Advanced Manufacturing to Enable the Next Generation of Nuclear Plants

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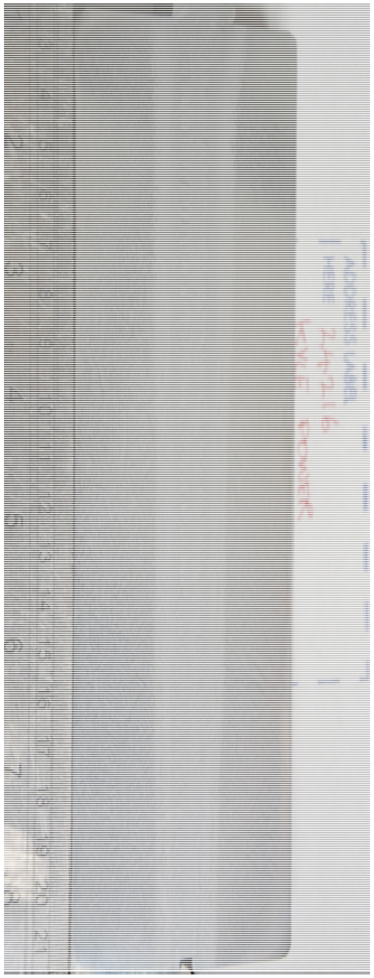
Imagine if You Could Produce a Reactor Pressure Vessel in Under 12 Months!

Advanced Manufacturing
-Objectives

- Develop/Demonstrate New Methods for Manufacture/ Fabrication of a Reactor Pressure Vessel (RPV) in **<12 months**
- **Eliminate 40%** from the cost of an SMR RPV, While **reducing** the Schedule by **18 Months**
- Rapidly Accelerate the Deployment of SMRs



200mm Electron Beam Weld

Background

- EPRI, DOE, and various vendors have been working on a number of advanced manufacturing technologies over the past 5 years:
  - EB and RPEB welding
  - Powder metallurgy-HIP
  - Diode laser cladding
  - Dissimilar metal weld joining
  - Cryogenic machining
- Industry is looking to develop and demonstrate new technologies for the manufacture/fabrication of SMRs
- The current project will support work to fabricate specific large scale components using these technologies

Enabling the Next Generation of Nuclear Plants -Scope

- Manufacture Major Critical Components to **<u>Assemble a 2/3-Scale SMR Reactor Pressure Vessel</u>**

- Jointly Funded Collaboration
  - EPRI, Nuclear-AMRC, DOE, NuScale Power
- Others
  - Carpenter, Synertech-PM, TWI, Sheffield Forgemasters, Sperko Engineering, etc.

- **Advanced Processes Employed:**
  - PM/HIP, Electron Beam Welding, Diode Laser Cladding, Cryogenic Machining, and Elimination of DMWs

Photograph provided courtesy: NuScale Power

What Once Took Weeks,
We Can Now Do In Hours…

Electron Beam (EB) Welding

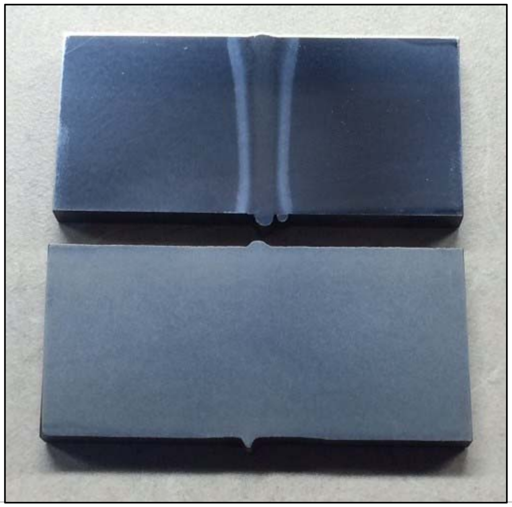
Why EBW?

- One-pass welding!
- No filler metal required.
- EBW can produce welds w/ minimal HAZ
- TWI, Rolls-Royce, Nuclear-AMRC & EPRI have demonstrated low volume or reduced pressure EBW on thick section alloys
  - Enables field/shop welding!

Inspection, Costs?

- Huge savings in welding costs (again, one pass welding)
- Potential to eliminate in-service inspection!

65mm (thick) x 3m length x 1.8m diameter
Welding time: <10 minutes
Photograph provided courtesy: TWI



Electron Beam Weld 1) as-received and 2) solution annealed and Q&T conditions

Powder Metallurgy-Hot Isostatic Pressing (PM-HIP)

Why PM-HIP?

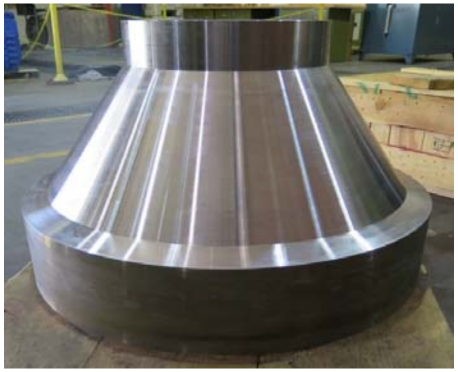
- Near-net shape and complex components (reduces materials cost and machining)
- Alternate supply route, shorter turn-around times
- Considerable EPRI/Industry development over last 5 years.
- Ideal for multiple penetration applications (RPV or CNV head) vs expensive forgings

Inspection, Costs?

- Homogeneous--Excellent inspection characteristics
- Costs roughly equivalent to forging

Large 316L SS Valve Body

Steam Separator Inlet Swirler



3700 lb BWR nozzle

Partial RPV Ring Section

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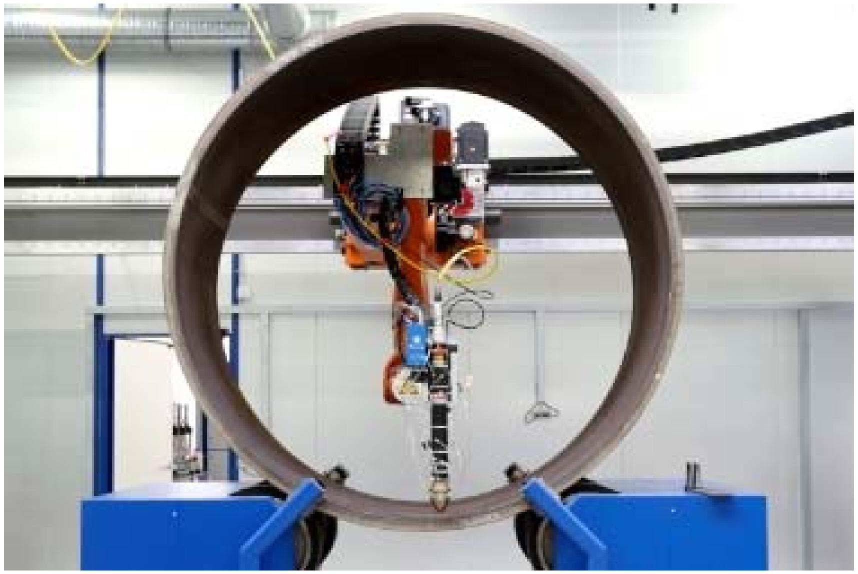
Diode Laser Cladding (DLC)

Why DLC?

- Robotic machine welding
- High deposition rates
- Significantly reduces cladding thickness required to 1mm thick
- Up to 45mm width

Inspection, Costs?

- lbs. (or kgs.) of material required is significantly reduced since thinner layers can be applied.
- **No machining after cladding required**

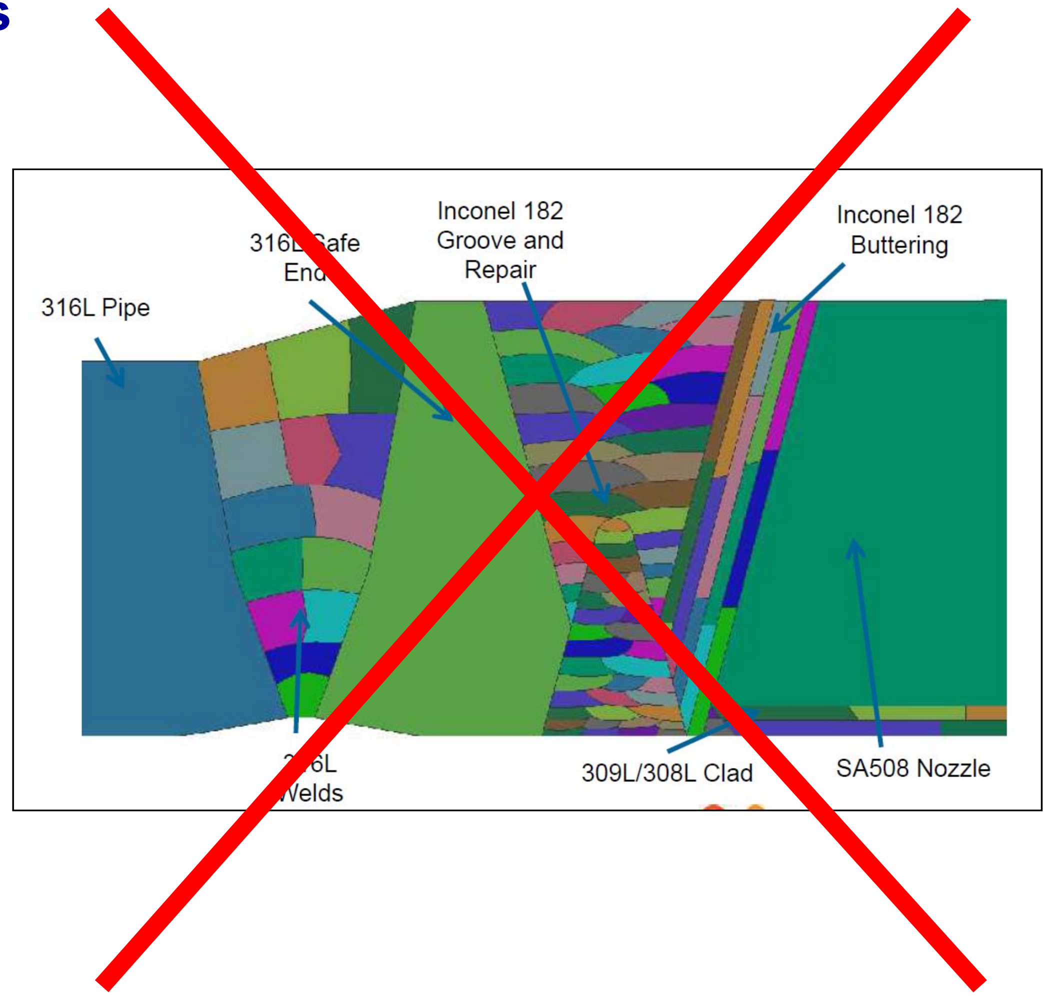


Diode Laser Cladding equipment setup
(courtesy of N-ARMC)

Elimination of Dissimilar Metal Welds

How Do We Eliminate DMWs?

- PM-HIP has been used to bond dissimilar metals with nickel-based powder in between.
- Successfully demonstrated A508-to-347SS and A508-to-316LSS



Inspection, Costs?

- Eliminates need for difficult to inspect weld(s)
- Metallurgical bond lines are perpendicular to surface for significantly improved inspection
- Cost is ~60% of welded costs

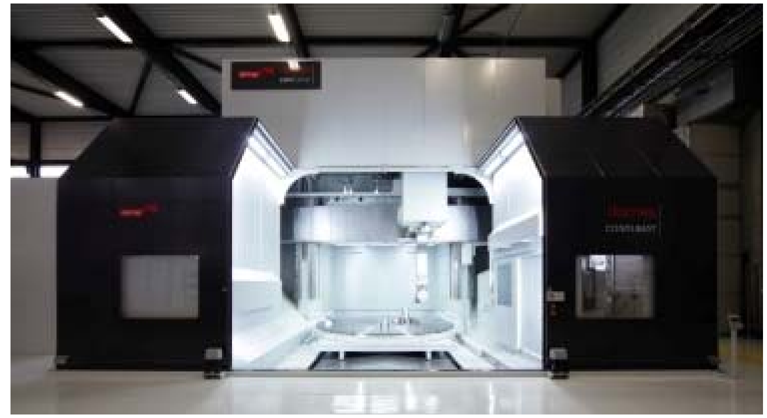
Advanced Machining

Advancements

- Machine Prep RPV ring sections and heads for EBW joining
- Machine Prep Horizontal and Vertical Weld Joints
- Boring of steam plenum and CRD penetrations

Costs?

- Technologies developed by N-ARMC seek **4X** reduction in machining time



3m x 5m Vertical Turning/Milling Capability (Courtesy of N-AMRC)

12m x 5m Horizontal Boring Mill Capability (Courtesy of N-AMRC)

Where Do the Cost & Schedule Savings Come From?

- Eliminates need to procure forgings well ahead of construction
  - Often 2-5 years lead-time for forgings; Major components--produced by PM-HIP in 6-12 months
  - Reactor heads savings anticipated: >$2-3M each
  - Lengthens decision making window
- Electron Beam Welding can reduce welding time significantly:
  - For 100mm RPV shell, a reduction from 120 welding/PWHT days to 12-15 welding/PWHT days
- Diode Laser Cladding can reduce the welding material costs required by >50%
- PM-HIP provides near-net shaped components and can eliminate 1000s of hours of machining.
- Cryogenic Machining can reduce machining time by up to 4X.

Eliminate 40% from the Cost of an SMR RPV
Reduce Manufacturing Schedule by 18 Months

Project Tasks

1. Lower Reactor Assembly
2. Upper Reactor Assembly
   Middle Reactor Assembly (not included)

3A. Thick Section EBW Development

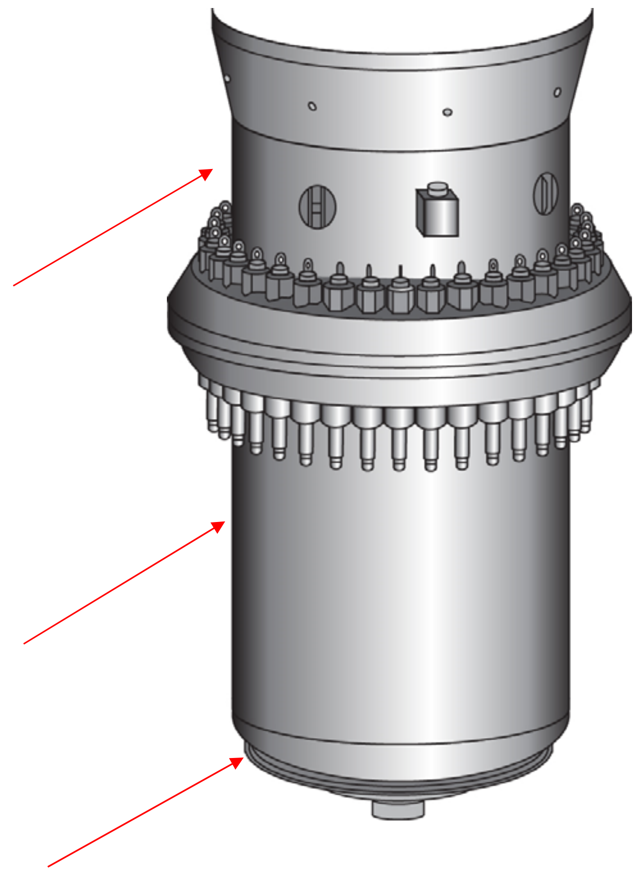
3B. Reduce Pressure EBW Development

4. Diode Laser Cladding Development
5. Elimination of DMWs—for Nozzle Applications
6. Elimination of In-Service Inspection via Solution Heat Treatment
7. ASME BPVC Code Development
8. ORNL Mechanical and Metallurgical Testing

Representative Model of NuScale Power Reactor Vessel

Task 1—Lower Reactor Assembly (508 materials)

1. RPV Lower Head
   - Manufacture via PM-HIP in two halves
   - EBW halves together, solution annealed, Q&T
   - LDC completed lower head
   - BAM center boss and core supports
2. RPV Flange Shell
   - Manufacture shell and flange via forging
   - EBW sections together, solution annealed, Q&T
   - LDC completed flange shell
3. Upper RPV Flanged Transition Shell
   - Manufacture 4 ring sections via PM-HIP and flange via forging
   - EBW sections together, solution annealed, Q&T
   - LDC completed flange shell



Representative Model of NuScale Power Reactor Vessel

Task 2—Upper Reactor Assembly (1) (508 materials)

4. RPV Top Head
   – Manufacture via PM-HIP in two halves
   – EBW halves together, annealed, Q&T
   – LDC completed top head

5. RPV PZR Shell
   – Same as Item 2 above

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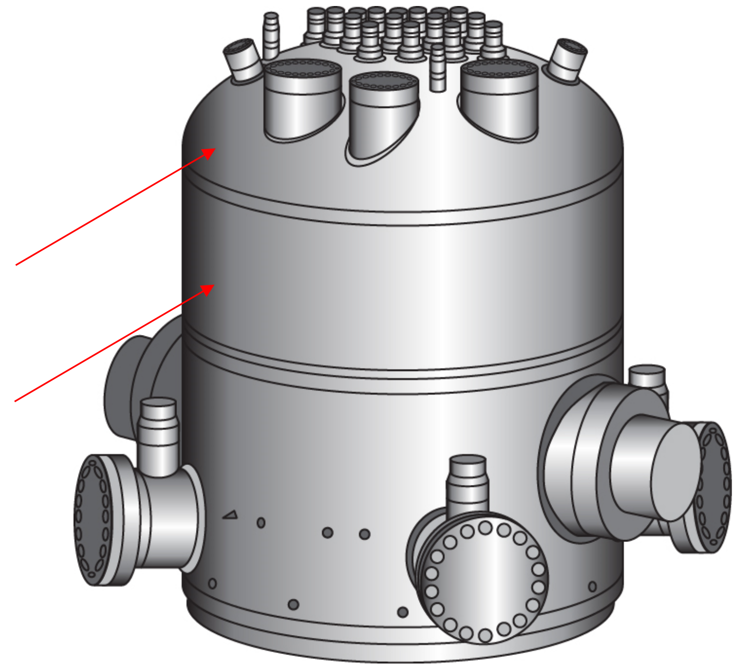

Representative Model of NuScale Power Reactor Vessel

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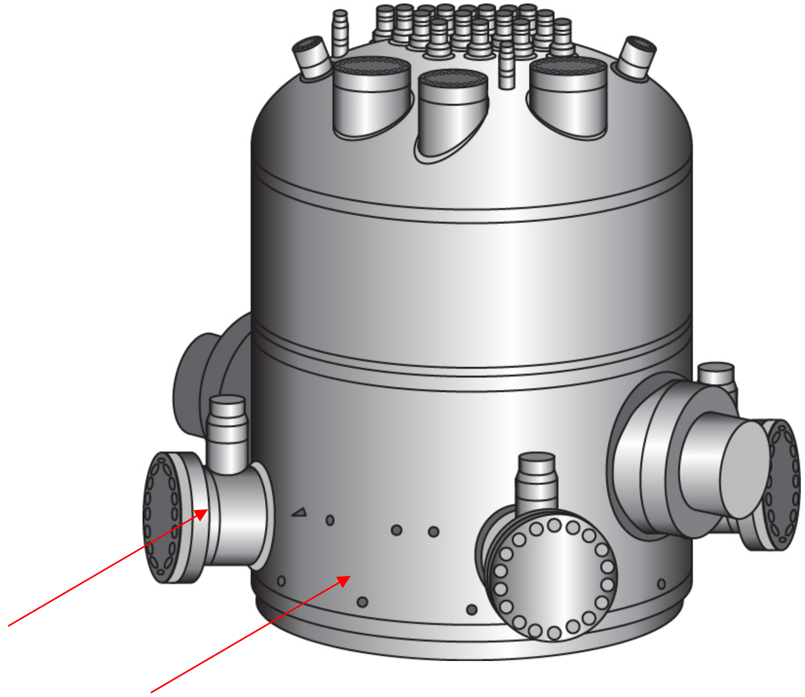
Task 2—Upper Reactor Assembly (2) (508 materials)

6. <u>Integral Steam Plenum</u>
   - Manufacture via PM-HIP in two sections
   - EBW together, annealed, Q&T
   - LDC completed plenum

7. <u>Steam Plenum Access Port Assembly</u>
   - Manufacture via PM-HIP in two sections
   - Machine prep
   - EBW access port assemblies into integral steam plenum



Representative Model of NuScale Power Reactor Vessel

Middle Reactor Assembly
--Not Manufactured/Fabricated In Project

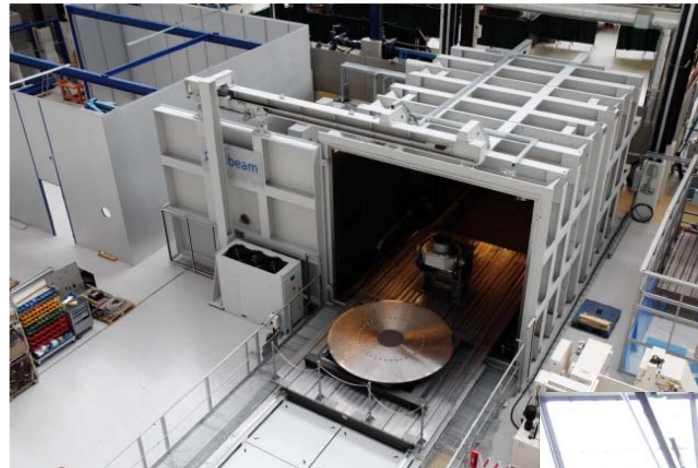
- Upper RPV SG Shell
- Lower RPV SG Shell
- Technologies addressed elsewhere in project (under Tasks 1 & 2)

Carbon steel pipe welded with EBW
Photo courtesy of TWI

Tasks 3A and 3B

- **Task 3A. Thick Section EBW Development**
  – Several organizations (NAMRC, EPRI, TWI, RR, UOM) have been developing EBW for thick RPV materials
  – Nuclear-AMRC has a 4.5m x 5.0m x 9m chamber which permits a 6m x 3.5m (19.7 x 11.5m) coupon to be fabricated in the chamber.
  – 3A will focus on additional process/parameter development for handling RPV sections

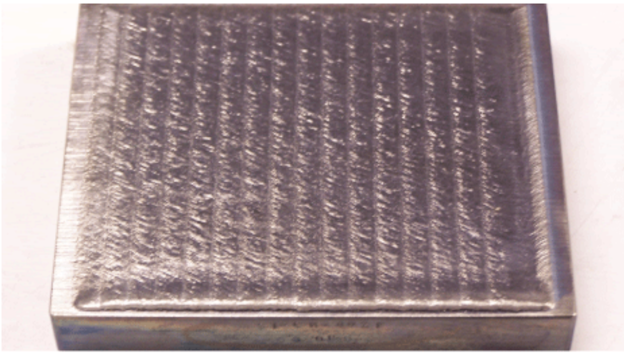
- **Task 3B. Reduce Pressure EBW Development (optional task)**
  – Additional development is required for out-of-chamber welding
  – TWI has demonstrated capability up to about 3 inches (75mm)
  – More development will be required to move to 4.375 inches (110mm)



(Courtesy of N-AMRC)

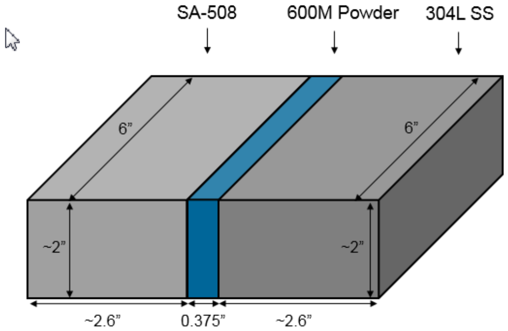
Task 4—Diode Laser Cladding Development

- Develop/demonstrate cladding for:
  - RPV Shell
  - Upper and Lower Heads
  - Nozzles
  - Plenum



Task 5—Elimination of DMWs for Nozzle Applications (optional task)

- Produce test blocks to demonstrate:
  - A508-to-690
  - A508-to-304L
- Manufacture/demonstrate nozzle-to-safe end (A508-to-690)
- Manufacture/demonstrate nozzle-to-safe end A508-to-304L



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Task 6—Elimination of In-Service Inspection via Solution Heat Treatment

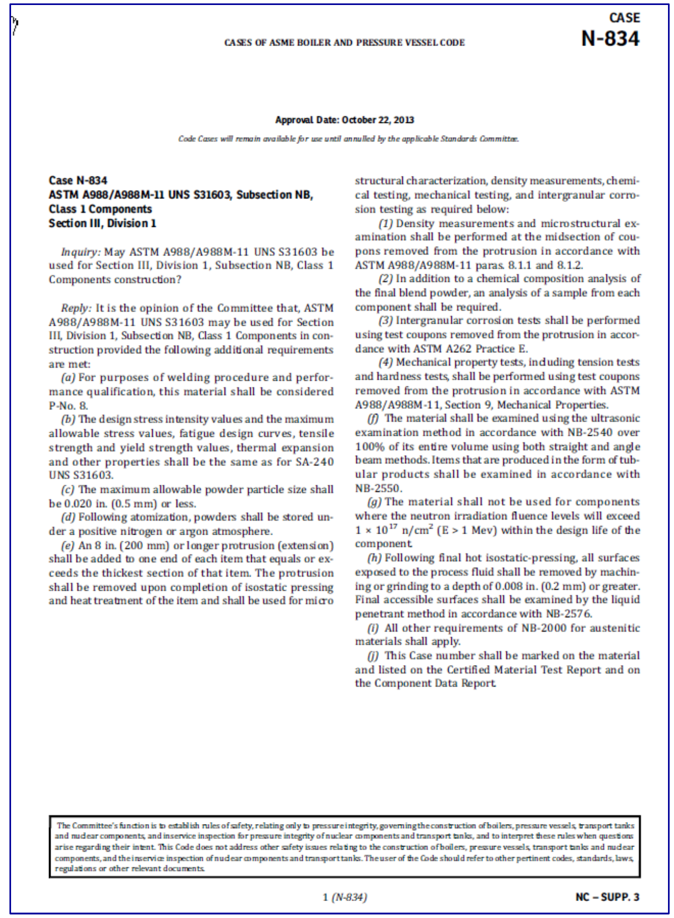
- Modeling:
  - flange to RPV shell
  - circumferential shell weld
- Local PWHT – safe handling of shells/head
- Plate Trials
  - Understand distortion and microstructure
  - Cladding, EB welds, PWHT, Soln Anneal, Q&T
  - Inspection
- Distortion Measurements
  - Circumferential weld
  - Weld to join two halves of torispherical head together
  - Inspection
- Full Section Heat Treatment
  - Lower flange shell
  - Model and solution HT
  - Distortion measurements

Thick section RPEB weld. Courtesy of TWI

Task 7--ASME BPV Code Development

- Task will focus on working with ASME and EPRI Utility Requirements Document (URD)

- Example Code Cases/Changes anticipated:
  - Elimination of periodic ISI for solution HT, quench and tempered EB welds
    - ➢Volumetric upon manufacturing only
  - Acceptance of 508 using PM-HIP as Code Case for production of vessel materials
  - Inspection criteria for Diode Laser Cladding on RPV materials (shells, nozzles, etc)
  - Reduce Pressure EB welding
  - Bulk Area Manufacturing


CASES OF ASME BOILER AND PRESSURE VESSEL CODE

CASE
N-834

Approval Date: October 22, 2013

Code Cases will remain available for use until annulled by the applicable Standards Committee.

Case N-834
ASTM A988/A988M-11 UNS S31603, Subsection NB, Class 1 Components
Section III, Division 1

Inquiry: May ASTM A988/A988M-11 UNS S31603 be used for Section III, Division 1, Subsection NB, Class 1 Components construction?

Reply: It is the opinion of the Committee that, ASTM A988/A988M-11 UNS S31603 may be used for Section III, Division 1, Subsection NB, Class 1 Components in construction provided the following additional requirements are met:

(a) For purposes of welding procedure and performance qualification, this material shall be considered P-No. 8.

(b) The design stress intensity values and the maximum allowable stress values, fatigue design curves, tensile strength and yield strength values, thermal expansion and other properties shall be the same as for SA-240 UNS S31603.

(c) The maximum allowable powder particle size shall be 0.020 in. (0.5 mm) or less.

(d) Following atomization, powders shall be stored under a positive nitrogen or argon atmosphere.

(e) An 8 in. (200 mm) or longer protrusion (extension) shall be added to one end of each item that equals or exceeds the thickest section of that item. The protrusion shall be removed upon completion of isostatic pressing and heat treatment of the item and shall be used for micro structural characterization, density measurements, chemical testing, mechanical testing, and intergranular corrosion testing as required below:

(1) Density measurements and microstructural examination shall be performed at the midsection of coupons removed from the protrusion in accordance with ASTM A988/A988M-11 paras. 8.1.1 and 8.1.2.

(2) In addition to a chemical composition analysis of the final blend powder, an analysis of a sample from each component shall be required.

(3) Intergranular corrosion tests shall be performed using test coupons removed from the protrusion in accordance with ASTM A262 Practice E.

(4) Mechanical property tests, including tension tests and hardness tests, shall be performed using test coupons removed from the protrusion in accordance with ASTM A988/A988M-11, Section 9, Mechanical Properties.

(f) The material shall be examined using the ultrasonic examination method in accordance with NB-2540 over 100% of its entire volume using both straight and angle beam methods. Items that are produced in the form of tubular products shall be examined in accordance with NB-2550.

(g) The material shall not be used for components where the neutron irradiation fluence levels will exceed 1×10^{17} n/cm^2 (E > 1 Mev) within the design life of the component.

(h) Following final hot isostatic-pressing, all surfaces exposed to the process fluid shall be removed by machining or grinding to a depth of 0.008 in. (0.2 mm) or greater. Final accessible surfaces shall be examined by the liquid penetrant method in accordance with NB-2576.

(i) All other requirements of NB-2000 for austenitic materials shall apply.

(j) This Case number shall be marked on the material and listed on the Certified Material Test Report and on the Component Data Report.

The Committee's function is to establish rules of safety, relating only to pressure integrity, governing the construction of boilers, pressure vessels, transport tanks and nuclear components, and inservice inspection for pressure integrity of nuclear components and transport tanks, and to interpret these rules when questions arise regarding their intent. This Code does not address other safety issues relating to the construction of boilers, pressure vessels, transport tanks and nuclear components, and the inservice inspection of nuclear components and transport tanks. The user of the Code should refer to other pertinent codes, standards, laws, regulations or other relevant documents.

1 *(N-834)* NC – SUPP. 3

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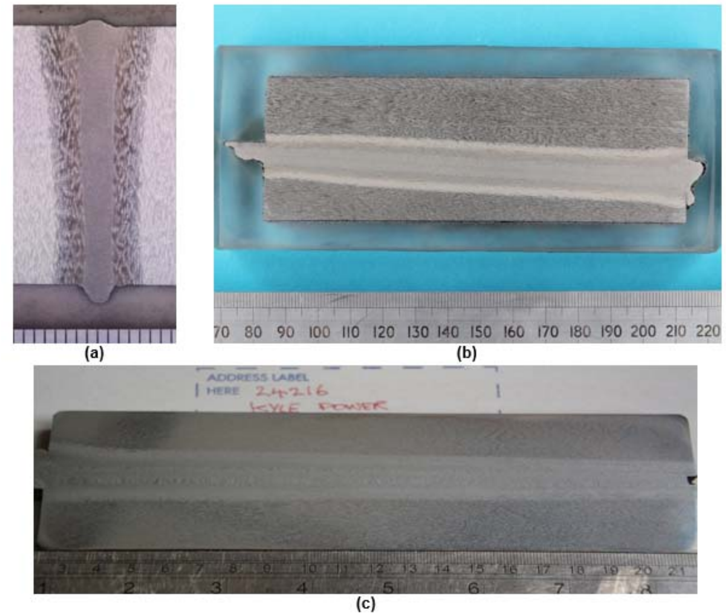
What Are The Critical Gaps That Must Be Addressed? (1)

- EBW must be demonstrated
  - 4.375-inch (110mm) thick (RPV)
  - currently demonstrated at 4-inches (100mm)

- ATLAS HIP facility must be built
  - to increase HIP size capabilities
  - up to 3.1m diameter x 5m length
  - Can manufacture 2/3rds scale coupons today.



30mm, 130mm, and 200mm EB welds

- EBW of SA508 RPV sections
  - Does a vessel that has been EB welded, solution annealed, and quenched and tempered require subsequent in-service inspections?
  - Is EB really a weld after solution annealing? No filler metal.
  - Need to demonstrate fracture toughness following solution anneal

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What Are The Critical Gaps That Must Be Addressed? (2)

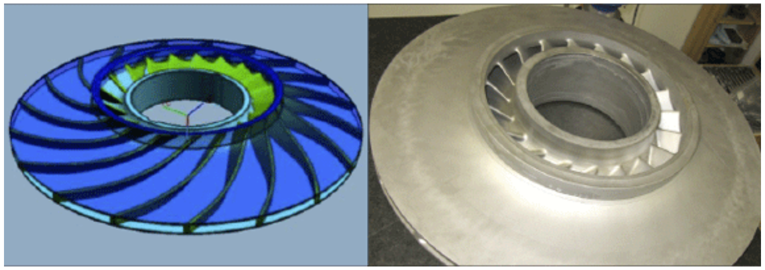
- Diode Laser Cladding must be demonstrated
  - Vessels, nozzles, etc.
  - Robotic cladding up to 90mm wide, but <5mm thick
- Understand Irradiation Effects on PM-HIP Components
  - NEUP project for PM-HIP samples are underway
  - 304L, 316L, SA508, Grade 91, Alloys 625 and 690
- Additional development around SA508.
  - We have demonstrated good fracture toughness and other properties, but we need to develop more understanding here.
  - Utility Requirements Document modification
- ASME Code Case Development
  - PM-HIP of SA508
  - Elimination of DMWs
  - EB welding of RPV sections

How Do We Get There? -Strategic Plan

- Not aimed at First-of-a-Kind
- Could use ring forgings (or PM-HIP rings).
- Definitely PM-HIP for top head, bottom head, plenum caps, and elimination of DMWs
- EBW & Solution Anneal eliminates several major shell horizontal welds

What Once Took Weeks, We Can Now Do In Hours…

316LN SS End cap for Hadron Collider (courtesy Metso)



40-inch Large Inconel 625 Impeller (courtesy Synertech PM and GE Oil & Gas)

Applicability of Advanced Manufacturing Processes

- Multiple SMR Plant Designs
- ALWR Plant Components
- GEN IV Designs
  - multiple nickel-based alloys will be required
- Ultra-Supercritical Plant Components
- Supercritical CO_2 Plant Components

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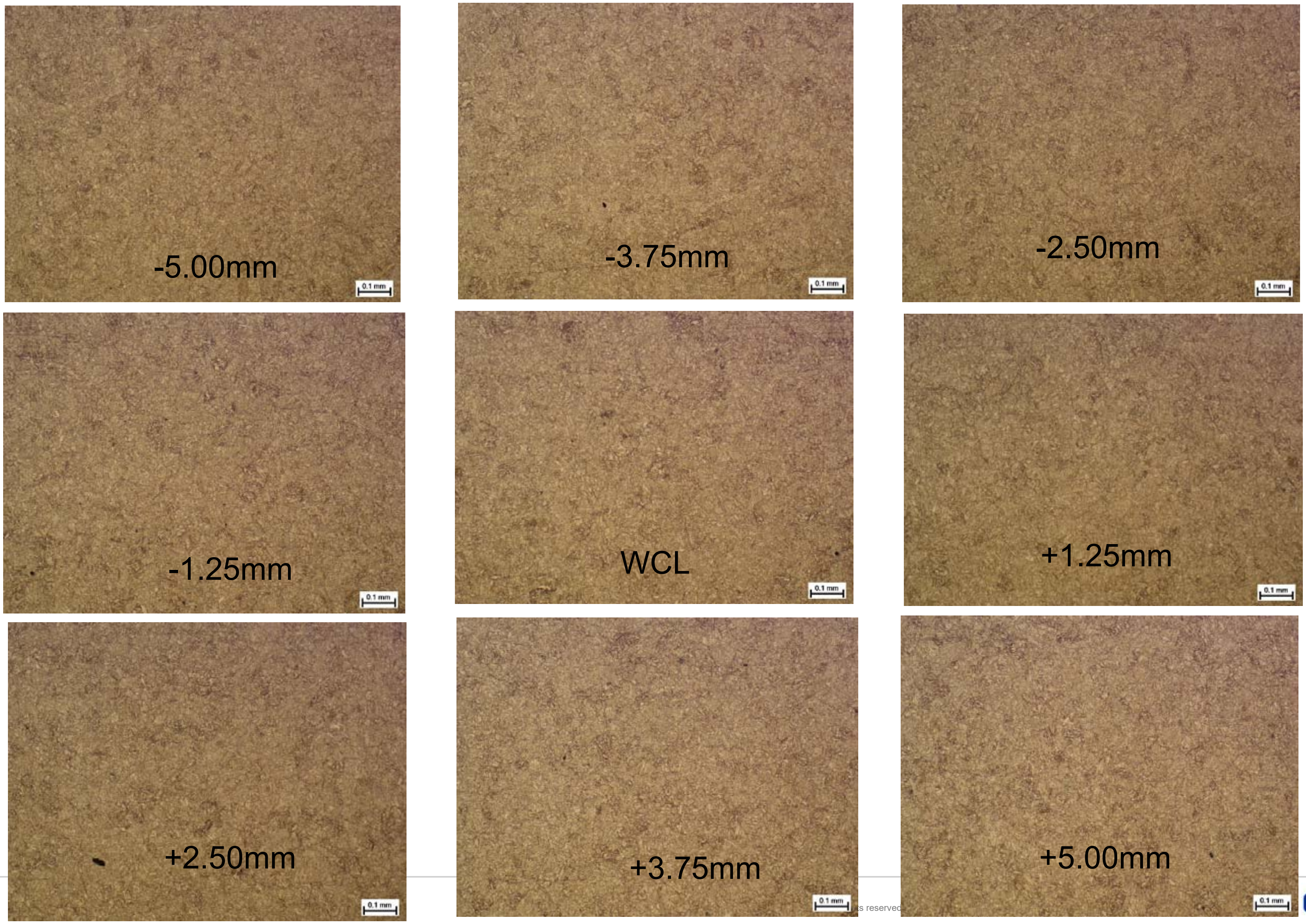
Summary

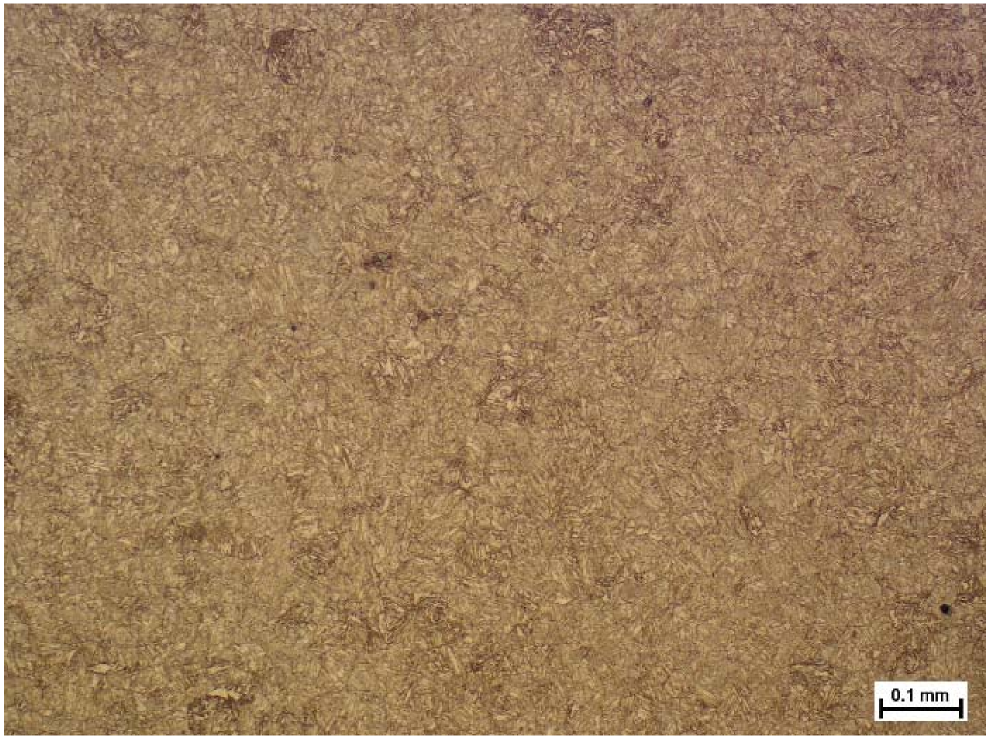
Utilizing Adv. Manufacturing/Fabrication Technologies (eg., PM-HIP and Electron Beam Welding), EPRI/Nuclear-AMRC project will:

- Develop/Demonstrate New Methods for Manufacture/ Fabrication of a Reactor Pressure Vessel (RPV) in **<12 months**
- **Eliminate 40%** from the cost of an SMR RPV, While **reducing** the Schedule by **18 Months**
- Rapidly Accelerate the Deployment of SMRs
- Technologies are applicable across SMRs, ALWRs, and Gen IV units

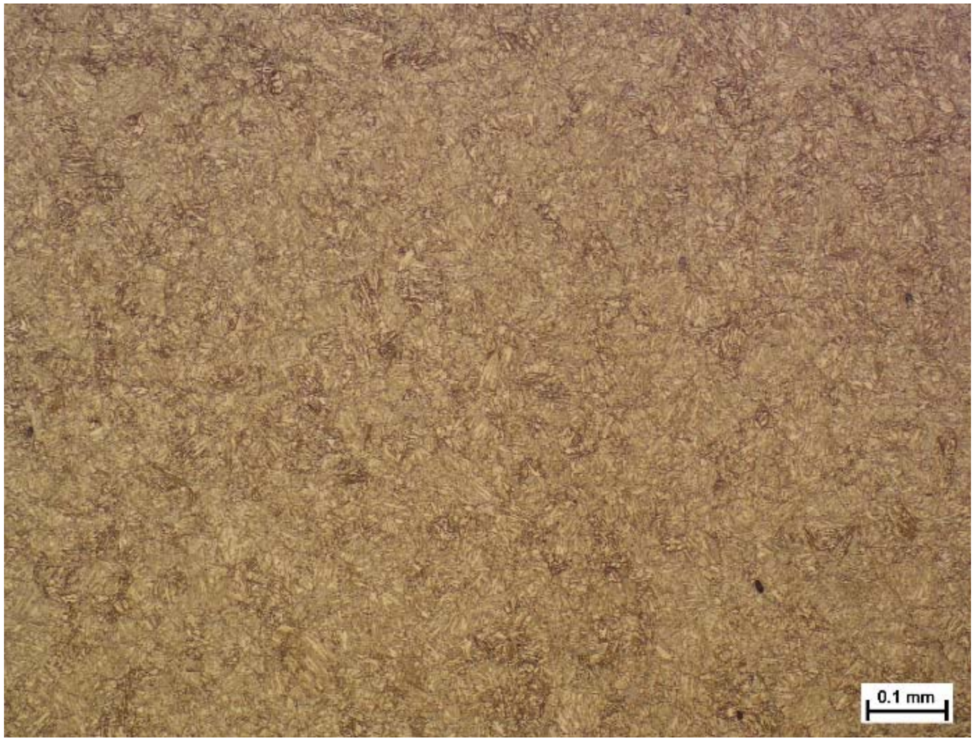
Together…Shaping the Future of Electricity


-5.00mm
-3.75mm
-2.50mm
-1.25mm
WCL
+1.25mm
+2.50mm
+3.75mm
+5.00mm

WCL of EB Weld vs 5mm distance (following Solution Anneal and Q&T) – 100X

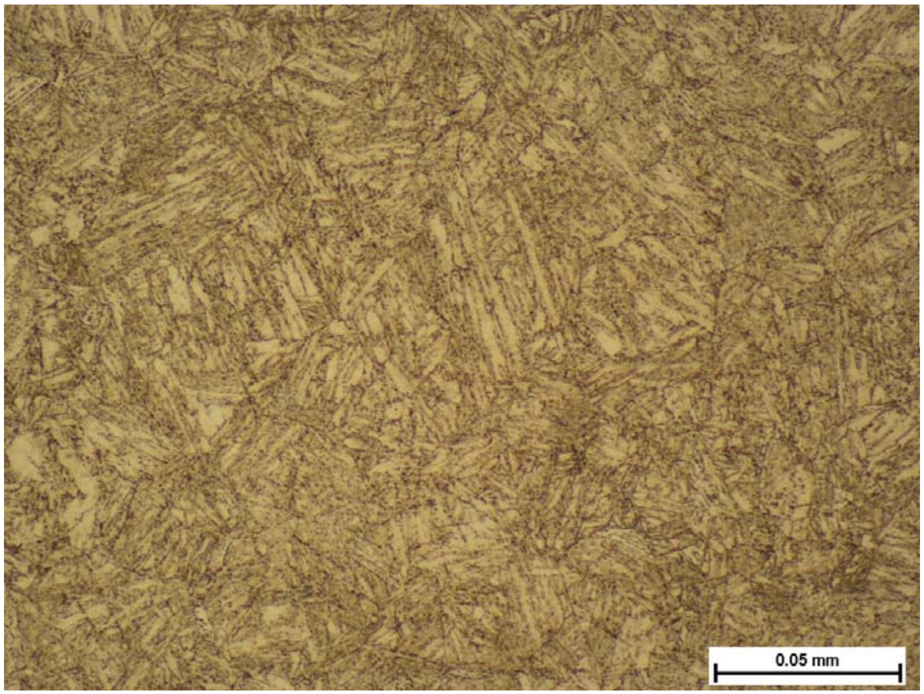


WCL microstructure @ 100X

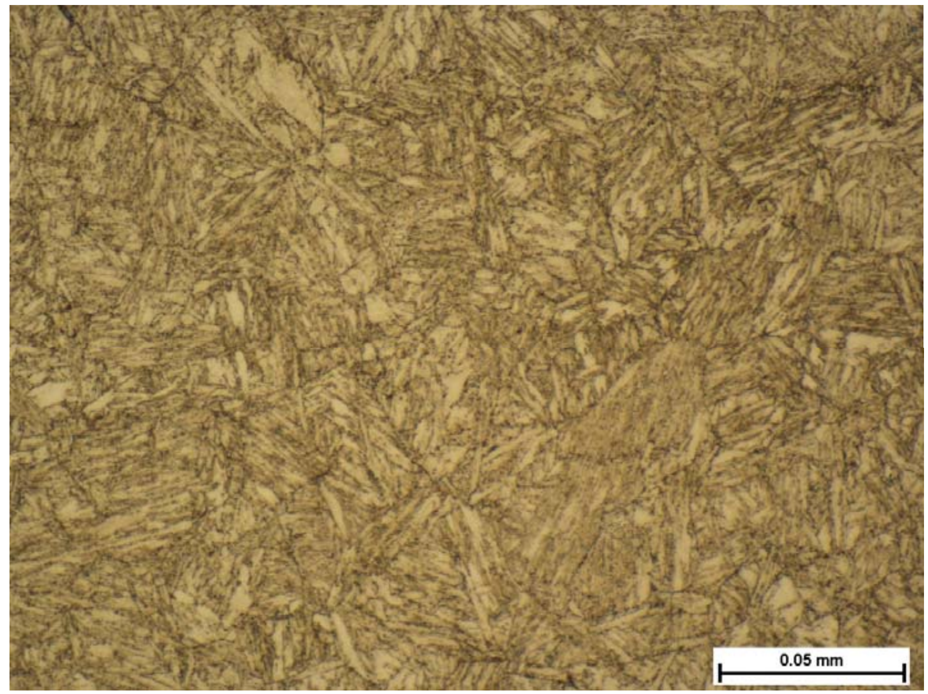


Microstructure 5mm from WCL @ 100X

WCL of EB Weld vs 5mm distance (following Solution Anneal and Q&T) – 500X



WCL microstructure @ 500X



Microstructure 5mm from WCL @ 500X

"We choose to go to the moon!... We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, ***because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one we intend to win.***"

JFK Speech – September 12, 1962