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Initial testing for the recommendation of improved gas metal arc welding procedures for HY-80 steel plate butt joints at Norfolk Naval Shipyard

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MONTEREY, CALIFORNIA

THESIS

INITIAL TESTING FOR THE RECOMMENDATION OF IMPROVED GAS METAL ARC WELDING PROCEDURES FOR HY-80 STEEL PLATE BUTT JOINTS AT NORFOLK NAVAL SHIPYARD

by

Veronika J. Rice

December 2015

Thesis Advisor: Young Kwon
Second Reader: Ryan McCrillis

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Pulsed gas metal arc welding (GMAW-P) is the ideal process for shipboard hull welding applications, theoretically. Butt joint samples were created using HY-80 steel plate so that the following comparisons could be made: 90%Ar-10%CO_2 versus 95%Ar-5%CO_2 shielding gases and their effect upon weld penetration, Miller brand versus Lincoln Electric brand power supply synergic GMAW-P algorithm performance, and Single-V versus Double-V butt joint design.

Based upon the creation of butt joint samples, it was determined that 90%Ar-10%CO_2 is a more ideal gas mixture for this application and that Lincoln Electric brand machines have preferred interface by Norfolk Naval Shipyard welders. Future research is still needed in a controlled environment to develop optimized GMAW-P procedures.

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LIST OF ACRONYMS AND ABBREVIATIONS

AIM	Advanced Industrial Management
AWS	American Welding Society
C/L	Centerline
GMAW	Gas Metal Arc Welding
GMAW-P	Gas Metal Arc Welding Pulsed Spray Transfer
GMAW-S	Gas Metal Arc Welding Spray Transfer
HAZ	Heat Affected Zone
HC#1	Hull Cut #1
I_{RMS}	Current Root Mean Square
NAVSEA	Naval Sea Systems Command
NDT	Non-Destructive Testing
NNSY	Norfolk Naval Shipyard
SMAW	Shielded Metal Arc Welding
SSBN	Ship, Submersible, Ballistic, Nuclear
T	Plate Thickness
UT	Ultrasonic Testing
V_{RMS}	Voltage Root Mean Square
WFS	Wire Feed Speed

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I. INTRODUCTION

Norfolk Naval Shipyard (NNSY) in Portsmouth, Virginia, is one of the four public shipyards run by Naval Sea Systems Command (NAVSEA) that overhauls submarines for the United States Navy. One of the most essential abilities of any shipyard with this mission is the capacity to efficiently and effectively reinstall submarine hull cuts. The reinstallations of hull cuts are critical path work during dry dock availabilities because the access granted by their removal is critical to other required work; hull cut installation is one of the last major jobs that will be completed prior to the key event of Undocking.

The most complicated hull cut routinely performed at NNSY is Hull Cut #1 (HC#1) on Ship, Submersible, Ballistic, Nuclear (SSBN) 726 Ohio Class submarines: HC#1 is composed of HY-80 steel plate approximately five-centimeters thick and extends across four structural frames. The size and complexity of this hull cut creates large demands for materials and labor during installation. It is deducible that if NNSY can master the installation of HC#1, they can master the installation of any hull cut.

A. NEED FOR THIS RESEARCH

Problems during the welding of hull cuts can easily generate schedule delays and excessive cost. A recent illustration of this point occurred during the installation of HC#1 on SSBN 736: As shown in Table 1, the total labor charges for that job were three times as high as any other HC#1 installation at NNSY within the past decade. A record number of welding repairs had to be performed because of the significant number of defects discovered during post-installation non-destructive testing (NDT). It is evident that welding proficiency has a direct effect upon shipyard cost performance.

Gas metal arc welding (GMAW) is typically preferred in private industry for hull cut applications because the process is more efficient than shielded metal arc welding (SMAW) in terms of both labor and material. On SSBN 734 & SSBN 736, NNSY implemented the use of GMAW transfer methods for HC#1 installation to attempt to improve efficiency. Contrarily, NNSY experienced the opposite effect (see Table 1).

Performance of SSBN 736 was so poor that NNSY reverted to the exclusive use of SMAW for the installation of HC#1 on SSBN 738, resulting in the question: Why did NNSY experience a significant increase in cost while using a more efficient welding process? The answer is simple: NNSY did not execute that process with a proficient workforce.

Table 1. NNSY Historical Installation Labor Charges versus Post-Installation Rejectable UT Indications for HC#1 (In Reverse Chronological Order).[1]

	SSBN 738	SSBN 736	SSBN 734	SSBN 732	SSBN 729	SSBN 728
Welding (man-hours)	4304.5	10915	3780	2636	2256	2242
Structural Work (man-hours)	1144	3967	980	1036	992	992
NDT Inspections (man-hours)	783.46	1280.5	392	402	396	398
Total Labor (man-hours)	8832.46	24707	8810	6644	5398	5388
Welding Process	SMAW	SMAW GMAW-S	SMAW GMAW-P	SMAW	SMAW	SMAW
Rejectable UT indications	43	182	89	31	105	127

Adapted from [1]: Advanced Industrial Management Database. [Online]. Available: https://snntsewb2.nnsy.navy.mil/XenApp/site/default.aspx?CTX_CurrentFolder=%5cCorporate%20Applications%5cAim/. Accessed Oct. 2014.

The proficiency of a shipyard's workforce is dependent upon its training in the use of optimized processes. NNSY did not adequately prepare its skilled labor to execute GMAW on such a large scale on the waterfront. This lack of preparation manifested itself in increased welding defects and negatively impacted the bottom line. First-time quality is critical to schedule and cost performance. If NNSY is to perform competitively as a shipyard in the field of hull cut installations, it must develop better processes for GMAW in butt joints based upon research, and train its workforce to be proficient in these new processes prior to application.

[1] Historical man-hour charges were compiled directly from the NNSY AIM Database [1]. The total number of rejectable UT indications were compiled directly from corresponding certified Technical Work Documents as scanned into the NNSY Hit Kit Database [2].

B. OBJECTIVE AND STRUCTURE OF THIS THESIS

The objective of this thesis is to use weld theory to make recommendations for future hull cut welding process development and testing based upon observations gathered during preliminary welding trials. Several factors will be explored using the GMAW-P transfer method including two different welding machines, two different argon/carbon dioxide shielding gas mixtures, and several butt joint designs.

To this end, NNSY needs to re-examine its welding processes pertaining to hull cut installation in order to optimize them before refining its training program. This will involve gathering research with conditions mimicking those present during welding execution at NNSY. Only then can ideal processes be developed. Chapter II will explore fundamental principles of arc welding through a guided comparison of SMAW and GMAW. With that foundation laid, Chapter III will describe the specimen design that will be tested. Chapter IV will show results collected from this experiment. Chapter V will review the meaning of those results and make suggestions for future related research topics.

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II. WELD THEORY

A. UNDERSTANDING ARC WELDING TERMINOLOGY

In arc welding, an electrical "arc is struck between the work piece and the tip of the electrode" [3]. When using consumable electrodes, a current is passed through a rod or wire. The heat of the arc will quickly melt a small amount of the work piece (base metal) and the tip of the electrode (filler metal). The two molten metals will combine resulting in weld metal. The microstructure of a small layer of base metal contacting the weld metal will be changed by the heat of welding; this is called the heat affected zone (HAZ). There are several factors that affect the outcome of welding a joint.

A stable arc refers to an arc that holds a steady position relative to the electrode tip. When the arc is not stable it can lead to the generation of spatter. Spatter refers to the generation of unwanted molten droplets created by the welding arc, not to be confused with molten filler material. Spatter can cause erratic patterns that disrupt the formation of a continuous welding bead. Erratic shaped welding beads are very undesirable, because sharp angles and corners can hinder proper weld penetration through a weld joint and increase the potential for the formation of voids within a weld, weakening the joint.

The term weld penetration refers to "the distance that fusion extends into the base metal… from the surface melted during welding" [4]. According to [4], variables affecting weld penetration include arc current, polarity, type of welding, travel angle (of electrode), shielding gas type, electrode diameter, and travel speed (of electrode). A greater arc current results in greater penetration. Positive polarity directs more arc energy into the base metal resulting in greater penetration, whereas negative polarity directs more energy into the electrode. A travel angle perpendicular to the surface of the base metal will result in the greatest weld penetration because it is directing the most energy into the base metal. "Shielding gases with a higher rate of thermal conductivity, such as 100% carbon dioxide (CO_2) … will produce welds with a broader, deeper penetration profile. While shielding gases with a lower rate of thermal conductivity, such as 100% argon (Ar) … have a shallower penetration profile" [4]. Current density is the amperage per square inch of the electrode cross-sectional area. With the same arc current, a smaller diameter electrode will have a smaller cross-sectional area, thus a greater current density. Greater current density will have greater weld penetration, however it must be noted that "every electrode diameter has a maximum current density before the welding arc becomes very unstable" [4]. Current density is the limiting factor for minimum electrode size at a specific current. Weld deposition rate is the rate at which filler metal is deposited by weight during welding. "Weld deposition rates vary directly in relation to the current density used" [3]. Travel speed and penetration are inversely related because the faster an electrode is moving the less time it has to transfer heat into a specific point of the weld.

B. COMPARISON OF ARC WELDING TRANSFER METHODS

Generally, arc welding is well suited for hull cut applications. The equipment is portable, which is a necessity to weld shipboard, and the potential for high weld deposition rates is essential in such a high volume application. A ship's hull serves as a ground, so using a positively charged electrode facilitates the striking of an arc for welding. The electrical arc acts as a heat source to melt the filler metal and base metal, allowing welding to take place.

SMAW is one of the oldest and most widely used methods of arc welding. SMAW welding had been used on hull cuts at NNSY for a very long time. The simple equipment setup and less stringent preparation requirements make it very versatile. GMAW, on the other hand, requires more complicated equipment and a more controlled work environment. In hull cut applications, private industry has proven that GMAW can be an easier welding process to execute and more efficient if properly planned. Table 2 compares advantages and disadvantages of SMAW and GMAW pertaining to hull cut welding. This section will explore those differences specifically pertaining to submarine hull cut applications.

1. Shielded Metal Arc Welding

SMAW is an arc process that uses a consumable electrode with a flux coating that decomposes when the heat of an arc is applied to provide shielding, pictured in Figure 1. Because of the shape of the electrodes, SMAW is also known as "stick" welding. The

SMAW process is simple and hardy; it will better tolerate less than ideal work conditions. SMAW requires less equipment, which is much easier to set up and makes it a better choice in tight spaces. It can also be used in any position.

Table 2. Comparison of GMAW and SMAW ↑Advantages/↓Disadvantages.

	GMAW "MIG"		SMAW "Stick"	
Operating Factor	↑	35%	↓	25%
Minimum Filler Material Waste	↑	5%	↓	40%
Weld Penetration	↑	Greater (Less Excavation)	↓	Smaller (More Excavation)
NNSY Deposition Rate	↑	36.3 kgs per day	↓	9.1 kgs per day
Equipment Setup	↓	Complicated	↑	Simple
Equipment Maintenance Requirements	↓	High	↑	Low
Risk of Defects (if surface contaminants)	↓	High	↑	Minimal
Risk of Porosity (if wind & drafts)	↓	High	↑	Minimal
Risk of Slag Inclusion	↑	Minimal	↓	Increased
Welding Position	–	Transfer Mode Dependent	–	All Positions
Automated Processes	↑	YES	↓	NO
Slag Generation	↑	NO	↓	YES
Good for Tight Accesses	↓	NO	↑	YES

One of the main reasons that SMAW has the simplest equipment is the sacrificial flux covering the metal core. When the heat of the arc is applied, this coating breaks down, stabilizes the arc, displaces the inert gases in ambient air, "releases deoxidizers and other scavengers that purify the weld" [3], and creates a physical barrier called slag covering the molten weld.

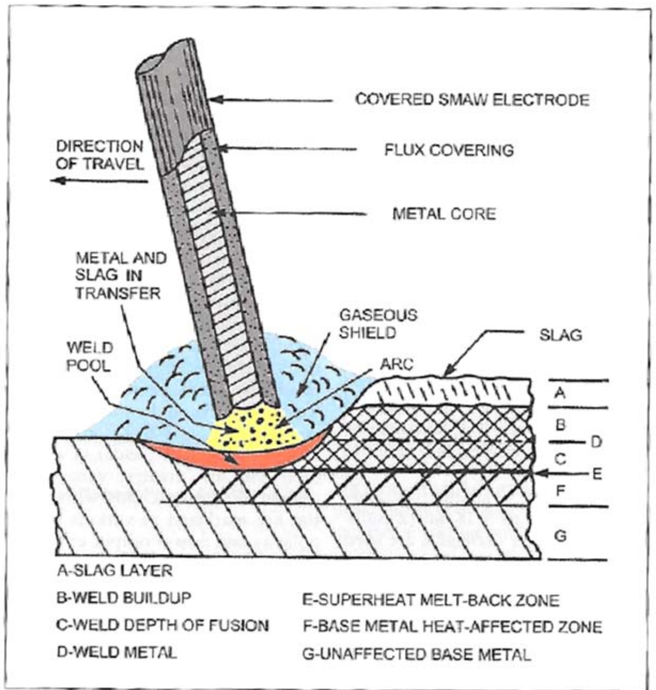

Figure 1. Schematic Representation of Shielded Metal Arc Welding.

Source [3]: *Welding Handbook, Volume 1: Welding Science and Technology,* 9th ed., Miami, FL, 2006.

SMAW's very basic equipment setup creates unavoidable disadvantages when compared to GMAW. Operating factor is the estimated percentage of a welder's workday actually spent welding for a given welding method. According to NNSY welding engineers, SMAW is slower than GMAW and is estimated to have an operating factor of 25%. Because the SMAW process requires the welder to constantly switch out welding rods, less time can be spent laying weld metal. Using rods is also very inefficient material-wise: Only about 60% of the rod material by weight is estimated to be deposited as weld material. The rod coating is used up in the creation of slag, which must be discarded, and a large percentage of the rod material is thrown out because not all of the rod can be used before it must be changed out. Additionally, using welding rods means that as the rod is used up, the position that the welder must hold the rod relative to the weld joint is constantly changing. Greater welder skill is required to maintain the tip of the electrode at a consistent distance from the base metal.

2. Gas Metal Arc Welding

GMAW or Metal Inert Gas “MIG” welding is a semi-automatic arc process that uses a consumable electrode wire that is fed through a gas nozzle, which provides an inert gas for shielding, pictured in Figure 2. Since a bare wire electrode is used without a flux coating, it is important to maintain a clean worksite and good coverage of shielding gases. The lack of flux means that only deoxidizers present in the weld metal are available to carry impurities out. Surface contaminants can quickly exhaust deoxidizers and become trapped within the weld. Ambient air leaks in the shielding gas supply or a drafty work area can easily allow excess amounts of reactive gases (hydrogen, oxygen, or nitrogen) to enter weld metal and contribute to porosity. Despite all of these additional risks, “if the variables are properly balanced, less skill is required for the gas metal arc welding than for the SMAW” process according to [3]. Because wire is fed through a nozzle, the distance from the nozzle to the work piece does not need to constantly change in order to maintain a proper distance between the electrode and the base metal.

Wire feeding also eliminates the need to change out welding rods. Welding only needs to be routinely stopped when the welder needs to adjust position. This reduction in interruptions contributes to a higher operating factor of 35%. Additionally, filler wire comes in long spools; wire does not need to be discarded every time a new arc is struck, only when reaching the end of a spool. The more efficient design and the lack of sacrificial flux allow an estimated 95% of the wire material to be deposited as weld material. NNSY welding engineers estimate that the GMAW weld deposition rate is four times faster than the SMAW deposition rate (see Table 2).

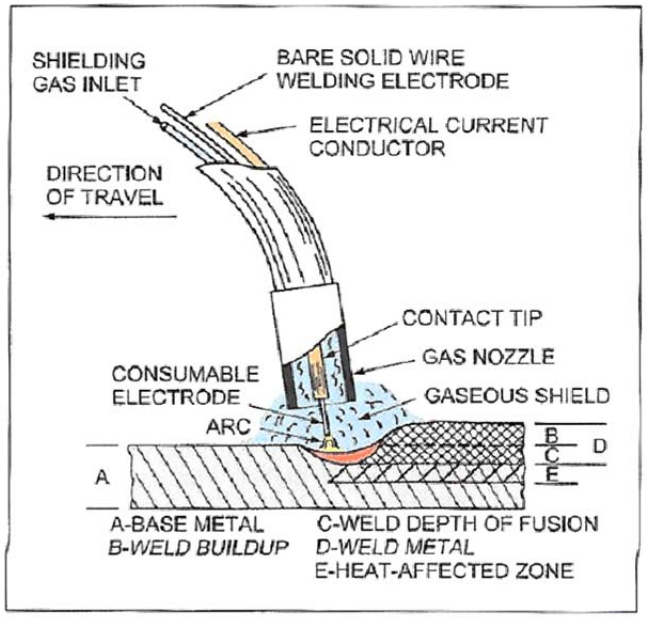

Figure 2. Schematic Representation of Gas Metal Arc Welding.

Source [3]: *Welding Handbook, Volume 1: Welding Science and Technology,* 9th ed., Miami, FL, 2006.

Different GMAW transfer modes[2] can be created by controlling the current density (illustrated in Figure 3). The two most common transfer modes used for hull plate applications are GMAW-Spray Transfer (GMAW-S) and GMAW-Pulsed Spray Transfer (GMAW-P). There are welding position limitations based upon the specific transfer mode.

"Transition current density level is defined as the current density level above which spray transfer occurs" [3]. Figure 3 illustrates the relative orientation of spray transfer, globular transfer, and pulsed spray transfer around the transition current density. Above the transition current density, molten droplets of smaller diameter than the electrode tip detach from the electrode and propel across a stable arc onto the base metal. Weld deposition rate is very fast and the molten droplets tend to be propelled in the

[2] GMAW transfer modes are the different ways in which the tip of the electrode wire forms a molten droplet that separates from the electrode and travels to the weld surface. The transfer mode is determined by the current density of the arc.

direction the electrode is pointing, giving the welder more control over the direction of the molten filler material with very little spatter. The filler material is deposited so quickly that there is a high risk of the molten weld metal succumbing to gravity and dripping to form ridges on the surface before solidifying. These ridges cause stress points that can lead to fractures in the weld joint. This is why spray transfer mode should only be used in horizontal applications.

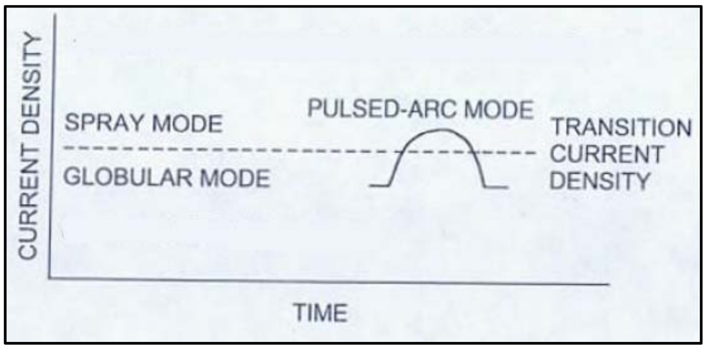

Figure 3. Gas Metal Arc Welding Transfer Mode Comparison.

Adapted from [3]: *Welding Handbook, Volume 1: Welding Science and Technology*, 9th ed., Miami, FL, 2006.

Slightly below the transition current density, globular transfer occurs where molten droplets of larger diameter than the electrode tip form. When they detach, “the metal globules are propelled from randomly varying positions with respect to the center of the electrode tip” [3]. This gives the welder little control over the direction of the molten filler and generates a lot of spatter. The droplets transfer to the weld at a slower rate than in spray transfer, allowing the molten weld to solidify before gravity would cause it to drip.

Pulsed spray transfer combines the droplet control of spray transfer with the slower deposition rate of globular transfer by varying the current density as illustrated in Figure 4. The base current density is below the transition current density in the range of globular transfer. The current density will then be increased above the transition current density with enough time for a single droplet to form and detach (ideally only one) before returning to the globular transfer range. This control is dependent upon modern equipment and software. When set up is correct, pulsed spray transfer will result in a slow controlled spray of droplets that can be used in any joint orientation.

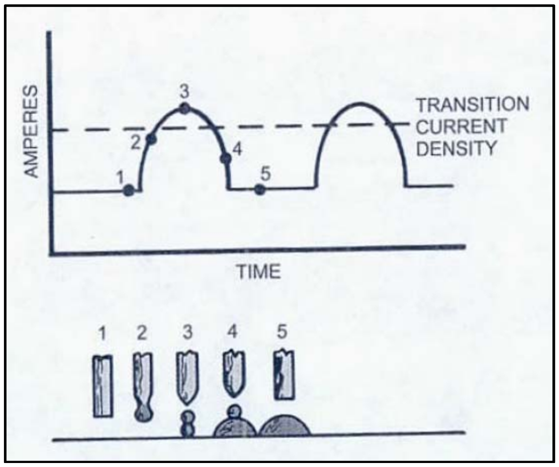

Figure 4. Pulsed Gas Metal Arc Welding.

Source [3]: *Welding Handbook, Volume 1: Welding Science and Technology,* 9th ed., Miami, FL, 2006.

Shielding gas composition can have an impact upon the transition current density. Gases with a greater thermal conductivity will result in a higher transition current density. For the same welding method, increasing the CO_2 content of an Ar/CO_2 mixture from 95%Ar-5%CO_2 to 90%Ar-10%CO_2 will raise the transition current density, allowing a higher current density to be used, which will increase weld penetration.

In theory, GMAW is a much more efficient welding process than SMAW. Since hull cut welding rarely allows the opportunity to weld in a perfectly horizontal position, GMAW-P's versatility makes it a better suited transfer method for hull cut applications than GMAW-S in a shipboard environment.

III. EXPERIMENTAL PROCESS

A. STATEMENT OF PROBLEM

The variables impacting weld joints are numerous. The only way to substantiate that welding processes are optimum for specific working conditions is to conduct trials using the same equipment, materials, joint designs, and procedures that would be used in application. To support the goal of NNSY implementing GMAW-P as a preferred welding process in the application of submarine hull cuts, trials need to be conducted to determine the ideal weld joint design and process.

B. DESIGN OF SPECIMENS

1. Specimen Dimensions

A standard specimen design was used for all of the trials. A 929-square centimeter (30.5 centimeters by 30.5 centimeters) of HY-80 steel plate[3] was used of plate thickness (T) either 1.9 cm or 3.8 cm for all tests, as seen in Figure 5. Each plate was divided into two 15.2-cm wide halves, beveled to the appropriate butt joint design, and tacked into place before welding. All welding beads started at the 0.0-cm position (Reference A in Figure 5) and moved in the direction of the 30.5-cm position. Reference B is the center of the weld joint. Where UT testing was performed, testing was only completed along the weld area from 2.5 cm to 27.9 cm so that discontinuities generated by the end of the sample would not interfere with overall sample results.

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[3] All plates were composed of HY-80 low-alloy steel with specifications in compliance with [5].

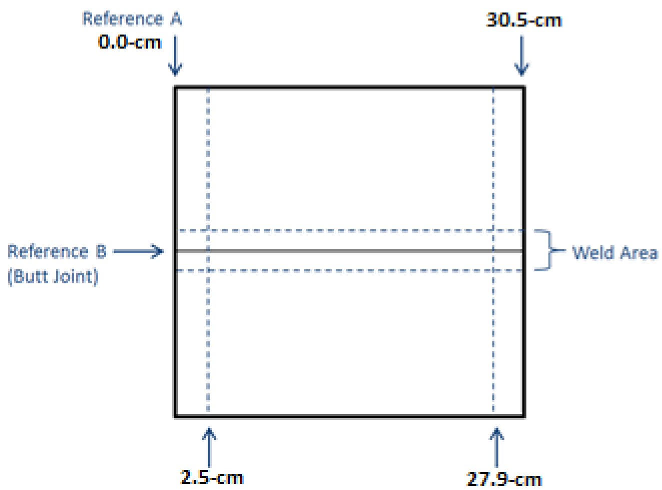

Figure 5. Weld Specimen Design Dimensions.

2. Butt Joint Designs

Figure 6 shows basic butt joint orientation terminology in accordance with [6]. "T" is the plate thickness. The "Root Face" is the portion of the groove face adjacent the point at which the back of the weld intersects the base metal surfaces. The "Root Opening" is the distance between the two root faces. The "Groove Angle" is the total angle of the groove between the two metal pieces to be welded.

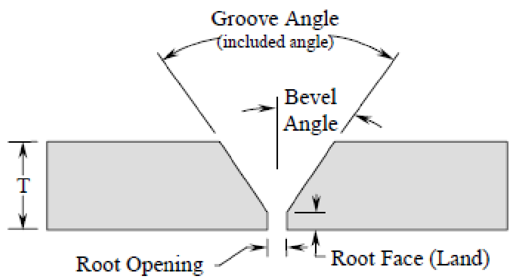

Figure 6. Butt Joint Orientation Terminology.

Source [6]: Standard Naval Shipyard Procedure for Fabrication, Welding and Repair of Submarine Structure ,WP-1688 Rev. B., Portsmouth, VA: Norfolk Naval Shipyard, 2014.

Five different butt joint designs were used as listed in Table 3. The joint design numbers are in accordance with NNSY Local Procedure [6] and pictured as relevant to this experiment in Figures 7 through 9. The widest portion of the bevel was always the first side to be welded. All trials were performed in the horizontal welding position with a 60° groove angle and a 0.5-cm root opening.

Table 3. Trial Joint Designs.

Design	Joint #	Root C/L	T, Plate Thickness
A	B1V.1	-	1.9 cm
B	B2V.1	-	1.9 cm
C	B2V.1	70/30	3.8 cm
D	B2V.3	2/3, 1/3	3.8 cm
E	B2V.3	50/50	3.8 cm

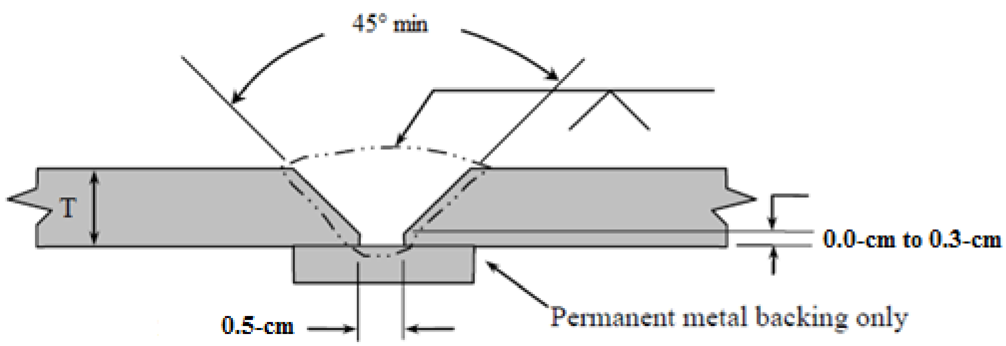

Figure 7. B1V.1 Joint: Single-V Butt Joint Welded on Permanent Metal Backing.

Adapted from [6]: *Standard Naval Shipyard Procedure for Fabrication, Welding and Repair of Submarine Structure,*WP-1688 Rev. B., Portsmouth, VA: Norfolk Naval Shipyard, 2014.

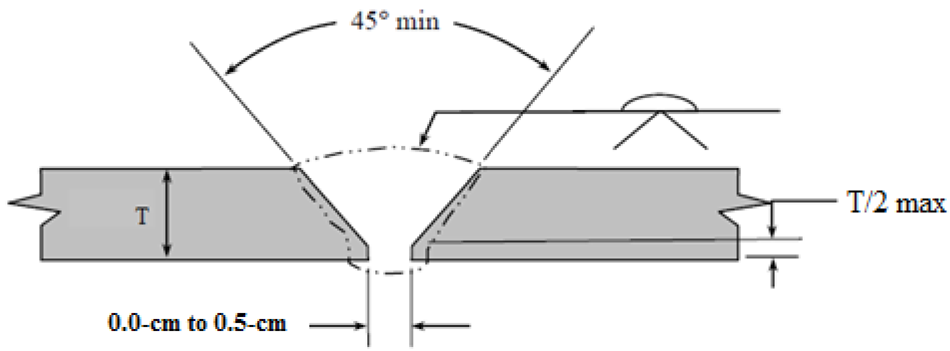

Figure 8. B2V.1 Joint: Single-V Butt Joint Welded Both Sides.

Adapted from [6]: *Standard Naval Shipyard Procedure for Fabrication, Welding and Repair of Submarine Structure,*WP-1688 Rev. B., Portsmouth, VA: Norfolk Naval Shipyard, 2014.

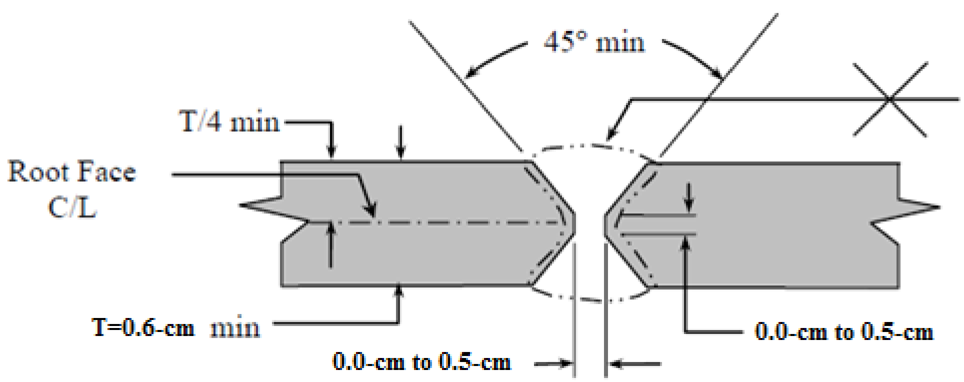

Figure 9. B2V.3 Joint: Double-V Butt Joint.

Adapted from [6]: *Standard Naval Shipyard Procedure for Fabrication, Welding and Repair of Submarine Structure,*WP-1688 Rev. B., Portsmouth, VA: Norfolk Naval Shipyard, 2014.

3. Welding Sequence

After specimens were cut and beveled to specific joint design specifications, they were tack welded onto a welding work bench. Prior to that step, joint design A listed in Table 3 required a metal backing to be tacked in place, which was a strip composed of HY-80 steel measuring 30.5-cm long by 2.5-cm wide and 0.6-cm thick. All specimens were pre-heated to 65.6°C prior to welding.

The generic welding sequence is depicted in Figure 10. All welds were performed in the horizontal position. Initially the beveled edge was welded, or in the case of joint design D with a Double-V design, the wider beveled area was welded first. Joint designs A and B would at this point be considered complete. Joint designs C through E were excavated on the underside of the weld only as deep as required to find good metal.[4] Joint design C was excavated using back-gouging because of the larger volume of metal requiring removal to reach the base of the initial weld. Joint designs D and E were excavated using grinding because only minimum excavation was necessary to reach good metal. Finally, the backside of the weld was completed also in the horizontal position.

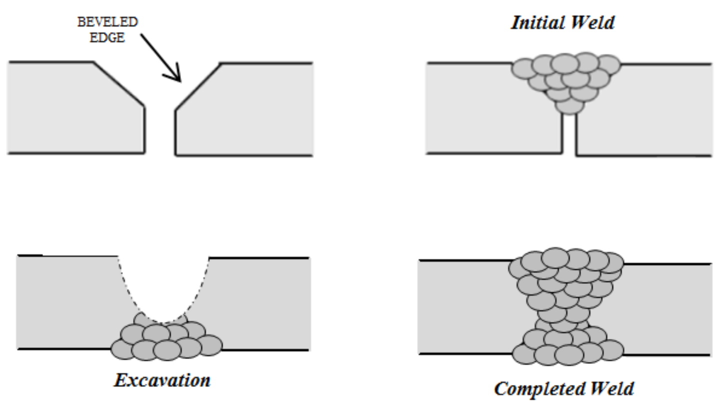

Figure 10. Generic Specimen Welding Sequence.

4. Specimen Assembly

All specimens were welded by NNSY qualified welders using Miller and Lincoln Electric brand welding machines in accordance with Lincoln Electric operator's instructions for GMAW-P configuration. WP-1688 NNSY Welding Technique Sheet S1-4-20 "Semi-Auto (manual) Gas Metal Arc Welding Pulse (GMAW-P)" [6] was adapted

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[4] "Good metal" is the term commonly used by welders to describe weld metal and/or base metal that is free of visual irregularities. During excavation, a welder will keep removing metal until reaching "good metal" that passes a visual inspection and is most likely to provide sound metal base for a good weld.

for use in this experiment to use Lincoln Electric machines so that a 90% Argon/10% CO_2 shield gas could be used.[5]

Material composition was kept constant in all specimens. Base metal was composed of HY-80 steel adhering to NAVSEA requirements outlined in [5]. Filler wire (electrode) was Type 100S-1 adhering to NAVSEA requirements outlined in [7]. Electrode diameter was kept constant at 1.1-mm. S1-4-20 recommends an electrode tip to work distance of 15.9-mm (12.7-mm to 22.2-mm allowable). Recommended Wire Feed Speed (WFS) is 444.5 to 1016 centimeters per minute in the horizontal position and 444.5 to 558.8 centimeters per minute in the vertical position.

[5] NNSY does not yet have approved Technique Sheets for the Lincoln Electric Machines used in this experiment. Existing guidance is approved for Miller brand welding equipment, which is not currently authorized for use at NNSY with a 90Ar/10CO_2 shield gas solution. Lincoln Electric brand machines were recently procured in support of process improvement initiatives.

IV. RESULTS

A. SHIELDING GAS COMPARISON

Greater weld penetration is ideal in butt joint applications, because greater weld penetration increases the chances of complete weld fusion with minimizing the formation of discontinuities within the metal microstructure. Research was done to evaluate 90%Ar-10%CO_2 versus 95%Ar-5%CO_2 and determine which mixture would be best suited for the remaining experiments.

1. Experimental Criterion

According to [4], the greatest factor affecting weld penetration is arc current. The impact is so strong that it can be concluded that arc current is proportional to weld penetration. Two specimens were made using the Lincoln Electric Power Feed 25M and the Lincoln Electric Power Wave S350 with the GMAW-P process for Joint Design A in the horizontal position. The only variable was the gas mixture: One specimen was welded using a 90%Ar-10%CO_2 gas mixture, and the other using a 95%Ar-5%CO_2 gas mixture. Over twenty passes were made to fill each joint, and the resulting Current Root Mean Square (I_{RMS}) readout of the arc was recorded for each pass. In the case of this experiment where all other factors were held to be constant, it can be assumed that the mixture producing the higher I_{RMS} for a programmed Voltage Mean Root Square (V_{RMS}) will produce greater weld penetration.

2. Experimental Results

Thermal conductivity in shielding gases has a proportional relationship to weld penetration. At temperatures in excess of 537.8°C, carbon dioxide gas has a greater thermal conductivity than argon gas. Because of this, it is expected that the 90%Ar-10%CO_2 gas mixture would have greater thermal conductivity and facilitate greater weld penetration than the 95%Ar-5%CO_2 gas mixture in GMAW applications. Just as expected, the 90%Ar-10%CO_2 gas mixture consistently facilitated a 20% greater arc current than the 95%Ar-5%CO_2 gas mixture (graphed for comparison in Figure 11).

Since the electrode diameter was held constant at 1.1-mm, the current density was also greater for the 90%Ar-10%CO_2 gas mixture.

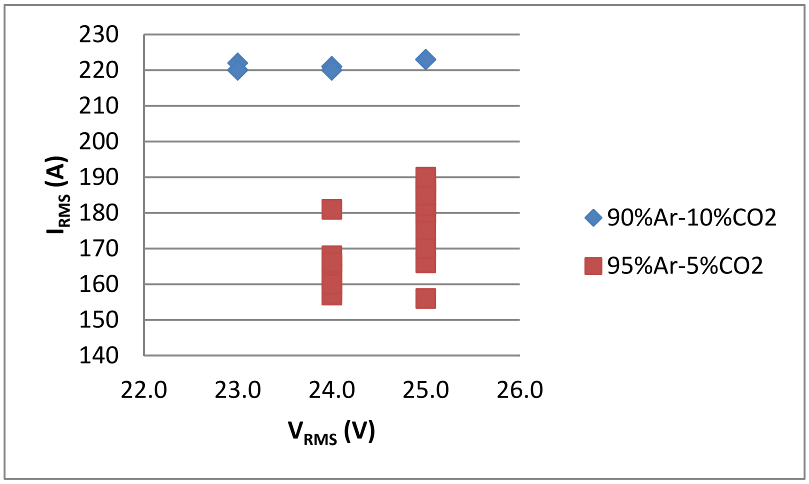

Figure 11. I_{RMS} versus V_{RMS} Comparison with Different Ar/CO_2 Gas Mixtures Using GMAW-P.

B. POWER SOURCE COMPARISON

Presently, NNSY's procedures for GMAW submarine hull cuts [6] only include parameters and settings for using the Miller brand welding equipment. To modernize, NNSY has procured twenty-five Lincoln Electric brand welding setups. A basic performance comparison for GMAW-P welding was performed between the Miller PipeWorx FieldPro Smart Feeder wire feeder with the Miller XMT 350 MPA power supply versus the Lincoln Electric Power Feed 25M wire feeder and Lincoln Electric Power Wave S350 power supply (pictured in Figure 12). Technique Sheet S1-4-20 from [6] was adapted for use with both machines. As an additional change, a 90%Ar-10%CO_2 gas mixture was used in lieu of a 95%Ar-5%CO_2 gas mixture because of the desirable increase weld penetration characteristics.

Figure 12. Miller PipeWorx FieldPro System (left) and Lincoln Electric Power Wave System (right).

Adapted from [8]: Miller Electric Mfg. Co. [Online]. Available: https://www.millerwelds.com. Accessed Oct. 2014. Adapted from [9]: The Lincoln Electric Company. [Online]. Available: http://www.lincolnelectric.com/en-us/Pages/default.aspx?locale=1033. Accessed Oct. 2014.

1. Experimental Criterion

Both GMAW-P setups for the Miller brand and Lincoln Electric brand machines use a setting called synergic welding. The goal of synergic welding is to allow for uniform filler material droplet size during welding transfer with a minimal amount of setting adjustments required by the welder. The welder will select the correct program for the filler material type and diameter to be used, and then the program will vary pulse frequency based upon WFS. An algorithm in the program will automatically make minor adjustments to maintain a constant arc current, which should translate into consistent weld penetration and bead size.

A total of eight specimens were made. Four specimens were made using the Lincoln Electric Power Feed 25M and the Lincoln Electric Power Wave S350 (pictured in Figure 12) with the GMAW-P process for Joint Design A with two joints welded in the horizontal position and two joints welded in the vertical position. Four specimens were made using the Miller PipeWorx FieldPro Wire Feeder and the Miller XMT 350 Power Source (pictured in Figure 12) with the GMAW-P process for Joint Design A with two joints welded in the horizontal position and two joints welded in the vertical position. Two variables were used: weld machine and welding position (horizontal versus vertical).

All specimens were welded using a 90%Ar-10%CO_2 gas mixture. Over twenty passes were made to fill each joint, and the resulting Current Root Mean Square (I_{RMS}) readout of the arc was recorded for each pass. The energy input of the heat source was calculated for each pass and compared to WFS. In the case of this experiment, it can be assumed that the machine producing an arc with a more consistent energy input per WFS will produce a more consistent weld.

$$Energy\ Input\left[\frac{J}{mm}\right] = \frac{Arc\ Voltage\left[V\right]\times \text{ Arc Current}\left[\text{A}\right]}{Wire\ Feed\ Speed\left[\frac{mm}{s}\right]}$$

2. Experimental Results

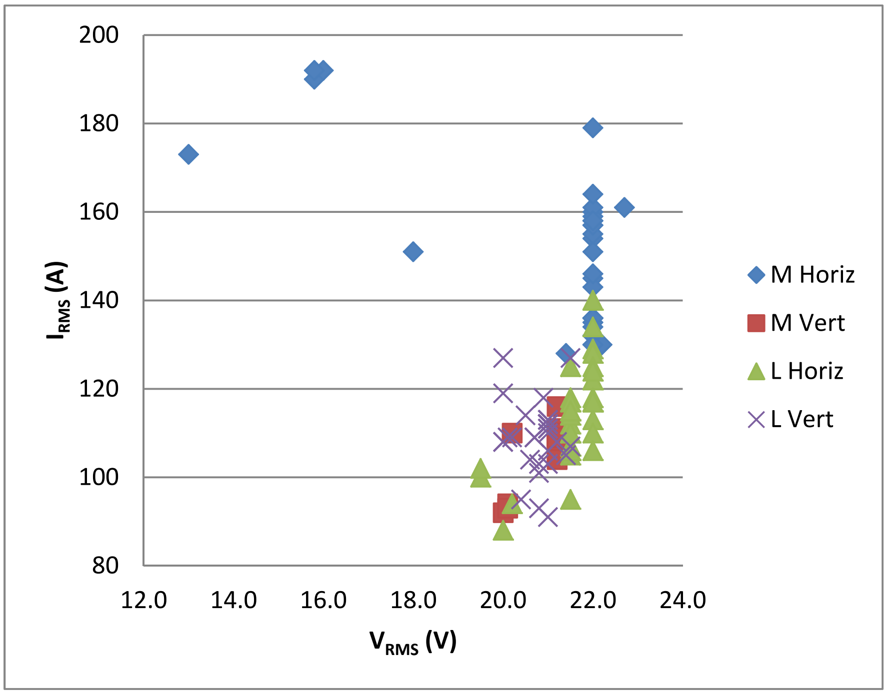

Figure 13. I_{RMS} versus V_{RMS} Comparison with Miller and Lincoln Welding Machines in the Horizontal and Vertical Positions Using GMAW-P.

It is clear when examining the resulting arc currents in Figure 13 that there was a significant spread in currents in the horizontal Miller trials. In referring to Figure 14, it is evident that much higher WFS were chosen for those trials than for the other six trials. Higher WFS may have contributed to the difference in behavior of the algorithm. Both figures show a much larger spread of results between horizontal and vertical joints on the Miller machines than on the Lincoln Electric machines. This could mean that the Miller synergic algorithm does not perform as consistently across different welding positions. It is also a possibility that this set of trials demonstrates poor electrode positioning by the welders for those trials. Even though the intent was to change only two variables, there may be more factors making this data unreliable or at the very least inconclusive. Future experiments should use the same welder and WFS settings so that the algorithm's behavior can be more accurately compared between trials. Results displayed Figure 14 show fairly consistent energy input per WFS for all of the trials for both positions and machines. Both machines enabled higher WFSs by the welders in the horizontal, as expected.

Out of both machines one clear advantage Lincoln Electric has over Miller is that its user interface is unanimously preferred by the welders. This metric does not appear in our collected data, but it is logical to conclude that welders who are more comfortable using machines are going to position a welding gun more consistently for a more consistent arc length. This is an important fact not to overlook, and alone justifies more testing of these machines.

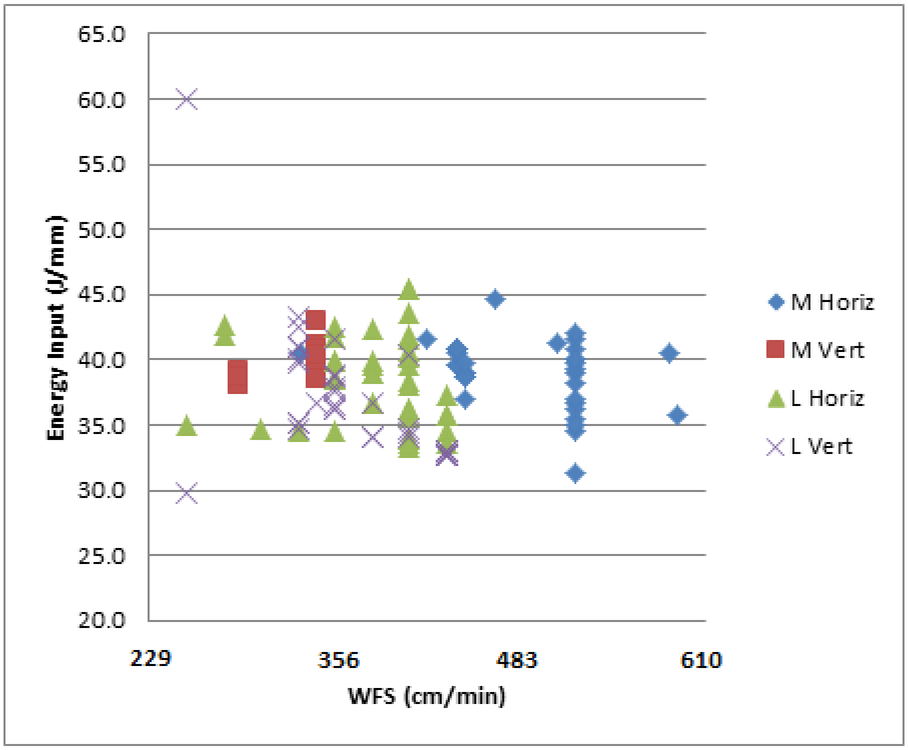

Figure 14. Energy Input of Heat Source versus WFS with Miller and Lincoln Welding Machines in the Horizontal and Vertical Positions Using GMAW-P.

C. BUTT JOINT COMPARISON

There are many different factors to consider when choosing a joint design. A good joint design will facilitate a fast fit-up, require a minimum number of welding passes, reduce sharp angles, allow thorough testing, and minimize material waste. Contrary to modern private industry, NNSY has been using a single-V butt joint for submarine hull cuts for decades.

In thick plate applications, a single-V butt joint will waste more material than a double-V. A long root face on a single-V joint requires a significant amount of excavation (typically by back-gouging) to reach the root weld. A small root face on a single-V joint has a much larger volume opening that will require more welding passes and material to fill. Another disadvantage of a single-V joint with a long root face, which is typical of the kind of butt joint that NNSY is currently using for submarine hull cut applications, is that it requires a greater volume of material to be ground off if surface contact is made during a pre-installation fit-up.

Double-V butt joints are preferred by private industry for hull cut applications. Significantly less material is wasted during the installation process. If quality welding processes are used, a minimal amount of material is required to be excavated. Grinding can be used in lieu of back-gouging in situations requiring less excavation, which is a much safer excavation method that eliminates the fire-hazard. A minimized root face minimizes the amount of material removal or build-up required if there are discrepancies discovered during the pre-installation fit-up. This design of joint can even allow welding on both sides concurrently after initial welding passes seal the joint.

1. Experimental Criterion

A total of six samples were made with two each of Joint Designs C, D, and E (from Table 3) constructed. Joint Design C[6] is a 70/30 Single-V while both Joint Designs D and E are Double-V (2/3-1/3 and 50/50 respectively). All samples were welded using the GMAW-P Lincoln Electric Weld Equipment Setup in the horizontal position with a 90%Ar-10%CO_2 gas mixture. After being made, UT testing was performed from 2.5-cm to 27.9-cm on each sample (as illustrated in Figure 5) by NNSY qualified UT inspectors. Excavation depth and UT indications were recorded and compared to ascertain if any of the joint designs had an advantage over the others.

2. Experimental Results

Table 4 summarizes the details of the six samples prepared.[7] All samples were observed achieving similar arc currents and heat inputs, so weld penetration was likely comparable in all samples. Zero indications were discovered using UT in both of the Double-V 50/50 samples. It is also worth noting that both of those samples were also

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[6] Joint Design C, a 70/30 Single-V butt joint, is the butt joint design currently used at NNSY for submarine hull cuts.

[7] Page 2 of each UT report which has a drawing depicting where indications were discovered in each sample were included in Appendix. The Serial Number on each UT Report Form in Appendix corresponds with 135-[UT Report # listed in Table 4] for each sample.

excavated to the greatest depth. It is possible that inadequate shielding during the root weld passes allowed the generation of indications in all samples, but the Double-V 50/50 samples were the only ones properly excavated to good metal. An example of incomplete fusion was observed in one of the Single-V 70/30 sample cross-sections that was polished and stained in the NNSY Weld Engineer Testing Lab (pictured in Figure 15). This sample shows that it was not excavated deeply enough because the circled defect is just below the excavation area.

Table 4. Summary of Experimental Joint Design Results.

Joint #	***Root C/L***	***UT Report #***	***Weld Thick-ness [mm]***	***Exca-vation Depth [mm]***	***# of Indica-tions***	***Inches Rejected (Length) [cm]***	***Reject MIN Depth [mm]***	***Reject MAX Depth [mm]***	***Avg Current [A]***	***Avg H [J/mm]***
B2V.1	70/30	313-15	44.5	7.9	1	1.8	5.1	10.2	172	40
B2V.1	70/30	316-15	43.2	12.7	2	18.2	14.0	19.0	193	46
B2V.3	2/3, 1/3	314-15	35.6	*15.9	3	8.4	17.8	22.9	192	46
B2V.3	2/3, 1/3	315-15	44.5	*15.9	2	3.6	16.5	20.3	198	46
B2V.3	50/50	312-15	45.7	22.2	0	0	-	-	190	45
B2V.3	50/50	311-15	45.7	25.4	0	0	-	-	190	45

*Indicates where grinding was used for excavation instead of back-gouging.

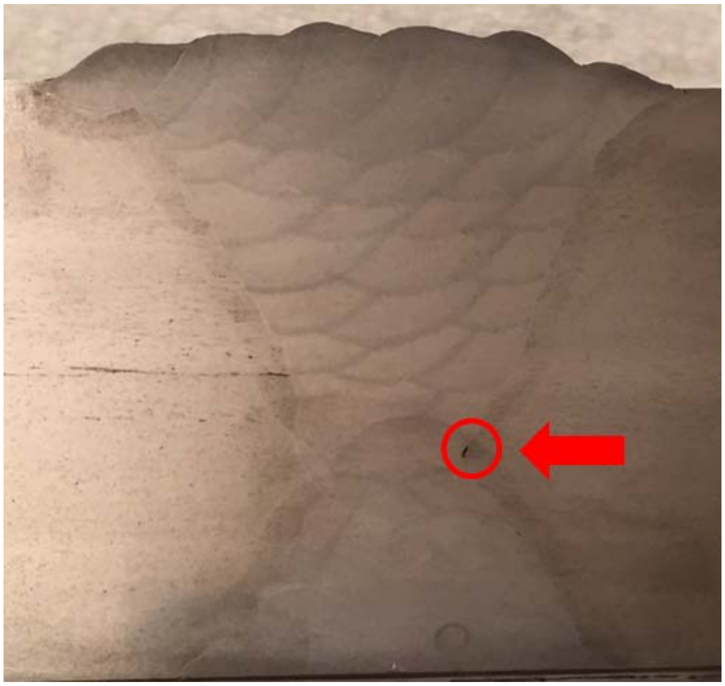

Figure 15. Incomplete Fusion Found in an Experimental B2V.1 70/30 Butt Joint.

Grinding was used for excavation in both of the Double-V 2/3, 1/3 in lieu of back-gouging. This, however, did not prove to be an advantage because of the amount of defects still discovered during the UT. Due to the location of the rejected indications in the UT reports (refer to Appendix) it is most likely that they were also located in the root weld passes and would have been removed with proper excavation.

Unfortunately, due to suspected improper excavation, the results of these experiments are inconclusive. The theoretical advantages of Double-V butt joints will need to be proven with further testing in a more controlled environment before a recommendation can be made for hull cut applications.

D. PRE-HEATING AND POROSITY

The presence of excess reactive gases such as Hydrogen, Oxygen, and Nitrogen in weld metal can cause porosity and delayed cracking to occur. If quantities of reactive gases are present during welding, they will break down within a weld arc and dissolve within molten weld metal. Oxides and nitrides will react with deoxidizers present in the steel, form slag, and float to the surface or the weld. Reactive gases that become trapped in steel can reduce its ductility and notch toughness.

1. Cooling Rate

At a certain temperature, reactive gases are no longer soluble in steel and will become trapped if they have not had enough time to escape. Because of this, it is critical to reduce the cooling rate of weld metal to allow sufficient time for reactive gases to escape and avoid porosity and other problems that result from the trapped metals. The most common way to accomplish this is preheating base metal. By decreasing the difference in temperature between the molten weld metal and the surrounding base metal, the rate at which the molten weld metal cools will be slowed down.

2. Inconsistent Use of Pre-Heat

Some of the samples that were created for this thesis were cross-sectioned, polished, and stained. There were several examples of porosity found within weld metal of samples, similar to those pictured in Figure 16. The presence of this porosity suggests that proper preheating procedures were not followed by the welders who generated these samples. This could also have been a source of rejectable indications that were reported in the UT reports from the joint design samples. This doubt validates the need for controlled testing to be conducted by superiorly skilled individuals in a lab environment to produce conclusive findings that will help develop modern welding procedures at NNSY.

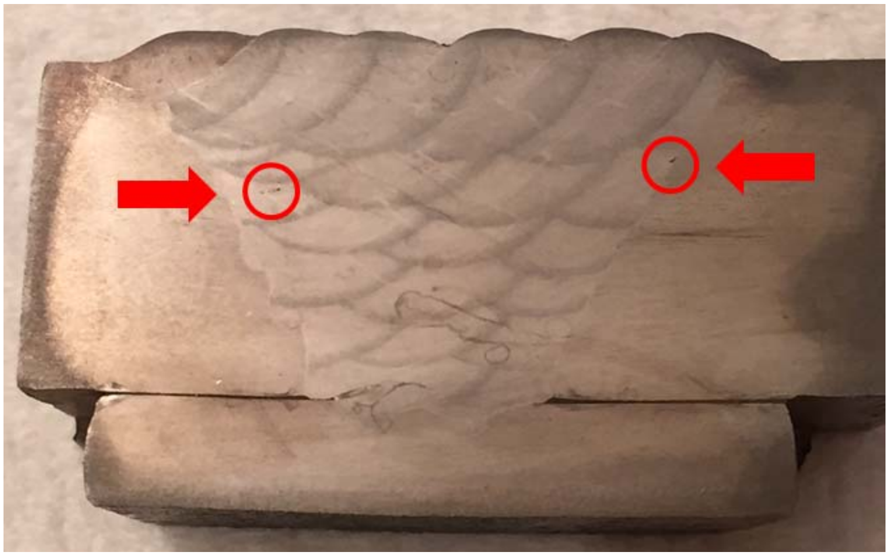

Figure 16. Porosity Found in Joint Design “A” Using 90%Ar-10%CO_2 Gas Mixture.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The purpose of this thesis was to use weld theory to make recommendations for future submarine hull cut welding process development and testing at NNSY. The following conclusions resulted from the preliminary research and trials conducted for this thesis:

1. GMAW-P is theoretically the most efficient welding technique for waterfront submarine hull cut applications. It maximizes production, minimizes material waste, and allows for the most joint position versatility.
2. For GMAW-P, a 90%Ar-10%CO_2 gas mixture will produce a greater arc current density resulting in greater weld penetration in HY-80 steel than a 95%Ar-5%CO_2 gas mixture. This makes it a more ideal gas mixture for hull welding applications.
3. In trials, it was inconclusive whether Lincoln Electric brand machines or Miller brand welding machine synergic GMAW-P algorithms produced a more consistent energy input per WFS.
4. Both Lincoln Electric brand machines and Miller brand machines enable higher WFS in the horizontal position.
5. Porosity was discovered in weld metal of samples that were improperly pre-heated before welding.
6. Shear wave UT revealed the least amount of rejectable indications in the 50/50 Double-V butt joint design. Those samples also had the deepest excavation before filling the back-side of the weld joint.
7. Double-V butt joint designs minimize filler metal waste by reducing the required excavation volume.

B. RECOMMENDATIONS FOR FURTHER STUDY

In order for NNSY to be competitive with private industry in the performance of submarine hull cut welding, procedures need to be developed for preferred welding methods. Additional research using GMAW-P in HY-80 steel plate butt joint applications at NNSY is required before adequate procedures can be developed. The following controlled experiments at NNSY will provide additional critical research that will aid in the creation of improved welding procedures for submarine hull cuts:

1. A controlled GMAW-P comparison for Lincoln Electric equipment programmed synergic algorithms using and 90%Ar-10%CO_2 gas mixture

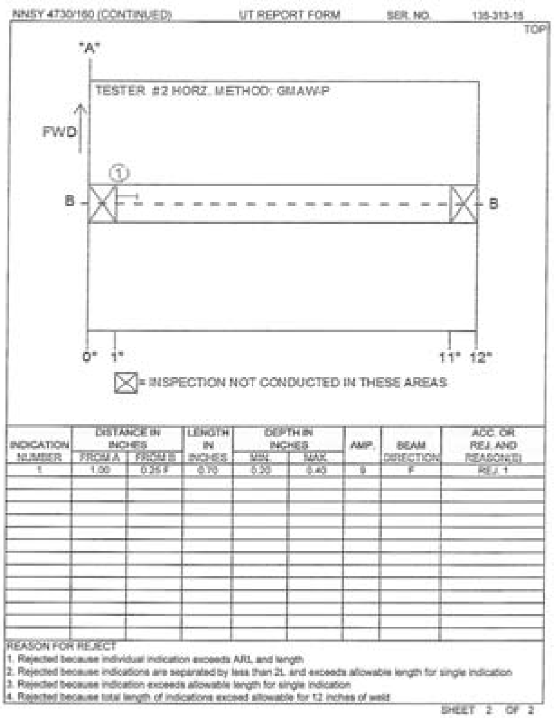
to weld HY-80 steel that will result in a recommendation for a preferred program setting on Lincoln Electric machines for this process.

2. A controlled Double-V butt joint comparison for multiple joint bevel designs using Lincoln Electric equipment, 90%Ar-10%CO_2 gas mixture, and GMAW-S & GMAW-P techniques to welding HY-80 steel will result in an ideal butt joint design that will minimize material waste while optimizing welder access to the weld surface.
3. A controlled WFS comparison for programmed speeds using Lincoln Electric equipment, 90%Ar-10%CO_2 gas mixture, and GMAW-S & GMAW-P techniques to welding HY-80 steel will result in a recommendation for ideal WFS settings yield optimized weld penetration with a minimal chance of defects.

APPENDIX

UT Inspection reports for experimental joint designs listed in Table 4.

Joint #	*Root C/L*	*UT Report #*
B2V.1	70/30	313-15
B2V.1	70/30	316-15
B2V.3	2/3, 1/3	314-15
B2V.3	2/3, 1/3	315-15
B2V.3	50/50	312-15
B2V.3	50/50	311-15



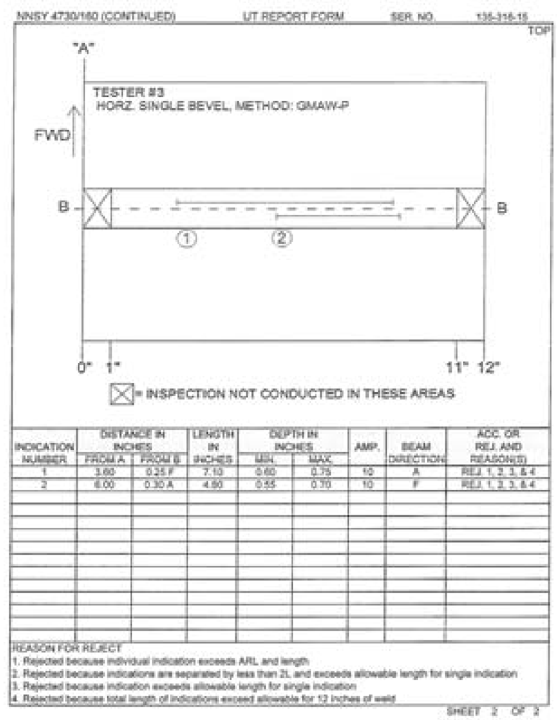
NNSY 4730/160 (CONTINUED) UT REPORT FORM SER. NO. 135-313-15

TOP

INDICATION NUMBER	DISTANCE IN INCHES FROM A	DISTANCE IN INCHES FROM B	LENGTH IN INCHES	DEPTH IN INCHES MIN.	DEPTH IN INCHES MAX.	AMP.	BEAM DIRECTION	ACC. OR REJ. AND REASON(S)
1	1.00	0.25 F	0.70	0.30	0.40	9	F	REJ. 1

REASON FOR REJECT
1. Rejected because individual indication exceeds ARL and length
2. Rejected because indications are separated by less than 2L and exceeds allowable length for single indication
3. Rejected because indication exceeds allowable length for single indication
4. Rejected because total length of indications exceed allowable for 12 inches of weld

SHEET 2 OF 2



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1	3.60	0.25 F	7.10	0.60	0.75	10	A	REJ. 1, 2, 3, & 4
2	6.00	0.30 A	4.80	0.55	0.70	10	F	REJ. 1, 2, 3, & 4

REASON FOR REJECT
1. Rejected because individual indication exceeds ARL and length
2. Rejected because indications are separated by less than 2L and exceeds allowable length for single indication
3. Rejected because indication exceeds allowable length for single indication
4. Rejected because total length of indications exceed allowable for 12 inches of weld

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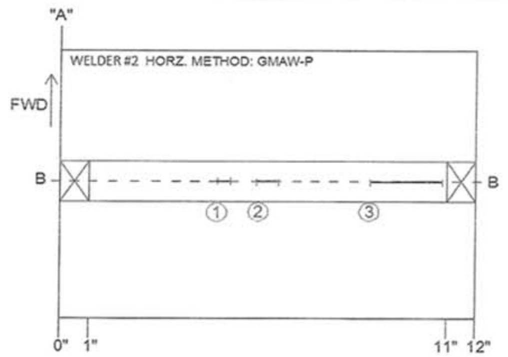

☒ = INSPECTION NOT CONDUCTED IN THESE AREAS

INDICATION NUMBER	DISTANCE IN INCHES		LENGTH IN INCHES	DEPTH IN INCHES		AMP.	BEAM DIRECTION	ACC. OR REJ. AND REASON(S)
	FROM A	FROM B		MIN.	MAX.			
1	5.10	0.00	0.20	0.70	0.80	3	A	REJ. 2 & 4
2	6.20	0.00	0.70	0.70	0.80	6	A	REJ. 2 & 4
3	8.35	0.00	2.40	0.80	0.90	5	A	REJ. 2, 3, & 4

REASON FOR REJECT
1. Rejected because individual indication exceeds ARL and length
2. Rejected because indications are separated by less than 2L and exceeds allowable length for single indication
3. Rejected because indication exceeds allowable length for single indication
4. Rejected because total length of indications exceed allowable for 12 inches of weld

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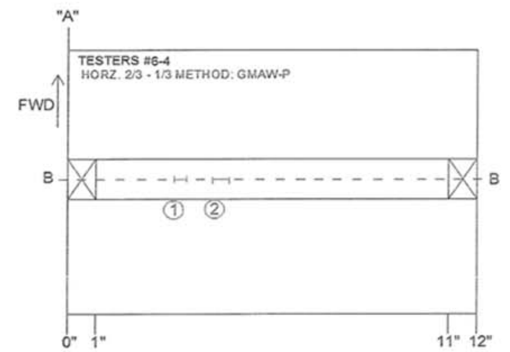

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INDICATION NUMBER	DISTANCE IN INCHES		LENGTH IN INCHES	DEPTH IN INCHES		AMP.	BEAM DIRECTION	ACC. OR REJ. AND REASON(S)
	FROM A	FROM B		MIN.	MAX.			
1	3.05	0.00	0.60	0.65	0.75	5	A	REJ. 2
2	4.10	0.00	0.80	0.65	0.80	7	A	REJ. 2 & 3

REASON FOR REJECT
1. Rejected because individual indication exceeds ARL and length
2. Rejected because indications are separated by less than 2L and exceeds allowable length for single indication
3. Rejected because indication exceeds allowable length for single indication
4. Rejected because total length of indications exceed allowable for 12 inches of weld

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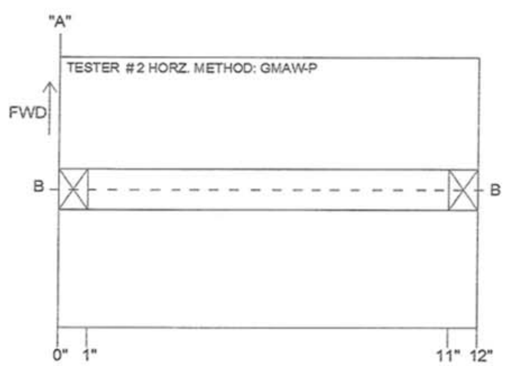

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			NO RECORDABLE INDICATIONS FOUND					

REASON FOR REJECT
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2. Rejected because indications are separated by less than 2L and exceeds allowable length for single indication
3. Rejected because indication exceeds allowable length for single indication
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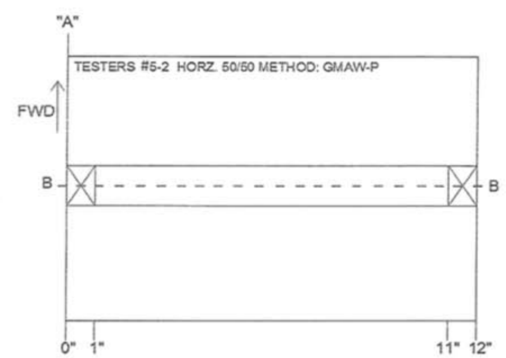

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INDICATION NUMBER	DISTANCE IN INCHES		LENGTH IN INCHES	DEPTH IN INCHES		AMP.	BEAM DIRECTION	ACC. OR REJ. AND REASON(S)
	FROM A	FROM B		MIN.	MAX.			
			NO RECORDABLE INDICATIONS FOUND					

REASON FOR REJECT
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SHEET 2 OF 2

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