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Tech Pub Qualification Scheme Development for Arc Directed Energy Deposition Additive Manufacturing

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ABSTRACT

A prescriptive qualification scheme was completed for Arc Directed Energy Deposition (DED) metal Additive Manufacturing (AM) processes for austenitic single-sided builds. Robotic arc DED AM qualification builds used stainless steel consumables with the gas metal arc welding - pulse (GMAW-P) process. A matrix of standard qualification builds were made to develop, evaluate, and recommend the preferred process qualification build schemes. The qualification scheme explored a range of heat inputs, deposit sizes, and deposition rates; and the effects of interpass temperature that can be a limiting productivity factor for robotic arc DED metal AM builds. The standard qualification builds evaluated the effects of thickness (thin and thick geometric build features) where the process deposit (heat input) and process build thermal features (preheat and interpass temperature) are controlled over smaller ranges. The builds were examined with both ultrasonic and radiographic inspection, and a standard set of destructive tests (tensile, bend, macros, etc). Arc DED stainless steel builds showed good tolerance and consistent properties over the range of features tested. A prescriptive qualification scheme provides a clear path to accelerate implementation of high impact DED AM technology. Additional standard qualification build designs and testing plans are underway for ferrous materials, and with and without integrated build plates to provide prescribed qualification requirements for the most common applications of arc DED AM processes.

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1. INTRODUCTION

Additive manufacturing (AM) enables designers the ability to build parts directly from computer-aided design (CAD) files. In its simplest form, AM provides a CAD-to-part manufacturing build process. Here, AM systems use computer-aided models (CAM) to solve the build plan, prepare the machine build file, and download the machine build parameters. For metal AM, there are two process categories per ASTM: powder bed and directed energy deposition (DED).

Metal AM technology is rapidly maturing. The impact to the U.S. Navy has been limited by the availability of standards and U.S. Navy Technical Publications (Tech Pub). Several American standard bodies, including ASTM, AWS, ASME, SAE and others, are developing consensus-based standards to ANSI requirements. The standards development process is slow. The main reasons for the lack of speed include:

- The rapid growth in the number of AM process types and derivatives that increases complexity of new standards.
- Lack of proven qualification and certification schemes.
- Lack of machine-to-machine reproducibility with powder-bed processes.
- Supplier-to-supplier property variability with metal powder feedstocks.

DED processes, especially the processes that use wire consumables, have the least risk. Arc DED processes leverage welding technology for process equipment and consumables. Arc DED processes that use wire feedstocks can leverage mature standards that include hundreds of codes, specifications, methods, and best practices to ensure integrity of AM structures.

Existing metal fabrication/welding standards provide a body of knowledge for developing this Arc DED Metal AM Tech Pub. These standards provide technical information for material property requirements, integrated build plate (base material), filler metal specifications, process qualification, operator qualification, inspection, and repair to name a few. The Navy is using content from the following standards wherever possible to harmonize manufacturing requirements for welding and additive AM structure:

- NAVSEA Technical Publication S9074-AQ-GIB-010/248: "Requirements for Welding and Brazing Procedure and Performance Qualifications"[1]
- NAVSEA Technical Publication S9074-AR-GIB-010/278: "Requirements for the Fabrication Welding and Inspection, and Casting Inspection and Repair for Machinery, Piping, and Pressure Vessels"[2]
- NAVSEA Technical Publication T9074-BD-GIB-010/0300: "Base Materials for Critical Applications: Requirements for Low Alloy Steel Plate, Forgings, Castings, Shapes, Bars, and Heads of HY-80/100/130 and HSLA-80/100"[3]
- AWS D20.1/D20.1M:2019: "Specification for Fabrication of Metal Components using Additive Manufacturing"[4]

Industry has used welding processes to build near-net shape objects for years, where the structural features are qualified as buttering. Historically, these shapes were limited to the capability of the robot and/or mechanized system and the programming skill of the operator. Using welding technology and computer-aided robotics (CAR) and/or computer numerical control (CNC) machines, a range of DED processes are available to rapidly build structure in high mix environments. These processes include but are not limited to:

- Gas tungsten arc welding (GTAW) – cold or hot wire (CW or HW),
- GTAW – synchronized pulse wire feed (SPWF) (i.e., TopTIG),
- Plasma arc welding (PAW) – cold or hot wire (CW or HW),
- Gas metal arc welding (GMAW) – spray (S)
- GMAW – pulse (P),

- GMAW – pulse short circuit (PSC), (i.e., STT),
- GMAW – reciprocating wire feed (RWF), (i.e., CMT), and
- Tandem GMAW,

The selection of individual DED processes for specific applications is a tradeoff between many process and application conditions. The DED process selection may consider use of existing facility equipment, complexity of process and apparatus, need for preheat and interpass temperature management, metal deposition stability and ability, start/stop quality and ability, chamber or local shielding, and system cost, etc. Non-consumable electrode processes (GTAW, PAW) offer independent base metal heating and feedstock deposition. In general, independent heating and deposition provide enhanced start/stop parameter control and fusion robustness but may be more complex to control. Whereas, GMAW-based processes that have less complex apparatus, may require overlapping bead starts and stops and in-process machining/grinding to blend these areas to ensure soundness. The preferred process choice may also consider feature size range and/or mechanical properties to feature characteristics.

This project developed one qualification scheme for arc DED metal AM that will be incorporated into technical publication requirements. Similar to a welding qualification test, the scheme sought to develop standard qualification build designs and respective specimen test matrixes for the most common DED AM applications.

The standard qualification build design was configured to provide both block (multi-pass wide and tall) and wall (single pass wide) features, and permit removal of property specimens in multiple directions (x, y, z). The properties of AM build features may vary based on many conditions including microstructure, hatch (bead) size, hatch overlap, heat input, cooling rate, anisotropy (property changes in longitudinal (x), transverse (y), z- or 45-degree orientations, and build height), direction of deposition, fabrication of ledges and overhangs, and surface condition (as-built surface, peened, machined, polished).

The qualification builds included block and wall features but did not include an integrated build platform. A matrix of builds were made using two different bead sizes, and at two different interpass temperature ranges. The GMAW-P process was selected for this project based its duty cycle and ability to produce both small and large bead features. Stainless steel was selected for this initial program to provide data for a high usage (austenitic) AM material. Work is in-progress to complete a range of qualification build designs and respective specimen test matrixes for ferrous materials, and with and without integrated build plates.

304L / ER308Lstainless steel welding fabrication requirements typically specify a preheat / interpass range of room temperature / 350F max. This project made builds using these requirements and with a high preheat / interpass of 500 / 750F max. Higher interpass temperatures offer potential for increased productivity and lower residual stresses as long as the material properties and / or quality are not degraded. Different bead size deposits were examined to explore qualification of bead size range. A bead size range is needed to shape parts like elbows, saddle-shaped nozzles, complex ducts, and other fittings (for example) that require changes in wall thickness and height in each build layer.

2. Qualification Build Design

A procedure qualification scheme was developed for qualifying arc DED AM procedures for non-ferrous, non-integrated build platform condition. Here, the build platform is not incorporated into the final built part. This qualification scheme consisted of the following:

a) A standard build platform designed to provided sufficient restraint for a large qualification build (Figure 1). The build platform used 2-inch x 4-inch wide plate positioned to provide 4-inches of build restraint.

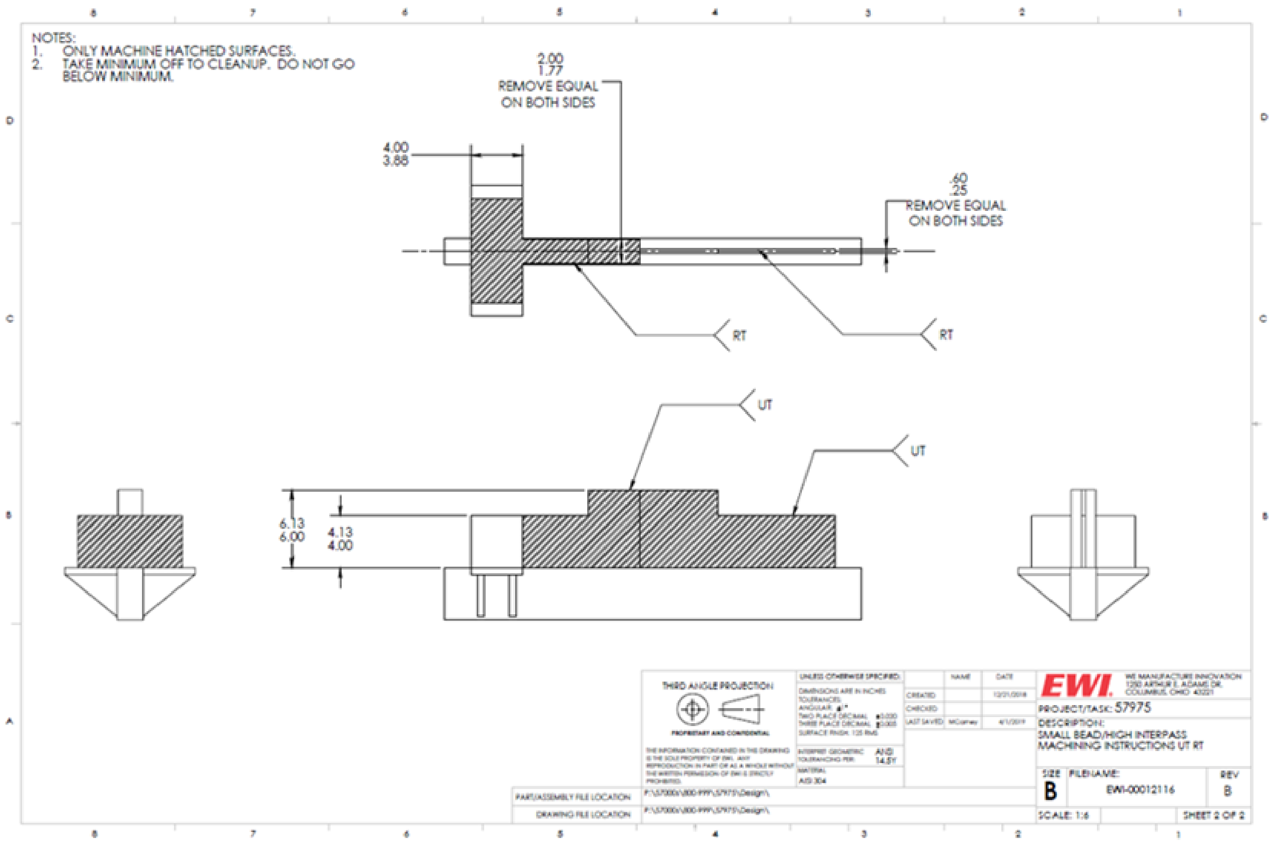


Figure 1 – Standard qualification build for austenitic

b) A standard build design (i.e. the combination of the build and the build platform) that provided “wall” and “block” features, and sized to provide specimens in multiple directions or planes.
c) A standard test specimen matrix (Figure 2) for the condition: Austenitic, single sided build without integrated build platform
d) Specification of the nondestructive testing types, application requirements, and acceptance criteria,
e) Specification of the destructive testing types (i.e. mechanical testing, metallurgical testing, etc.), layout within the standardized qualification build design, and acceptance criteria, and
f) Proposed AM procedure specification (AMPS) and procedure qualification record (AM-PQR) document formats.

This qualification scheme was validated and demonstrated by producing build coupons using the robotic gas metal arc pulse (GMA-P) DED process, alloy 304L stainless steel build platforms, 0.045-inch ER308L stainless steel filler wire, and four build combinations of bead size and inter-pass temperature. The two bead sizes and the two pre-heat / inter-pass temperature ranges were selected to bracket the desired operating window for the robotic GMA DED process for the ER308L build material. The outer surface of the completed builds were machined to remove undulations.

Each of the four builds was subjected to nondestructive testing (Radiographic (RT) and

Ultrasonic (UT)) per NAVSEA Technical Publication T9074-AS-GIB-010/271[5] using MIL-STD-2035 nondestructive testing acceptance criteria[6].

Destructive testing[1,7] in accordance with the respective test specimen matrix for austenitic builds without integrated build platform, and properties were compared to commercial ASME SA240 and AWS A5.9 standards for base and filler materials, respectively.[8,9]

The robotic GMA-P arc DED system included a Motoman MA1440 6-axis robot, an MHT-95 single axis positioner, and a DX200 controller; and a Fronius welding system - TPS 500i power source, a WF 25i Real, an SB 60i wire buffer and hose pack, and a water cooled WF 60i Robacta Drive CMT torch.

Build parameters were developed for each bead size by evaluating different wire feed speeds (currents via synergic GMA-P control) at constant wire feed speed to travel speed ratios of 15 and 30. These deposit sizes were equivalent to 0.2 and 0.3-inch fillet welds (leg length). Arc length was held constant at 1/8-inch. The shielding gas was 99% argon – 1% CO2 at 45-cfh. The preferred stead-state parameters used for each build are shown in Table 1. The build matrix included two bead size and two pre-heat / inter-pass temperature combinations:

- Small bead (WFS/TS = 15) and low pre-heat / inter-pass (0/350F) temperature,
- Small bead (WFS/TS = 15) and high pre-heat / inter-pass (500/750F) temperature,
- Large bead (WFS/TS =30) and low pre-heat / inter-pass (0/350F) temperature, and
- Large bead (WFS/TS =30) and high pre-heat / inter-pass (500/750F) temperature.

For simplicity these build conditions are respectively referred to as 15L, 15H, 30L, and 30H.

Table 1 – Welding Parameters - ER308L Builds.

GMA-P Paramters					
Build#	**WFS (ipm)**	**TS (ipm)**	**I (amps)**	**V (volts)**	**# BEADS**
15L	305	20	226	24.1	1452
15H	305	20	226	24.1	1589
30L	250	8	186	22.1	788
30H	250	8	186	22.1	793

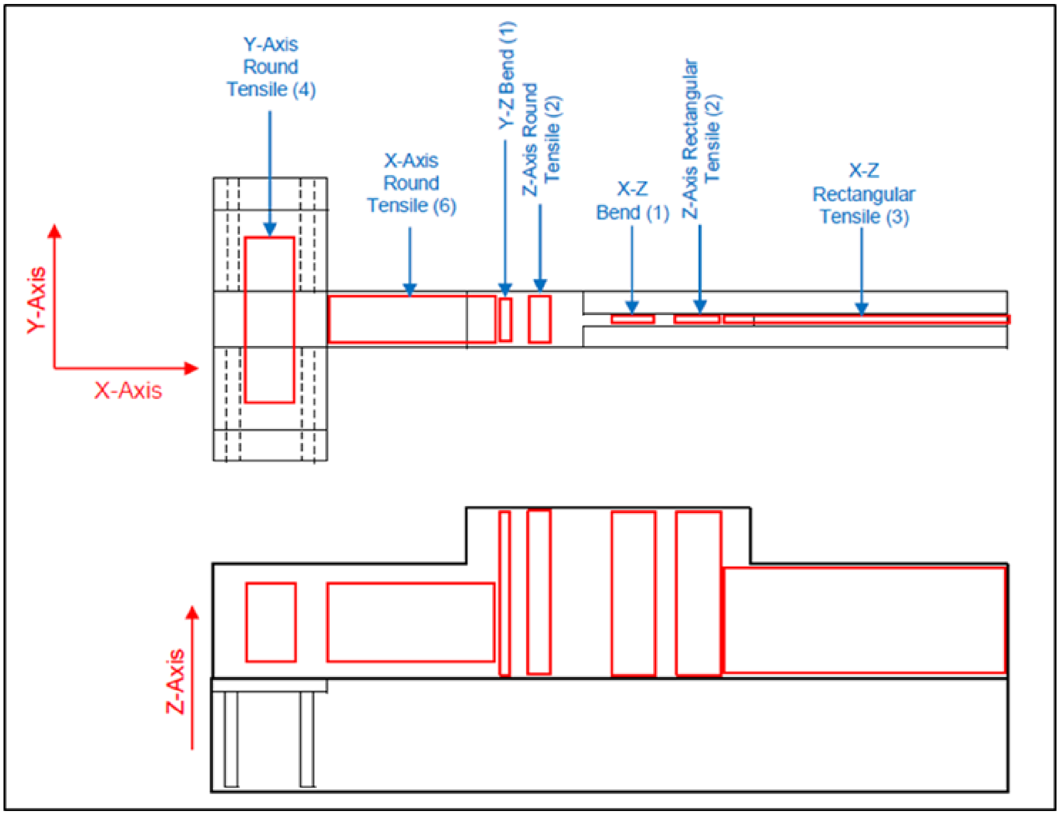
The builds used a bi-symmetric build progression where a center bead was made in the middle of the 2-inch plane, then the sides of the block layer were made bead by bead working outward on each side. A whole layer would be made using the robot, and then an infrared sensor was programmed to hold robot until build was under the interpass max of that build test condition. The small bead builds (15L, 15H) took 1452 and 1589 passes to complete. Note, the latter had more beads as width and height were adjusted between builds to provide more stock. The large bead builds (30L, 30H) required 788 and 793 passes to complete.

A heating system for maintaining pre-heat and inter-pass temperature was used for the high pre-heat / inter-pass temperature build condition. The system consisted of a Miller XMT 304 CC/CV power source, an Athena FFS-C-480 controller, a resistive heating blanket, and a thermocouple. The thermocouple was tack welded to the build platform. Spacers were placed between the build platform and the positioner plate. The resistive heating blanket was placed between an insulation blanket and the lower surface of the build platform. The Athena FFS-C-480 controller regulated the power output of the Miller XMT 304 power supply. The temperature of the build platform thermocouple location was regulated between the lower (500F) and upper (750F) control limits.

For austenitic builds without integrated build platform, the following specimen matrix was tested for each bead size and preheat / interpass build conditions per Figure 2:

- 17 tensiles (6-longitudinal, 4 transverse, and 2 z-direction from block area / 3-longitudinal and 2 z-direction from wall areas)
- 1y-z bend from block area
- 1 x-z bend from wall area

Figure 2 – Location and type of test.



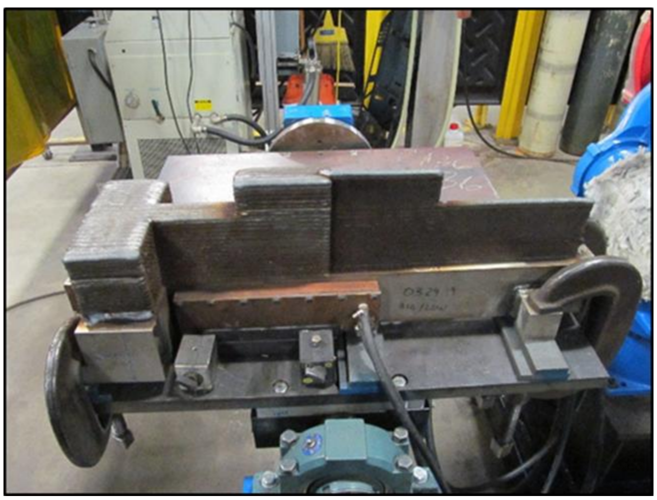


Figure 3 – Example of completed qualification build.

3. Testing Results

The outer surfaces of each build was machined to remove as-deposited surface undulations (bead overlap waviness on edges and final top surface), Figure 3. Each build was inspected using ultrasonic and radiographic inspection methods where the 1-inch of the ends (start/stop area) was ignored; this build scheme qualification assumed the start/stops are removed in the build design. If start/stop areas are incorporated in build design, the standard qualification builds must incorporate start/stop methods and conditions within the build and is an area for future procedure development and testing. All four builds (15L, 15H, 30L, 30H) passed these inspections and were deemed sound, and required no repairs for unacceptable flaws. The bend samples were tested to 20% strain using a bend test fixture. All bend specimens passed the test further demonstrating soundness and ductility in X-Y plane for block feature, and X-Z plane for wall feature. Round tensile specimens (0.5-in diameter) were removed from the block feature, and rectangular tensile specimens were removed from the wall area.

The results of tensile tests are shown in Tables 2 and 3 for block and wall features, and further compared in Figure 4 and 5, respectively.

Table 2 – Block Feature Tensile Properties.

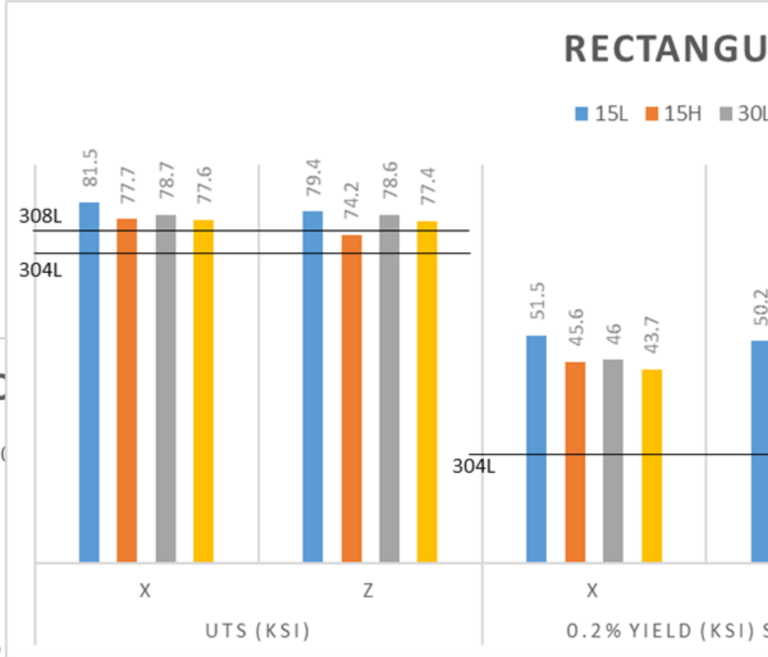
	Round (0.5-inch dia.)								
	UTS (ksi)			0.2% Yield (ksi)			Elongation (%)		
Build#	x	y	z	x	y	z	x	y	z
15L	84.3	86.3	84.7	58.5	65.6	56.4	44.5	38.7	39.9
15H	80.9	83	80.6	50.7	57.9	49	43.5	38.6	40.4
30L	80.8	85	83	52.2	60.4	51.9	44.9	36.2	39.6
30H	80.1	84	80.7	47.8	56	48.4	41.7	34.4	41.6

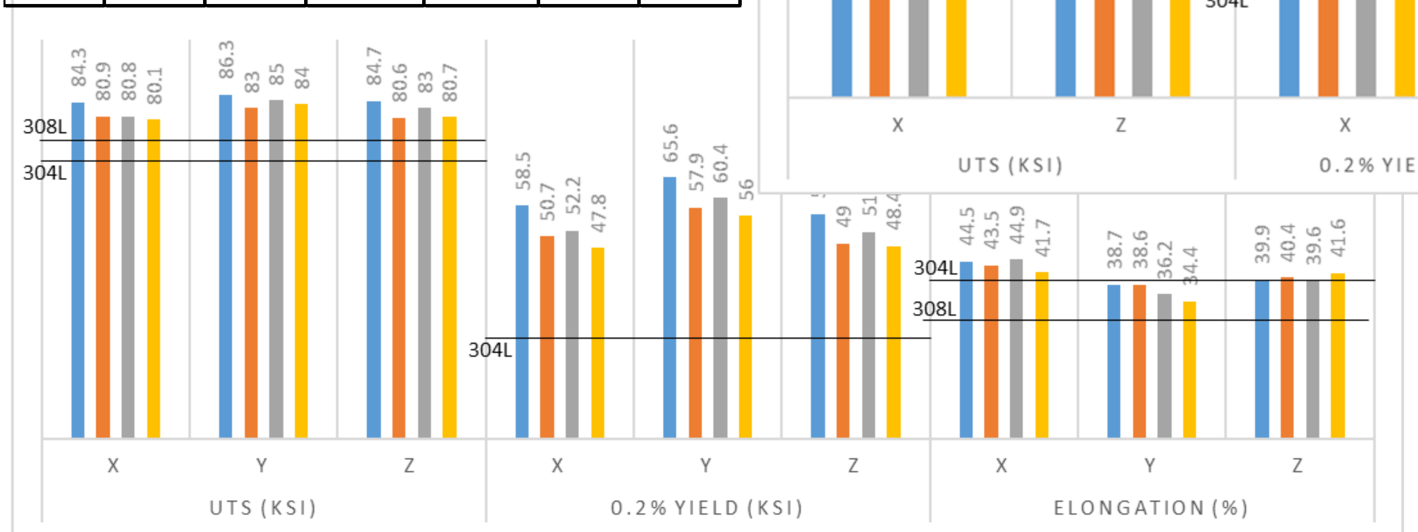
Table 3 – Wall Feature Tensile Properties.

Figure 4 – Tensile properties of block feature.

The tensile results were compared to 304L base metal per ASME SA240, and ER308L electrode per

	Retangular					
	UTS (ksi)		0.2% Yield (ksi) Stress		Elongation (%)	
Build#	x	z	x	z	x	z
15L	81.5	79.4	51.5	50.2	42.1	38
15H	77.7	74.2	45.6	44.9	44.5	40.3
30L	78.7	78.6	46	47.8	45	43.6
30H	77.6	77.4	43.7	45.6	47.1	43.7





AWS A5.9 requirement standards. Per SA240, the minimum specified requirements were 25-ksi, yield, 70-ksi ultimate and 40% elongation. For AWS A5.4, the minimum specified requirements for ER308L are 75-ksi ultimate, and 30% elongation. These minimums are shown as horizontal lines in Figure 4 and 5 bar charts.

All tensile tests exceeded ER308L tensile ultimate strength except build 15H z-direction wall feature where the strength was slightly below 75-ksi requirement at 74.2-ksi. It should be noted that AWS filler specifications only specify properties for weld metal tensiles in x- and y-direction (longitudinal) and the x- and y-direction properties exceeded AWS requirements in all build conditions. The best ultimate strength was achieved in the 15L condition where the strengths were 84.3-ksi and 81.5-ksi for block and wall features, respectively. For the block feature, the best ultimate strengths were achieved in y-direction for all build conditions. In general, ultimate strength was slightly reduced with larger bead size especially low interpass temperature.

All yield strength measurements exceeded the 304L base material requirements and all elongation measurements exceeded ER308L requirements for all build conditions and test directions. Elongations in the x-directions exceeded 304L base material requirements and averaged 43 to 45% for block feature and 42 to 47% for wall feature. Elongations

Figure 5 – Tensile properties of wall feature.

in y-direction (block feature) were under base material requirements for all test conditions and ranged from 34.4 to 38.7%. There are no weld elongation requirements for y- direction tensile tests per AWS 5.9 since the gauge section is welded section that includes base material.

The lower elongations in y-direction may be attributed to the higher yield strengths in this direction. Per Figure 4, the yield strength in the y-direction of the block features was typically higher than the x- and z-direction. Metallurgical analysis was not performed but historically these difference in ER308L yield strength and elongation are attributed to grain structure in austenitic materials. The yield strength of the block feature averaged 54.6-ksi when averaging specimens in all three directions and build conditions. Likewise, the average yield strength of all wall specimens averaged 46.9-ksi, Figure 5. Flat tensile specimens are known to produce slightly lower yield strength, compared to round tensiles, as yield instabilities occur on faster on corners. There might be grain structure effect too when comparing a single bead wide wall to multi-bead wide block material, and is an area for future metallurgical analysis,

Comparing Builds 15L to 15H, higher preheat / interpass temperature was found to produce material with slightly lower yield and ultimate strengths. The ultimate strength was found to be 3- to 4-ksi lower for block feature and 4- to 5-ksi lower for wall feature at high preheat / interpass conditions. Likewise the yield strength was found to be 7- to 8- ksi lower for block feature and 4- to 5-ksi lower for wall feature at high preheat / interpass build conditions.

Comparing builds 15L to 30L, bead size affected properties more in the block feature than the wall feature. The yield strength of the small bead build was 5.5- to 6-ksi higher in the block feature, and 2.4- 5.5-ksi higher in the wall feature than the large bead build. The greatest differences tended to be in x-direction. There was no consistent difference in ultimate strength or elongation from bead size.

Overall, the investigators were quite pleased with the quality and limited variations in properties since the builds were up to 2” wide x 4” high for x-direction 8” wide x 4” high for y-direction, and 2” wide x 6” high for z-direction build materials, Figure 1. Builds of this size could be used to a range of manufactured components. The build properties exceeded filler material properties requirements at both low and high preheat/interpass temperature in x- and y-direction. As noted, work is in-progress to develop additional qualification schemes for ferrous materials, and for single-sided and double-sided integrated build platform applications.

Conclusions

1. An arc DED AM qualification scheme was developed for austenitic builds with nonintegrated build platform. The build design provided a dimensional stable condition for producing specimens in all directions.
2. The GMAW-P process produced sound builds that met ultrasonic and radiographic inspection criteria. Bend tests further demonstrated soundness of multi-bead, multilayer deposits in different planes.
3. Tensile properties of the ER308L standard qualification build exceeded all property requirements for the ER308L filler material per AWS A5.9 in x- and y-directions.
4. ER308L builds exceeded property requirements for 304L base materials for yield and ultimate strength per ASME SA 240. Elongations were slightly lower than base metal requirement of 40% in y- and z-directions.
5. Yield strength decreased in ER308L builds with increasing bead size and preheat / interpass temperature. The greatest strengths were in the small bead and low preheat / interpass build condition.

References

1. NAVSEA Technical Publication S9074-AQ-GIB-010/248: "Requirements for Welding and Brazing Procedure and Performance Qualifications",
2. NAVSEA Technical Publication S9074-AR-GIB-010/278: "Requirements for the Fabrication Welding and Inspection, and Casting Inspection and Repair for Machinery, Piping, and Pressure Vessels",
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5. NAVSEA Technical Publication T9074-AS-GIB-010/271: "Requirements for Nondestructive Testing Methods",
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7. AWS B4.0:2016 "Standard Methods for Mechanical Testing of Welds",
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9. AWS A5.9 "Bare Stainless Steel Welding Electrodes & Rods"