

# Hybrid Laser-GMA Welding for Improved Affordability

E. W. Reutzel<sup>1</sup>, S. M. Kelly<sup>1</sup>, M. J. Sullivan<sup>2</sup>, T.D. Huang<sup>3</sup>, L. Kvidahl<sup>3</sup>, R. P. Martukanitz<sup>1</sup>

1. Applied Research Laboratory, Pennsylvania State University, State College, PA
2. General Dynamics NASSCO, San Diego, CA
3. Northrop Grumman Ship Systems, New Orleans, LA

## ABSTRACT

*Maturing high power solid-state laser technology is fueling an interest in hybrid laser-GMA welding for shipyard fabrication activities. Hybrid laser-GMA welding has demonstrated an ability to both reduce the distortion of thin steel butt welds and increase the production rate of pipe welds relative to conventional joining techniques, both leading to improved affordability. The paper discusses the potential benefits of hybrid laser-GMA welding, results of experiments to address both distortion and production rate, and provides an overview of a hybrid pipe welding system recently installed in a shipyard.*

**KEY WORDS:** welding; laser beam welding; hybrid welding; welding distortion; pipe welding

## INTRODUCTION

It has been a quarter of a century since researchers first conceived of combining a conventional welding arc with a laser beam in a hybrid process (Steen and Eboo 1979, Steen 1980), but only recently has commercial laser technology advanced to the point that hybrid laser-GMA welding has begun to take hold in industrial applications. Lasers are now significantly more industrially robust and energy efficient than they were just a few short years ago.

Laser beam welding (LBW) offers relatively high welding speed and high penetration compared to conventional arc-based joining processes. Unfortunately, due to the small spot size typically utilized in LBW, it has limited success in certain welding applications due to an inability to provide adequate reinforcement (i.e. filler material) and due to poor gap bridging capabilities. Consequently, laser beam welding requires high precision during edge preparation and setup, an added cost during manufacturing operations. Additionally, the focused energy of the laser beam results in a narrow heat affected zone (HAZ) that can lead to steep spatial and temporal thermal gradients that can result in brittle microstructures.

In contrast, conventional Gas Metal Arc Welding (GMAW) offers the ability to easily bridge gaps in the joint by introducing filler metal to the process. The composition of the filler materials can be customized to produce improved material properties. The additional heat results in reduced cooling rates,

which can lead to improved ductility. However, the high heat associated with the process can also cause undesirable distortion or buckling, and the nature of the process prevents deep penetration welds. As a result, thick sections often require multiple weld passes.

In certain applications these shortcomings can be overcome by marrying the LBW and GMAW processes. Not only is this helpful in accommodating gaps and reducing weld-head positioner tolerance requirements while maintaining deep penetration (Engstrom, Nilsson and Flinkfeldt 2001), but it has also been known to enable operation at even greater welding speeds and to provide an improved weld microstructure upon cooling (Walz, Seefeld and Sepold 2001). Additionally, the combination of LBW and GMAW may significantly reduce overall weld time in thick sections by joining in a single pass what would require multiple passes using conventional techniques.

This document outlines recent results of various investigations into the potential advantages of hybrid laser-GMA welding. The first section discusses the use of hybrid welding for reducing distortion of thin steel butt welds realized by reducing the overall heat input, and presents recent experimental results. The second section discusses the use of hybrid welding for improving production rate, and provides an overview of an effort to develop and implement hybrid welding technology for joining pipe. Experimental results are presented, and a description of the installation of the system in the shipyard, along with results of an initial pre-production time study are detailed.

# HYBRID WELDING FOR REDUCING DISTORTION IN THIN STEEL

## Background

The use of thin steel (less than 10 mm thick) in shipbuilding has increased significantly in the last 20 years, from less than 10% before 1990 to greater than 90% in 2000 (Huang, Dong, DeCan and Harwig 2003). The increased usage of thin steel is driven by ship designs requiring a reduction in weight, offering performance increases in the final product. At the same time, U.S. shipyards have faced difficulty in dealing with the inherent problems in fabricating large structures with thin material and as a result, have experienced significant cost increases due to problems associated with distortion. One of the large contributors to distortion in thin steel structures is the welding process. It has been estimated that the welding of panel seams leads to significant additional costs during fabrication of the major platforms.

On-going research at the Applied Research Laboratory at Penn State University (ARL Penn State) under an ONR MANTECH Program has been directed at the use of hybrid laser arc welding (HLAW) technology for joining of thin steel panel structures (panel seams, inserts and stiffeners), with the objective of reducing distortion in the final product. Northrop Grumman Ship Systems (NGSS) has been actively involved in this program. The goals of the program are to (1) develop a hybrid welding process that can be easily implemented in the U.S. shipyard, (2) perform necessary testing to ensure a qualification-ready process, (3) demonstrate the process on large scale panels at NGSS on their panel line, and (4) deliver an implementation roadmap for the technology that specifies a system and required qualification testing. The program is initially focused on the welding of 5 to 10 mm thick higher strength steel such as American Bureau of Shipping (ABS) grade AB/DH36 and AB/EH36. The experiments in the section report on the measured reduction in distortion achieved when the hybrid laser arc welding process is used to join thin steel panels.

Conventional welding processes such as submerged arc welding offer low capital equipment cost and are readily implemented in the production environment of the U.S. shipyard. One significant drawback to conventional welding processes such as submerged arc welding (SAW) are the high levels of heat input used. Heat input, or weld power imparted to the plate divided by the travel speed {kJ/in.}, is proportional to weld distortion. As heat is added to the weldment, residual stresses are generated resulting in distortion. Buckling distortion is problematic in thin panel structures since the critical buckling strength are proportional to the thickness-squared. For example, the critical buckling strength in 10 mm plate is 4 times greater than in 5 mm plate, while the welding-induced longitudinal residual stress levels are relatively constant for these ranges of thicknesses (Huang, Dong, DeCan and Harwig 2003)

Masubuchi (1984) summarized the relationship between heat input and distortion for welding of 0.25 inch steel panels. The data presented by Masubuchi indicates that a 1% increase in heat input can correspond to a 24.7% increase in out of plane distortion in 0.25 inch thick steel stiffened panel structures.\* Recent experiments by Kelly et al. investigated the use of laser beam, hybrid laser arc and gas metal arc welding to join 10 mm thick inserts into 5 mm thick panel of higher strength steel (Kelly, Martukanitz, Michaleris, Bugarewicz, Huang and Kvidahl 2006). The results of this work indicated that for a 1% increase in heat input, distortion would increase between 2.5 and 2.8%, depending on the size of the panel. Clearly while there is a relationship between heat input and buckling distortion, the magnitude varies considerably with processing, thickness and panel size.

The current shipyard welding process for butt-welding panel seams, conventional SAW, imparts approximately 3.5 times more heat than the hybrid welding process. The tandem submerged arc welding process, which is receiving considerable interest by shipyards because of its potential for increased productivity imparts approximately 2.5 times more heat than a hybrid welding process for 5 mm butt welds.

## Experiment

In order to quantify the heat input achieved with hybrid welding and the associated distortion in thin steel panels, the HLAW process was used to weld 2 by 10 foot panels that were nominally 0.25 inches thick. The panels, provided by GD NASSCO, consisted of the higher strength structural steel ABS grade AH-36. The joint edges were machined to a square-butt configuration, and gaps were held to less than 0.002 inches. In the absence of automated seam tracking, the panel was fixtured to minimize vertical and lateral movement of the joint during welding (Figure 1). Processing conditions are summarized below and in Table 1 and compared with conventional two-sided submerged arc welding processes. Out of plane distortion (z) was measured while fixtured before and after welding (after cooling to room temperature) using a dial indicator at a nominal transverse and longitudinal spacing of 6 and 12 inches, respectively. The difference in the out of plane shape was then calculated, and the data linearly interpolated to produce a graphical representation of the plate shape.

---

\* In Masubuchi's work, the final central deflection of a 0.78 kJ/mm weld was 0.095 mm, while the final central deflection of a 1.35 kJ/mm weld was 1.87 mm. Thus a 79% increase in heat input corresponds to a 1867% increase in distortion.

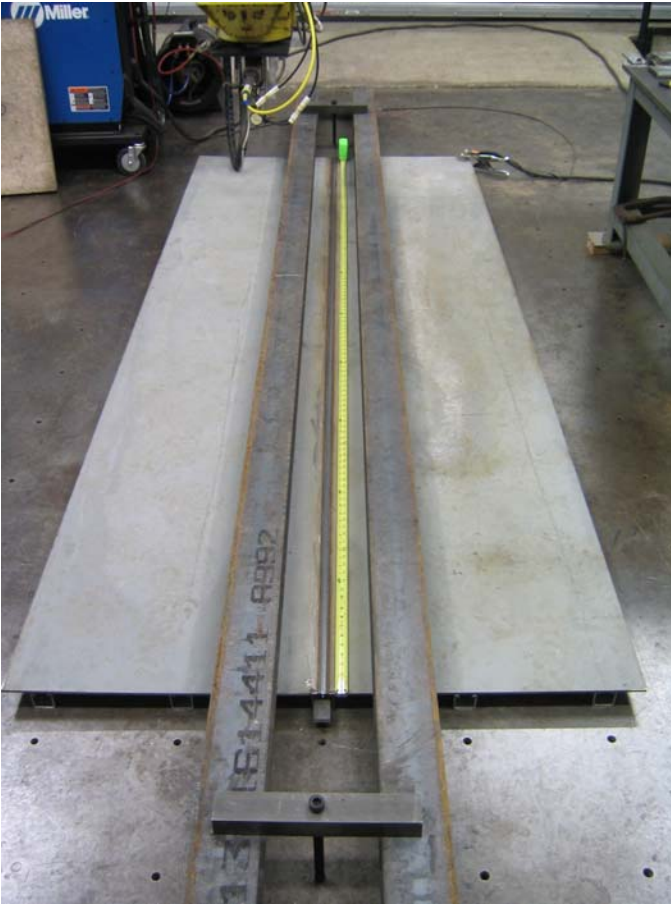


Figure 1. Photograph of the fixture used during hybrid welding. The fixture consisted of two steel I-beams placed on both sides of the welded joint and clamped to the welding bed.

40 inches per minute, with motion controlled by a 5 axis gantry robot. The heat input of the single sided HLAW was approximately 15.8 kJ/in.

## Results.

**Hybrid butt welds.** A photograph of the hybrid welded panel can be seen in Figure 2. The panel exhibited minor transverse angular distortion, and no buckling distortion.



Figure 2. Photograph of the hybrid welded panel.

A macrograph of the weld cross section is shown in Figure 3. All welds were visually acceptable according to MIL-STD-2035. Crown and root reinforcement measured at 0.037 and 0.045 inches, respectively. The MIL-STD-2035 limit on both crown and root reinforcement for 0.25 inch thick plate is 0.0625 inches. Neither destructive nor nondestructive testing have yet been conducted on the welded panel. Vickers microhardness values of the base metal, heat affected zone, and weld metal are shown in Table 2. The average weld metal hardness measured was  $244 \pm 17$  HV<sub>200gf</sub> with a maximum value of 284 HV<sub>200gf</sub>. The average base metal hardness was  $157 \pm 7$  HV<sub>200gf</sub>. The values compare well with those previously reported by McPherson et al. (2005) for hybrid laser arc welded AB/DH36 steel.

Table 1. Summary of processing conditions used.

Process	Travel Speed {in/min}	Heat input {kJ/in}
HLAW	40.0	15.8
2-sided SAW	29.5	54.0

**HLAW.** The hybrid laser arc welding process utilized a 4.5kW Nd:YAG laser with a 5.9 inch (150 mm) focal length and 0.023 inch (0.6 mm) beam diameter at focus. The laser was defocused 0.200 inch above the substrate for the weld. The gas-metal arc component of the hybrid process used a Miller AutoAccess 450 power supply, operating in pulsed mode (GMAW-P) with a wire feed rate of 250 inch/min, and average arc voltages and currents of 30V and 200A, respectively. The laser led the arc process with a separation between laser focus and the electrode of 0.24 inches (6 mm). The GMA torch supplied Ar-10%CO<sub>2</sub> shield gas at 95 SCFH; the gas provided shielding for both for the arc and laser processes. A 0.045 inch diameter ER70S-6 electrode (Lincoln Electric L-56) was used, with a contact tip to workpiece distance of 0.75 inches and torch angle of 20° from vertical. The welding travel speed was

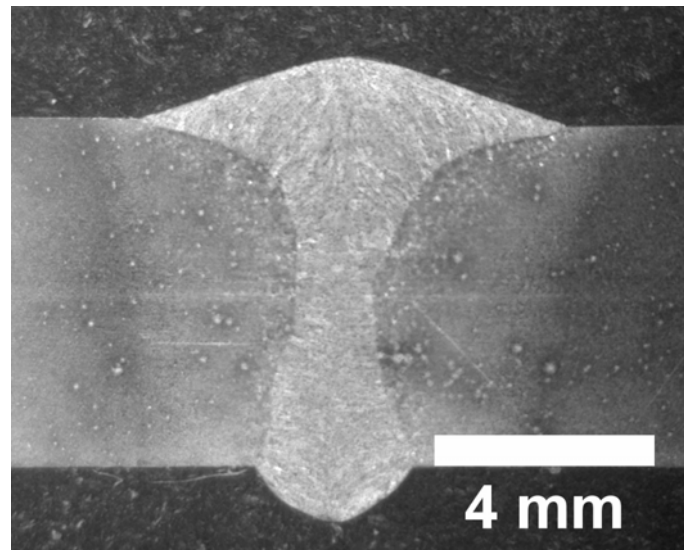


Figure 3. Weld cross section of the full penetration hybrid weld in 0.25 inch (6 mm) thick material.

Table 2. Vickers microhardness values measured from the weld cross section

Location	Average Vickers Hardness HV <sub>200gf</sub>
Base Metal	157 ± 7
Heat Affected Zone	222 ± 25
Weld metal	244 ± 17

The distortion results are presented in Figure 4 as a contour map of the difference in plate shape before and after welding. The data presented in the figure is interpolated to provide finer details of the plate shape. A maximum upwards deflection of 0.086 inches is located at the lower right hand corner of the weld. Adjacent to this upward deflection is the maximum downward deflection of -0.065 inches. Both of these extremes correspond to a region of the panel that had been previously “kinked” during handling. During the fitting and tacking of the plate, it was necessary for the welder to force-fit the plates, thereby introducing anomalous extreme values.

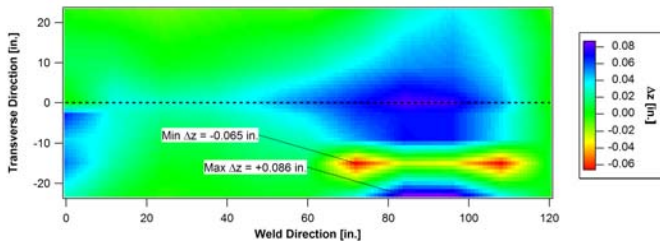


Figure 4. Contour plot of the difference in out of plane distortion in a hybrid welded panel.

The amount of distortion induced during welding can be quantified several ways such as the maximum out of plane displacement, as indicated in Figure 4. The average distortion over the entire panel is  $0.024 \pm 0.029$  inches. A more comprehensive measure of the total weld distortion is by determining the distorted volume by numerically integrating the absolute value of the distortion data. The total distorted volume of the hybrid welded panel is approximately  $143 \text{ in}^3$ .

Future work will compare the distortion observed in the hybrid panel described in this work to like panels joined using standard shipyard welding techniques.

### Ongoing research into hybrid welding for thin steel panel structures.

In addition to butt welds, other joints typically welded on a panel line are also the focus of prior and ongoing research. Initially, insert welds were targeted as a potential hybrid application due to inherent distortion problems caused with their use (Huang, Dong, DeCan and Harwig 2003, Huang, Harwig, Dong and DeCan 2005). Hybrid laser arc and gas metal arc welding of small scale mock-up insert panels was completed. A photograph of the 2 by 4 foot insert (10 mm thick) welded into a 4 by 8 foot panel (5 mm thick) is shown below, in Figure 5.

The proportions of angular and buckling distortion were computed using a least squares minimization comparing measured and theoretical (eigenvalue analysis) shapes of 3 by 3 foot insert welded panels (Bugarewicz 2005, Kelly, Martukanitz, Bugarewicz and Michaleris 2006). The resulting increase in distortion associated with increasing heat input attributed to various joining techniques is shown in Figure 6. There is a significant increase in buckling and total distortion associated with the GMAW process.



Figure 5. Photograph of 2 by 4 foot insert (AB/EH36, T=10 mm) hybrid laser arc welding into a 4 by 8 foot panel (AB/DH36, T=5 mm).

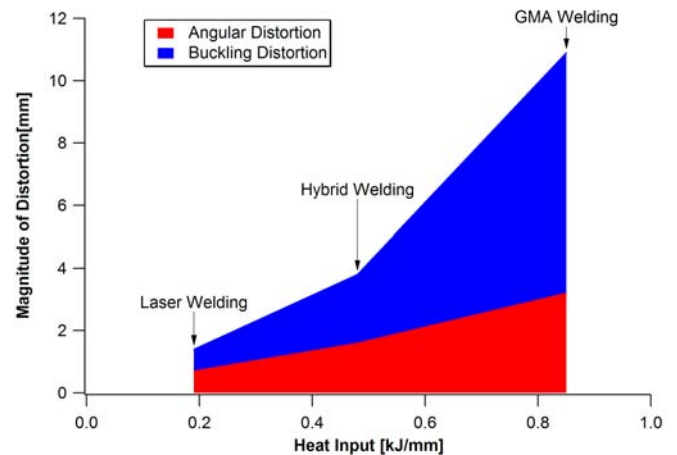


Figure 6. Magnitude of the components of weld distortion as a function of heat input for different welding processes used to join 18 by 18 inch inserts (AB/EH36, T=10 mm) into 36 by 36 inch panel (AB/DH36, T=5 mm). Magnitudes were predicted using a least squares minimization technique.

An additional application of interest for hybrid welding on the panel line is the joining of stiffeners to panel. An example is shown in Figure 7, where a two sided full penetration weld was made using approximately 13.5 kJ/inch of heat input at a travel speed of 60 in/min. These values represent a 22% decrease in heat input and a 114% increase in travel speed over the conventional welding process in place at Northrop Grumman Ship Systems. Future efforts will focus on further optimizing the hybrid welding process for joining stiffeners to panel.

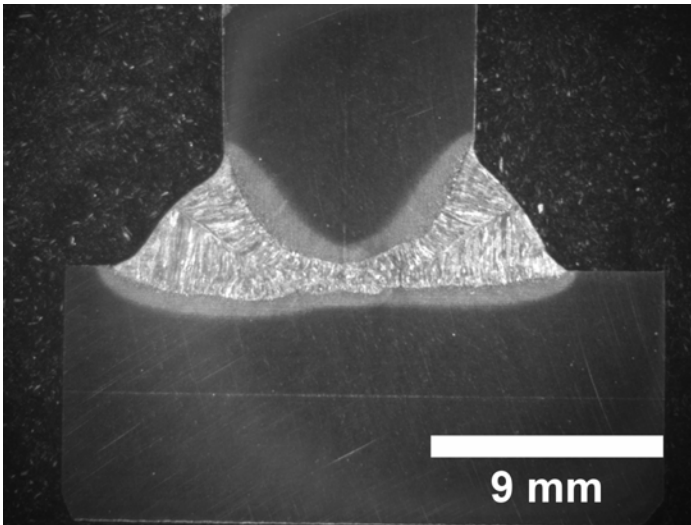


Figure 7. Photomicrograph of a double sided hybrid welded stiffener to panel (both AB/EH36, T=10 mm).

## HYBRID WELDING FOR IMPROVING PRODUCTION RATE IN PIPE WELDS

### Background

Welding of pipe represents a significant cost in the construction of tankers and other ships. Though much welding of pipe must occur *in situ* on board the ship, as much pipe as possible is rolled in a pipe shop and manually welded in the downhand position. Figure 8 illustrates a current joining technique employed at the General Dynamics National Steel and Shipbuilding Company (GD NASSCO). In the figure, the pipe is fixtured to a rotary positioner that rotates the pipe beneath the arc weld torch. The torch is manually manipulated by the operator.



Figure 8. Photograph of the conventional pipe welding process (courtesy GD NASSCO).

At GD NASSCO, the steel pipe ranges in thickness from 6.0 to 12.7 mm (0.237 to 0.500 inch). For thicker sections, producing an adequate joint requires the execution of multiple weld passes. Figure 9 shows a cross section of a multipass pipe weld in 12.7 mm (0.500 inch) wall thickness pipe.

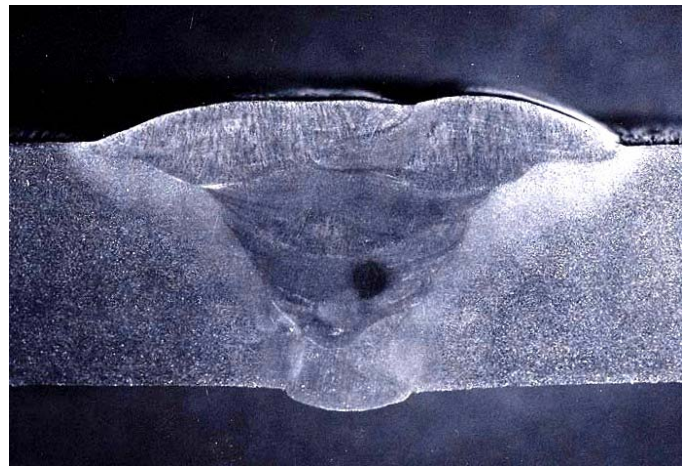


Figure 9. Cross section of conventional multipass pipe weld with 12.7 mm (0.5 in) thickness (courtesy GD NASSCO).

To help determine potential savings in converting to a single-pass hybrid weld, a detailed study was undertaken to assess current practice (Reutzel, Mikesic, Tressler, Crue, Gwinn and Sullivan 2005). It was determined that the joining process takes up to 82 minutes for 4 inch diameter pipe, and up to 232 minutes for 30 inch diameter pipe (total time). The multipass conventional weld portion of the process contributes significantly to this time, in large part because joining pipes requires 2 to 5 passes at 0.13 to 0.25 m/min (5 to 10 ipm) weld travel speed. A time study was conducted to determine the time spent on each of the various operations used to join two pipes. A sample of the results for an open root joint over a range of pipe diameters is shown in Figure 10.

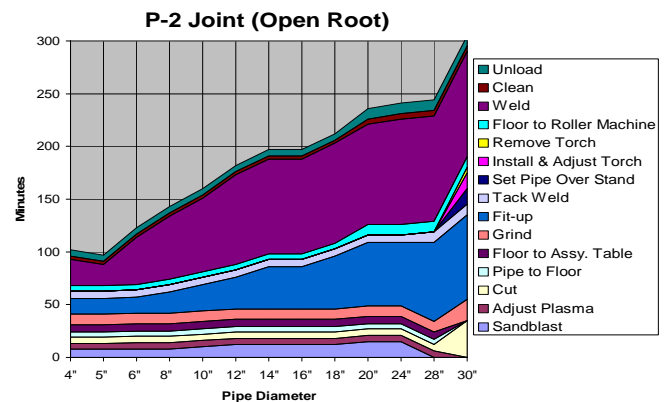


Figure 10. Plot of process times for entire pipe joining process for an “Open Root” joint.

Based on this, successful implementation of a single-pass hybrid weld can be expected to result in dramatic savings in time and

money, as well as a reduction in weld wire consumption, hazardous gaseous process emissions, and total heat input (for decreased distortion). Additionally, reducing the number of weld starts and stops will result in fewer opportunities for defects. Comparing the fusion zones of hybrid<sup>†</sup> and conventional welds, shown in Figure 11, emphasizes these savings.

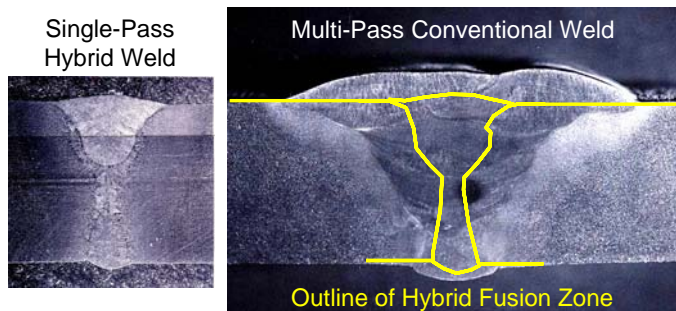


Figure 11. Macrographs comparing fusion zone of single-pass hybrid weld of 12.7 mm (0.500 inch) thick plate vs. a multipass conventional weld.

The study indicates that the money saved by switching to a hybrid welding process would pay for the cost of a hybrid pipe welding system in two years. A single laser can often be utilized to service a variety of welding stations, and this would further improve the return on investment. These potential benefits provide strong justification for developing a joint design and weld parameter selection strategy that are straightforward and that result in a robust manufacturing process. The next sections present experiments designed to provide insight and guidance into these issues, and follow the development of a hybrid pipe welding system through shipyard implementation for pre-production evaluations.

## Experiments

The marriage of laser and GMA welding results in a wide variety of processing parameters which affect the weld quality. Experiments have been conducted to investigate various aspects of the steady state welding process, including joint design (bevel angle and land height), laser-lead vs. GMA torch-lead, laser to GMA torch spacing, travel speed, laser power, GMA wire feed speed, contact tip distance, and shield gas and plasma suppression gas configuration and characteristics. Additional practical aspects of the process, not related to the steady state

<sup>†</sup> Note that “hybrid” welding can be defined in a variety of ways. Throughout this paper, “hybrid” refers to a laser beam weld and GMA weld taking place simultaneously in close proximity. It has been noted in the literature that “hybrid” often refers to laser beam and GMAW wire impinging on the part within 0–2 mm. In many of our experiments, the laser beam led the GMAW wire by 10 mm or more. It was suggested that “tandem welding” may be a better way to refer to welds that use this spacing. Though we have chosen not to use this terminology in this paper, it is a noteworthy distinction. The referenced figure utilizes a 16 mm spacing.

process parameters and specific to pipe welding or the pipe welding system, include air knife configuration (for spatter protection), welding over tack welds, welding with gaps, welding with ceramic backing, and heat management in the overlap (or tie-in) region (including laser power ramping and laser-GMA timing). The results of these experiments are detailed in Reutzel, Kelly, Tressler and Martukanitz (2005) and Reutzel, Kern and Tressler (2006), and are not discussed herein. However, one specific set of experimental results is provided to illustrate the complex interactions involved in bringing together a deep penetration laser keyhole weld with a conventional GMA weld.

This set of experiments investigated the effect of increasing spacing between the laser and the GMAW torch. Cross-sections of the welds are shown in Figure 12. It has been widely reported that a synergistic effect occurs when the two processes are spaced near one another, however in this type of bevelled butt joint additional observations can be made.

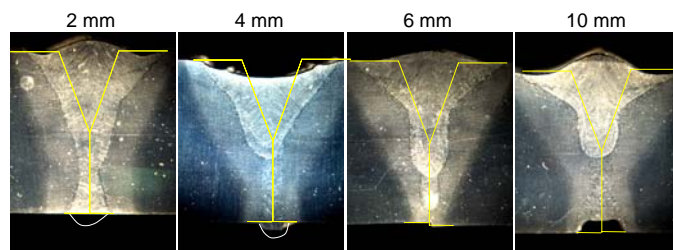


Figure 12. Macroscopic cross-sections illustrate how increasing spacing changes the fusion zone profile [10 mm thick, 5 mm land, 40° included angle, 0.9 m/min (36 ipm) travel speed, 8.9 m/min (350 ipm) WFS].

For this set of processing parameters, at both 2 and 4 mm spacing, it appears that full penetration has been achieved and full mixing throughout the fusion zone has occurred. However, while not completely evident in the cross-sections, significant backside blow-through was present in both cases, resulting in unacceptable weld quality. At slightly more distant spacing, 6 mm, full penetration was not achieved and there appear to be two separate solidification events occurring, as evidenced by the two distinct fusion zones. At still more distant spacing, full penetration is again achieved. However, there are clearly two separate fusion zones, so mixing between the filler material and the laser keyhole melt pool is minimal. Additionally, the same backside undercut is observed as in the autogenous laser welds.

It is believed the reason for these observations is that at near spacing the laser beam must penetrate the base metal *as well as* the additional material provided by the filler wire (which tends to flow slightly ahead of the wire). In this case, the combined process provides enough heat to result in full penetration, albeit accompanied by backside blow-through. As the spacing is increased to 10 mm, the melt puddle formed by the laser *leads* the GMAW puddle, so that no additional material is introduced

to the joint in the region where the laser beam is striking the substrate. This is illustrated in Figure 13.

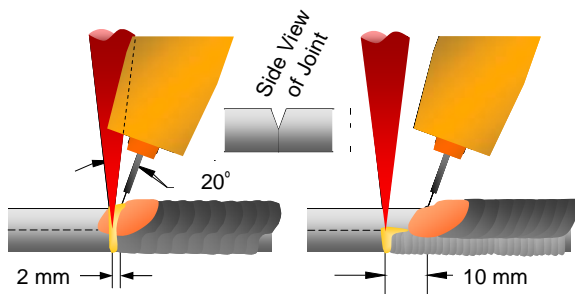


Figure 13. Illustrates how close spacing may cause the laser beam to interact with the GMAW puddle, while increased spacing permits laser to directly irradiate the bottom of the joint.

**Spacing and Travel Speed Effects.** In this set of experiments, both laser-to-GMAW torch spacing and travel speed were varied to observe the effect on fusion zone geometry. In this case, the land height and the joint angle are reduced (3 mm and 12°, respectively). The results are shown in Figure 14.

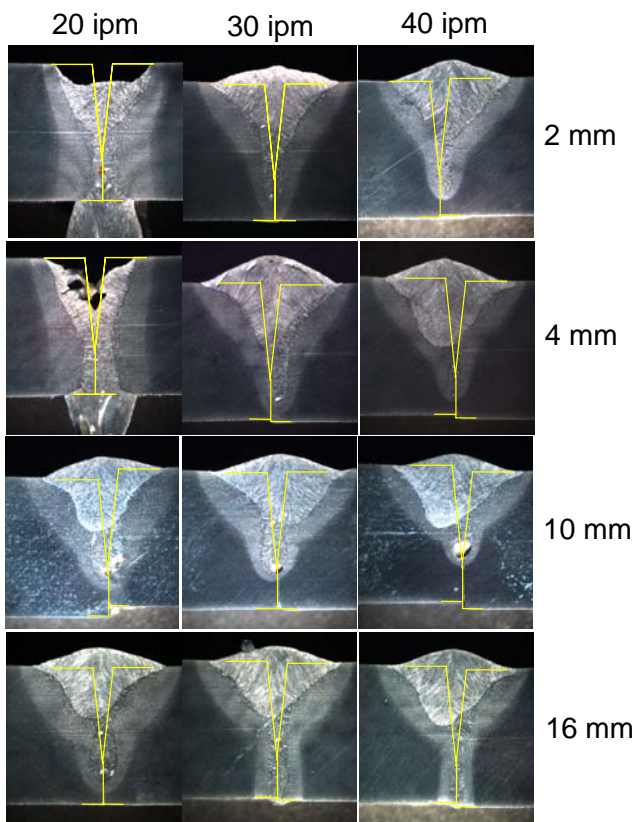


Figure 14. Macroscopic cross-sections illustrate effects of laser-to-GMAW torch spacing and travel speed on fusion zone geometry. [10 mm thick, 3 mm land, 12° included angle, 0.51, 0.76, 1.0 m/min (20, 30, 40 ipm) travel speed, 5.1, 7.6, 8.9 m/min (200, 300, 350 ipm) WFS].

At low travel speed [0.51 m/min (20 ipm)] and near spacing, good mixing is again achieved, but the process is prone to backside blow-through (an unacceptable condition, as backside weld bead geometry is extremely inconsistent). At this travel speed, however, more distant spacing does not lead to full penetration. This seems to indicate that at low travel speed the laser beam interacts with the material introduced by the GMAW process, even at laser-to-GMAW torch spacing up to 16 mm.

As speed is increased with near spacing, the reduced heat flux per unit length prevents full penetration. However, as laser-to-GMAW torch spacing is increased, complete penetration is observed to occur at much higher travel speeds. Additionally, the narrow joint angle has prevented undercut on the backside. This indicates that at higher speeds and distant laser-to-GMAW torch spacing, the laser beam does not interact with material introduced by the GMAW process. Melting of the bevel walls at lower speeds may also influence penetration characteristics.

### Weld Test Results

Based on these experiments and the best available information, a hybrid pipe welding system was constructed, details of which are discussed in the next section. This system was utilized to develop process parameters for the range of pipe wall thicknesses from 6.0 to 12.7 mm (0.237 to 0.500 inch), corresponding to 4 inch SCH-40 to 16 inch SCH-XS pipe. Visual tests, radiographic tests, macro-section evaluations, tensile tests, face-and-root bend tests were conducted in accordance with the qualification requirements of the American Bureau of Shipping (ABS). On 23 March 2007, the weld procedure for 6 inch SCH-40 pipe, with 7.1 mm (0.280 inch) wall thickness, was qualified for use by ABS, the first such qualification of hybrid welding by ABS in the United States. The single-pass weld was performed with a machined square butt pipe edge preparation, i.e. no bevel, at a travel speed of 0.76 m/min (30 ipm) with a 4.5 kW fiber laser, delivered by a 300 micron passive fiber and focused through a 200 mm focal length lens with Ar plasma suppression gas directed above the keyhole, leading the GMA torch by 25 mm, running at 6.4 m/min (250 ipm) WFS in synergic pulse mode with 50 scfh of Ar-10%CO<sub>2</sub> shield gas. Photographs of the outside of a hybrid welded 6 inch SCH-40 pipe joined using the approved procedure is shown in Figure 15, and the inside in Figure 16. Photographs of the mechanical tests are shown in Figure 17.



Figure 15. Photograph of the outside of a hybrid pipe weld produced at GD NASSCO, focused on the overlap region.



Figure 16. Photograph of the inside of the same hybrid pipe weld, illustrating the consistent reinforcement along the inside diameter.

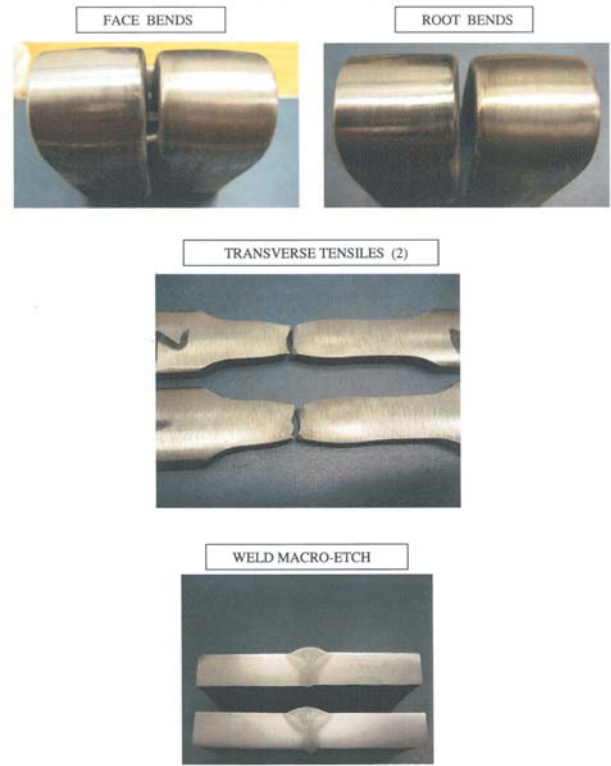


Figure 17. Results of macro-section and mechanical tests of welds for 6 inch SCH-40 pipe [wall thickness of 7.1 mm (0.280 inch)].

The test results are compiled in Table 3, below.

Table 3. Test results for hybrid welding of 6 inch SCH-40 pipe.

Guided Bend Tests					
Specimen No.	Type of Bend	Mandrell Radius {inch}	Specimen Width {inch}	Specimen Thickness {inch}	Result
#1	Root	0.560	1.5	0.280	Accept
#2	Root	0.560	1.5	0.280	Accept
#3	Face	0.560	1.5	0.280	Accept
#4	Face	0.560	1.5	0.280	Accept

Tensile Tests					
Specimen No.	Width {inch}	Thickness {inch}	Ultimate Strength {psi}	Location of Fracture	Result
TR-1	0.749	0.260	74,987	Base Matl	Accept
TR-2	0.749	0.260	73,754	Base Matl	Accept

Weld Macro Tests	
Specimen No.	Result
#1	Accept
#2	Accept

Non-Destructive Tests	
Type	Result
Visual Inspection	Accept
Radiograph	Accept



Radiographic testing was also conducted for the various pipe schedules in accordance with ABS requirements. In most cases, the welds were acceptable, though attempts are ongoing to further reduce porosity throughout, particularly near the overlap region.

These results are indicative of testing that is being undertaken over the entire range of pipe schedules in order to support the generation of Procedure Qualification Records (PQRs) to support weld certification by ABS.

## Hybrid Pipe Welding System Implementation

Though substantial investigation into hybrid laser-GMA weld parameter development was undertaken prior to delivery of the hybrid pipe welding system, it is the system that was used to make the qualified pipe weld above, and it is the system that is currently installed on the shipyard production floor. A system specification was generated to address numerous practical considerations of welding with this new hybrid laser-GMA welding technology in a pipe shop. Critical items that were addressed in the specification include an ability to roll pipe assemblies, with potentially substantial moments as elbows are rotated, while maintaining a tightly controlled rotational velocity in order to maintain weld travel speed, ability to track the joint with high resolution to ensure the laser keyhole fully envelops the joint, ability to specify the laser power ramping and weld tie-in characteristics, ability to store all process parameters for each weld, simple user interface and operation, and others.

Wolf Robotics was selected to design and build the system. The system was delivered to the Applied Research Laboratory at Penn State University for transfer of process parameters developed on plate to pipe, then it was shipped to GD NASSCO shipyard and installed in a custom safety enclosure within their pipe shop. The installation is shown in Figure 18.



Figure 18. Aerial view of the hybrid pipe welding station and the safety enclosure installed in the GD NASSCO pipe shop.

The typical procedure for using the hybrid pipe welding system to join a pipe spool (typically welding pipe to a fitting) is outlined below:

1. Load
  - Remove the previous pipe from the rotary positioner
  - Load the current pipe onto the rotary positioner
  - Check cover glass, clean if necessary
2. Teach Joint
  - Input set-up data at the Wolf Cell Controller, including the serial number
  - Teach weld starting point
  - Finish set-up
3. Weld
  - Weld the pipe
  - Inspect the weld

In each case, after the pipe is loaded into the rotary positioner (overhead crane access is provided for large pipe spools), the operator selects the weld diameter and schedule from the user interface, and the pre-determined welding parameters are loaded into the welding program. The operator must then jog the robot head close enough to the joint for the seam tracking system to register the joint, to serve as the weld starting point (a close-up image of the operator teaching a test joint is shown in Figure 19). Robot safety and laser safety are important considerations, and the system is designed to offer redundant interlocks and user controls to address these concerns. When the operator is safely outside the welding area, the weld can proceed and the operator can watch through a laser-safe window covered with a conventional arc welding curtain. After the robot completes the weld, it moves safely back to a so-called PARK position to enable a crane to off-load the welded spool.



Figure 19. Photograph showing the operator jogging the robot to teach the approximate joint location.

Once hybrid laser-GMA parameters were developed to produce visually acceptable welds on a set of pipe schedules that covered the range of wall thicknesses, a small production run was conducted to provide an initial view into potential production rate. In order to mimic the random order of pipe spools that come through a welding cell in the course of a normal day, the pipes were presented in a pseudo-random order so that the operator was required to re-teach the location of each joint prior to executing the weld. A photograph of the ten welded pipes is provide in Figure 20, and the results of the time study are presented in Table 4.

Note that the time to load, teach, and weld 10 joints averages under 7 minutes per weld. This substantial improvement over conventional techniques can be contributed to the ease in utilizing the system due to the automatic seam tracking, and both the higher travel speeds and reduction in number of passes.



Figure 20. Photograph of pipes joined with a hybrid laser-GMA weld for the small production test run time study.

Table 4. Results of the small production test run time study.

Pipe Dia. {inch}	Pipe Schedule	Load {min:sec:}	Teach Joint {min:sec:}	Weld {min:sec:}
4	40	00:32	05:25	06:35
6	40	11:05	14:15	16:05
4	80	18:30	22:55	24:00
8	40	25:25	29:55	30:35
8	80	33:15	36:55	38:35
4	40	39:50	42:40	44:20
6	40	46:10	49:35	50:55
6	80	52:10	55:10	57:10
8	40	58:00	61:10	62:35
8	80	64:00	67:05	68:40
Total				68 min 40 sec

Not addressed in this initial investigation is the comparison of pipe preparation time. To date, only machined pipe edges have been utilized, straight butt for thinner wall pipes and special

bevels for thicker wall pipes. Portable pipe edge preparation tools are available to perform these machining operations. A cost-benefit analysis that considers any increases in pipe edge preparation time is underway.

## CONCLUSIONS

Quarter inch thick, two by ten foot AB/AH36 steel panels were joined using a hybrid laser arc welding process having a heat input of 15.8 kJ/in. The weld was visually acceptable. The resulting distortion consisted of minor angular distortion and no observable buckling attributed to the welding process. The average out of plane difference before and after welding was  $0.024 \pm 0.029$  inches. The calculated heat input is approximately 71% less than the conventional welding process. Ongoing and future research were presented on hybrid welding for panel line applications targeting plate thicknesses less than 10 mm thick.

A hybrid pipe welding system capable of joining pipe in a single pass was developed, designed, built and implemented at GD NASSCO for pre-production evaluation. Significant effort was spent to determine suitable process parameters, and weld quality sufficient for ABS qualification was produced for pipe schedules ranging from 4 to 10 inch diameter and up to 0.5 inch wall thickness. A series of ten pipes were joined in just over an hour using the hybrid pipe welding system, suggesting substantial savings may be realized if the process proves itself robust in actual production and if joint edge preparation time can be kept in check.

## ACKNOWLEDGEMENTS

The authors would express their sincere gratitude to the following people for their contributions and support: Kevin Carpentier from the Center for Naval Shipbuilding Technology, Ludwig Kern, Jay Tressler, Ed Good, Chris Sills, Bill Rhoads, and Jim McDermott from the Applied Research Laboratory at Penn State, and Juan Avalos, Efren Villa, and Randy Doerksen from General Dynamics NASSCO.

This material is based in part upon work supported by the Office of Naval Research through the Naval Sea Systems Command under contract No. N00024-02-D-6604, Delivery Order No. 0019, and by the Office of Naval Research through the Manufacturing Technology Program's Center for National Shipbuilding Technology (CNST) under Contract No. N00014-03-C-0413, Subcontract No. 2005-352. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect views of the Office of Naval Research or the Naval Sea Systems Command.

## REFERENCES

BUGAREWICZ, M.B., M.S. Thesis, The Pennsylvania State University, 2005.

- ENGSTROM, H., NILSSON, K. and FLINKFELDT, J. (2001) Laser hybrid welding of high strength steels, *Proceedings of the International Congress on Laser and Electro-Optics (ICALEO 2001)*, LIA, Jacksonville, FL, USA, Paper No. 303.
- HUANG, T.D., DONG, P., DeCAN, L.A., AND HARWIG, D.D., "Residual Stresses and Distortion in Lightweight Ship Panel Structures" *Northrop Grumman Technology Review Journal* (2003).
- HUANG, T.D., HARWIG, D.D., DONG, P., DeCAN, L.A., "Engineering and Ship Production Technology for Lightweight Structures" *Northrop Grumman Technology Review Journal* (2005).
- KELLY, S. M., MARTUKANITZ, R.P., MICHALERIS, P., BUGAREWICZ, M., HUANG, T.D., AND KVIDAHL, L., "Low heat input welding for thin steel fabrication" *J. Ship Prod.* 22 (2), 105 (2006).
- KELLY, S.M., MARTUKANITZ, R.P., BUGAREWICZ, M., AND MICHALERIS, P., Low heat input welding for thin steel, Technical Memorandum, No. TM 06-057, Applied Research Laboratory, The Pennsylvania State University, 2006/08/04.
- MASUBUCHI, K, *Analysis of Welded Structures*, Pergammon, 1984, p. 300.
- McPHERSON, N.A., SUAREZ-FERNANDEZ, N., MOON, D.W., TAN, C.P.H., LEE, C.K., BAKER, T.N., "Laser and laser assisted arc welding processes for DH 36 microalloyed steel ship plate" *Science and Technology of Welding & Joining* 10, 460 (2005).
- ONR MANTECH Program, S2073: "Development and Implementation of Hybrid Laser Arc Welding for Shipyards"
- REUTZEL, E.W., KELLY, S.M., TRESSLER, J.F., and MARTUKANITZ, R.P. (2005) Experimental analysis of practical aspects of hybrid welding of thick sections, *Proceedings of the International Congress on Laser and Electro-Optics (ICALEO 2005)*, LIA, Miami, FL, USA, Paper No. 306.
- REUTZEL, E.W., MIKESIC, D.A., TRESSLER, J.F., CRUE, R.A., GWINN, E.A. and SULLIVAN, M.J. (2005) Laser Pipe Welding: Technology Evaluation and Cost Analysis, ARL Penn State Technical Report No. 04-014, Feb 2005 (available at [www.nsrp.org](http://www.nsrp.org)).
- REUTZEL, E.W., KERN, L.A. and TRESSLER, J.F. (2006) Continued experimental analysis of practical aspects of hybrid welding of thick sections, *Proceedings of the International Congress on Laser and Electro-Optics (ICALEO 2006)*, LIA, Scottsdale, AZ, USA, Paper No. 1906.
- STEEN, W.M. and EBOO, M. (1979) Arc augmented laser welding, *Constr. III* (7), pp.332-336.
- STEEN, W.M. (1980) Arc augmented laser processing of materials, *J.Appl.Phys.*, Vol.51, No.11, pp.5636-5641.
- WALZ, C., SEEFELD, T. and SEPOLD, G. (2001) Process stability and design of seam geometry during hybrid welding, *Proceedings of the International Congress on Laser and Electro-Optics (ICALEO 2001)*, LIA, Jacksonville, FL, USA, Paper No.305.