Additive Manufacturing Overview

Research Focus Area: 8
Advanced Materials and Manufacturing

Stephen Tate
EPRI Welding and Repair Technology Center

NSRP Joint Welding Technology and Electrical Technologies Panel Meeting
September 17, 2024

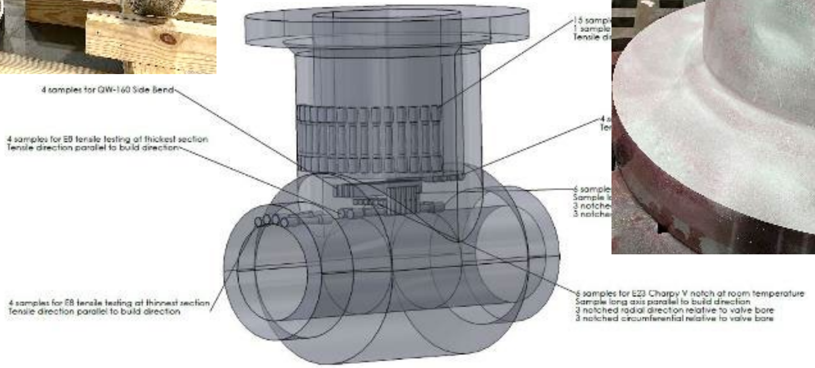
Directed Energy Deposition Development: 316L (RFA 8)

Project Objective & Scope

- Project Objective
  - Reduce barriers to implementation of advanced manufacturing, specifically ASME
- Project Scope & Approach
  - Mechanical testing and microstructure evaluation to generate data supporting ASME Code implementation of 316L

Deliverable and Collaboration

- Technical Report
- Potential tech transfer with utility installations
- Support / Collaboration
  - Lincoln Electric, Flowserve
  - BEES (Korea)



Schedule & Upcoming Work

- Project Schedule
  - Experimental work complete
  - EPRI-ASM Conference Paper submitted
  - Continue supporting Code Cases drafts for wire arc DED

Crack Growth Rate & Fatigue Testing of DED 316L (RFA 8)

Project Objective & Scope

- Project Objective
  - Reduce barriers to implementation of advanced manufacturing, specifically regulatory
- Project Scope & Approach
  - Stress corrosion crack growth rate testing in BWR and PWR environments: base material, cold worked, and HAZ samples
  - Fatigue testing to look at ground versus machined surface

Deliverable and Collaboration

- Technical report, 2025
- Support / Collaboration
  - Collaboration with IMR, interest from AM3, ANT
  - Lucideon testing contractor

Schedule & Upcoming Work

- Project Schedule
  - Sample welding and machining complete May 2023
  - Autoclave testing in 2023 and 2024 (complete)
  - Fatigue testing in 2024 (complete)

Directed Energy Deposition Development: Alloy 690 (RFA 8)

Project Objective & Scope

- Project Objective
  - Reduce barriers to implementation of advanced manufacturing, specifically ASME
- Project Scope & Approach
  - Mechanical testing and microstructure evaluation to generate data for implementation of alloy 690 DED

Deliverable and Collaboration

- Technical Report, 2025
- ASME engagement
- Support / Collaboration
  - Collaboration with ANT, AM3
  - KHNP collaboration
  - BEES contractor for wire arc DED

KHNP

BEES
Best Engineering in Energy Solutions

Schedule & Upcoming Work

- Project Schedule
  - Initiated October 2022
  - Delay with filler wire sourcing
    - Switched from 52MSS-Ta to 52M and 52MSS
  - Interim report in progress

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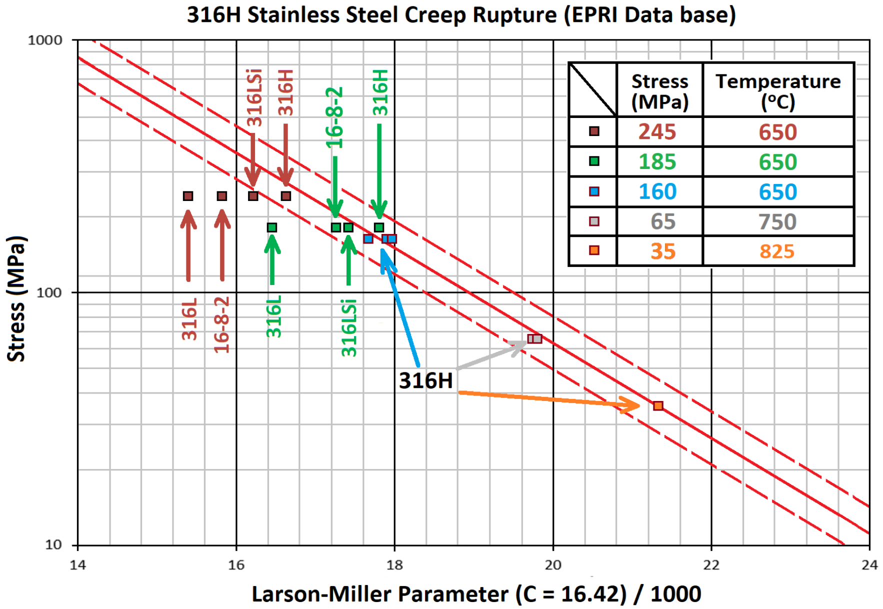
Directed Energy Deposition Development: High Temp Alloys (RFA 8)

Project Objective & Scope

- Project Objective
  - Initial understanding of DED of alloys to be used in high temperature reactors
- Project Scope & Approach
  - Start with wire based DED (GMAW), basic testing to evaluate high temperature properties
  - Understand what may be a good screening tool and compare to wrought



Deliverable and Collaboration

- ASME engagement, technical report
- Support / Collaboration
  - Collaboration with AM3, ANT, P229
  - Collaborative project with Navy Nuclear Laboratory at Colorado School of Mines

Schedule & Upcoming Work

- Project Schedule
  - Creep testing of 316H, 316L, 316LSi, 16-8-2 completed
  - Characterization of tested samples mostly complete
  - PVP 2024 paper submitted
  - Work supported larger EPRI-ASM paper as well

Direct Energy Deposition 316L Project

Introduction: Current Applications of Additive in Commercial Nuclear Power

- Secondary systems
  - Fire service pump impeller at Krsko
  - Valve at TVO
- Fuel/Internals
  - Channel fastener at TVA Browns Ferry
  - Thimble plugging device at Constellation Byron
  - Unknown parts at KKG Switzerland
  - Tie plate at Forsmark

- All laser powder bed fusion (LPBF)
- EPRI current focus is GMA-DED for pressure boundary parts

https://www.tvo.fi/en/index/news/pressreleasesstockexchangereleases/2021/valveproducedusing3dprintingtechnologytestedinolkiluoto.html

https://world-nuclear-news.org/Articles/Westinghouse-3D-printed-component-installed-in-ind

Introduction

Why Gas Metal Arc-DED

316L valve, 220 pounds (100 kg)

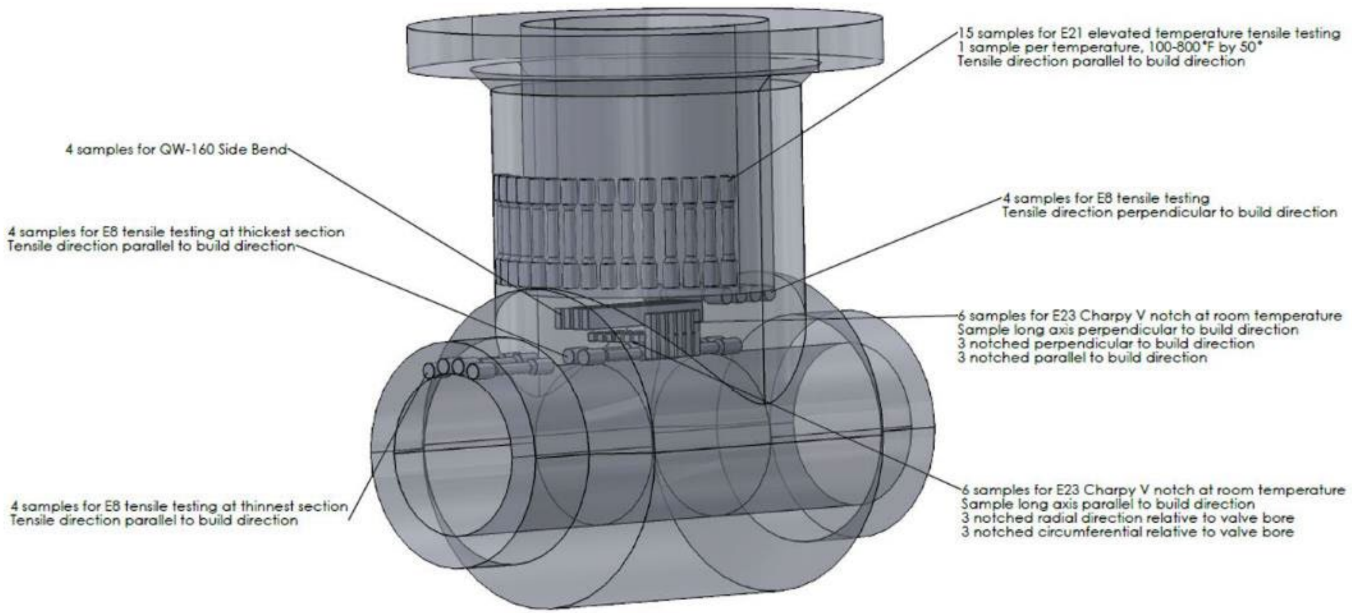
316LSi valve body, 1600 pounds (700 kg)

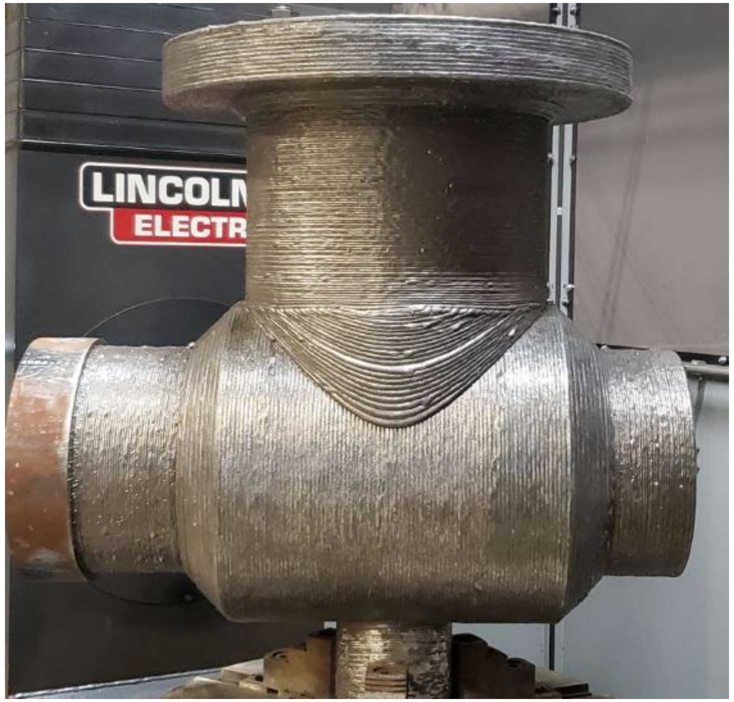
Primary driver is lead time

Potential limitations: need to consider material, machining, and NDE

GMA-DED 316LSi Valve Bodies Overview

- 316LSi GMA-DED material produced by Lincoln Electric Additive Solutions
  - Typical process parameters: 25 in/min. (10.6 mm/s) travel speed, 400 in/min (169 mm/s) wire feed speed
  - Solution anneal at 1120 C for 3 hours





ASME Code Progress

- Process Qualification: Article VI in 2023 edition of ASME Section IX
  - Rules for bracketed qualification of GMA-DED
- Part Qualification: ASME Special Committee GMA-DED **Draft** Code Case
  - Section II in agreement to not need Appendix V data package for every material
- Outside of ASME, we have data to support discussions with Code/Regulatory bodies

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Code Case XXXX
Additive Manufacturing Construction of Pressure Equipment using the Direct Energy Deposition Process with Wire Feedstock, Section I, Section III, Division 1 – Subsection NB/NC/ND Components, Section VIII, Division 1

Inquiry: May pressure equipment be manufactured using the additive manufacturing direct energy deposition process with wire feedstock?

Reply: It is the opinion of the Committee that pressure equipment may be manufactured using the additive manufacturing direct energy deposition process and wire feedstock provided the following requirements are met.

Section III goal to have wire arc DED in 2025

Where to go for NDE Requirements?

- Section III Draft Code Case:
  - “Materials in Section II, Part D, Subpart 1, Tables 1A, 1B, 2A and 2B may be selected as a corresponding material, as applicable to the Section III class of the item being constructed. The material produced by wire-DED shall be subject to examination based on that of the corresponding material.”
- Section III Div 1. NB-2500 requires volumetric and surface exam
  - Forging gets UT
  - Casting gets RT, except ferritic materials can opt for UT
  - MT or PT for surface exam
  - Acceptance criteria scale with part thickness

- PT, UT and RT completed on 2 valve body builds

Penetrant Testing

- Surfaces prepped by machining or hand grinding
- Examinations produced indications consistent with small voids similar to ones observed in polished samples

Grind then Penetrant Testing

- Up to 4 cycles of grind and repeat PT to get clean surfaces
- All of saddle cleaned up with significant material removal

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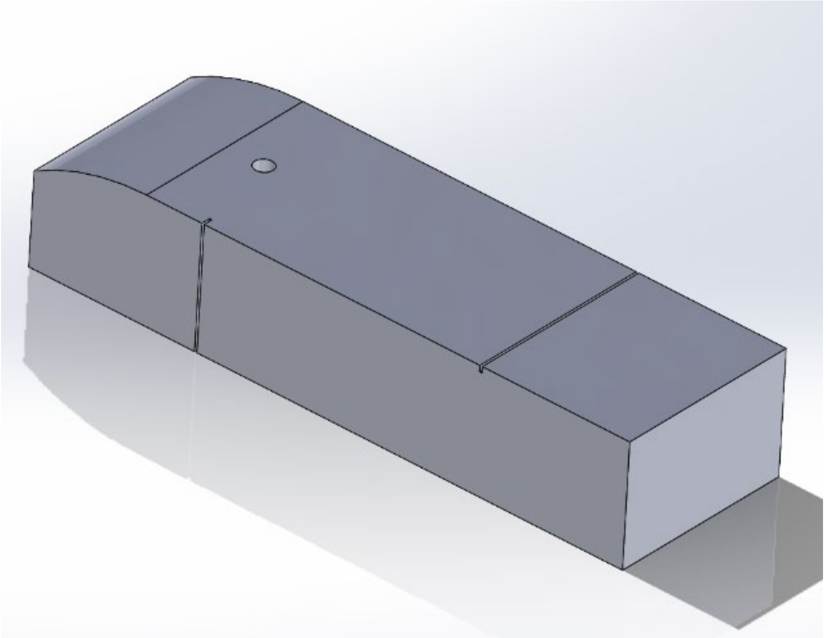
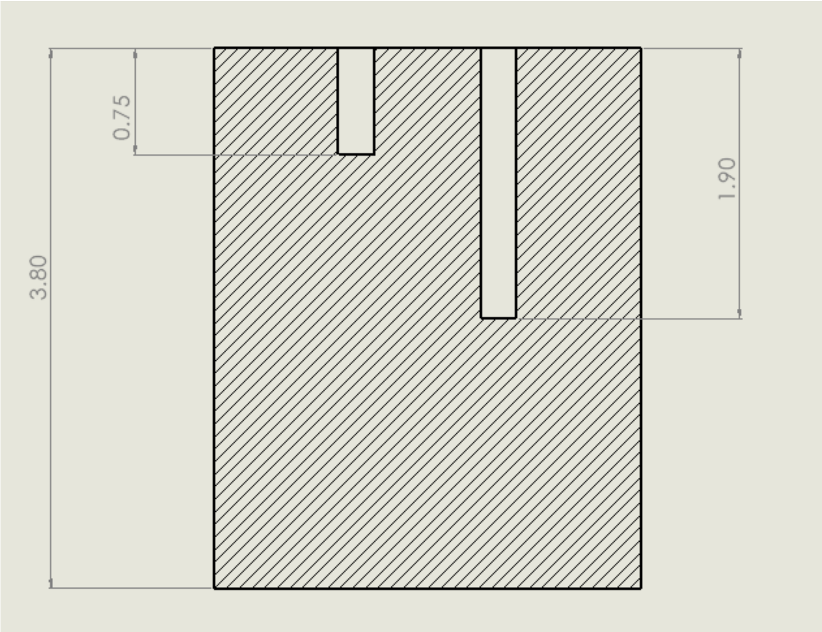
Ultrasonic Testing Reference Blocks

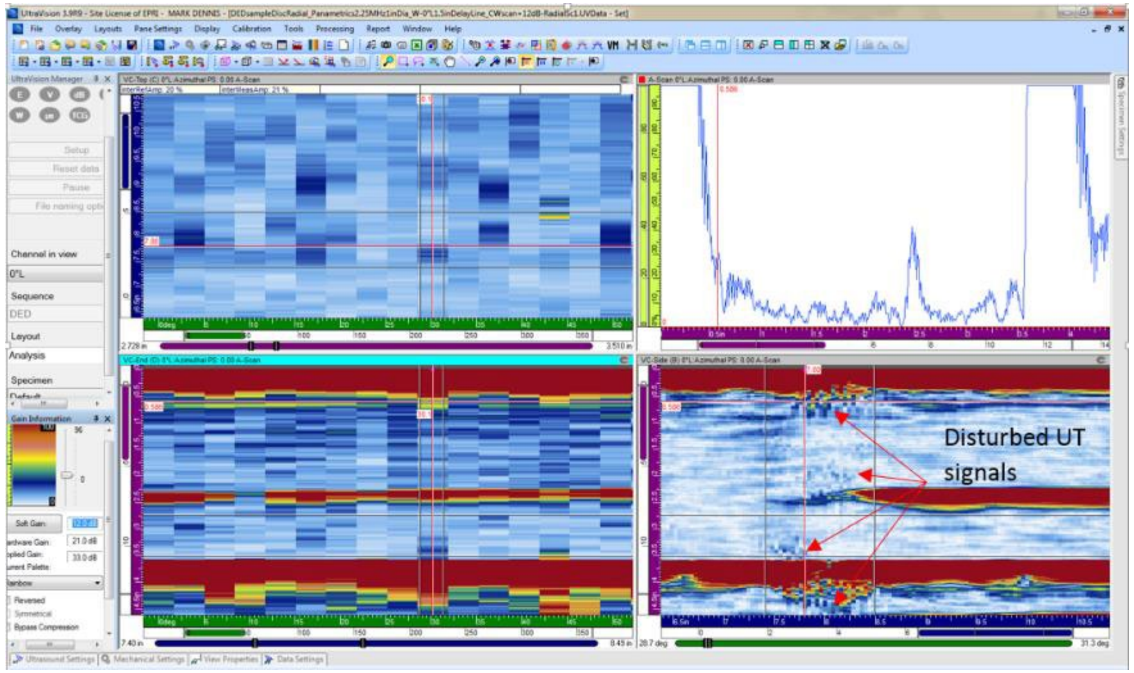
- Reference block 1, 8x2.5x1.5 inches
  - 0.25 inch flat bottom holes at approximately 0.75 and 1.5 inch in depth to assist in the evaluation of the lack of bond indications
  - Two 5% notches were added for angle beam references as well
- Reference block 2 at increased thickness with 0.25 inch flat bottom holes
- Reference blocks made of K91W 316LSi GMA-DED material, but grain orientations were not always consistent with the direction of scanning





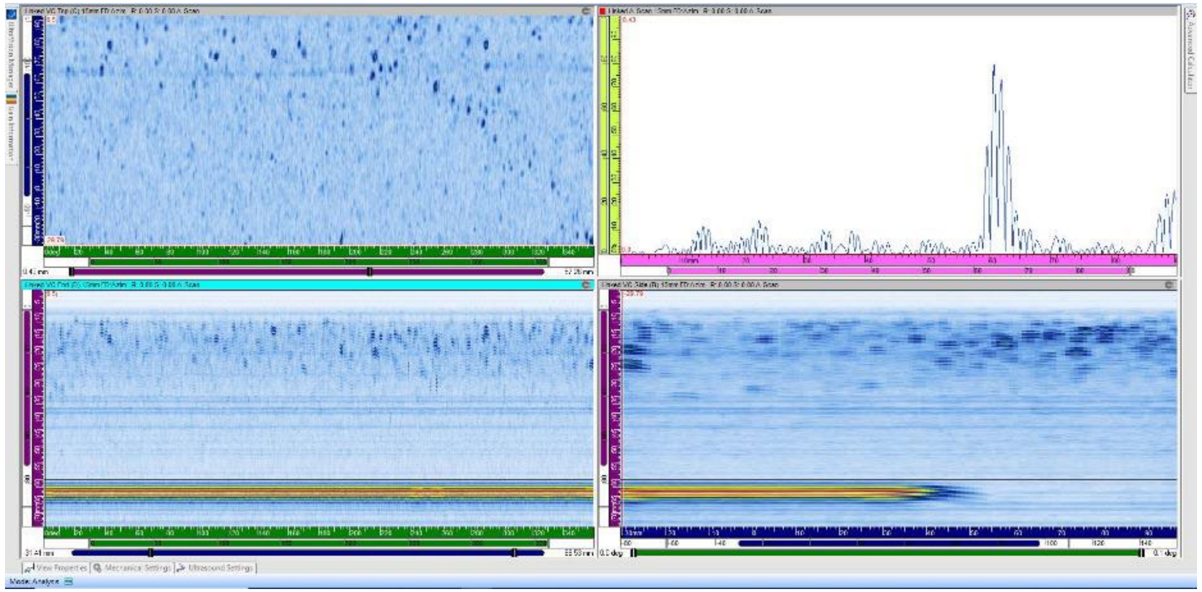
SA-745 Ultrasonic Testing (J01P Body)

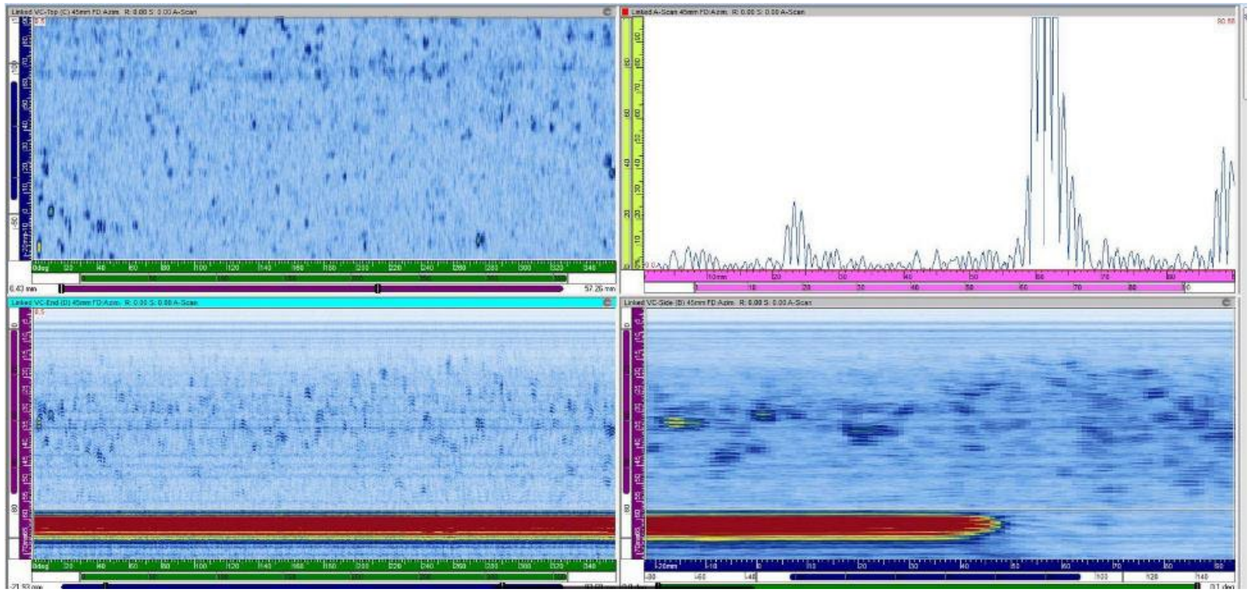
- No reportable indications according to the criteria for SA-745
  - Reportable threshold of 50% of reference acceptance curve
- The indications observed were all attributable to the wavy surface conditions, caused by grinding on the surface, or due to the as welded conditions of the inside surface
- Use of pulse-echo 0° transducers creates a 0.5 inch dead zone that you could reduce with dual element pitch catch style probes.
- Suggest using longitudinal waves to inspect it, possibly a cast procedure may be more appropriate



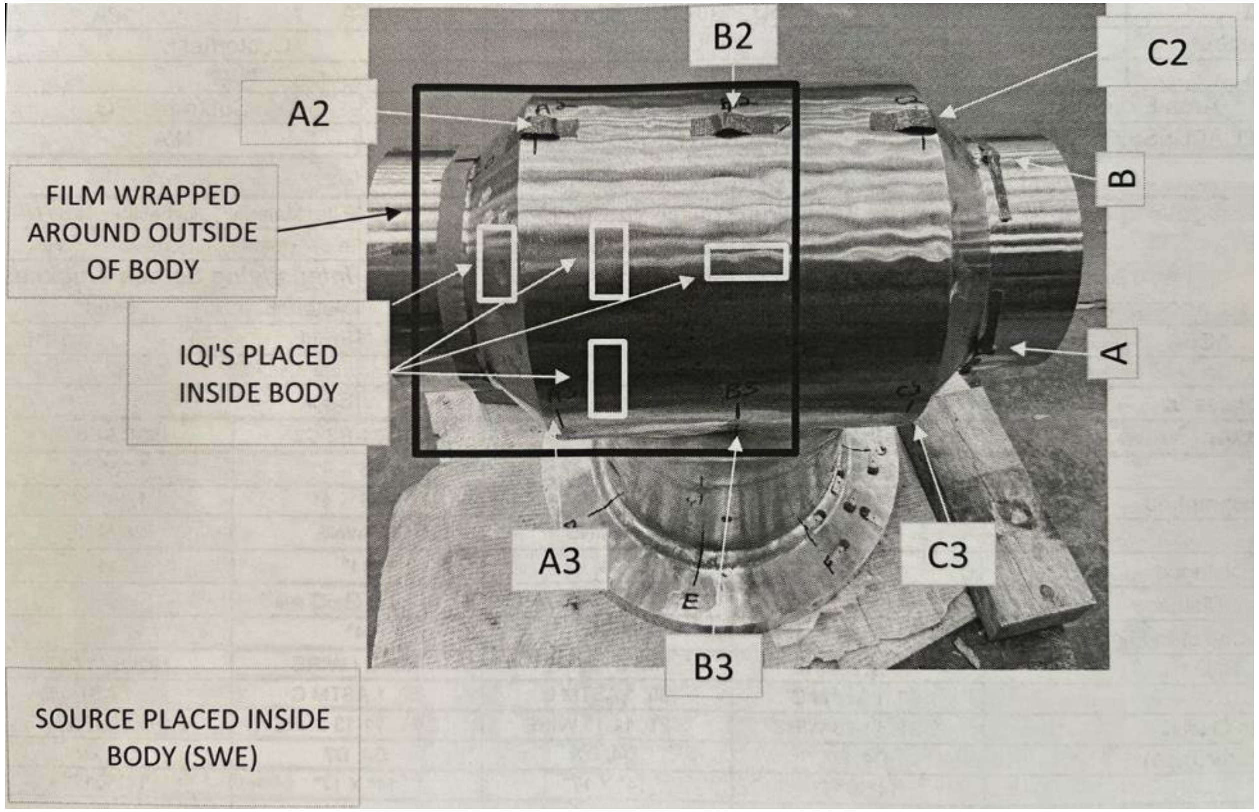
Enhanced Technique Ultrasonic Testing (N97F Body)

- Exams were conducted with different frequency (1.5, 2, and 4MHz) dual-element probes
- Conventional and phased array probes were evaluated
- Straight beam (zero degree) and angle beam techniques were employed
- Material was highly attenuative and lower frequencies appeared to achieve better results
- Many small indications were observed in the initial data, some areas cleaner than others
- Sizing was approximate, but believe there were no rejectable indications to SA-745 criteria



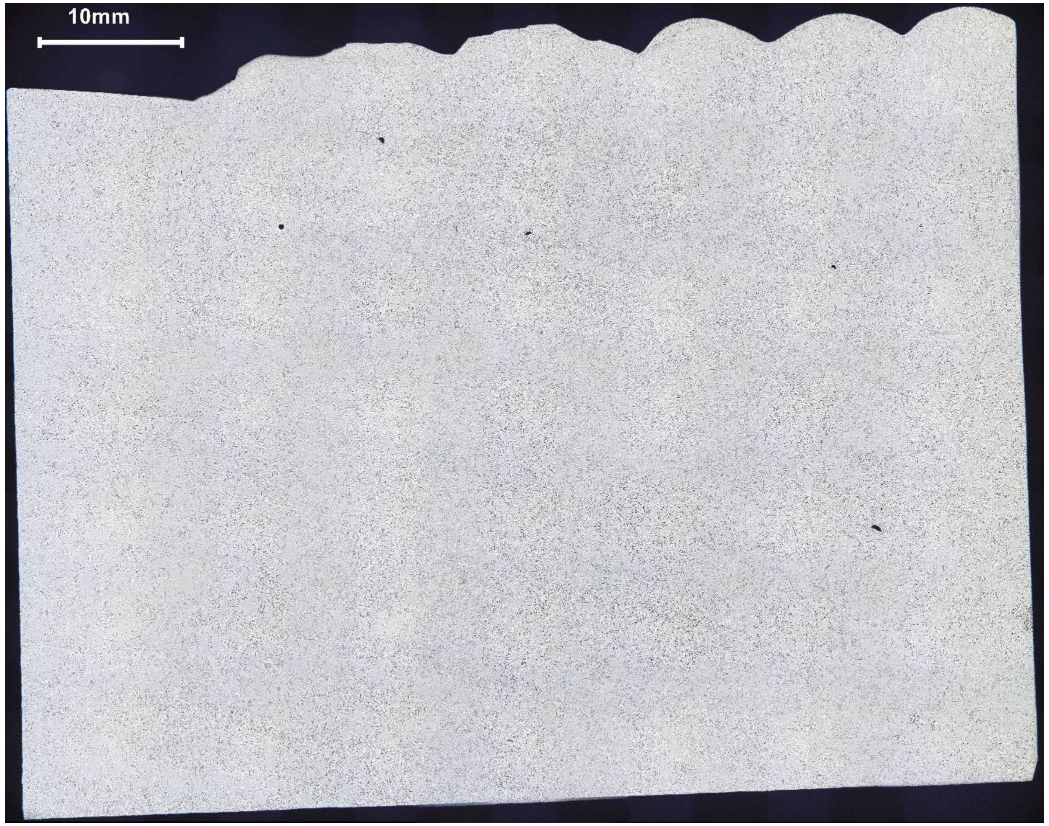


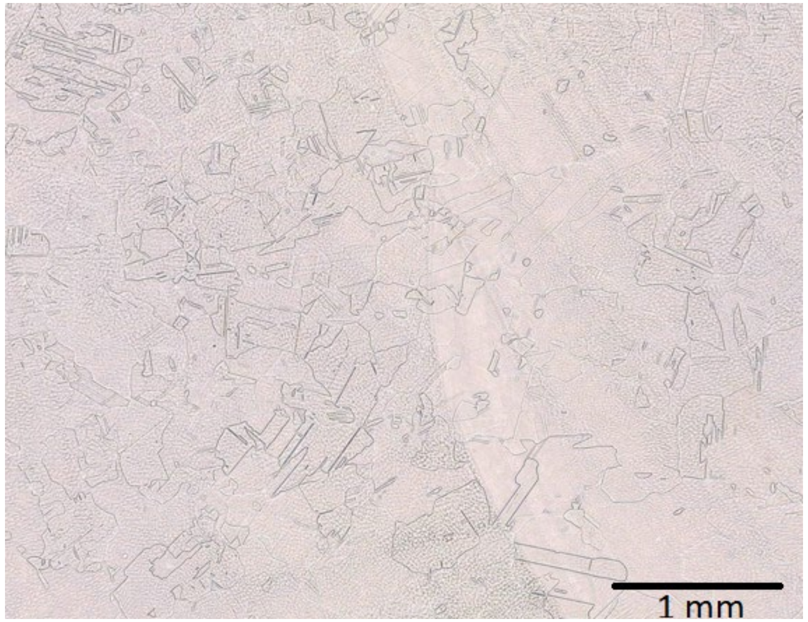
Radiographic Testing



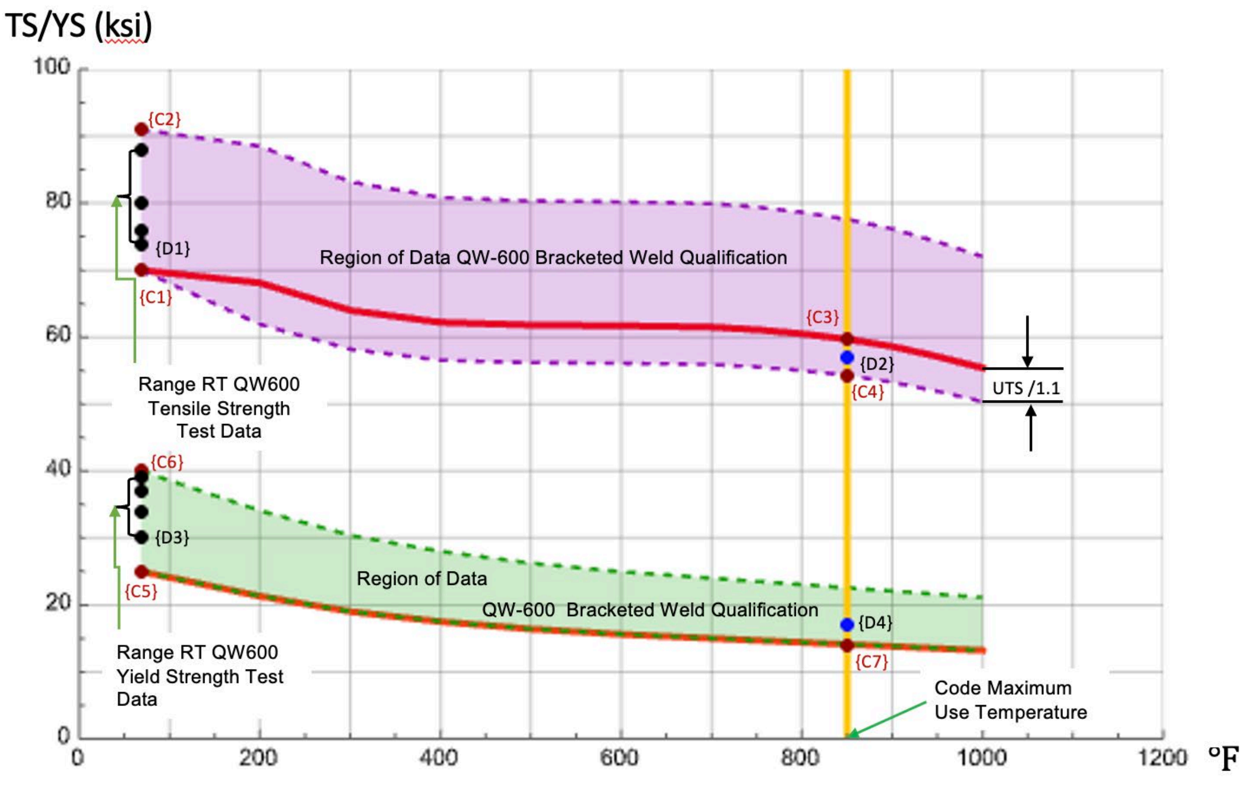
- Thanks to Flowserve
- 64 shots in a variety of setups for J01P body
- 55 scattered rounded indications of 0.031 to 0.125 inch
- 1 elongated indication of 0.125 inch
- Agrees with enhanced UT technique results

Microstructure

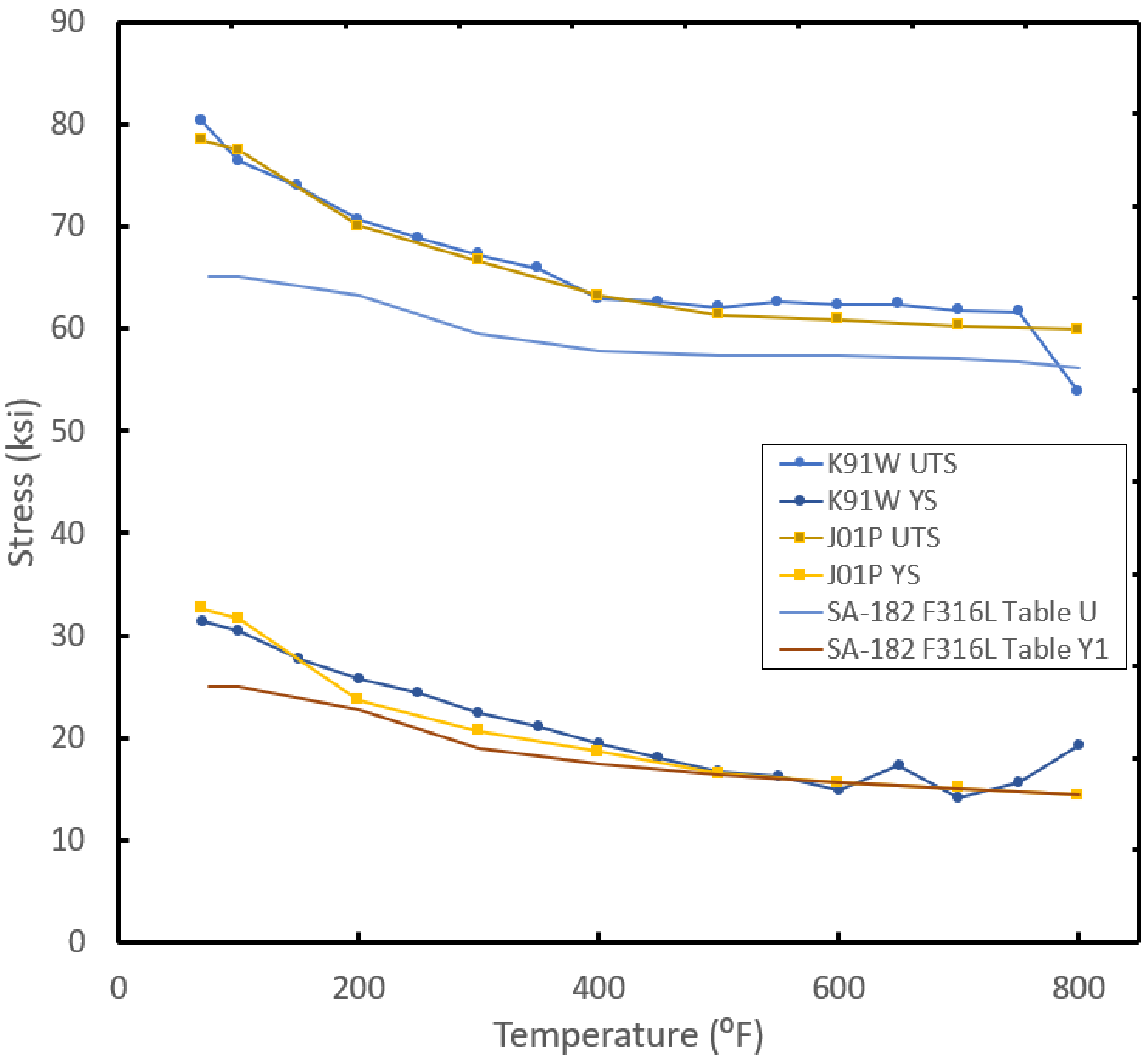




Mechanical Results - Tensile



Draft Code Case for GMA-DED
(Record Number 22-1598)



Opportunity to improve yield strength by tailoring solution anneal

Conclusions and Outlook

- Challenge for inspection is surface finish and machining
- Builds examined met Section III Class 1 forging acceptance criteria
- Acceptable mechanical properties in solution annealed GMA-DED 316LSi
- Processing-Microstructure-Property relationships behave similar to other 316L materials

R. Rettew et al. "API and ASME Qualification of a Printed Pressure Component." ICAM 2022

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NB-2500 NDE Methods and Acceptance Criteria

- PT
  - Section III Div. 1 NB-2546 sends to Section V, Article 6 for method
  - 3/16 inch (5 mm) limit for linear or rounded indications
- UT
  - Section III Div. 1 NB-2542 sends to Section V, Article 5 which sends to SA-745
  - 1/4 inch (6 mm) flat bottom hole calibration block produced, based on Quality level 2

(b) Imperfections producing the following relevant indications are unacceptable:

(1) any linear indications greater than $^1/_{16}$ in. (1.5 mm) long for material less than $^5/_8$ in. (16 mm) thick, greater than $^1/_8$ in. (3 mm) long for material from $^5/_8$ in. (16 mm) thick to under 2 in. (50 mm) thick, and $^3/_{16}$ in. (5 mm) long for material 2 in. (50 mm) thick and greater;

(2) rounded indications with dimensions greater than $^1/_8$ in. (3 mm) for thicknesses less than $^5/_8$ in. (16 mm) and greater than $^3/_{16}$ in. (5 mm) for thicknesses $^5/_8$ in. (16 mm) and greater;

(3) four or more relevant indications in a line separated by $^1/_{16}$ in. (1.5 mm) or less edge to edge;

(4) ten or more relevant indications in any 6 in.^{2} (4 000 mm^2) of area whose major dimension is no more than 6 in. (150 mm) with the dimensions taken in the most unfavorable location relative to the indications being evaluated.

12.1.1 *Straight Beam:*

12.1.1.1 Material producing an indication response whose maximized amplitude equals or exceeds 100 % of the primary reference or distance-amplitude correction curve at the estimated discontinuity depth shall be considered unacceptable.

(a) QL-1—A distance-amplitude curve shall be based upon the amplitude response from No. 8 flat-bottom hole (8⁄64 in. [3 mm]). — >3 inch

(b) QL-2—A distance-amplitude curve shall be based upon the amplitude response from No. 16 flat-bottom hole 16⁄64 in. [6 mm]). — 3-8 inch

(c) QL-3—A distance-amplitude curve shall be based upon the amplitude response from No. 24 flat-bottom hole 24⁄64 in. [10 mm]). — 8-12 inch

NB-2500 NDE Methods and Acceptance Criteria

- RT
  - Section III Div. 1 NB-2500 for castings sends to ASTM E446, E186 or E280
    - Severity level 2, 0.2 fraction of indication length to feature length
  - Section III Div. 1 NB-5000 weld acceptance criteria
    - Rounded indications of 0.156 inch random, 0.250 inch isolated

NB-5320 RADIOGRAPHIC ACCEPTANCE STANDARDS

Indications shown on the radiographs of welds and characterized as imperfections are unacceptable under the following conditions:

(a) any indication characterized as a crack or zone of incomplete fusion or penetration;

(b) any other elongated indication that has a length greater than:

(1) $\frac{1}{4}$ in. (6 mm) for *t* up to $\frac{3}{4}$ in. (19 mm), inclusive

(2) $\frac{1}{3}t$ for *t* from $\frac{3}{4}$ in. (19 mm) to $2\frac{1}{4}$ in. (57 mm), inclusive

(3) $\frac{3}{4}$ in. (19 mm) for *t* over $2\frac{1}{4}$ in. (57 mm)

where *t* is the thickness of the thinner portion of the weld;

(c) internal root weld conditions are acceptable when the density change or image brightness difference as indicated in the radiograph is not abrupt; elongated indications on the radiograph at either edge of such conditions shall be unacceptable, as provided in (b) above;

(d) any group of aligned indications (excluding non-relevant indications) having an aggregate length greater than *t* in a length of 12*t*, unless the minimum distance between successive indications exceeds 6*L*, in which case the aggregate length is unlimited, *L* being the length of the largest indication;

(e) rounded indications in excess of that shown as acceptable in Section III Appendices, Mandatory Appendix VI.

ASME Code Progress

Item No.	ASME or NBIC Description/Action Title	Status *(PM / Lead)*
22-1598 **24-181**	**BPTCS**, Primary 'Base' Code Case for Direct Energy Deposition (DED) Additive Manufacturing using wire feedstock (Time-Independent)	**Both SC Approved** *Rawls (EPRI Contractor)*
23-721	**ASME LLC**, **Research Project 0198**, Extension of Arc DED into time-dependent regime for ASME BPVC, Weld Metal Data – Gathering/generating Time Dependent B91 (and other) data to support Time-Dependent use of AM	**EPRI ASME/LLC Contract Awarded May 2024** *(John Siefert)*
21-841	**B31** (B31.1 and B31.3), Code Case for Direct Energy Deposition Additive Manufacturing using wire feedstock (or direct incorporation in Appendix (?) per discussion meeting April 2024)	**On Hold pending SI, SIII, & SVIII** *Gingrich (Amentum)/Deubler (Becht))*
21-1702, **21-1913,** **24-625**	**Section I, III, & VIII, respectively,** Code Case for DED (Direct Energy Deposit) Additive Manufacturing using wire feedstock (Time-Independent)	**Section III Balloted at SC level (Disapproved, Closed 5/10/2024. SI & SVIII TG Ballot expected 6/2024,** *(Becker (EPRI), Rawls (EPRI Contractor), Melfi (Lincoln Electric)*
22-1816	**Section I**, Code Case for DED (Direct Energy Deposit) Additive Manufacturing using wire feedstock (Time-Dependent)	**On Hold** *(Melfi (Lincoln Electric))*
21-1858/ 23-1033	**Section I**, Code Case for AM PBF stainless steel PRV valve parts	**Approved, *Rev. pending*** *(Tuttle, Coleman)*
TBD	**B16,** TG to develop Code Cases or alt. approach for use of AM for B16	**Approved**, *McMahon, (Emerson)*
A23-09	**NBIC Part 3**, Supplemental – Engineering Alteration, Developing Rules for Additive Manufacturing of Pressure Parts	**Review and Comment Ballot 4/2024,** *Galanes (DTS, Inc.)*