Mechanical Property and Fabrication Cost Comparison of Purchased HFRW Structural Shapes vs. GMAW Fabricated Structural Shapes Panel Project

May 18, 2018

EWI Project No. 56788GTH

NSRP Subcontract No. 2017-419

Submitted to:
National Shipbuilding Research Program
Summerville, SC

Public Release
Electric Boat public release authorization MTPR/MRV-18-014

Data Category B
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Report

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on

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April 30, 2018

David Workman, William Mohr, Nancy Porter, Steven Blevins
EWI
1250 Arthur E. Adams Drive
Columbus, OH 43221

Robert Gillies, Mike Acquaviva, Roger Ball, Peter DiNapoli
General Dynamics Electric Boat
75 Eastern Point Rd.
Groton, CT 06340-4989

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Executive Summary

The objective of this project was to determine the design equivalency between purchased commercial, off the shelf ("COTS") High Frequency Resistance Welded (HFRW) standard shape square tube to COTS plate fabricated gas metal arc welded (GMAW) square tube in terms of physical strength and fabrication costs. To determine design equivalency, static and fatigue mechanical tests were performed. The HFRW tubes performed better than the GMAW tubes in four-point bend fatigue testing, which showed at least a two-fold increase in fatigue life. Since the base materials used had similar yield strengths, this would indicate that the tube design and fabrication method have an impact on fatigue life. The weld strength in both tube designs was adequate. However, the Charpy V-notch (CVN) toughness of the HFRW weld was not as good as expected, as the HFRW tube had not been tempered. Post-weld tempering will increase the toughness of the HFRW weld and produce acceptable CVN results; the necessary post-weld tempering parameters can be determined in future research. Overall, this study shows the use of HFRW tubes could be pursued to achieve a significant cost savings per foot, at least a two-fold increase in four-point bend fatigue performance, and structural weight reduction. The return on investment is estimated to be 1.86 for current construction and 0.71 for future construction.

Abbreviated Terms

CVN	Charpy V-notch
DT	destructive testing
GMAW	gas metal arc welding
HFRW	high frequency resistance welding
HSS	high-strength steel
HSLA	high strength low alloy steel
HY	high-tensile, high yield strength, low alloy steel
NAVSEA	Naval Sea Systems Command
NDT	nondestructive testing
NRE	non-recurring engineering
NSWCCD	Naval Surface Warfare Center – Carderock Division
TWH	Technical Warrant Holder
UTS	ultimate tensile strength

1.0 Introduction

In the early 1980s, NAVSEA approved Ingalls and Bath Iron Works to use HSLA-80 t-stiffeners designed for HFRW and installed them on the CG-47 guided missile cruisers (Aegis Class). CG-47 cruisers are still in service and there have been no reported failures of the HFRW t-stiffeners in their 30+ years of service. After all ship sets were provided for the Aegis Class, the HFRW t-stiffener supplier went out of business and the Navy did not establish another supplier. Therefore, some level of re-qualification is needed to enable use of HFRW HY-80 shapes on existing or planned ship platforms.

Electric Boat is investigating alternatives for HY-80 fabricated shapes. While HFRW hollow structural shapes ("tube") in HSS steel grades per ASTM A-500 are approved for submarine use the high-strength low alloy steel grades (HSLA-80 /HY-80) are not. Electric Boat is interested in using HY-80 HFRW tube as it is believed to be equivalent in strength to the GMAW fabricated HY-80 tube currently used in submarine and surface ship construction.

An industry search identified Thermatool as a leader in HFRW technology and Electric Boat has discussed opportunities with Thermatool to incorporate HFRW structural shapes. HFRW standard tube shapes are manufactured differently than GMAW fabricated tube. GMAW fabricated square tube manually fits two "L" shaped manually formed plates to two backing bars see Figure 1. HFRW shape is formed by a mechanized roller conveyor which continuously feeds sequentially formed plate into the HFRW welder, see Figure 2. This process eliminates all manual forming and fitting and produces a dimensionally accurate and consistent product. By replacing fabricated HY-80 tube with purchased HFRW standard shapes, Electric Boat will realize a significant reduction in piece part counts, direct / support labor, construction span, decreased welding shrinkage and distortion (improved dimensional consistency), and improved fatigue life

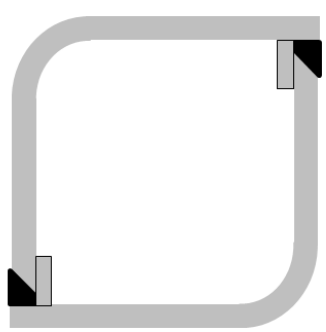

Figure 1. Tube Designed for GMAW

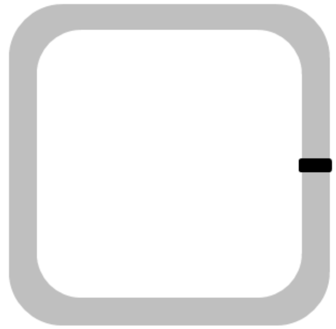

Figure 2. Tube Designed for HFRW

Electric Boat is currently engaged in several cost reduction initiatives to implement the use of HFRW structural shapes in current and future ship designs: Fast Fit, Design for Affordability and Structural Process Improvement.
This project will demonstrate equivalency between a purchased HY-80 HFRW tube versus the corresponding baseline fabricated GMAW tube in terms of physical strength and will compare fabrication costs. Project results will be used by Electric Boat to leverage/supplement the above ongoing.
Moving from HSLA/HY grade tube designed for GMAW to HSLA/HY HFRW tube supports the call for improved quality in ship design, construction, and repair through continuous improvement of advanced technologies and processes.

2.0 Objectives

The goal of this project was to demonstrate equivalency between a purchased HFRW tube design versus the corresponding baseline fabricated GMAW tube design in terms of physical strength and to compare fabrication costs.

Specific objectives for this project include:

- Demonstrate and compare static strength.
- Demonstrate and compare fatigue strength.
- Compare purchased tube cost to estimated GMAW fabrication costs.

Project results will be used by Electric Boat to leverage/supplement ongoing efforts to implement HY-80 HFRW tube into their designs.

3.0 Experimental Procedure

3.1 Material Selection

The original plan was to test tubes made from HY-80 or HSLA-80 material. Thermatool provided the team with a quote for HSLA-80 or HY-80 HFRW tube that would require purchasing a mill run of material for $420K. Thermatool then provided a quote to provide 13 HSLA-80 or HY-80 HFRW tubes for $73K. As both options were prohibitively expensive, EWI asked Thermatool to find another solution. After 10 months of extensive search for materials, Thermatool found 10 tubes made from similar material (CSA G40 20-13/G40 21-13 Grade 480WT) for $14K.

Table 1 contains the chemical composition requirements of HSLA-80 per MIL-S-24645 (excerpts of which are in Appendix A), CSA G40 20-13/G40 21-13 Grade WT480 (excerpts of which are in Appendix B), and ASTM A656 Grade 80 (excerpts of which are in Appendix C). The Grade 480WT is a Canadian high toughness weldable steel that is low in Ni, Cr, Mo, V, and Cu.

Table 1. Material Compositions

Element	HSLA-80 per MIL-S-24645	Grade 480WT per CSA G40 20-13/G40 21-13	ASTM A656 Grade 80
	Ship Material	HFRW Tube Material	GMAW Tube Material
	Weight %	Weight %[1]	Weight %
Carbon	0.06	0.07	0.18
Manganese	0.40-0.70	1.41	1.65
Phosphorus	0.020	0.011	0.025
Sulfur	0.006	0.002	0.030
Silicon	0.40	0.13	0.60
Nickel	0.70-1.00	0.012	
Chromium	0.60-0.90	0.037	
Molybdenum	0.15-0.25	0.002	
Copper	1.00-1.30	0.11	
Niobium[2]	0.02-0.06	0.15[3]	0.008-0.10
Vanadium			0.08-0.15
Titanium			0-0.15
Aluminum		0.033	

The revised plan was to weld GMAW tubes from the same CSA Grade 480WT material used for the HFRW tubes. After an extensive effort to procure a similar CSA grade of material for the GMAW tubes, only one similar material (ASTM A656 Grade 80) was obtainable during the project's period of performance. ASTM A656 Grade 80 plate was obtained for GMAW specimens.

There was a concern the CSA Grade 408WT material (available for testing) is not age hardenable. Naval Surface Warfare Center - Carderock Division (NSWCCD) concurred with using CSA Grade 408WT as long as HFRW and GMAW specimens were fabricated with the same material type and subjected to fatigue and other mechanical testing to obtain an apples-to-apples comparison. Since only similar materials could be procured, mechanical tests were requested for all base materials and all welded materials evaluated during this study.

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[1] Actual chemistry from the mill certification.
[2] Niobium and Columbium (Cb) are different names the same element in the periodic table. Cb is used the MIL and ASTM specifications used in this report
[3] See Table 3, Footnote (c) in CSA G40.20-13/G40.21-13 (see Appendix B).

As no precipitation or age hardenable steels were available for purchase, fine-grained weldable steels that were available were used. These steels were rated for low temperature toughness but were not capable of producing any appreciable toughness at the -120°F Navy temperature.(1) The A656 Grade 80 and the CSA Grade 480WT did reportedly have toughness in the -60°F regime and with special treatments could show moderate toughness below -80°F.(2) Reviewing papers such as Smith et al.,(3) a test temperature of -60°F was selected as the steels would have incoming toughness that could be impacted by the welding procedure. Although the project was not focused on welding toughness for the materials/process combination, the opportunity to learn how these steels might fair at moderate temperatures was used to assess the HFERW process.

3.2 Mechanical Testing

Limited mechanical testing was conducted to establish the relative performance of the HFRW tube design versus the GMAW tube design. EWI conducted the fatigue testing and the mechanical testing listed in Table 2.

Table 2. Mechanical Testing

Mechanical Test	Weld Type	Test Coupon Quantity
Fatigue	GMAW	3
	HFRW	3
Charpy	GMAW	6
	HFRW	6
Metallography	GMAW	2
	HFRW	2
Root Bends	GMAW	3
	HFRW	3
Face Bends	GMAW	3
	HFRW	3
Transverse Tensiles	GMAW	3
	HFRW	3
Transverse Tensiles (base metal only)	GMAW	3
	HFRW	3
Charpy (base metal only)	GMAW	6
	HFRW	6

3.2.1 Static Testing

The fatigue tests listed in Table 2 were conducted with HFRW tube and GMAW tube designs. The other mechanical tests in Table 2 were conducted with test coupons cut from GMAW welded specimens and HFRW tube.

Since shipyard materials were not used, there were no required NAVSEA acceptance criteria for nondestructive testing (NDT) or destructive testing (DT) that could be used to compare weld performance. To compare the performance of the base materials, the GMAW welds, and the HFRW welds, the team selected acceptance criteria for the base materials where possible (if extant). Where no base material property data existed, Tech Pub 248 NDT or DT requirements were used.

Per Tech Pub 248 (Table VII, Footnote 2(a)), Charpy testing is required for "…1/2 inch and over in material thickness when both the base metal specification and the filler metal specification have impact requirements". Since ASTM A656 base material does not require Charpy impact testing and the CSA Grade 480WT material was tested to temperatures outside the required temperatures, the impact testing was performed to generate data points for comparison only. The materials used here would not likely meet any NAVSEA requirements despite being called low-temperature toughness material.

Per Tech Pub 248 requirements and AWS B4.0 testing procedures, acceptance criteria for the Charpy tests, root bends, face bends, and transverse tensile tests are listed below. There were no required NAVSEA acceptance criteria. The criteria below were selected as a "yard stick" against which to compare material/weld performance.

CVN acceptance criteria:

- CSA G40 20-13/G40 21-13 Grade 480WT = 20 ft-lbs. at -20°F
- ASTM A656 Grade 80 = no requirements per the specification

Bend testing acceptance criteria is based on welding filler metal type:

- CSA G40 20-13/G40 21-13 Grade 480WT = 22% minimum elongation
- ASTM A656 Grade 80 = 22% minimum elongation
- Equation in AWS B4.0 used to calculate bend radius.

Transverse tensile testing acceptance criteria - ultimate tensile strength (UTS):

- CSA G40 20-13/G40 21-13 Grade 480WT = 85 ksi UTS minimum
- ASTM A656 Grade 80 = 90 ksi UTS minimum, with 15% elongation over 2 in.

3.3 Fatigue Testing

Fatigue testing was conducted to compare the bending fatigue life of HFRW versus GMAW tube designs. This is a simple test to compare the actual geometric effect of the tubes in bending. Given the fact that this program will not be used to support certification, NSWCCD recommended that EWI use its engineering judgement to design the fatigue tests run in this project.

Based on this direction, EWI decided to conduct a four-point bend test in fatigue, with a stress range that theoretically would cause a failure between 50,000 cycles and 2,000,000 cycles in both structure designs. EWI bound the run out based on prior/similar work found in the literature for comparison purposes (e.g., fatigue design curves of similar joint categories in D1.1 or Eurocode 3: BS EN 1993-1-9, or something similar, to select a run out).

The two designs are slightly different in that the HFRW-welded sample was symmetrical about both the horizontal and longitudinal planar axes, whereas the GMAW-welded tube was symmetric about one diagonal planar axis due to the opposing reinforcements. The backing bar reinforcements were not included in the calculations for testing stress, as there is no significant benefit from their addition.

Testing was conducted at a load to place the outer fibers of the tube in 35,000 PSI tensile stress with an R of +1 (see explanation below for stress justification). The testing was stopped based on sensing an increased amount of deflection with a consistent load application. This increased deflection acted as the crack detection system. This approach is used in many tests as it allows the machine to make an objective comparison of tubes or other structures tested in fatigue. The increased deflection in this case indicated that a crack had grown to the point of impacting the integrity of the tube in bending. Cracking that was visible could occur without detection, but without significantly affecting the stiffness of the tube.

The appropriate joint class was selected for the HFRW and GMAW joints and a load selected that would guarantee a failure in less than 2,000,000 cycles. The HFRW tube best fits into a Class B joint design and the GMAW tube best fits into a Class D joint per British Standard BS 7608/1993. The corresponding average fatigue life for 2,000,000 cycle life of each of the joints in the prescribed time was estimated at 15 KSI for the GMAW tube and 30 KSI for the HFRW tube at run-out load per BS 7608/1993 page 100 showing the S-N curves for the different corresponding designs in Figure 3 below. The load was therefore increased to 35 KSI to ensure failures.

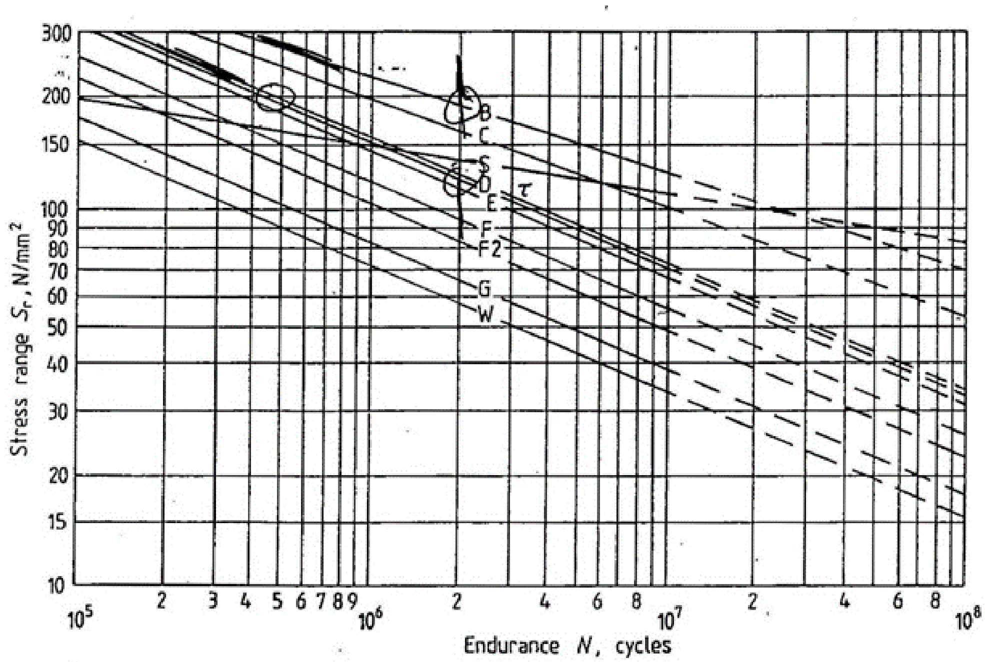


Figure 3. **S-N Curves for Different Weld Joint Classes in Welded Tubing**

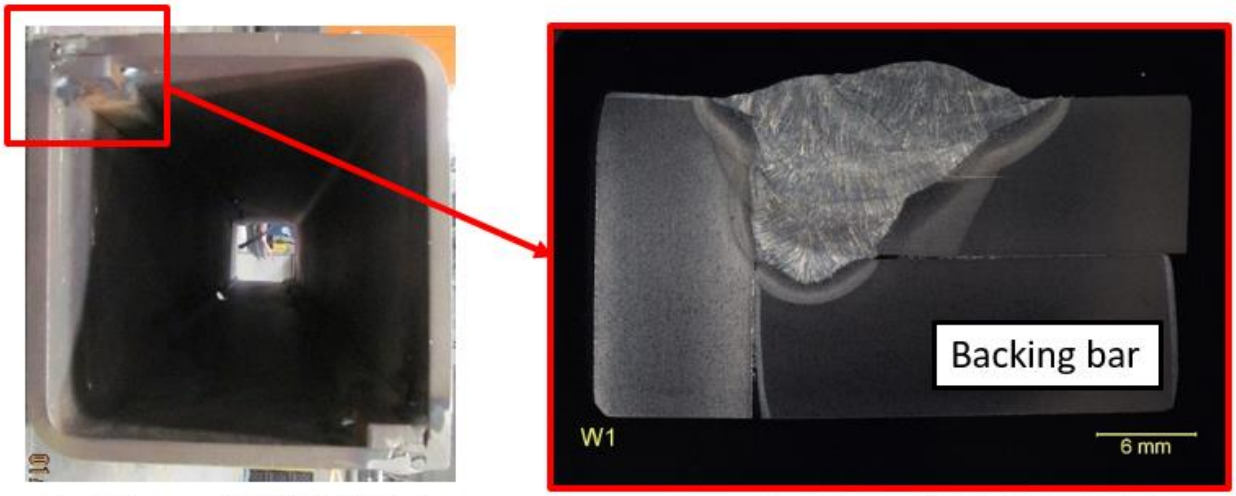
3.4 Test Specimen Production

The team determined the size, shape, and quantity of fatigue and static test specimens to be produced for the testing. Electric Boat produced GMAW specimens (the baseline) and Thermatool provided HFRW specimens.

3.4.1 Test Specimens

3.4.1.1 GMAW Process Specimens (baseline)

Based on current production data, Electric Boat identified a GMAW fabricated tube design to use as the baseline (Figure 4). The GMAW tube is 7×7 in. with a wall thickness of 0.38 in. (these are the same dimensions as the selected HFRW tube). GMAW tubes were welded using current Electric Boat practices. The GMAW tubes were produced from ASTM A656 Grade 80 material.



End View of GMAW Tube

Cross Section of GMAW Weld

Figure 4. Baseline GMAW Tube Design

GMAW tubes are made from cut and beveled plate press formed into two L-shaped sections. The “L” shaped plates are then fit to two backing bars which run the length of the tube; assembly of these four piece parts forms the tube shape. Fitting requires much measurement, requires highly skilled trades and is labor intensive. The piece parts are tack welded together after fit-up but before final welding. However, the dimensional variability of fabricated GMAW tube is much greater than HSS tube made by HFRW. The dimensional variability in the shape makes does not adequately support mechanized welding processes and makes for a poor candidate for robotic / automated welding. The multiple welds required to complete fabrication of the tube create geometric variability caused by welding shrinkage and distortion which affects installation of the tube and / parts joined to the tube in downstream construction.

As shown in Figure 4, the welds in a GMAW tube design are in two opposing corners. This configuration does not lend itself to producing Charpy, bend, or tensile test coupons. To make the required Charpy, bend, and tensile test coupons, Electric Boat GMAW welded ASTM A656 Grade 80 plates with a B1V.5 single bevel groove weld (Figure 5) as defined by MIL-STD-22D. Figure 6 contains a photo of the 0.38-in. thick plates prepared for welding. The long plate was prepared with a 45-degree included angle single bevel; the rolling direction was parallel with the length of the plate. The small plates were prepared with a square butt weld and the rolling direction is shown with white arrows. The small plates were welded to the long plate with a 0.25-in. wide gap (weld location shown as a red line). The small plates were not welded to each other.

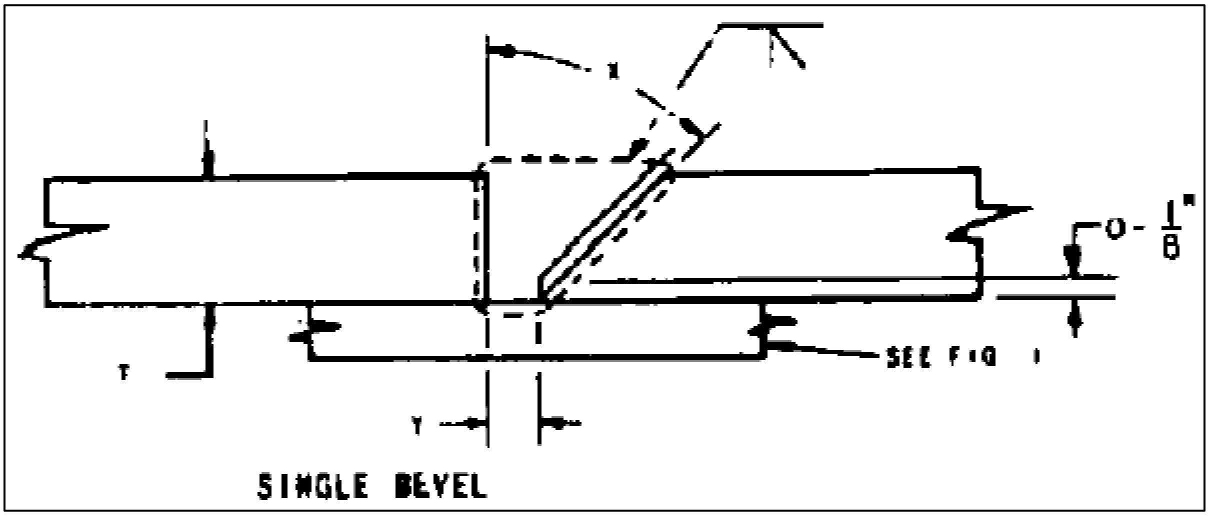


Figure 5. B1V.5 Weld Joint for GMAW Mechanical Test Weld Specimen

Figure 6. GMAW Mechanical Test Specimen Prepared for Welding

3.4.1.2 HRFW Process Specimens

For testing, Thermatool identified a HFRW tube made from CSA Grade 480WT. Tube dimensions were 7×7 in. with a wall thickness of 0.38 in. Photos of an as welded HFRW tube is shown in Figure 7. Since the HFRW weld is in the middle of the tube side wall, Charpy, bend, and tensile test coupons were easily extracted from an as-welded tube section.

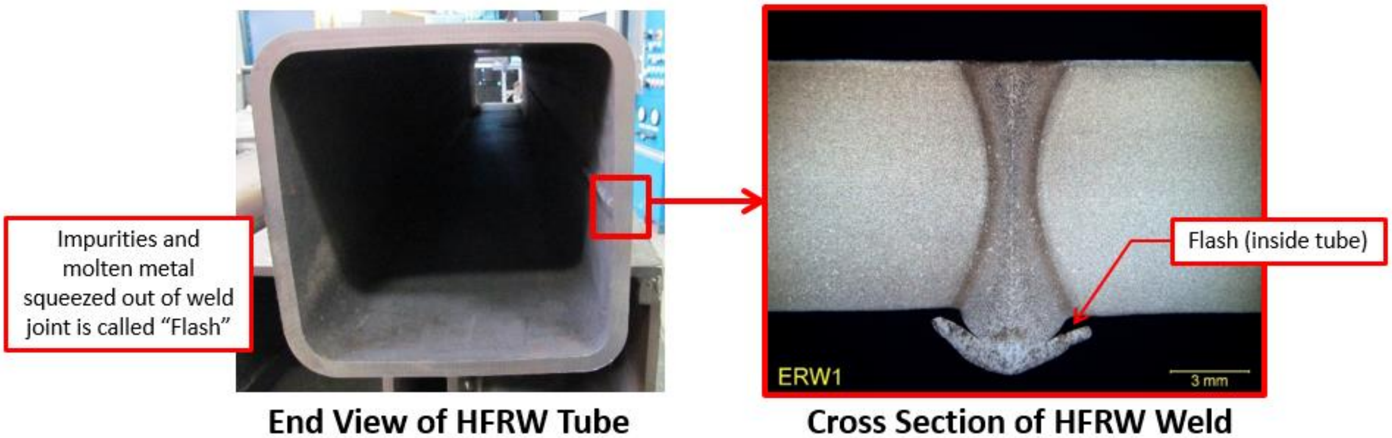


Figure 7. As-welded HFRW Tube Specimen

The HFRW process is a high production rate process that produces a solid-state weld down the axial length of tubing in a consistent manner. The process is set up at the end of a roll forming line and welded tube is produced in a continuous fashion from coil end to coil end. The HFRW lines runs at a comparatively high rate of speed and a large volume of tubing can be produced in a very short period. The labor content in this process is very low compared to other traditional arc welding processes. As the process is solid state, the machine controls the process taking properly slit flat sheet, rolling it into the correct geometry, producing a weld to form a tube, and shearing the weld flash from the outer diameter of the tube. This process creates a tube that is uniform from the start of the coil to the end.

The reduced labor content in the tube, speed, and elimination of multiple forming steps significantly reduces the cost of the HFRW tubing. It is likely, however, that the biggest cost savings is due to the consistent tube size. As the tubing is produced in a roll forming mill, the forming is consistent from the start of the coil until the end of the coil. This consistency allows the tubes to be installed with significantly reduced fit-up labor currently required to account for the variability of size and welding distortion present in GMAW tube designs.

3.5 Conduct Business Case Analysis

A limited business case analysis was conducted to establish the relative costs for both purchased HY-80 tube and fabricated HY-80 tube. Electric Boat conducted the business case analysis and documented the differences in fabrication processing time, process steps (e.g., set-up time, the equivalent of arc on time, production rate, processing steps, etc.) and cost.

3.6 NAVSEA Stakeholder Feedback

The project team liaised with Matt Sinfield of NSWCCD who represented the interests of the Welding Technical Warrant Holder (TWH) Joe Blackburn and Structural TWH Jim Gardner. The project team also liaised with former NAVSEA TWH (Allen Manuel) who approved the previous use of HFRW t-stiffeners on the Aegis Class cruisers. NAVSEA input is incorporated throughout the report and in the recommendations.

4.0 Results and Discussion

4.1 Fatigue Testing

4.1.1 GMAW Tube Design – Fatigue Test Results

The fatigue test results for GMAW tube design are shown in Table 3.

Table 3. GMAW Tube Design – Fatigue Test Results

Sample Number	Applied Loading (lbs)			Fatigue Life (cycles)	Comments
	Maximum	Minimum	Range		
Arc-#1	133818.410	13381.8	120436.6	122,004	Corners failed at the roller site
Arc-#2	133818.889	13381.9	120437.0	203,628	Corners failed at the roller site
Arc-#3	133818.889	13381.9	120437.0	96,683	Corners failed at the roller site

4.1.2 HFRW Tube Design – Fatigue Test Results

The fatigue test results for HFRW tube design are shown in Table 4.

Table 4. HFRW Tube Design – Fatigue Test Results

Sample Number	Applied Loading (lbs)			Fatigue Life (cycles)	Comments
	Maximum	Minimum	Range		
HFW-#C3	133818.889	13381.9	120437.0	206,096	Corners failed at the roller site
HFW-#C2	133818.889	13381.9	120437.0	412,473	Corners failed at the roller site
HFW-#B4	133818.889	13381.9	120437.0	328,113	Corners failed at the roller site bottom

4.1.3 Fatigue Test Results Comparison

The fatigue tests of the HFRW tubes lasted longer than the fatigue tests of the GMAW-welded tubes. The GMAW tubes lasted an average of 140,772 cycles to failure. The HFRW tubes lasted an average of 315,561 cycles to failure. This is a factor of two increase in the life of the HFRW tube reflecting the design differences between the two geometries. As the steels had very similar yield strengths, this suggests that the design of the tube is the source of the difference in fatigue performance. This conclusion is further supported as the failure locations were not at the weld joints but were influenced by the design of the GMAW tubes.

The GMAW tube design appears to create a structure that relies on one side of the tube to accommodate the tensile strain in loading. Subsequently, tube rotation occurred, and the rotation is significant enough to cause permanent deformation of the tube shown in Figure 8 (indicated by red triangle next to square edge). Figure 9 shows that the HFRW tube still retains the initial tube symmetry after fatigue testing.

Figure 8. Residual Asymmetry in the GMAW Tube Deformation after Fatigue Testing

Figure 9. Symmetry in the HFRW Tube Deformation after Fatigue Testing

Cracking occurred on one side of the GMAW tube in the area of the 90-degree bend as shown in Figure 10 (top view). A close-up side view of this cracking and deformation is shown in Figure 11. Cracking occurred on two sides of the HFRW tube as shown in Figure 12. A close-up side view of this cracking and deformation is shown in Figure 13.

Figure 10. Large Failure Site Cracking in GMAW Tube

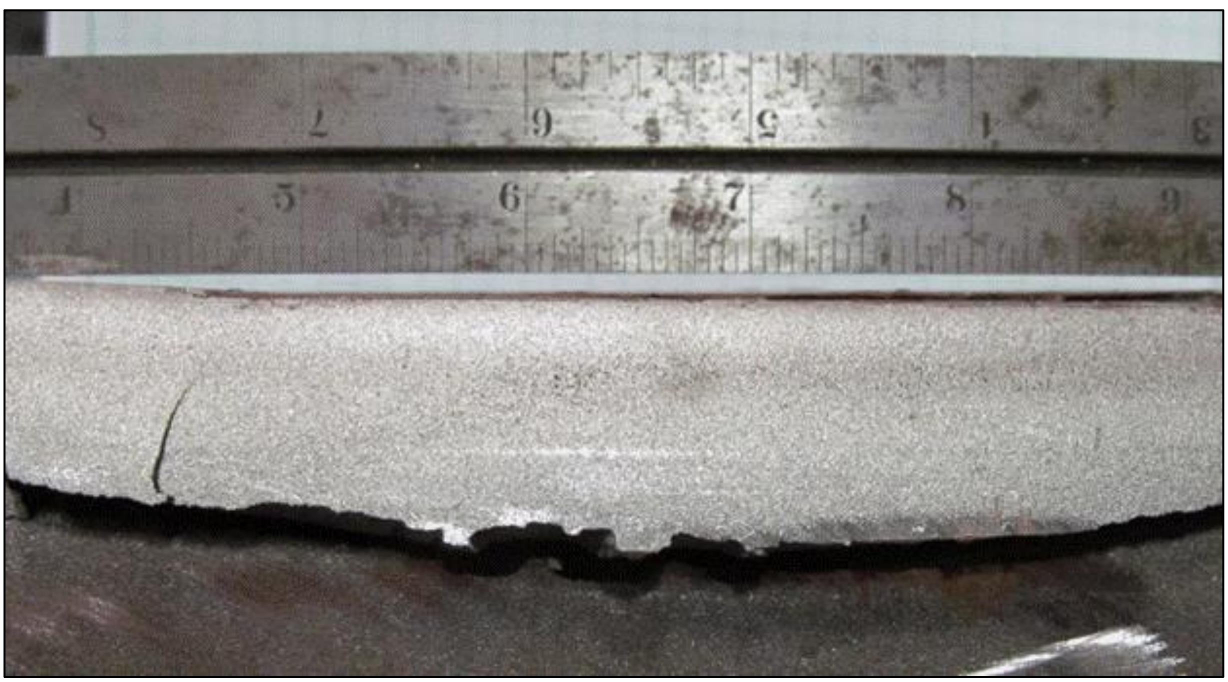


Figure 11. Up Close Side View of Cracking in GMAW Tube

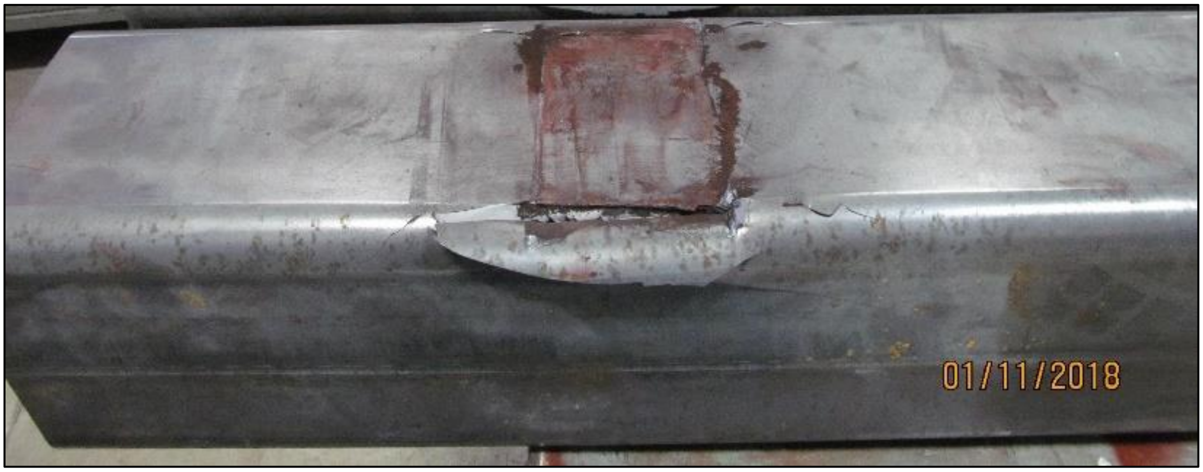


Figure 12. Cracking in HFRW Tube Showing Uniform Cracks in Two Corners

Figure 13. Up Close Side View of Cracking in HFRW Tube

4.2 Static Test Results

Static testing (CVN, bend, and tensile) was conducted as a method to produce data that could be used to compare the GMAW welds, HFRW welds, and the base materials used to fabricate the tubes.

4.2.1 Base Materials – Static Test Results

The base materials differed slightly for the GMAW and HFRW tubes, so testing was conducted to compare material performance. The tensile test results for the GMAW and HFTW tubes are shown in Table 5 and Table 6, respectively. The graphical representation of the tensile data for the GMAW and HRFW base materials are in Figure 14 and Figure 15, respectively. The minimum required UTS is shown with a black line in both figures.

Table 5. Tensile Test Results for the GMAW Base Materials

Specimen ID	Tensile Orientation	UTS (psi)	0.2% Yield Stress (psi)	Elongation (%)
17149-4-T1	Transverse	99,300	79,500	28.6
17149-4-T2	Transverse	94,200	80,700	14.8
17149-4-T3	Transverse	97,600	81,600	11.1

Table 6. Tensile Test Results for the HFRW Base Materials

Specimen ID	Tensile Orientation	UTS (psi)	0.2% Yield Stress (psi)	Elongation (%)
17149-3-T1	Transverse	86,000	69,700	36.4
17149-3-T2	Transverse	85,600	67,800	38.7
17149-3-T3	Transverse	85,100	69,800	39.2

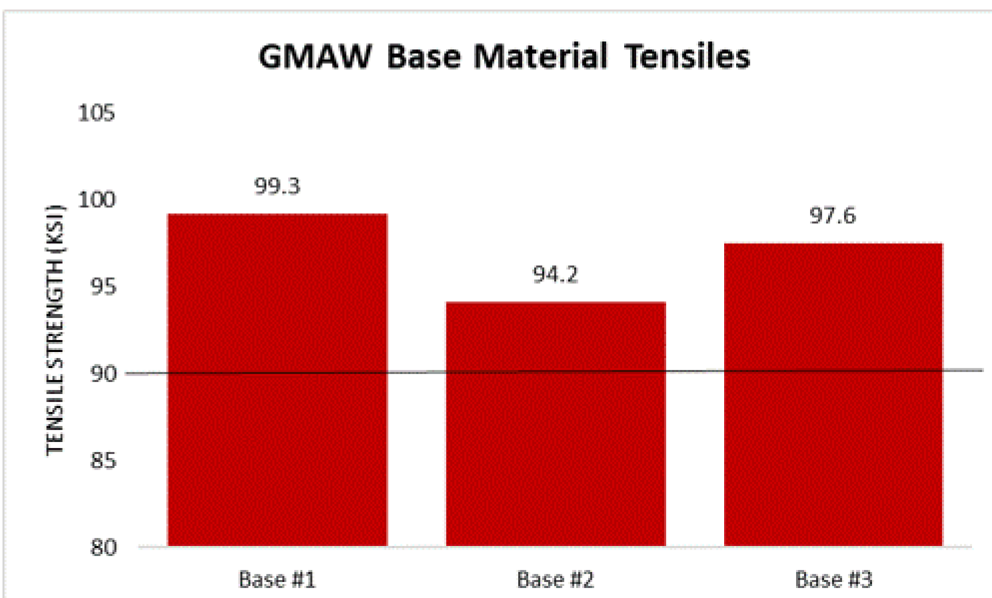


Figure 14. Tensile Test Graph for GMAW Base Material

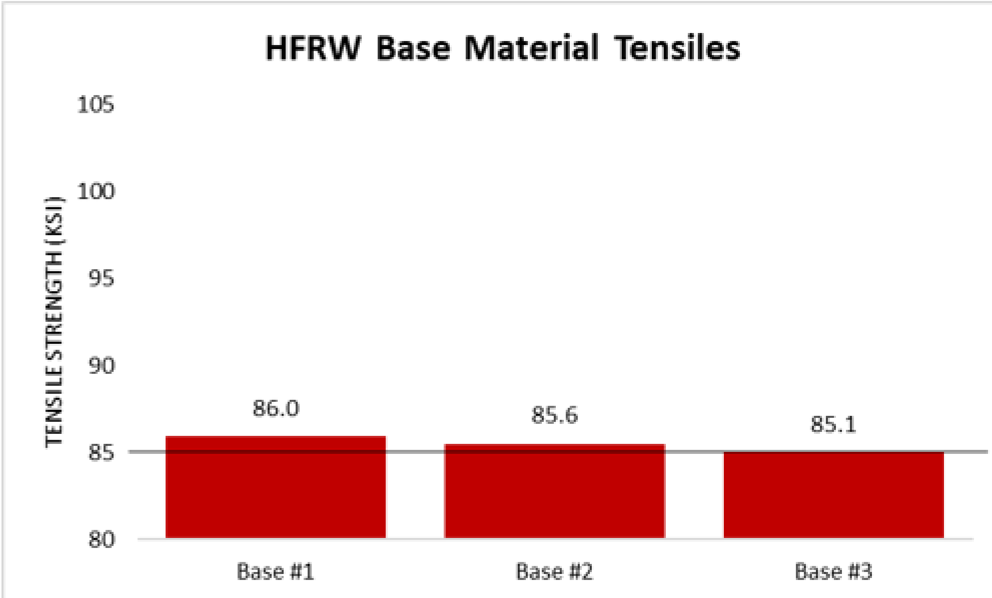


Figure 15. Tensile Test Graph for HFRW Base Material

At 30°F and -60°F, the CVN test results for the GMAW and HFTW tubes are shown in Table 7and Table 8, respectively. The graphical representation of the CVN data for the GMAW and HRFW base materials are in Figure 16 and Figure 17, respectively. There were no minimum CVN requirements. This data was obtained for comparison purposes only.

Table 7. CVN Test Results for GMAW Base Material

Specimen ID	Notch Location	Test Temp. (°F)	Absorbed Energy (ft-lbs)
17149-4-C1	Base	30	89
17149-4-C2	Base	30	105
17149-4-C3	Base	30	110
17149-4-C4	Base	-60	9
17149-4-C5	Base	-60	8
17149-4-C6	Base	-60	8

Table 8. CVN Test Results for HFRW Base Material

Specimen ID	Notch Location	Test Temp. (°F)	Absorbed Energy (ft-lbs)
17149-3-C1	Base	30	53
17149-3-C2	Base	30	58
17149-3-C3	Base	30	52
17149-3-C4	Base	-60	38
17149-3-C5	Base	-60	33
17149-3-C6	Base	-60	34

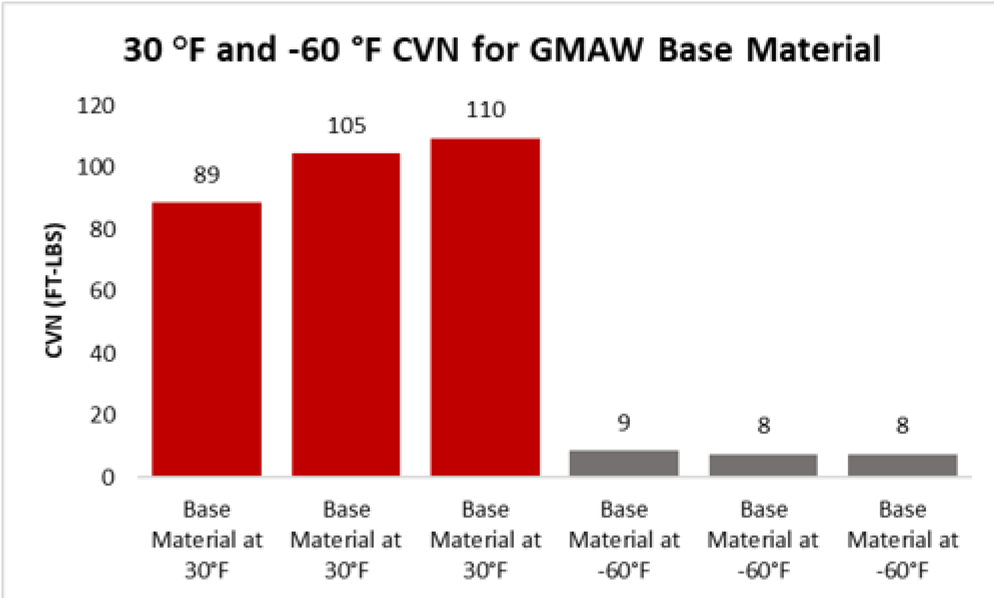


Figure 16. **CVN Graph for GMAW Base Material Tested at 30°F and -60°F**

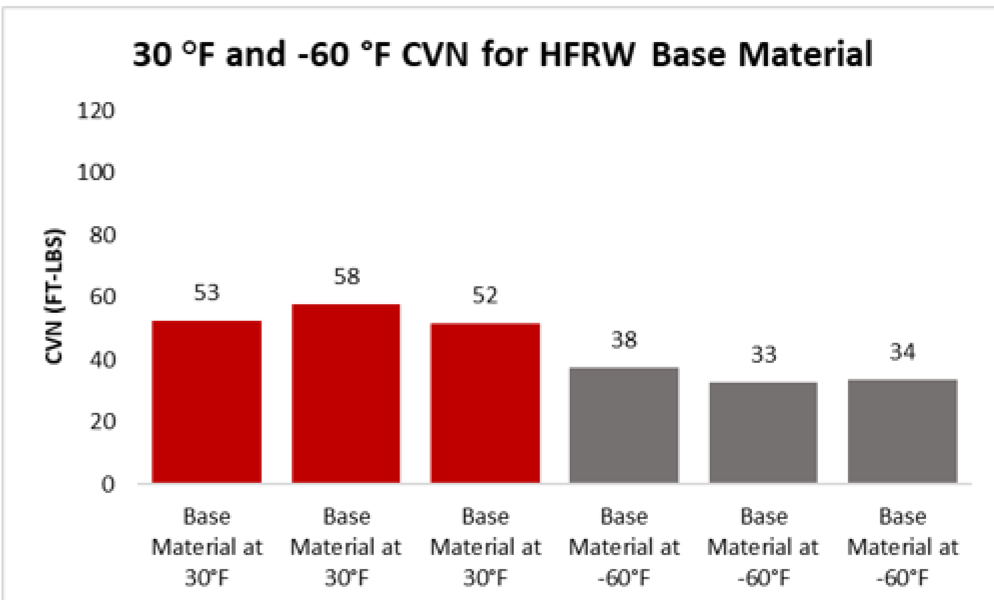
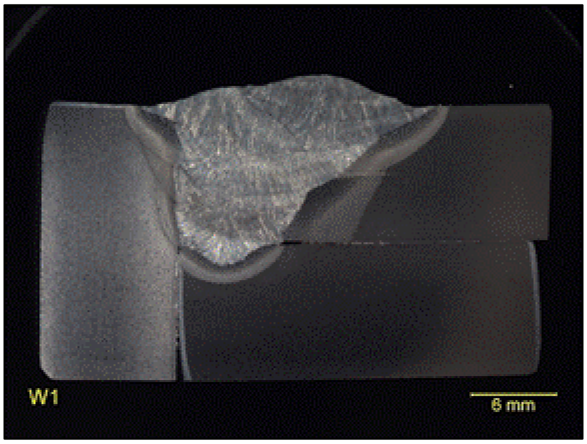


Figure 17. **CVN Graph for HFRW Base Material Tested at 30°F and -60°F**

Appendix D contains the full EWI lab test reports for GMAW and HFRW tube base metals.

4.2.2 GMAW Welds – Static Test Results

Macrographs of the GMAW welds are shown in Figure 18.



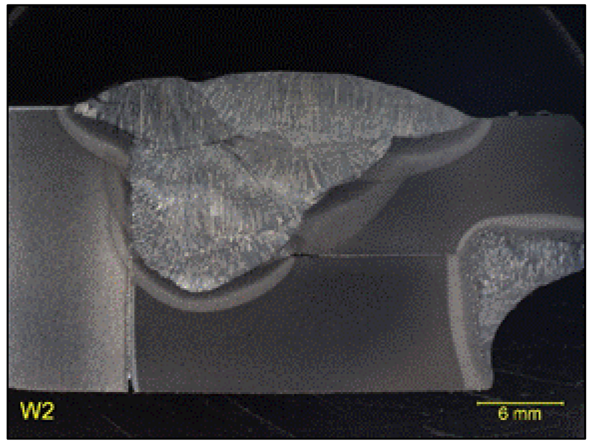


Figure 18. GMAW Macrographs

The tensile test results for the GMAW weld are shown in Table 9. The graphical representation of the tensile data is in Figure 19. The minimum required UTS is shown with a black line in both figures. The base metal acceptance criterion is 90 ksi UTS minimum, with 12% elongation in 2 in. The UTS of one test coupon passed; the elongation of two test coupons passed. One test coupon passed UTS and elongation requirements.

Table 9. GMAW Weld Transverse Tensile Results

Specimen ID	Tensile Orientation	UTS (psi)	0.2% Yield Stress (psi)	Elongation (%)	Failure Location
17149-2-T1	Transverse	78,300	76,600	14.3	HAZ
17149-2-T2	Transverse	98,800	82,200	24.0	HAZ
17149-2-T3	Transverse	86,800	75,900	7.9	HAZ

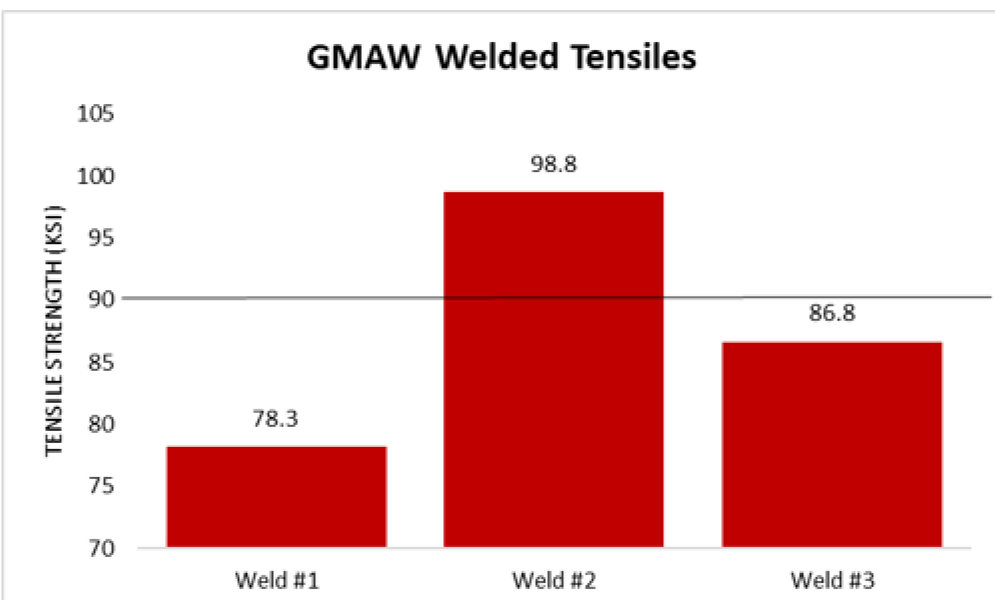


Figure 19. Tensile Test Graph for the GMAW Welds

The GMAW weld root and face bend test results are shown in Table 10 and Table 11, respectively. The acceptance criterion is 22% minimum elongation, with acceptable visual defects as defined in Section 3.2.1. All test coupons passed.

Table 10. GMAW Weld Root Bend Test Results

Specimen ID	Bend Orientation	Bend Mandrel Dia. (in.)	Elongation (%)	Bend Results
17149-2-B1	Root	1.3	22	Pass - no cracking
17149-2-B1	Root	1.3	22	Pass - no cracking
17149-2-B1	Root	1.3	22	Pass - no cracking

Table 11. GMAW Weld Face Bend Test Results

Specimen ID	Bend Orientation	Bend Mandrel Dia. (in.)	Elongation (%)	Bend Results
17149-2-B1	Face	1.3	22	Pass - no cracking
17149-2-B1	Face	1.3	22	Pass - no cracking
17149-2-B1	Face	1.3	22	Pass - no cracking

At 30°F and -60°F, the CVN test results for the GMAW weld are shown in Table 12. The graphical representation of the CVN data is in Figure 20. Per material specification ASTM A656 Grade 80, there are no CVN requirements. This data was obtained for comparison purposes only.

Table 12. GMAW Weld CVN Test Results

Specimen ID	Notch Location	Test Temp. (°F)	Absorbed Energy (ft-lbs)
17149-2-1	Weld fusion zone	30	88
17149-2-2	Weld fusion zone	30	102
17149-2-3	Weld fusion zone	30	91
17149-2-4	Weld fusion zone	-60	76
17149-2-5	Weld fusion zone	-60	81
17149-2-6	Weld fusion zone	-60	77

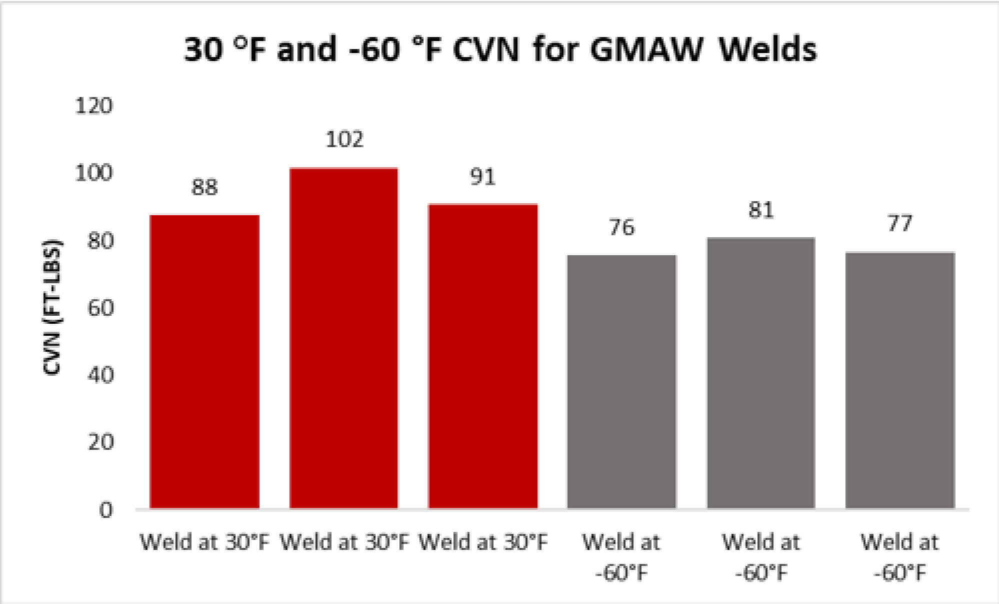


Figure 20. CVN Graph for GMAW Welds Tested at 30°F and -60°F

Appendix E contains the full EWI lab test reports for GMAW test specimens.

4.2.3 HFRW Welds - Static Test Results

Macrographs of the HFRW welds are shown in Figure 21.

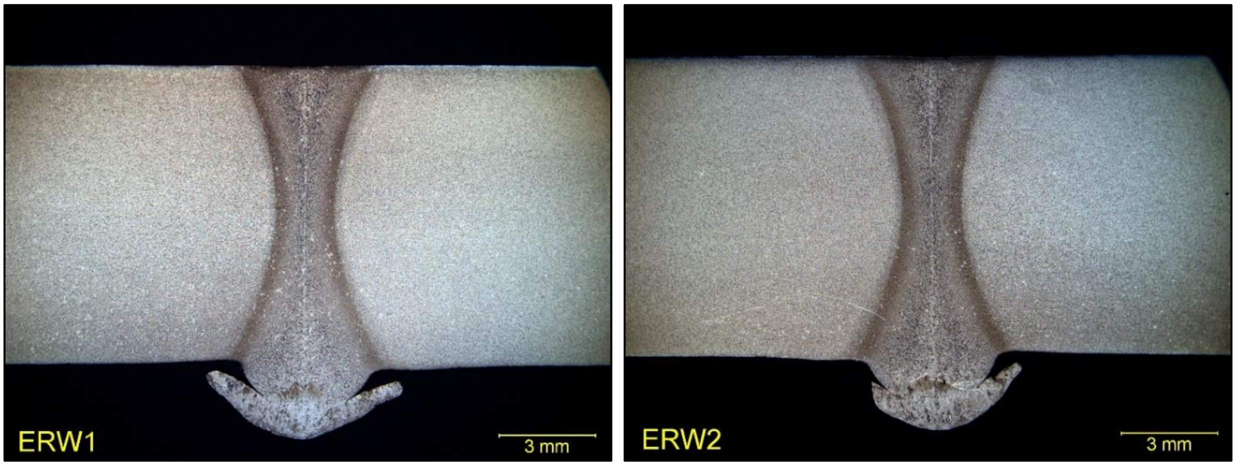


Figure 21. HFRW Macrographs

The tensile test results for the HFRW weld are shown in Table 13. The graphical representation of the tensile data is in Figure 22. In the figure, the minimum required UTS is shown with a black line. The base metal acceptance criterion is 85 ksi UTS minimum, with 14% elongation in 2 in. The UTS of all test coupons passed. No coupons passed the elongation test.

Table 13. HFRW Transverse Tensile Results

Specimen ID	Tensile Orientation	UTS (psi)	0.2% Yield Stress (psi)	Elongation (%)	Failure Location
17149-1-T1	Transverse	90,400	76,100	7.7	Base material
17149-1-T2	Transverse	90,400	74,700	4.5	Base material
17149-1-T3	Transverse	90,000	87,800	10.1	Base material

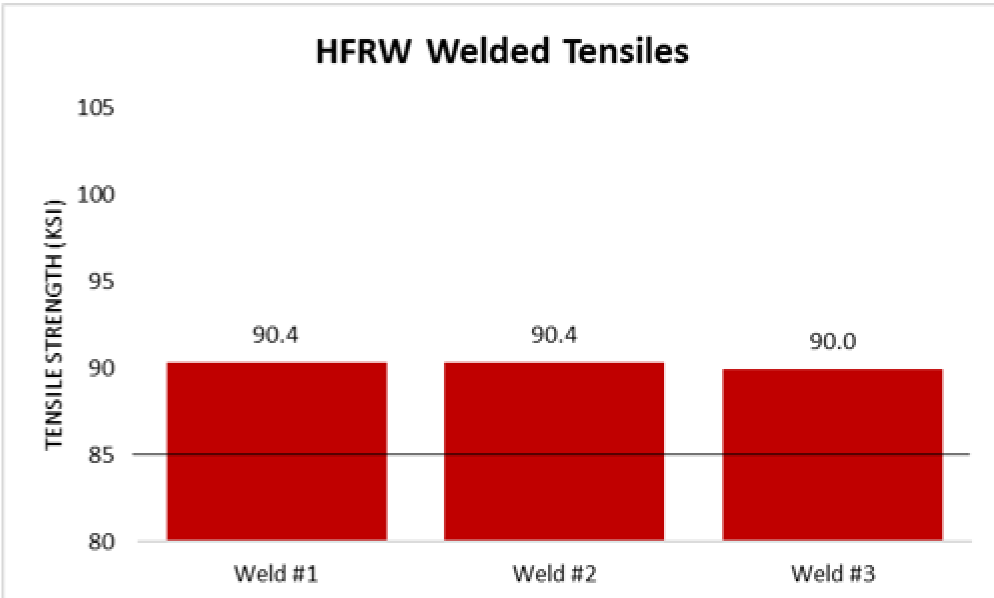


Figure 22. Tensile Test Graph for the HFRW Weld

The HFRW root and face bend test results are shown in Table 14 and Table 15, respectively. The acceptance criteria are 22% minimum elongation, with visual defects as defined in Section 3.2.1. All test coupons passed.

Table 14. HFRW Root Bend Test Results

Specimen ID	Bend Orientation	Bend Mandrel Dia. (in.)	Elongation (%)	Bend Results
17149-1-B4	Root	1.3	22	Pass - no cracking
17149-1-B5	Root	1.3	22	Pass - no cracking
17149-1-B6	Root	1.3	22	Pass - no cracking

Table 15. HFRW Face Bend Test Results

Specimen ID	Bend Orientation	Bend Mandrel Dia. (in.)	Elongation (%)	Bend Results
17149-1-B1	Face	1.3	22	Pass - no cracking
17149-1-B2	Face	1.3	22	Pass - no cracking
17149-1-B3	Face	1.3	22	Pass - no cracking

At 30°F and -60°F, the CVN test results for the HFRW weld are shown in Table 16. The graphical representation of the CVN data is in Figure 23. For CSA Grade 480WT base material, the CVN acceptance criteria is 20 ft-lbs of absorbed energy at -20°F; there are no requirements at 30°F and -60°F. This data was obtained for comparison purposes only. The HFRW welded joints did not meet the base material acceptance criteria; however, the base metal test coupons did (Table 8).

Table 16. HFRW CVN Test Results

Specimen ID	Notch Location	Test Temp. (°F)	Absorbed Energy (ft-lbs)
17149-1-1	Weld Center	30	7
17149-1-2	Weld Center	30	6
17149-1-3	Weld Center	30	6
17149-1-4	Weld Center	-60	3
17149-1-5	Weld Center	-60	2
17149-1-6	Weld Center	-60	2

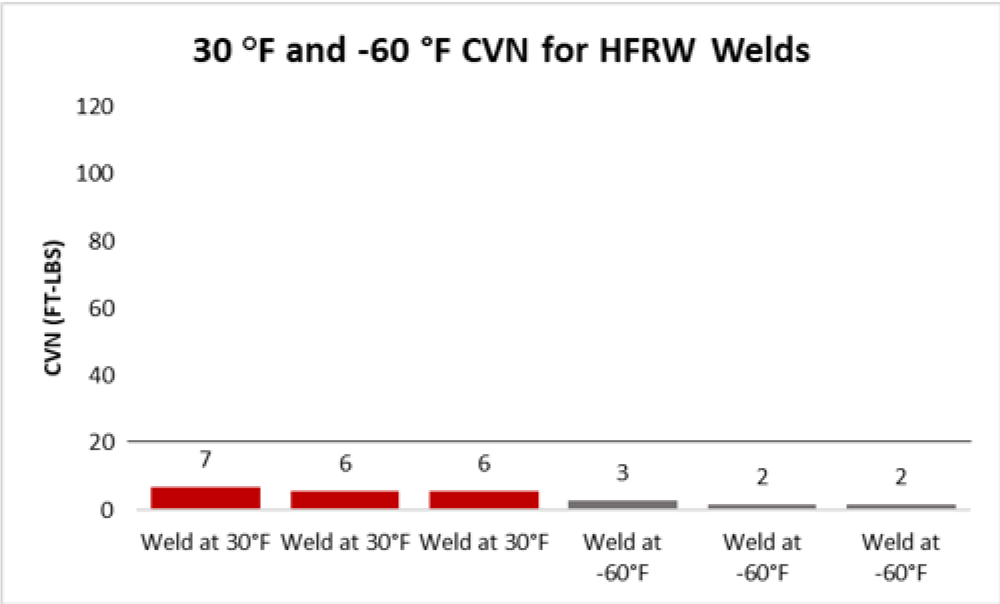


Figure 23. CVN Graph for HFRW Welds Tested at 30°F and -60°F

The CVN test results for the HFRW welds (Table 16) are low compared to the base material performance (Table 8), which meets the CSA base material requirements for low temperature service. This is of little significance to the research effort, because the goal of the project was to compare the performance of different tube *designs*. This fact does, however, highlight the need for HFRW weld process optimization when applying this process to Navy materials and structures.

Appendix F contains the full EWI lab test reports for HFRW test specimens.

4.2.4 Static Test Results Comparison

The static test results of the GMAW and HFRW welds were similar. The CSA Grade 480WT specification lists 85 ksi minimum UTS; the weldments in most cases exceeded that strength. The GMAW welded samples exhibited excellent toughness. The HFRW samples displayed low toughness even at 30°F. Some basic research was conducted to identify the root cause of the lower than expected toughness. A hardness map of the HFRW weld joint is shown in Figure 24. A high hardness area is located on the weld joint centerline where the CVN test coupon was extracted. This higher hardness area is likely the cause of the lower than expected toughness values.

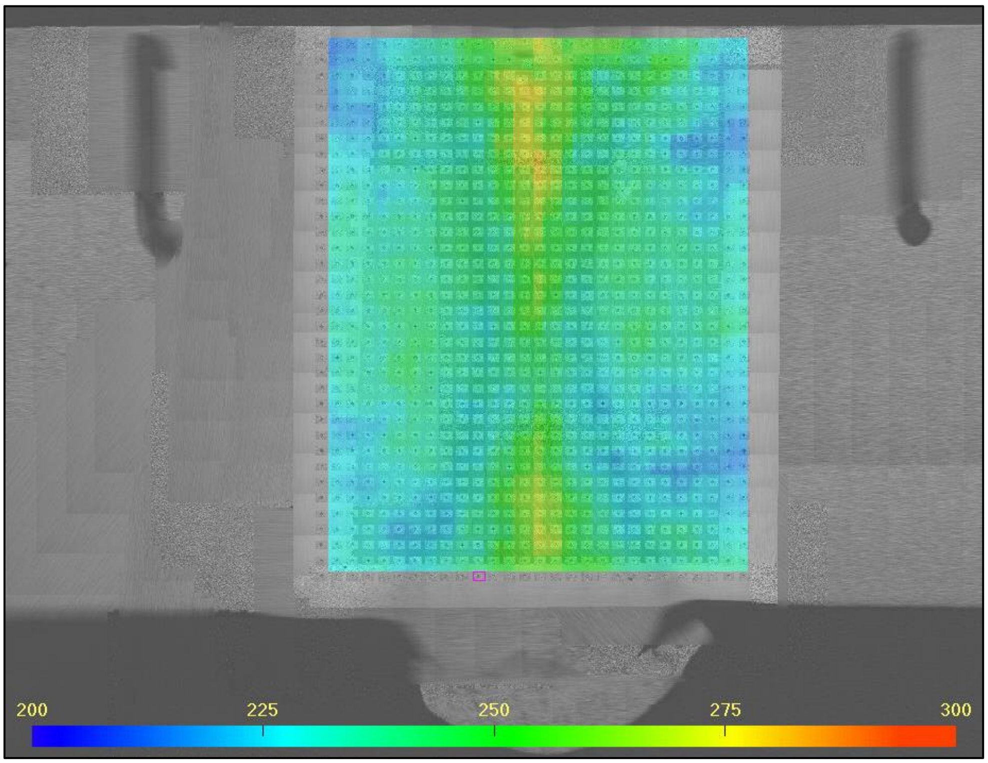


Figure 24. Vickers Hardness Map of the HFRW Tube Weld Joint

Figure 25 is a photomicrograph of the HFRW weld. The grains are relatively fine but appear acicular in nature suggesting that a rapid cooling rate was present. This microstructure is roughly 27 Rockwell C hardness based on the hardness map in Figure 24. The hardness values and the appearance suggest the microstructure is martensitic.

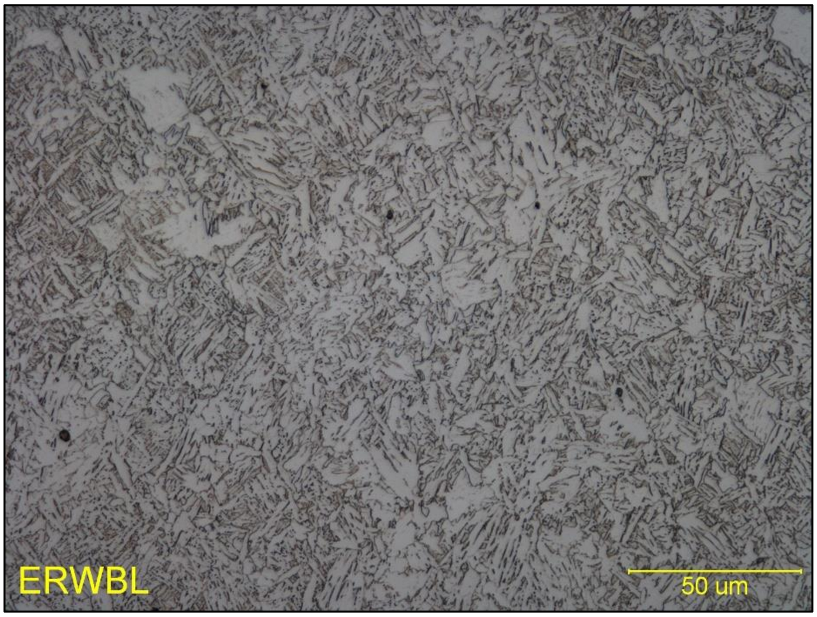


Figure 25. HFRW Weld at 500× Magnification

The addition of a tempering treatment can be applied to an HFRW weld to eliminate high hardness areas and to improve weld toughness. A material with lower Mn content will decrease hardenability. A material with the addition of more grain size stabilizers, such as Ti and Nb, will increase toughness. Using HY-80 that is quenched and tempered, will require a post-weld tempering process and/or reduced welding heat input. Using HSLA-80 will require attention to HFRW welding process parameters but may not require a post-weld heat treatment. The weld hardness and toughness issues will require further research to produce acceptable quality HFRW welds for Navy materials.

5.0 Benefits

Electric Boat conducted a limited business case analysis to establish the relative costs for both purchased HFRW tube and fabricated GMAW tube.

5.1 Cost Benefit Analysis

The HFRW process is highly automated and produces structural shapes at rates upward of 100 feet per minute. A 6-ft long, HFRW 8-in. square tube with a 0.75-in. nominal wall thickness is estimated to cost $600 and takes 0.06 minutes (3.6 seconds) to weld. The same size tube fabricated from two plates using GMAW costs approximately $8,800 and takes 108 minutes (6,480 seconds) to make the six required passes per weld (12 weld passes total per tube). Table 17 contains the cost benefit analysis for the GMAW and HFRW tubes.

Table 17. Cost Benefit Analysis of GMAW vs. HFRW Tubes

Savings Attribute	Benefit	Metric: How Measured	Current state	Future State	Why	Control
Fabrication Labor						
Ship Fitting	H	Actual Trade Hours	45%	5	Eliminated	Design change
Welding	H	Actual Trade Hours	55%	0%	Eliminated	Design change
Cutting & Forming	L	Actual Trade Hours		75% less	Cut & Bevel only	Design change
Inspection	H	Inspection Count	20 per tube	0	Eliminated	Design change
Material Conveyance	M	Part Count		75% less	1 part; fewer moves	Work package
Planning & Admin Services	M	Shop Order Line Items		75% less	Work pkg line items	Work package
Material & Supplies; Inventory						
Piece Part Count per Tube	H	Bill of Material	4	1		Design change
Weld Filler, lbs per ft	H	Eliminated	3	0	Eliminated	Design change
Weld Filler, Cost per lb	L	Eliminated	6		Eliminated	
Temporary Attachments	H	Eliminated	Not measurable	0	Eliminated	Design change
Shop Consumables	M	Less used	Not measurable	0	Eliminated	Design change
Backing Bar cost per ft	L	Length	$1		Eliminated	
Labor + material	**H**	**Cost per 6 ft length of tube**	**$8,800**	**$600**	**Not fabricated**	**Purchased std part**

GMAW tube fabrication (Figure 26) is complicated and challenging as it involves multiple formed piece parts and is highly reliant on skilled workmanship. Multiple piece parts require material acquisition and planning processes. The tube fabrication process features a lot of handling and transporting, in addition to numerous fabrication steps. The resultant tube is distorted from the two large welds and subsequently requires additional labor to mitigate dimensional inaccuracies when fitting and welding tubes to other structures.

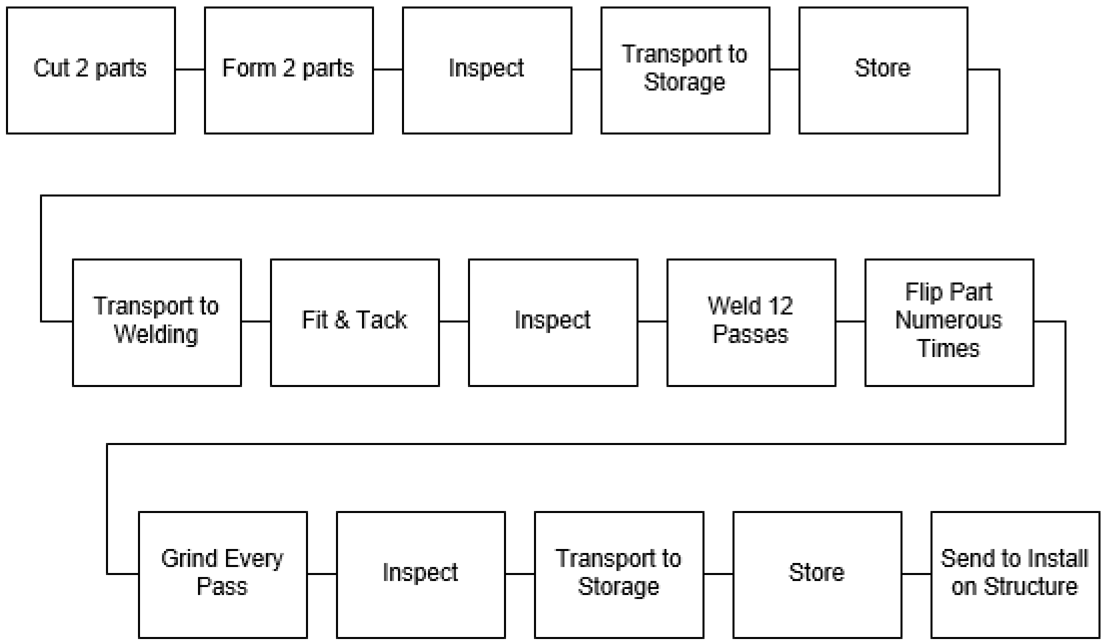


Figure 26. GMAW-fabricated Tube Process Map

Purchased HFRW tube fabrication (Figure 27) is much less complicated. The reduction in piece parts simplifies material acquisition and planning processes. Higher product geometric consistency is expected to reduce downstream labor used to fit and weld tubes to other structures. Purchased HFRW tube is expected to hold a tighter exterior corner radius, which simplifies the joining of attachments to the tube. Using HFRW tube eliminates the GMAW fabrication steps thus allowing the shipyard to re-allocate skilled resources and floor space for more productive use.

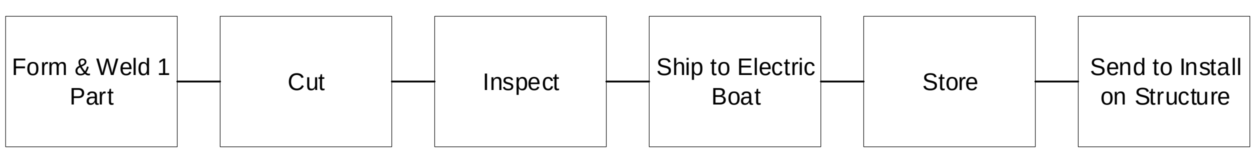


Figure 27. Purchased HFRW Tube Process Map

In addition to productivity gains, other benefits can also be realized. Using other tube material types may facilitate the use of smaller, but stronger cross sections when the design permits.

This project generated data that demonstrates some benefits of using structural shapes designed for HFRW outweigh using fabricated structural shapes welded with GMAW. This data can be used by shipyards as a starting point to pursue NAVSEA approval for implementing HFRW structural shapes.

5.2 Business Case Analysis

Non-recurring Engineering (NRE) Costs

NRE includes HFRW weld qualification cots and updates to design data

Total NRE:	$1,307,600

Recurring Construction Savings

Current construction designs savings, per hull	$407,818
Future construction designs savings, per hull	$770,425

Current construction Payback: 1.86 hulls:

- Savings = $407,818

Future construction Payback: 0.71 hulls

- Savings = $770,425

Industry-wide concerns with the high yield strength of HSS grade tube may lead to additional conversion to HY grades.

6.0 Conclusions

This key take-away from this project is the significant increase in fatigue life observed when purchased HFRW tube is compared to GMAW fabricated tube. Although the original objective of the project intent was to test HY-80 steel the small quantities needed for testing were not available at reasonable cost. The materials tested were both “cold temperature” steel grades which were the closest high yield steels available within the budgetary constraints of the project. EB fabricated GMAW tube and purchased HFRW tube were four-point bend fatigue tested and the HFRW tube had at least a two-fold increase in fatigue life compared to GMAW fabricated tube.

Baseline testing of mechanical and impact properties objectively compared GMAW fabricated tube properties to purchased HFRW purchased tube.The baseline results were mostly comparable; with the exception CVN impact test results for the HFRW welds were lower than expected. This was attributed to a hardened metallurgical phase (martensite) in the centerline of the HFRW cold temperature steel weld. This phase also occurs in HY-80 steel and post weld tempering will convert the martensite, reduce hardness and improve CVN properties. Unlike HY-80 steel, the cold temperature steels used in this test are not routinely post weld heat treated. However, post-weld tempering can be done in-line on the HFRW unit and should produce acceptable CVN results. This is an action for future qualification testing and is considered a minor technical risk.

Using HFRW tube eliminates many hours of labor needed to fabricate the GMAW tube which significantly reduces construction cost. The controlled HFRW tube forming process holds tighter tolerances than the GMAW fabrication process, which reduces complexity and cost when attaching parts to the tube or the tube to larger structures. HFRW does not require the GMAW backing bars which reduces the weight per foot. This study shows HFRW tubes achieved significant increase in fatigue life, will cost less per foot and weigh less. The return on investment is estimated to be 1.86 per hull for current construction class designs and 0.71 per hull for future class designs.

7.0 Recommendations

Based on the results of this research, implementing HFRW tube designs in lieu of GMAW tube design shows promise to reduce fabrication costs and increase structural performance. Future research should be conducted on the actual ship materials of interest with two objectives identified:

1. The HFRW weld process changes necessary to develop a weld with the desired toughness.
2. Determine if HFRW structures with actual ship materials demonstrate the same promising performance compared to legacy structures.

8.0 Future Work

- Determine candidate legacy structural shapes and NAVSEA material types to be replaced.
- Using the same NAVSEA material type, test and compare the performance of the HFRW structural shape design to an equivalent legacy structural shape.
- Determine tempering parameters for the HFRW welding process to produce acceptable weld toughness.

9.0 References

1. Wilson, A.D.; "High strength, weldable precipitation aged steels. journal of metals, , p. 38, March 1987
2. A656 information flyer by ArcelorMittal USA, "Bethstar Grade80 A656 shows toughness well below - 50F", *Fehrer, F., ArcelorMittal USA Bethstar A656, Grade 80 specifications*.
3. Smith, N.J., McGrath, J.T., Gianetto, J.A., and Orr, R.F., "Microstructure/mechanical property relationships of submerged arc welds in HSLA 80 steel", *Welding Journal*, Research Supplement, pp. 112-s to 120-2, March 1989.

10.0 Disclaimer

Appendix A

Excerpts of MIL-S-24645

INCH-POUND
MIL-S-24645A(SH)
10 January 1990
SUPERSEDING
MIL-S-24645(SH)
4 September 1984
(See 6.9)

MILITARY SPECIFICATION

STEEL PLATE, SHEET, OR COIL, AGE-HARDENING ALLOY, STRUCTURAL, HIGH YIELD STRENGTH (HSLA-80 AND HSLA-100)

This specification is approved for use by the Naval Sea Systems Command, Department of the Navy, and is available for use by all Departments and Agencies of the Department of Defense.

1. SCOPE

1.1 Scope. This specification covers 80,000 (HSLA-80) and 100,000 (HSLA-100) pounds per square inch (lb/in^2) high yield strength, age-hardening alloy steel plate, sheet, and coil intended primarily as replacements for steel grades HY-80 and HY-100, respectively, for approved uses in critical structural applications where notch-tough high-strength materials are required. The requirements apply to grade HSLA-80 up to and including 1-1/4 inches thick and HSLA-100 up to 4 inches thick.

1.2 Classification. Steel plate, sheet or coil covered by this specification shall be of the following types and grades as specified (see 6.2).

Type I	-	Plate, sheet or coil for which ultrasonic testing for soundness and thickness is not performed.
Type II	-	Plate over 1/2-inch in thickness for which ultrasonic testing for soundness and thickness is performed. Unless otherwise specified (See 4.4.2.7 and 6.2), each plate over 1/2-inch in thickness shall be classified as Type II.
Grade HSLA-80	-	80,000 lb/in^2 tensile yield strength, minimum.
Grade HSLA-100	-	100,000 lb/in^2 tensile yield strength, minimum.

Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: Commander, Naval Sea Systems Command, SEA 55Z3, Department of the Navy, Washington, DC 20362-5101 by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

AMSC N/A FSC 9515

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited

3.2.3 Recovered materials. Unless otherwise specified herein, all equipment, material, and articles incorporated in the products covered by this specification shall be new and may be fabricated using materials produced from recovered materials to the maximum extent practicable without jeopardizing the intended use. The term "recovered materials" means materials which have been collected or recovered from solid waste and reprocessed to become a source of raw materials, as opposed to virgin raw materials. None of the above shall be interpreted to mean that the use of used or rebuilt products is allowed under this specification unless otherwise specifically specified.

3.3 Chemical composition. The chemical composition, heat and product shall be as specified in table I.

TABLE I. Chemical composition (heat and product analysis).

Element	Maximum percent by weight [1] unless a range is shown or otherwise noted	
	Allowable chemical compositions for the following plate gauges and grades	
	Grade HSLA-80	Grade HSLA-100
	≤ 1.25-inch	All plate gauges
Carbon	0.06[2]	0.06[2]
Manganese	0.40-0.70	0.75-1.05
Phosphorous	0.020	0.020
Sulfur	0.006[3]	0.006[3]
Silicon	0.40	0.40
Nickel	0.70-1.00	3.35-3.65
Chromium	0.60-0.90	0.45-0.75
Molybdenum	0.15-0.25	0.55-0.65
Copper	1.00-1.30	1.45-1.75
Columbium	0.02-0.06	0.02-0.06
Aluminum	[4]	[4]
Tin	0.030	0.030
Vanadium	0.03	0.03
Titanium	0.02	0.02
Arsenic	0.025	0.025
Antimony	0.025	0.025
Nitrogen	[5]	[5]

[1] Except for carbon and sulphur, the chemical tolerances as specified in

ASTM A 6 are to be applied to product analysis. For elements not listed in ASTM A 6, the product analysis shall not exceed the specified maximum.

[2] For HSLA-80 thicknesses 3/4-inch and under, a maximum of 0.07 percent shall be permitted in heat analysis. The product analysis tolerance shall be 0.02 percent over the specified maximum limit for all thicknesses of HSLA-80 and HSLA-100.

[3] The product analysis tolerance shall be 0.002 percent over the specified maximum.

[4] Minimum acid-soluble aluminum content of 0.010 percent or minimum total aluminum content of 0.015 percent for each ladle of each heat.

[5] For information only.

3.4 Mechanical properties. The material shall meet the tensile property requirements as specified in table II and the impact property requirements as specified in table III after all heat treatments.

TABLE II. Tensile properties.

	Grade HSLA-80		Grade HSLA-100	
	< 0.25 in	≤ 0.25 in	≤ 0.75 in	> 0.75 in
Ultimate tensile strength, (lb/in²)	1/	1/	1/	1/
Yield strength, 0.2 percent offset (lb/in²) 4/	80,000 to 110,000	80,000 to 100,000	100,000 to 130,000	100,000 to 125,000
Elongation in 2 inches, minimum (percent)	14	20	[2]17	18
Reduction in area, minimum round specimen (percent)	3/	[3]50	3/	45

1/ To be recorded for information only.

2/ For HSLA-100 material less than 1/4-inch in thickness, elongation shall be 12 percent, minimum.

3/ A minimum percent reduction in area is not required for plate thicknesses equal to or less than 3/4-inch.

4/ For HSLA-80 materials equal to or less than 1/2-inch in thickness, maximum yield strength shall be 110,000 lb/in².

TABLE III. Impact requirements, Charpy V-notch, transverse.1/

Thickness nominal (inch)	Test (Coolant) temperature	Energy[2] foot-pounds, average of three tests, minimum		Shear fracture, percent average of three tests, minimum	
	(°F)	Grade HSLA-80	Grade HSLA-100	Grade HSLA-80	Grade HSLA-100
3/8-inch and over 3/	-120 ± 3	60	60	35	35
	0 ± 3		80		90

1/ Dynamic tear testing transverse to the final direction of plate rolling shall be performed at minus 40 ± 3 degrees Fahrenheit (°F) on plate thickness over 5/8-inch and the results shall be recorded for information only.

2/ No single value shall be below the minimum average required by more than 5 foot-pounds, or equivalent fraction as designated by the appropriate standard subsize specimen, for the Charpy test.

3/ For material thicknesses below 7/16-inch, Charpy test subsize specimens shall be as specified in ASTM A 673. Equivalent absorbed energy requirements for subsize specimens shall be as specified (see 6.2).

3.5 Heat treatment. Unless otherwise specified (6.2), the contractor shall determine the detailed procedure to produce products meeting the mechanical property requirements of this specification with the following restrictions:

(a) The heat treatment shall be as specified (see 6.2) for treatment of class 1 or class 3 as follows:

Class 1 - Controlled rolled and precipitation heat treated. This class is permissible only for HSLA-80 plate, sheet or coil up to and including 1/2-inch in thickness unless otherwise specifically approved by NAVSEA.

Class 3 - Solution treated, quenched and precipitation heat treated.

(b) The plate shall not be stress relieved.

Appendix B

Excerpts of CSA G40 20-13/G40 21-13

Table 24
Thickness overtolerance* of sheet
(See Clause 5.5.)

(a) Metric

Specified width, mm	Specified minimum thickness, mm						
	> 4.5–6.0 incl	> 2.5–4.5 incl	> 2.0–2.5 incl	> 1.8–2.0 incl	> 1.5–1.8 incl	> 1.3–1.5 incl	1.2–1.3 incl
300–375 incl	0.36	0.36	0.31	0.31	0.31	0.31	0.25
> 375–500 incl	0.41	0.41	0.36	0.36	0.36	0.31	0.25
> 500–800 incl	0.46	0.41	0.36	0.36	0.36	0.31	0.31
> 800–1000 incl	0.46	0.46	0.41	0.36	0.36	0.31	0.31
> 1000–1200 incl	0.51	0.51	0.41	0.36	0.36	0.36	0.31
> 1200–1500 incl	—	0.51	0.41	0.36	0.36	0.36	—
> 1500–1800 incl	—	0.56	0.46	0.41	0.41	—	—
> 1800–2000 incl	—	0.61	0.46	0.41	—	—	—
> 2000	—	0.61	0.51	—	—	—	—

(b) Imperial

Specified width, in	Specified minimum thickness, in						
	> 0.179–0.229 incl	> 0.098–0.179 incl	> 0.082–0.098 incl	> 0.070–0.082 incl	> 0.059–0.070 incl	> 0.051–0.059 incl	0.044–0.051 incl
12–15 incl	0.014	0.014	0.012	0.012	0.012	0.012	0.010
> 15–20 incl	0.016	0.016	0.014	0.014	0.014	0.012	0.010
> 20–32 incl	0.018	0.016	0.014	0.014	0.014	0.012	0.012
> 32–40 incl	0.018	0.018	0.016	0.014	0.014	0.012	0.012
> 40–48 incl	0.020	0.020	0.016	0.014	0.014	0.014	0.012
> 48–60 incl	—	0.020	0.016	0.014	0.014	0.014	—
> 60–72 incl	—	0.022	0.018	0.016	0.016	—	—
> 72–80 incl	—	0.024	0.018	0.016	—	—	—
> 80	—	0.024	0.020	—	—	—	—

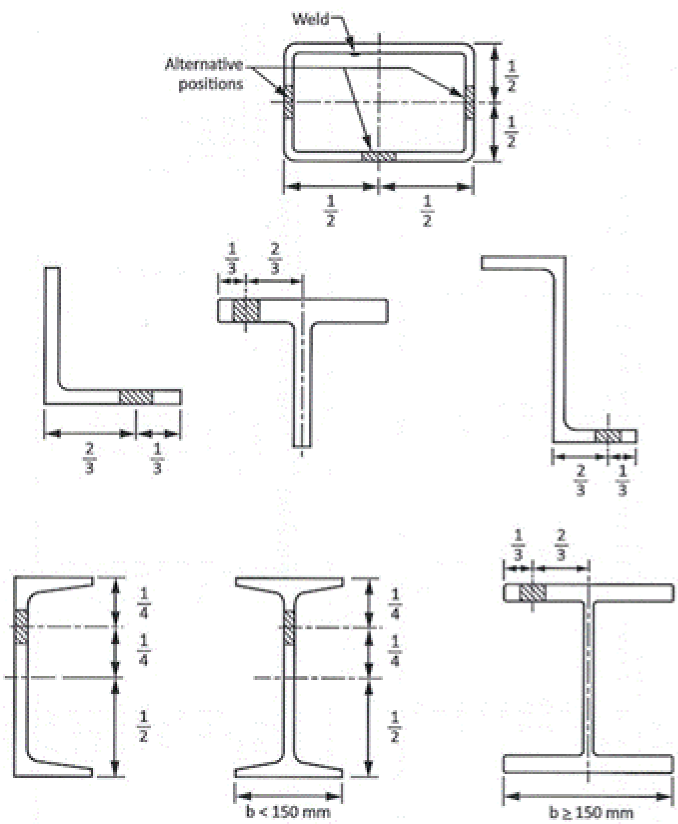
**There shall be no under tolerance.*

Notes:

(1) *Thickness shall be measured at any point across the width that is not less than 10 mm (3/8 in) from a cut edge and not less than 20 mm (3/4 in) from a mill edge.*

(2) *The specified thickness range captions also apply when sheet is specified to a nominal thickness, in which case the tolerances are divided equally over and under.*

B1

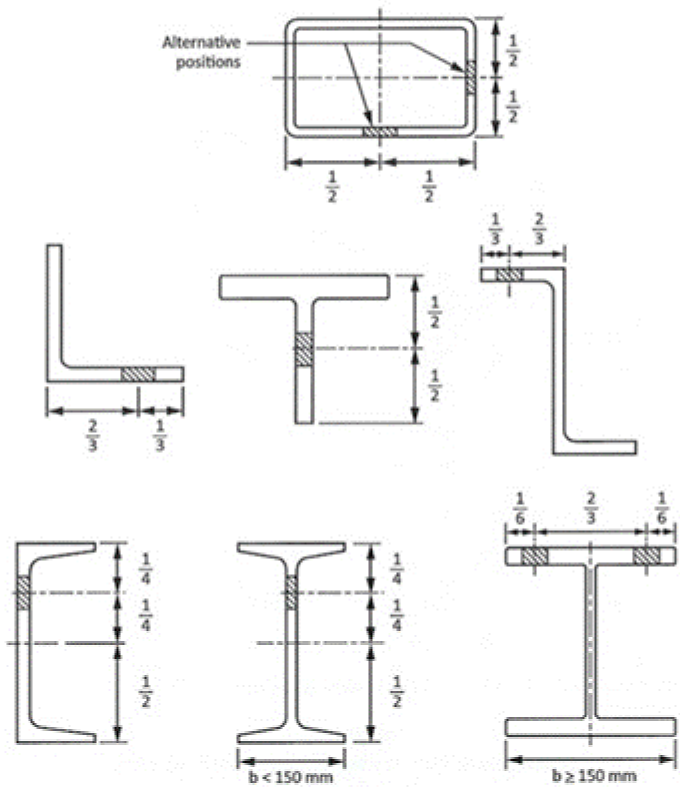


Notes:

(1) *Welded structural shapes shall be tested in accordance with the plate or bar testing requirements of Clauses 7 to 9.*

(2) *At the discretion of the manufacturer, the test piece may be taken from either leg of unequal angles.*

Figure 1
Position of test pieces for tensile tests
(See Clauses 4.2, 7.1.2.3, and 7.1.2.6.)

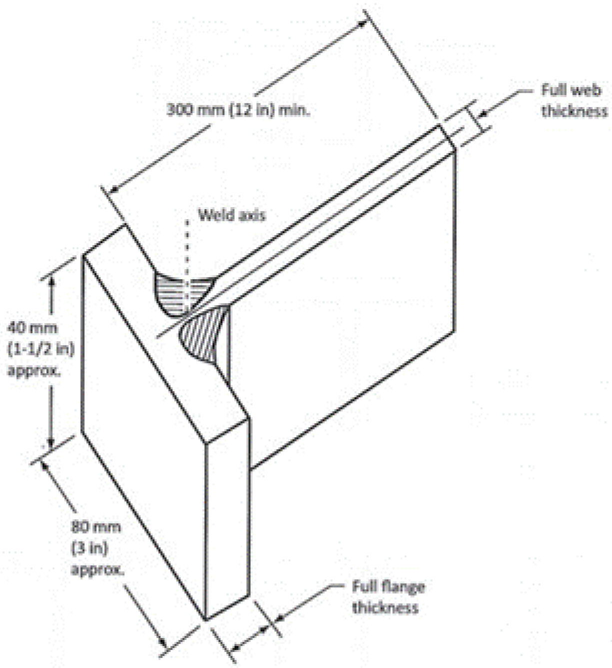


Notes:

(1) *Welded structural shapes shall be tested in accordance with the plate or bar testing requirements of Clauses 7 to 9*

(2) *At the discretion of the manufacturer, the test piece may be taken from either leg of unequal leg angles.*

Figure 2
Position of test pieces for impact tests
(See Clauses 4.2, 7.1.3.3, and 7.1.3.6.)



Note: *Test load shall be applied normal to weld axis in the plane of the web centreline.*

Figure 3
Specimen for welded-tee tension test
(See Clause 15.4.)

Flatness	
Plates, carbon, HSLA and alloy steel	ASTM A6/A6M
Plates, carbon, HSLA and alloy steel, restrictive	Table 4
Length	
Bars and bar-size shapes	ASTM A6/A6M
Channels and Z sections, cold-formed, ordered to length	Table 19
Plates, gas-cut	ASTM A6/A6M
Plates, sheared and universal mill	ASTM A6/A6M
Super light beams	ASTM A6/A6M
Sections, hollow, ordered to length	Table 17
Sheet	ASTM A568/A568M
Mass	
Sections, hollow	Table 10
Straightness	
Bars and bar-size shapes	ASTM A6/A6M
Channels and Z sections, cold-formed	Table 20
Sections, hollow	Table 15
Super light beams	Table 6
Welded shapes	Table 9
Thickness	
Channels and Z sections, cold-formed	Table 18
Flats	ASTM A6/A6M
Plates, 300 mm (15 in) and under in thickness, ordered to thickness	ASTM A6/A6M
Sections, hollow, wall thickness	Table 11
Sheet	Table 24
Twist	
Sections, hollow	Table 16
Warpage and tilt	
Welded structural shapes	Table 8
Waviness	**ASTM A6/A6M**
Width	
Flats	ASTM A6/A6M
Plates, rectangular, gas-cut	ASTM A6/A6M
Plates, sheared	ASTM A6/A6M
Plates, universal mill	ASTM A6/A6M
Sheet	ASTM A568/A568M

Appendix C

Excerpts of ASTM A656

Designation: A656/A656M – 13

Standard Specification for Hot-Rolled Structural Steel, High-Strength Low-Alloy Plate with Improved Formability[1]

This standard is issued under the fixed designation A656/A656M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This specification covers three types and five strength grades of high-strength low-alloy, hot rolled structural steel plate for use in truck frames, brackets, crane booms, rail cars, and similar applications. Steels that conform to this specification offer improved formability. These steels are normally furnished in the as-rolled condition. The type and strength grade furnished is as agreed upon between the manufacturer and the purchaser. The types and strength grades are shown in the tables.

1.2 The maximum thickness of plates shall be as follows:

Grade	Plate Thickness, max, in. [mm]
50	2 [50]
60	1½ [40]
70	1 [25]
80	1 [25]
100	½ [13]

1.3 The values stated in either inch-pound units or SI units are to be regarded as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other. Combining values from the two systems may result in nonconformance with this specification. See Appendix X3 of Specification A6/A6M for information on weldability.

1.4 For plates produced from coil and furnished without heat treatment or with stress relieving only, the additional requirements, including additional testing requirements and the reporting of additional test results, of Specification A6/A6M apply.

[1] This specification is under the jurisdiction of ASTM Committee A01 on Steel, Stainless Steel and Related Alloys and is the direct responsibility of Subcommittee A01.02 on Structural Steel for Bridges, Buildings, Rolling Stock and Ships.

Current edition approved Oct. 15, 2013. Published November 2013. Originally approved in 1972. Last previous edition approved in 2012 as A656/A656M – 12a[ε1]. DOI: 10.1520/A0656_A0656M-13.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A6/A6M Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling

3. General Requirements for Delivery

3.1 Plates furnished under this specification shall conform to the requirements of the current edition of Specification A6/A6M, for the specific plate ordered, unless a conflict exists, in which case this specification shall prevail.

3.2 Coils are excluded from qualification to this specification until they are processed into finished plates. Plates produced from coil means plates that have been cut to individual lengths from a coil. The processor directly controls, or is responsible for, the operations involved in the processing of a coil into finished plates. Such operations include decoiling, leveling, cutting to length, testing, inspection, conditioning, heat treatment (if applicable), packaging, marking, loading for shipment, and certification.

NOTE 1—For plates produced from coil and furnished without heat treatment or with stress relieving only, two test results are to be reported for each qualifying coil. Additional requirements regarding plate produced from coil are described in Specification A6/A6M.

4. Materials and Manufacture

4.1 The steel shall be made to fine grain practice.

5. Chemical Composition

5.1 Heat analyses shall conform to the chemical requirements given in Table 1. Dependent upon thickness, grade, and intended application, variations in the chemical composition are permitted within the limits given in Table 1 for the applicable type. Where it is of particular importance, the manufacturer should be consulted for specific chemical composition.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

*A Summary of Changes section appears at the end of this standard

TABLE 1 Chemical Requirements

NOTE 1—An ellipsis (. . .) indicates that element is not defined for that Type.

Elements	Composition, %		
	Type 3	Type 7	Type 8
Carbon, max[A]	0.18	0.18	0.18
Manganese, max[A]	1.65	1.65	1.65
Phosphorus, max	0.025	0.025	0.025
Sulfur, max	0.030	0.030	0.030
Silicon, max	0.60	0.60	0.60
Vanadium, max	0.08	0.15[B]	0.15[C]
Nitrogen, max	0.030	0.030	0.030
Columbium	0.008–0.10	0.10 max[B]	0.10 max[C]
Titanium, max	. . .	. . .	0.15[C]

[A] For each reduction of 0.01 percentage point below the specified maximum for carbon, an increase of 0.06 percentage points above the specified maximum for manganese is permitted, up to a maximum of 1.75 % for Grades 50, 60, and 70; up to a maximum of 1.90 % for Grade 80; and up to a maximum of 2.10 % for Grade 100.

[B] The contents of columbium and vanadium shall additionally be in accordance with one of the following:
columbium 0.008–0.10 % with vanadium <0.008 %;
columbium <0.008 % with vanadium 0.008–0.15 %; or
columbium 0.008–0.10 % with vanadium 0.008–0.15 % and columbium plus vanadium not in excess of 0.20 %.

[C] The sum of columbium, vanadium, and titanium shall be between 0.008 and 0.20 %.

TABLE 2 Tensile Requirements[A]

	Grade 50 [345]	Grade 60 [415]	Grade 70 [485]	Grade 80 [550]	Grade 100 [690]
Yield point, min, ksi [MPa]	50 [345]	60 [415]	70 [485]	80 [550]	100 [690]
Tensile strength, min, ksi [MPa]	60 [415]	70 [485]	80 [550]	90 [620]	110 [760]
Elongation in 8 in. [200 mm], min, %	20[B]	17[B]	14[B]	12[B]	12[B]
Elongation in 2 in. [50 mm], min, %	23[B]	20[B]	17[B]	15[B]	15[B]

[A] See Specimen Orientation under the Tension Tests section of Specification A6/A6M.

[B] For plates wider than 24 in. [600 mm], the elongation requirement is reduced two percentage points for Grade 50 [345] and three percentage points for Grades 60, 70, 80, and 100 [415, 485, 550, and 690]. See Elongation Requirement Adjustments in the Tension Tests section of Specification A6/A6M.

5.2 *Product Analysis*—If a product analysis is made, it shall conform to the requirements given in Table 1, subject to the product analysis tolerances of Specification A6/A6M.

5.3 Where steel is to be welded, it is presupposed that a welding procedure suitable for the grade of steel and intended use or service will be utilized.

5.4 Unless specifically ordered, the type is at the discretion of the producer.

6. Tension Test

6.1 The plates as represented by the test specimens shall conform to the requirements given in Table 2.

7. Keywords

7.1 high-strength low-alloy steel; steel plates; structural applications

SUMMARY OF CHANGES

Committee A01 has identified the location of selected changes to this standard since the last issue (A656/A656M – 12a$^{\varepsilon 1}$) that may impact the use of this standard. (Approved Oct. 15, 2013.)

(1) Revised Table 1 to modify sulfur limits.

Committee A01 has identified the location of selected changes to this standard since the last issue (A656/A656M – 12) that may impact the use of this standard. (Approved Nov. 1, 2012.)

(1) Adjusted Table 1 Footnote A, increasing maximum permissible manganese for grade 100 from 1.90 % to 2.10 %.

Appendix D

EWI Lab Test Reports – Tube Base Materials

GMAW Tube Material

EWI
We Manufacture Innovation

1250 Arthur E. Adams Drive, Columbus, OH 43221

Customer: ATI Advanced Technology International	Project Number: 56788GTH
Contact: Justin Montague	EWI Contact: Dave Workman
Address:	Phone: 614-688-5244
	Email: dworkman@ewi.org
Customer Sample ID: Plate Base Material	Specification: Guidance to AWS B4.0
LIMS Sample ID: 17149-4	Material Type: Carbon Steel
Heat/Lot Number: N/A	

Rectangular Tensile Test, ASTM E8

Initial Loading Rate (IPM): .05 Test Temp (C): 23 Released By: Rich Minshall

Final Loading Rate (IPM): .15 Test Date: 1/31/2018

Specimen ID (N/A)	Tensile Orientation (N/A)	Original Width (in)	Original Thickness (in)	Orig GL (in)	UTS (psi)	0.2% Yld Stress (psi)	Elongation (%)	ROA (%)	Failure Location (N/A)	Condition (N/A)
17149-4-T1	Transverse	0.250 6.4 (mm)	0.364 9.2 (mm)	1.013 25.7 (mm)	99300 685 (MPa)	79500 548 (MPa)	28.6	71.1	Base Material	As Received
17149-4-T2	Transverse	0.251 6.4 (mm)	0.364 9.2 (mm)	1.007 25.6 (mm)	94200 650 (MPa)	80700 557 (MPa)	14.8	45.3	Weld	As Received
17149-4-T3	Transverse	0.251 6.4 (mm)	0.364 9.2 (mm)	1.014 25.8 (mm)	97600 673 (MPa)	81600 563 (MPa)	11.1	31.4	HAZ	As Received

Notes: Samples were machined transverse across the weld and not base material.

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GMAW Tube Material

EWI

We Manufacture Innovation

1250 Arthur E. Adams Drive, Columbus, OH 43221

Customer: ATI Advanced Technology International	Project Number: 56788GTH
Contact: Justin Montague	EWI Contact: Dave Workman
Address:	Phone: 614-688-5244
	Email: dworkman@ewi.org
Customer Sample ID: Plate Base Material	Specification: Guidance to AWS B4.0
LIMS Sample ID: 17149-4	Material Type: Carbon Steel
Heat/Lot Number: N/A	

Notched Bar Impact Test, ASTM E23

Specimen Type: A (V-Notch) Test Date: 1/31/2018 Released By: Rich Minshall

Specimen ID (N/A)	Notch Location (N/A)	Notch Orientation (N/A)	W (mm)	D (mm)	Test Temperature (C)	Abs. Energy (J)	Lateral Expansion (mm)	Shear Area (%)	Condition (N/A)
17149-4-C1	Base	T-L	7.50 0.295 (in)	10.01 0.394 (in)	-1.0 30 (F)	120.0 89 (ft-lb)	0.44 0.017 (in)	100	As Received
17149-4-C2	Base	T-L	7.50 0.295 (in)	9.97 0.393 (in)	-1.0 30 (F)	142.0 105 (ft-lb)	0.14 0.006 (in)	100	As Received
17149-4-C3	Base	T-L	7.50 0.295 (in)	10.01 0.394 (in)	-1.0 30 (F)	149.0 110 (ft-lb)	1.37 0.054 (in)	100	As Received
17149-4-C4	Base	T-L	7.49 0.295 (in)	10.01 0.394 (in)	-51.0 -60 (F)	12.0 9 (ft-lb)	0.11 0.004 (in)	30	As Received
17149-4-C5	Base	T-L	7.49 0.295 (in)	10.01 0.394 (in)	-51.0 -60 (F)	11.0 8 (ft-lb)	0.07 0.003 (in)	24	As Received
17149-4-C6	Base	T-L	7.50 0.295 (in)	10.01 0.394 (in)	-51.0 -60 (F)	11.0 8 (ft-lb)	0.11 0.004 (in)	13	As Received

Notes:

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HFRW Tube Material

EWI

We Manufacture Innovation

1250 Arthur E. Adams Drive, Columbus, OH 43221

Customer:	ATI Advanced Technology International	Project Number:	56788GTH
Contact:	Justin Montague	EWI Contact:	Dave Workman
Address:		Phone:	614-688-5244
		Email:	dworkman@ewi.org
Customer Sample ID:	Box Base Material	Specification:	Guidance to AWS B4.0
LIMS Sample ID:	17149-3	Material Type:	Carbon Steel
Heat/Lot Number:	N/A		

Rectangular Tensile Test, ASTM E8

Initial Loading Rate (IPM): .05 Test Temp (C): 23 Released By: Rich Minshall

Final Loading Rate (IPM): .15 Test Date: 1/31/2018

Specimen ID (N/A)	Tensile Orientation (N/A)	Original Width (in)	Original Thickness (in)	Orig GL (in)	UTS (psi)	0.2% Yld Stress (psi)	Elongation (%)	ROA (%)	Failure Location (N/A)	Condition (N/A)
17149-3-T1	Transverse	0.250 6.4 (mm)	0.361 9.2 (mm)	1.010 25.7 (mm)	86000 593 (MPa)	69700 481 (MPa)	36.4	73.8	Within Gage Length	As Received
17149-3-T2	Transverse	0.250 6.4 (mm)	0.361 9.2 (mm)	1.009 25.6 (mm)	85600 590 (MPa)	67800 468 (MPa)	38.7	73.7	Within Gage Length	As Received
17149-3-T3	Transverse	0.250 6.4 (mm)	0.361 9.2 (mm)	1.009 25.6 (mm)	85100 587 (MPa)	69800 481 (MPa)	39.2	76.1	Within Gage Length	As Received

Notes:

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HRFT Tube Material

EWI
We Manufacture Innovation

1250 Arthur E. Adams Drive, Columbus, OH 43221

Customer:	ATI Advanced Technology International	Project Number:	56788GTH
Contact:	Justin Montague	EWI Contact:	Dave Workman
Address:		Phone:	614-688-5244
		Email:	dworkman@ewi.org
Customer Sample ID:	Box Base Material	Specification:	Guidance to AWS B4.0
LIMS Sample ID:	17149-3	Material Type:	Carbon Steel
Heat/Lot Number:	N/A		

Notched Bar Impact Test, ASTM E23

Specimen Type: A (V-Notch) Test Date: 1/31/2018 Released By: Rich Minshall

Specimen ID (N/A)	Notch Location (N/A)	Notch Orientation (N/A)	W (mm)	D (mm)	Test Temperature (C)	Abs. Energy (J)	Lateral Expansion (mm)	Shear Area (%)	Condition (N/A)
17149-3-C1	Base	T-L	7.50 0.295 (in)	10.01 0.394 (in)	-1.0 30 (F)	72.5 53 (ft-lb)	1.43 0.056 (in)	100	
17149-3-C2	Base	T-L	7.50 0.295 (in)	9.97 0.393 (in)	-1.0 30 (F)	79.0 58 (ft-lb)	1.38 0.054 (in)	100	
17149-3-C3	Base	T-L	7.50 0.295 (in)	10.01 0.394 (in)	-1.0 30 (F)	76.0 56 (ft-lb)	1.37 0.054 (in)	100	
17149-3-C4	Base	T-L	7.49 0.295 (in)	10.02 0.394 (in)	-51.0 -60 (F)	52.0 38 (ft-lb)	0.97 0.038 (in)	84	
17149-3-C5	Base	T-L	7.49 0.295 (in)	10.03 0.395 (in)	-51.0 -60 (F)	45.0 33 (ft-lb)	0.92 0.036 (in)	84	
17149-3-C6	Base	T-L	7.48 0.294 (in)	10.03 0.395 (in)	-51.0 -60 (F)	46.0 34 (ft-lb)	0.89 0.035 (in)	100	

Notes: Shear difficult to determine due to delamination.

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Appendix E

EWI Lab Text Report – GMAW Test Coupons

Customer:	ATI Advanced Technology International	Project Number:	56788GTH
Contact:	Justin Montague	EWI Contact:	Dave Workman
Address:		Phone:	614-688-5244
		Email:	dworkman@ewi.org
Customer Sample ID:	GMAW	Specification:	Guidance to AWS B4.0
LIMS Sample ID:	17149-2	Material Type:	Carbon Steel
Heat/Lot Number:	GMAW		

Notched Bar Impact Test, ASTM E23

Specimen Type: A (V-Notch) Test Date: 1/26/2018 Released By: Steve O'Mara

Specimen ID (N/A)	Notch Location (N/A)	Notch Orientation (N/A)	W (mm)	D (mm)	Test Temperature (C)	Abs. Energy (J)	Lateral Expansion (mm)	Shear Area (%)	Condition (N/A)
17149-2-1	WCL	T-L	7.51 0.296 (in)	10.00 0.394 (in)	-1.0 30 (F)	119.0 88 (ft-lb)	1.79 0.070 (in)	100	As Received
17149-2-2	WCL	T-L	7.51 0.296 (in)	10.00 0.394 (in)	-1.0 30 (F)	138.0 102 (ft-lb)	2.08 0.082 (in)	100	As Received
17149-2-3	WCL	T-L	7.51 0.296 (in)	10.00 0.394 (in)	-1.0 30 (F)	124.0 91 (ft-lb)	1.94 0.076 (in)	100	As Received
17149-2-4	WCL	T-L	7.51 0.296 (in)	10.00 0.394 (in)	-51.0 -60 (F)	103.0 76 (ft-lb)	1.58 0.062 (in)	100	As Received
17149-2-5	WCL	T-L	7.51 0.296 (in)	10.00 0.394 (in)	-51.0 -60 (F)	110.0 81 (ft-lb)	1.61 0.063 (in)	88	As Received
17149-2-6	WCL	T-L	7.51 0.296 (in)	10.00 0.394 (in)	-51.0 -60 (F)	105.0 77 (ft-lb)	1.68 0.066 (in)	88	As Received

Notes:

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EWI

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1250 Arthur E. Adams Drive, Columbus, OH 43221

Customer: ATI Advanced Technology International	**Project Number:** 56788GTH
Contact: Justin Montague	**EWI Contact:** Dave Workman
Address:	**Phone:** 614-688-5244
	Email: dworkman@ewi.org
Customer Sample ID: GMAW	**Specification:** Guidance to AWS B4.0
LIMS Sample ID: 17149-2	**Material Type:** Carbon Steel
Heat/Lot Number: GMAW	

Rectangular Tensile Test, ASTM E8

Initial Loading Rate (IPM): .05 **Test Temp (C):** 23 **Released By:** Steve O'Mara

Final Loading Rate (IPM): .15 **Test Date:** 1/26/2018

Specimen ID (N/A)	Tensile Orientation (N/A)	Original Width (in)	Original Thickness (in)	Orig GL (in)	UTS (psi)	0.2% Yld Stress (psi)	Elongation (%)	ROA (%)	Failure Location (N/A)	Condition (N/A)
17149-2-T1	Transverse	0.253 6.4 (mm)	0.366 9.3 (mm)	1.009 25.6 (mm)	78300 540 (MPa)	76600 528 (MPa)	14.3	42.3	Within Gage Length	As Received
17149-2-T2	Transverse	0.253 6.4 (mm)	0.367 9.3 (mm)	1.008 25.6 (mm)	98800 681 (MPa)	82200 567 (MPa)	24.0	72.5	Within Gage Length	As Received
17149-2-T3	Transverse	0.253 6.4 (mm)	0.362 9.2 (mm)	1.006 25.6 (mm)	86800 599 (MPa)	75900 523 (MPa)	7.9	26.9	Within Gage Length	As Received

Notes:

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We Manufacture Innovation

1250 Arthur E. Adams Drive, Columbus, OH 43221

Customer:	ATI Advanced Technology International	Project Number:	56788GTH
Contact:	Justin Montague	EWI Contact:	Dave Workman
Address:		Phone:	614-688-5244
		Email:	dworkman@ewi.org
Customer Sample ID:	GMAW	Specification:	Guidance to AWS B4.0
LIMS Sample ID:	17149-2	Material Type:	Carbon Steel
Heat/Lot Number:	GMAW		

Bend Test, ASTM E190/E290

Test Type: Semi Guided (ASTM E290, Wrap Around) **Test Date:** 2/5/2018

Test Temperature (F): Ambient **Released By:** Steve O'Mara

Specimen ID (N/A)	Bend Orientation (N/A)	Thickness (in)	Width (in)	Bend Mandrel Dia (in)	Bend Angle (Degrees)	Elongation (%)	Bend Results (N/A)	Pass/ Fail (N/A)
17149-2-B1	Face Bend	0.375 9.5 (mm)	1.499 38.1 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass
17149-2-B2	Face Bend	0.375 9.5 (mm)	1.499 38.1 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass
17149-2-B3	Face Bend	0.375 9.5 (mm)	1.501 38.1 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass
17149-2-B4	Root Bend	0.375 9.5 (mm)	1.502 38.2 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass
17149-2-B5	Root Bend	0.375 9.5 (mm)	1.501 38.1 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass
17149-2-B6	Root Bend	0.375 9.5 (mm)	1.497 38.0 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass

Notes:

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Appendix F

EWI Lab Text Report – HFRW Test Coupons

EWI

We Manufacture Innovation

1250 Arthur E. Adams Drive, Columbus, OH 43221

Customer: ATI Advanced Technology International Contact: Justin Montague Address:	Project Number: 56788GTH EWI Contact: Dave Workman Phone: 614-688-5244 Email: dworkman@ewi.org
Customer Sample ID: HERW LIMS Sample ID: 17149-1 Heat/Lot Number: N/A	Specification: Guidance to AWS B4.0 Material Type: Carbon Steel

Bend Test, ASTM E190/E290

Test Type: Semi Guided (ASTM E290, Wrap Around) **Test Date:** 2/5/2018

Test Temperature (F): Ambient **Released By:** Steve O'Mara

Specimen ID (N/A)	Bend Orientation (N/A)	Thickness (in)	Width (in)	Bend Mandrel Dia (in)	Bend Angle (Degrees)	Elongation (%)	Bend Results (N/A)	Pass/ Fail (N/A)
17149-1-B1	Face Bend	0.365 9.3 (mm)	1.500 38.1 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass
17149-1-B2	Face Bend	0.365 9.3 (mm)	1.499 38.1 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass
17149-1-B3	Face Bend	0.366 9.3 (mm)	1.500 38.1 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass
17149-1-B4	Root Bend	0.365 9.3 (mm)	1.501 38.1 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass
17149-1-B5	Root Bend	0.365 9.3 (mm)	1.500 38.1 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass
17149-1-B6	Root Bend	0.365 9.3 (mm)	1.501 38.1 (mm)	1.300 33.0 (mm)	180	22	No Visual Defects	Pass

Notes:

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EWI®

We Manufacture Innovation

1250 Arthur E. Adams Drive, Columbus, OH 43221

Customer:	ATI Advanced Technology International	Project Number:	56788GTH
Contact:	Justin Montague	EWI Contact:	Dave Workman
Address:		Phone:	614-688-5244
		Email:	dworkman@ewi.org
Customer Sample ID:	HERW	Specification:	Guidance to AWS B4.0
LIMS Sample ID:	17149-1	Material Type:	Carbon Steel
Heat/Lot Number:	N/A		

Notched Bar Impact Test, ASTM E23

Specimen Type: A (V-Notch) Test Date: 1/26/2018 Released By: Steve O'Mara

Specimen ID (N/A)	Notch Location (N/A)	Notch Orientation (N/A)	W (mm)	D (mm)	Test Temperature (C)	Abs. Energy (J)	Lateral Expansion (mm)	Shear Area (%)	Condition (N/A)
17149-1-1	WCL	T-L	7.51 0.296 (in)	10.02 0.394 (in)	-1.0 30 (F)	7.0 5 (ft-lb)	0.12 0.005 (in)	24	As Received
17149-1-2	WCL	T-L	7.51 0.296 (in)	10.02 0.394 (in)	-1.0 30 (F)	7.0 5 (ft-lb)	0.09 0.004 (in)	24	As Received
17149-1-3	WCL	T-L	7.51 0.296 (in)	10.02 0.394 (in)	-1.0 30 (F)	6.0 4 (ft-lb)	0.08 0.003 (in)	24	As Received
17149-1-4	WCL	T-L	7.51 0.296 (in)	10.01 0.394 (in)	-51.0 -60 (F)	3.0 2 (ft-lb)	0.03 0.001 (in)	13	As Received
17149-1-5	WCL	T-L	7.51 0.296 (in)	10.01 0.394 (in)	-51.0 -60 (F)	2.0 1 (ft-lb)	0.02 0.001 (in)	13	As Received
17149-1-6	WCL	T-L	7.51 0.296 (in)	10.01 0.394 (in)	-51.0 -60 (F)	2.0 1 (ft-lb)	0.02 0.001 (in)	13	As Received

Notes:

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EWI

We Manufacture Innovation

1250 Arthur E. Adams Drive, Columbus, OH 43221

Customer:	ATI Advanced Technology International	Project Number:	56788GTH
Contact:	Justin Montague	EWI Contact:	Dave Workman
Address:		Phone:	614-688-5244
		Email:	dworkman@ewi.org
Customer Sample ID:	HERW	Specification:	Guidance to AWS B4.0
LIMS Sample ID:	17149-1	Material Type:	Carbon Steel
Heat/Lot Number:	N/A		

Rectangular Tensile Test, ASTM E8

Initial Loading Rate (IPM): .05 Test Temp (C): 23 Released By: Steve O'Mara

Final Loading Rate (IPM): .15 Test Date: 1/26/2018

Specimen ID (N/A)	Tensile Orientation (N/A)	Original Width (in)	Original Thickness (in)	Orig GL (in)	UTS (psi)	0.2% Yld Stress (psi)	Elongation (%)	ROA (%)	Failure Location (N/A)	Condition (N/A)
17149-1-T1	Transverse	0.253 6.4 (mm)	0.365 9.3 (mm)	1.008 25.6 (mm)	90400 623 (MPa)	76100 525 (MPa)	7.7	70.7	Outside Gage Length	As Received
17149-1-T2	Transverse	0.253 6.4 (mm)	0.365 9.3 (mm)	1.005 25.5 (mm)	90400 623 (MPa)	74700 515 (MPa)	4.5	69.9	Outside Gage Length	As Received
17149-1-T3	Transverse	0.253 6.4 (mm)	0.365 9.3 (mm)	1.007 25.6 (mm)	90000 621 (MPa)	87800 606 (MPa)	10.1	70.4	Outside Gage Length	As Received

Notes:

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