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Procedure Qualification Scheme Portfolio for Metal Directed Energy Deposition Additive Manufacturing

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ABSTRACT

Standard requirements for directed energy deposition (DED) additive manufacturing (AM) of parts were needed for a new NAVSEA Technical Publication. DED procedure qualification schemes were developed for integrated and non-integrated build platforms and for both single-sided and double-sided build applications. A double-sided build platform approach is widely preferred for distortion control and build productivity. These procedure qualification requirements were developed for arc, laser, and electron beam welding-based DED processes using wire or powder consumables. Each procedure qualification scheme included a standard qualification build (SQB) design, nondestructive evaluation test map, property specimen test matrix and qualification records for each application and process combination. Since these metal AM processes cover a range of feature size capabilities that are defined by minimum deposit bead width, SQBs were designed for full-scale (~> 5 mm), sub-scale (~2 – 5 mm) and mini-scale (< 2 mm) deposit width features. As a result, there are nine baseline SQB designs that include different combinations of specimens depending on the material, scale and application. In addition, each SQB evaluated the effects of thickness using thin (single pass wide wall) and thick (multi-pass wide block) features to extract property specimens in different directions and scales. These DED procedure qualification schemes should be considered by Army compliance organizations to harmonize requirements across the Department of Defense (DOD) and reduce manufacturing qualification and certification process costs of supply chains.

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1. INTRODUCTION

Standard requirements for directed energy deposition (DED) additive manufacturing (AM) of parts were needed for a new Technical Publication (Tech Pub) – NAVSEA Process Requirements for Metal Directed Energy Deposition Additive Manufacturing. Here, the Tech Pub requirements for DED AM applications are divided into two parts: procedure qualification and part verification. Procedure qualification establishes process-feature-property relationships and can support a range of part and component DED applications. Part verification demonstrates the ability to manufacture high quality DED AM parts and components that may have specific geometric features and process control requirements. A series of projects[1] have been completed to develop a portfolio of DED procedure qualification schemes.

DED processes are used for digital manufacturing of structure, adding features to structure, and repair. As such, Tech Pub requirements need to accommodate both integrated and non-integrated build platforms (for adding features or repair) conditions. DED procedure qualification schemes were developed for integrated and non-integrated build platforms and for both single-sided and double-sided build applications. A double-sided build platform approach is widely preferred for distortion control and build productivity. These procedure qualification requirements were developed for arc, laser, and electron beam welding-based DED processes using wire or powder consumables. Each procedure qualification scheme (Figure 1) included a standard qualification build (SQB) design, nondestructive evaluation (NDE) test map, property specimen test matrix and qualification records for each application and process combination. Since these metal AM processes cover a range of feature size capabilities that are defined by minimum deposit bead width, SQBs were designed for full-scale (~> 5 mm), sub-scale (~2 – 5 mm) and mini-scale (< 2 mm) deposit width features. As a result, there are nine baseline SQB designs for plate that include combinations of tensile, bend, Charpy, hardness, metallographic, and composition specimens depending on the material, scale, and application (integrated build platform (IBP) versus non-integrated build platform (NIBP)), and single-sided versus double-sided build approach). In addition, each SQB evaluated the effects of thickness using thin (single-pass wide wall) and thick (multi-pass wide block) features to extract property specimens in different directions and scales.

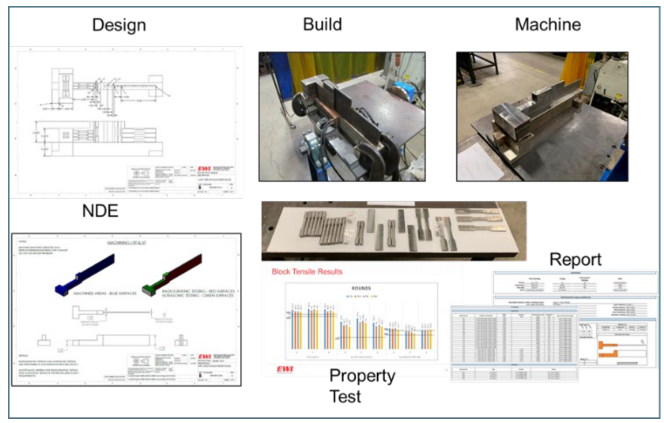


Figure 1. Procedure Qualification Scheme Elements
Select SQB Design and Property Specimen Test Matrix, Build using DED Procedure, Machine for NDE, Evaluate Surface and Volumetric NDE, Test and Evaluate Property Specimen Test Matrix, and Report AM Procedure Qualification Record.

The buildability of these SQBs and process-feature-property relationships were demonstrated using stainless steel consumables (308L wire or 316L powder). Here a gas metal arc pulse (GMA-P) full-scale NIBP SQB and a wire laser (WL) sub-scale IBP SQB were completed, and a powder laser (PL) mini-scale IBP SQB was in-process. The specimen matrix within each SQB were configured to minimize build volume and costs (Figure 2). These builds were examined with visual, surface (dye penetrant testing) and volumetric (ultrasonic and radiographic testing) inspection methods, and tested utilizing standard sets of property test specimens. The completed stainless steel DED builds showed good tolerance and consistent properties over the range of tested features.

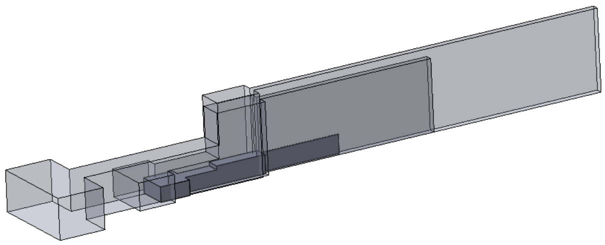


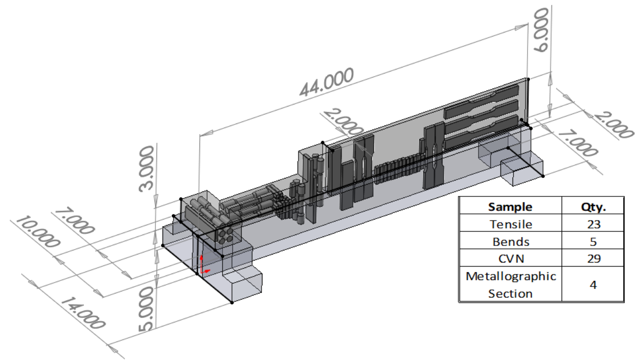
Figure 2. Build Volume Scale Comparison for Single-sided Integrated Build Platform (SS-IBP) SQBs – Full-scale 256 in.^{3}, Sub-scale 103 in.^{3}, and Mini-scale 14 in.^{3}

2. Development Approach

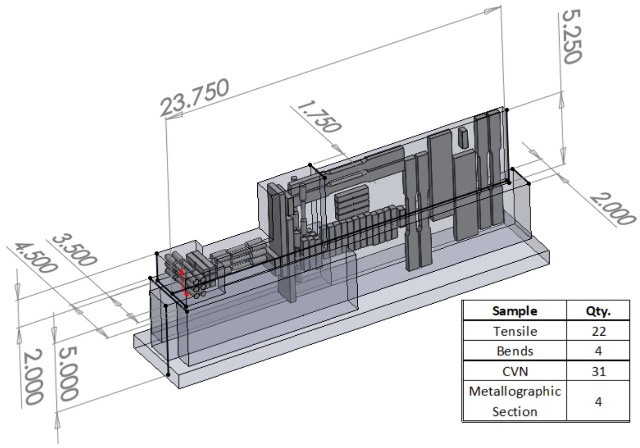
The procedure and fabrication requirements for DED AM leverage existing requirements[2-11] for welding, casting, inspecting and producing metal alloys. This includes known essential variables and relationships for arc, laser and electron beam welding processes, material preheat and inter-pass / interlayer requirements, and NDE inspection methods to name a few. A standard qualification build scheme consists of an SQB design (build platform and build design), an NDE test map, a property specimen test matrix, and a procedure qualification test report (PQTR) form. The build applications defined by these efforts are:

- Single-sided build with a flat non-integrated build platform (SS-NIBP)
- Single-sided build with a flat integrated build platform (SS-IBP)
- Double-sided build with a flat integrated build platform (DS-IBP)

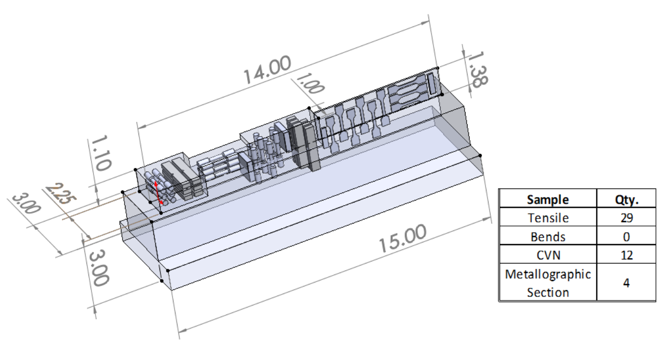
For single-sided builds, the platform was made from plates where the thickness was sized based on SQB block section thickness. Property specimens were arranged in the block and wall sections to evaluate properties in the x-, y-, and z-directions, and x- and z-directions, respectively (Figure 3 example for SS-IBP designs). The specimens were nested to minimize the build volume and cost for each application.



a) Full-scale SS-IBP



b) Sub-scale SS-IBP



c) Mini-scale SS-IBP

Figure 3. SS-IBP SQB portfolio showing specimen test matrix based on scale

A double-sided integrated build platform SQB can use thinner plate by incorporating an incremental layering approach for side 1 and side 2 during the build. By alternating layers between sides, the DS-IBP SQBs showed no observable distortion upon completion (Figure 4 example).

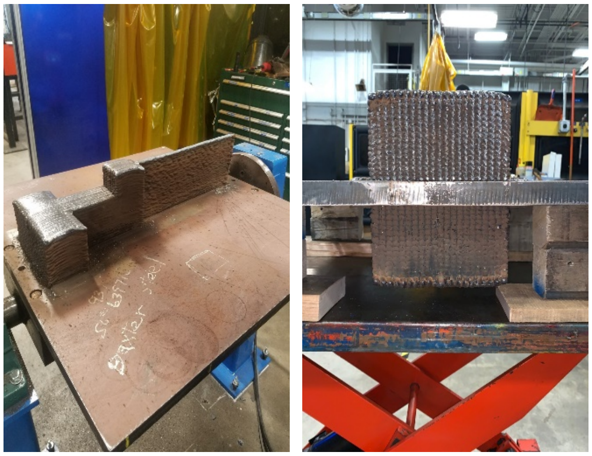


Figure 4. Full-scale DS-IBP Example on High Strength Steel

In the prior paper[1], SQB designs were developed for full-scale property specimens. In this paper, sub- and mini-scale SQBs were designed for smaller build feature processes on the three build platform applications. As a result, the DED procedure qualification scheme portfolio for plate consisted of nine different SQB applications as follows:

- FS-DS-IBP - Full-scale DS-IBP
- FS-SS-IBP - Full-scale SS-IBP
- FS-SS-NIBP - Full-scale SS-NIBP
- SS-DS-IBP - Sub-scale DS-IBP
- SS-SS-IBP - Sub-scale SS-IBP
- SS-SS-NIBP - Sub-scale SS-NIBP
- MS-DS-IBP - Mini-scale DS-IBP
- MS-SS-IBP - Mini-scale SS-IBP
- MS-SS-NIBP - Mini-scale SS-NIBP

To demonstrate the schemes on stainless steel plate platforms, the following builds were made and reported here:

- GMA-P DED on 304L FS-SS-NIBP using ER308L wire with argon - 1% CO_2 shielding.
- WL DED on 304L SS-SS-IBP using MIL-308L wire with argon shielding.
- PL DED on 316 L MS-SS-IBP using 316L powder with argon shielding.

For the ER308L GMA-P DED build, a 7-axis Motoman DED system (Figure 5) was used with a Fronius TPS 500i power supply. For the MIL-308L WL build, an 8-axis Motoman DED system and a Laserline LDF 10000-60 laser with an OTS-5 focusing optic and custom wire feed solution were used (Figure 6a). For the 316L PL DED build, an 8-axis Motoman DED system was used with a Trumpf TruDisk 6002 laser and D70 Laser Metal Deposition (LMD) system (Figure 6b).

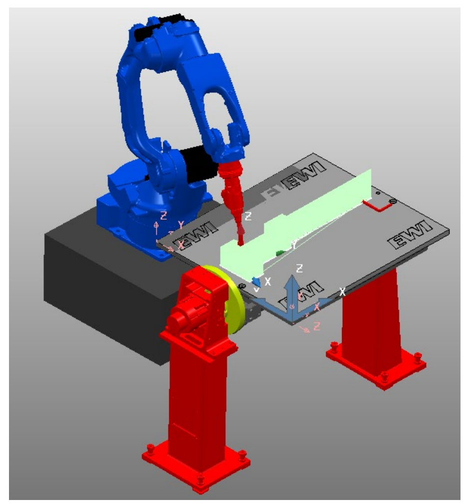


Figure 5. Digital twin of 7-axis Motoman GMA-P DED system showing a FS-SS-IBP design

a) Wire Laser DED test-bed

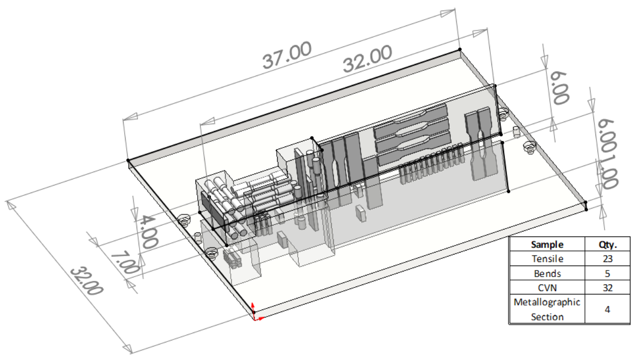
b) Powder Laser DED test-bed

Figure 6. 8-axis Motoman robotic test-beds for: a) Wire Laser DED and b) Powder Laser DED

3. Procedure Qualification Schemes

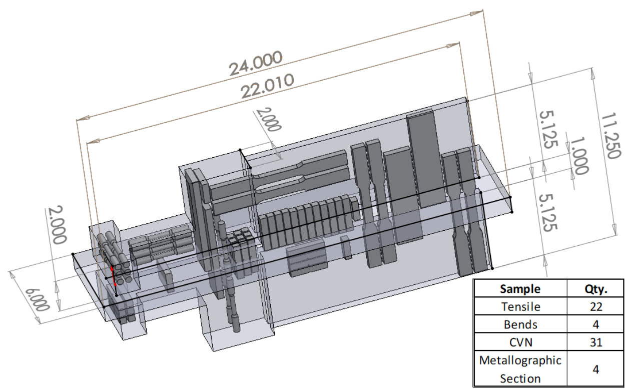
Procedure qualification schemes were developed for qualifying arc, laser and electron beam DED AM procedures for the nine scale / application / build platform conditions. Each qualification scheme consisted of the following:

a) A standard build platform designed to provided sufficient restraint.
b) An SQB design (i.e., combination of build and build platform) that provided "wall" and "block" features, and sized to provide specimens in multiple directions or planes.
c) A standard specimen test matrix for each build application. Figure 3 shows the SQB portfolio for SS-IBP and SS-NIBP (omit build interface & heat affected zone (HAZ) specimens) conditions. Figure 7 shows the SQB portfolio for DS-IBP conditions.
d) NDE test map drawing specifying NDE process evaluation coverage and requirements. Figure 8 shows an NDE test map example for the FS-SS-IBP SQB.
e) Detailed sectioning and machining drawings for all destructive test specimens (mechanical, metallurgical, composition), layout within the SQB design.
f) PQTR form for documenting all essential elements of the DED procedure and resulting mechanical, metallurgical, and composition test results.



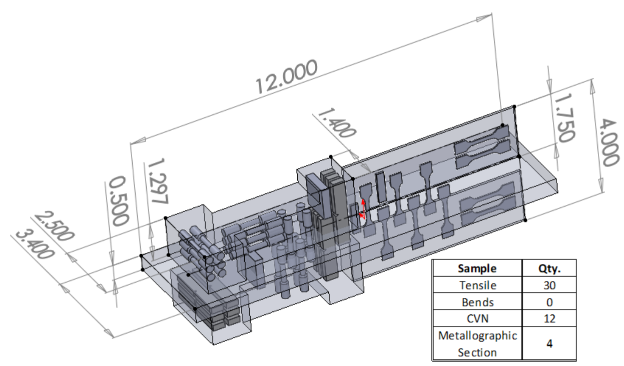
Sample	Qty.
Tensile	23
Bends	5
CVN	32
Metallographic Section	4

a) Full-scale DS-IBP



Sample	Qty.
Tensile	22
Bends	4
CVN	31
Metallographic Section	4

b) Sub-scale DS-IBP



Sample	Qty.
Tensile	30
Bends	0
CVN	12
Metallographic Section	4

c) Mini-scale DS-IBP

Figure 7. DS-IBP SQB portfolio showing specimen test matrix based on scale

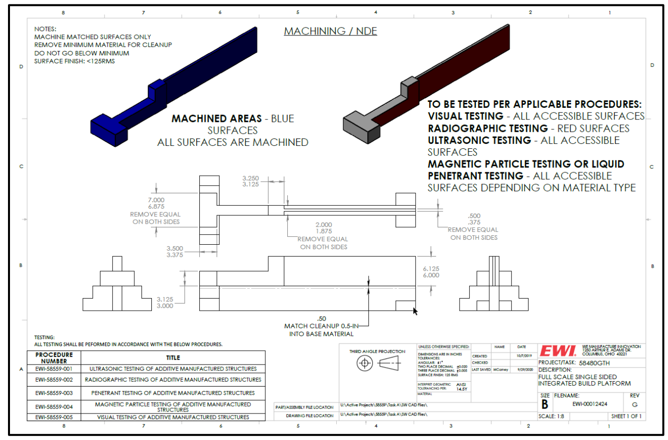


Figure 8. FS-SS-IBP SQB NDE Test Map

4. DED Build and NDE Test Results

Two qualification schemes were demonstrated, and one was in-process at the time this paper was prepared. Stainless steel full-scale, sub-scale and mini-scale SQBs were made using the GMA-P, WL and PL DED (in-process) processes respectively. The nomenclature abbreviations used to describe the SQB test conditions can be summarized as follows:

- ER308L GMA-P DED – 304L FS-SS-NIBP SQB
- MIL-308L WL DED – 304L SS-IBP SQB
- 316L PL DED – 316L MS-SS-IBP SQB

All builds were subjected to nondestructive testing (Radiographic (RT) and Ultrasonic (UT)) per NAVSEA Technical Publication T9074-AS-GIB-010/271[6] after machining using MIL-STD-2035A Class 1 nondestructive testing acceptance criteria[7].

Destructive testing[2,8] was performed in accordance with the SQB build's specimen test matrix where properties were compared to commercial ASME SA240 and MIL-E-19933E standards for base and filler materials, respectively.[9,11] Each build was inspected using ultrasonic and radiographic inspection methods where the areas within 1-inch (GMA-P DED) and 0.5-in (WL DED) of the ends (start/stop area) were ignored. If start/stop areas are incorporated in the build design, the SQB must incorporate deposit starts/stops within the build.

For GMA-P DED, high integrity start/stop methods are an area for future procedure development and testing.

The GMA-P builds were reported in the prior paper[1] and were sound. No indications were detected during RT and UT that were unacceptable to MIL-STD-2035A Class 1 requirements.

These builds evaluated both small and large bead sizes at both low (60°F/350°F) and high (500°F/750°F) preheat / inter-pass temperature conditions. The 60°F conditions were slightly below room temperature (no preheat condition). The 350°F max inter-pass was selected based on welding fabrication requirements[3] for stainless steel. The 500°F preheat and 750°F inter-pass were used to examine high inter-pass build conditions that offer higher productivity (less wait time for cooling) where the 750°F temperature was selected below the sigma phase embrittlement range that starts at approximately 800°F for stainless steel. A heating system was used for maintaining 500°F preheat for the high preheat / inter-pass temperature build condition.

For the WL DED build, the beads on a layer were produced continuously, without inter-pass temperature control, and the build temperature was controlled between layers. The build used 60°F and 350°F for the required minimum and maximum interlayer temperatures.

The temperature requirements for both the GMA-P and WL DED builds were met by using an infrared spot sensor that was integrated on each robot. The infrared sensor monitored the SQB temperature and controlled the start of each deposit for the GMA-P builds, or layer for the WL builds. For the GMA-P SQBs, each DED bead was not started until the build was below the maximum inter-pass temperature but above the minimum preheat temperature. For the WL SQB, each layer was not started until the build was above the minimum interlayer temperature but below the maximum interlayer temperature.

GMA-P DED SQB build parameters are shown in Table 1. For the ER308L GMA-P DED - 304L FS-SS-NIBP SQB, the build matrix included two bead size and two preheat / inter-pass temperature combinations (WFS = wire feed speed, TS = travel speed):

- Small bead (WFS/TS = 15) and low preheat / inter-pass (60°F/350°F) temperature,
- Small bead (WFS/TS = 15) and high preheat / inter-pass (500°F/750°F) temperature,
- Large bead (WFS/TS =30) and low preheat / inter-pass (60°F/350°F) temperature, and
- Large bead (WFS/TS =30) and high preheat / inter-pass (500°F/750°F) temperature.

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

Table 1. GMA-P DED Parameters

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 block and then formed the single pass wide wall. The block layer was made bead by bead working outward on each side of the center-bead. For GMA-P DED, the small bead builds (15L, 15H) took 1452 and 1589 passes, respectively, 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.

The MIL-308L WL DED on 304L SS-SS-IBP SQB was made using 6000W laser power. The laser work and travel angles were set at 0 degree from normal (vertical). Travel speed varied from 60 ipm for multiple pass per layer block area and 45 ipm for single pass per layer wall area. The MIL-308L, 0.045-in. diameter wire was fed into the back of the melt pool at 155 ipm. Argon shielding gas was used at a flow rate of 350 cfh.

During MIL-308L WL DED on 304L SS-SS-IBP SQB procedure development, it was determined adequate shielding gas support near the start end of the build was critical to maintain surface quality. As the build height progressively increased above the build platform surface, the build platform no longer supported uniform dispersion of shielding gas near the start end. It was hypothesized that shielding gas flow variations aspirated air into the pool and resulted in build height variations at the start end. Shims were added as the build height increased to ensure uniform shielding gas coverage near the start end of the build. As a result, the build height and geometry were demonstrated to remain very stable and consistent. The build height variations at the start were attributed to loss of pool control from air contamination. Small amounts of air can introduce oxygen into the melt pool. Oxygen is considered a surface-active element which reduces the melt pool surface tension and can promote excessive undulations at the bead starts.

The volume of the MIL-308L WL DED on 304L SS-SS-IBP SQB was 60% of that of the FS-SS-IBP SQBs. The calculated SQB build time was 13 hours for robotic deposition without interlayer temperature control. This calculated build time did not include the cool-down time between layers that was required to reach maximum interlayer temperature before the next deposit pass was started. The significant amount of time spent waiting for interlayer temperature supports the need to investigate and develop advanced inter-pass / interlayer cooling technologies, such as cryogenic cooling. Due to interlayer cooling, actual build times were 4X-5X the calculated SQB build time on builds of this size.

A total of 3,925 deposit beads were required to produce the MIL-308L WL DED on 304L SS-SS-IBP SQB (Figure 9). The lower section (single wall, thin block, and thick block) of the SQB required 2,127 beads, and the upper section (single wall and thin block) of the SQB required 1,798 beads.

The theoretical build volume for this SQB is 102.5 in.^{3}. The actual build volume for the SQB was 107 in.^{3}, which is 4% more than the theoretical build volume. The width and height of each section of the SQB were slightly greater than the specified dimensions in the build coupon drawing to enable sound build material to be present when the build was machined in preparation for NDE.

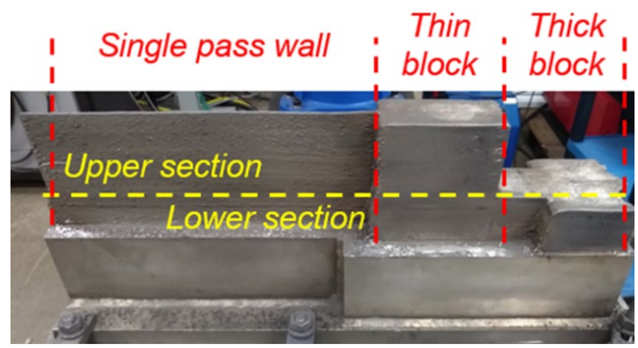


Figure 9. MIL-308L WL DED on 304L SS-SS-IBP SQB before final machining

The sides and adjacent build platform of the MIL-308L WL DED on 304L SS-SS-IBP SQB were machined to sound metal in accordance with the NDE test map. The start and stop ends of this SQB were not completely machined to sound build metal. In compliance with the draft Technical Publication, the areas within 0.5 in. of each end were not included in interpretation of the NDE results. No indications were detected during VT, RT, and UT of this SQB that were unacceptable to the Class 1 requirements of MIL-STD-2035A. One location near the top and end of the wall, that was not completely machined to sound metal, did not meet the PT requirements. This location was partially above the minimum build height, and not in an area subjected to destructive testing. Therefore, the wall thickness was not machined further to achieve sound metal in that localized area. All other locations of the SQB met the Class

1 PT requirements. The NDE data, along with the fact that no notable discontinuities were detected on the fracture surfaces of tensile test specimens or within the deposit metal (DM) and DM/HAZ metallographic sections, indicated that build soundness was acceptable and validated the NDE testing procedures and results.

5. Bend and Tensile Testing Results

For the GMA-P DED builds, and the WL DED build, all bend specimens passed with 20% elongation imposed, demonstrating soundness and ductility in y-z plane for block feature, and x-z plane for wall feature.

For the ER308L GMA-P DED - 304L FS-SS-NIBP SQBs, the 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 Table 2 and Figure 10. The tensile results were compared to 304L base metal per ASME SA240, and MIL-308L electrode requirement standards. Per SA240, the minimum specified requirements were 25-ksi yield, 70-ksi ultimate, and 40% elongation. The minimum specified requirements for MIL-308L are 75-ksi ultimate, and 35% elongation. These minimums are shown as horizontal lines in the Figure 10 bar charts.

Table 2. ER308L GMA-P DED Deposit Material (DM) average tensile properties for block (round specimens) and wall (rectangular specimens)

	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

	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

All tensile tests exceeded the MIL-308L tensile ultimate strength except for one specimen from build 15H z-direction wall feature where the strength was slightly below the 75-ksi requirement at 73.8-ksi. It should be noted that filler wire specifications only specify properties for weld metal tensile specimens in x- and y-directions and the x- and y-direction tensile properties exceeded requirements in all GMA-P DED build conditions. The best ultimate strength in the x-direction was achieved in the 15L condition where the average 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 and higher inter-pass temperature.

All yield strength measurements exceeded the 304L base material requirements and all elongation measurements exceeded MIL-308L requirements[11] for all build conditions and test directions. Elongations in the x-direction exceeded 304L base material requirements and averaged 41.7 to 44.9% for block feature and 42.1 to 47.1% for wall feature. Elongations in the y-direction (block feature) were under base material requirements for all test conditions and the averages ranged from 34.4 to 38.7%. There are no weld elongation requirements for the y- direction weld tensile tests in MIL-E-19933E since the gauge section includes base material.

The lower elongations in the y-direction may be attributed to the higher yield strengths in this direction. Per Figure 10, 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 differences in 308L 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 was 46.9-ksi, Figure 10. Rectangular tensile specimens are known to produce slightly lower yield strength, compared to round tensile specimens, as yield instabilities occur faster on corners. Grain structure may affect tensile properties when comparing 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 / inter-pass temperature was found to produce material with slightly lower yield and ultimate strengths. The average 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 / inter-pass conditions. Likewise, the average 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 / inter-pass build conditions.

Comparing builds 15L to 30L, bead size affected properties more in the block feature than the wall feature. The average yield strength of the small bead build was 4.5- to 6.3-ksi higher in the block feature, and 2.4- to 5.5-ksi higher in the wall feature than the large bead build. The greatest differences tended to be in the 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 GMA-P DED properties since the builds were up to 2-in wide x 4-in high for the x-direction, 8-in wide x 4-in high for y-direction, and 2-in wide x 6-in high for z-direction build materials. Builds of this size could be used for a range of manufactured components. The build properties exceeded filler material properties requirements at both low and high preheat/inter-pass temperature in x- and y-direction.

The mechanical testing results for the MIL-308L wire laser DED on 304L SS-SS-IBP met the requirements of referenced specifications[9,11] (Figure 11). This SQB had specimens that evaluated both the build DM and the DM / HAZ interface. The block DM tensile and x-axis wall DM tensile specimens met the tensile strength and elongation requirements of MIL-308L wire.

Two of the z-axis wall DM tensile specimens met the tensile strength requirement of MIL-308L wire, but due to yielding outside of the gauge length, the elongation values were voided. For the two z-axis wall DM tensile specimens, one end of the reduced section coincided with the DM/HAZ interface, so the yielding occurred in the softer build platform HAZ. It is recommended that for future SQB designs and SQB design iterations, all z-axis DM tensile specimens be located with the specimen's reduced section and radii entirely in build deposit material. The DM/HAZ interface tensile specimens for both the block and the wall met the minimum tensile strength requirements of both the MIL-308L wire and the 304L base material. The bend test specimens, which were tested with 20% elongation, all passed.

The chemistry of the DM block metallographic section was within the limits of the specification for MIL-308L wire. The DM wall metallographic section had chromium that was about 1% less than the lower limit of the specification; the source of Chromium loss should be investigated in the future.

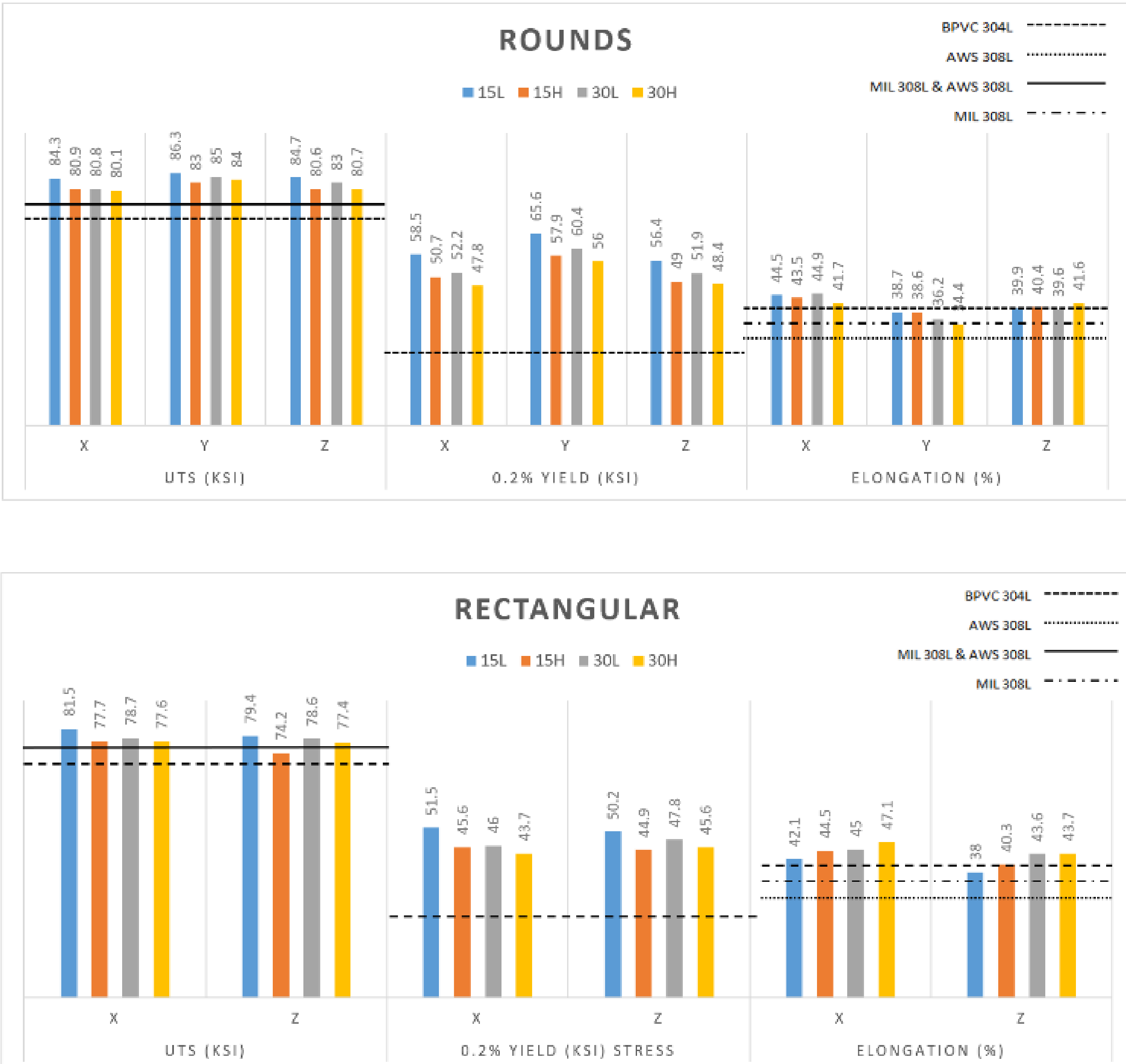


Figure 10. ER308L GMA-P DED DM average tensile properties for block (round specimens) and wall (rectangular specimens)

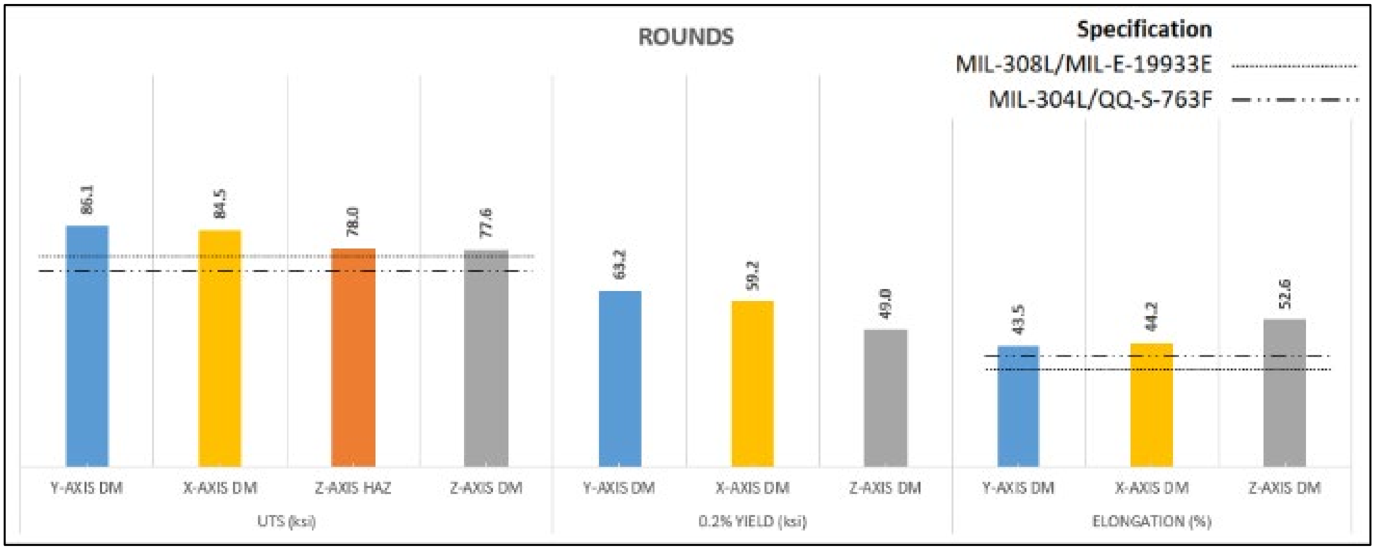


Figure 11 Continued. ER308L GMA-P DED DM average tensile properties for block (round specimens) and wall (rectangular specimens)

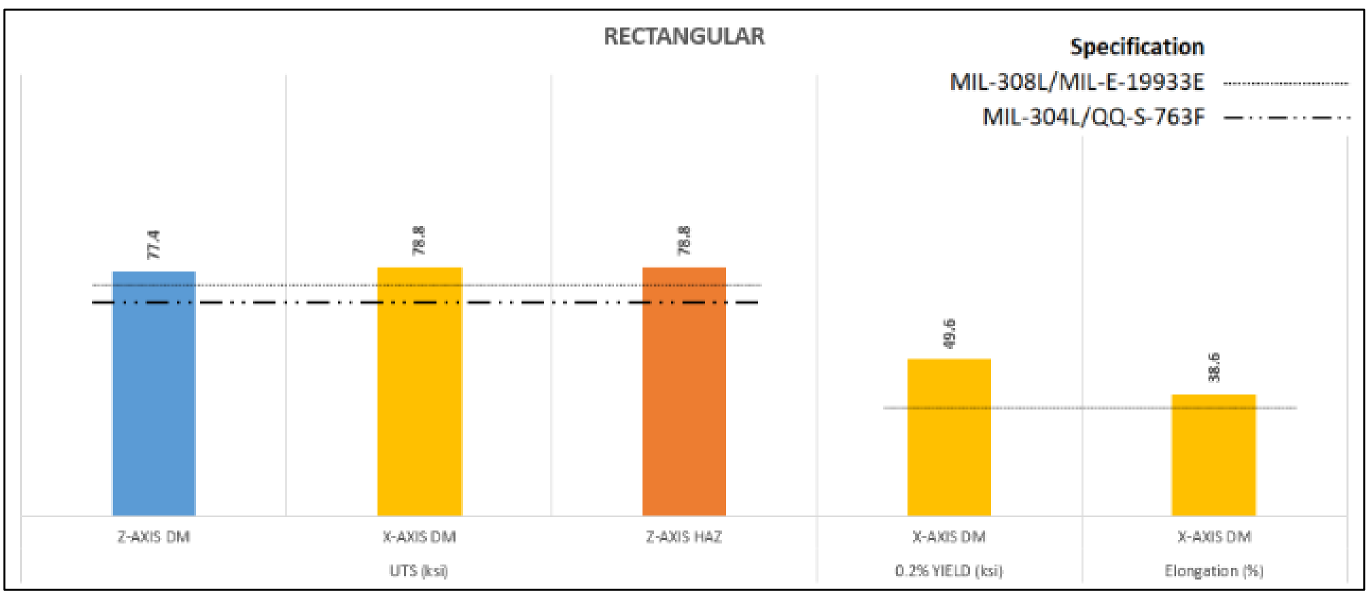


Figure 12. MIL-308L WL DED DM and DM / HAZ Interface (HAZ) average tensile properties for block (round specimens) and wall (rectangular specimens)

Conclusions

1. A prescriptive qualification scheme provides a clear path to accelerate implementation of high impact DED AM technology. These DED procedure qualification schemes should be considered by Army compliance organizations to harmonize requirements across the Department of Defense and reduce manufacturing qualification and certification process costs of supply chains.
2. The sub-scale SQB designs had theoretical volumes that were 55% (SS-SS-NIBP), 60% (SS-SS-IBP), and 62% (SS-DS-IBP) less than that of the comparable full-scale SQB designs.
3. The GMA-P and WL DED processes produced sound builds that met ultrasonic and radiographic inspection criteria. Bend tests further demonstrated soundness of multi-bead, multilayer deposits in different planes.
4. Tensile properties of the ER308L GMA-P DED FS-SS-NIBP SQBs exceeded all property requirements for MIL-308L filler wire in the x- and y-directions. These builds exceeded property requirements for 304L base material for yield and ultimate strength per ASME SA 240. Elongations were slightly lower than the base metal requirement of 40% in the y- and z-directions.
5. Yield strength decreased in ER308L GMA-P DED builds with increasing bead size and preheat / inter-pass temperature. The greatest strengths were in the small bead and low preheat / inter-pass build condition.
6. The mechanical testing results for the MIL-308L WL DED on 304L SS-SS-IBP SQB met the requirements of the corresponding referenced specifications. The DM/HAZ interface tensile specimens for both the block and the wall met the minimum tensile strength requirements of both the MIL-308L wire and the 304L base material.

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