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FINAL REPORT

A PRELIMINARY STUDY OF DOUBLE-SIDED ARC WELDING PROCESS IN SHIP STRUCTURE MANUFACTURING

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0.1 ABBREVIATIONS

ASE: Advance Shipbuilding Enterprise
CRMS: Center for Robotics and Manufacturing Systems
DSAW: Double-Sided Arc Welding
EB: Electric Boat Corporation
GTAW: Gas Tungsten Arc Welding
NSRP: National Shipbuilding Research Program
PAW: Plasma Arc Welding
TTT: Through-The-Thickness
UK: University of Kentucky

0.2 ABSTRACT

Double-sided arc welding (DSAW) is a novel process invented and developed at the University of Kentucky (UK). The uniqueness of this process lies in its strong penetration capability and its symmetric hour glass-shaped welds. A previous shipyard's preliminary study conducted by Warren Mayott at the Electric Boat suggested this process has potential use in minimizing distortion while at the same time improving throughput when making butt welds. If shown to be of practical value to the shipbuilding industry, a process could result that would be cheaper to implement and have greater versatility than the laser welding process which is being developed for ship construction with distortion reduction as a primary goal.

The early work on DSAW was done using the tungsten of a gas tungsten arc welding (GTAW) torch as the second electrode. Later work showed that a metal backing bar can act in the same capacity. The process thus has a potential for making full penetration welds in material up to about ½ inch without the need for a beveled plate and with all welding done from one side just like a regular arc welding process. It was believed that this modification could thus greatly improve the applicability of DSAW in shipyards.

The majority of the previous work in this area has been focused on process fundamentals and technological developments using the GTAW torch for the second electrode. Before venturing into a full development program, further research must be done to establish the practical feasibility of the DSAW process in ship structure manufacturing. Hence, this project first modified DSAW process using a stationary bar as the second electrode such that DSAW can be operated like a regular arc welding process. Then the process control technology has been developed to ensure the modified process can be operated to achieve full penetration. The range of the parameters which can result in quality welds have been determined. The applicability and robustness of the modified system has been verified by making welds under different positions and different fit-up gaps. With the addition of filler metal, positive reinforcement has been achieved on the both sides of the weld and thus made it feasible to make welds on plates up to ½ in. thick in a single pass without bevels. Further, various tests have confirmed that the welds made using DSAW on DH 36 satisfy all the requirements of mechanical properties, including hardness, toughness (both weld metal and HAZ), tensile, bend, etc. The proposed goal for the project, i.e., assessing the acceptability of the welds made and the practical feasibility of DSAW process in ship structure manufacturing and preparing data for a full-scale NSRP ASE R&D proposal, has been fulfilled.

1. INTRODUCTION

1.1 PROCESS PRINCIPLE

With a three-year grant from the National Science Foundation and the support from the Center for Robotics and Manufacturing Systems, a novel arc welding process, referred to as double-sided arc welding (DSAW), has been developed at the University of Kentucky (UK) [1-10]. This arc welding process can achieve deep narrow penetration and symmetric hour glass-shaped welds [5] to reduce distortion and potentially improve welding throughput. By using this process, a number of butt welded joints on a ship can be completed by welding from one side with minimal distortion.

To understand the principle of DSAW, let's first examine the regular arc welding system shown in Figure 1(A). As can be seen, the regular arc welding system uses an electrical connection (ground cable) between the workpiece and power supply to allow the welding current to complete the loop. The electric arc is established between the workpiece and the torch. In DSAW system, the workpiece is disconnected from the power supply and a second torch is placed on the opposite side of the workpiece to complete the current loop (Figure 1(B)). As a result, electric arcs are simultaneously established between the workpiece and each of two torches [5]. UK's previous DSAW system shown in Figure 2 used a PAW torch and a GTAW torch as the primary and second torch, respectively. As will be stated, DSAW possesses a few unique characteristics, not found in other arc welding processes, which are desirable for distortion minimization.

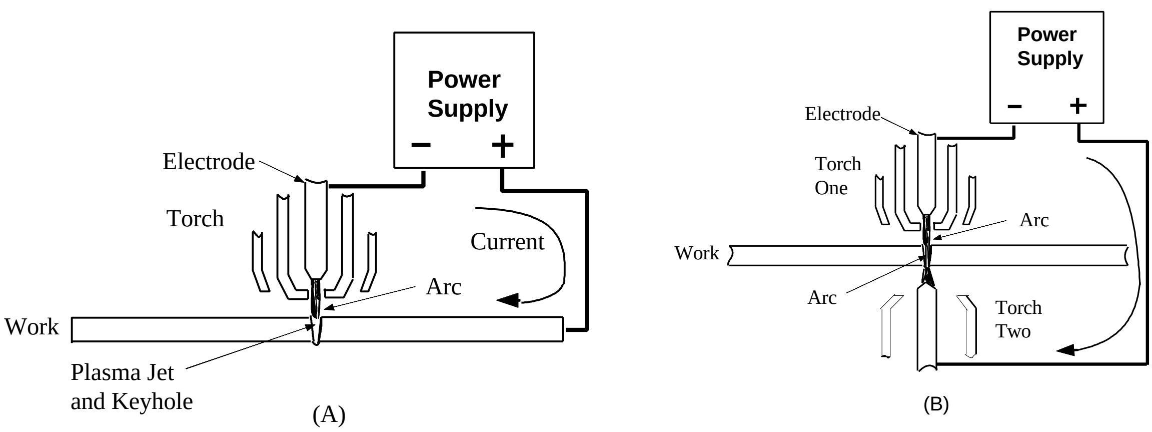


Figure 1: Schematic Diagrams of Welding Systems.
(A) Regular welding system; (B) Double-sided arc welding system.

1.2 STRATEGIC INVESTMENT PLAN FIT

Welding of ship hulls and structures represents a major investment in the form of equipment, facilities, and skilled labor force. The welding and shipbuilding industries are continually investigating means of producing cheaper weldments while maintaining the required quality level. The welding process researched in this project directly supports the NSRP/ASE "Shipyard Production Process Technologies" major initiative. In particular, the DSAW process has the potential for minimizing distortion which is part of a stated sub-initiative under this major initiative.

Ever since welding was introduced as a joining process for manufacturing ships, there has been a continuing effort to improve or develop new welding processes, filler materials and power supplies. Historically, emphasis has been placed on developing higher deposition rate processes, better consumables to meet the increasing demands of ship performance requirements, and improved output characteristics of power supplies for ease of operation and arc control. Efforts have been generally related to the welding of steels since this is the primary material for ship hulls and structures.

Although the various classes of ships result in a number of different configurations of the hull and associated structures, all ships have a common need to weld individual steel plates together to complete a hull, assembly, or other structure. These are normally joined together as a full penetration butt well which, except for very limited and controlled applications, requires welding from both sides of the weld joint. In most cases, the second side of the weld joint needs some degree of weld joint preparation before second side welding can begin. Associated with this welding is a level of distortion that occurs as a result of non-uniform weld shrinkage. This weld distortion becomes a more significant factor as the plates being welded become thinner. Since many of the hulls on today's surface ships are in the ½ inch or less range, weld distortion can become a major concern and cost driver.

1.3 BACKGROUND

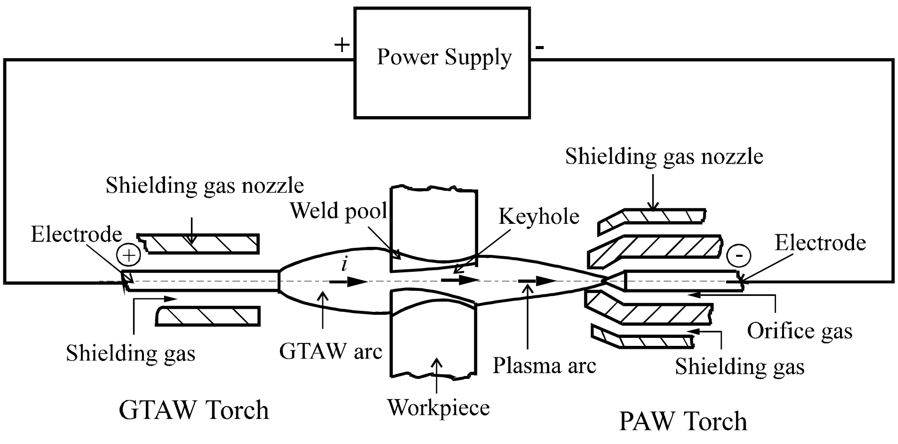


Figure 2: UK's Previous DSAW system.

To explore the possibility of using DSAW to reduce distortion in shipyard applications, UK research team has been working with Mr. Warren Mayott of Electric Boat Corporation. In 1999, Mr. Mayott visited UK and witnessed the DSAW process. Using the developed automatic penetration control technology [2, 5], UK successfully butt welded the 3 ft long, 2 ft wide, and 3/8 in. thick DH 36 plates supplied by EB. Dr. YuMing Zhang gave a presentation on DSAW at the recent symposium entitled "How to Competitively Weld the 21st Century Ships" in Norfolk, VA [5]. Based on the evaluations done at EB, Mr. Mayott concluded that "The DSAW process can produce full penetration butt welds on various materials up to 1/2" in thickness; The testing done by the University of Kentucky demonstrates that this process has potential use in making butt welds; Further development of this process is warranted." [11]

As an arc welding process, DSAW, if shown to be of practical value to the shipbuilding industry, could result in a process that would be cheaper to implement and have greater versatility than the laser welding process which is being developed for ship construction. Representatives from Electric Boat, Newport News Shipbuilding, Bath Iron Works, NASSCO, Naval Surface Warfare Center, Alabama Shipyard, and Ingalls Shipyard indicated a strong interest in assessing the practical acceptability of this process at the recently held SP-7 meeting at Newport News on February 20 and 21, 2001. If it is determined that DSAW has the stated potential, they will support a follow up proposal under the NSRP/ASE program to fully develop the process, associated equipment and welding parameters, including implementation at a selected shipyard.

The National Science Foundation funded research at the University has been focused on the fundamentals of DSAW. To determine its potential in the shipbuilding industry, more specific issues must be addressed. Hence, this project aims at feasibility studies which assess, determine, and demonstrate the merits of DSAW as a potential arc welding process for distortion minimization and welding production throughput in the shipbuilding environment. To this end, let's begin with the characteristics of the DSAW process.

2. PROCESS DESCRIPTION AND DEVELOPMENT

2.1 CHARACTERISTICS

The potential of DSAW in distortion minimization depends on its unique characteristics summarized below. These characteristics have been discussed in [1-10].

- In DSAW process, the current has to flow through the thickness of the workpiece. This direction of current is referred to as through-the-thickness (TTT) direction. However, in regular arc welding, the TTT direction is not found because the majority of the welding current flows from the arc into the surface of the workpiece [12].
- The unique TTT direction results in the presence of the current in the keyhole [1]. As can be seen in Figure 2, UK's previous DSAW system employed a PAW torch as the primary torch which makes it possible to produce a keyhole. With the establishment of the keyhole, the current may take the keyhole and/or its surrounding metal as its TTT path to flow from one torch to another. If the surrounding metal is the path, the electrons must enter the metal and re-emit from the metal. An additional cathode-anode pair will be generated (Figure 3(A)). The TTT path of the current thus adds approximately additional 10 V voltage drop. If the keyhole is the path, the current will travel through the keyhole without adding an additional cathode-anode pair. The TTT path of the current thus only adds a voltage drop associated with the arc column along the keyhole (Figure 3(B)). For 1/2 in. or thinner plates, the voltage

drop along the keyhole is much lower than that of the additional cathode and anode pair. The current thus tends to take the keyhole as its TTT path. However, in regular keyhole PAW, the current does not flow through-the-thickness and the keyhole is filled with the electrically neutral mix of ions and electrons.

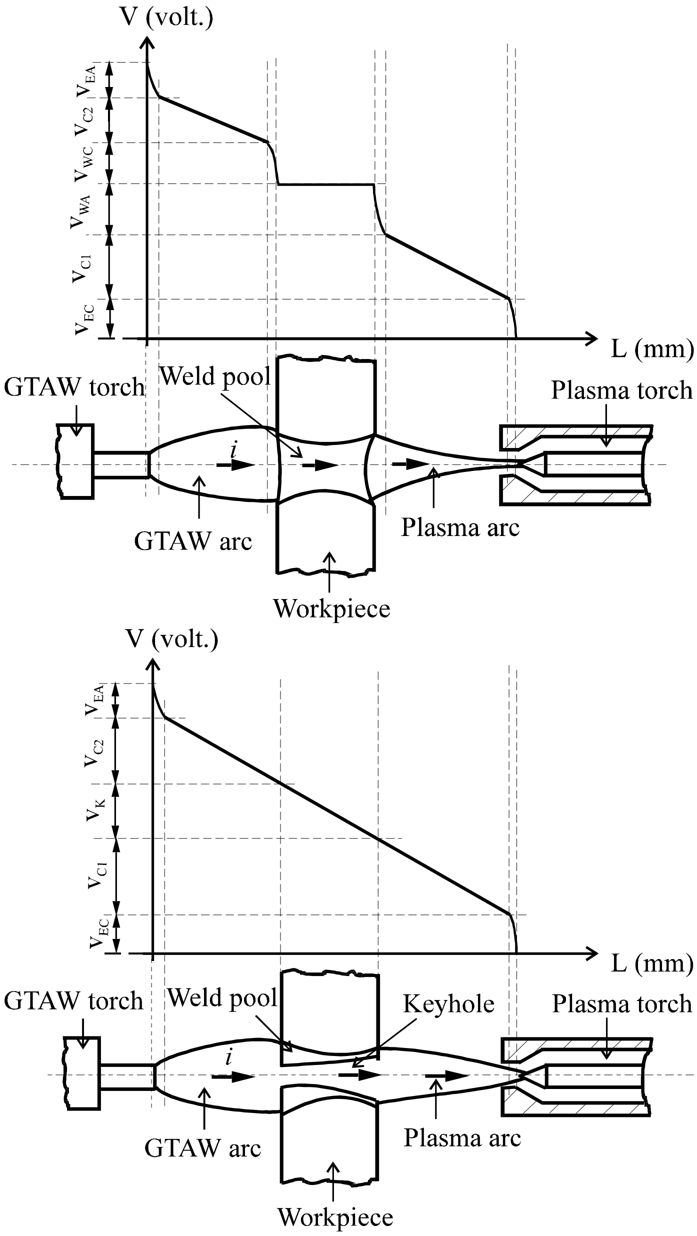


Figure 3: Voltage Decomposition in DSAW.

- The presence of the current in the keyhole generates a unique TTT heat generation mechanism [1]. Because of the presence of the arc in the keyhole, an arc column is established along the keyhole. In regular keyhole PAW, the plasma jet, as an electrically neutral mix of ions and electrons, only consumes its initial energy, gained before entering the keyhole, when it travels along the keyhole through-the-thickness. In keyhole DSAW, the current in the keyhole establishes an arc column through-the-thickness. This TTT arc column results in a mechanism to generate heat to compensate the heat lost to melt the workpiece (compensating the heat lost). Such a TTT heat generation and compensation mechanism makes it possible to achieve deep narrow penetration as shown in Figure 4.
- In addition to the TTT heat generation mechanism, the unique TTT current direction plays an important role in concentrating the arc. In regular PAW, the surface of the weld pool, which is severely deformed by the arc pressure, serves as an electrode. The voltage minimum principle makes the current find the shortest path between the electrodes, i.e., the tungsten electrode and the weld pool surface. Because of the severe deformation of the weld pool surface, it is likely that the current flow has to diverge in order to approach the weld pool surface at the shortest

path. The divergence of the current flow will make the electromagnetic force produce a divergence component to further the total divergent force. In DSAW, the weld pool surface does not serve as an electrode to force the current to approach it at the shortest path. The deformed surface caused-arc divergence is thus eliminated. As a result, the arc on the plasma torch becomes much more concentrated than the plasma arc in regular PAW [1, 10].

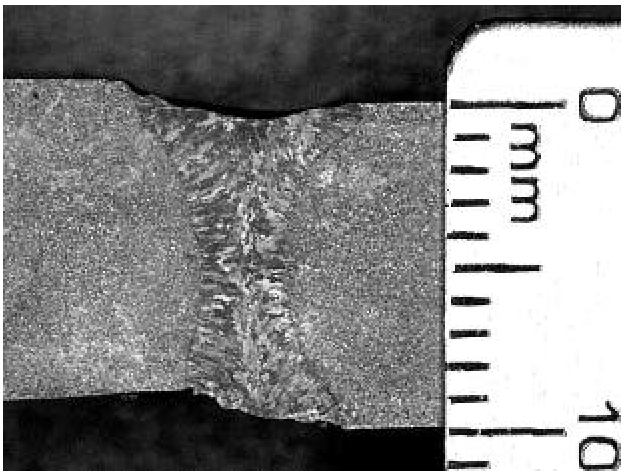


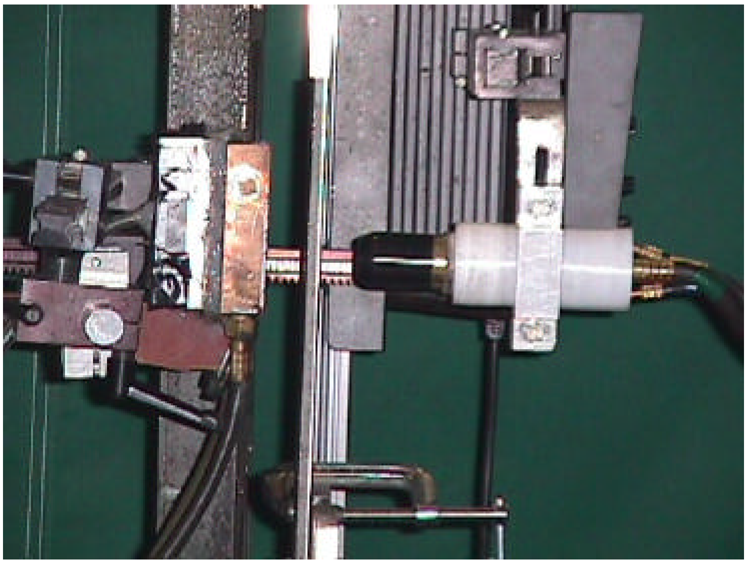
Figure 4: Butt Weld Made Using Controlled Pulse Keyhole DSAW Process. Thickness: 10 mm, Material: DH36, Welding position: vertical-down, Filler metal: none, Travel speed: 120 mm/minute, peak current: 140 A, base current 80 A.

- Of course, the most pronounced characteristic of DSAW process is its symmetric hour glass shaped weld as can be seen in Figure 4. This unique characteristic, together with the deep narrow penetration capability due to the heat compensation mechanism and arc concentration, is highly desirable for reducing angular distortion and thermal stress.

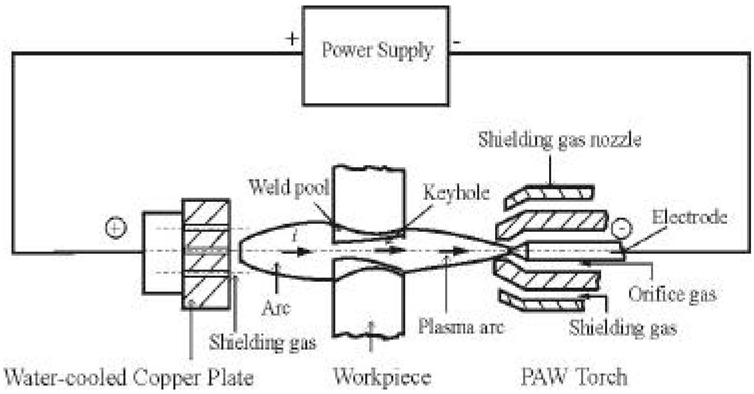
2.2 ADVANTAGES

Studies at the University showed that the DSAW has significant advantages in weld penetration/angular distortion reduction and process applicability which are highly desirable for shipyard applications.

- Deep Narrow Penetration: It is found that DSAW can penetrate up to ½ in. thick plates in a single pass with a narrow weld as can be seen in Figure 4 [5]. The TTT heat generation mechanism, the arc concentration, and double-sided heating are all responsible.
- Reduced Heat Input: To penetrate plates up to 3/8 in. thick, DSAW reduces the heat input by more than 70 percent in comparison with regular PAW process [1]. Even compared with laser process, DSAW needs only 4 times more heat input to penetrate ½ in. thick plates when compared to a 10 kW laser [1].
- Symmetric Welds: DSAW achieves nearly symmetric hour glass-shaped welds [5] due to the double-sided and TTT heating.
- Reduced Angular Distortion and Residual Stress: Symmetry in the weld and reduction in the heat input both help reduce the thermal distortion and residual stress. UK has butt welded 3/8 in. thick, 3 ft long and 2 ft wide DH36 plates for EB [11]. Although no fixture had been applied to constrain the plates during welding, no noticeable distortion was observed.



(A)



(B)

Figure 5: Experimental set-up for verification of modified DSAW system. (A) System photograph; (B) System diagram.

- Automated Penetration Control: An automated penetration control system has been developed to ensure 100 percent full penetration despite variations in manufacturing conditions such as root opening and mismatch [2, 5]. This system, which uses no additional sensors except for the power supply's current sensor [2, 5], is ideal for shipyard applications.
- Arc Welding Equipment and Operation [5]: DSAW is in essence an arc welding process and inherits the majority of the advantages of arc welding processes over laser. For example, DSAW process is easier to operate than laser, especially for large structures as those in shipyards. The equipment is easier to maintain than that of the laser. In addition, DSAW process is much more cost effective than laser. It is also much more tolerant of the joint preparation.

2.3 PROPOSED MODIFICATION

However, UK's previous DSAW system has three shortcomings which must be eliminated in order for DSAW to become a promising production process for shipbuilding.

- Simultaneous Motion: The previous system requires the PAW torch and the GTAW torch to move simultaneously on the two sides of the workpiece. This type of operation is not desirable for the large structures in shipyards.

- No Fill Metal Addition: The previous system does not have the capability to add filler metal. The addition of filler metal complicates the keyhole establishment and control and thus requires a modified control scheme to operate.
- Low Toughness: Low toughness has been observed in the weld metal for the welds made using the previous system which does not add filler metal. There are two possible factors responsible for the observed low toughness: cooling rate or weld metal chemistry. Calculation shows that the heat input for DSAW is well within the range for DH 36 (10 KJ/inch. to 100 KJ/inch). Hence, the weld metal chemistry may be responsible for the observed low toughness. Adding filler metal may improve the toughness to an acceptable level.

The use of the second torch, GTAW torch, is a major factor which differentiates DSAW from conventional arc welding. If the second torch can be eliminated such that the requirement of the simultaneous motion is eliminated, DSAW will be able to be operated similarly as a conventional single torch operation welding. Further, if the control scheme can be modified to stabilize the process with the presence of filler metal so that the required toughness is achieved in both the weld metal and HAZ, the deep narrow penetration capability and symmetric weld can make DSAW an attractive arc welding process for increasing penetration, reducing angular distortion, and residual stress.

To explore the possibility of eliminating the second torch, let's examine the welding system shown in Figure 5. The difference between this system and the DSAW system in Figure 2 is that the GTAW torch in Figure 2 is replaced by the water-cooled copper plate which is 1 in. thick, 4 in. wide, and 4 in. long. During welding, the water-cooled copper plate is shielded and moves simultaneously with the PAW torch. It is evident that the arc can also be established between the copper plate and the workpiece. Hence, the copper plate may be used as a replacement of the GTAW torch to operate DSAW process. The question is whether the arc between the copper plate and the workpiece will be established between two arbitrary points (regions) on the copper plate and the workpiece. Or, can these two points (regions) be controlled such that the arcs on the two sides of the workpiece be aligned as in the case of a GTAW torch? Or will the arcs on the two sides become much broader such that the deep narrow penetration capability associated with DSAW is weakened?

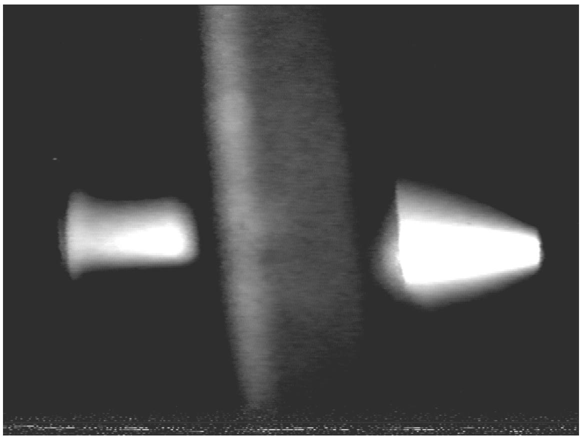


Figure 6: Arc Behavior during DASW Using Stationary Bar.

To answer the above questions, studies have been done at UK. It was found that if the non-keyhole process is used, the arc between the copper plate and the workpiece may not be aligned with the plasma arc. However, when the keyhole process is used, the arc is aligned as shown in Figure 6. The desired deep penetration and symmetric weld shape both remain (Figure 7). In fact, when the keyhole is established, the efflux plasma exit from the workpiece provides an ideal condition to maintain the arc between the copper plate and the workpiece. Hence, when the plasma torch travels, the arc between the copper plate and the workpiece follows the plasma arc because of the efflux. This has been referred to as the arc-following phenomenon.

The arc-following phenomenon enables a large stationary bar or plate to replace the GTAW torch as the second electrode to perform DSAW. This replacement makes it possible to operate DSAW like a regular arc welding process without the necessity of simultaneous torch motion. Further, the stationary bar can be water-cooled such that the amperage limit is solely determined by the PAW torch. Hence, this feasibility study project proposed replacing the GTAW torch with a stationary bar to eliminate the simultaneous motion requirement. If experiments verify that the modified DSAW system is capable of being used for shipbuilding applications, further research can be done to further increase the current and speed for improving the productivity, in addition to minimizing the distortion.

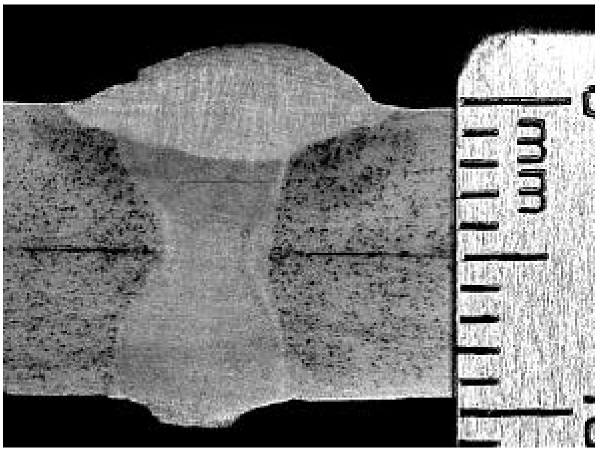


Figure 7: Cross-section of Bead-on-plate Weld Obtained Using Stationary Bar. Material: DH 36, Thickness: 3/8 in, Position: Vertical-down, Welding Speed: 150 mm/minute (6 in./min), Welding Current: 160 A. The cover pass was done using GMAW.

3. OBJECTIVES

The work done by the University of Kentucky, if shown to be of practical value to the shipbuilding industry, could result in a process that would be cheaper to implement and have greater versatility than the laser welding process which is being developed for ship construction. The ultimate goal of this feasibility study project is thus to demonstrate the proposed modification for the DSAW technology which uses a stationary bar to simplify DSAW operation and demonstrate the potential and capabilities of this modified DSAW technology in shipbuilding through welding of selected material DH 36. To this end, the following objectives are proposed for this feasibility study.

- Develop a modified DSAW system which uses a stationary bar.
- Develop a modified control scheme for the modified system.
- Determine the capability of the modified system to make welds made at different positions for plates up to ½ in. thick.
- Determine the practicality and robustness of DSAW using varying fit-up gap.
- Determine the mechanical properties of welds made using the modified system and modified control scheme.

The principal steels in use in the shipbuilding industry are of the plain carbon, carbon manganese and low alloy/heat treated varieties. These steels will play a continuing role in the design of ships for a number of years to come because of their relatively low cost, good weldability, and performance characteristics. Hence, EB recommended DH 36 as the primary material to be welded in this project.

4. DESCRIPTION OF RESEARCH

4.2 SYSTEM MODIFICATION

4.1.1 System Modification

As demonstrated in Figs. 5-7, an experimental system had been previously developed to conduct DSAW using a water-cooled copper plate as the second electrode. Under this project an experimental system has been designed, manufactured and assembled for DSAW which uses a stationary water-cooled copper pipe as the second electrode. The shielding gas is provided from the bottom of the enclosure formed by the workpiece (for the front) and a back-side cover (for the back and two sides). The copper pipe is placed in the enclosure (Figure 8(a)).

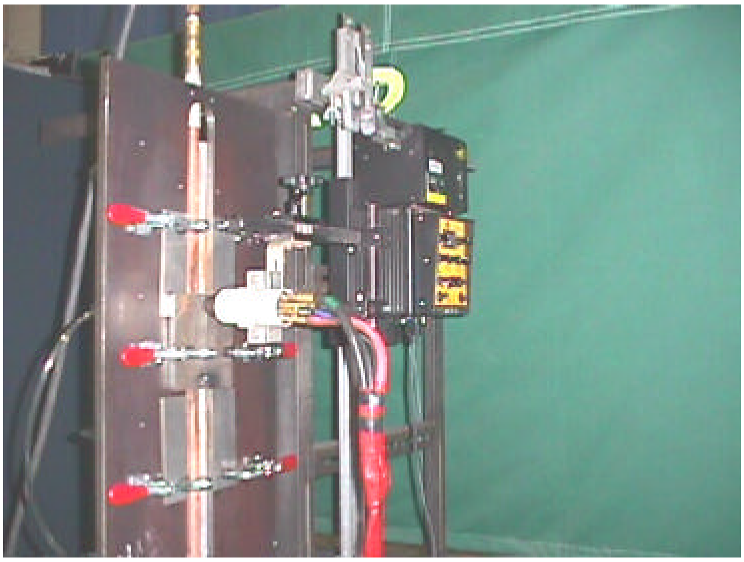
Figure 8(b) shows the control system principle. When both switches are open, the system is at the DSAW mode. If the switch 1 is closed, the arc is only established on the plasma torch side. The process will be plasma arc welding (PAW). When switch 1 is open and 2 is closed, part of current flows between the two electrodes (DSAW current) and rest between the plasma electrode and the base metal (PAW current). This mode of operation is referred to as PAW-aided-DSAW. Hence, the process can switch from DSAW to PAW and to PAW-aided-DSAW. As will be seen later, this switching capability makes the control of the process easy.

Figure 8(c) illustrates a system which can be easily formed to control the process using two conventional constant-current power supplies without using (high-current) switches. In this preliminary study, this two power supply system is used. If commercialization is considered from the DSAW process, a devoted system which may include a conventional CC power supply, two high-current switches, and control electronics should be designed and the switches should be integrated with the control electronics to form a “control box.”

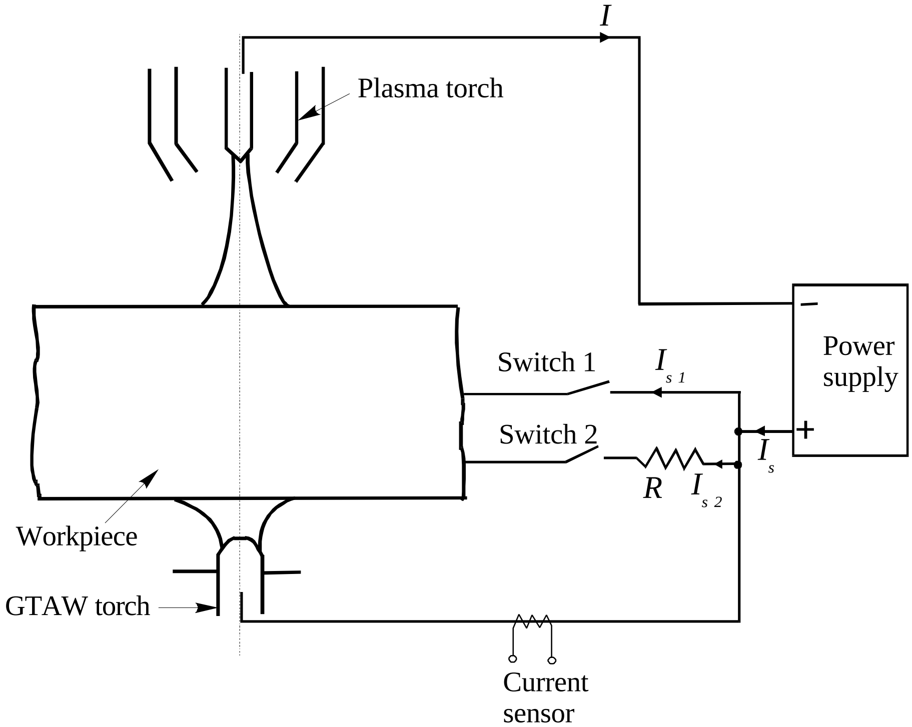
The basic procedure for controlling the DSAW process is as follows: (1) First, a PAW process is applied to establish the keyhole (PAW cycle). (2) Once the keyhole is established, the efflux plasma can establish an electrical passage so that the DSAW process can be established; the process can thus enter DSAW cycle. (3) After the DSAW cycle runs for 200 ms, the DSAW current is adjusted to zero. As a result, the keyhole will close to minimize the heat input and prevent burn-through. (4) After a 5ms delay, the PAW current is reapplied to reestablish the keyhole. After the keyhole is established, because of the efflux plasma, the double-sided arc automatically resumes and starts a new cycle. Once the DSAW arc is established, the output of the current sensor will become non-zero. The control system will adjust the PAW current to zero after a non-zero output of the current sensor is confirmed.

From operation’s point of view, the modified DSAW system is like a conventional arc welding in which only one torch needs to be operated. Hence, the modified DSAW system simplifies the operation of DSAW. Figure 8(d) shows the modified system at work.

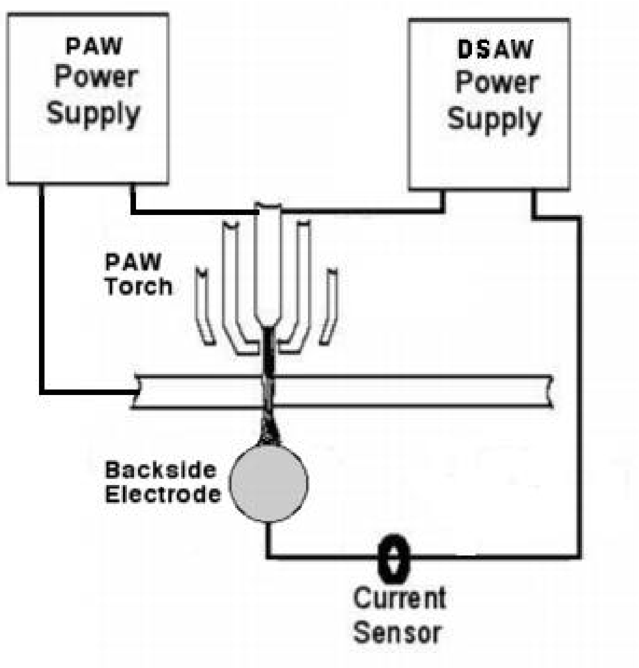
Experiments show that the stationary-bar based DSAW system can achieve better arc stability and shield.



(a) Experimental system



(b) Principle of control method



(C) An implementation of proposed control method

(b) Experimental system at work

Figure 8: Stationary-bar Based DSAW Experimental System.

4.1.2 Welding Parameters

Experiments have been done to establish suitable welding parameters for 3/8 in. thick plates in three positions: vertical-down, horizontal, and flat. In particular, experiments have been done to determine suitable welding parameters for 1/2 in. thick plates in the vertical-down and horizontal positions, and suitable welding parameters for 3/8 in. thick plates with pre-place weld filler wire at flat position. Cross sections of welds on 3/8 in. thick DH36 plates are shown in Figure 9.

Vertical Position: Experiments have verified that good welds can be achieved with both 3/8 and 1/2 in. thick plate at the vertical-down position with the modified DSAW system. It is a good position to double-sided arc weld both 3/8 and ½ in. thick plates. The parameters are:

3/8": Double-sided Current =155A, Plasma Current=180A-270A, Travel speed=5.5 in,/min (140 mm/min)
1/2": Double-sided Current=140A, Plasma Current=220A-300A, Travel speed=3.1 in./min (80 mm/min)

Horizontal Position: Experiments have verified that good welds can be achieved with both 3/8 and 1/2 in. thick plate at the horizontal position with the modified DSAW system. It is a good position to double-sided arc weld both 3/8 and ½ in. thick plates. The parameters are:

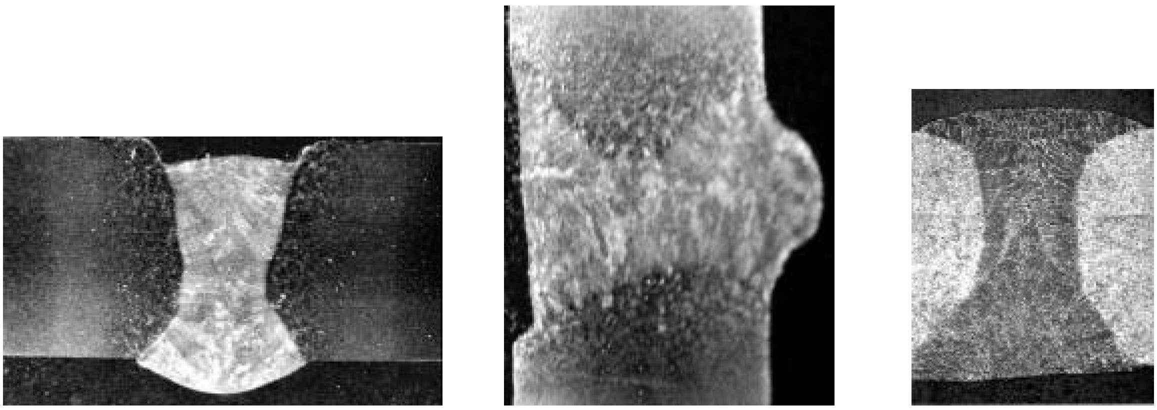
3/8": Double-sided Current =150A, Plasma Current=200A-270A, Travel speed=5.1 in./min (130 mm/min)
1/2": Double-sided Current=160A, Plasma Current=220A-300A, Travel speed=3.5 in./min (90 mm/min)

Flat Position: Experiments have verified that good welds can be achieved with 3/8 in. plate at the flat position with the modified DSAW system. It is a good position to double-sided arc weld 3/8 thick plates. The parameters are:

3/8": Double-sided Current =145A, Plasma Current=200A-270A, Travel speed=5.5 in/min (140 mm/min)

Use of Pre-Deposited Filler Metal: Experiments have been carried out using plates with pre-deposited filler metal (ER-70s, the filler metal used for GMAW of DH36). It is found that suitable reinforcement (good weld shape) can be obtained on both sides. The parameters are:

3/8": Double-sided Current =155A, Plasma Current=180A-270A, Travel speed=4.7 in./min (120 mm/min)



(A) (B) (C)

Figure 9: Cross-section of Double-sided Arc Welds on 3/8 in. DH36. (A) Flat position; (B) Horizontal position; (C) Vertical—down position with pre-deposited filler metal.

4.2 ADDITION OF ER-70S FILLER METAL

Testing results for the welds made using the modified system without adding filler metal or with pre-deposited ER-70s filler metal both fail to meet the minimal requirement of the toughness, 17 ft-lb. It was determined that pre-deposition could not add sufficient amount of filler metal. Also, pre-deposition of filler metal adds a step in the procedure. Hence, research has been conducted toward adding filler metal during welding and increasing the amount of filler metal. To this end, this research team has tried to increase the gap.

4.2.1 Small Gap

First, experiments have been carried out using ER-70S filler wire, 0.035" (0.9mm) diameter, added during the experiments for bead-on-plate and butt-joint with small gaps ($\leq$ 0.08" (2mm)) on 3/8 inch thick DH36 plates. The parameters are:

Bead on Plate:

Orifice: 0.11" (2.8mm), wire feed speed = 80 in/min
$I_{PAW:}$ [180A,270A]
$T_{DSAW,max}$ =200 ms, I_{DSAW} =100A
Travel speed = 3.54 in/min (90 mm/min)

0.06" (1.5mm) gap:

Orifice: 0.11" (2.8mm), wire feed speed = 80 in/min
$I_{PAW:}$ [180A,270A],
$T_{DSAW,max}$ = 200ms, I_{DSAW} = 105A
Travel speed = 3.54 in/min (90 mm/min)

0.08" (2.0mm) gap:

Orifice: 0.126" (3.2mm), wire feed speed = 100 in/min
$I_{PAW:}$ [180A,270A]
$T_{DSAW,max}$ = 150ms, I_{DSAW} = 90A
Travel speed = 2.76 in/min (70 mm/min)

For each of these cases it has been found that suitable reinforcement (good weld shape) can be obtained on both sides (Figure 10 shows results for 0.06" gap). However, the toughness of the weld is still insufficient, although it does increase with the size of the gap (bead-on-plate: 5.8 ft-lbs, 0.06": 7.5 ft-lbs, 0.08": 9.3ft-lbs @ -4^{o}F). (The previous testing results obtained at Electric Boat suggest the toughness is only mechanical property of double-sided arc welds which can not meet the minimal requirement. Hence, only methods which can produce welds satisfying the minimal toughness requirement can receive further consideration and complete tests.) Hence, experiments involving larger gaps need to be conducted.

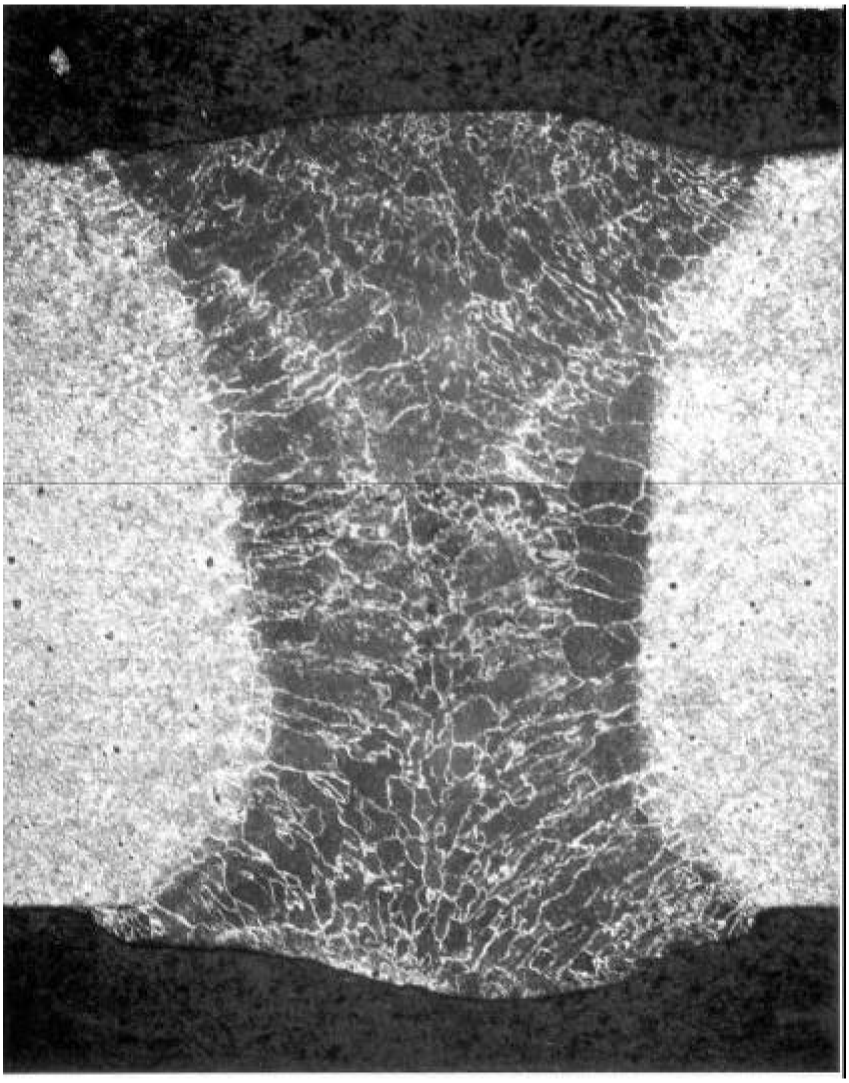


Figure 10: Cross-section of 3/8” DH36 with 0.06” Gap and ER-70S Filler Metal.

It should be pointed out that the travel speed has been reduced after the filler metal is introduced from 5.5 in/min to 3.5 in./min. It is true that double-sided arc welding produces a narrower arc than the standard arc welding process; but the narrower arc, while consisting of a higher energy density than that a standard plasma arc welding arc, seemed unable to both maintain the integrity of the weld pool and melt large quantities of filler metal without compromising process stability. In order to maintain stability and melt enough ER-70S to adequately reinforce the weld, the torch was required to travel at a slower rate.

4.2.2 Large Gap and Challenge

Conventional GMAW using ER-70S can achieve the required mechanical properties on DH36 including the toughness. The major difference between DSAW and GMAW is that the weld metal in GMAW primarily consists of the filler metal because the weld is made by filling the groove using filler metal, while the DSAW uses no groove and the percent of the filler metal in the weld metal is limited. A logic way to improve the toughness of double-sided arc welds appears to find ways to increase the percent of the filler metal in the weld metal. Because no groove is needed for DSAW, it was thought that increasing the gap may result in a sufficient percent of filler metal in the weld metal so that the required toughness be achieved. Hence, experiments have also been carried out for workpieces with a 0.12" (3mm) gap and ER-70S filler wire.

The experiments using 0.12" (3 mm) gap suggested that the placement of the filler wire with respect to the arc is critical. When the wire and the arc become misaligned, the wire may not be melt efficiently. This reduces the weld quality and can lead to the filler wire shorting to the backside electrode (water-cooled copper pipe).

To improve the robustness of the system with respect to the misalignment of the filler metal, the distance from the plasma torch to the work piece (torch-to-work distance) has been increased from 5-7mm in the earlier experiments to a range of 12-16mm. This is because the double-sided arc is very concentrated; although a concentrated arc can achieve deep penetration and reduce the heat input, it requires good alignment between the arc and the wire to be melted. An increased torch-to-work distance makes the double-sided arc to be broader and may obtain a better trade-off between the penetration capability and the tolerance of the wire-arc misalignment. Of course, this increase also increases the arc length and thus the arc voltage or total heat input so that a larger melting rate of the wire, which is needed for filling a larger gap, can be obtained. As a result, the arc voltage increases from 45 V to 50 V. (The Lincoln Electric Power Wave 455 used in this study has an open-circuit voltage of approximately 90 V. It is capable of supplying 100 A current at 50 V. However, conventional power supplies are designed for conventional arc welding which would consider an arc voltage which is significantly higher than that of conventional process to be abnormal and thus intentionally restrict the upper limit of the arc voltage. For the use in DSAW, the artificially set upper limit of arc voltage needs to be increased in order to supply larger current at higher voltage.)

Although the broader arc associated with an increased torch-to-work distance effectively improves the robustness of the system with respect to the misalignment of the filler metal wire, the resultant increase in the heat input is limited and further increase of melting rate of the wire, needed to fill a large gap, requires further increase in the heat input. Otherwise, unmelted wire will affect the stability of keyhole process. An increase of DSAW current may increase the total heat input and helps increase the melting rate of the filler metal wire. However, it increases the heat input on both sides of the work piece. On the other hand, the heat input for the back-side of the work piece is determined by the demand for penetration of the workpiece, not the melting of the workpiece. Hence, increasing the double-sided arc current would supply excessive heat input to the back-side of the workpiece. It is apparent that more heat input is needed for the front-side (PAW torch-side) for melting the electrode. To resolve this issue, it is proposed that a plasma arc current is also applied during the DSAW cycle. This PAW current will be responsible for providing the heat needed for melting the filler metal wire.

In summary, the challenge imposed by the need for larger melting rate of the filler metal wire for the large gap calls for adding a PAW current to compensate for the energy consumption for filler metal wire melting. Because the melted filler metal will distribute throughout the weld pool, a zero PAW current would imply an imbalance of heat input between the two sides of the workpiece. Hence, use of a PAW current during DSAW cycle would also help preserve the major advantage of DSAW, i.e., achieving symmetrical welds. Further, because the PAW current is on-line adjustable and the DSAW current is not adjustable, the PAW current can thus be adjusted to improve the robustness of the process with respect to the variations and fluctuations in the manufacturing conditions such as the arc length, gap, filler metal, etc. (Note: DSAW requires a higher arc voltage than conventional arc welding. Lincoln Electric PowerWave 455 used in this project for supplying DSAW current can supply such a high voltage but its current can only be pre-programmed not on-line adjusted. In the future, this power supply can be modified so that its current can be on-line adjusted. A representative of Lincoln has recently indicated another power supply has become available which can supply the voltage needed for DSAW with the capability of on-line adjustment of current.) The process will thus become more adaptive to the manufacturing conditions to maintain the stability of the keyhole process. Hence, an improved control system which uses an auxiliary PAW current needs to be explored.

4.3 IMPROVEMENT OF CONTROL SYSTEM

The most important issue in implementing the improved control scheme with an auxiliary PAW arc is the determination of the amplitude of the plasma current. Now the question is what criterion should be used for this determination. If the heat balance is the only criterion, one can calculate the heat needed for filler metal melting and use it to calculate the plasma current needed. However, its calculation may not be accurate because part of the arc heat radiates and the arc efficiency is unknown. An alternative criterion would be to determine the plasma current to stabilize the process with a minimized heat input. The advantage of this method is that it can use the on-line adjustable plasma current to change the heat input needed to stabilize the process when the manufacturing conditions fluctuate. The double-sided arc current (which is not adjustable because of the limitation of the power supply) can thus be set at a minimal level and the insufficiency of the heat input will be compensated by the heat generated from the auxiliary plasma current. The heat input can thus be kept to a minimal level necessary for stabilization of the process.

The current of the auxiliary plasma arc current I_{plasma} is determined using a PID feedback control algorithm:

$$I_{plasma}(t) = K[(I^*_{DSAW} - I_{DSAW}(t)) + \frac{1}{T_i}\int_0^t (I^*_{DSAW} - I_{DSAW}(t))dt + T_d \frac{d}{dt}(I^*_{DSAW} - I_{DSAW}(t))]$$

where I_{DSAW} is the actual DSAW current; I^*_{DSAW} the desired DSAW current which has been set for the DSAW power supply; (K, T_i, T_d) are the parameters of the PID controller and are referred to the proportional gain, integral time constant, and differential time constant respectively. The essence behind this feedback control algorithm is to maintain the process stability via controlling the actual DSAW current at its desired (nominal) level which has been set for the DSAW power supply.

Why the process stability can be controlled using the actual DSAW current as a feedback? This can be explained from the fundamental principle of the keyhole DSAW. When the keyhole is established, most of the DSAW current flows directly through the keyhole from one electrode to another. In this case, only one pair of anode and cathode exists for this part of current. If no keyhole is present, the current will have to flow through the workpiece in order to complete the current loop. Two pairs of anode and cathodes will thus be established. The resultant current will become higher. As a result, because of the V-A characteristic of the power supply, the actual DSAW will reduce. In this way, the actual DSAW current is used as a measurement of the state of the keyhole. If the keyhole is reducing, the actual DSAW current reduces. If the keyhole is increases, the actual DSAW current will increase. Hence, controlling the actual DSAW at its desired level stabilizes the DSAW process and maintains the keyhole open at a desired diameter.

Recall that the plasma arc current which is used to establish the keyhole is fixed. When the manufacturing conditions change or fluctuate, the plasma current needed to establish the keyhole changes. Before the control system is improved by using an auxiliary PAW current and PID control, the major contributor to the process instability and weld quality imperfection is the DSAW cycle. After the DSAW cycle is improved, it was found that the plasma arc welding used to establish the keyhole also has certain effect on the weld quality. It should also be adjusted based on the need for establishing the keyhole and thus varies with the manufacturing conditions. As a result, it was further proposed that an adaptive control algorithm is introduced to select the staring I_{PAW} to reduce the effective heat input to the system by attempting to minimize the time required to establish the keyhole. This was accomplished by choosing the starting I_{PAW} value to be a weighted average of the maximum I_{PAW} values from the previous 4 weld cycles. Once the keyhole is established, the PID control from the previous work is applied to stabilize the keyhole. Hence, the improved control scheme includes: an auxiliary PAW being determined by a PID controller and an adjustable staring I_{PAW} determined by an adaptive algorithm. The following gives the parameters for the improved control scheme:

PID controller parameters: $K = 5$, $K_i = 3s, K_d = 3s$.

Nominal values for flat position:

I_{DSAW} = 65 A	I_{PAW} = 140A-240A to establish keyhole
Travel speed = 90 mm/s	approximately 50A during DSAW cycle
Bead-on plate and Butt joint	ER-70s filler material

It was found that the improved control system significantly improved the process stability and repeatability. However, the desired toughness is still not achieved.

Calculation indicates that despite the increase in the percent of the filler metal in the weld metal, the major part of the weld metal is still from the base metal, not the filler metal. On the other hand, ER-70S is designed for the use of GMAW where the majority of the weld metal is from the filler metal. Hence, it was determined that it may not be feasible to improve the toughness by adding ER-70S for DSAW. Ideally, another type of filler metal needs to be designed specifically for DSAW. However, because of the relatively short period and the limited budget of the project, it was determined that it is unrealistic to pursue the development of the filler metal. As a result, nickel-rich filler metal was suggested. Because of the relatively small amount of the filler metal assumption, cost of nickel-rich filler metal appears not an important issue. Therefore, it was determined that an INCONEL filler metal is used to achieve the desired toughness. If the desired toughness and other mechanical properties can be achieved, it would lead to the verification of the practicability of DSAW for shipbuilding applications and thus fulfill this ultimate goal of this project. Then a detailed analysis can be done to determine the cost. Further, in the follow-up full-scale research targeted by this preliminary study, a more economic filler metal should be identified or developed.

4.4 USE OF INCONEL® FILLER METAL 625

All tested welds that used the INCONEL® 625 filler metal (61 % Ni, 22% Cr, 9% Mo, 4% Nb, 3% Fe) demonstrated toughness values at least 3 times greater than the minimum value required by the specifications in both the weld metal and HAZ. The parameters are listed below.

Nominal values of parameters for flat position:

I_{DSAW} = 65 A	I_{PAW} = 180A-270A to establish keyhole
Travel speed = 90 mm/s	INCONEL® 625 filler metal, 0.045” dia.,
Butt joint	1.6 in/sec feed rate

Nominal values of parameters for vertical-down position:

I_{DSAW} = 60 A	I_{PAW} = 140A-240A for establishing keyhole, 30A-40A for maintaining keyhole.
Travel speed = 90 mm/s	INCONEL® 625 filler metal, 0.045” dia.,
Butt joint, 1/8” gap	1.6 in/sec feed rate

Figs. 11 and 12 give the toughness test results for the weld metal and HAZ.

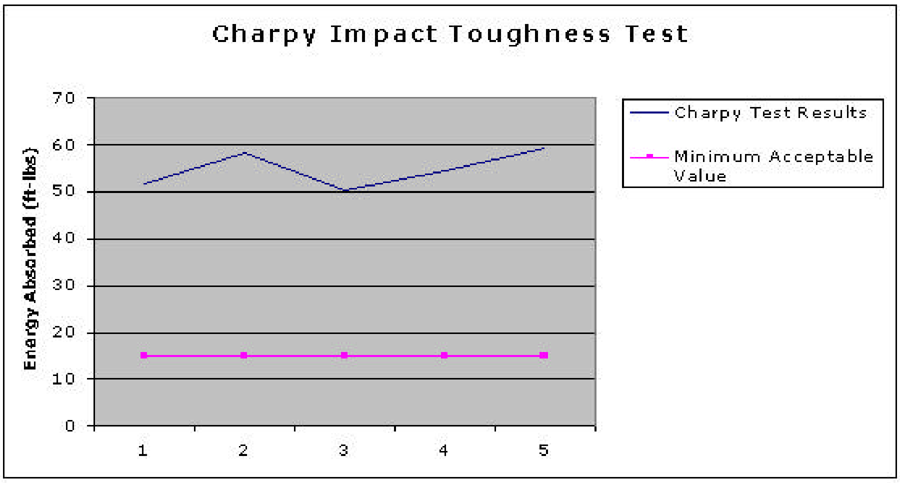


Figure 11: Toughness Values for DSAW Samples Using INCONEL® 625 Filler Metal.

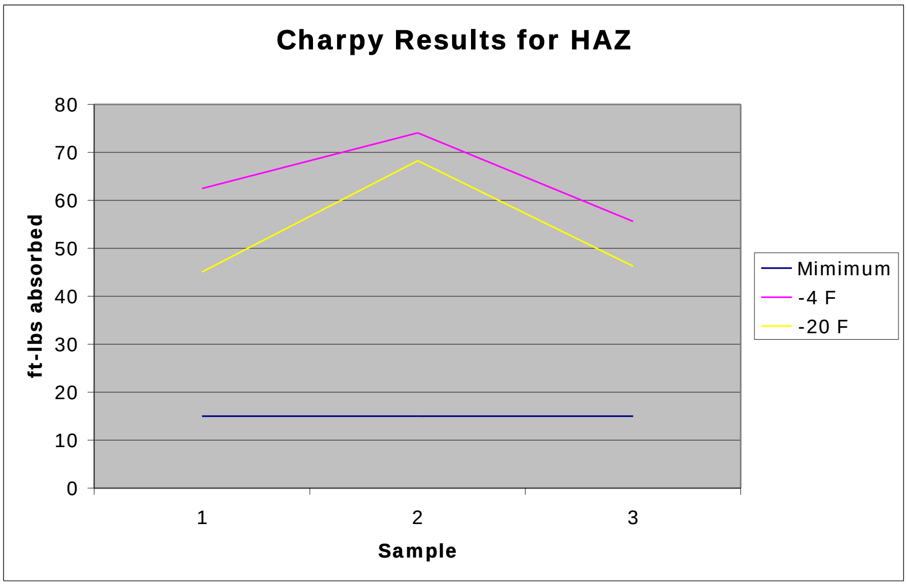
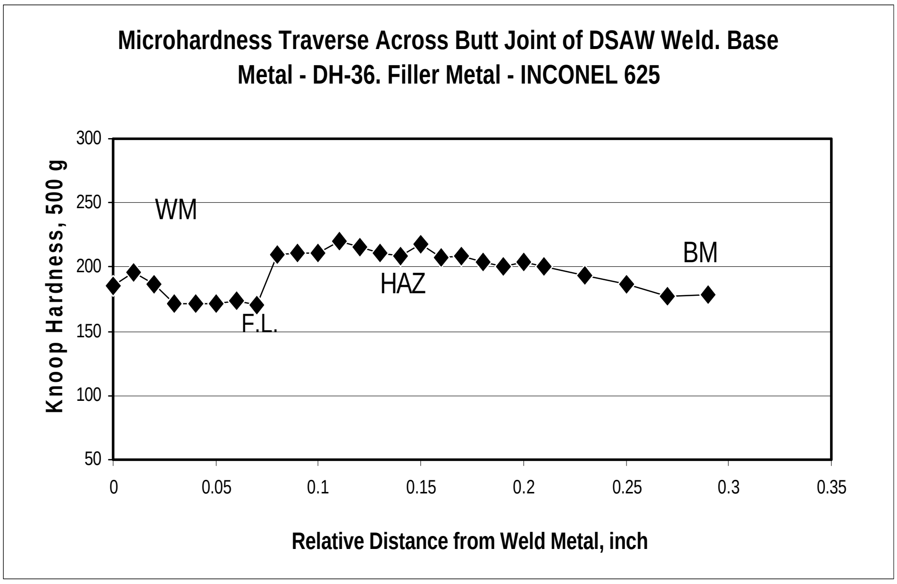


Figure 12: Toughness Values for HAZ of the DSAW Samples Using INCONEL® 625 Filler metal. All test coupons were ¾ sub-sized and the results were converted per SAE J1194.

The micro-hardness, tensile, and bending tests have been done by Warren Mayott [11] at Electric Boat previously and all met the requirements. To verify that those results are also valid for the welds made using the modified system, process, and control scheme with the use of INCONEL® 625 filler metal, those tests have repeated again. It is found that all the new testing results meet the requirements and are similar to those of previous study at Electric Boat [11].

Micro-hardness: These results are well acceptable.



Tensile:

Specimen One: Cracked and had a ductile failure in the base metal at 78,633 psi.

Specimen Two: Cracked and had a brittle failure in the HAZ at 78,705 psi.

Bending:

Specimen One: Bent around a 0.75 in. radius and passed the test.

Specimen Two: Bent around a 0.75 in. radius and passed the test.

4.5 ANALYSIS

4.5.1 Heat Input

It is estimated that the heat input of the DSAW process is 60 KJ per inch weld. This figure is obtained based on the following calculation:

> Assume that the effective voltage for DSAW current and plasma stabilizing current (30 A to 40 A) are 35 V (the anode voltage on the water-cooled copper and the cathode voltage on the electrode in PAW torch must be subtracted in order to calculate the effective voltage) and 28 V. The heat input per minute will be between (60X35+30X28)X60=176 KJ to 193 KJ. The travel speed is 3.54 in/min. The heat input per inch weld is thus between 50 KJ to 55 KJ. In addition, during the keyhole establishment period, the plasma current increases to 140 A to 240 A. However, the DSAW current is zero during this period. Further, the keyhole establishment period is very brief. Hence, the addition of the heat input due to the use of higher PAW current for keyhole establishment is limited. As a result, one can safely estimate that the heat input is 60 KJ or lower for each inch weld produced.

This heat input is higher than 40 KJ/inch, the heat input in one pass during conventional GMAW. This is because

> For GMAW process, in each pass, the arc input is 350A x 30V x 60 s/min / 15 in/min = 42 KJ/in. Because the arc efficiency in GMAW process is nearly 1, the heat input into the worpiece should be close to 40 KJ/inch.

However, the heat input of 60 KJ/min in DSAW it is still within the range permitted for DH 36 which is 10 KJ/inch to 100 KJ/inch. Hence, the toughness of the HAZ is well above the minimum values for toughness tests.

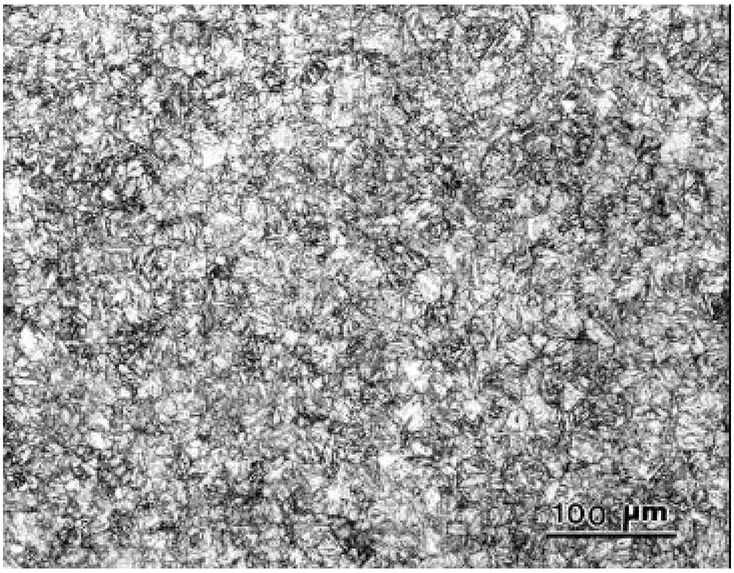
For 3/8 in. thick plate, a 10 kW laser beam can achieve full penetration at the travel speed of 80 in./min [13]. The heat input is thus 10000Wx60s/80in./min=7.5 KJ/in. The heat input is lower than the minimal level for appropriate cooling rate.

On other hand, for 3/8 in. thick plate, GMAW requires multiple passes, for example 4 to 5 passes, and each pass has approximately 2/3 of the heat input of DSAW. The total heat input into the workpiece is thus much more than that of DSAW. Further, the heat input is asymmetrical in each pass in GMAW. The distortion thus accumulates. For DSAW, the heat input is symmetrical and the total heat input is 1/4 to 1/3 of that of GMAW. The distortion is thus not observable.

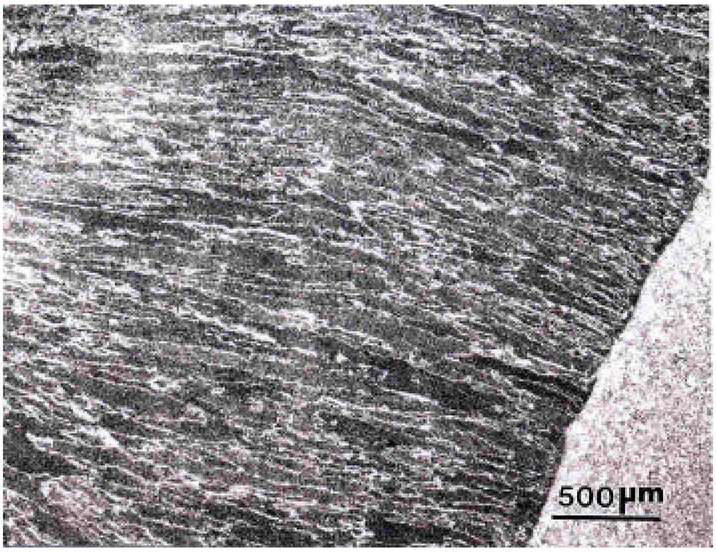
4.5.2 Metallurgy

A. Weld Metal

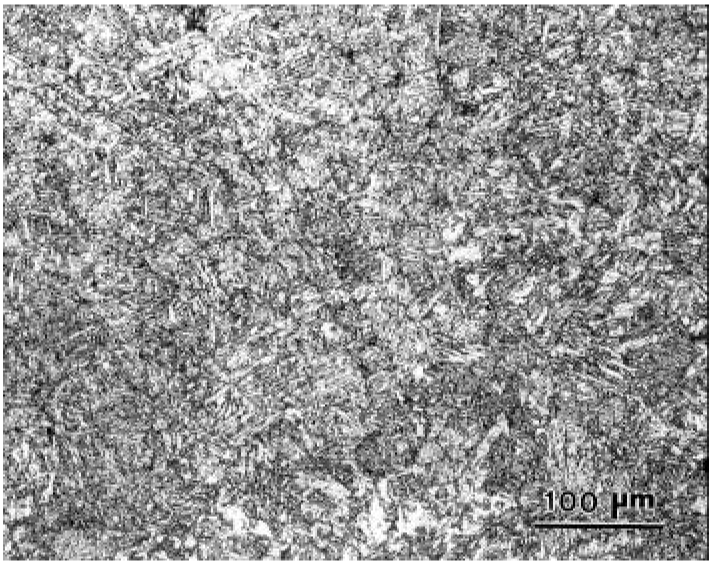
The use of INCONEL® 625 filler metal makes it difficult to observe the grain structures in the weld metal. However, studies have been conducted on two high strength steels, A514 and Domex 100XF [14]. Unique feature of microstructure of weld metal was observed in all test DSAW weldments. That is, the columnar structure in weld metal, which is typical in conventional arc welding process, was not well developed. Instead, a great fraction of fine equiaxed grains are present in weld metal. In Figure 13, the microstructures of the base metal (DH 36), GMAW weld metal with ER-70S filler metal, and DSAW weld metal with ER-70S filler metal are given. While the columnar structure is obvious in GMAW weld metal, it is not clearly observable in the DSAW weld metal.



(a) Base Metal



(b) GMAW Weld Metal with ER-70S filler metal

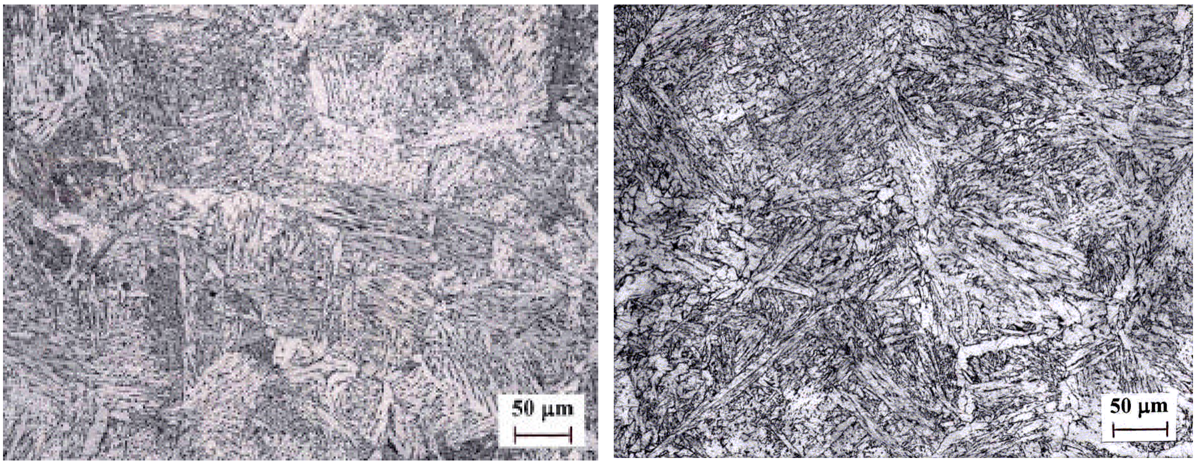


(C) DSAW Weld Metal with ER-70S filler metal

Figure 13: Microstructures of DH36 Base Metal, GMAW Weld Metal, and DSAW Weld Metal

B. HAZ

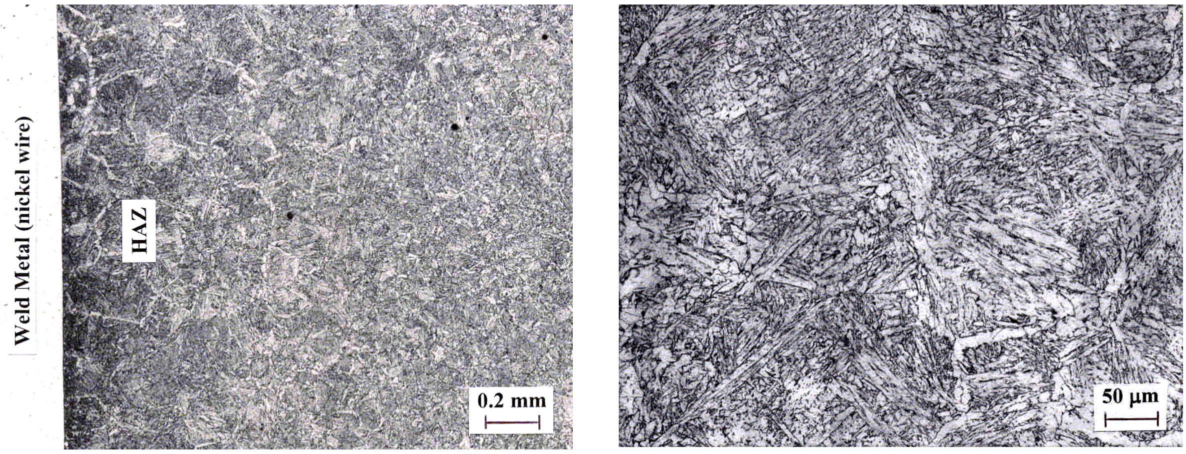
Figure 14 shows that microstructure of HAZ in GMAW and DSAW on DH 36. The microstructures exhibit similarities. This is due to the similar level of heat input. Hence, although the cooling rate in DSAW is lower because of the slower speed, the cooling rate in GMAW and DSAW should be in the same range. Since the microstructures in HAZ are primarily determined by the cooling rate, two types of welds should have similar microstructures in HAZ. This also explains why both DSAW and GMAW can pass the HAZ toughness testing.



(a) GMAW HAZ (b) DSAW HAZ

Figure 14: HAZ Microstructures on DH-36 Plates

Figure 15 gives the comparison of the DSAW HAZ in different magnification.



(a) GMAW HAZ (b) DSAW HAZ

Figure 15: DSAW HAZ in Different Magnification

4.5.3 Practicability Analysis

An important issue in determining the practicability is the cost. The use of INCONEL® 625 filler metal increases the cost for filler metal. However, because no groove is used, the majority of the weld metal is from the base metal. The amount of the filler metal in the weld metal is thus small. In particular, based on the parameters used, the feed rate of the INCONEL® 625 filler metal wire is only 25 in. per inch weld, or 1 lb filler metal for 500 inch or 40 ft weld. Based on the price the University of Kentucky paid, the filler metal cost would be $0.45 per foot weld. If a large quantity is purchased, the price would drop significantly. The estimated filler metal cost would be approximately $0.2 per foot weld.

Another important issue is the time needed to set up the system. Because the current must flow through the water-cooled pipe back to the power supply, the back-side arc will automatically track the back-side electrode (water-cooled copper pipe). The requirement on the alignment between the weld seam and the back-side pipe is low and no fine adjustment is needed. Hence, the set-up time of the system is minimal.

The speed of DSAW is currently slow. However, it only requires a single pass to produce the required weld. Further, it requires no groove and accurate control of the fit-up and gap because of the robustness of the control scheme. Further, it produces no observable distortion. It is expected that the actual productivity would be significantly improved in comparison with GMAW for vertical and horizontal positions. Moreover, it is estimated that the travel speed of DSAW can be increased at least three times by using a power supply to provide up to 400 A adjustable current at 60 V.

Most importantly, the modified system can be operated like a conventional process with a single torch to operate. Because of the proved properties and the robustness of the controlled process with respect to the manufacturing conditions, the principal investigator is confident that the DSAW is a practical process for welding of ship hulls. A commercial system can be developed to further demonstrate the practicability at shipyard sites.

5. CONCLUSIONS AND FUTURE WORK

5.1 CHARACTERISTICS OF DSAW

- Concentrated arc: Observation shows that the diameter of the plasma arc beam in DSAW is less than 1/3 of that in conventional PAW. The energy density is thus 10 times of that of conventional PAW. Analysis shows that the unique current direction in DSAW generates an concentrating electromagnetic force which is responsible for the improvement of the energy beam density.
- Deep narrow penetration: The concentrated arc improves the capability of the arc to penetrate the workpiece without generating a wide weld pool. The resultant weld pool is thus narrow and along the thickness like a laser weld pool, although it is wider than that of laser.
- Penetration capability: The deep narrow penetration makes DSAW be capable of penetrating ½ in. thick plates using 70 A in a single pass. It is suspected that thicker plates, possible up to ¾ in., can be penetrated in a single pass on square butt joint.
- Symmetric weld shape and minimal angular distortion: The symmetrical heating and small heat input associated with the DSAW, because of the deep narrow penetration capability, generate symmetrical weld pool shape and minimize the distortion.

5.2 ADVANTAGES

- Robustness with respect to manufacturing conditions: The process is controlled using the pulse keyhole method so that the welding parameters are automatically adjusted to establish the keyhole when the manufacturing conditions such as the gap vary.
- Single-pass process: Plates up to ½ in. thick plate can be welded in a single pass without joint preparation on square butt joint in a single pass. This single-pass process also produces the desired positive reinforcement on both sides of the weld.
- Elimination of Distortion: Symmetrical heating and weld bead shape eliminate the angular distortion.
- Single-torch operation: The modified DSAW which uses the stationary metal bar requires only a single torch move along the weld seam like a regular arc welding.
- Single-side weld: Ship hulls are normally joined together as a full penetration butt weld which, except for very limited and controlled applications, requires welding from both sides of the weld joint. DSAW provides an opportunity to join ship hulls from one side.
- Easy set-up: The stationary metal bar requires no accurate alignment with the weld seam. This is because that the current must form the loop and will thus automatically search for the stationary metal bar. The back-side stationary bar can be magnetically attached to the workpiece.
- Easy fit-up and joint preparation: The gap can vary from zero to 2.5 mm. No bevels are needed and the square butt joint can be prepared using plasma cutter. This is because the process is controlled using a pulse keyhole method so that the input energy is automatically adjusted based on the need for establishing the keyhole.

5.3 COMPARISON WITH LASER

- Low capital investment: The equipment cost is comparable with conventional arc process.
- Labor force: DSAW requires no extra personnel other than conventional arc welding operators.
- Portability: DSAW system is portable similarly as conventional arc welding systems.
- Safety: DSAW creates no specific safety issues.
- Appropriate heat input and cooling rate: The DSAW reduces the number of pass from multiple in conventional GMAW to one with significantly increasing the heat input of one pass. The cooling rate is thus similar to that in conventional GMAW which has been proved to be capable of welding DH36. However, laser has a much higher cooling rate. Disfocusing the laser can reduce the cooling rate but reduces the penetration capability and requires increase of laser power.

5.4 COMPARISON WITH CONVENTIONAL GMAW

- DSAW eliminates the distortion which is substantial in conventional GMAW.
- DSAW reduces the number of passes to one for plates up to ½ in. thick.
- DSAW eliminates the need for bevels.
- DSAW eliminate the need for turnover of workpiece.

- The cost of a DSAW system and its operation is comparable to that of conventional GMAW.
- DSAW reduces the usage of filler metal and electricity.
- DSAW improve the productivity: Although the travel speed in DSAW is lower, it requires only a single pass. The actual speed is thus improved.

5.5 SATISFACTORY WELD PROPERTIES

- Experiments in this project show that all weld properties satisfy the requirements for DH36.
- The pulse keyhole control technology guarantees that the establishment of the keyhole and thus the required full penetration.

5.6 FUTURE WORK

In summary, this project has verified the feasibility of DSAW process for shipyard applications. Based on the previous plan, a follow-up full-scale development proposal should be prepared for the NSRP-ASE program. The proposed NSRP-ASE project will focus more practical issues related to commercialization outlined below.

- A commercial system is needed to demonstrate the DSAW in shipyards.
- Alternative filler metals are needed. Although the amount of the filler metal used is much smaller than that in conventional GMAW, more economic filler metal would further reduce the overall cost of DSAW process.
- Higher welding speed is desired. The current power supply used in this preliminary study was not capable of supplying reasonable current at the voltage required by DSAW. For higher welding speed, it is desired that a larger current can be supplied at 55 V. As mentioned earlier in this report, it is possible to modify the software by increasing the allowed voltage so that the power supply can supply larger currents at 55 V. Further, power supplies have recently become available at Lincoln Electric to provide 300 A at 55 V. As a result, the welding speed will be increased.
- Experiments with other materials and thicker plates need to be explored.
- The control system needs to be improved based on better understanding and modeling of the DSAW process.

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7. KEY PERSONNEL

YuMing Zhang of the University of Kentucky and Mr. John Matthews of Electric Boat have been the principal and co-principal investigators. Mr. Warren Mayott served as the co-principal investigator from July 2001-December 2001. In addition to visiting the University of Kentucky for observing the process and determining the system design and research directions, Mr. Matthews and Mr. Mayott also coordinate the shipyards and the SP-7 committee for the assessment and the review of the results from this project.