Laser Hybrid Tack Welding of Structural Steel Fillet Weld Joints

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Topics

Problem to Solve

Current Application of Hybrid Laser in Shipbuilding

Preliminary Welding Trials and Results

Metallographic Analysis

Toughness Evaluation

Mechanical Testing

Fillet weld shear, compact tension

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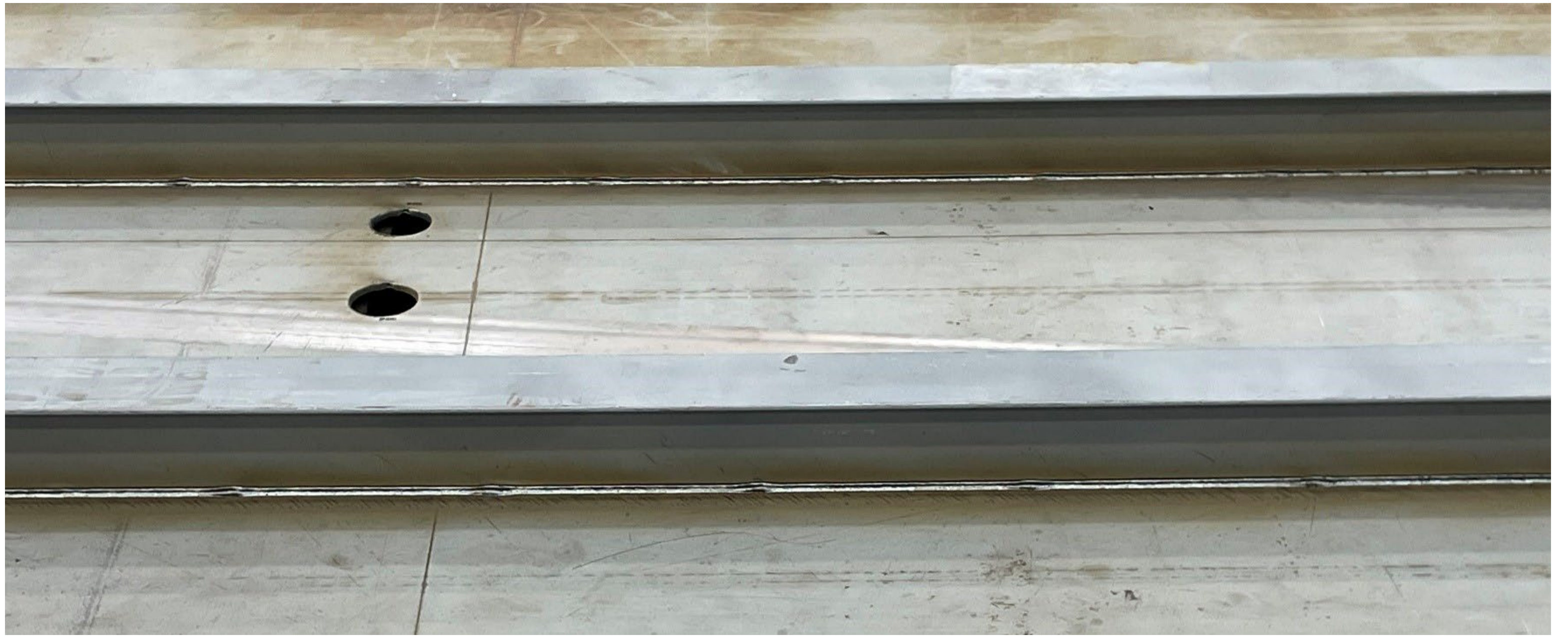
Problem to Solve

Tack welds made using manual or semi-automatic welding processes

Tack size equal to or greater than required weld size

Mechanized welding over tacks



Current Application of Hybrid Laser in Shipbuilding

Seaming of S-1 materials for ship structure using hybrid laser

Fillet welding of stiffener to deck connections

Handheld laser hybrid for sheetmetal applications

Preliminary Welding Trials and Results

Thick and thin materials

3/16” and 1/2” material

Extremes of welding parameters

Power from 950 to 1500 watts

Wire feed speed from 10 to 25 ipm

Travel speed from 10 to 25 ipm

Wobble and frequency

Wide range of heat inputs

2500 J/in for low wattage, high travel

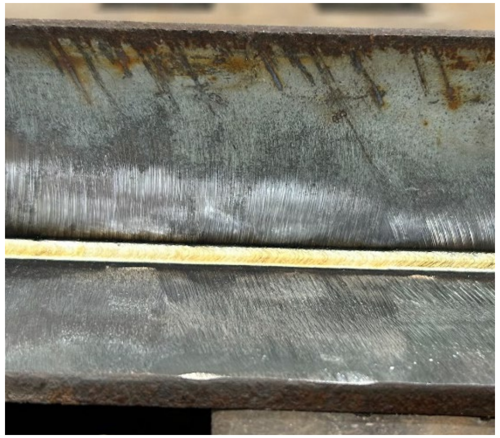
9500 J/in for high wattage, slow travel

Preliminary Welding Trials and Results

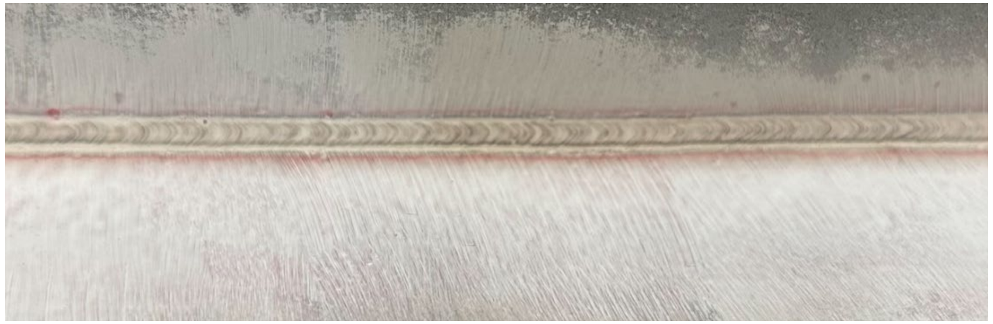
Plate Thickness	Wattage	Wire Feed Speed	Wobble Width	Wobble Frequency
3/16"	950	10	0	0
			9	50
		25	0	0
			9	50
	1250	10	0	0
			9	50
		25	0	0
			9	50
	1500	10	0	0
			9	50
		25	0	0
			9	50
1/2"	950	10	0	0
			9	50
		25	0	0
			9	50
	1250	10	0	0
			9	50
		25	0	0
			9	50
	1500	10	0	0
			9	50
		25	0	0
			9	50

Preliminary Welding Trials and Results

Visual Inspections



Dye Penetrant



Macro Etch

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Preliminary Welding Trials and Results

Visual Inspection Results

Low travel speeds and high wobble conditions showed rejectable visual indications

Dye Penetrant Results

All samples passing VT were subject to PT, with all results acceptable

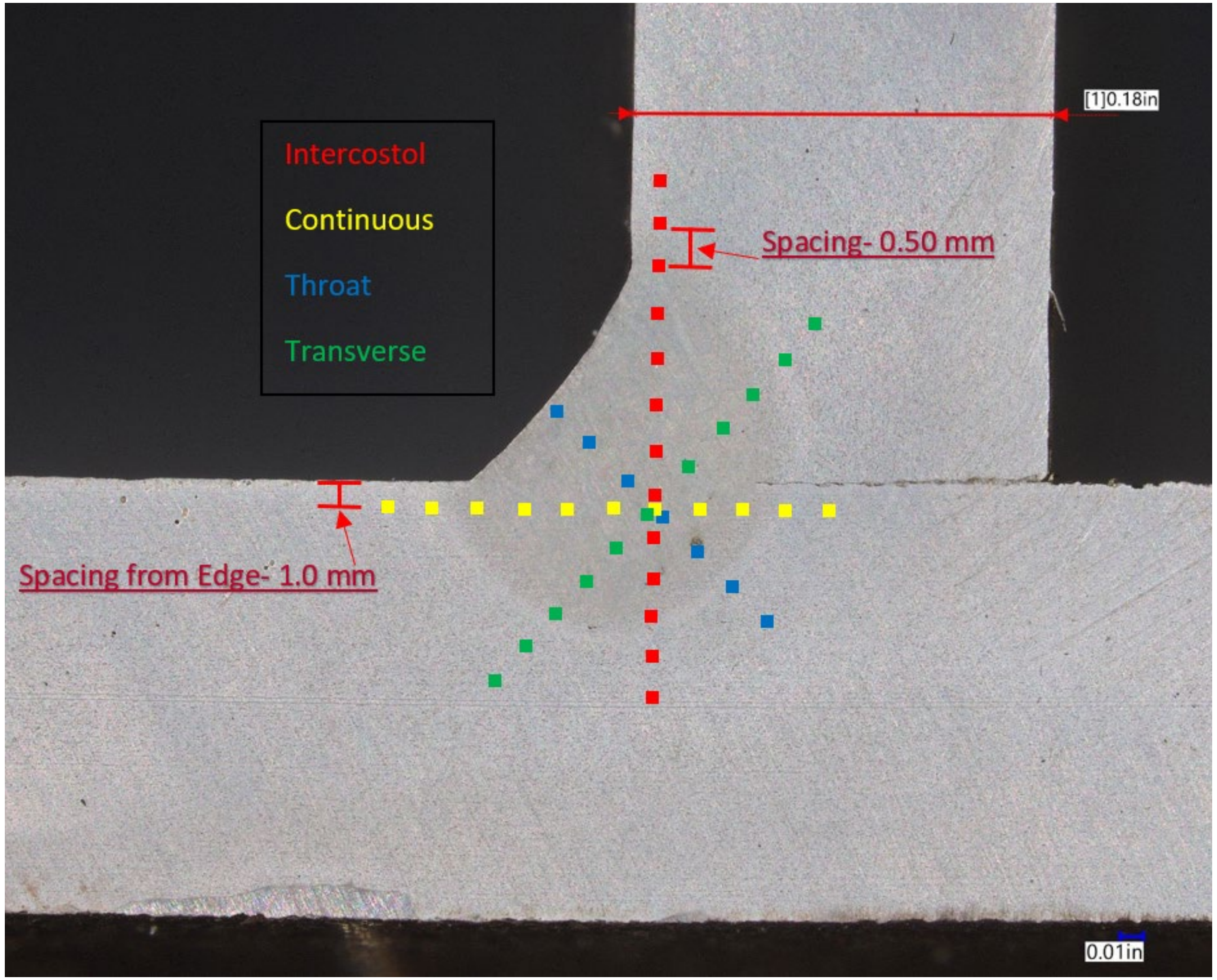
Macro Etch

High travel speeds and high wobble conditions showed lack of fusion in the root

Decreased travel speeds and increased power created larger HAZ and weld cross sections

Preliminary Welding Trials and Results

Hardness Mapping



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Preliminary Welding Trials and Results

When travel speed and power were held constant, hardness increased as plate thickness increased

As travel speed increased, with other variables constant, hardness delta decreased between plate thicknesses

Wobble width and frequency had no noticeable influence on hardness

Welding over laser hybrid tacks with conventional welding processes reduced hardness but did not completely consume the tack

Preliminary Welding Trials and Results

Laser Hybrid Tacks Welded over with FCAW

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Preliminary Welding Trials and Results

Laser Hybrid Tacks Welded over with FCAW

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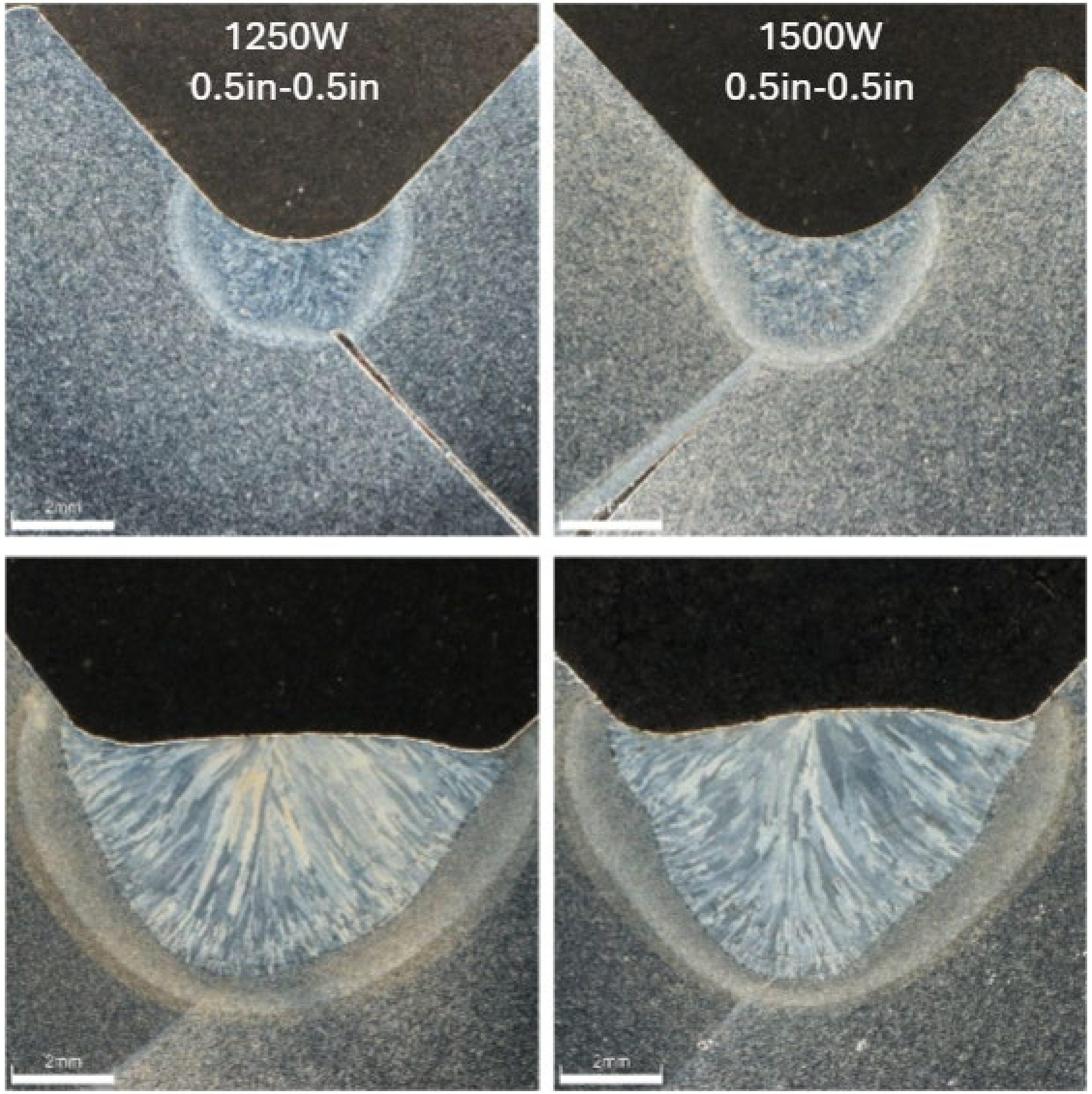
Metallographic Analysis

Extent of Prior Tacks in Rewelded Samples (0.5in-0.5in)



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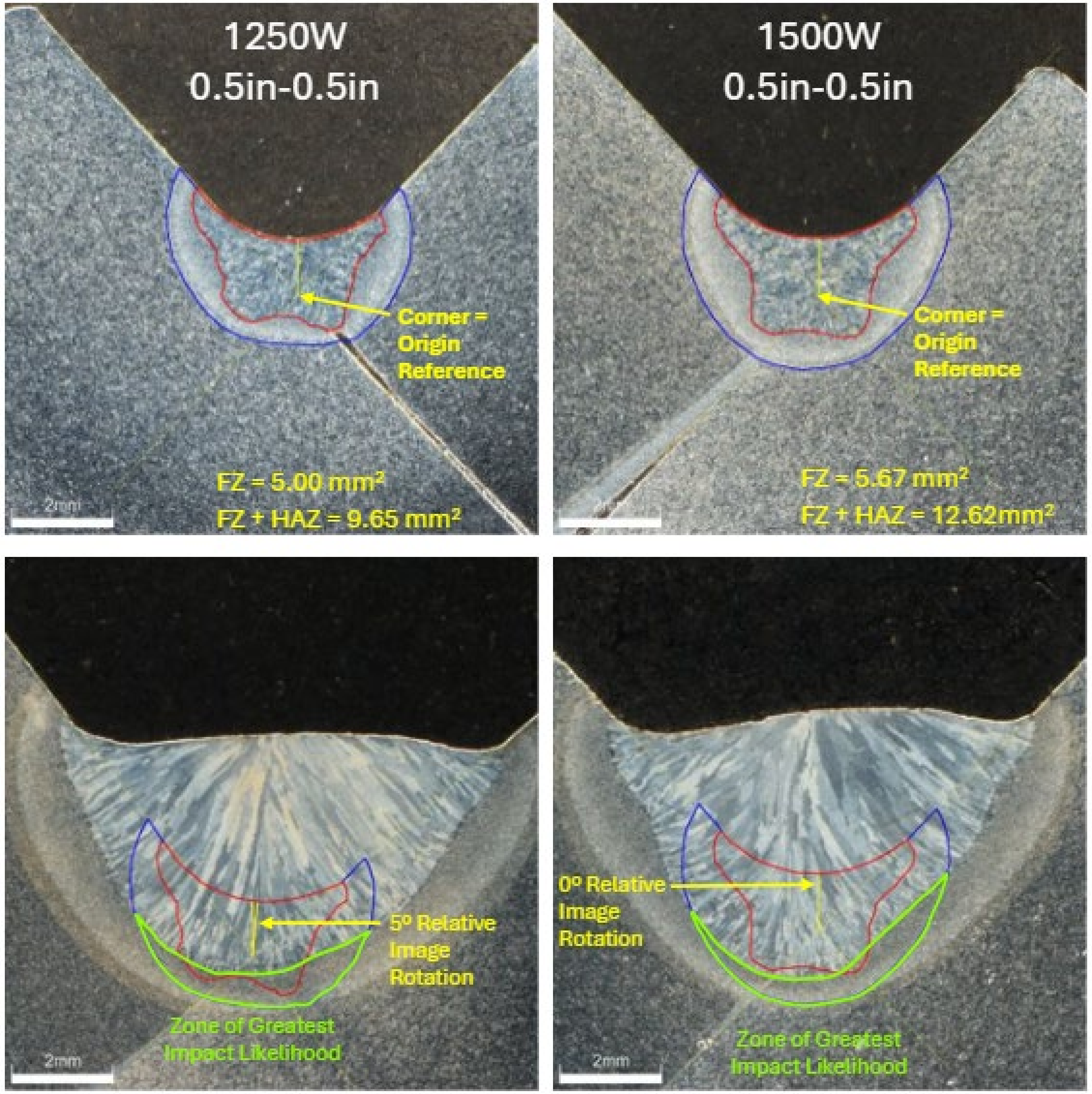

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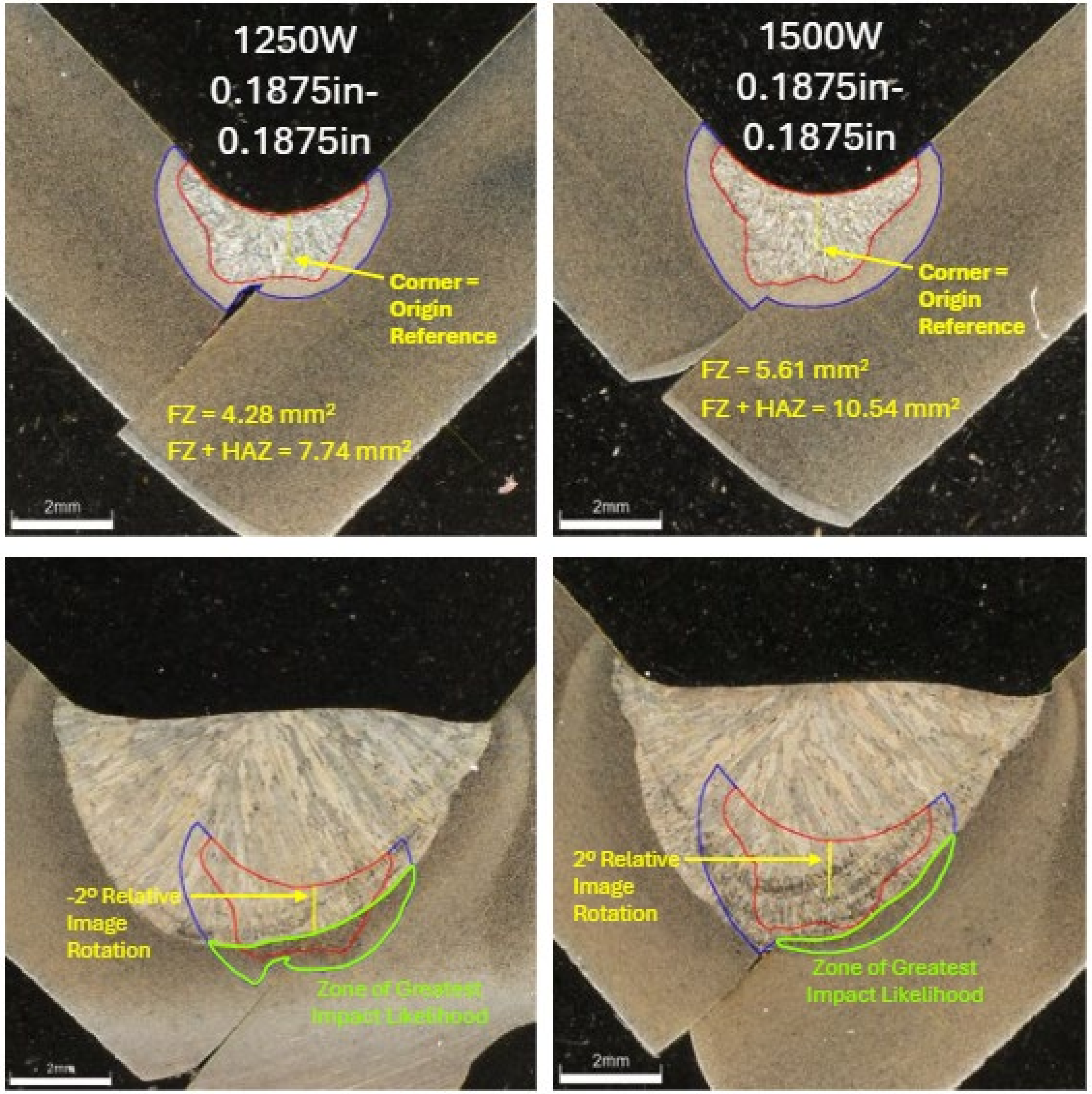
Metallographic Analysis

Extent of Prior Tacks in Rewelded Samples (0.1875in-0.1875in)



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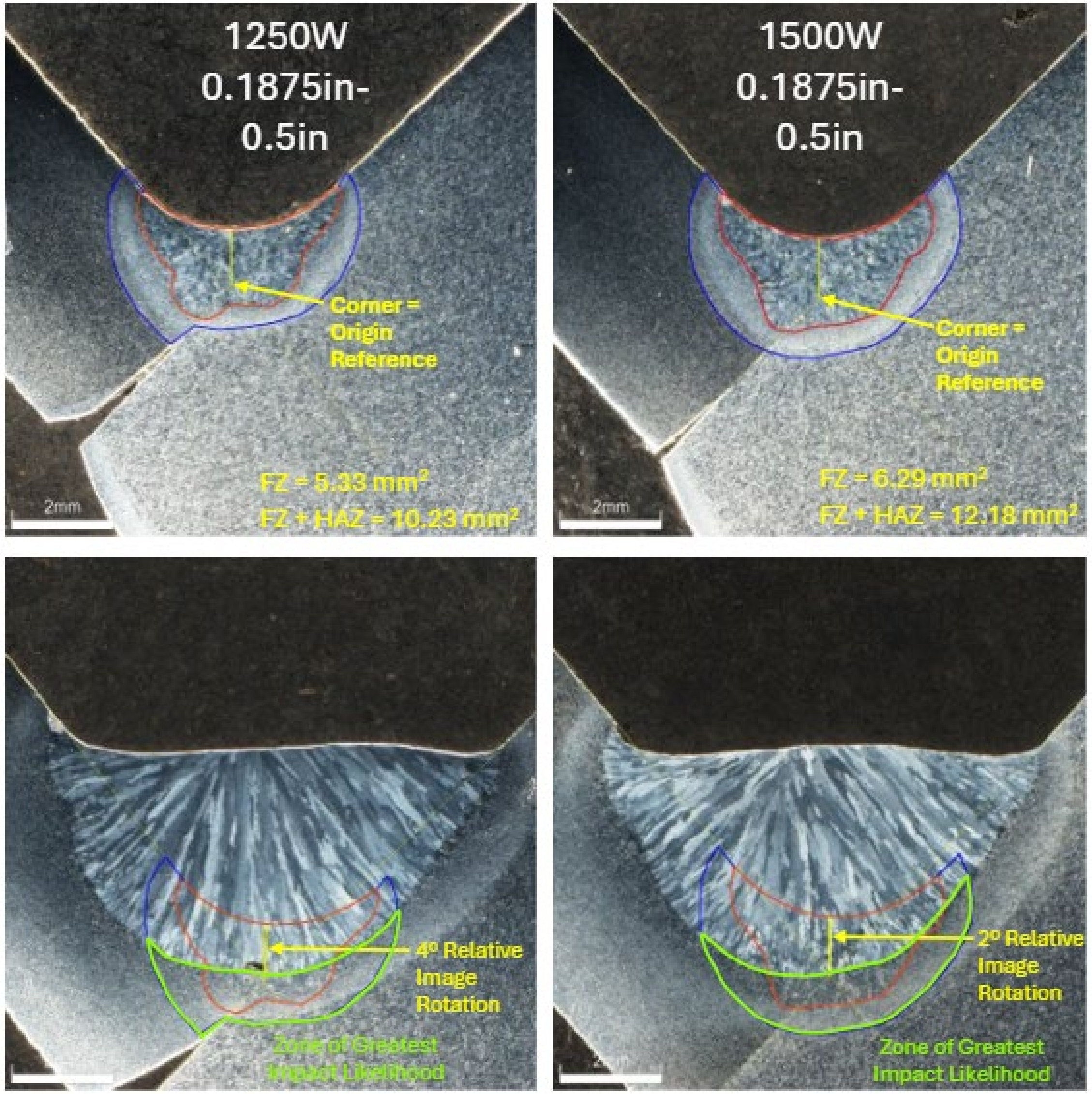

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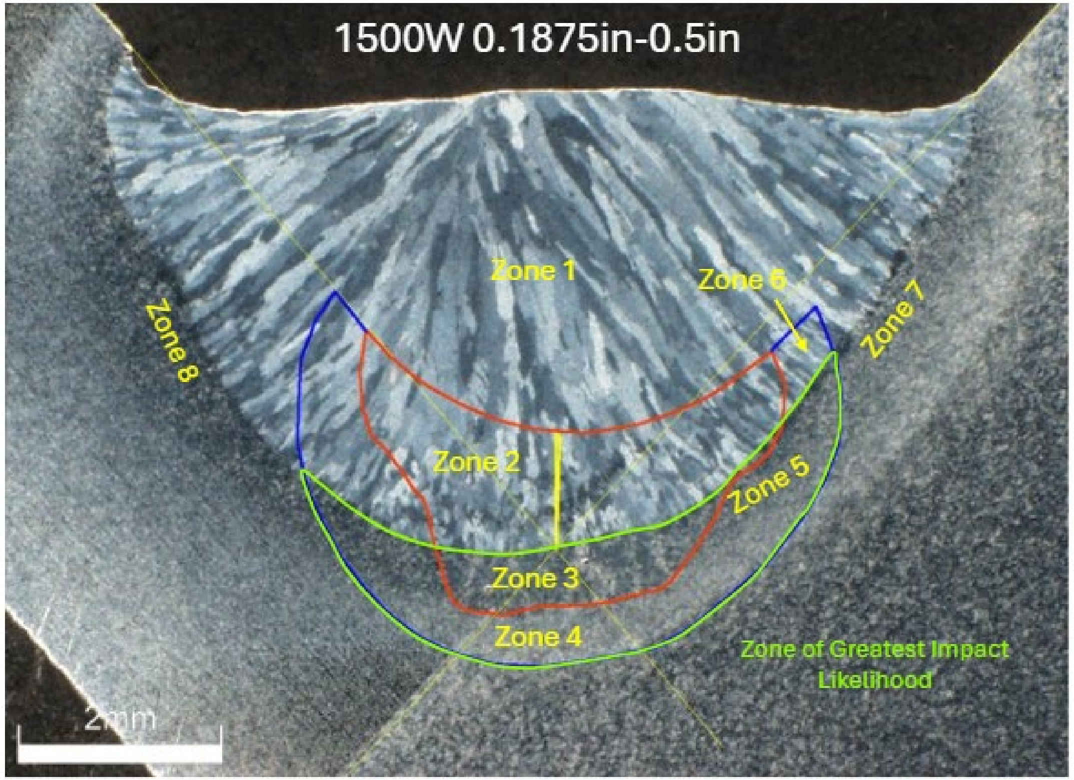
Metallographic Analysis

Subzones



- Zone 1: FCAW FZ
- Zone 2: Laser Tack FZ – FCAW FZ
- Zone 3: Laser Tack FZ – FCAW CG
- Zone 4: Laser Tack CG – FCAW FG/IC
- Zone 5: Laser Tack CG – FCAW CG
- Zone 6: Laser Tack CG – FCAW FZ
- Zone 7: FCAW CG (Thick)
- Zone 8: FCAW CG (Thin)

FZ = Fusion Zone
CG = Coarse Grained HAZ
FG = Fine Grained HAZ
IC = Intercritical HAZ

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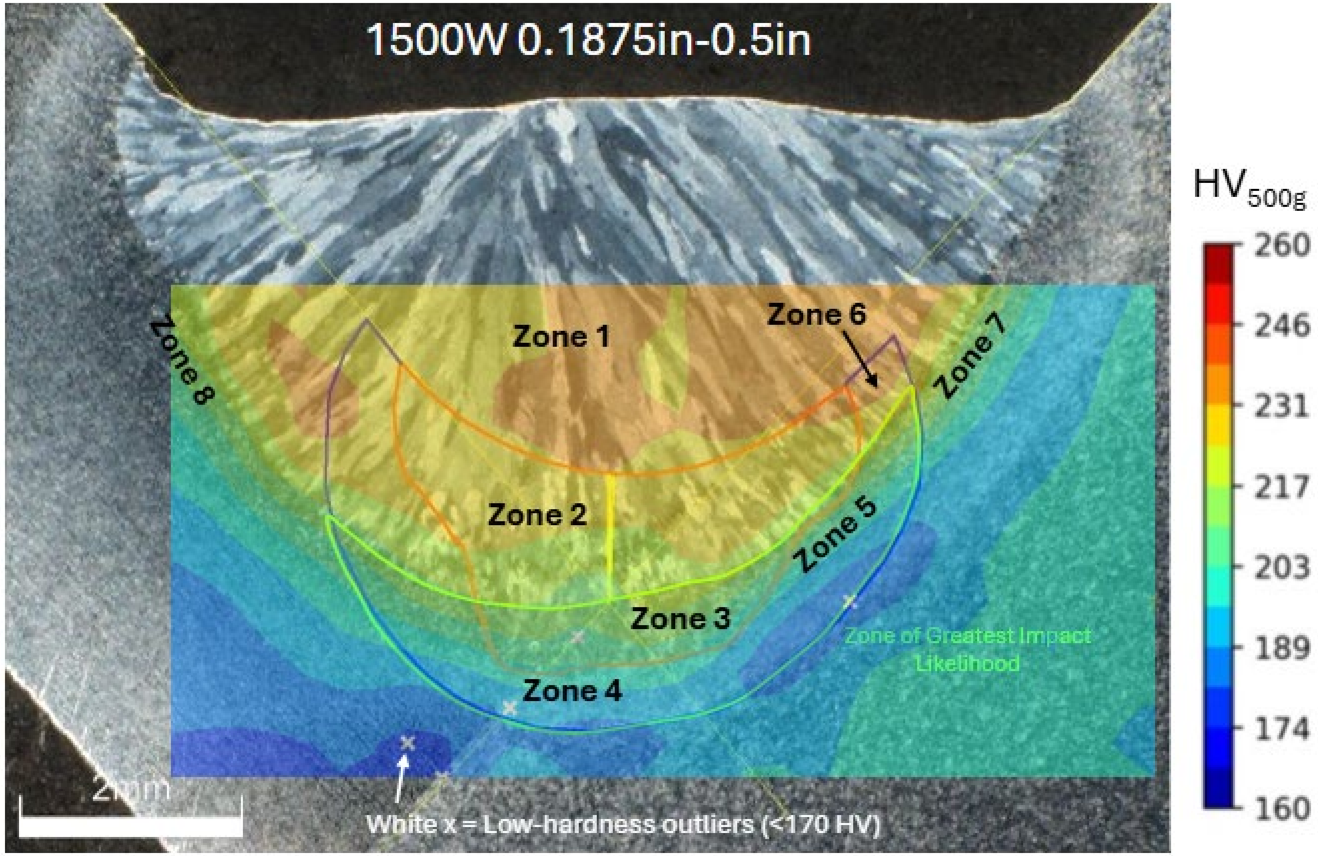
Metallographic Analysis

Coarse Microhardness Map
300 Micron Spacing



Reference values (5 indents):

- Unaffected Thick: 199 ± 6 HV
- Unaffected Thin: 182 ± 6 HV

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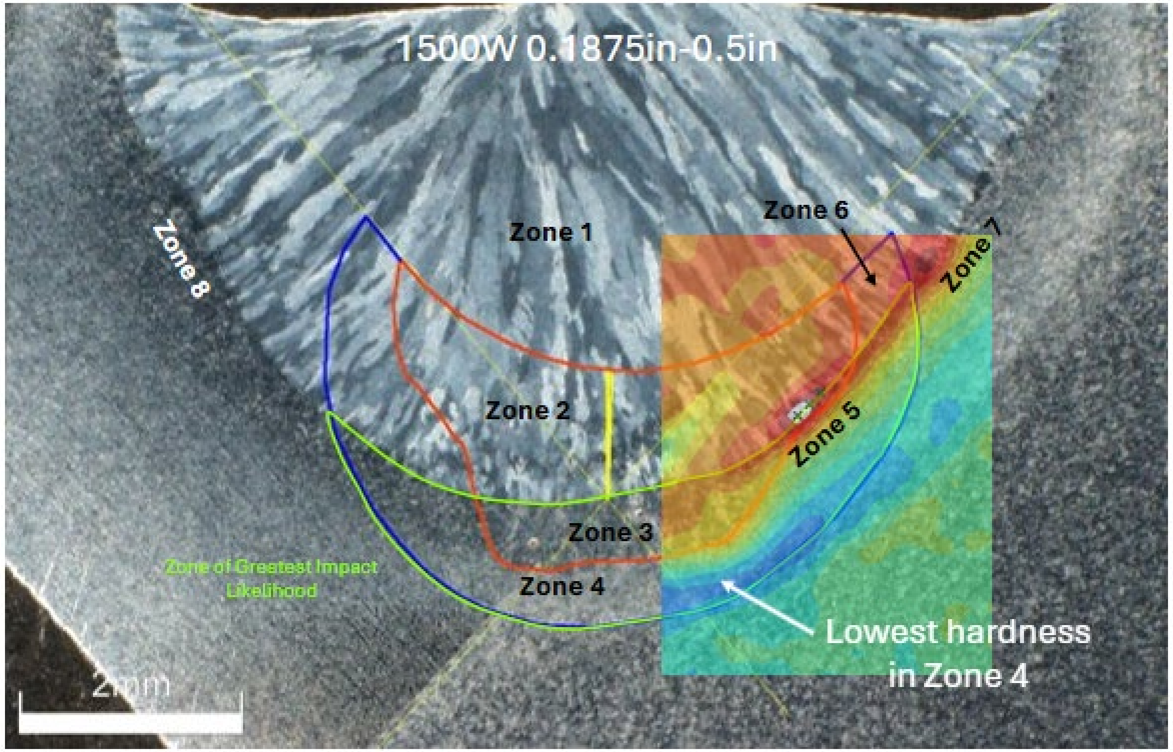
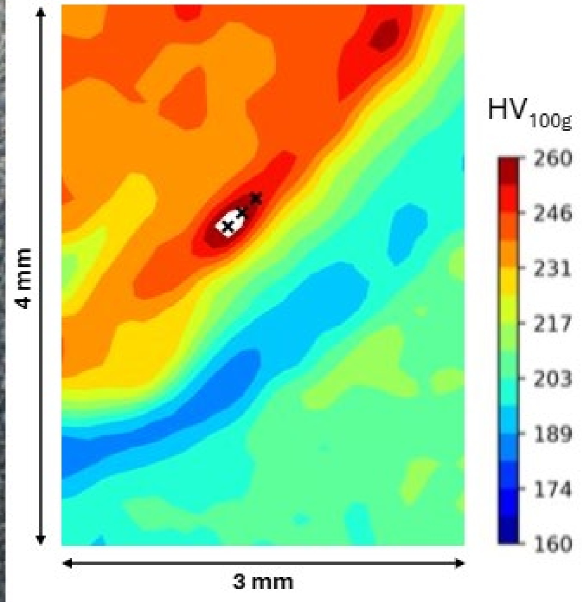
Metallographic Analysis

Refined Microhardness Map
100 Micron Spacing





Key Takeaway: Hardness mapping alone does not reflect unique microstructure features that could be determinantal to mechanical properties

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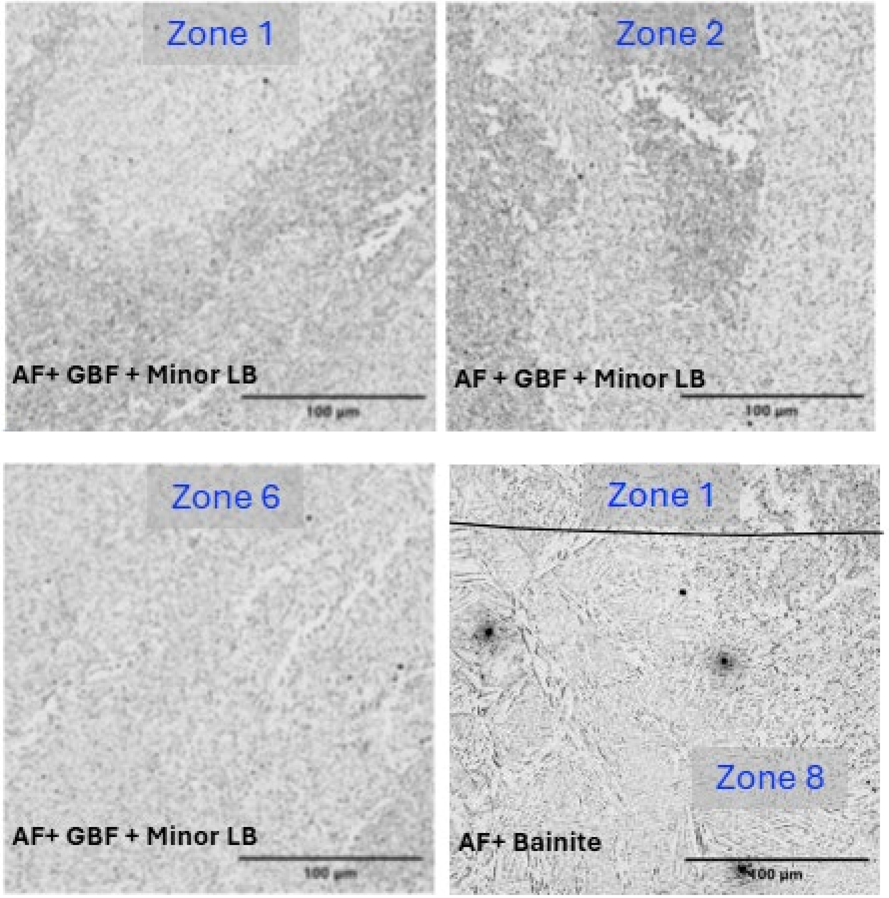
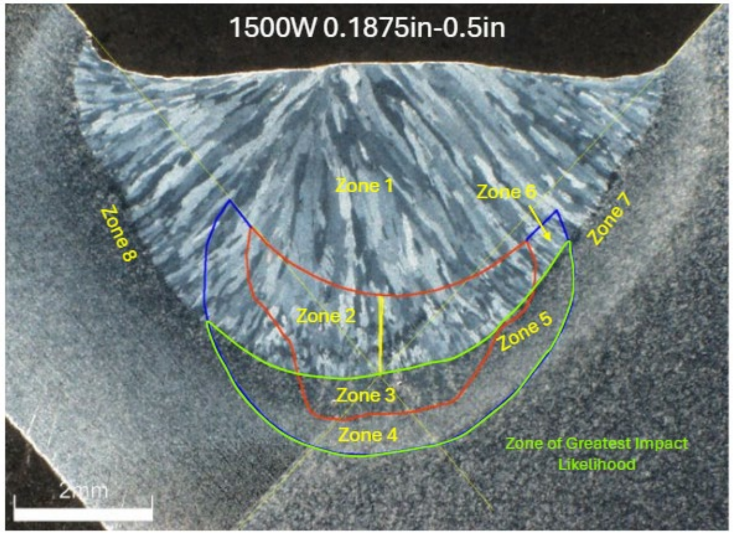
Metallographic Analysis

Nital Etched Microstructures, Outside ZGIL



- AF = acicular ferrite
- GBF = grain boundary ferrite
- PF = polygonal ferrite
- LB = lower banite
- UB = upper banite



Key takeaway: FCAW FZ and all remelted regions have similar microstructure (Zones 1, 2, and 6)

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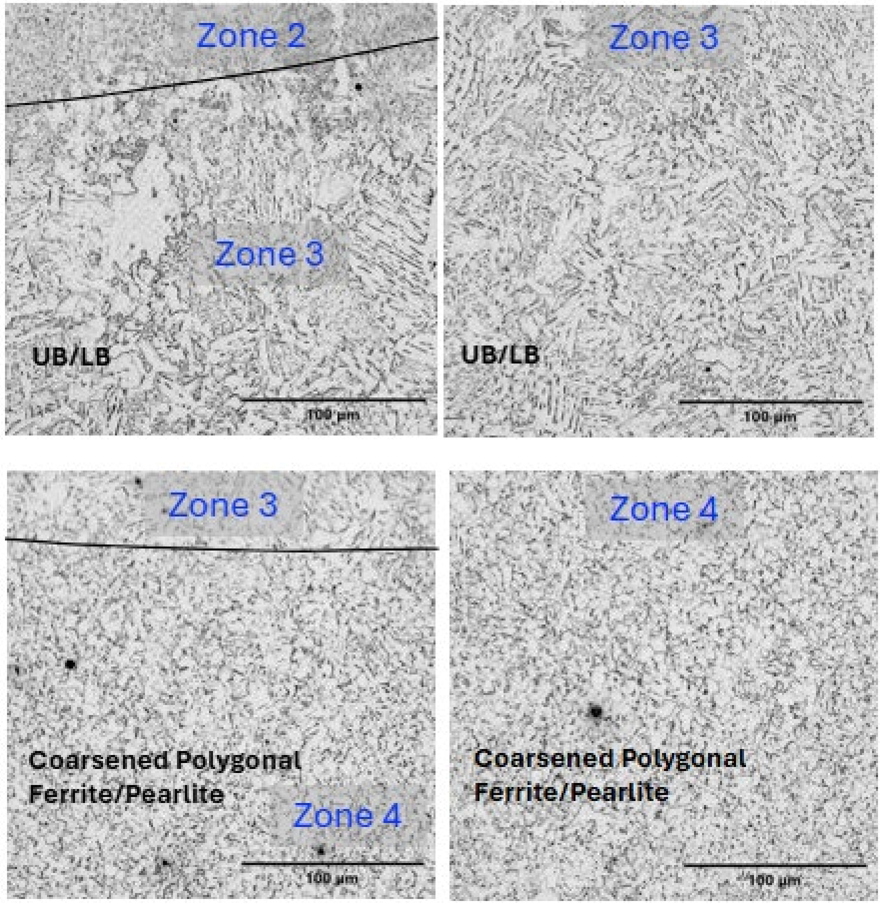
Metallographic Analysis

Nital Etched Microstructures, Within ZGIL

Lower toughness microstructures



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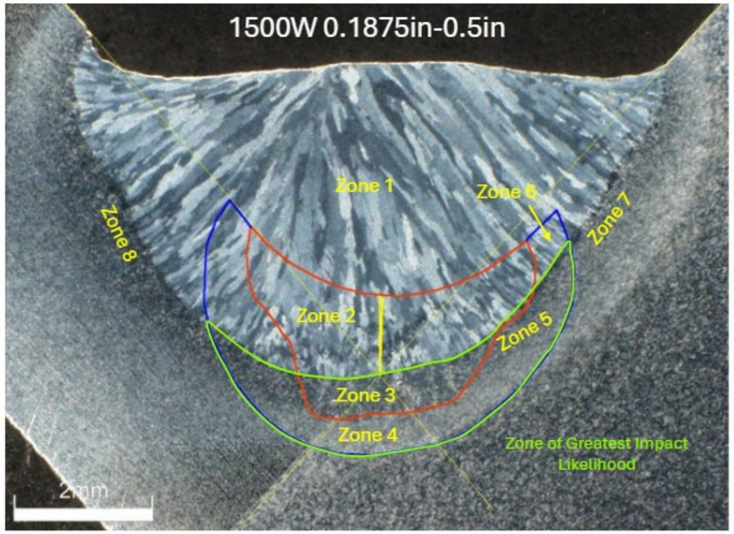


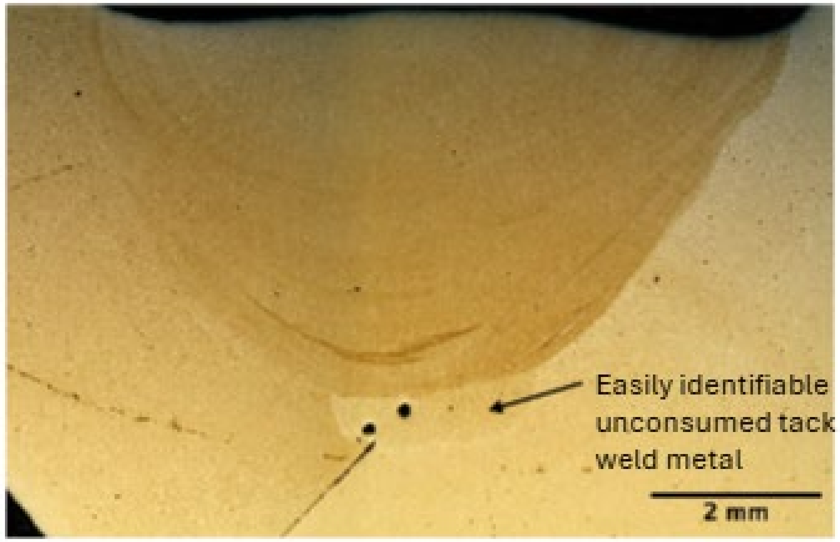
Key takeaway: Unconsumed fusion zone of laser weld, Zone 3, is area of interest

Metallographic Analysis

Martensite-Austenite Constituents in Weldments

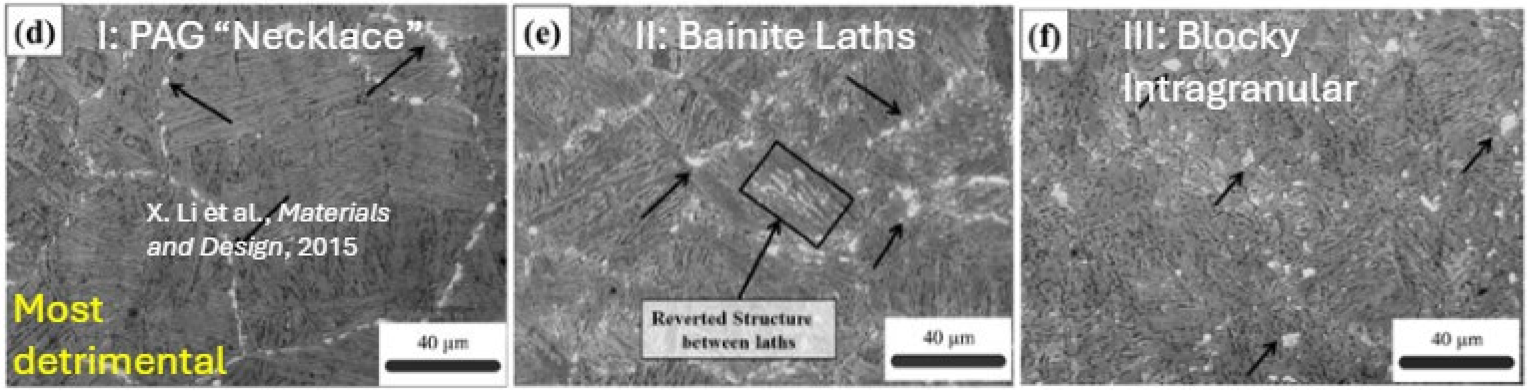
Factors Affecting MA (martensite-austenite) Influence on Toughness

- Distribution
- Intra-Particle Morphology
- Overall Fraction
- Aspect Ratio

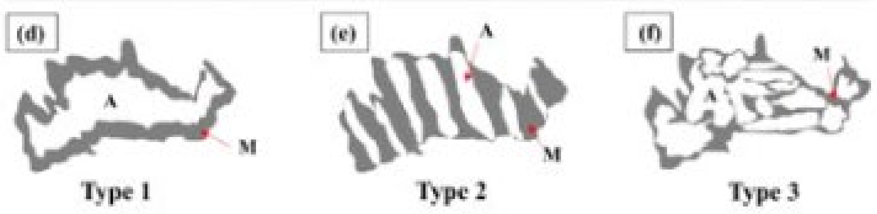


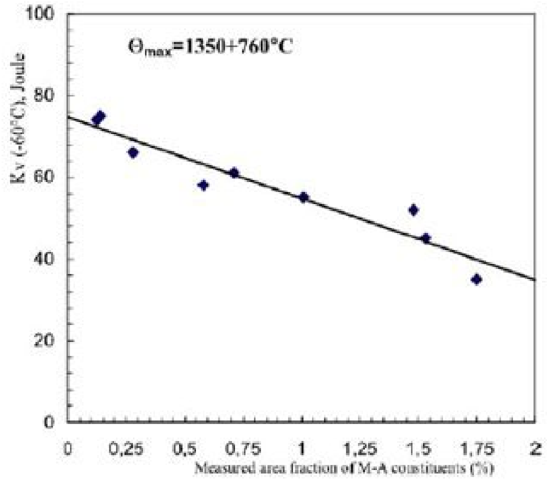
Metallographic Analysis

Factors Affecting MA Influence on Toughness



MA (martensite/austenite) constituents within microstructure





Submicron resolution of MA

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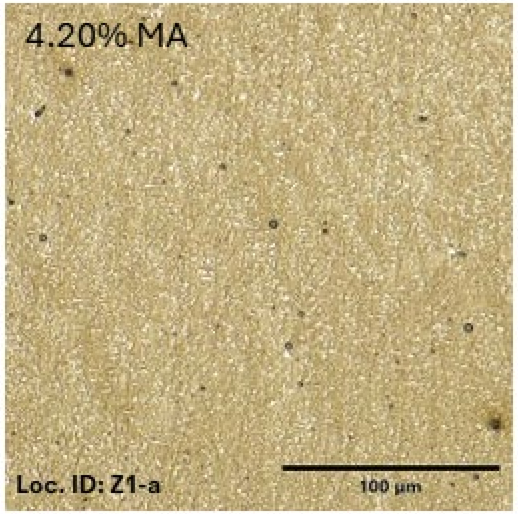
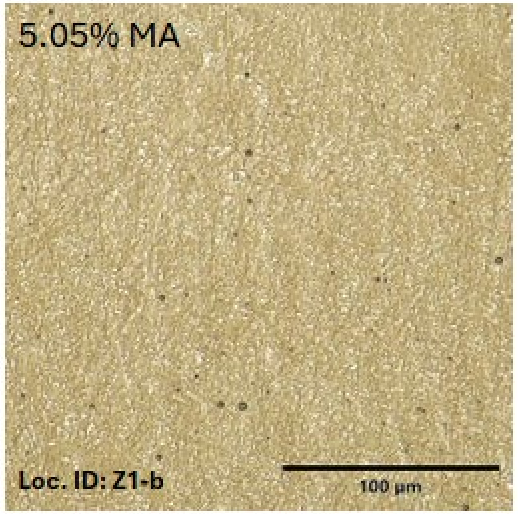
Metallographic Analysis

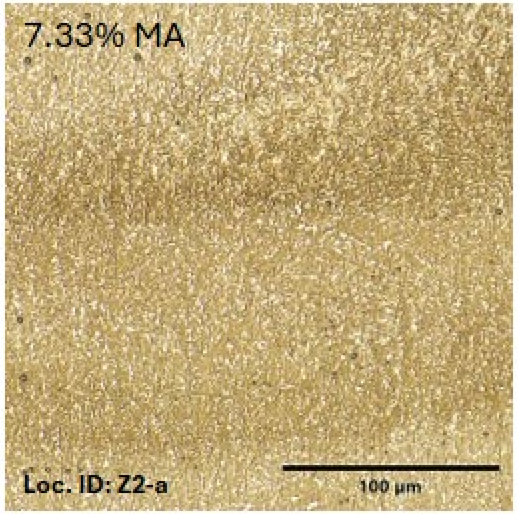
MA Etch, Weld Metal Zones

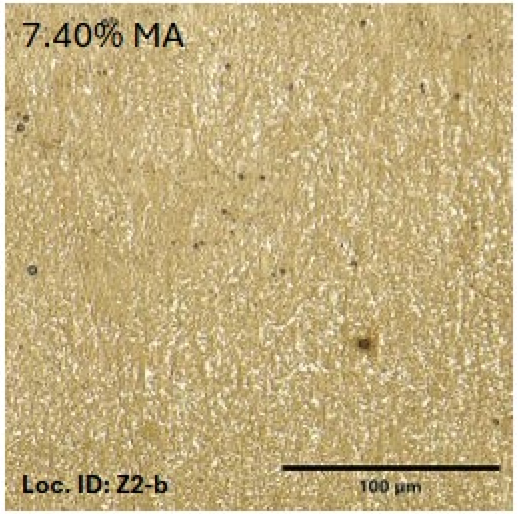
Zone 1: FCAW FZ

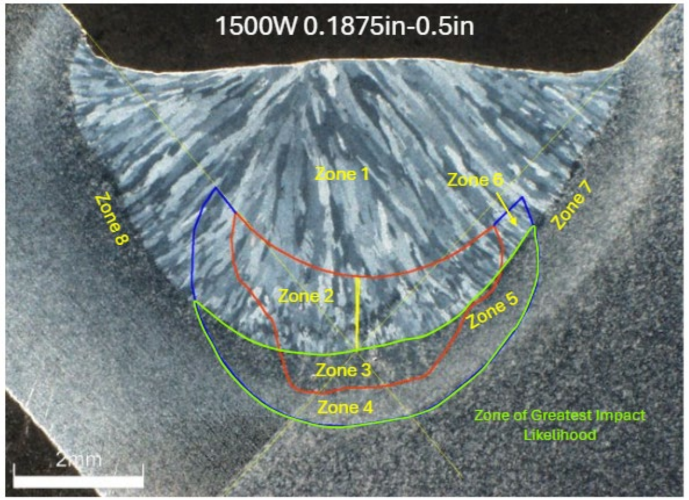




Zone 2: Laser Tack FZ – FCAW FZ







Zone 1 becomes baseline.

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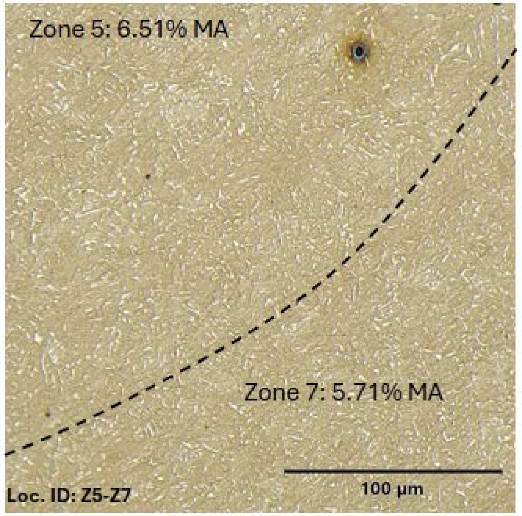
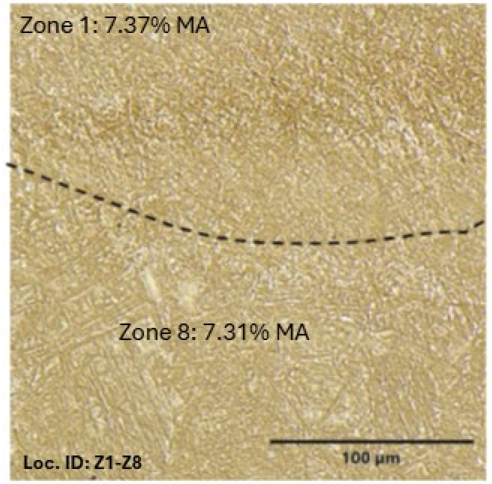
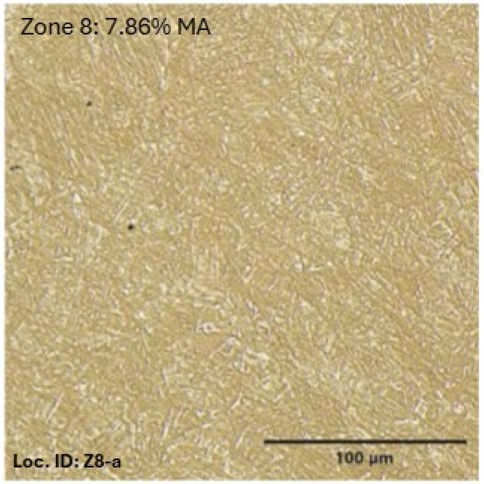
Metallographic Analysis

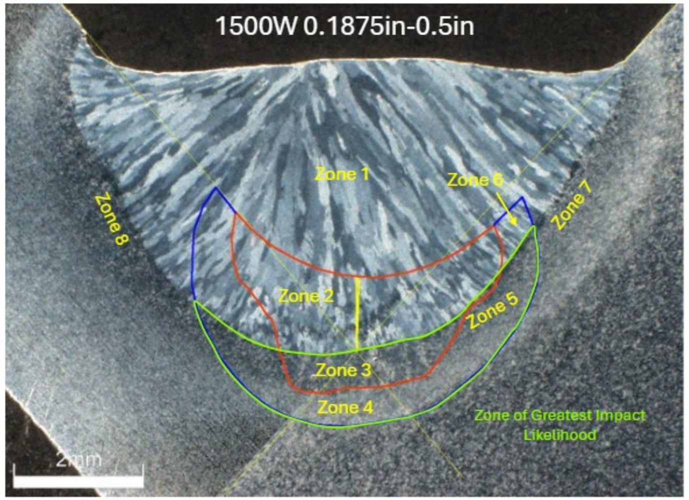
MA Etch, Unaffected FCAW CGHAZ Zones



Zone 8: FCAW CG (Thin)







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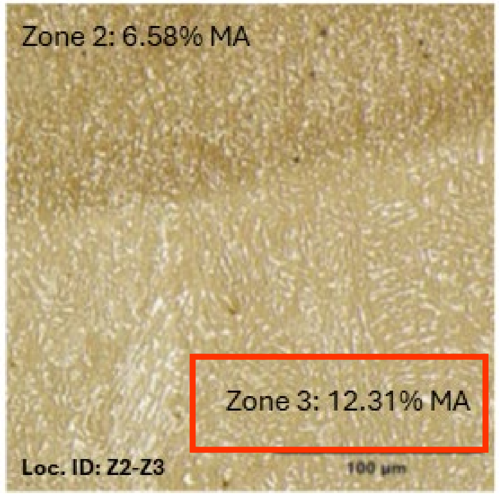
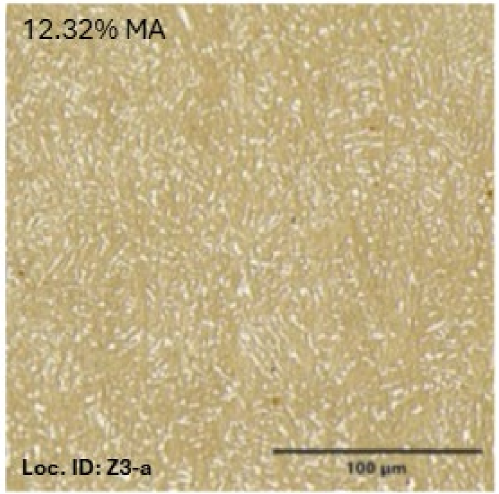
Metallographic Analysis

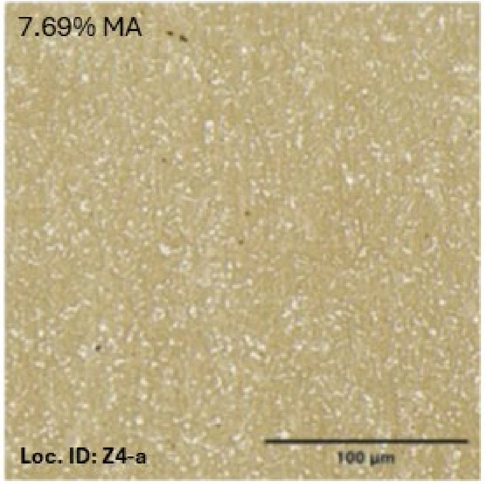
MA Etch, ZGIL Zones

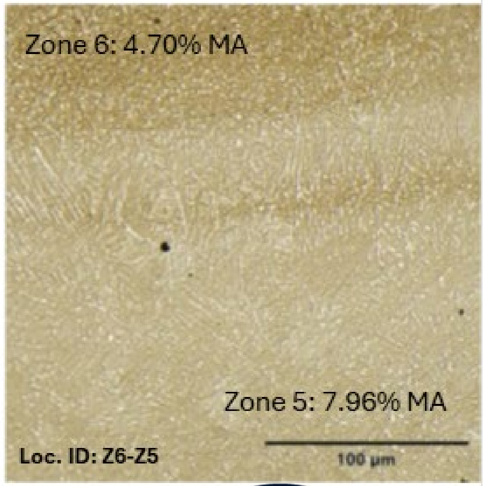
Zone 3: Laser Tack FZ – FCAW CG

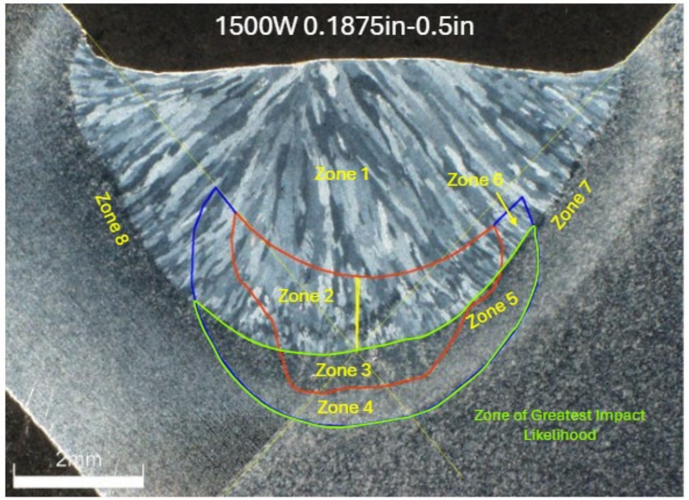




Zone 4: Laser Tack CG – FCAW FG/IC







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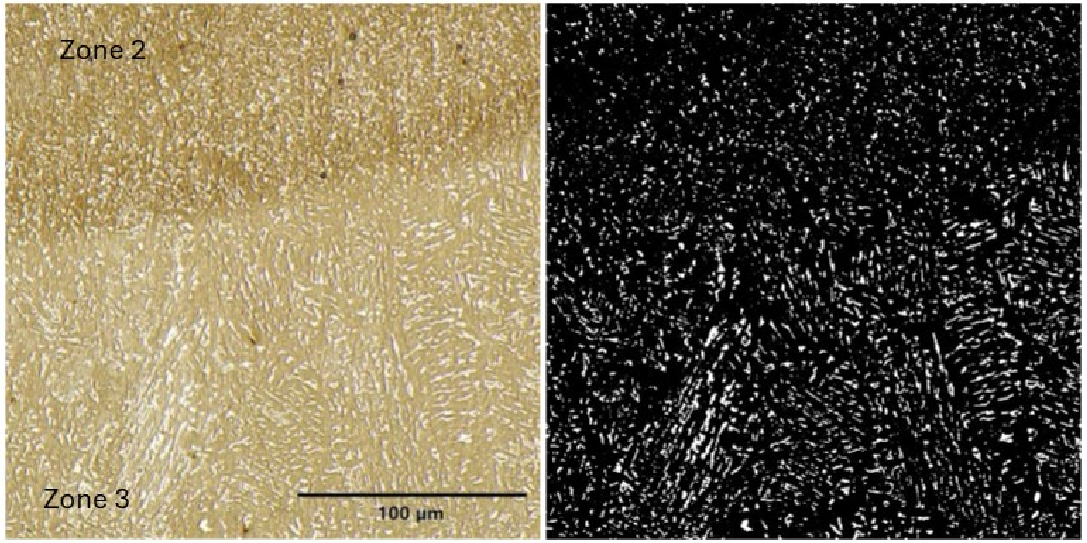
Metallographic Analysis

MA Etch, Image Thresholding and Statistics Generation



Zone #	Zone Description	Total Image Area Assessed (μm^2)	% MA	Number Density > 3 μm^2 (mm^{-2})	Median Aspect Ratio > 3 μm^2	Mean Aspect Ratio > 3 μm^2
1	FCAW FZ	133224	5.11%	923	2.24	2.52
2	Tack FZ - FCAW FZ	129488	7.25%	3483	2.14	2.40
3	Tack FZ - FCAW CG	90025	12.32%	12019	2.38	2.84
4	Tack CG - FCAW FC/IC	137420	7.27%	4614	2.02	2.30
5	Tack CG-FCAW CG	75941	7.33%	3147	2.94	3.59
6	Tack CG-FCAW FZ	66785	6.85%	1782	2.18	2.55
7	FCAW CG (Thick)	21911	5.71%	1780	2.52	3.28
8	FCAW CG (Thin)	86288	7.66%	3674	2.81	3.54
Ref -1	Thick Base Mat.	54878	1.45%	36	Insufficient Sample Size	Insufficient Sample Size
Ref -2	Thin Base Mat.	54878	0.08%	36	Insufficient Sample Size	Insufficient Sample Size

Metallographic Analysis

MA Etch, Image Thresholding and Statistics Generation

Consistent increase in %MA in Zone 3

Sample	"Zone 3" % MA	"Zone 2" % MA	"Zone 5" % MA
1500 W HLAW - Replicate 1	12.32%	7.25%	7.33%
1500 W HLAW - Replicate 2	7.24%	2.31%	4.85%
1250 W HLAW - Replicate 1	6.94%	3.84%	4.25%

Key Takeaway: Combination of UB/LB seen in Nital Etch and increased %MA in MA etch confirmed Zone 3 is the performance limiting region

Toughness Evaluation

Can Charpy Impact Testing be Performed?

Standard Charpy impact (CVN) specimen is 10mm thick with 2mm deep notch

Typically taken from full penetration butt weld from material 12 mm thick or greater

Possible to test weld metal and HAZ, dependent on joint design

Options?

- Full penetration butt weld with laser process for weld metal impact testing
- Laser clad of joint edge followed by welding of full penetration butt weld with FCAW process
- Specialized double bevel groove weld with laser root and single FCAW pass on both sides

Toughness Evaluation

Can Charpy Impact Testing be Performed?

Option 1: Full penetration butt weld with laser process for weld metal impact testing

Attempted on 1/2in HSLA65 plate, single bevel with backing

Difficulty in following joint

Tremendous build-up of visible porosity as additional weld passes were made

Various parameters were attempted that were known to provide acceptable fillet welds, with no success in producing sound welds

Toughness Evaluation

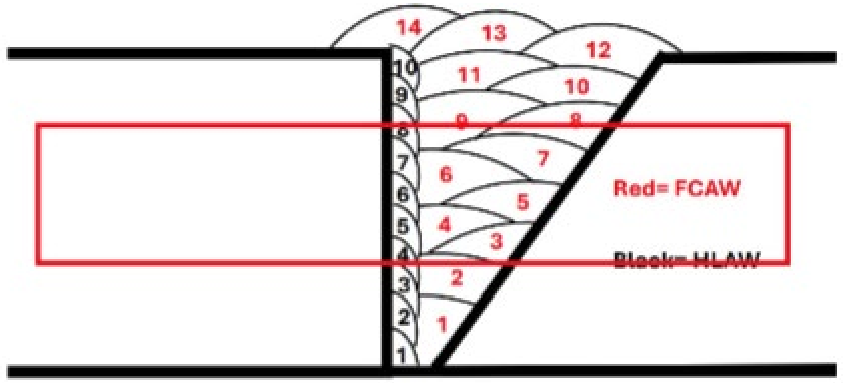
Can Charpy Impact Testing be Performed?

Option 2: Laser clad of joint edge followed and welding of full penetration butt weld with FCAW process

3/4in HSLA65 plate, B2(S)V.1 joint design

Laser Weld Metal CVN at -20°F (ft-lbs)
264, 264, 208, 78, 158

Laser HAZ at -20°F (ft-lbs)
264, 264, 264, 254, 220



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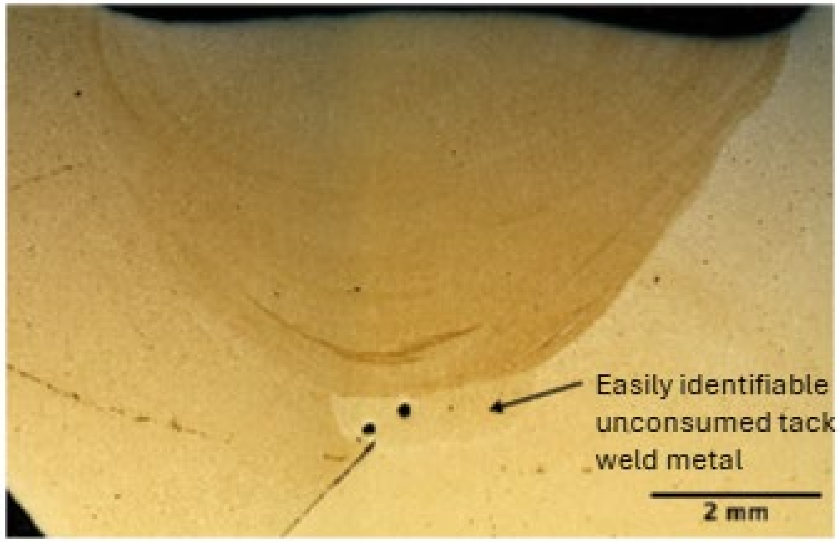
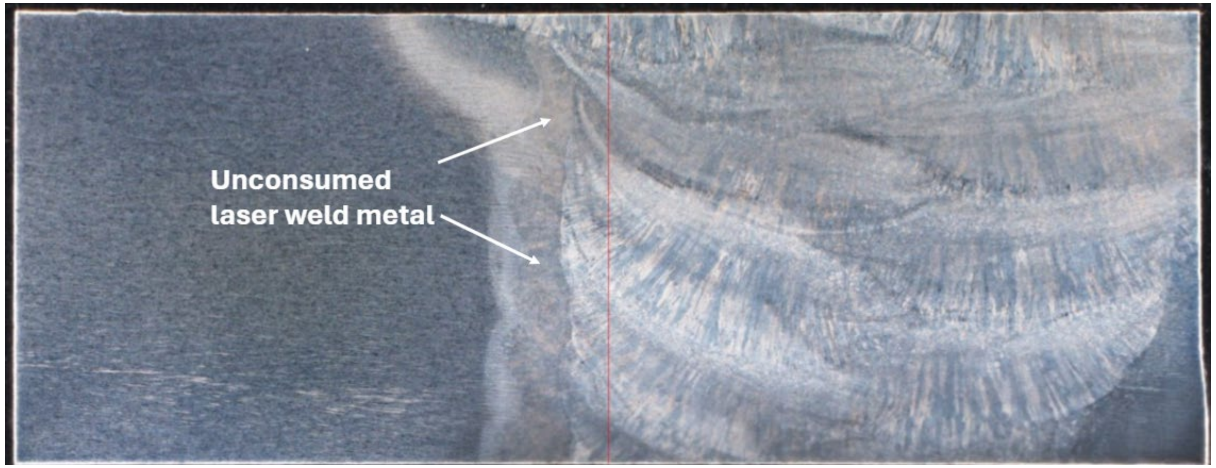
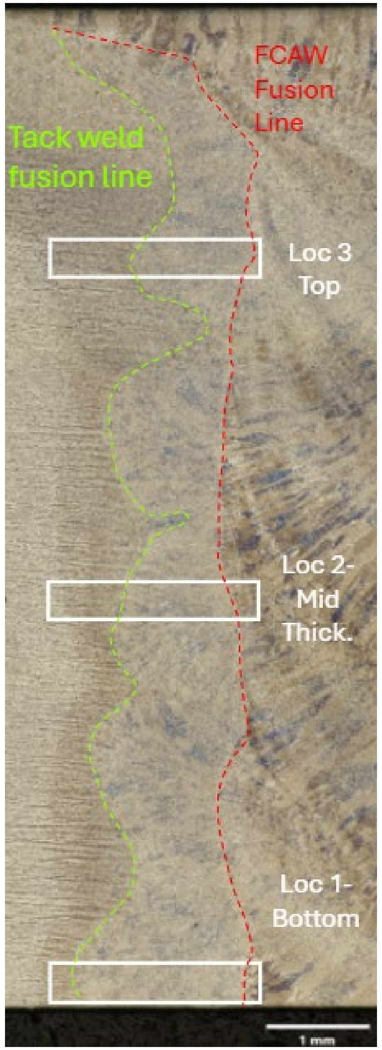
Toughness Evaluation

Can Charpy Impact Testing be Performed?







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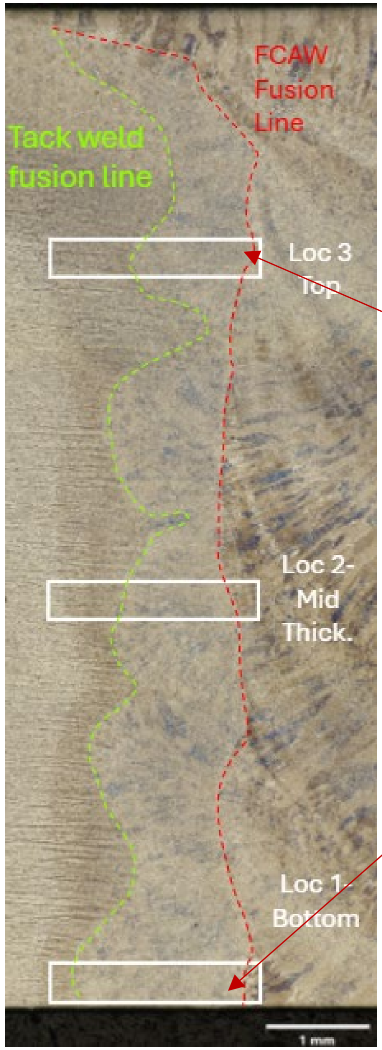
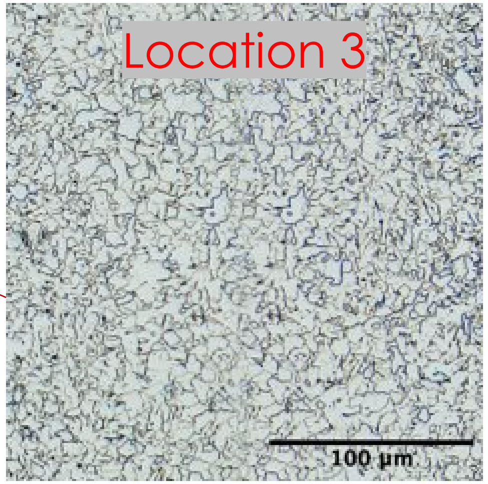
Toughness Evaluation

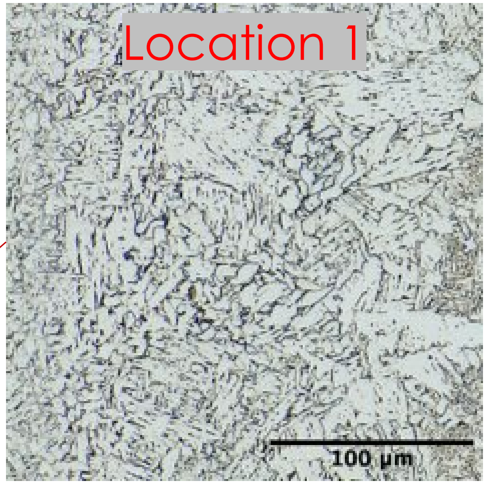
Can Charpy Impact Testing be Performed?





Intended Zone 3 replicate, top of weld

Bainite fractions not present, Zone 3 was not duplicated through thickness of weld



Intended Zone 3 replicate, bottom of weld

Bainite fractions present, indicates Zone 3 constituents are present

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Toughness Evaluation

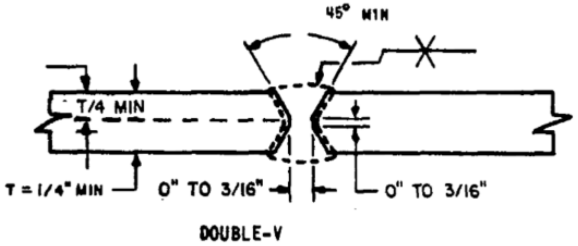
Can Charpy Impact Testing be Performed?

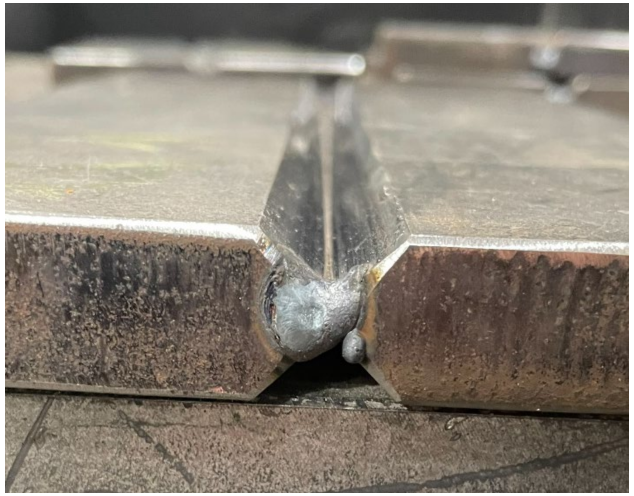
Option 3: Specialized double bevel groove weld with laser root and single FCAW pass on both sides

Using 3/4in HSLA-65 plate

B2V.3

- 90° included bevel angle
- Varying land dimensions
- Varying laser power





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Toughness Evaluation

Can Charpy Impact Testing be Performed?

Option 3: Specialized double bevel groove weld with laser root and single FCAW pass on both sides

This method was not successful due to excessive porosity observed in radiographic testing. Porosity was located in the root of the no back gouge portion of the laser weld.

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Fillet Weld Testing

Fillet Weld Strength Testing

In an effort to quantify some type of mechanical properties, fillet weld cruciform and shear testing was evaluated.

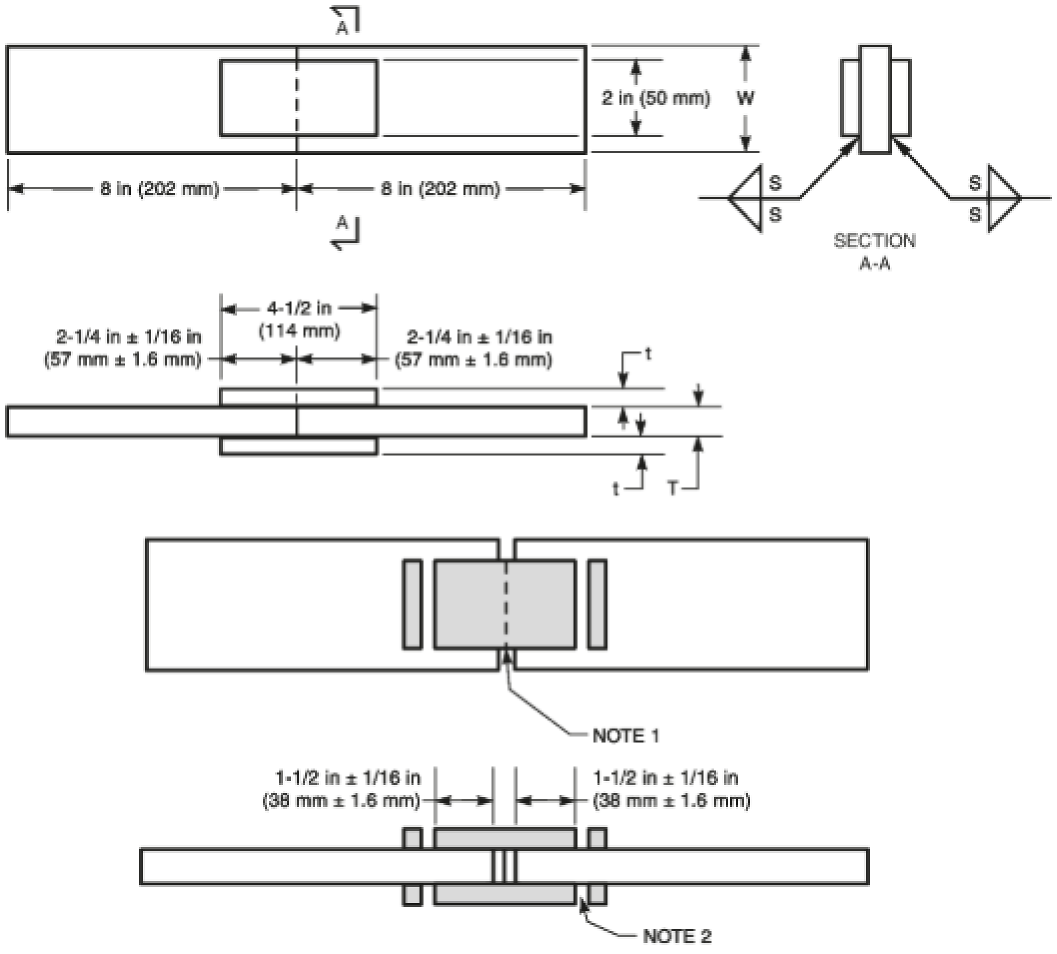
AWS B4.0 longitudinal and transverse shear testing was performed, along with loaded cruciform tensile testing.

Two sets of three specimen types were made for each test.

- FCAW with no laser tacks to represent baseline
- FCAW with GMAW tacks to represent NNS method of welding of stiffener to deck connections
- FCAW with laser root to represent future state

Fillet Weld Testing

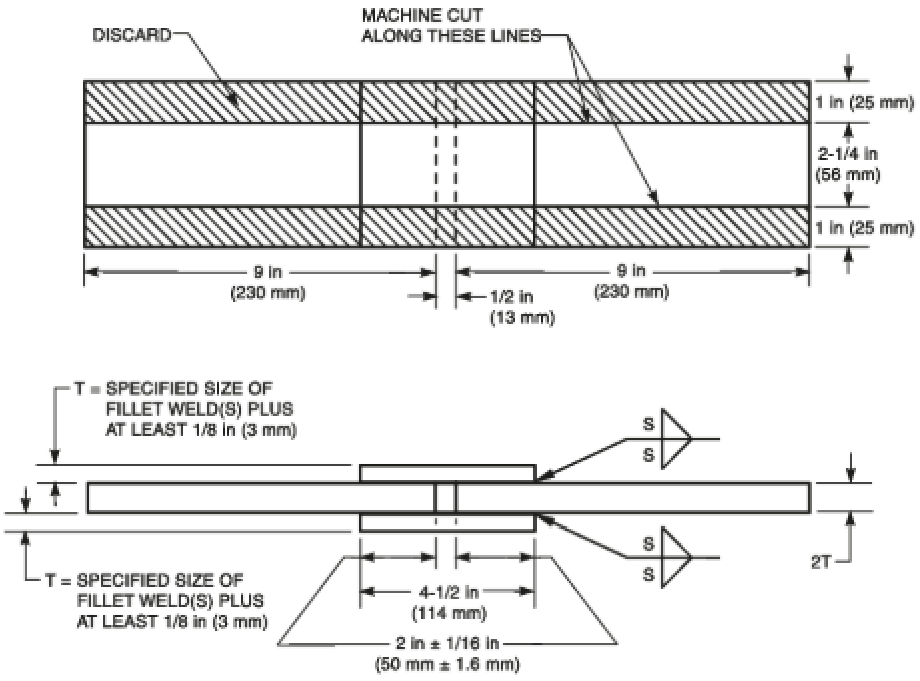
Longitudinal Shear Test Specimen



(B) AFTER MACHINING

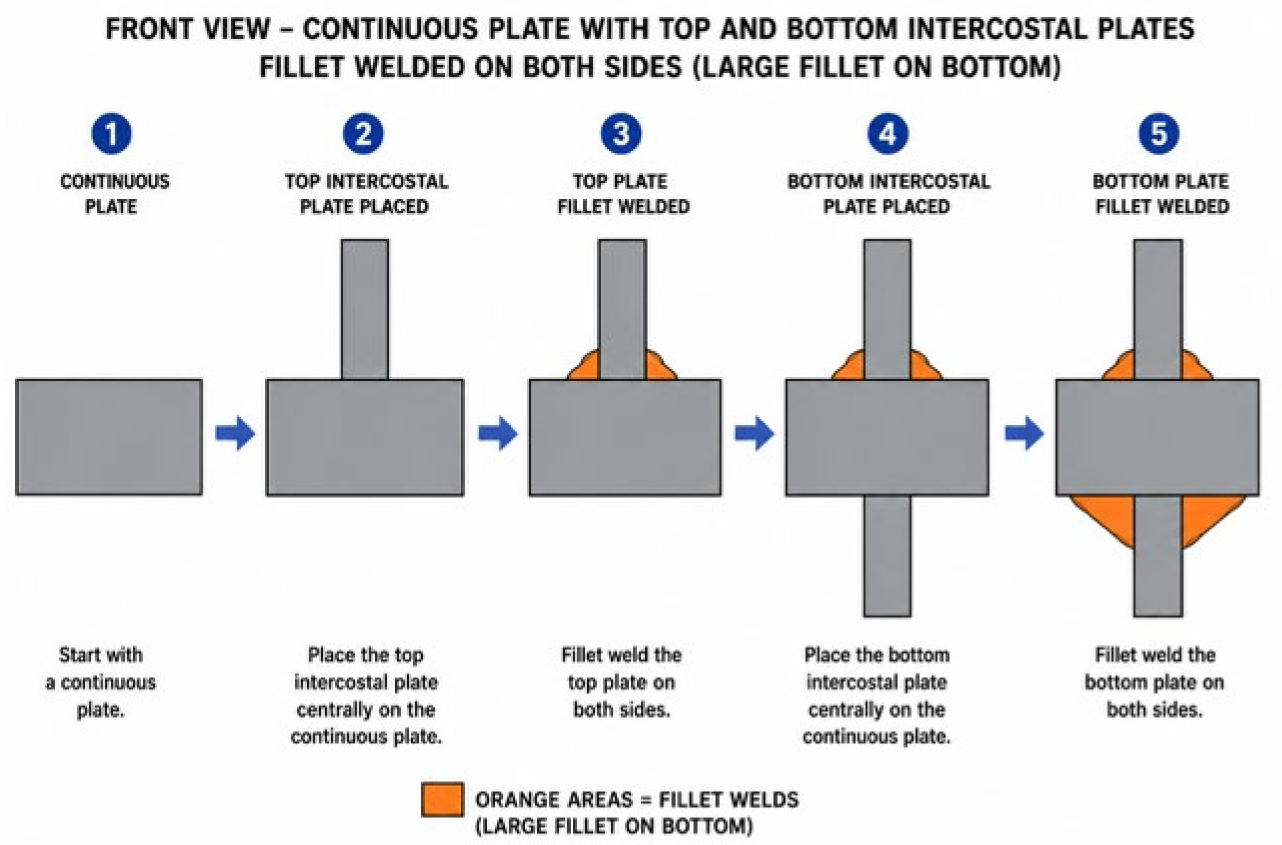
Fillet Weld Testing

Transverse Shear Test Specimen



Fillet Weld Testing

Loaded Cruciform



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Fillet Weld Testing

Test Type	Weld Type	Load (lbs)	Shear Strength (ksi)
Transverse Shear	FCAW Only	89000	101.3
		87100	99.1
	FCAW with Laser Root	90900	Invalid
		91900	Invalid
	FCAW with GMAW Tack	91100	103.7
		89200	101.5
Loaded Cruciform	FCAW Only	73000	100.1
		73800	109.3
	FCAW with Laser Root	76300	104.6
		76900	105.5
	FCAW with GMAW Tack	76600	96.3
		77300	92.4
Longitudinal Shear	FCAW Only	63500	65.7
		68100	69.4
	FCAW with Laser Root	84800	79.7
		92900	92.0
	FCAW with GMAW Tack	63800	63.9
		68300	70.6

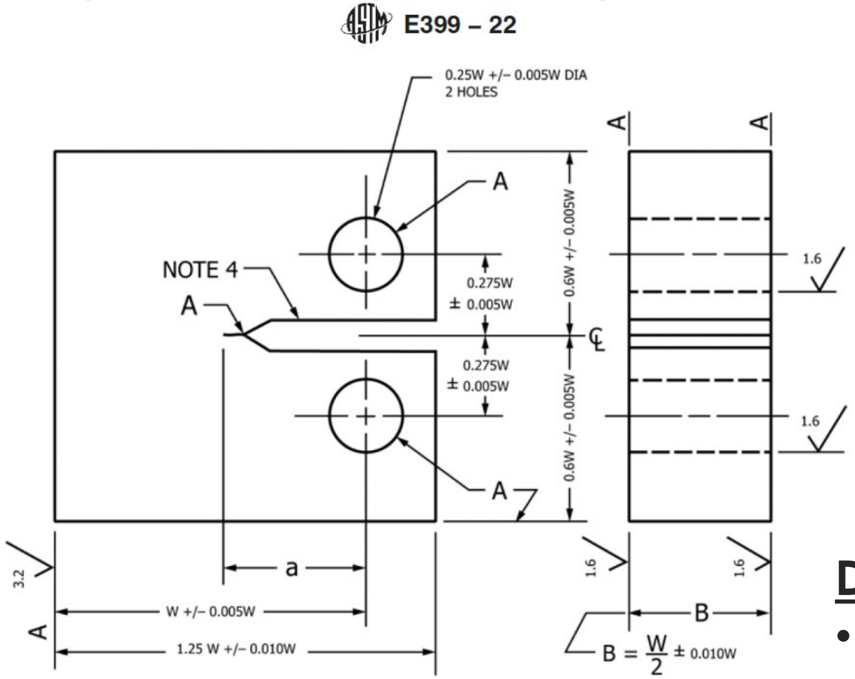
S9074-A1-GIB-010/1628 Specification Requirements

Average Longitudal Shear Strength – 64 ksi

Calculated Transverse Shear Strength – 85 ksi

Compact Tension Specimens

ASTM E399 Geometry

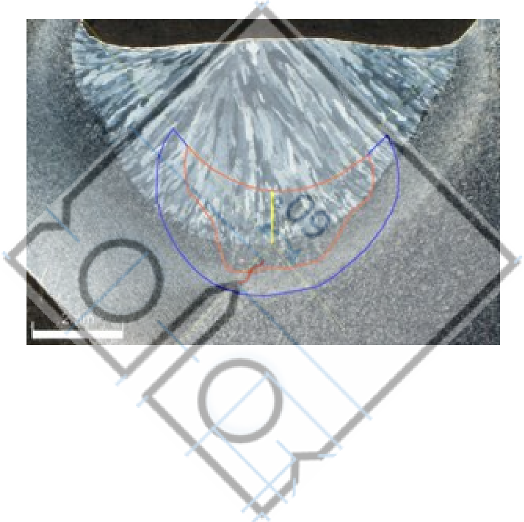


Dimensions scale to "W":

- Side length = 1.25W
- Pin diameter = 0.25W
- Thickness = 0.5W
- Standard pin geometries of 1.5 or 2 mm allow for a discrete side-length of either 7.5 mm or 10 mm (W = 6 or 8 mm)

Compact Tension Specimens

- Advantages
  - Directly samples the "real-world" geometry with no thermal history convolution
  - Zone 3 is located at the end of the gap between the workpieces, which can function as the notch with minimal machining cleanup
  - Could be performed on existing samples with known Zone 3 – a guaranteed evaluation
- Disadvantages
  - Sensitive to initial loading in root of weldment
  - Not widely standardized in industry
    - Requires direct comparison between samples with and without HLAW to be valuable/meaningful
  - Small size could create testing challenges



Key Takeaways

Parameters sets were established that provided acceptable welds via visual (VT), dye penetrant (PT), and macro etch evaluation

Welding over laser tacks was successful, with no noticeable difference in areas of tacked versus untacked weldment

Metallurgical analysis indicates areas of undesired microstructure in remnant tack weld metal after being welded over

Toughness could not be evaluated due to weld defects or non-comparable micro structure

Fillet weld shear testing showed adequate strength in weldments

Ongoing compact tension testing for comparative analysis

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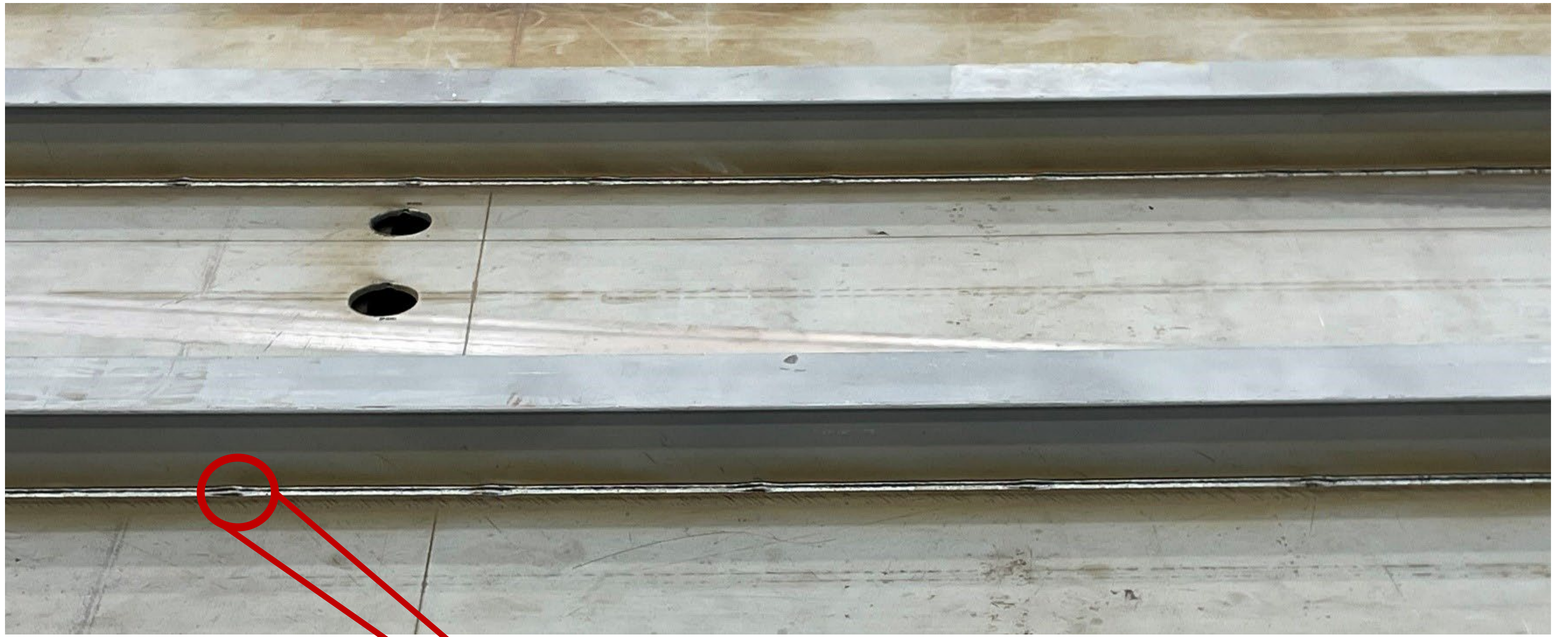
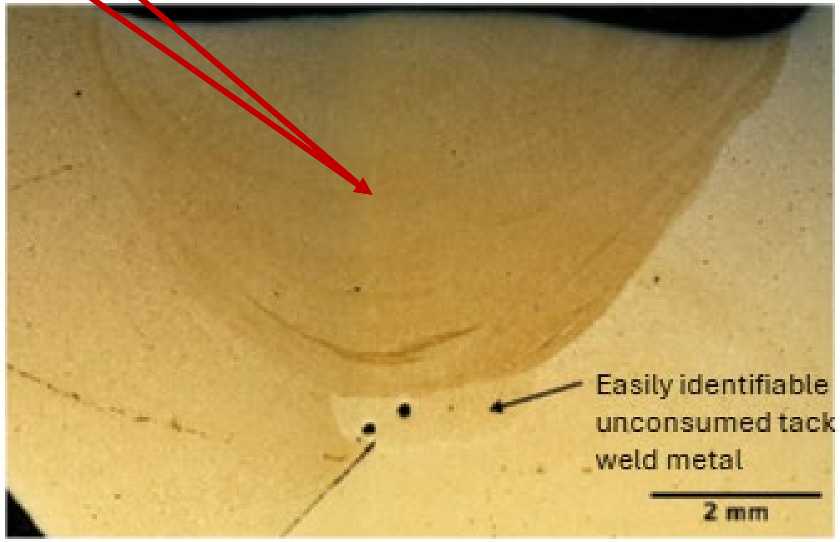
Big Picture





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