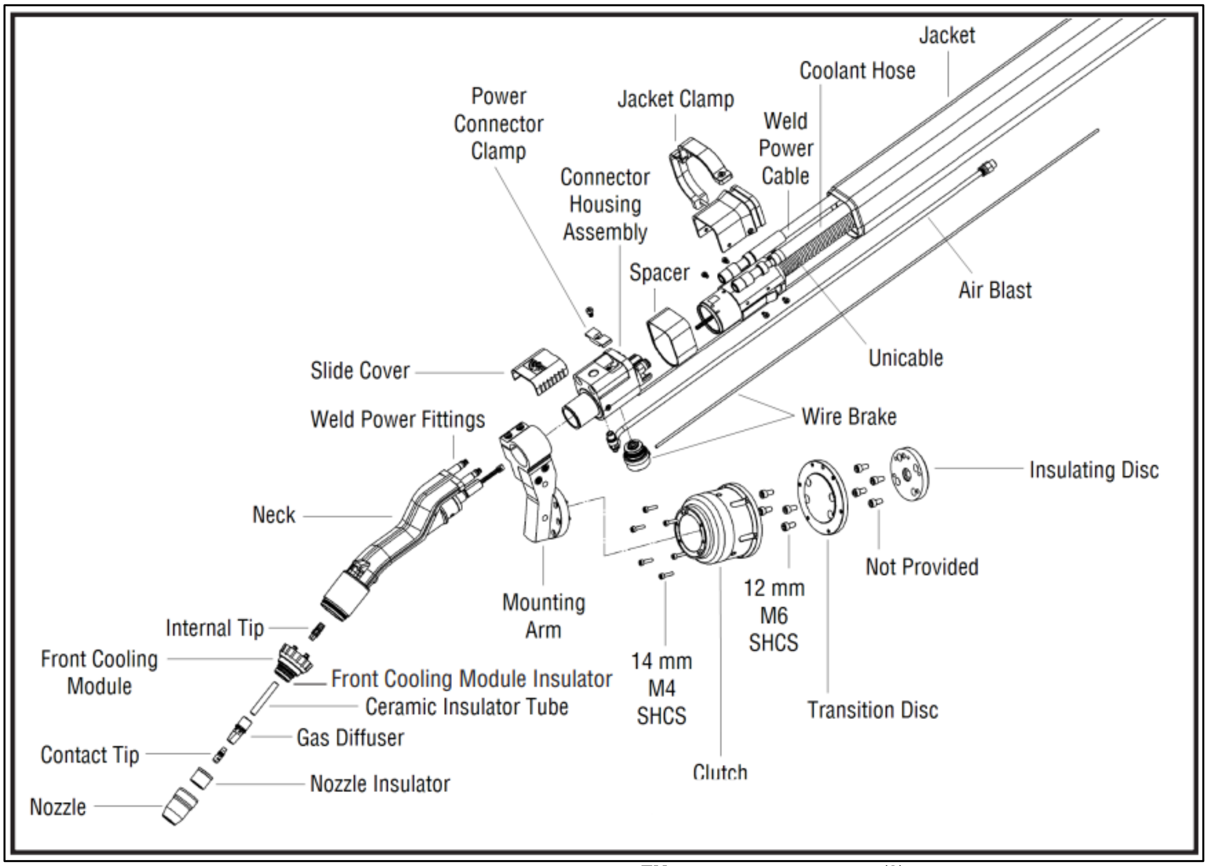



**Figure 5. Miller Hercules™ torch breakout**(2)

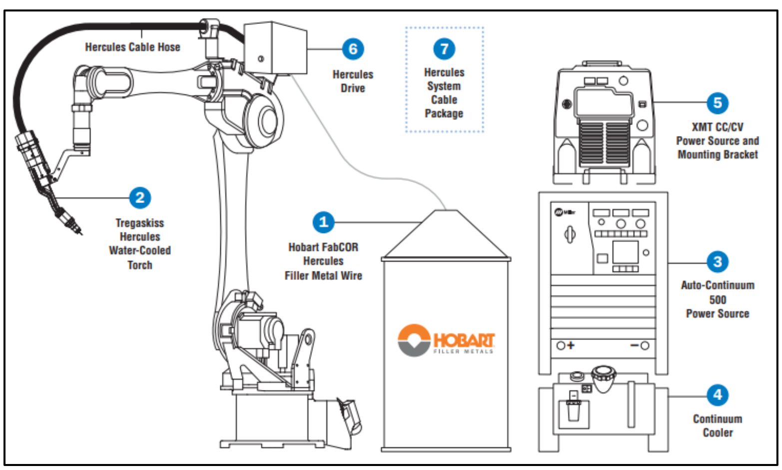



**Figure 6. Miller Hercules™ System Setup**(2)

### 4.2.3 Fronius TPS/i TWIN

Fronius TPS/i TWIN is a tandem wire process (two wire torch using two independent electrically isolated contact tips). This GMAW solution is designed for semiautomatic and automatic applications. Figure 7 shows the Fronius TPS/i TWIN welding torch (left) and the system setup (right). The system is more complex since it uses two power supplies, one feeder, and a custom tandem GMAW torch. The process is not omni-directional and requires alignment of the contact tips with the travel direction for maximum travel speed. A benefit of two independent wires and power supplies is the use of different types of GMAW waveform combinations like Cold Metal Transfer (CMT™) also known as reciprocating wire feed (RWF), pulse metal transfer (P), and spray transfer (S). These waveforms can be used in a range of combinations to maximize precision fillet or high deposition rate GMA. Deposition rates are stated above 35 lb/hr robotically with an example shown in Figure 8.

**Figure 7. Fronius TPS/i TWIN welding torch, left, and system setup, right**(3)

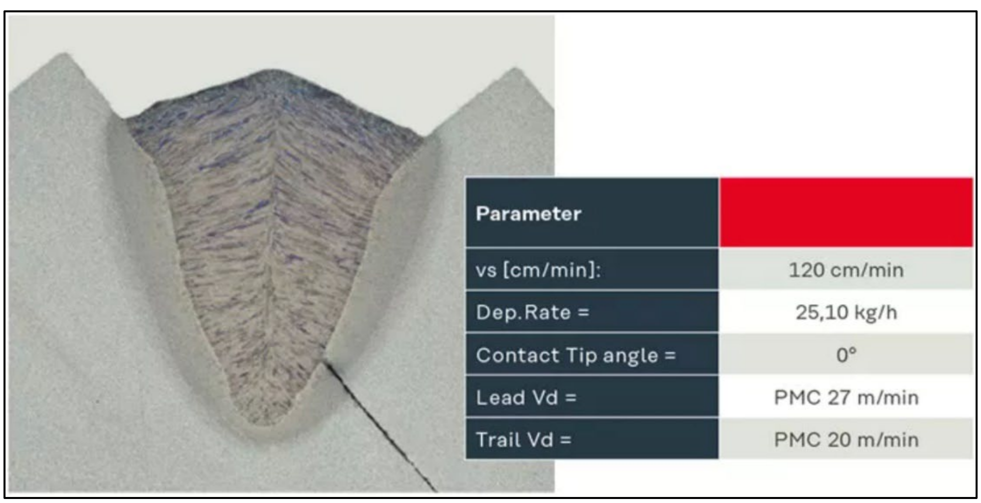



**Figure 8. Example of Fronius TPS/I TWIN high speed welding parameters**(3)

### 4.2.4 CLOOS Tandem Synergy Pro

CLOOS Tandem Synergy Pro is a tandem wire (two-wire torch using two independent electrically isolated contact tips). This GMAW process is designed for semi-automatic and automatic applications. Figure 9 shows the CLOOS Tandem Synergy Pro welding torch (left) and EWI's laboratory setup (right). This system is more complex compared to single-wire processes as it uses two power supplies and two feeders that integrate in a custom, high-duty (900 amp 100%) tandem torch. The process is not omni-directional and requires alignment of the contact tips with the travel direction for maximum travel speed. The Cloos tandem process is also very flexible and can use different waveforms and metal transfer mode combinations. Deposition rates are stated above 35 lb/hr robotically.

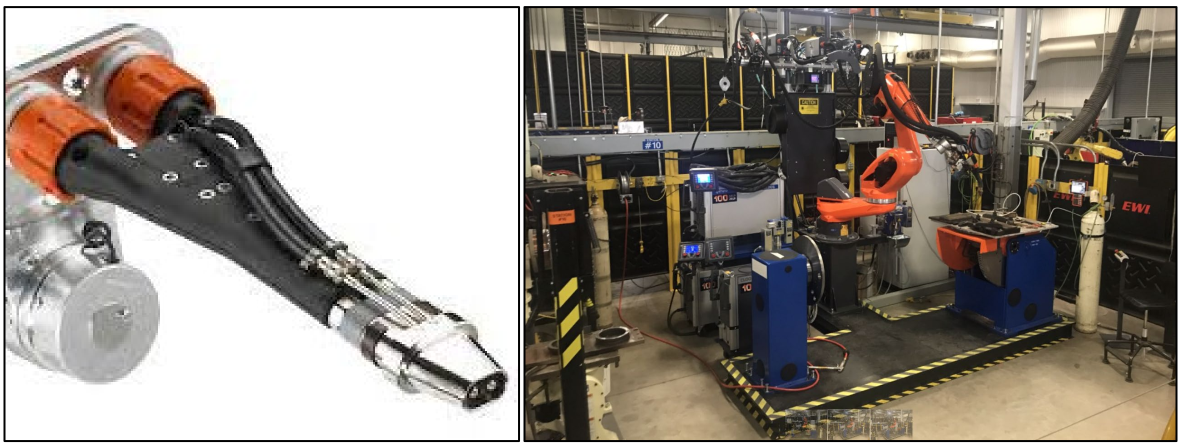


**Figure 9. CLOOS, left,[4] and EWI's CLOOS laboratory setup, right**

### 4.2.5 OTC Synchro-feed

OTC discontinued all double electrode processes in 2008. Using its Synchro-feed (i.e., RWF) system the max deposition rate is 18 lb/hr and is designed for semi-automatic and automatic applications. Figure 10 shows OTC's Synchro-feed system layout (left) and EWI's OTC Synchro-feed laboratory setup (right). The process uses one power supply, one feeder, and passes through one contact tip. This makes the process omni-directional and easy to use.

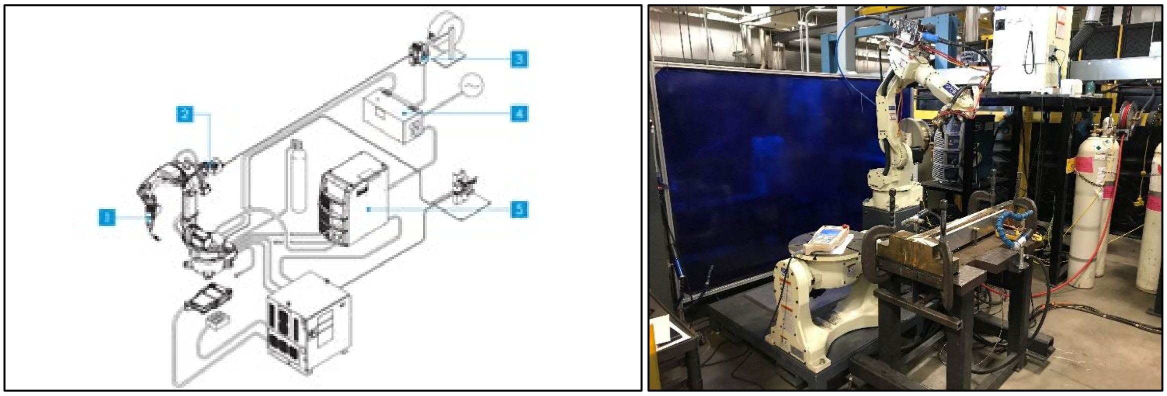



**Figure 10. OTC Synchro-feed system layout, left,[5] and EWI's OTC Synchro-feed laboratory setup, right**

### 4.2.6 Hobart Consumables

Only offered one commercial-off the-shelf (COTS) option for high-speed welding with the Hercules™ process. Hobart FabCOR® Hercules Certificate of Conformance is shown in Figure 11 and is required for the Hercules™ process.

HOBART FILLER METALS

**Certificate of Conformance**
**to Requirements for Welding Electrode**

| | |
|---|---|
| Product Type: | **FabCOR Hercules/Elevate** |
| Classification: | **E70C-6M H4** |
| Specifications: | **AWS A5.18/A5.18M; ASME SFA 5.18** |
| Diameter Tested: | **.052"** |
| Date Tested: | **12/16/2022** |
| Date Generated: | **12/19/2022** |

This is to certify that the product named above and supplied on the referenced order number is of the same classification, manufacturing process, and material requirements as the material which was used for the test that was concluded on the date shown, the results of which are shown below. All tests required by the specifications shown for classification were performed at that time and the material tested met all requirements. It was manufactured and supplied by the Quality System Program of Hobart Brothers, which meets the requirements of ISO 9001, ANSI/AWS A5.01, and other specification and Military requirements, as applicable. This document supplies actual test results of non-specific inspection in conformance with the requirements of EN 10204, type 2.2 certification.

**THE STEEL USED IN THIS LOT OF MATERIAL WAS MELTED AND MANUFACTURED IN THE U.S.A.**

**Test Settings**

| Shielding Medium | Amps / Polarity | Volts | WFS in/min(m/min) | ESO in(mm) | Preheat F(C) | Interpass F(C) | Travel Speed in/min(cm/min) |
|---|---|---|---|---|---|---|---|
| M21-ArC-25 | 300 / DCEP | 30 | 340 (8.6) | 3/4 (19) | Room Temp | 300(149) | 12 (30.5) |

**Mechanical Properties - Tensile**

| Shielding Medium | Ref. No. | Testing Conditions | Ult. Tensile Strength psi (MPa) | Yield Strength psi (MPa) | Elong.% in 2" |
|---|---|---|---|---|---|
| M21-ArC-25 | PE5246 | Aged 48 Hrs 220F | 84,000 ( 578 ) | 71,000 ( 487 ) | 26 |

**Mechanical Properties - Impact**

| Shielding Medium | Ref. No. | Testing Conditions | Temp. F (C) | Individuals ft.lb.(J) | Avg. ft.lb.(J) | Type |
|---|---|---|---|---|---|---|
| M21-ArC-25 | pe5246 | As Welded | -20 (-29) | 38,43,39 (52,58,53) | 40 ( 54 ) | Charpy-V-Notch |
| M21-ArC-25 | pe5246 | As Welded | -40 (-40) | 37,35,27 (50,47,37) | 33 ( 45 ) | Charpy-V-Notch |

| Ref.No. | Radiographic Inspection | Fillet Weld Test | | | | | |
|---|---|---|---|---|---|---|---|
| PE5246 | Conforms | Horizontal : | | Overhead : | | Vertical : | |

**Chemical Analysis**

| Shielding Medium / Ref. No | C | Mn | P | S | Si | Cu | Cr | V | Ni | Mo | Al | Ti | Nb | Co | B | W | Sn | Fe | Sb | N | Mg | Zn | Be | Sb | As |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M21-ArC-25 / CD81193 | 0.05 | 1.30 | 0.010 | 0.023 | 0.46 | 0.09 | 0.03 | < .01 | 0.36 | 0.02 | | | | | 0.0008 | | | | | | | | | | |

**Diffusible Hydrogen Collected per AWS A4.3**

| | |
|---|---|
| M21-ArC-25 | 2.3 ml/100g of weld metal for .052 in diameter 14% relative humidity |

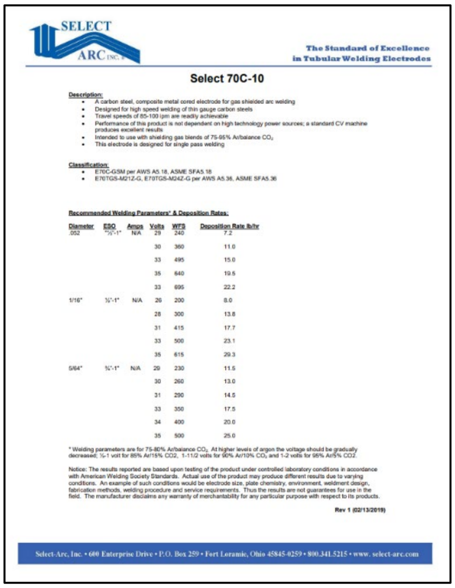
James A. Owens, Q.A. Specialist

Certification and Limited Warranty - Data for the above supplied product are those obtained when welded and tested in accordance with the above specification. All tests for the above classification were satisfied. Other tests and procedures may produce different results.

**Figure 11. Hobart FabCOR® Hercules Certificate of Conformance[6]**

### 4.2.7 Select-Arc Consumables

Select Arc manufactures a few options that are COTS and are tailored to high-speed welding (automotive). If a project has a need, the company is willing to tailor custom electrodes. Select-Arc 70C-10 product sheet is shown in Figure 12.





**Select 70C-10**

**Description:**
- A carbon steel, composite metal cored electrode for gas shielded arc welding
- Designed for high speed welding of thin gauge carbon steels
- Travel speeds of 85-100 ipm are readily achievable
- Performance of this product is not dependent on high technology power sources; a standard CV machine produces excellent results
- Intended to use with shielding gas blends of 75-95% Ar/balance $CO_2$
- This electrode is designed for single pass welding

**Classification:**
- E70C-GSM per AWS A5.18, ASME SFA5.18
- E70TGS-M21Z-G, E70TGS-M24Z-G per AWS A5.36, ASME SFA5.36

**Recommended Welding Parameters* & Deposition Rates:**

| Diameter | ESO | Amps | Volts | WFS | Deposition Rate lb/hr |
|---|---|---|---|---|---|
| .052 | "½"-1" | N/A | 29 | 240 | 7.2 |
| | | | 30 | 360 | 11.0 |
| | | | 33 | 495 | 15.0 |
| | | | 35 | 640 | 19.5 |
| | | | 33 | 695 | 22.2 |
| 1/16" | ½"-1" | N/A | 26 | 200 | 8.0 |
| | | | 28 | 300 | 13.8 |
| | | | 31 | 415 | 17.7 |
| | | | 33 | 500 | 23.1 |
| | | | 35 | 615 | 29.3 |
| 5/64" | ¾"-1" | N/A | 29 | 230 | 11.5 |
| | | | 30 | 260 | 13.0 |
| | | | 31 | 290 | 14.5 |
| | | | 33 | 350 | 17.5 |
| | | | 34 | 400 | 20.0 |
| | | | 35 | 500 | 25.0 |

* Welding parameters are for 75-80% Ar/balance $CO_2$. At higher levels of argon the voltage should be gradually decreased; ½-1 volt for 85% Ar/15% CO2, 1-11/2 volts for 90% Ar/10% $CO_2$ and 1-2 volts for 95% Ar/5% CO2.

Notice: The results reported are based upon testing of the product under controlled laboratory conditions in accordance with American Welding Society Standards. Actual use of the product may produce different results due to varying conditions. An example of such conditions would be electrode size, plate chemistry, environment, weldment design, fabrication methods, welding procedure and service requirements. Thus the results are not guarantees for use in the field. The manufacturer disclaims any warranty of merchantability for any particular purpose with respect to its products.

**Rev 1 (02/13/2019)**

Select-Arc, Inc. • 600 Enterprise Drive • P.O. Box 259 • Fort Loramie, Ohio 45845-0259 • 800.341.5215 • www. select-arc.com

**Figure 12. Select-Arc 70C-10 Product Sheet**(7)

### 4.2.8 Abicor Binzel SpinArc® Automatic MIG Gun

The SpinArc® Automatic MIG Gun process uses a custom torch that rotates the contact tip using different diameter settings that are incorporated into the torch setup mechanism. Rotating electrode GMAW processes are not new and were originally commercialized by Panasonic. Rotating electrode processes offer better bead shape at high speeds and have the potential for high speed through the arc seam tracking. Binzel's SpinArc torch is designed for automated and robotic applications. Figure 13 shows Abicor Binzel's SpinArc® Automatic MIG Gun (left) and Rotation (right). The tool-free spin diameter is adjustable, and a digital motor control circuit is used to control precise spin speed.

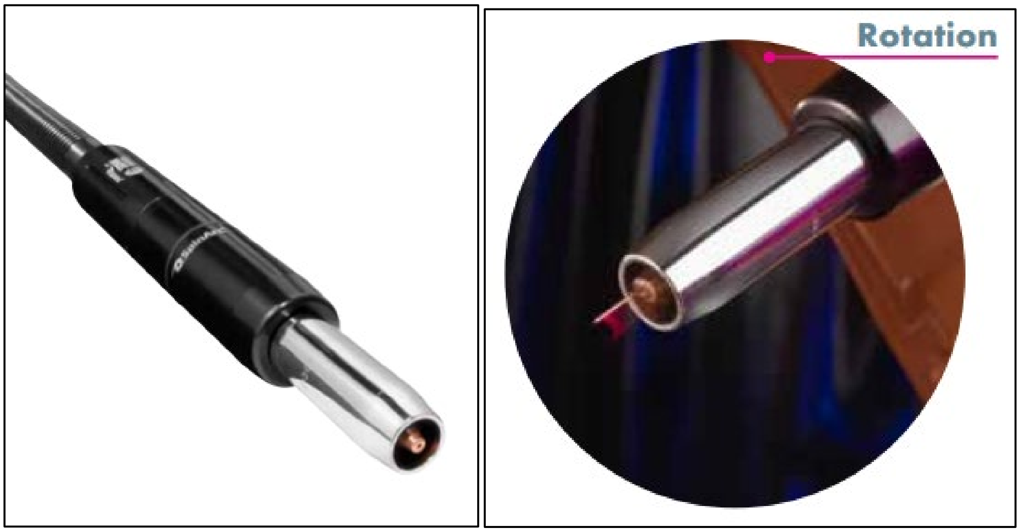



**Figure 13. Abicor Binzel SpinArc® Automatic MIG Gun, left, Rotation, right**[8]

### 4.2.9 D/F Specialties Water-Cooled Tandem Machine Barrel

D/F Specialties manufactures an 850 Amp (1700 Amps Max), 100% Duty cycle, adjustable contact tip geometry tandem torch. The distance between the tandem contact tips (the wires) can vary by removing the body screws of one or both inner bodies. This allows rotation of each inner body, increasing or decreasing the distance between the two welding wires. The inner bodies can also be either straight or bent to desired degrees to help achieve different center-point distances between the two tandem contact tips and are easily changeable. The adjustable tip spacing setup enables the use of larger electrodes (0.052 and 0.062 in.), longer contract tip to work distances (CTWDs), and higher currents. At high currents, larger spacings are needed to control the attractive coupling force between the electric arcs. Figure 14 shows the adjustable Water-Cooled Tandem Machine Barrel.

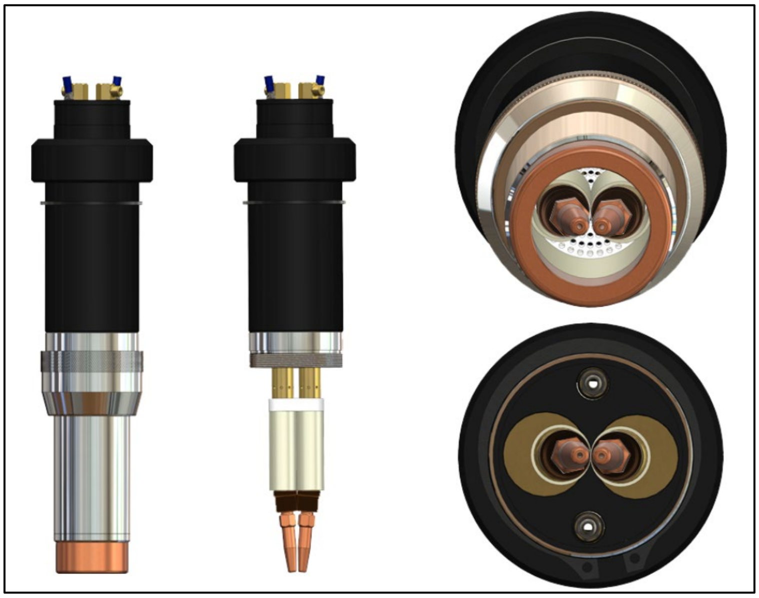


**Figure 14. D/F Specialties adjustable Water-Cooled Tandem Machine Barrel**[9]

### 4.2.10 Wenglor Automated Weld Seam Tracking

In addition to GMA process equipment, special seam tracking sensors are needed for high-speed fillet welding. For reflective surfaces and high-speed welding, Wenglor's sensor has tools, filters, and algorithms built into the sensors to handle reflective surfaces and high-fidelity measurements for precision fillet welding.  Offered in both red and blue lasers from 2M to 3B of power. This sensor can support travel speeds up to 2 m/min using a look ahead distance of at least 0.44 mm. Figure 15 shows the Wenglor Automated Weld Seam Tracking MLZL 2D/3D Profile Sensor.


**Figure 15. Wenglor Automated Weld Seam Tracking MLZL 2D/3D Profile Sensor**[10]

## 4.3 Task 3 – Feasibility Testing of Next Generation DE-GMAW Processes

Welding processes that had a deposition rate greater than 20 lb/hr were down selected for Task 3 feasibility testing. Select-Arc consumables were also selected for Task 3 feasibility testing. Abicor-Binzel and D/F Machine Specialties were down selected, but no consignment was available. This is shown in Figure 16.

| COMPANY | TECHNOLOGY | NOTES |
|---|---|---|
| LINCOLN ELECTRIC | HyperFill™ | 24-lbs./hr. |
| Miller | Hercules™ | 30-lbs./hr. |
| Fronius | TPS/i TWIN | 35-lbs./hr. |
| CLOOS | Tandem Synergy Pro | 35-lbs./hr. |
| SELECT ARC INC. | Consumables | High Speed Electrodes |
| ABICOR BINZEL | No Consignment Available | |
| D/F MIG TIG | No Consignment Available | |

**Figure 16. Task 3 Feasibility Testing Down Selection**

### 4.3.1 Lincoln Hyper Fill

A single arm Fanuc robot was set up with a Lincoln Electric S500 power supply equipped with a HyperFill™ setup. Several iterations were made using 0.045-in diameter ER70S-6 electrodes using 94% Ar 6% $CO_2$ at the target 4-mm fillet size without success. Too much material was being transferred across the arc causing unacceptable undercut. EWI reached out to Lincoln Electric for additional support. They stated that HyperFill™ was not developed for this small of a fillet weld. They did state that there could be future development of an RapidArc waveform that could perform at smaller sizes but was not available within the project timeline. The best parameters were:

- 350-ipm WFS
- 30-ipm Travel Speed
- 0.85 Trim

Photos of the plate welds are shown in Figure 17 and the macrograph showing severe undercut is shown in Figure 18.

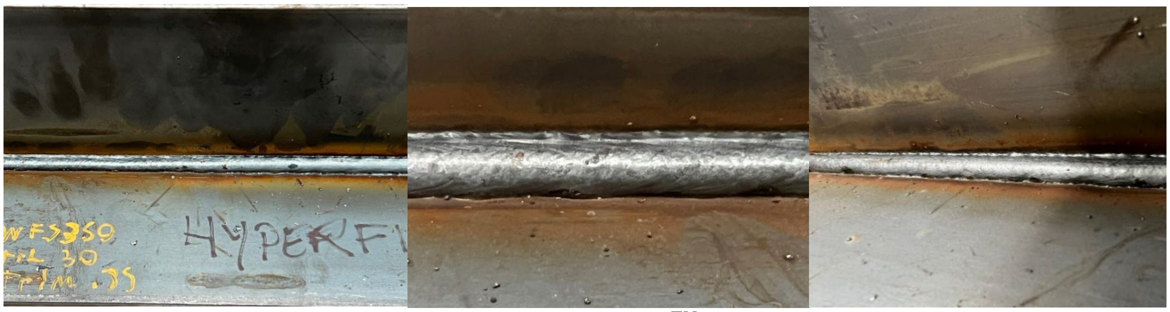



**Figure 17. Lincoln HyperFill$^{TM}$ Plate Photos**

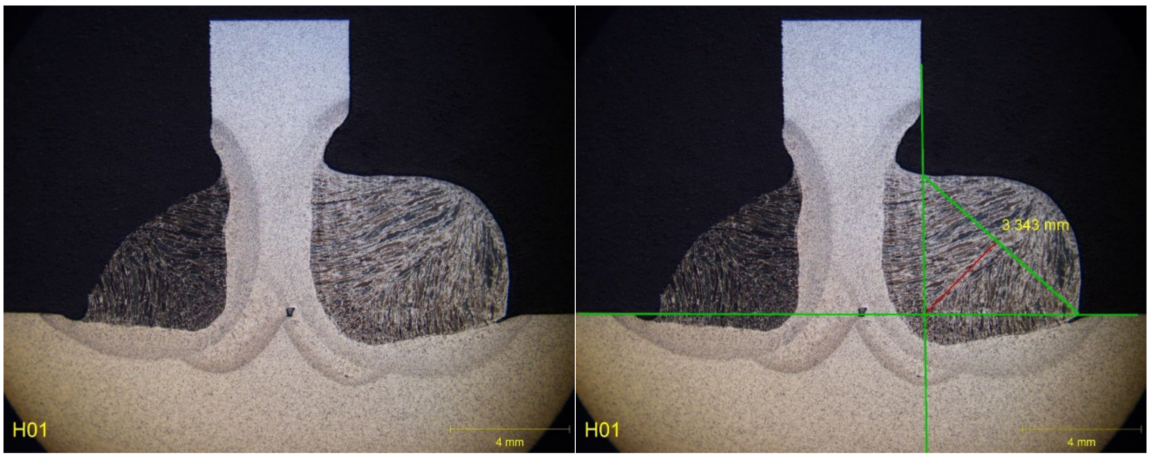



**Figure 18. Lincoln HyperFill$^{TM}$ Macrographs**

### 4.3.2 Miller Hercules$^{TM}$

These samples were welded by Miller at their Hobart facility in Troy, Ohio. Based on the size and the shape of the parts, minimal fixturing and locating were needed to secure the parts for welding. Three pins will locate the part on a table and a clamp used to crowd the part to the datums and secure it. It was found no vertical clamping was needed. This setup is shown in Figure 19.

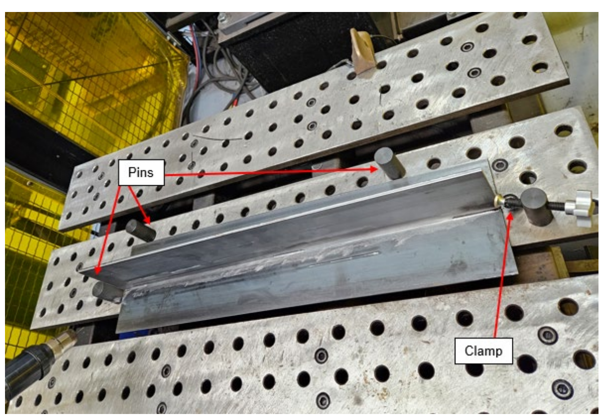


**Figure 19. Miller Hercules Fixture Setup**

A linear welding program was created to weld the sample. It consisted of a perch point, an approach point, the two welding points for the entire length of the sample (no weaving used), and a retract position. The program was tested first at a low speed (1.0 m/min). As welding speed was increased, it was observed that the welds on the samples were not wetting out along the toe at speeds 1.5 m/min and above. Several parameters were adjusted looking for a better weld profile. It was found that the welds were not wetting out because of the oxide on the steel test samples. The test samples were cleaned with a wire brush wheel to remove all the surface oxide to assist in bead appearance.

The Hercules torch used 0.052-in. wire from a drum-style package. It was welded with 90%Ar - 10%$CO_2$ shielding gas at 50-cfh flow. Several welds were made using the documented welding parameters. The process was repeatable, and all the welds had similar appearances visually. The final weld parameters are shown in Figure 20.

| | Set variables | | | | Observed | |
|---|---|---|---|---|---|---|
| | Volts | WFS (IPM) | Travel Speed (m/min) | Travel Angle | Volts | Amps |
| Data | 26 | 560 | 1.5 | 10 deg. Push | 26.1 (5.9) | 316 (185) |
| Wire Specification | AWS A5.18: E70C-6M<br>Part#: S279715-058 Diameter 0.052 (1.4) 1000 Lb (453.6 Kg) Recyclable Exacto-Pak | | | | | |
| Gas Specification | 90%Ar-10%CO2 | | | | | |

*output amps and volts are the average and are from the Continuum (XMT) power sources individually.

**Figure 20. Miller Hercules Feasibility Testing Parameters**

The welds were visually acceptable and shown in Figure 21.

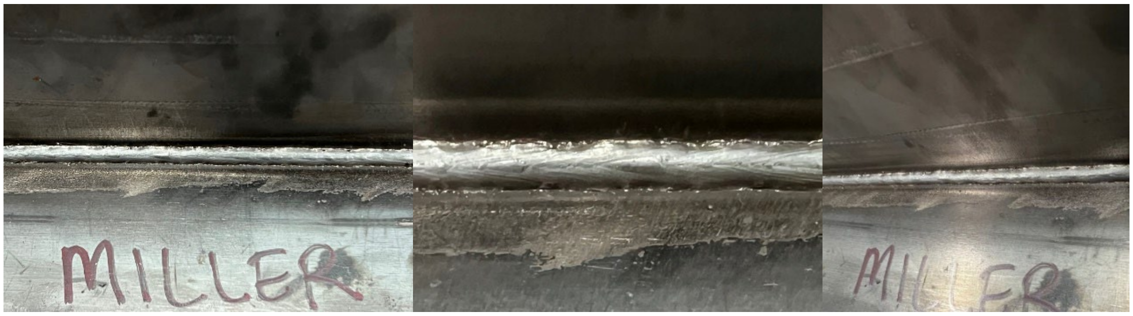


**Figure 21. Miller Hercules Feasibility Testing Plate Welds**

A defect was observed that may be a plasma jet induced defect. This will be investigated during Task 4 and is shown in Figure 22.

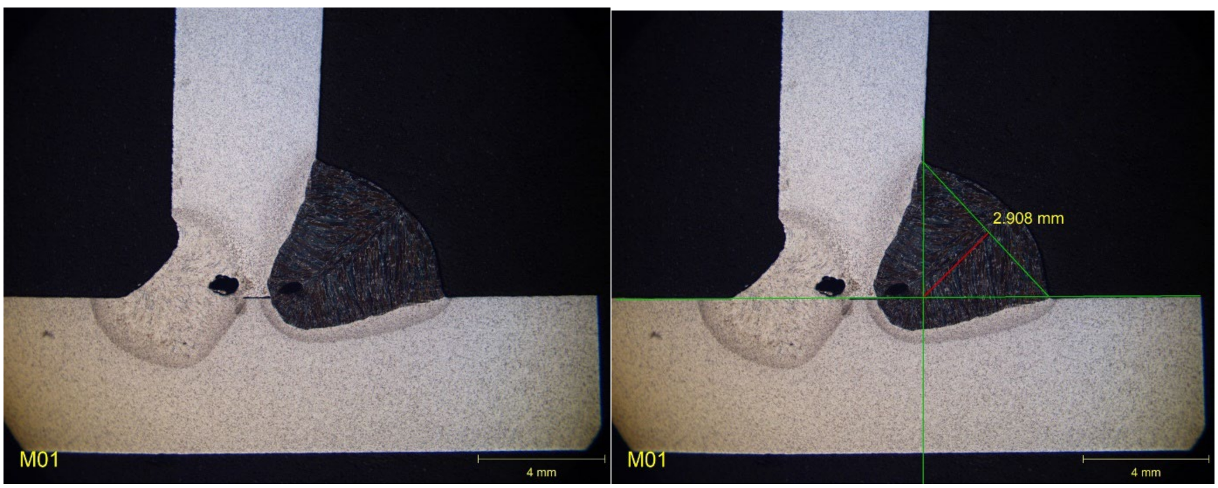


**Figure 22. Miller Hercules Macrographs. Test weld (right) has Small Pore in Root of Deposit (Root Cause Unknown Laser tacking or GMA plasma jet); Manual Laser Tack Weld (left) also had a Pore but Was Not Part of the Test**

#### 4.3.3 Fronius TPS/i TWIN

These samples were welded by Fronius at their facility in Portage, Indiana. All tests utilized the following setup: two TPS 600i power supplies, WF 60i Twin Hosepack, WF 30i R Twin Feeder, and a CU1800 chiller. The torch and plate setup are shown in Figure 23.

**Figure 23. Fronius TPS/i TWIN Torch and Plate Setup**

Both a 100% $CO_2$ test and a 94% Ar 6% $CO_2$ tests were trialed using 0.045-in ER70S-6 electrodes. The 100% $CO_2$ test showed excessive spatter as shown in Figure 24.

**Figure 24. Excessive Spatter from the 100% $CO_2$ Test**

The 94% Ar 6% $CO_2$ showed much better stability with a good weld profile as shown in Figure 25.

**Figure 25. TPS/i TWIN Plate Welds**

The Macrograph removed from Figure 25 showed only slight undercut which could be resolved with torch manipulation as shown in Figure 26.

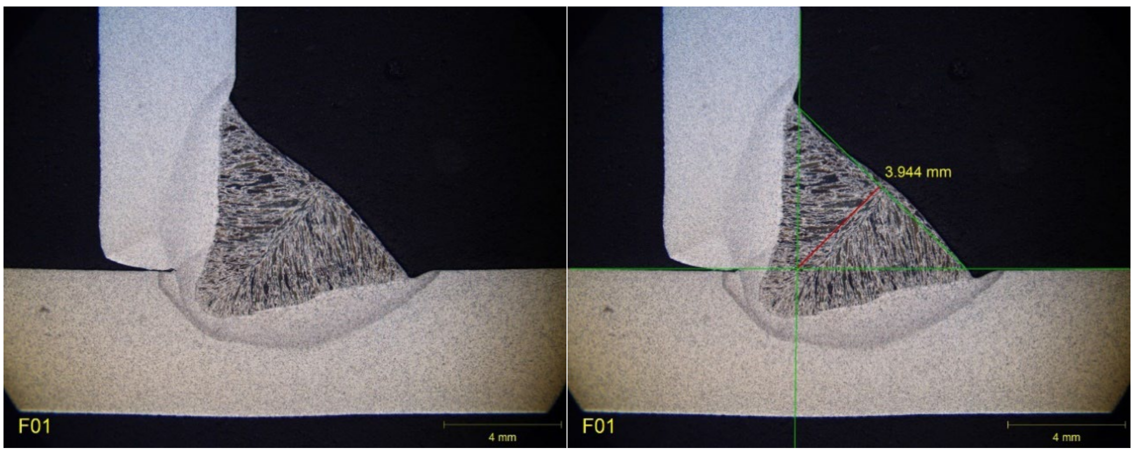



**Figure 26. TPS/i TWIN Macrographs**

The final welding parameters are shown in Figure 27.

| | | | |
|---|---|---|---|
| Layer | 1 | End Arclength correction | -3.0 |
| Shielding gas | M12 Ar+2-5%CO2 | End current time | 1.0 s |
| Name | EWI 94/6 60IPM Lead | SFI | on |
| Welding mode | MIG PMC | SFI Hot start | off |
| Characteristic | 3834 | Wire retract | 0.5 |
| Property | TWIN PCS | Penetration stabilizer | 0 ipm |
| Gas | M20 Ar+5-10%CO2 | Arc length stabilizer | 0.0 |
| Wire | EN: Steel, AWS: ER 70S-6 | CMT Cycle Step | off |
| Wire diameter | .045 inch | Gas preflow | 0.5 s |
| Trigger mode | S2-step | Gas postflow | 1.5 s |
| Welding process line | 1 | Command value gas | 45.0 CFH |
| Wire Feed Speed | 698 ipm | Gas factor | auto |
| Current | 407 A | Upper power correction limit | 0 % |
| Voltage | 29.6 V | Lower power correction limit | 0 % |
| Material Thickness | 0.878 inch | Upper arc length correction limit | 0.0 |
| Arclength correction | -1.8 | Lower arc length correction limit | 0.0 |
| Pulse/dynamic correction | 0.0 | Job slope | 0.0 s |
| Starting current | 85 % | Sampling rate | 0.1 s |
| Start Arclength correction | -0.8 | Limit reaction | ignore |
| Start current time | 0.3 s | Inching value | 19.685 ipm |
| Slope 1 | 0.1 s | Pulse Synchronization Ratio | auto |
| Slope 2 | 0.6 s | Phase shift Lead/Trail | auto |
| End current | 40 % | Ignition delay Trail | auto |

| | | | |
|---|---|---|---|
| Layer | 1 | End Arclength correction | -4.2 |
| Shielding gas | M12 Ar+2-5%CO2 | End current time | 0.1 s |
| Name | EWI 94/6 60IPM Trail | SFI | on |
| Welding mode | MIG PMC | SFI Hot start | off |
| Characteristic | 3565 | Wire retract | 0.4 |
| Property | TWIN universal | Penetration stabilizer | 0 ipm |
| Gas | M20 Ar+5-10%CO2 | Arc length stabilizer | 0.8 |
| Wire | EN: Steel, AWS: ER 70S-6 | CMT Cycle Step | off |
| Wire diameter | .045 inch | Gas preflow | 0.5 s |
| Trigger mode | S2-step | Gas postflow | 1.5 s |
| Welding process line | 1 | Command value gas | 45.0 CFH |
| Wire Feed Speed | 398 ipm | Gas factor | auto |
| Current | 253 A | Upper power correction limit | 0 % |
| Voltage | 24.9 V | Lower power correction limit | 0 % |
| Material Thickness | 0.280 inch | Upper arc length correction limit | 0.0 |
| Arclength correction | -2.3 | Lower arc length correction limit | 0.0 |
| Pulse/dynamic correction | -1.0 | Job slope | 0.0 s |
| Starting current | 80 % | Sampling rate | 0.1 s |
| Start Arclength correction | 0.0 | Limit reaction | ignore |
| Start current time | off | Inching value | 19.685 ipm |
| Slope 1 | 0.1 s | Pulse Synchronization Ratio | auto |
| Slope 2 | 0.1 s | Phase shift Lead/Trail | auto |
| End current | 30 % | Ignition delay Trail | auto |

**Figure 27. Fronius TPS/i TWIN Feasibility Testing Parameters**

### 4.3.4 CLOOS Tandem Synergy Pro

A Cloos robot system was set up with a Tandem Synergy Pro power supply equipped with a Tandem torch. Several iterations were made using 0.045-in ER70S-6 using 90% Ar 10% $CO^2$ at the target 4-mm fillet size with close success. The final parameters were:

- Travel Speed: 120-cm./min.
- Lead
  - WFS: 6-m./min.
  - Arc Length: -15
- Trail
  - WFS: 10-m./min.
  - Arc Length: 10

The weld profile is good and is shown in Figure 28.

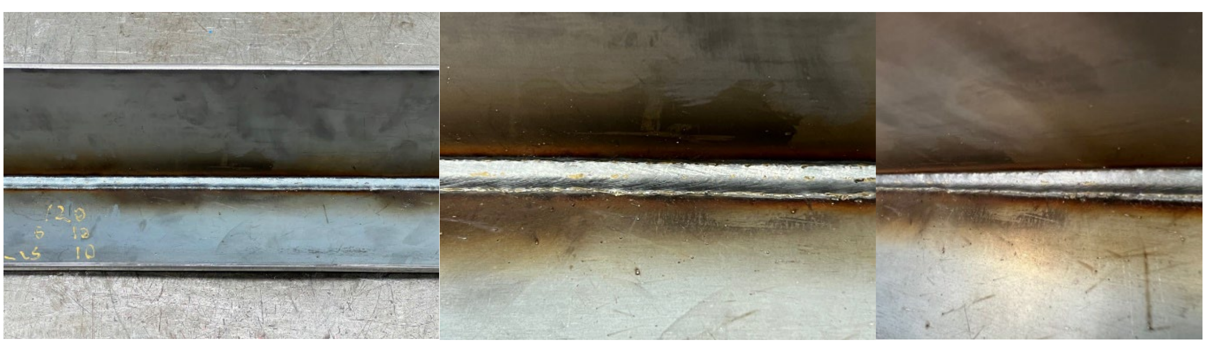


**Figure 28. CLOOS Tandem Plate Welds**

Macrograph cross-sections removed from Figure 28 tests are shown in Figure 29 which shows slight undercut and lack of fusion. This can be resolved going forward in Task 4.

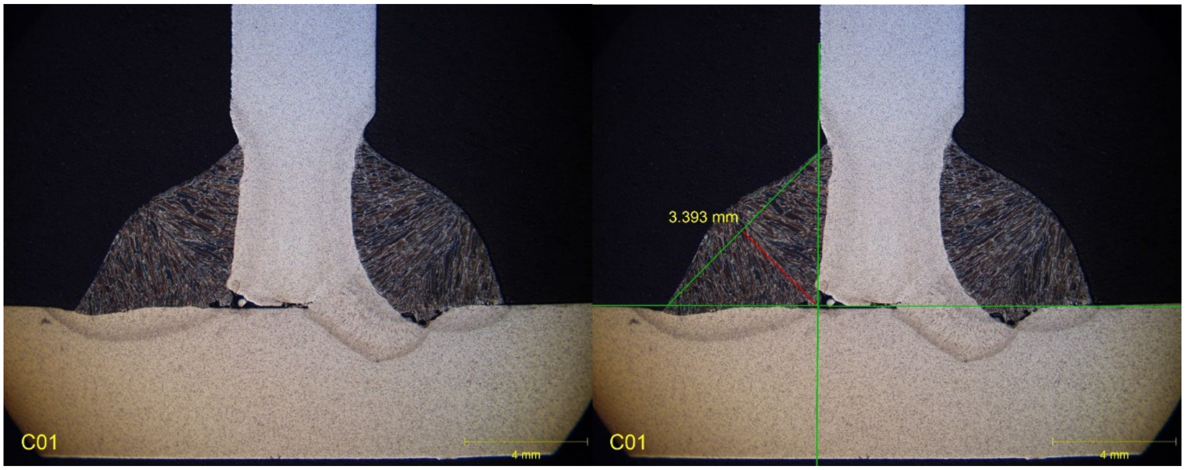



**Figure 29. CLOOS Tandem Macrographs**

### 4.3.5 Select-Arc

Select-Arc offered a few options that are COTS for high-speed welding (automotive) and supplied 70C-10 to the project. Initial testing showed small improvements in arc wetting. The product will continue to be evaluated if needed in Task 4. Product sheet shown in Figure 30.

**Select 70C-10**

*Carbon Steel / Gas Shielded / Metal Cored* PRODUCT DATA SHEET

**FEATURES**

- Designed for single pass welding of high-speed welding of thin gauge carbon steels.
- Travel speeds of 85-100 ipm are readily achievable.
- Performance of this product is not dependent on high technology power sources; a standard CV machine produces excellent results.
- Applications include welding automotive and truck frames, automotive cradle assemblies, farm machinery and other general purpose welding of light gauge components.

**CONFORMANCES**

| | |
|---|---|
| ASME SFA 5.18 | E70C-GSM |
| AWS A5.18 | E70C-GSM |

**DIAMETERS [in (mm)]**

0.045 (1.2), 1/16 (1.6), 5/64 (2.0)

**POSITIONS**

**SHIELDING GAS**

Ar + 5-25% CO2
Flow Rate: 40 - 50 CFM

**POLARITY**

Direct Current Electrode Positive (DCEP)

**TYPICAL MECHANICAL PROPERTIES**

| Shielding Gas | Tensile Strength ksi (MPa) | Yield Strength ksi (MPa) | Elongation (%) | Weld Condition |
|---|---|---|---|---|
| 75%Ar / 25%CO2 | 82 (562) | #Error | | As-Welded |

SELECT ARC INC.

Notice: The results reported are based upon testing of the product under controlled laboratory conditions in accordance with American Welding Society Standards. Actual use of the product may produce different results due to varying conditions. An example of such conditions would be electrode size, plate chemistry, environment, weldment design, fabrication methods, welding procedure and service requirements. Thus the results are not guarantees for use in the field. The manufacturer disclaims any warranty of merchantability or fitness for any particular purpose with respect to its products.

600 Enterprise Drive, P.O. Box 259, Fort Loramie, Ohio 45845-0259 • 800-341-5215 • www.Select-Arc.com

*Revision: 9/16/2022*

**Figure 30. Select-Arc 70C-10 Product Data Sheet**

### 4.3.6 IPG LightWELD

All tacking operation during this project was done using an IPG LightWELD system. It was capable of repeatedly welding at, or below, 1 mm. The system setup and macrograph are shown in Figure 31.


**Figure 31. IPG LightWELD System, left, and Macrograph, right**

### 4.4 Task 4 – Precision Fillet Weld Operational Windows, Bead Shape Maps, and Productivity Analysis

Welding processes that performed well in Task 3 were down selected into Task 4 operational window evaluations. This included Miller Hercules, Fronius TPS/i TWIN, and Cloos Tandem Synergy Pro. Lincoln HyperFill was removed during this down selection due to the process issues shown in Task 3. Select Arc 70C-10 should be considered when additional bead wetting is needed. This is shown in Figure 32.

| COMPANY | TECHNOLOGY | NOTES |
|---|---|---|
| Miller | Hercules™ | 30-lbs./hr. |
| Fronius | TPS/i TWIN | 35-lbs./hr. |
| CLOOS | Tandem Synergy Pro | 35-lbs./hr. |
| SELECT ARC INC. | Consumables | High Speed Electrodes |

**Figure 32. Task 4 Down Selection**

Systematic ARCWISE tests were performed on the three process combinations from Task 3. For each process combination, a series of constant deposit area (WFS/TS ratio) tests were performed at two arc lengths. The tests were performed over a full range of travel speeds (for example 0.25 to 2 m/min) to determine the minimum speed needed for fusion, the range of acceptable welding conditions, and the maximum speed to process failure. Each test was examined using visual and dimensional methods. Metallographic sections were removed from each test and used to characterize bead shape dimensions and fusion quality.

### 4.4.1 Cloos Tandem Synergy Pro

Using the results from Task 3, the WFS/TS ratio was fixed at 18.33 with a WFS ratio of 63.3% lead to trail WFS with the resulting fillet size of 4-mm. Travel speed was increased until the process became unstable at above 63-ipm. A total of five travel speeds at this WFS/TS ratio were tested at two arc lengths. Arc length was estimated by direct sight, with the short arc length being 1-mm, and the long arc length being 3-mm. A total of ten welds were completed and are summarized in Figure 33.

| Cloos Tandem Synergy Pro - Short Parameters | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PARAMETERS | | | | | | | | | | | LEAD | | | | TRAIL | | | | COMBINED | |
| TRAVEL (m/min) | TRAVEL (ipm) | $WFS_L$ (m/min) | $WFS_L$ (ipm) | $WFS_T$ (m/min) | $WFS_T$ (ipm) | $WFS_{TOTAL}$ (m/min) | $WFS_{TOTAL}$ (ipm) | $WFS_{RATIO}$ (%) | WFS/TS RATIO | ALC | $A_L$ | $V_L$ | $WFS_L$ (ipm) | $HI_L$ (kJ/in) | $A_T$ | $V_T$ | $WFS_T$ (ipm) | $HI_T$ (kJ/in) | Deposition Rate (lb/hr) | $HI_{TOTAL}$ (kJ/in) |
| [redacted] | | | | | | | | | | | | | | | | | | | | |
| 0.8 | 31.50 | 9.34 | 367.73 | 5.33 | 209.68 | 14.67 | 577.42 | 0.64 | 18.33 | 1 | 127 | 23.7 | 367.73 | 5.73 | 189 | 18.5 | 209.68 | 6.66 | 15.76 | 12.39 |
| 1 | 39.37 | 11.68 | 459.67 | 6.66 | 262.10 | 18.33 | 721.77 | 0.64 | 18.33 | 1 | 157 | 23.2 | 459.67 | 5.55 | 226 | 18.3 | 262.10 | 6.30 | 19.70 | 11.85 |
| 1.2 | 47.24 | 14.01 | 551.51 | 7.99 | 314.47 | 22.00 | 865.98 | 0.64 | 18.33 | 1 | 179 | 23.3 | 551.51 | 5.30 | 249 | 19.1 | 314.47 | 6.04 | 23.63 | 11.34 |
| 1.4 | 55.12 | 16.34 | 643.43 | 9.32 | 366.88 | 25.66 | 1010.32 | 0.64 | 18.33 | 1 | 200 | 23.8 | 643.43 | 5.18 | 272 | 20 | 366.88 | 5.92 | 27.57 | 11.10 |
| 1.6 | 62.99 | 18.68 | 735.35 | 10.65 | 419.30 | 29.33 | 1154.65 | 0.64 | 18.33 | 1 | 226 | 24.7 | 735.35 | 5.32 | 302 | 20.4 | 419.30 | 5.87 | 31.51 | 11.19 |
| [redacted] | | | | | | | | | | | | | | | | | | | | |

| Cloos Tandem Synergy Pro - Long Parameters | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PARAMETERS | | | | | | | | | | | LEAD | | | | TRAIL | | | | COMBINED | |
| TRAVEL (m/min) | TRAVEL (ipm) | $WFS_L$ (m/min) | $WFS_L$ (ipm) | $WFS_T$ (m/min) | $WFS_T$ (ipm) | $WFS_{TOTAL}$ (m/min) | $WFS_{TOTAL}$ (ipm) | $WFS_{RATIO}$ (%) | WFS/TS RATIO | ALC | $A_L$ | $V_L$ | $WFS_L$ (ipm) | $HI_L$ (kJ/in) | $A_T$ | $V_T$ | $WFS_T$ (ipm) | $HI_T$ (kJ/in) | Deposition Rate (lb/hr) | $HI_{TOTAL}$ (kJ/in) |
| 0.8 | 31.50 | 9.34 | 367.73 | 5.33 | 209.68 | 14.67 | 577.42 | 0.64 | 18.33 | 3 | 132 | 24.4 | 367.73 | 6.14 | 185 | 19.4 | 209.68 | 6.84 | 15.76 | 12.97 |
| 1 | 39.37 | 11.68 | 459.67 | 6.66 | 262.10 | 18.33 | 721.77 | 0.64 | 18.33 | 3 | 162 | 24.2 | 459.67 | 5.97 | 221 | 19.4 | 262.10 | 6.53 | 19.70 | 12.51 |
| 1.2 | 47.24 | 14.01 | 551.51 | 7.99 | 314.47 | 22.00 | 865.98 | 0.64 | 18.33 | 3 | 186 | 24.6 | 551.51 | 5.81 | 251 | 20.1 | 314.47 | 6.41 | 23.63 | 12.22 |
| 1.4 | 55.12 | 16.34 | 643.43 | 9.32 | 366.88 | 25.66 | 1010.32 | 0.64 | 18.33 | 3 | 208 | 25.8 | 643.43 | 5.84 | 279 | 21 | 366.88 | 6.38 | 27.57 | 12.22 |
| 1.6 | 62.99 | 18.68 | 735.35 | 10.65 | 419.30 | 29.33 | 1154.65 | 0.64 | 18.33 | 3 | 231 | 26.5 | 735.35 | 5.83 | 305 | 21.9 | 419.30 | 6.36 | 31.51 | 12.19 |

**Figure 33. Cloos Tandem Synergy Short Arc Length Parameters (top); Long Arc Length Parameters (bottom)**

After the completion of these welds, macrographs were taken, and a bead shape map was constructed. This is shown in Figure 34.

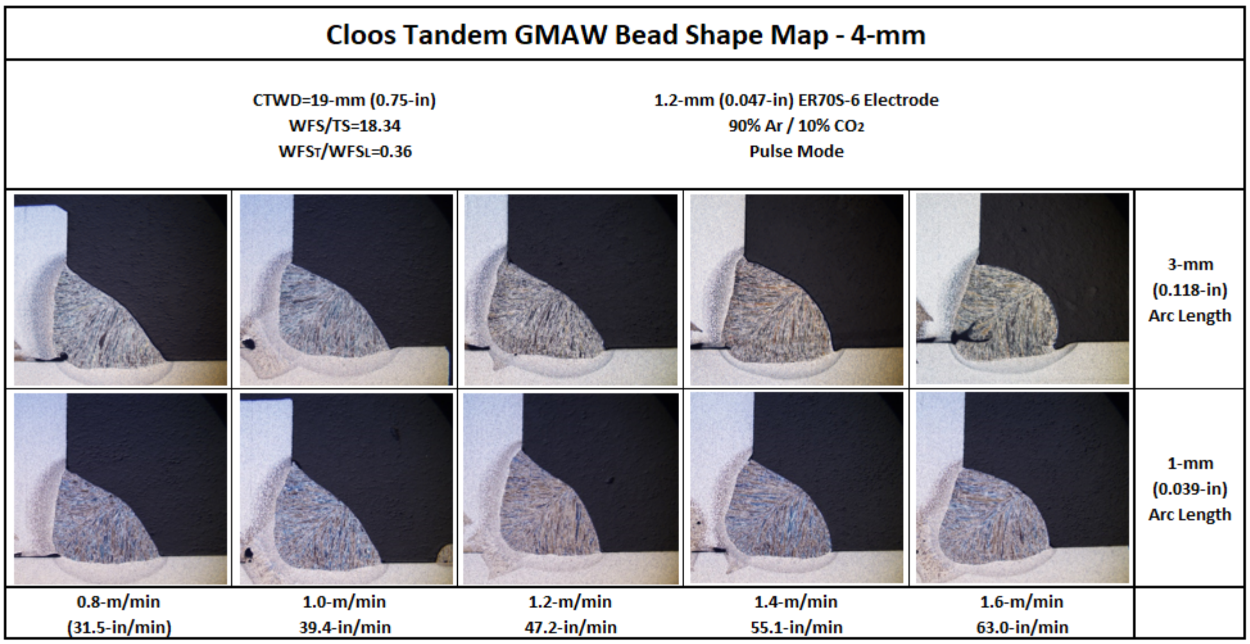



**Figure 34. Cloos Tandem Synergy Pro Bead Shape Map**

Macrographs were then analyzed. Weld size and maximum undercut were measured and are shown in Figure 35. Weld deposit sizes were similar throughout the map as expected using constant WFS/TS ratio tests. As travel speeds increased, the nugget area (deposit area plus base metal fusion area) increased due to increased process melting efficiency. This is measured by calculating base metal dilution (BMD). A minimum BMD is used as a measure of fusion quality to ensure resistance to lack of penetration and fusion defects.

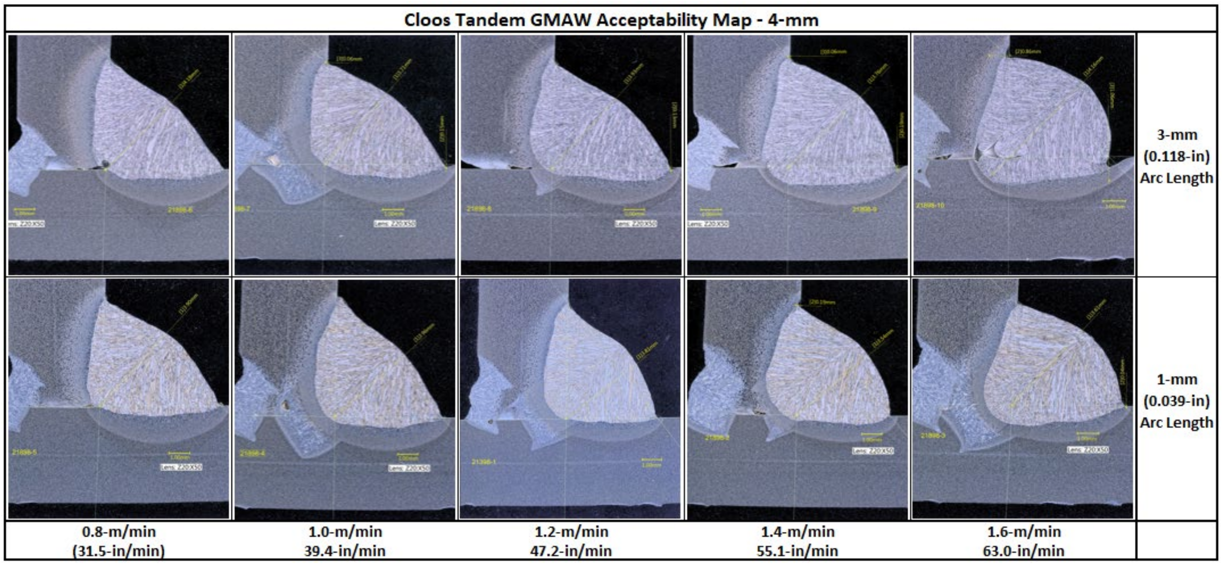



**Figure 35. Cloos Tandem Synergy Pro Measurement Map**

Using this data, an operation window map was then constructed and is shown in Figure 36. This window of acceptance is based on visual testing that was conducted per MIL-STD-2035A and acceptable bead shape.(11) Note that the test at a 3-mm arc length and 63.0-in./min travel speed was not acceptable due to excessive undercut (exceeded 1/64-in.).

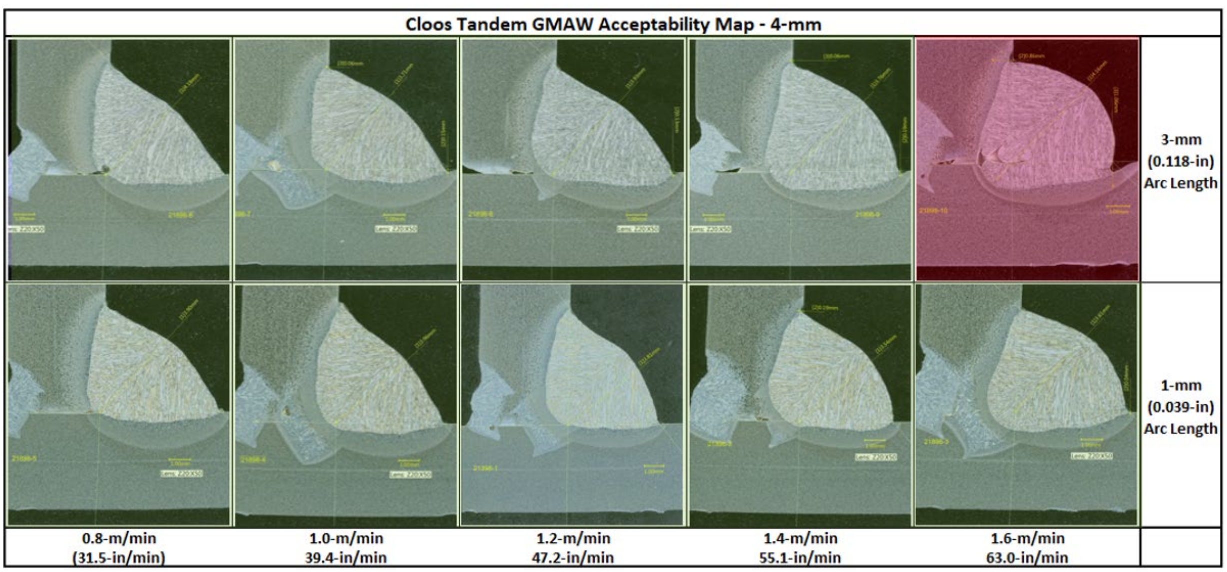



**Figure 36. Cloos Tandem Synergy Pro Acceptability Map**

### 4.4.2 Miller Hercules

Using the results from Task 3, the WFS/TS ratio was calculated at 9.48 for 0.052-in electrode. However, the test welds produced had a range of fillet sizes from 3  to 5 mm. Travel speed was increased until the process became unstable at above 69 ipm. A total of five travel speeds were tested at this WFS/TS ratio at two arc lengths. Arc length was estimated by direct sight, with the short arc length being 1 mm, and the long arc length being 3 mm. A total of 10 welds were completed and are summarized in Figure 37.

| Miller Hercules - Short Parameters | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PARAMETERS | | | | | ARC | | | | | CONDITIONING | | COMBINED |
| TRAVEL (m/min) | TRAVEL (ipm) | WFS (ipm) | WFS/TS RATIO | ALC | A | V | WFS | Deposition Rate (lb/hr) | HI (kJ/in) | A | V | HI (kJ/in) |
| 0.75 | 29.53 | 279.92 | 9.48 | 26 | 251.9 | 25.9 | 281.4 | 10.20 | 13.26 | Unknown | Unknown | 14.2 |
| 1 | 39.37 | 373.23 | 9.48 | 26 | 296.4 | 26.0 | 371.3 | 13.60 | 11.74 | Unknown | Unknown | 12.7 |
| **1.25** | **49.21** | 466.54 | **9.48** | 26 | 328.5 | 25.9 | 461.8 | 17.00 | 10.37 | Unknown | Unknown | 11.3 |
| 1.5 | 59.06 | 560.00 | 9.48 | 26 | 361.9 | 26.0 | 552.7 | 20.41 | 9.56 | Unknown | Unknown | 10.5 |
| 1.75 | 68.90 | 653.15 | 9.48 | 26 | 372.7 | 26.0 | 635.5 | 23.80 | 8.44 | Unknown | Unknown | 9.3 |

| Miller Hercules - Long Parameters | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PARAMETERS | | | | | ARC | | | | | CONDITIONING | | COMBINED |
| TRAVEL (m/min) | TRAVEL (ipm) | WFS (ipm) | WFS/TS RATIO | ALC | A | V | WFS | Deposition Rate (lb/hr) | HI (kJ/in) | A | V | HI (kJ/in) |
| 0.75 | 29.53 | 279.92 | 9.48 | 29 | 271.6 | 28.9 | 281.4 | 10.20 | 15.95 | Unknown | Unknown | 16.9 |
| 1 | 39.37 | 373.23 | 9.48 | 29 | 314.8 | 28.8 | 376.2 | 13.60 | 13.82 | Unknown | Unknown | 14.8 |
| **1.25** | **49.21** | 466.54 | **9.48** | 29 | 355.8 | 28.8 | 462.8 | 17.00 | 12.49 | Unknown | Unknown | 13.4 |
| 1.5 | 59.06 | 560.00 | 9.48 | 29 | 382.3 | 28.7 | 553.4 | 20.41 | 11.15 | Unknown | Unknown | 12.0 |
| 1.75 | 68.90 | 653.15 | 9.48 | 29 | 393.3 | 28.8 | 636.6 | 23.80 | 9.86 | Unknown | Unknown | 10.7 |

**Figure 37. Miller Hercules Short Arc Length Parameters (top); Long Arc Length Parameters (bottom)**

After the completion of these welds, macrographs were taken, and a bead shape map was constructed. This is shown in Figure 38.

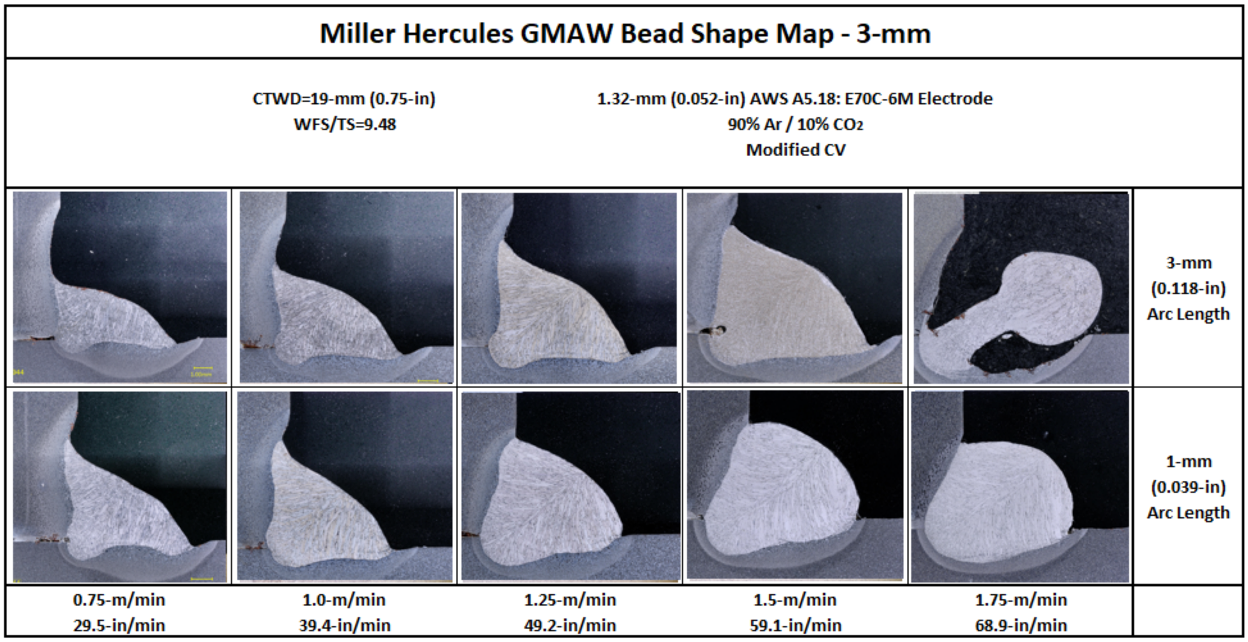



**Figure 38. Miller Hercules Bead Map**

Macrographs were then analyzed. Weld size and maximum undercut were measured and are shown in Figure 39. Weld deposit size was not similar throughout the map as expected, even though WFS/TS ratio was fixed. This variation in deposit area is either due to spatter, wire feed drive instabilities, or wire feed control/setting errors.

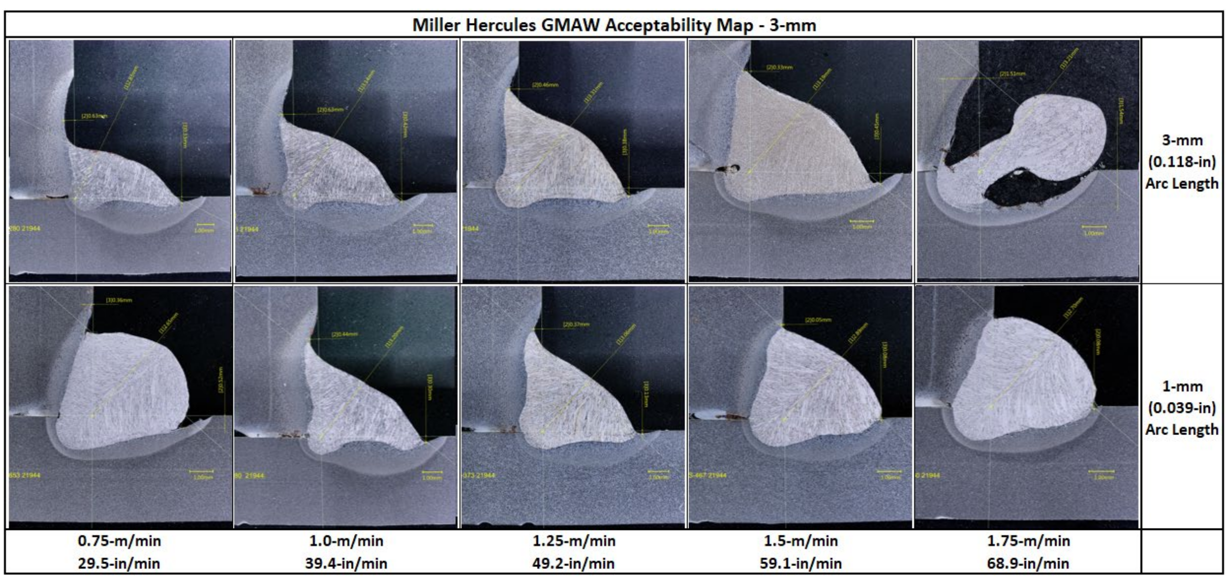



**Figure 39. Miller Hercules Measurement Map**

Using this data, an acceptability map was then constructed and is shown in Figure 40. This is in addition to visual testing that was conducted per MIL-STD-2035A.[11] Note all welds that were produced with 3-mm arc length were not acceptable as the undercut exceeded 1/64-in. This was also the case for welds made at 29.5 and 39.4-in./min travel speed at the 1-mm arc length.

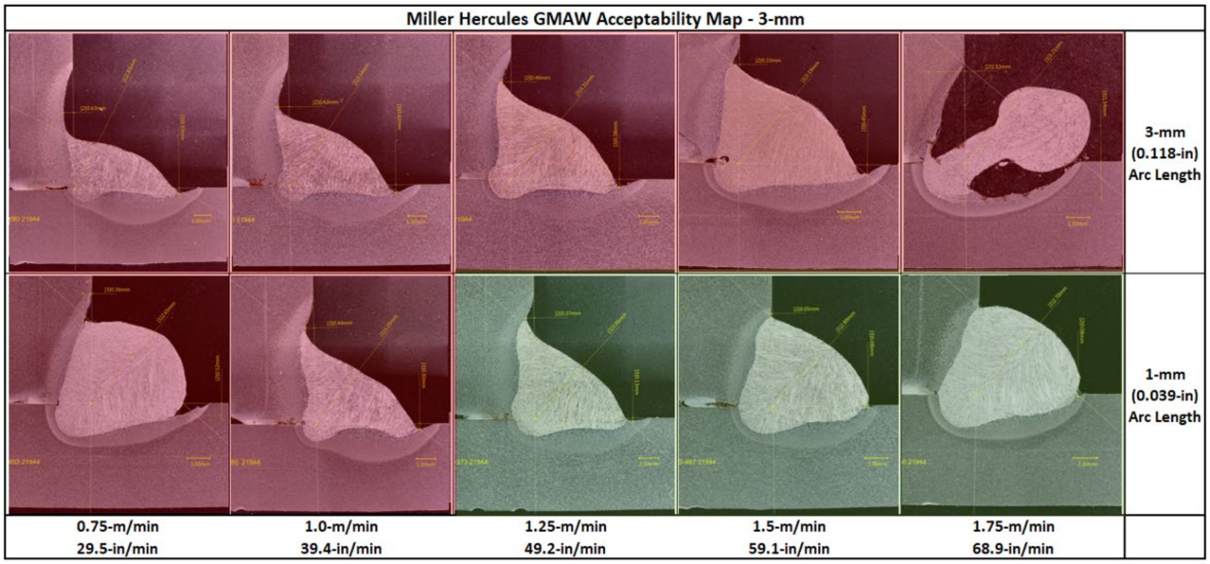



**Figure 40. Miller Hercules Acceptability Map**

### 4.4.3 Fronius TPS/i TWIN

Using the results from Task 3, the WFS/TS deposit ratio was fixed at 18.27 with lead/trail WFS ratio at 63.3% to produce a fillet size of 4 mm. Travel speeds were increased until the process became unstable which was above 80 ipm. Using constant ratios, a total of five travel speeds were tested at two arc lengths. Arc length was estimated by direct sight, with the short arc length being 1 mm, and the long arc length being 3 mm. A total of 10 welds were completed and are summarized in Figure 41.

| Fronius TPSi TWIN - Short Parameters | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PARAMETERS | | | | | | | LEAD | | | | TRAIL | | | | COMBINED | |
| TRAVEL (ipm) | $WFS_L$ (ipm) | $WFS_T$ (ipm) | $WFS_{TOTAL}$ (ipm) | $WFS_{RATIO}$ (%) | WFS/TS RATIO | ALC | $A_L$ | $V_L$ | $WFS_L$ | $HI_L$ (kJ/in) | $A_T$ | $V_T$ | $WFS_T$ | $HI_T$ (kJ/in) | Deposition Rate (lb/hr) | $HI_{TOTAL}$ (kJ/in) |
| [redacted] | | | | | | | | | | | | | | | | |
| 40 | 465.33 | 265.33 | 730.67 | 0.64 | 18.27 | -1.8 | 280 | 25.1 | 11.4 | 10.54 | 180 | 23.9 | 6.4 | 6.45 | 19.94 | 17.00 |
| 50 | 581.67 | 331.67 | 913.33 | 0.64 | 18.27 | -1.8 | 347 | 25.4 | 14.1 | 10.58 | 215 | 24 | 8.1 | 6.19 | 24.93 | 16.77 |
| **60** | **698.00** | **398.00** | **1096.00** | **0.64** | **18.27** | -1.8 | 397 | 26.4 | 16.8 | 10.48 | 255 | 24.7 | 9.7 | 6.30 | 29.91 | 16.78 |
| 70 | 814.33 | 464.33 | 1278.67 | 0.64 | 18.27 | -1.8 | 431 | 25.9 | 19.1 | 9.57 | 288 | 24.4 | 11.3 | 6.02 | 34.90 | 15.59 |
| 80 | 930.67 | 530.67 | 1461.33 | 0.64 | 18.27 | -1.8 | 429 | 26.8 | 15.9 | 8.62 | 300 | 23.8 | 12.5 | 5.36 | 39.88 | 13.98 |

[redacted]

| Fronius TPSi TWIN - Long Parameters | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PARAMETERS | | | | | | | LEAD | | | | TRAIL | | | | COMBINED | |
| TRAVEL (ipm) | $WFS_L$ (ipm) | $WFS_T$ (ipm) | $WFS_{TOTAL}$ (ipm) | $WFS_{RATIO}$ (%) | WFS/TS RATIO | ALC | $A_L$ | $V_L$ | $WFS_L$ | $HI_L$ (kJ/in) | $A_T$ | $V_T$ | $WFS_T$ | $HI_T$ (kJ/in) | Deposition Rate (lb/hr) | $HI_{TOTAL}$ (kJ/in) |
| [redacted] | | | | | | | | | | | | | | | | |
| 40 | 465.33 | 265.33 | 730.67 | 0.64 | 18.27 | -1 | 276 | 25.4 | 11.4 | 10.52 | 174 | 23.9 | 6.5 | 6.24 | 19.94 | 16.75 |
| 50 | 581.67 | 331.67 | 913.33 | 0.64 | 18.27 | -1 | 355 | 25.7 | 14.1 | 10.95 | 212 | 24.5 | 8.1 | 6.23 | 24.93 | 17.18 |
| **60** | **698.00** | **398.00** | **1096.00** | **0.64** | **18.27** | -1 | 396 | 26.9 | 16.9 | 10.65 | 249 | 25.1 | 9.7 | 6.25 | 29.91 | 16.90 |
| 70 | 814.33 | 464.33 | 1278.67 | 0.64 | 18.27 | -1 | 429 | 26.9 | 19.1 | 9.89 | 281 | 25.4 | 11.3 | 6.12 | 34.90 | 16.01 |
| 80 | 930.67 | 530.67 | 1461.33 | 0.64 | 18.27 | -1 | 458 | 27.7 | 21.7 | 9.51 | 300 | 25.1 | 13.1 | 5.65 | 39.88 | 15.16 |

[redacted]

**Figure 41. Fronius TPS/i TWIN Short Arc Length Parameters (top); Long Arc Length Parameters (bottom)**

After the completion of these welds, macrographs were taken, and a bead shape map was constructed. This is shown in Figure 42.

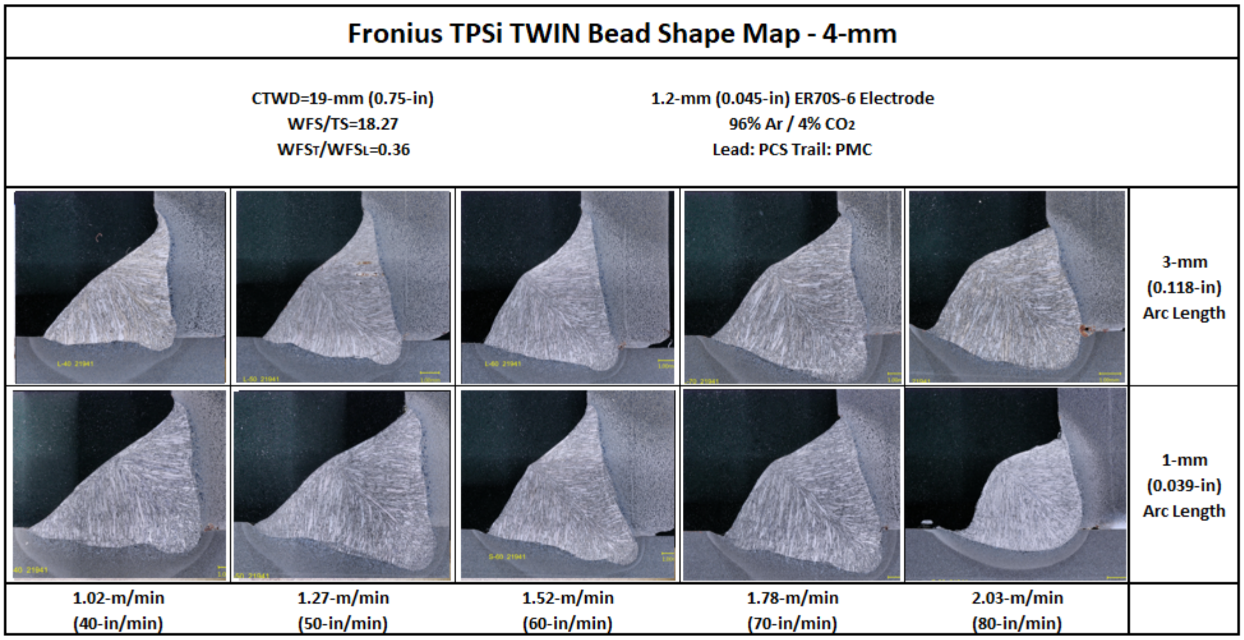



**Figure 42. Fronius TPS/i TWIN Bead Shape Map**

Macrographs were then analyzed. Weld deposit area, nugget area, and maximum undercut were measured and are shown in Figure 43. Weld deposit areas were similar throughout the map as expected, except for the weld made at 80 in./min with an arc length of 1 mm. This weld deposit size was smaller as the lead wire was shorting and spatter caused a loss of deposit section.

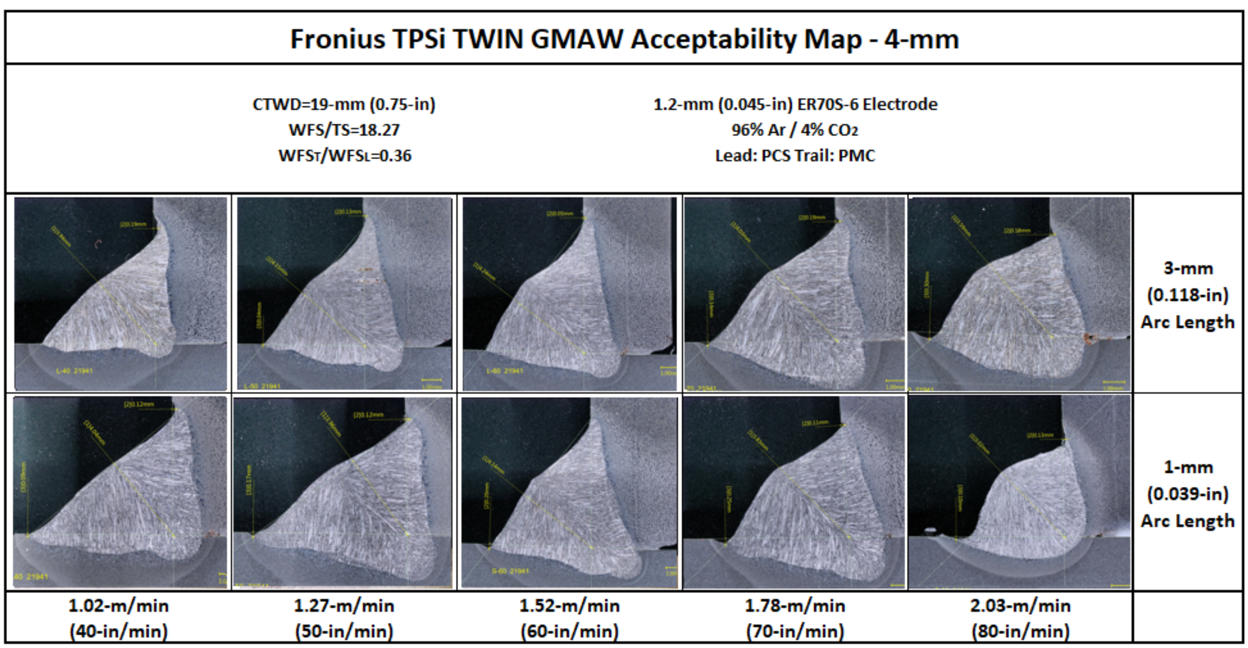



**Figure 43. Fronius TPS/i TWIN Bead Measurement Map**

Using this data an acceptability map was then constructed and is shown in Figure 44. This is in addition to visual testing that was conducted per MIL-STD-2035A.(11) Note that the weld at 1-mm arc length at 80.0-in./min travel speed was not acceptable as the undercut exceeded 1/64-in.

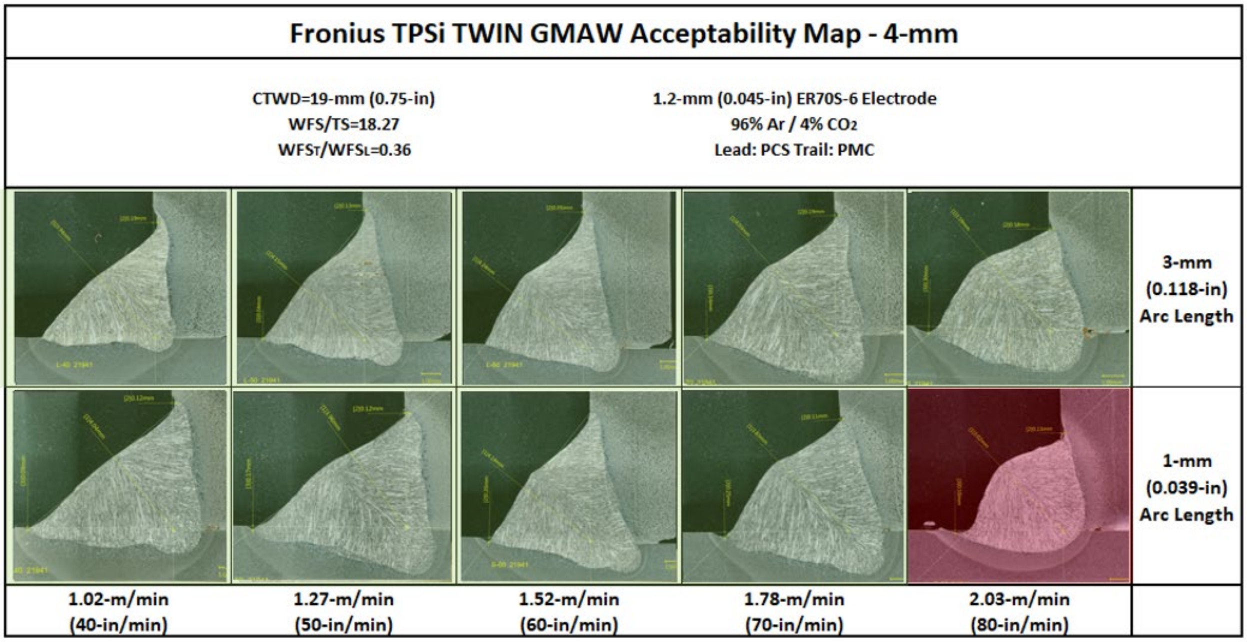
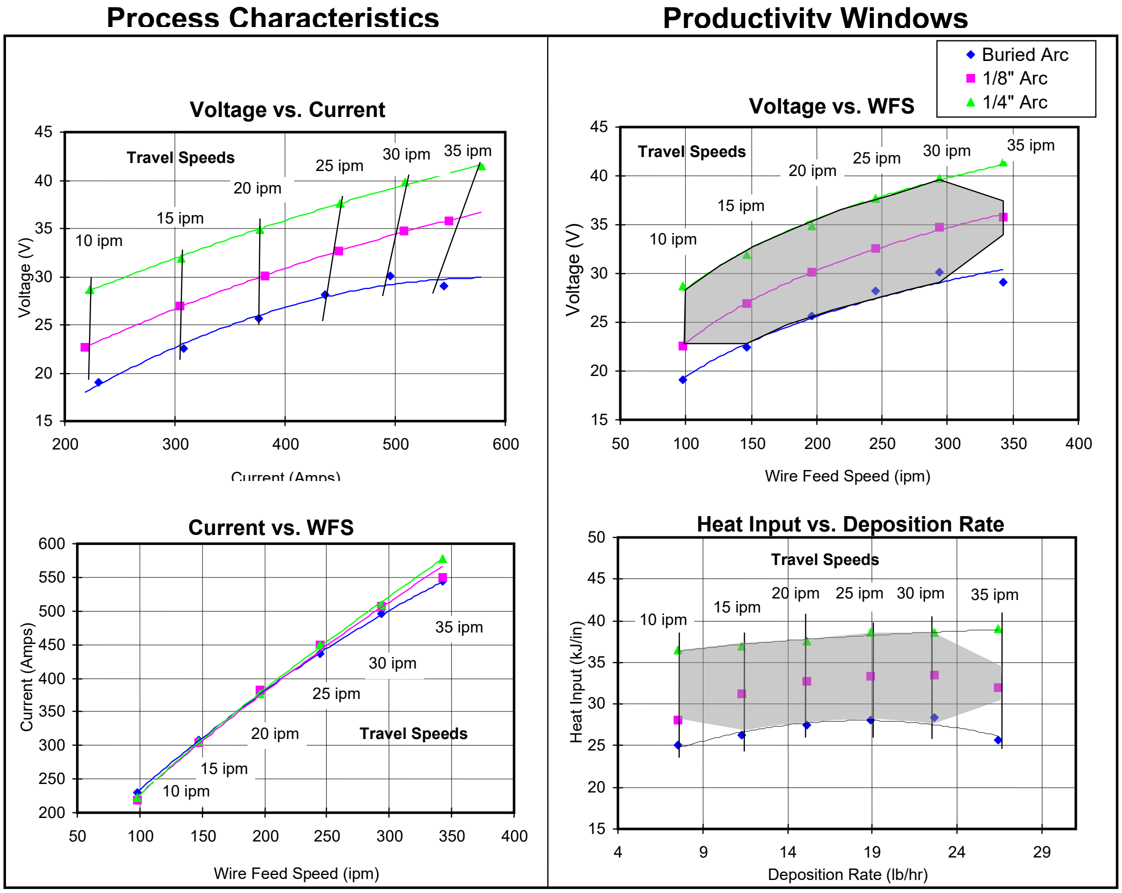



**Figure 44. Fronius TPS/i TWIN Acceptability Map**

### 4.5 Task 5 – DE-GMAW Process Benchmarking and Productivity Analysis

This task will analyze all the test data from Task 4. Operational windows will be used to determine process tolerance. The ARCWISE data set will include the operational windows and plots that characterize the relationship between voltage, current, and wire feed speed; heat input versus deposition rate; and bead-shape relationships. Recommended welding procedures will be determined from the operational windows for making precision 4-mm fillets. The Welding Productivity Windows shade regions of acceptable weld beads provides a measure of usable range. The colored circles connected all the appropriate bead shape test points in each graph. Based on the reject criteria, the boundary of the gray zone was approximated for weld tests with undesired bead quality, geometry and/or flaws. A linear approximation was made between welds with acceptable and unsatisfactory convexity. An example of this is shown in Figure 45.

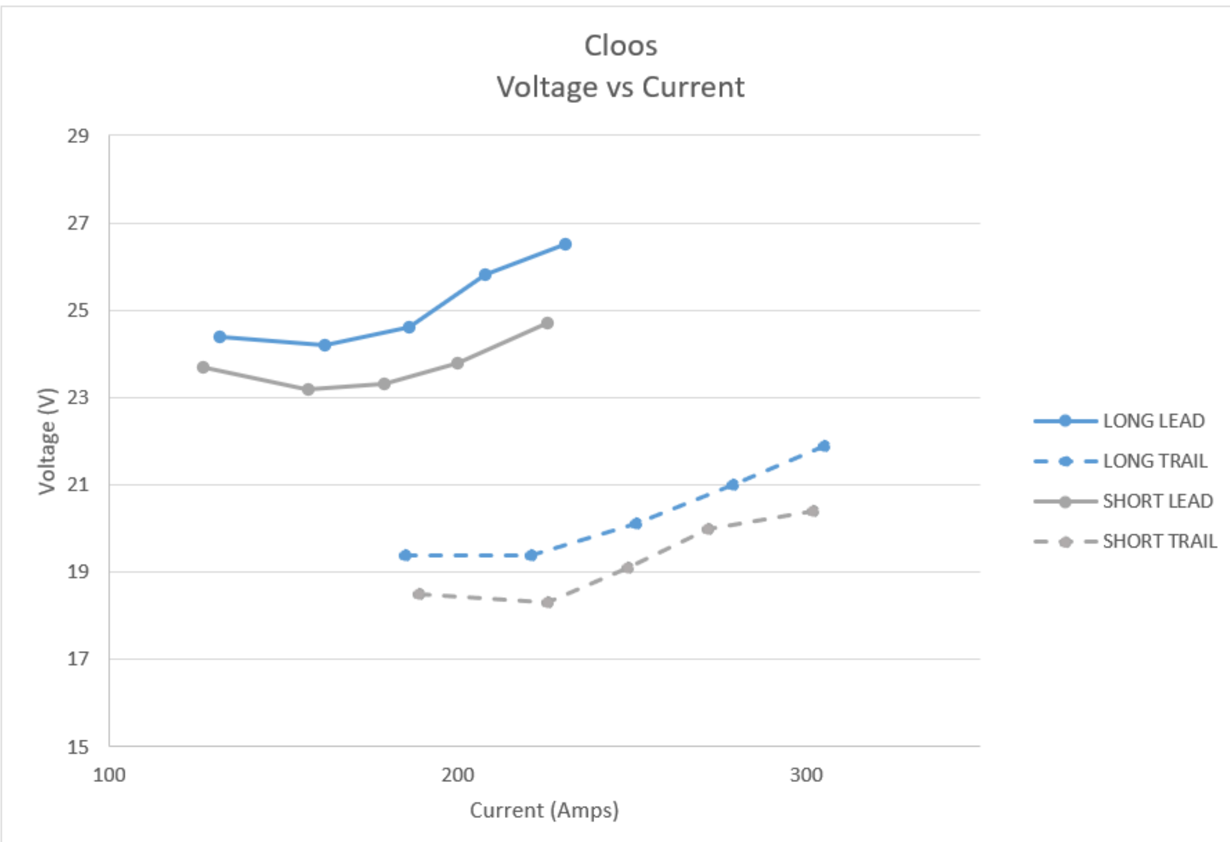



* E70T-1, 0.078-in. Diameter, 1-in. CTWD, CO2, O Degree Travel Angle, WFS/TS=9.81

**Figure 45. Example of ARCWISE Operational Windows**[12]

#### 4.5.1 Cloos Tandem Synergy Pro

Data was captured using an Impact ArcAgent 2100 and recorded in Figure 33. Data was plotted, and the Welding Productivity Windows were created as shown in Figure 46 and Figure 47. The Voltage vs. Current graph shows a trend of increasing voltage as current is increased, which is in line with melting rate and $I^2R$ heating for the arc voltage drops (electrical extension, anode, arc, and cathode). The Deposition Rate vs. Total Heat Input graph shows the process requires less heat input as the deposition rate increases. The process window is large and is stable at a maximum of 28.0 lb/hr between the two arc lengths. The preferred travel speed was 55 ipm based on the window analysis and bead shape quality in FiguresFigure 34 andFigure 35.



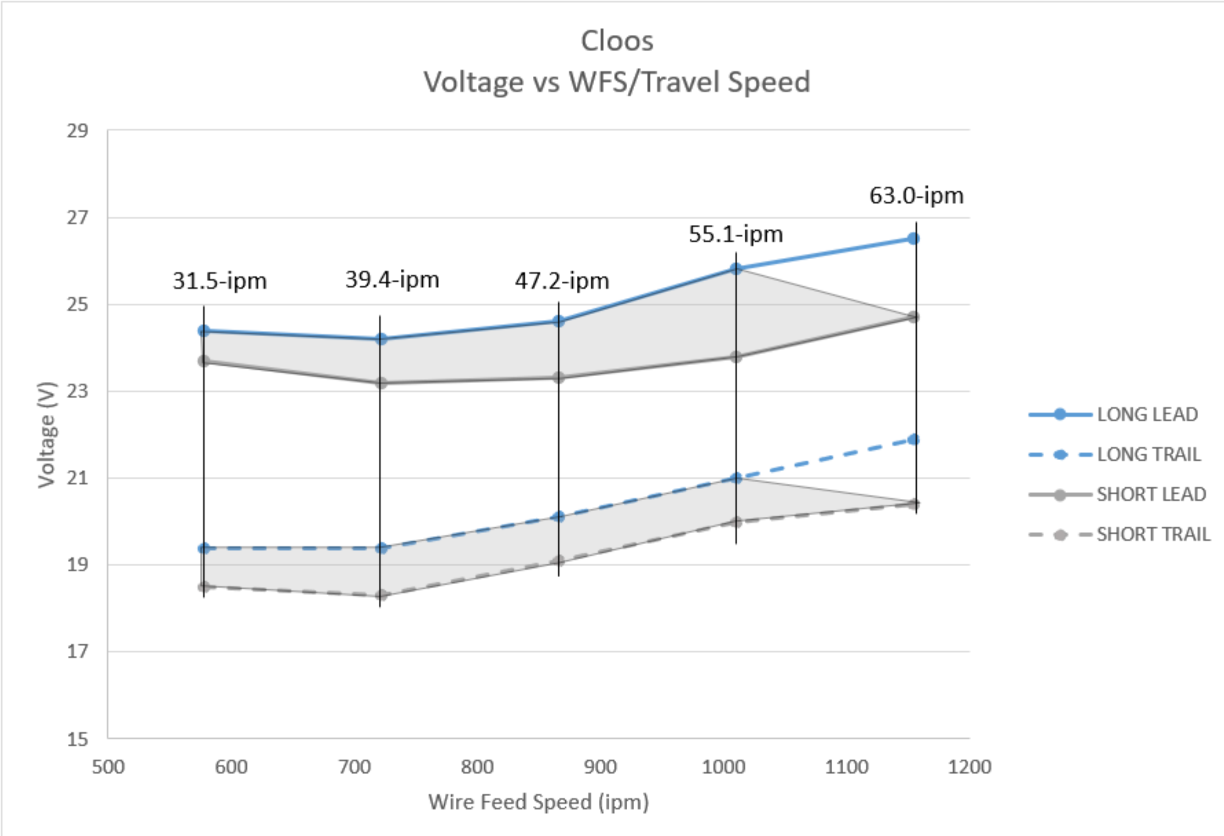
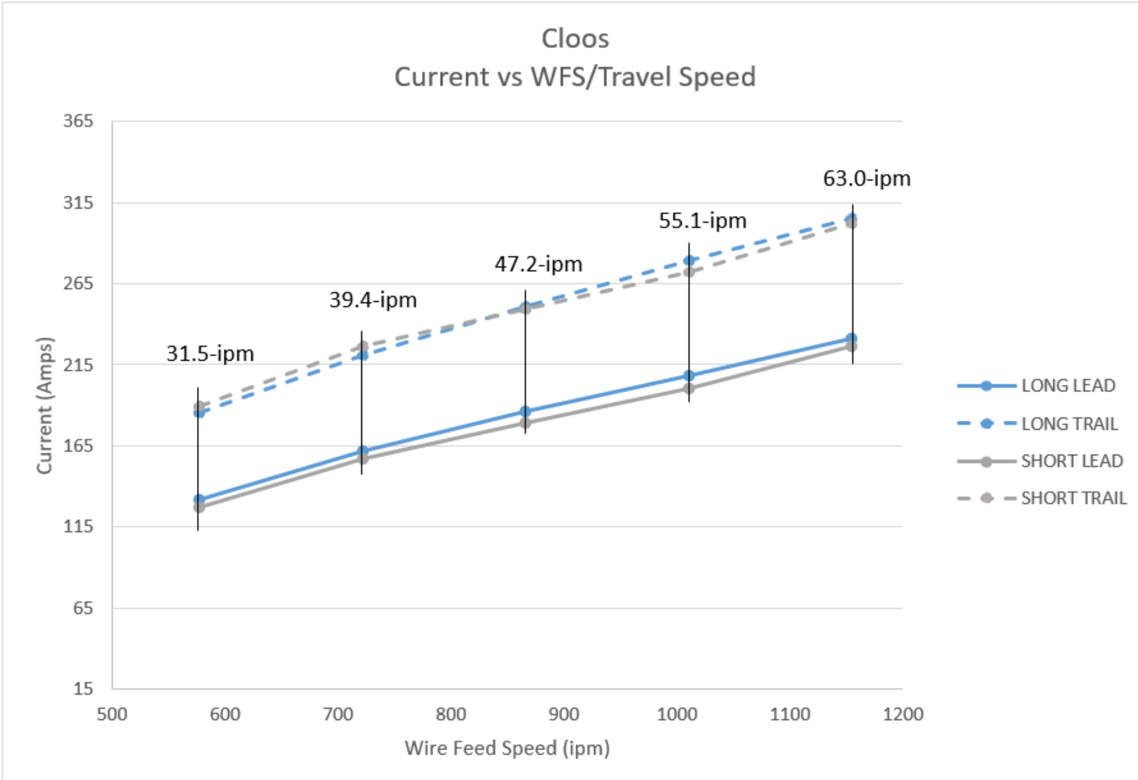



**Figure 46. Cloos Tandem Synergy Pro Productivity Maps – Voltage vs. Current (top) and Voltage vs. WFS/Travel Speed (bottom)**



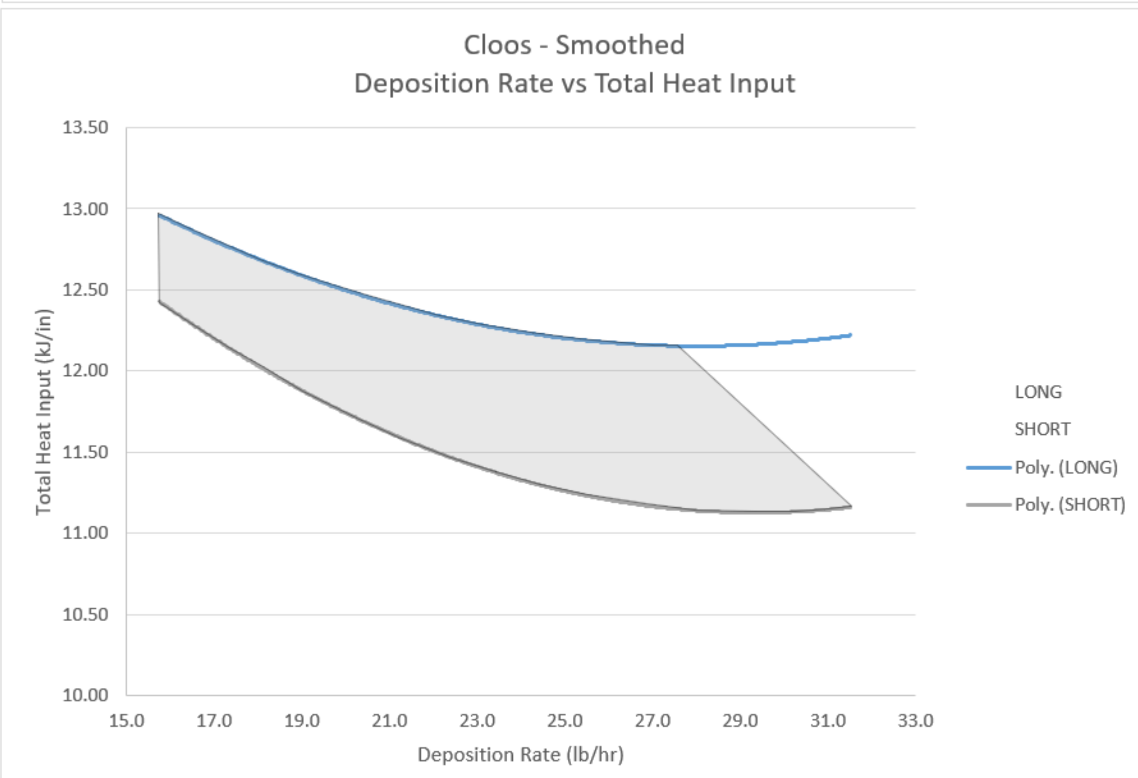
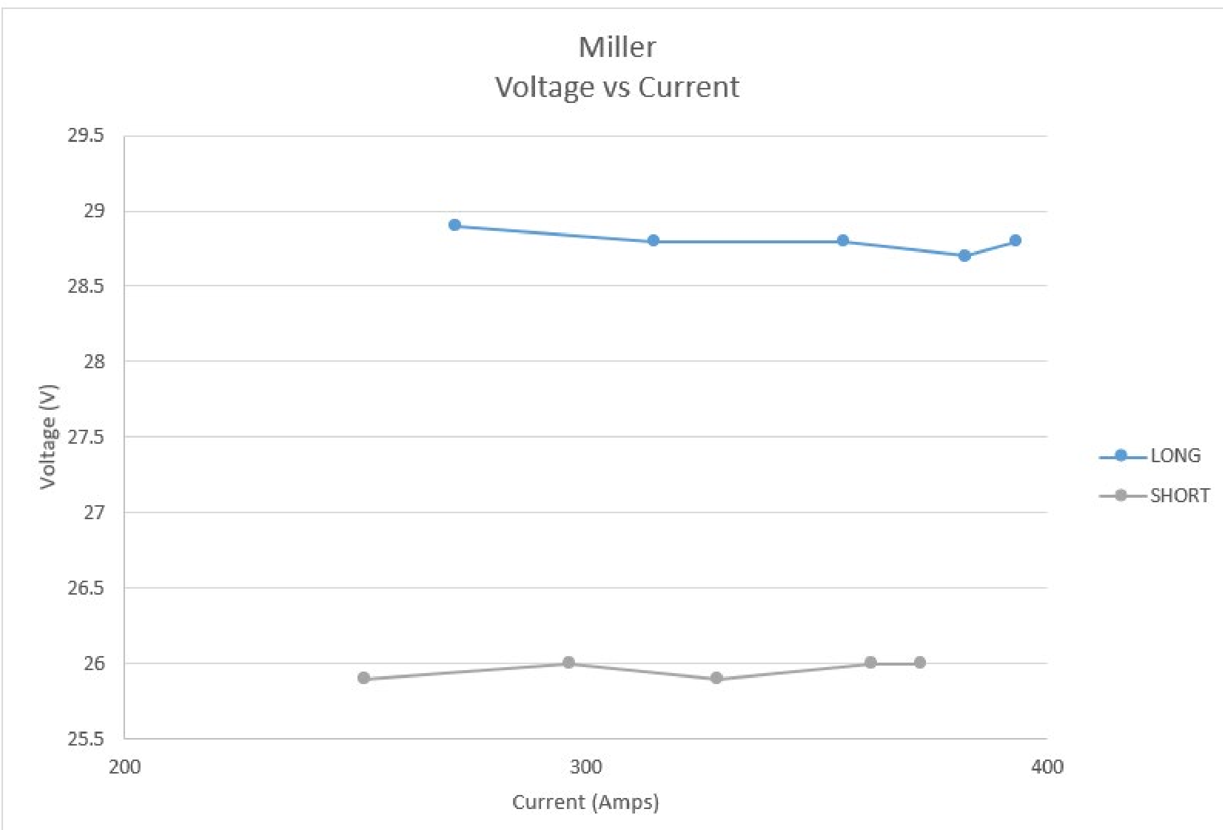




**Figure 47. Cloos Tandem Synergy Pro Productivity Maps – Current vs. WFS/Travel Speed (top) and Deposition Rate vs. Total Heat Input (bottom)**

### 4.5.2 Miller Hercules

Data was captured using Miller's Insight Welding Intelligence and recorded in Figure 37. Conditioning data was given only as a function of heat input. Data was plotted and the Welding Productivity Windows were created as shown in Figure 48 and Figure 49. Hercules is basically a hot wire (preheated electrical stickout) assisted CV process. The Voltage vs. Current graph was flat based on a fixed parameter relationship. Deposition Rate vs. Total Heat Input shows the process reduces less heat input as the deposition rate and travel speed increase. This relationship was non-typical, as heat input is usually constant for a constant deposit area, arc length, and metal transfer mode condition over a travel speed range. Typically, penetration increases with increasing travel speed since there is less time for heat conduction per unit length. This is measured by increasing base metal melting efficiency and dilution. The Hercules process window was small where the preferred parameters were at 60 ipm (1.5 m/min) travel speed at 1-mm arc length. Overall, there is significant potential for Hercules for high-productivity welding applications. Based on the window analysis, further parameter development is needed for high-speed welding.



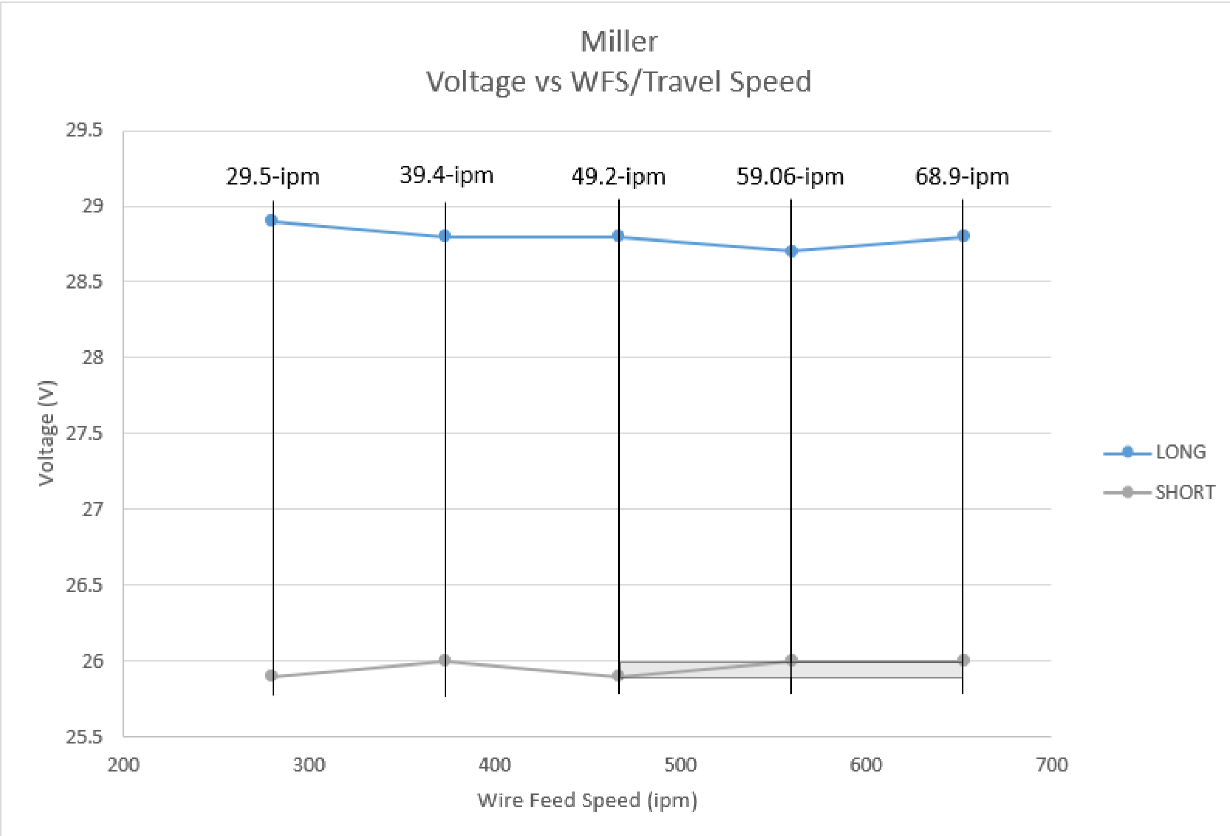



**Figure 48. Miller Hercules Productivity Maps – Voltage vs. Current (top) and Voltage vs. WFS/Travel Speed (bottom)**

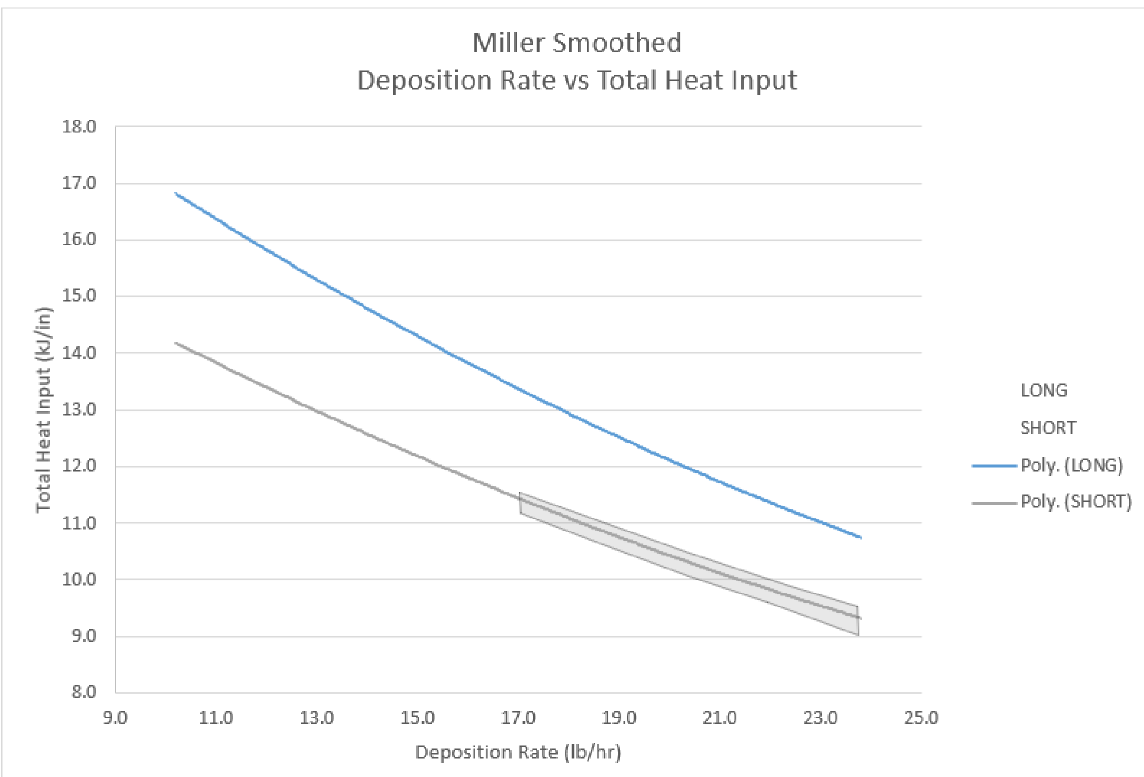
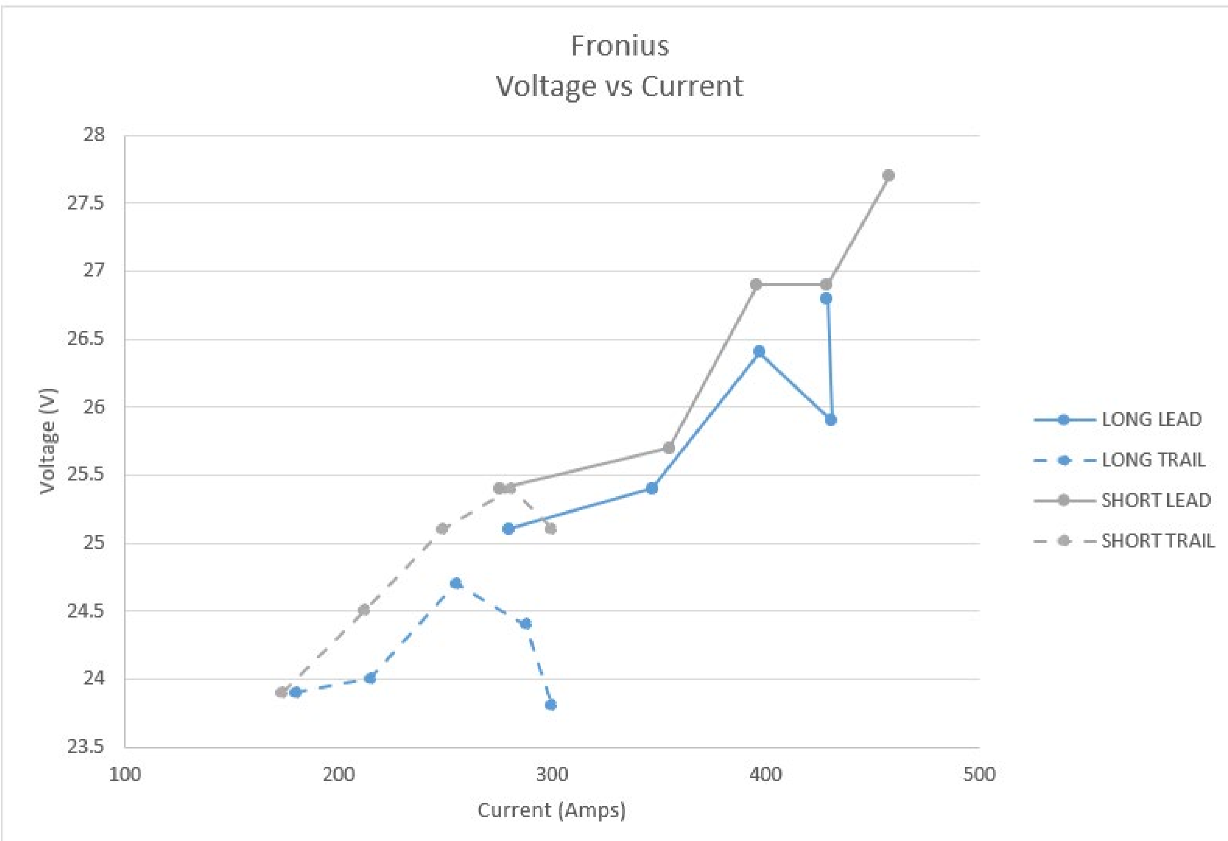




**Figure 49. Miller Hercules Productivity Maps – Current vs. WFS/Travel Speed (top) and Deposition Rate vs. Total Heat Input (bottom)**

### 4.5.3 Fronius TPS/i TWIN

Data was captured using Fronius's Data manager and was recorded in Figure 41. Data was plotted, and the Welding Productivity Windows were created as shown in Figure 50 andFigure 51. The Voltage vs. Current graph shows a general trend of increasing voltage as the current is increased which is in line with increasing wire feed speed and $I^2R$ voltage drops. The trail wire appears to be shorting at higher currents levels. The Deposition Rate vs. Total Heat Input graph shows the process reduces the heat input needed as the deposition rate increases. The process window is large, and the preferred travel speed was 35 in/min for maximum productivity.



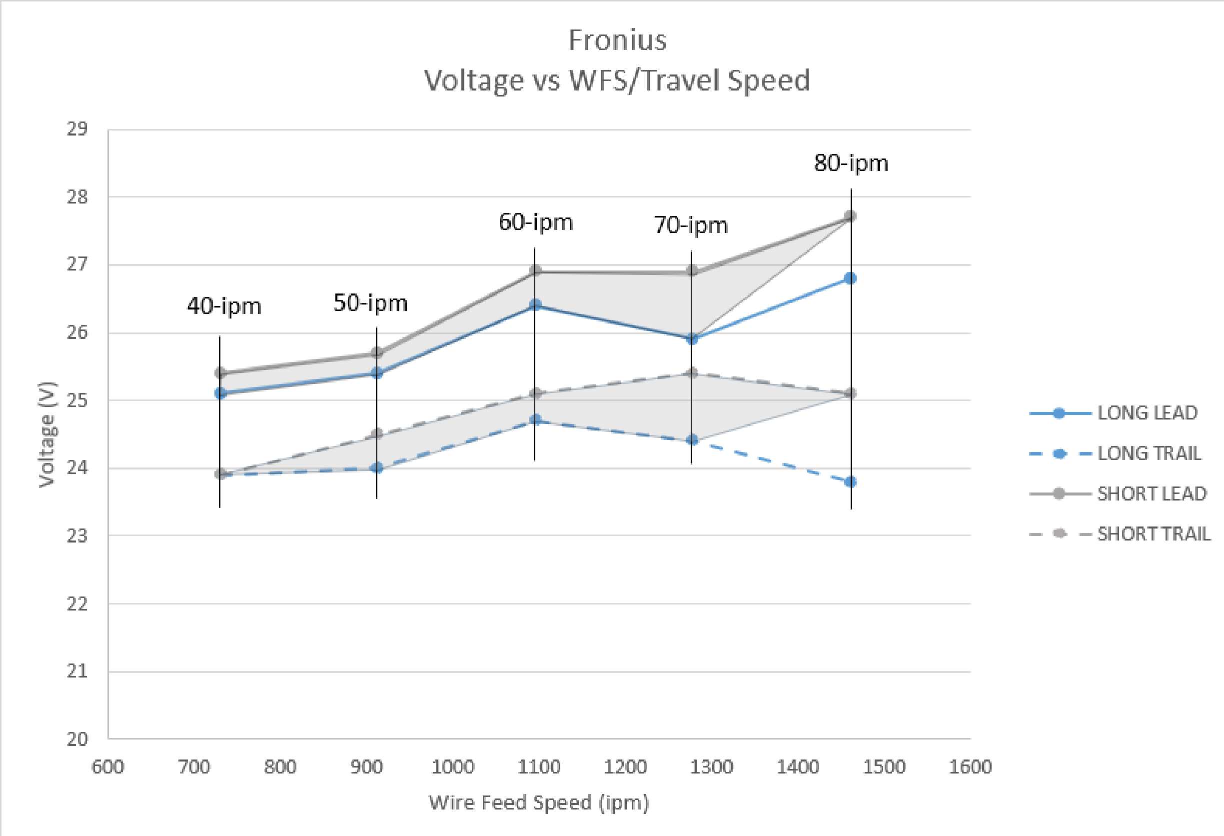
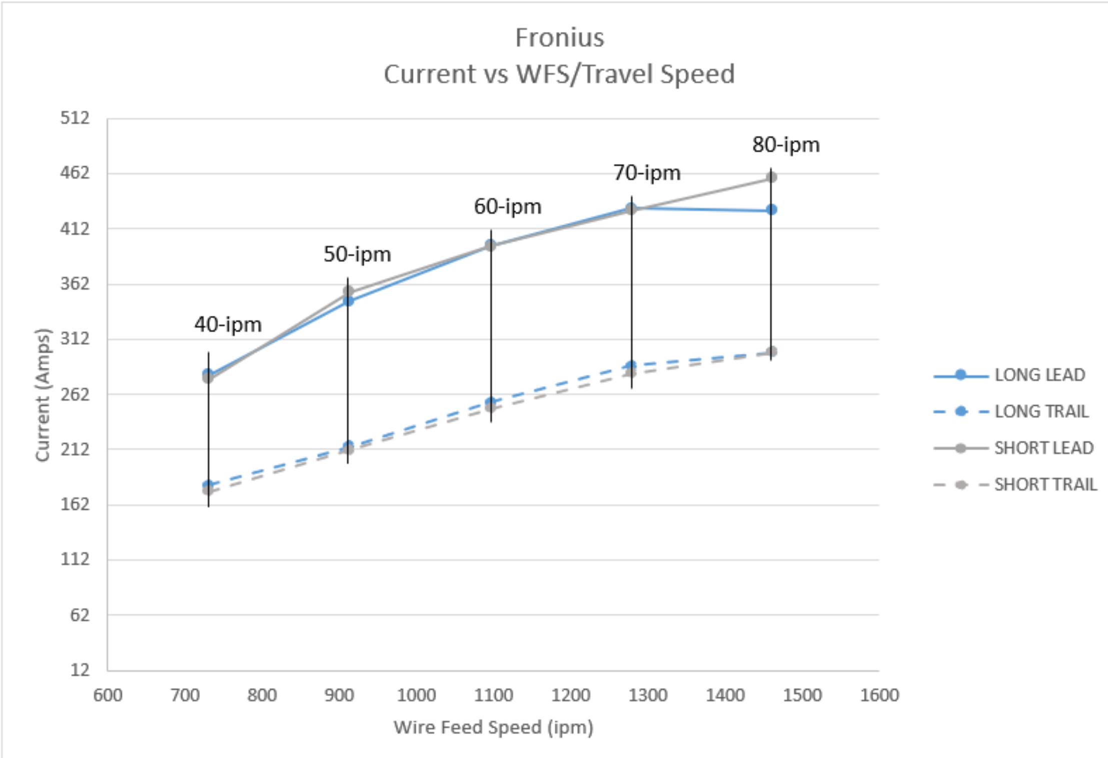



**Figure 50. Fronius TPS/i TWIN Productivity Maps – Voltage vs. Current (top) and Voltage vs. WFS/Travel Speed (bottom)**



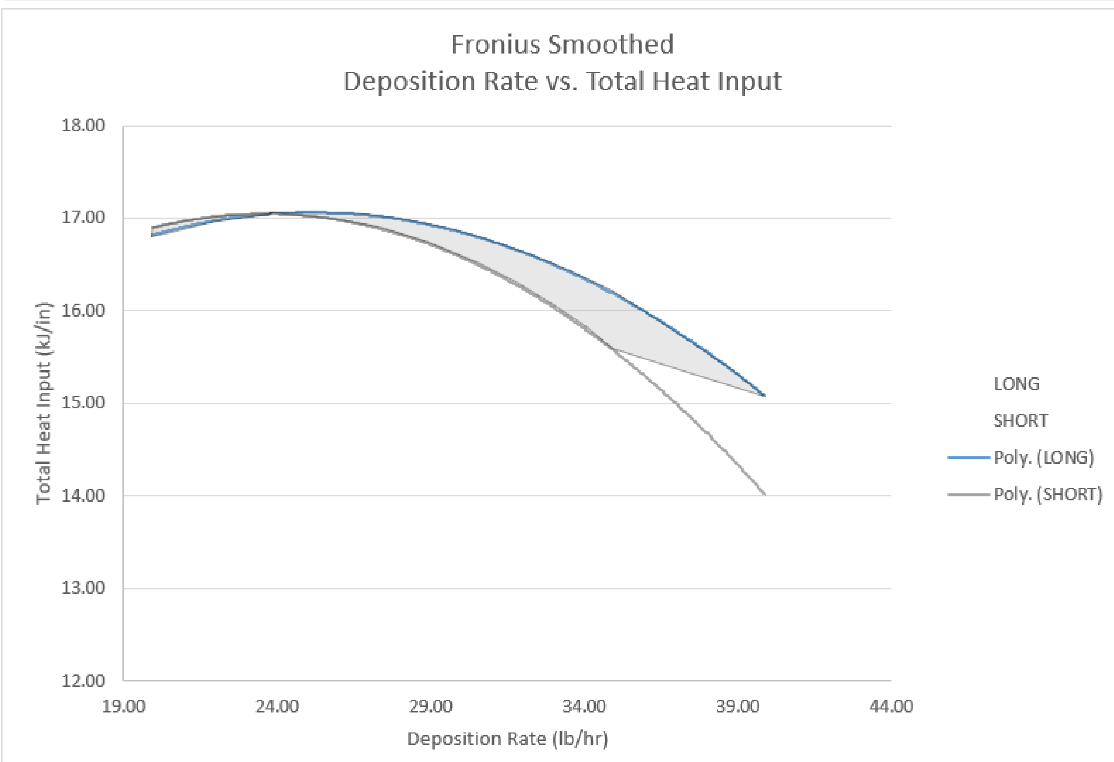




**Figure 51. Fronius TPS/i TWIN Productivity Maps – Current vs. WFS/Travel Speed (top) and Deposition Rate vs. Total HI (bottom)**

### 4.5.4 Process Comparison

Both Cloos and Fronius tandem GMAW process offer a 4-mm fillet welding capability. Both processes had preferred bead shape and weld quality at 65 to 70 in./min travel speed. The Cloos tandem process had better arc stability (window size) per Figure 52 at the higher wire-feed speeds. Note, this figure shows the variation in window shapes between processes. Most of this error is due to arc length control where shorting occurred at the lower arc length settings. In addition, Fronius and Miller probably did not have as much experience in performing constant arc length tests, so settings may not represent the target arc length. In addition, short circuit metal transfer significantly reduces heat input, can cause spatter, and reduces fusion quality, penetration, and base metal dilution. For this set of tests, the Cloos tandem system had the best preset voltage trim relationships as a function of wire feed speed. Overall, Cloos, Fronius, and Hercules offer opportunities for future work to optimize precision fillet welding.

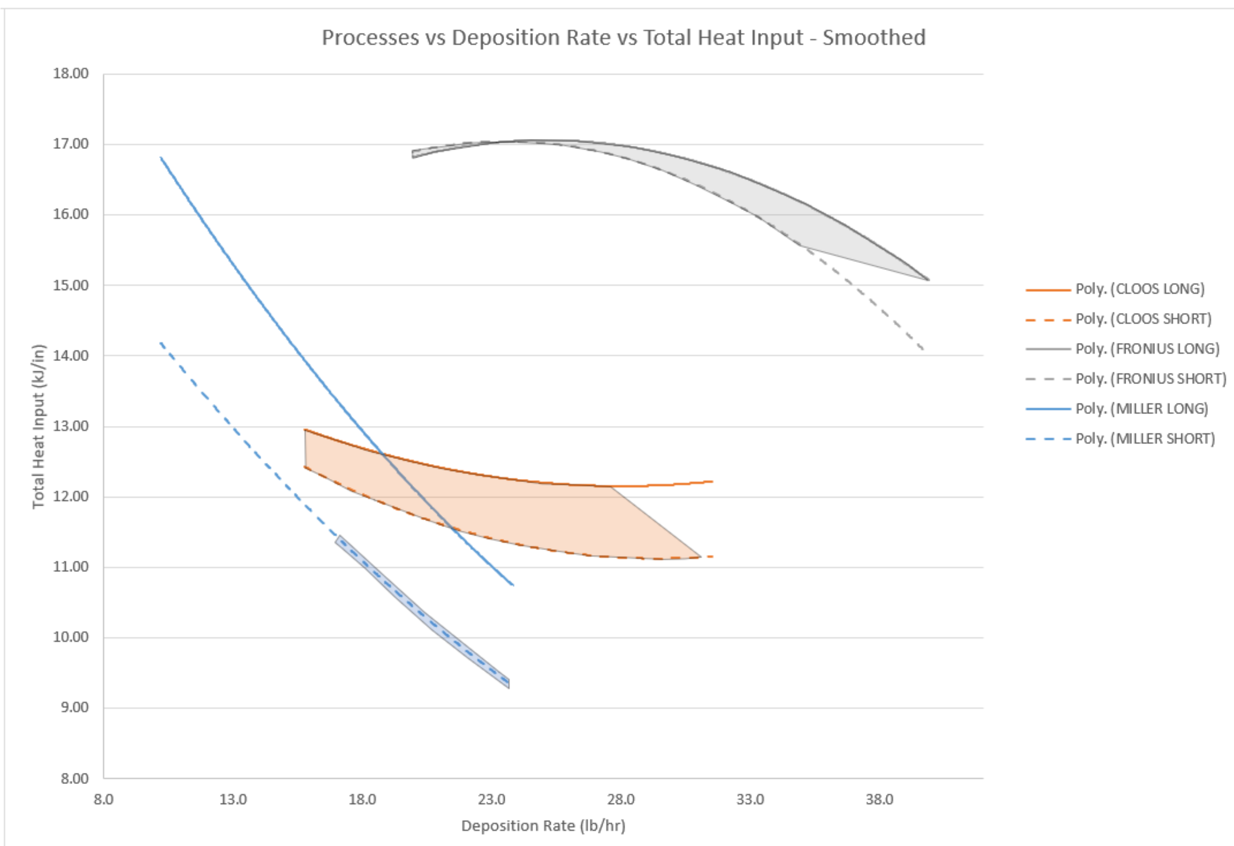



**Figure 52. Processes vs. Deposition Rate vs. Total Heat Input**

### 4.6 Task 6 – Next Generation DE-GMAW Technology Workshop

EWI hosted a technology transfer workshop at EWI in its Columbus, Ohio, facility on September 20, 2023. During this workshop, EWI demonstrated the preferred processes and reviewed performance data with HHI Ingalls Shipyard who was in attendance. The workshop included:

- The evaluation and benchmarking of advanced double electrode GMAW processes and consumables for high-speed fillet welding
- The survey results from industry, screening candidate processes, and selection of preferred process variants for feasibility testing
- The down selection and development of ARCWISE operational windows and bead shape maps for up to three variants with the target application of 4-mm horizontal fillet welds
    - Representative from HHI Ingalls Shipyard noted the good operational window, lower heat input, and higher deposition rates of the Cloos Tandem Synergy Pro.
- Demonstration of the Cloos Tandem Synergy Pro system and 4-mm fillet weld
    - Representative from HHI Ingalls Shipyard noted the high welding speed and good visual quality of weld.
- Demonstration of the IPG LightWELD system and sub 1-mm tack welds
    - Representative from HHI Ingalls Shipyard was trained and applied a tack within 5-minutes. Stated ease of use.

# 5.0 Discussion

Operational windows were developed using Cloos Tandem Synergy Pro, Miller Hercules™, and Fronius TPS/i TWIN that produced operational windows that met MIL-STD-2035 visual requirements. Some key topics from this project are discussed in the following sections.

**Cloos Tandem Synergy Pro:** This process was very stable across the constant deposit area test matrix at two arcs over a large travel speed range. During parameter development, the lead wire would short but was resolved with work angle. The combined lower heat input and high deposition rates set this process as the front runner for this project.

**Miller Hercules™:** This process was not stable across the testing matrix. The arc in most cases would drift up the sidewall of the vertical member causing undercut. As the arc length was shortened, the process ran more stable in a small deposition range. The combined process instability and lower deposition rate would remove this process as one of the front runners for this project. Further work is needed to develop better parameters for high-speed fillet welding.

**Fronius TPS/i TWIN:** This process was very stable across the testing matrix. There is some process variation shown in the Voltage vs. Current graphs, which is likely the trail wire shorting during transfer. The high deposition rates but higher heat inputs set this process as the runner-up for this project.

**Comparison to GMAW**: This project involved working with shipyards to improve capabilities for precision fillet welding, with a heavy emphasis on technology transfer. In the majority of U.S. shipyards, panels are manufactured using automated GMAW procedures. Robotic GMAW has been used in several American shipyards to fillet weld completely built panel structures with longitudinal and transverse stiffening. These shipyards can take advantage of this project to create and implement strategies for precision fillet welding processes.

Overall, this project demonstrated that repetitive, high-quality 4-mm fillet welds can be applied to shipyard panel fillet welding. Precision tacking and seam tracking technology are required to transition and implement 4-mm precision fillet welding. The LightWELD manual cold wire laser tacking process (Class 1 protected drag torch) is strongly recommended for further development and implementation. Laser profilometers are commercially available for seam tracking to provide a system solution.

## 6.0 Conclusions

- Cloos Tandem Synergy Pro and Fronius TPS/i TWIN both proved to be a suitable method for 4-mm fillet welds in shipyard production.
- Cloos Tandem Synergy Pro had a lower heat input and only a slight loss of productivity versus Fronius TPS/i TWIN.
- Miller's Hercules was able to deposit 3-mm fillet welds but had a small productivity window and needs further development.
- Lincoln's HyperFillTM was not able to produce repeatable 4-mm fillet welds.
- IPG's LightWELD system proved to be a suitable method for tacking under 1-mm fillet tacks which was fully consumed using preferred 4-mm welding parameters.

## 7.0 Recommendations

- This project demonstrated that repetitive high quality 4-mm fillet welds can be applied to shipyard panels. Future work should evaluate transition of next generation double electrode GMAW processes using a system approach that includes precision tacking and high-speed seam tracking.

- IPG's LightWELD system is highly recommended for future work to implement a precision manual tacking process. A precision tacking process is essential for 4-mm precision fillet welding.

## 8.0 References


1. Lincoln Electric. *HYPERFILL™*, https://ch-delivery.lincolnelectric.com/api/public/content/a31d4abdb7344350a86bea4a408c5dc0?v=34978a50
2. Miller. *Hercules™ High-Deposition Automated Welding System*, https://www.millerwelds.com/-/media/miller-electric/files/pdf/products/hercules/au55-0-hercules-system.pdf
3. Fronius. *OUR TPS/i TWIN SYSTEMSINTELLIGENT TANDEM WELDING*, https://www.fronius.com/en/welding-technology/product-information/tpsi-twin-systeme-tandem-welding
4. CLOOS. *Tandem Weld,* https://www.cloosrobot.com/de-us/processes/details/tandem-weld/
5. OTC. *Synchro-feed*, https://www.daihen-robot.com/en/items/synchro
6. Hobart. *Hobart FabCOR® Hercules Certificate of Conformance*, https://www.hobartbrothers.com/wp-content/uploads/hobart-catalog/certifications/FabCOR_HerculesTypCert.pdf
7. Select-Arc. *Select 70C-10*, http://www.select-arc.com/siteadmin/uploads/prod/prod-sheets/select-70c-10-rev-1.pdf
8. Abicor-Binzel. *SpinArc® Automatic MIG Gun.* https://www.binzel-abicor.com/uploads/Content/USA/PDF-Files/PDF_Files_MIGMAG/Catalogs/LIT.9249_ABIMIG_SpinArc_04-19_Web.pdf
9. D/F Machine Specialties, Inc. *Water-Cooled Tandem Machine Barrel,* https://www.dfmachinespecialties.com/downloads/Instruction-Manuals/Instruction%20Manual%201019%20Tandem.pdf
10. Wenglor. *Automated Weld Seam Tracking: MLZL 2D/3D Profile Sensors,* https://www.wenglor.com/en/2D3D-Profile-Sensors-MLZL-Enable-Exact-Seam-Placement/r/8796453527993
11. MIL-STD-2035A, DEPARTMENT OF DEFENSE TEST METHOD: NONDESTRUCTIVE TESTING ACCEPTANCE CRITERIA, May 1995
12. Harwig, D.D., et al 2000. A Wise Method for Assessing Arc Welding Performance and Quality. Welding Journal, Vol. 79(12), Dec. 2000

## 9.0 Disclaimer

EWI disclaims all warranties, express or implied, including, without limitation, any implied warranty of merchantability or fitness for a particular purpose.

Under no circumstances will EWI be liable for incidental or consequential damages, or for any other loss, damage, or expense, arising out of or in connection with the use of or inability to use the report delivered under this engagement. This report may not be reproduced or disseminated to individuals or entities outside of your organization without the prior written approval of EWI.