Lincoln Electric | Additive Solutions

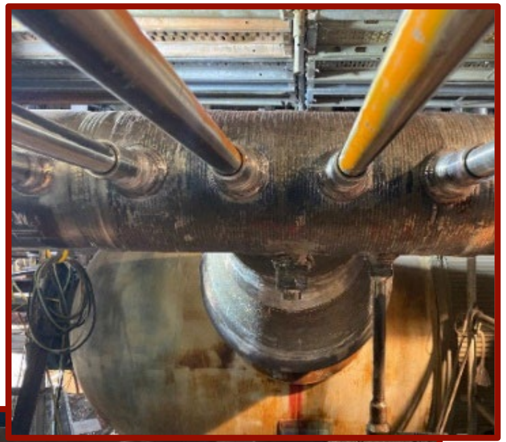
DED – Wire (*aka Welding*) Use Case Update NRC Workshop

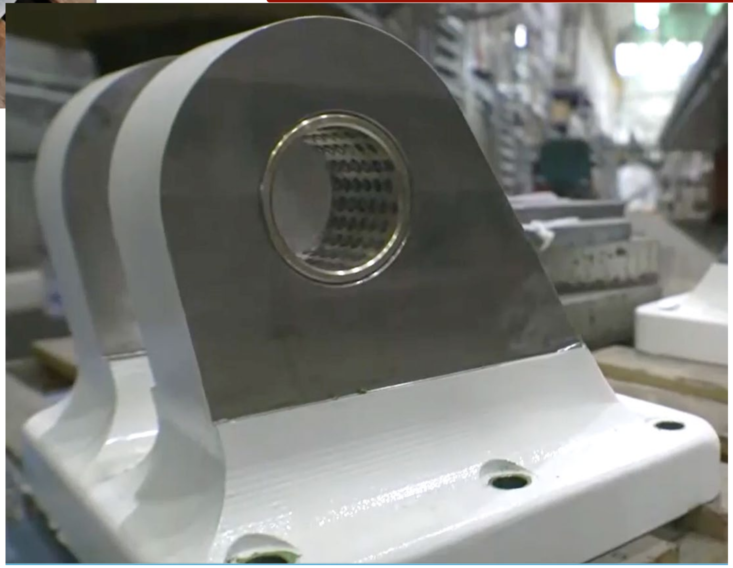
Teresa Melfi

October 2023

Alternative to Castings and Forgings

Faster Delivery





Nuclear Reactor Door Hinges
CVN-80 *Enterprise*
100ksi steel
3D Printing < 2 weeks
HY-80 castings—several months

Gulf Coast Refinery
Nickel 617—8 parts
Qualification + 3D Printing < 30 days
Nickel 800H castings—several months

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What's in a Name: Additive Manufacturing or Welding?

Additive Manufacturing (Drama)

- 3D printing, DED, WAAM
- Parts are "builds"
- Uses "feedstock"
- "Black Box" machine
- Non-portable procedures
- Parameters still not well known
- Often not fully dense
- NDT techniques not well established
- Properties often not well understood

Welding (Boring)

- GMAW, GTAW, EBW, LW
- Parts are "weld metal"
- Uses welding electrodes
- Welding systems
- Portable procedures
- Established "variables"
- Fully dense weld metals
- NDT techniques well known
- Material properties well known

Use Case – Weld Metal (DED-Wire) Additive
*High Temperature, Pressure Retaining Refinery Application**

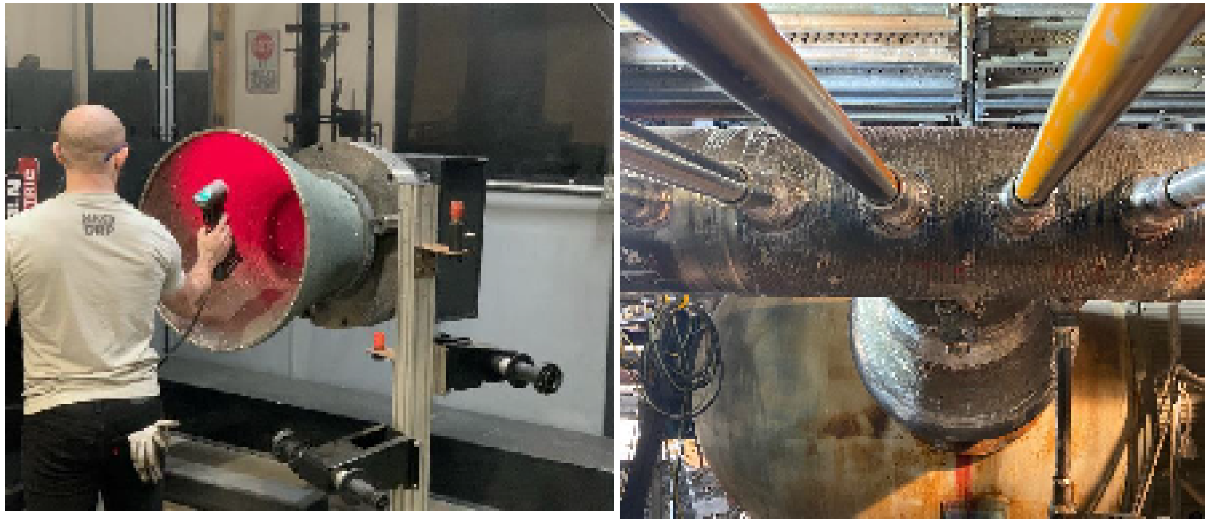
* Full presentations available upon request

Robert Rettew, Chevron
Teresa Melfi, Lincoln Electric
Ben Schaeffer, Lincoln Electric
Matt Sanders, Stress Engineering

A Refinery 3D Printing Success Story

- In early 2022, a facility turnaround needed replacements for several components in hydrogen furnace service. These components were critical path to restart the facility.
- Service requirements were 1500F and 300psi, with a design lifetime of 20 years.
- Application was for a furnace header. Previous installation was Alloy 800H with Alloy 617 weldments.
- Existing components were damaged and unusable. Replacement using traditional methods estimated ~3 months.
- 3D printing was used to deliver replacements in just under 4 weeks, **avoiding a significant shutdown.**

Piping components being printed at Lincoln Electric Additive Services

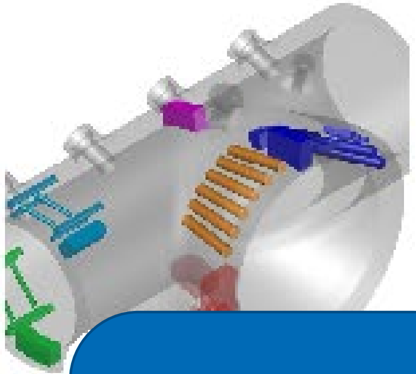


(left) Digital part verification, (right) Final Installation

Workflow of an Urgent WAAM Job

THE NEED
-Four tees and transitions
-Alloy 800H @ 1100 lb each
-3 month minimum lead time for forgings
-No prior work with Lincoln Electric Additive

DESIGN/ ENGINEERING REVIEW
-Alloy 617 proposed
-Some design optimization
-FEA analysis (1500°, 300 psi)
-Quality Audit
-Gather 617 electrode



MATERIAL TESTING
-ASME IX QW-600 testing
-Witness specimen tests
-API 20S sacrificial part tests
-Creep testing
-See following slides

PART TESTING & INSTALLATION
-See following slide for testing
-Machine bevels
-Install (by welding!!)

Inspection & Testing Summary

- Testing Conducted on Each Piece
  - Dimensional Checks
  - 100% Dye Penetrant surface inspection
  - Phased Array UT of Critical Locations
- Testing Conducted on Witness Coupons
  - Hardness Survey
  - Metallographical Assessment
  - Tensile Testing in multiple orientations
  - Chemistry
- Additional Testing Conducted on First Article
  - Pressure Testing at 6,000psi
  - Tensile Tests at elevated temperature, from wall thickness at various critical locations
  - Local RT Inspection
  - Creep testing using samples from sacrificial part

Printed Components Testing

- Hydrotest (photo on right)
- Acoustic Emissions
- Phased Array Ultrasonics in critical areas, require special qualification
- Radiographic Inspection of 100% Volumetric
- Dye Penetrant 100% surface

Production Images

Timeframe Recap

- Week One
  - First Inquiry
  - Meetings & Printability Assessment with Lincoln Electric
  - Determined code case and API guidance
- Week Two
  - Risk Assessment, supported by review of Lincoln and Industry Data
  - Visit to Lincoln, review QA/QC and manufacturing
  - Initial Mechanical Results, Surface Roughness, and FEA model
- Week Three
  - Hydrotest, PAUT, and RT on test piece
  - Grinding & photography of surface indications
- Week Four
  - Delivery of subsequent parts for final machining, inspection, & installation

Qualification and Testing Outline

- Qualify the deposition procedure using test pieces -- bracketing essential variables and thickness per ASME Section IX
- Compare results to a corresponding material specification
- Build the part(s), first article (if required) and witness specimens
- Destructively test the witness specimen
- Destructively test first article, if required by the referencing standard
- Non-destructively test the printed parts, as required by the referencing standard

ASME IX QW-600 Bracketed Qualification

- Must test the highest cooling rate to be used in production.
- Must test the lowest cooling rate to be used in production.
- Must test the thinnest wall to be printed in production.
- Must test the thickest wall to be printed in production.

Codes require validation that all production printing stayed within these qualification bounds and also meet all other variables and rules of Section IX

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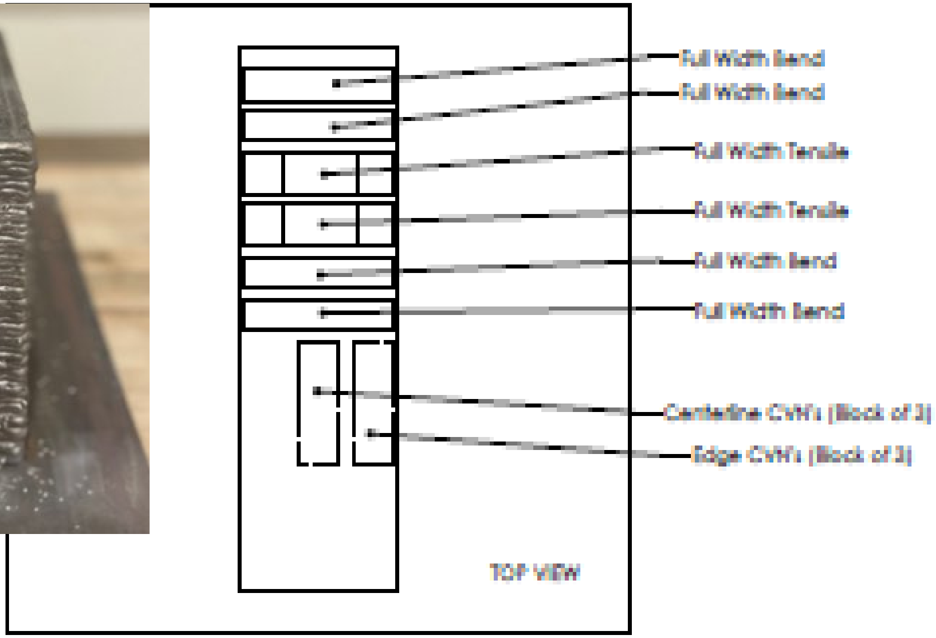
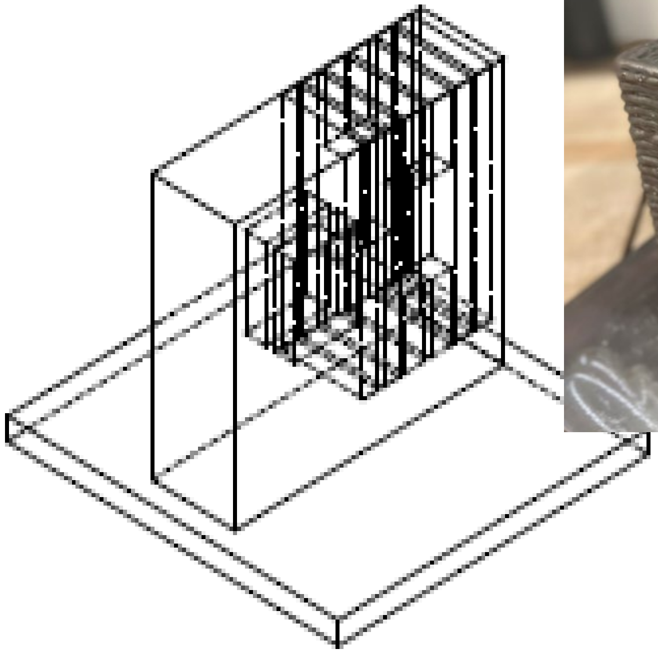
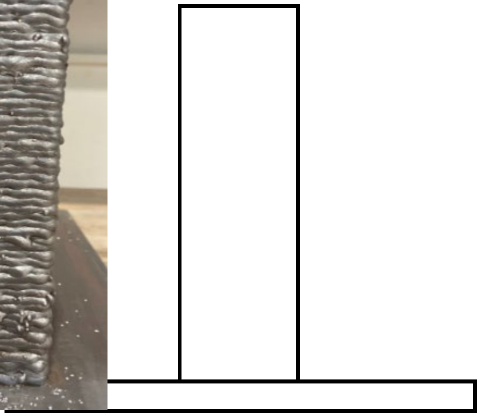
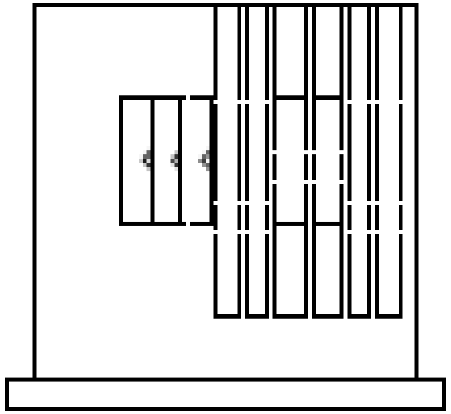
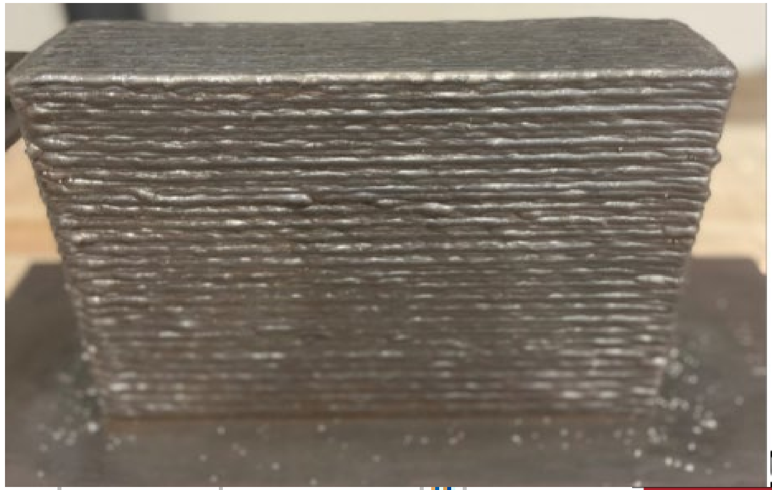
Thick Qualification Specimen Removal



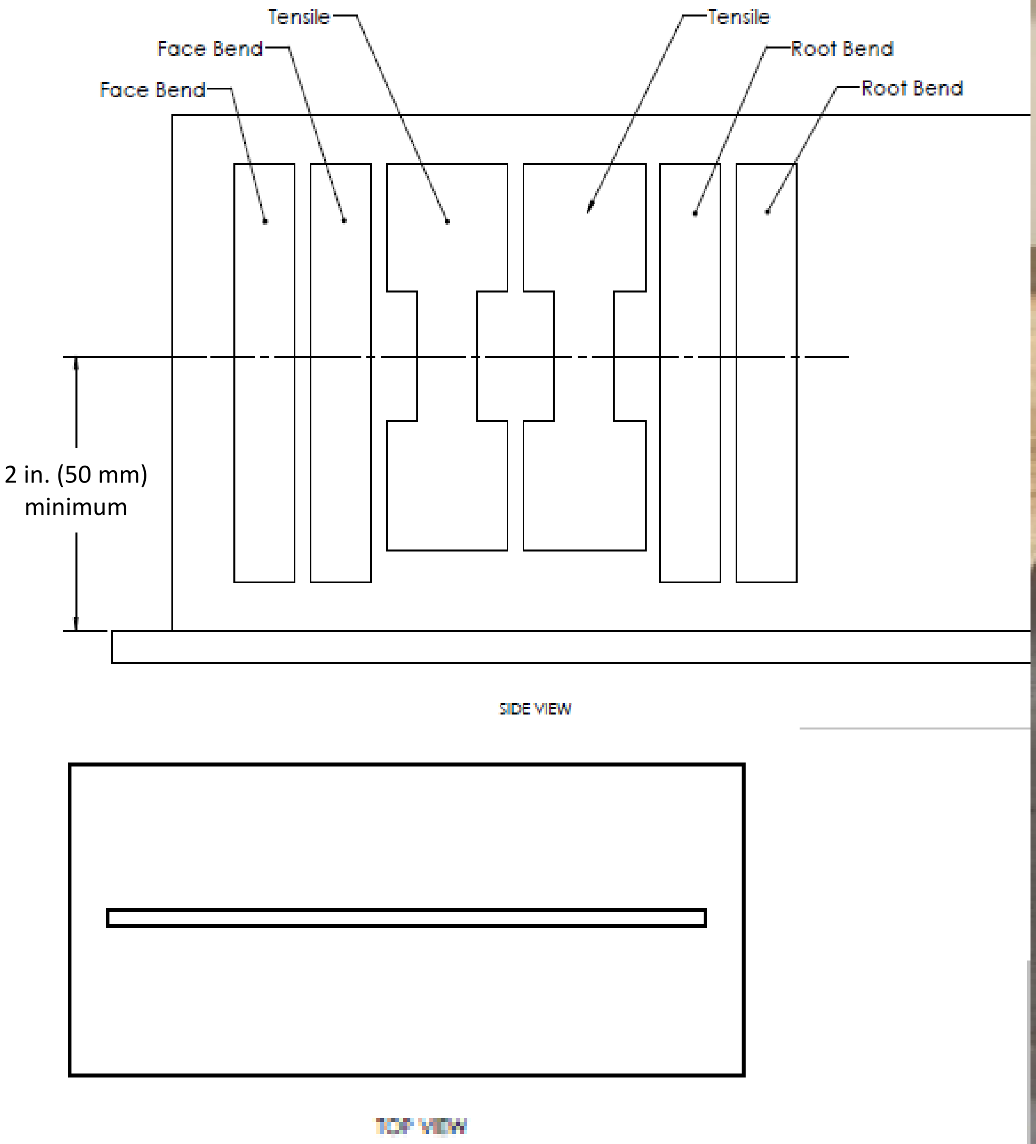








Thin Qualification Specimen Removal



ASME Research Project Execution

- Nearly **2 Tons** of weld metal deposited (**72 Walls, 15 Weeks**)
- **384 Tensile Specimens** machined and tested
- **544 CVN Specimens** machined and tested

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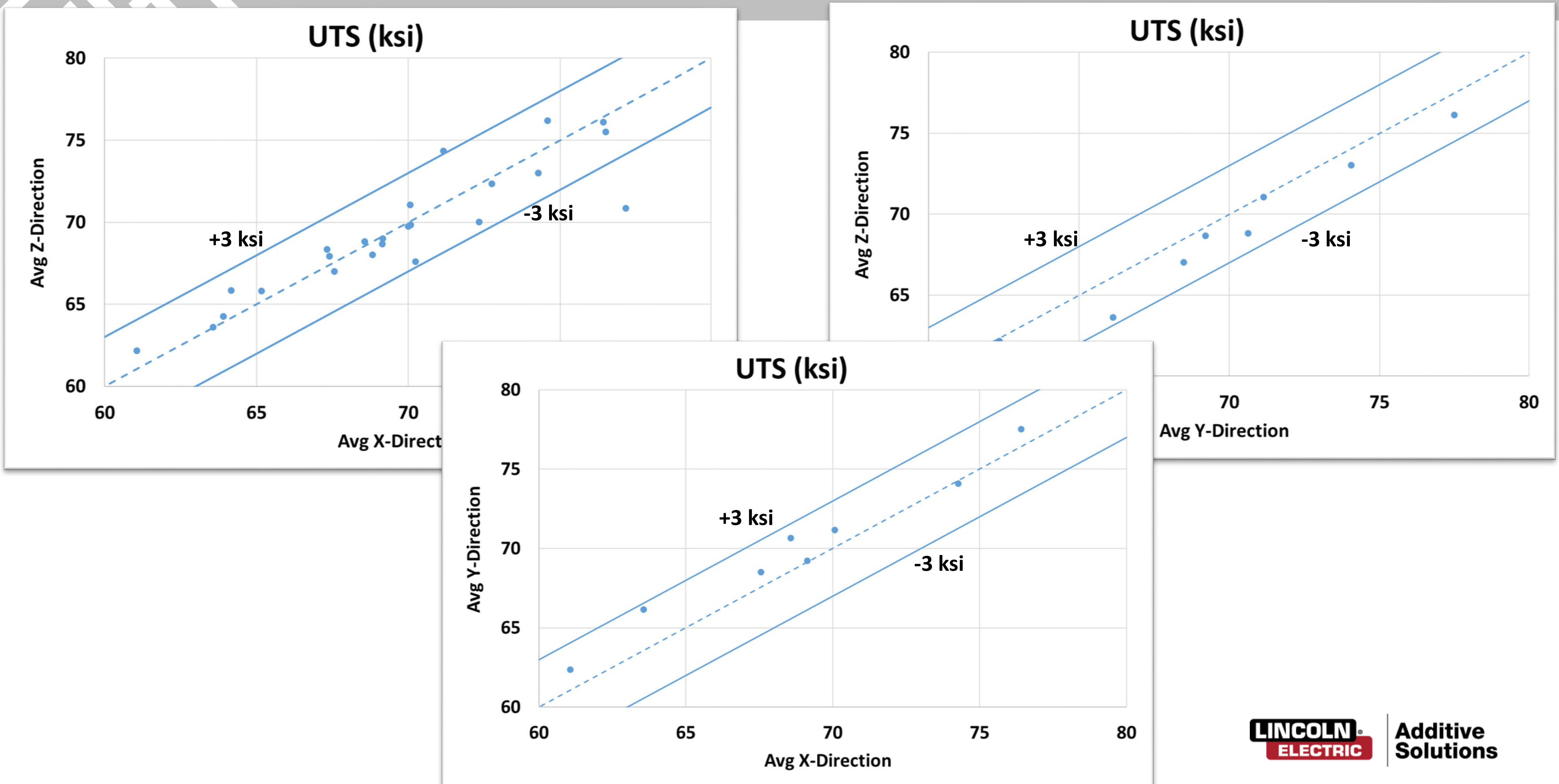
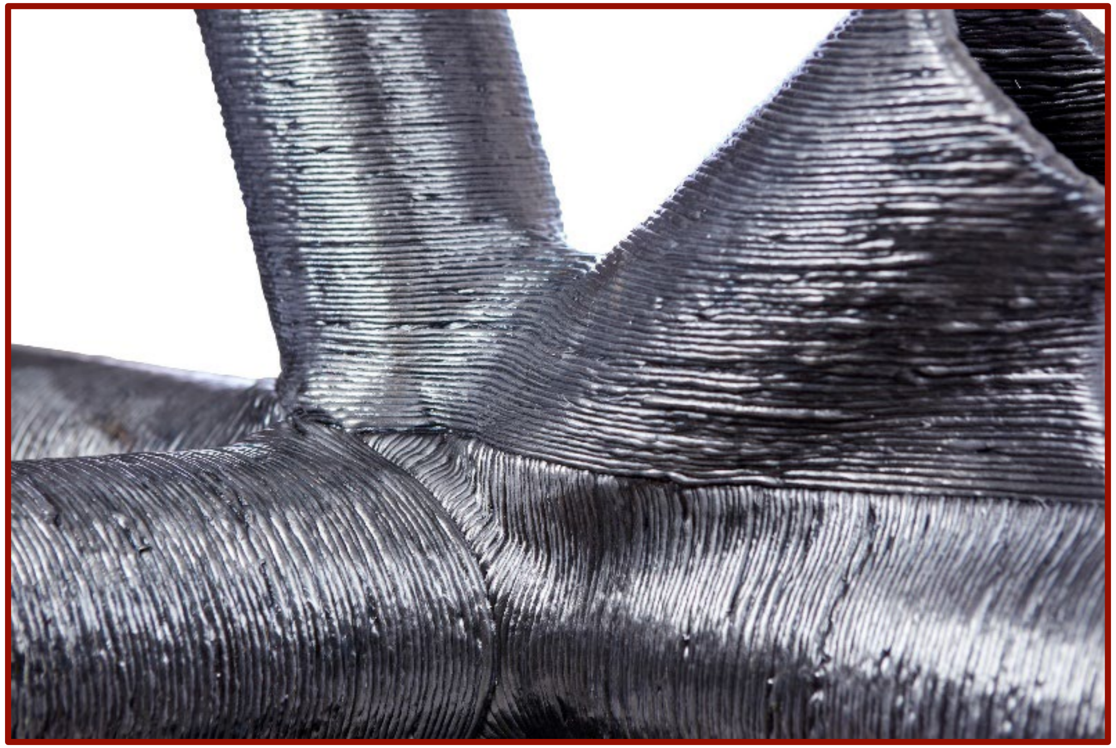
Results: UTS vs. Sample Orientation



Why Isotropy is Important

X-Y-Z Build Direction??



Corresponding Material Specification

- Results must meet the requirements of a *corresponding material specification*
- A corresponding material specification is often an ASTM specification for a different product form, for example:
  - A516 gr 70 plate
  - A182 F316L forging
  - A217 WC9 casting

Sets up an "equivalence" approach for use in design and construction standards

Requires validation that all production printing stayed within the qualification bounds

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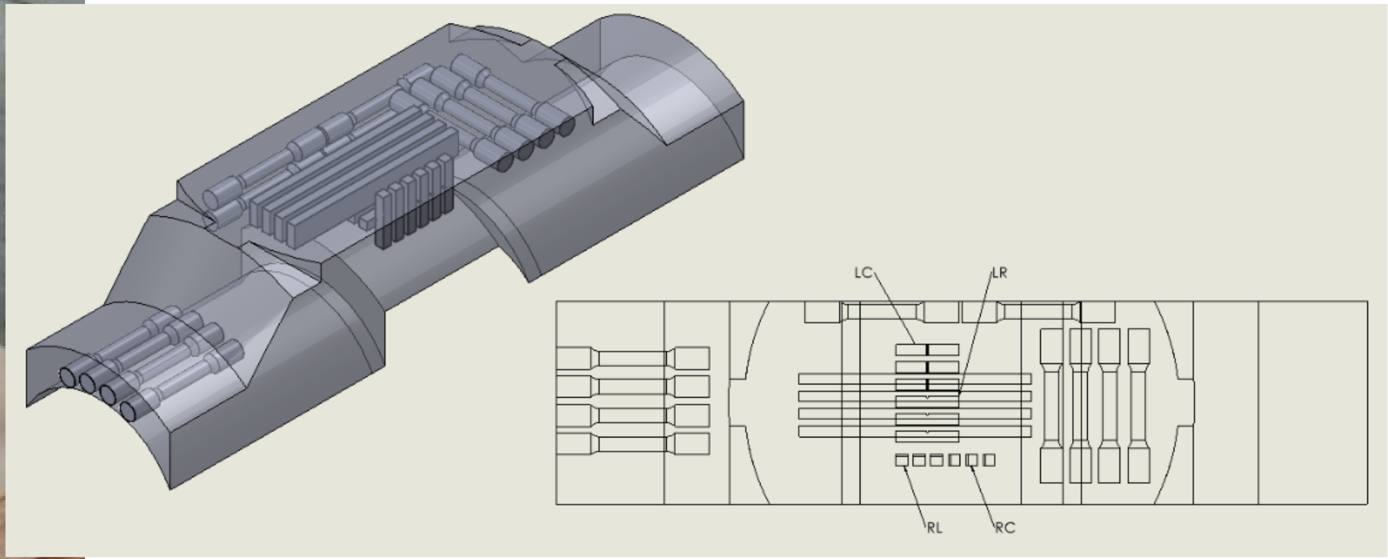
Does it work?

Replacement for 316L Valve Body

Project between Lincoln Electric & EPRI



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ER316LSi Qualification

GMAAM PQR Data Summary (welding in accordance with ASME BPVC-IX & Code Case 3020)

Electrode (feedstock) classification is ER316LSi (per AWS A5.9)

Cooling Rate	Welding Transfer Mode	PWHT	# Beads	Layer Width	Wall Thickness	Yield Strength	Ultimate Strength	Elongation	ROA	Side Bends	CVN Toughness	Note
(type)	*(type)*		*(per Layer)*	*(in)*	*(type)*	*(ksi)*	*(ksi)*	*(%)*	*(%)*	*(Result)*	*(ft-lbs@-320F)*	
Slow *High Heat Input & High Interpass*	Spray	Solution Anneal (3 hrs @ 2050F)	1	0.6	Thin	30.6	70.0	68.0	74	Pass	85	
						30.3	68.0	72.0	67		79	
											92	
			9	3.1	Thick	31.9	79.0	72.0	55	Pass	79	
						32.6	79.0	57.0	42		79	
						31.6	79.0	74.0	66		115	
						33.2	79.5	72.0	54		83	
						31.5	78.0	70.0	62		84	
						30.8	78.0	72.0	62		83	
Fast *Low Heat Input & Low Interpass*	Spray	Solution Anneal (3 hrs @ 2050F)	1	< 0.3	Thin	32.8	71.5	44.0	64	Pass	12	1/4-Size CVNs
						32.5	71.0	47.0	67		14	
											11	
			21	2.1	Thick	31.4	72.0	30.0	32	Pass	63	
						31.6	80.5	56.0	33		71	
						32.0	77.0	38.0	44		78	
						31.6	80.5	61.0	44		78	
											69	
											68	

	Yield Strength	Ultimate Strength	Elongation	ROA
Min	30.3	68.0	30.0	32
Max	33.2	80.5	74.0	74
Average	31.7	75.9	59.5	55

Replacement for 316L Valve Body

ASME IX Qualification

	Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation (%)
Min	30.3	68.0	30.0
Max	33.2	80.5	74.0
Average	31.7	75.9	59.5

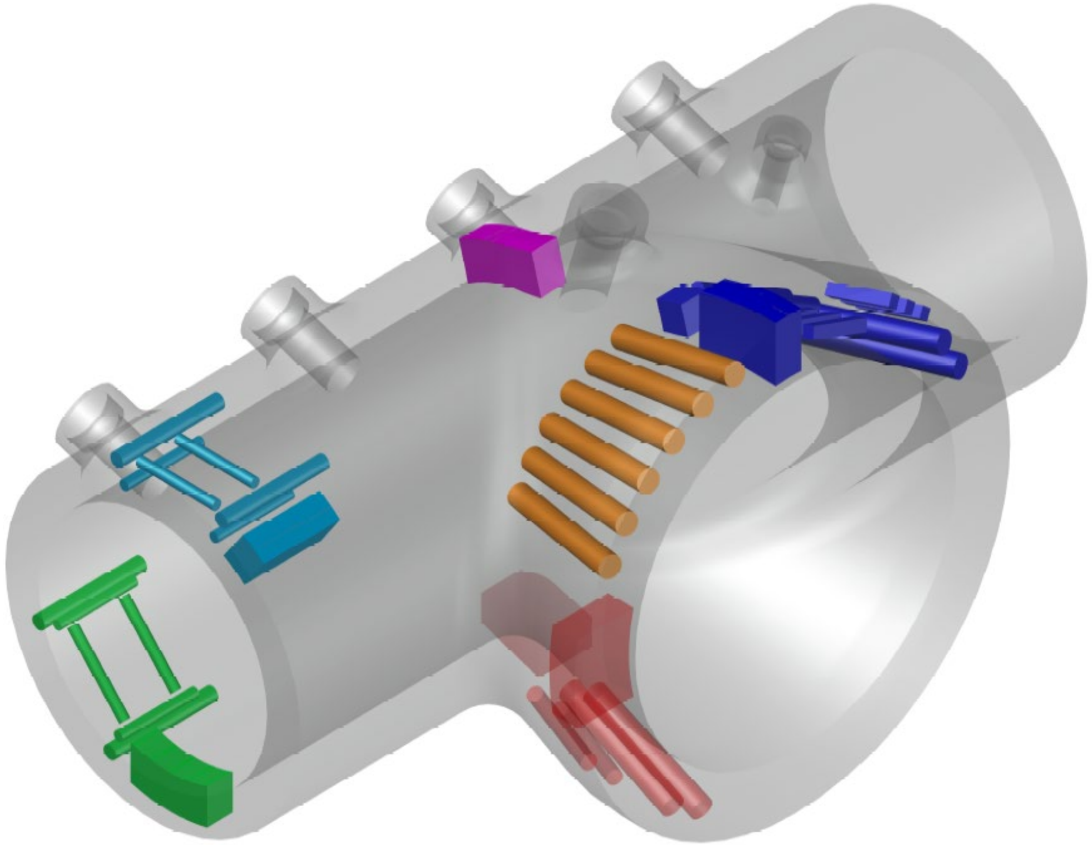
316LSi Printed Valve Body

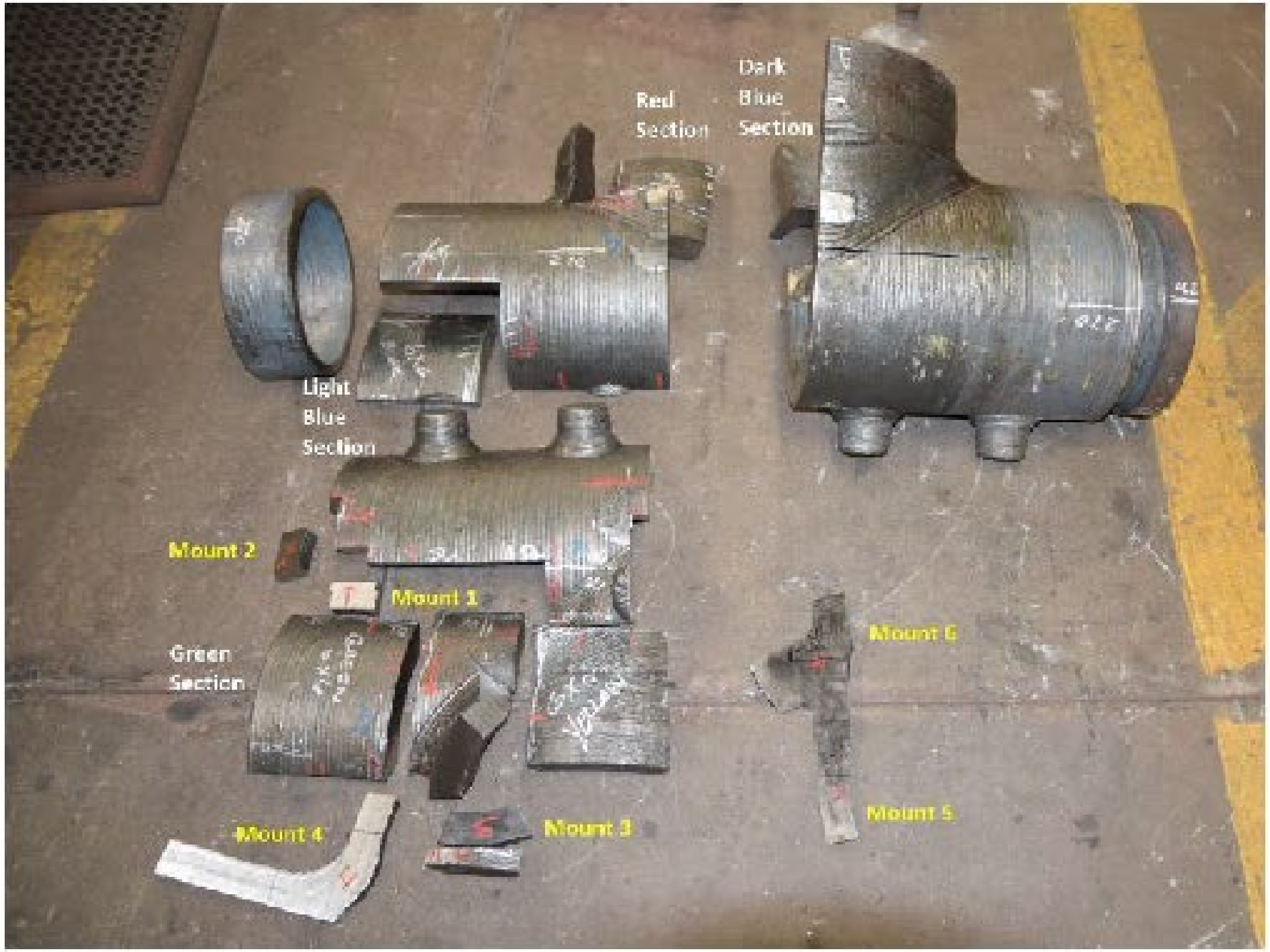
Table 5-8. Tensile Data at Room Temperature for K91W

Orientation	Sample ID	Temp. (°F)	Temp. (°C)	UTS (ksi)	UTS (MPa)	YS (ksi)	YS (MPa)	Elong. in 4D (%)
Build Direction, Thin Section	T16	70	21.1	80.2	553.0	31.3	215.8	67.8
	T17	70	21.1	80.2	553.0	32.3	222.7	66.8
	T18	70	21.1	80.2	553.0	31.6	217.9	67.6
	T19	70	21.1	80.1	552.3	32.1	221.3	68.1
Build Direction, Thick Section	T20	70	21.1	81	558.5	33	227.5	67.9
	T21	70	21.1	81.4	561.2	33	227.5	70
	T22	70	21.1	81.3	560.5	32.6	224.8	66.2
	T23	70	21.1	82.2	566.7	32.4	223.4	66.6
Transverse Direction	T24	70	21.1	82.2	566.7	35	241.3	60.8
	T25	70	21.1	34.9	240.6	28	193.1	7
	T26	70	21.1	78.4	540.5	32.8	226.1	38
	T27	70	21.1	82.2	566.7	33.4	230.3	63.4
Transverse, Retest	T28	70	21.1	80.2	553.0	32.9	226.8	58.4
	T29	70	21.1	80.3	553.6	32.9	226.8	56.4

Replacement for 800HT Furnace Header

First Article Testing





Red Section
Dark Blue Section
Light Blue Section
Mount 2
Mount 1
Green Section
Mount 6
Mount 4
Mount 3
Mount 5

ERNiCrCoMo-1 Qualification (Alloy 617)

GMAAM PQR Data Summary (welding in accordance with ASME BPVC-IX & Code Case 3020)

Electrode (feedstock) classification is ERNiCrCoMo-1 (per AWS A5.14)

Cooling Rate	Welding Transfer Mode	PWHT	# Beads	Layer Width	Wall Thickness	Yield Strength	Ultimate Strength	Elongation	ROA	Side Bends	CVN Toughness		Note
(type)	*(type)*		*(per Layer)*	*(in)*	*(type)*	*(ksi)*	*(ksi)*	*(%)*	*(%)*	*(Result)*	*(ft-lbs@-50F)*	*(ft-lbs@70F)*	
Slow *High Heat Input & High Interpass*	Spray	None	1	0.8	Thin	49.9	99.0	47.0	48	Pass	87		
						51.0	100.0	47.0	49		98		
											108		
			9	3.9	Thick	59.0	103.0	46.0	50	Pass		76	
						60.5	102.0	47.0	50			63	
						58.0	103.0	46.5	44			73	
						58.0	102.0	45.5	48			99	
						61.5	104.0	47.5	53			96	
						58.0	103.0	47.5	40			94	
Fast *Low Heat Input & Low Interpass*	Spray	None	1	< 0.3	Thin	57.0	96.5	50.0	55	Pass	17	17	1/4-Size CVNs
						56.0	96.5	54.0	64		20	17	
											15	22	
			9	2.2	Thick	63.5	107.0	56.0	42	Pass	94		
						63.5	98.0	33.0	35		97		
											124		
											122		
											120		
											126		

	Yield Strength	Ultimate Strength	Elongation	ROA
Min	49.9	96.5	33.0	35
Max	63.5	107.0	56.0	64
Average	58.0	101.2	47.3	48

Printed Replacement for 800HT

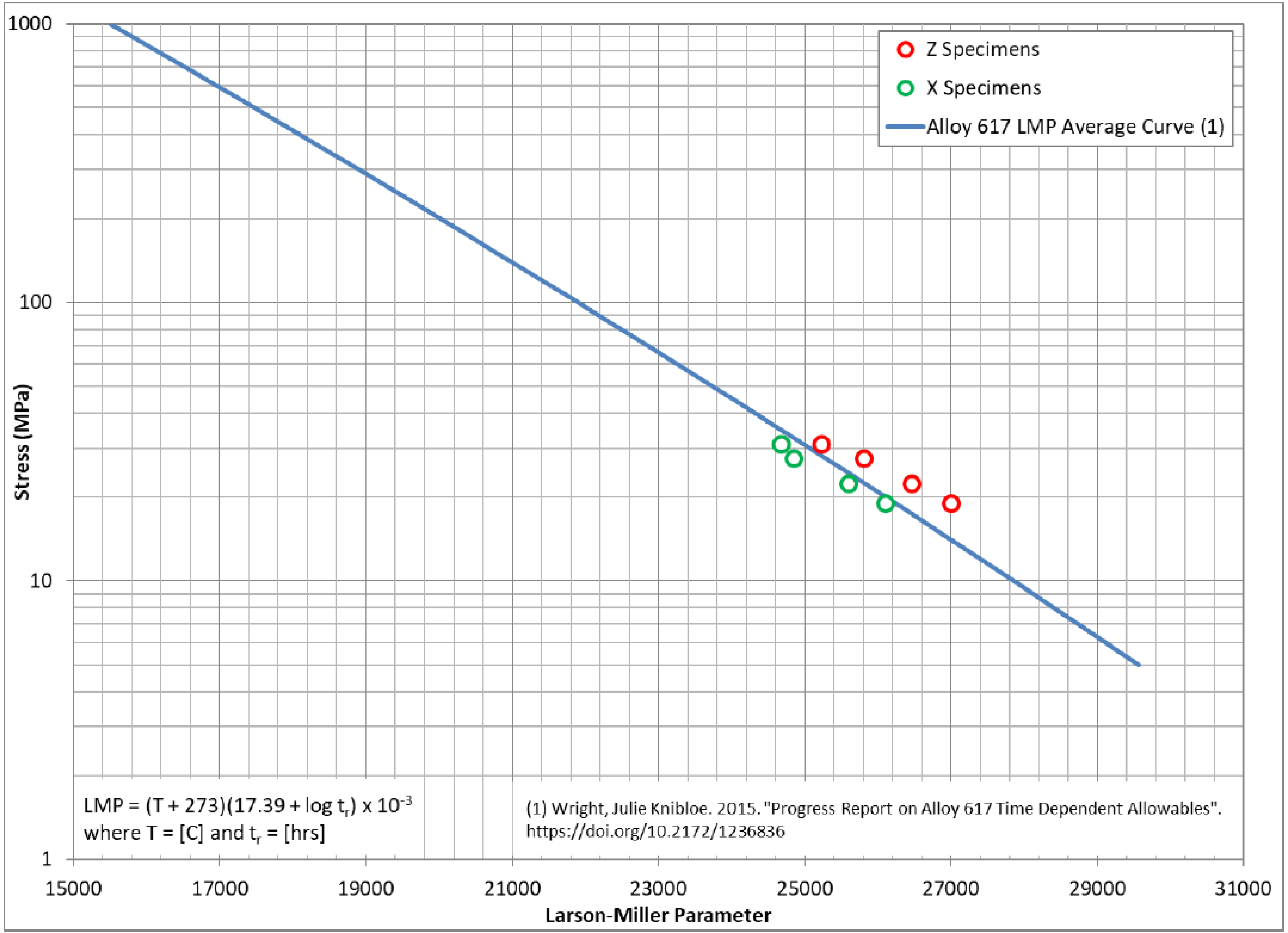
ASME IX Qualification

	Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation (%)
Min	49.9	96.5	33.0
Max	63.5	107.0	56.0
Average	58.0	101.2	47.3

First Article Testing

Orientation	Location	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)
Longitudinal	ID	57.6	102.5	44.8
		55.4	99.9	40.1
Longitudinal	OD	65.5	108.7	40.4
		66.4	108.7	40.5
Transverse	Mid-wall	60.9	106.1	45.5
		59.0	102.7	34.9
Transverse	Mid-wall	63.0	107.0	39.9
		61.6	107.9	37.4
Longitudinal	ID	58.0	101.8	43.1
		58.3	102.2	44.9
	OD	64.3	109.4	42.1
		66.7	108.6	42.5
Longitudinal	Mid-wall	60.9	101.8	47.0
		60.4	102.4	48.6
Transverse		61.0	104.2	44.4
		61.5	104.7	43.7
Longitudinal	Mid-wall	60.6	101.1	46.5
		60.5	101.1	46.8
Transverse		61.4	103.5	40.3
		62.5	105.4	40.5

Creep Testing – Chevron 617 Parts



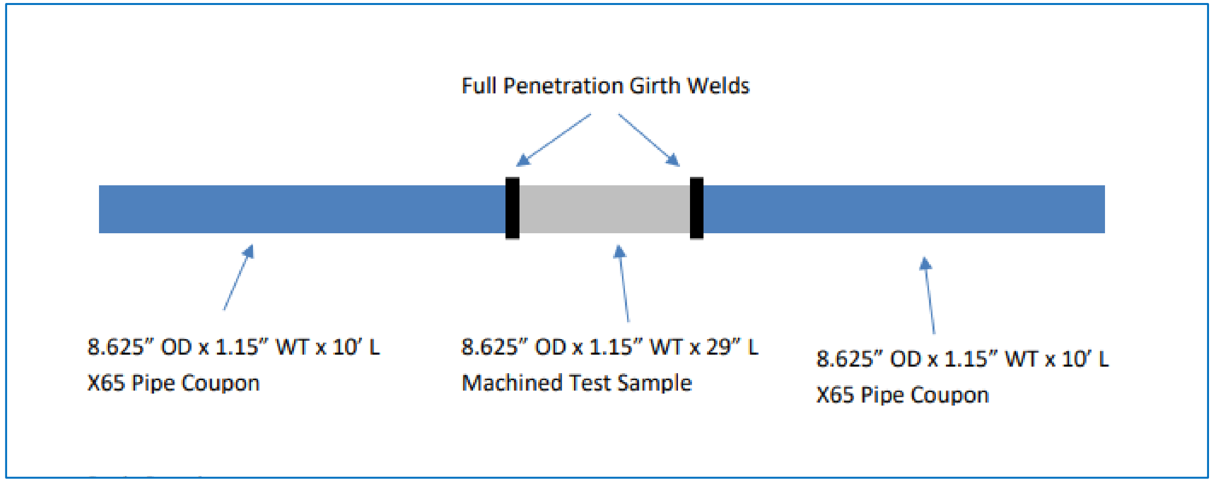
Additive Solutions

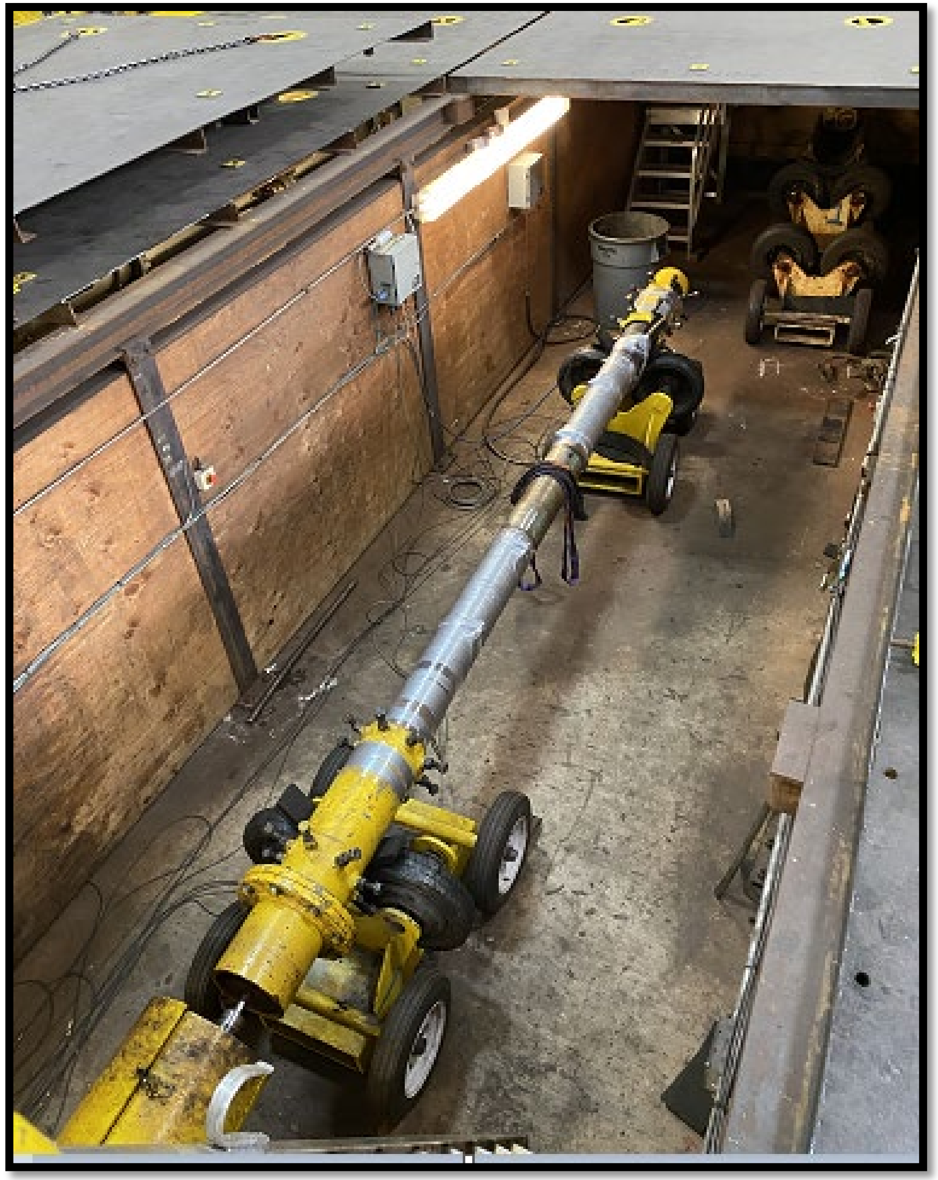
Application-based Fatigue Studies

- Georgia Tech - Ryan Sherman (USDOT FHWA)
- Printed blocks for material characterization
- Fatigue specimens printed
  - Testing as-printed and fully machined

Other Recent Fatigue Work

- U Mich – Pingsha Dong (USDOE)
- Stress Engineering – Offshore
- U of Toledo (VHCF / Eaton)
- Private industry





Is it new in pressure retaining applications?

- 1967 – Mitsubishi patented a method for construction of cylindrical and spherical pressure vessels entirely out of weld metal.
- 1976 - 64-ton pressure vessel 216 inches long, 71 inches in diameter and 8 inches thick manufactured from weld metal
- 1978 – 20 ton steel ring fabricated entirely from weld metal.
- 1980s – Shape welding in Germany
- 1980s – multiple companies produced large parts and buildups for repair of steam turbines
- 1980s – offshore oil and gas used weld metal "buildup" to increase the pressure ratings from 15,000 psi to 20,000 psi
- 1982 - 1993, approximately 450 steam turbine and 235 utility rotors were rebuilt using weld metal..Hartford has not reported a single failure of a rotor attributable to weld repair since the beginning of the program.

- For details see https://sperkoengineering.com/html/Additive.pdf

Is it new in nuclear applications?

- 1960 - Russians produce valve bodies using only weld metal. Used in nuclear facilities in USSR.
- 1998 -- German Nuclear Safety Standards Commission (KTA) allows use of products and components manufactured using "shape welding".
- Shape welding used by Siemens for nozzle openings and flange surfaces
- 1970s – CB&I BWR weld metal buildup on bottom head of each reactor to avoid purchase of a forged ring with an integrally forged skirt extension.
- Westinghouse anti-rotation key lugs are produced today from weld metal, eliminating material availability issues, allowing more precision in location and are more easily they ultrasonically examined compared to the prior plates attached with groove welds.
- Inconel weld metal is used to replace bar attaching partition plate in steam generator, which simplifies fabrication and improve Ultrasonic inspection due to grain orientation in the Inconel bar stock.
- Handholds, inspection ports, flange surfaces, nozzle projections and manways produced from weld metal for pressurizers, steam generators and heater bundles
- B&W produced at least one large Inconel elbow entirely from weld metal because of the long lead times for forged high alloy elbows and safe ends. Also produced cylinders, cones, flanges elbows and dished heads by "shape melting" but unsure where or if they were put into service.

- For details see https://sperkoengineering.com/html/Additive.pdf

“Weld Metal Buildup” Code Cases

Accepted by the NRC in Regulatory Guide 1.147 with no added restrictions

- N-853 PWR Class 1 Primary Piping Alloy 600 Full Penetration Branch Connection Weld Metal
- Buildup for Material Susceptible to Primary Water Stress Corrosion Cracking
- N-740, Full Structural Dissimilar Metal Weld Overlay for Repair or Mitigation of Class 1, 2, and 3 Items.
- N-653, Full Structural Overlaid Wrought Austenitic Piping Welds
- N-661, Wall Thickness Restoration of Class 2 and 3 Carbon Steel Piping for Raw Water Service
- N-766, Nickel Alloy Reactor Coolant Inlay and Overlay for Mitigation of PWR Full Penetration Circumferential Nickel Alloy Dissimilar Metal Welds in Class 1 Items.

» For details see https://sperkoengineering.com/html/Additive.pdf

Questions / Discussion

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