Joining Pipe with the Hybrid Laser-GMAW Process: Weld Test Results and Cost Analysis

BY EDWARD W. REUTZEL, MICHAEL J. SULLIVAN, AND DARLENE A. MIKESIC

If a successful hybrid system is implemented, it is estimated a pipe shop could save $500,000 in production costs annually

Fig. 1 — View of the conventional pipe welding process at General Dynamics NASSCO.

It has been nearly a quarter of a century since researchers first conceived of combining a conventional welding arc with a laser beam in a hybrid process (Refs. 1, 2), but only recently has laser-gas metal arc (GMA) hybrid welding begun to be utilized in industrial applications. Now, hybrid laser-GMA welding is fast making the transition from laboratory to production, in industries as diverse as shipbuilding to automobile manufacturing. Recent work investigating the potential benefit of applying this technology to a shipyard pipe shop suggests that significant cost savings may be realized. This paper presents ongoing efforts to study and evaluate hybrid welding, and to estimate potential cost savings that may be realized in a shipyard pipe welding shop.

Hybrid Laser-GMA Welding

Laser beam welding (LBW) offers high welding speed and deep penetration compared to conventional arc-based joining processes. With recent advances in commercial laser technology, laser suppliers can now deliver dramatically higher power systems in a much smaller package with a tenfold increase in energy efficiency compared to just a few years ago, all at significantly reduced cost. Unfortunately, due to the small spot size typically utilized in LBW, it has had limited success in certain welding applications due to an inability to accommodate gaps and mismatch typically found in industry. 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) characterized by high cooling rates that can result in a loss of ductility with certain materials.

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE
Joining Pipe with the Hybrid Laser-GMAW Process: Weld Test Results and Cost Analysis

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Pennsylvania State University,Applied Research Laboratory,State College,PA,16804

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

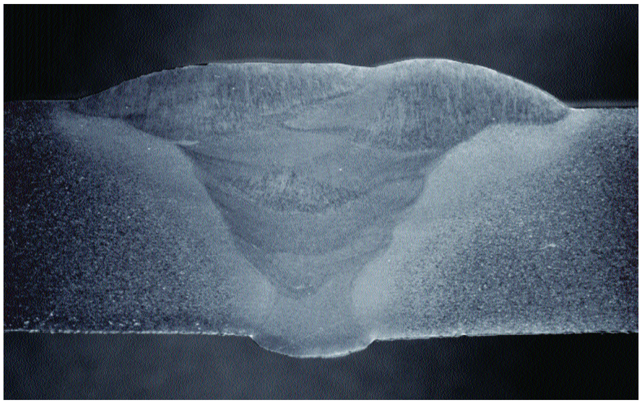

Fig. 2 — *Cross section of conventional multipass pipe weld with 0.50-in. (12.7-mm) thickness.*

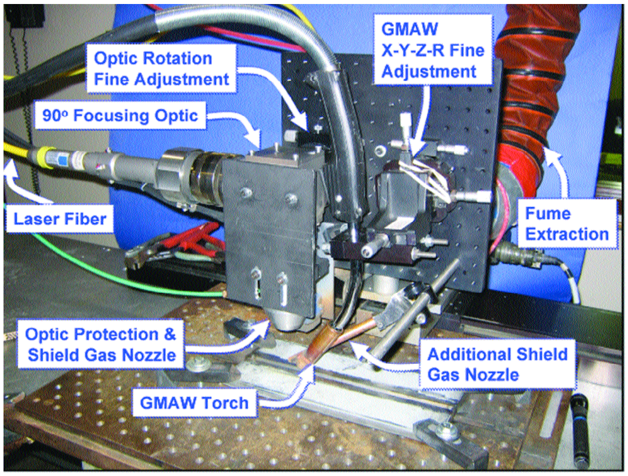

Fig. 3 — Experimental setup used to run experiments at ARL Penn State.

In contrast, conventional GMAW offers the ability to easily bridge gaps in the joint because of the diffuse heat source and the introduction of filler metal to the process. The composition of the filler materials can be customized to produce improved material properties. The additional heat generated by the process results in reduced cooling rates, which can lead to improved ductility. However, the nature of the process prevents deep penetration welds. As a result, joining 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 (Ref. 3), but it has also been shown to enable operation at even greater welding speeds and to provide an improved weld microstructure upon cooling (Ref. 4). 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, which can lead to the added benefit of reduced thermal-mechanical distortion. For these reasons, shipyards in the U.S. are showing growing interest in hybrid laser-GMA welding technology.

Hybrid Laser-GMA for Joining Pipe

Welding of pipe represents a significant cost in the construction of tankers and other ships. Though much welding of pipe must occur on board the ship, as much pipe as possible is rolled in the pipe shop and manually welded in the downhand position. Figure 1 illustrates a current joining technique employed at General Dynamics NASSCO. In the figure, the pipe is fixtured to a rotary positioner that rotates the pipe beneath the arc weld torch. The weld head is manually manipulated by the operator.

At NASSCO, the steel pipe ranges in thickness from 0.237 to 0.50 in. (6.0–12.7 mm), corresponding to 4-in. SCH-40 through 30-in. SCH-XS pipe. For the thicker sections, producing an adequate joint requires the execution of multiple weld passes, with up to five passes required for thicker sections. Typical travel speed for these welds is 5–10 in./min (0.13–0.25 m/min). Figure 2 shows a cross section of a typical multipass weld to join 0.50-in. (12.7-mm) -thick pipe.

NASSCO desired a cost-effective alternative welding technology that can join pipe in a single pass. Details of the experiments and cost analysis developed to support this effort follow.

Development of Hybrid Laser-GMA Welding Process

Experimental Objective

A series of experiments were conducted at the Applied Research Laboratory, Pennsylvania State University (ARL Penn State) to investigate the effects of varying joint design and hybrid laser-GMA welding process parameters on weld characteristics. Specifically, the effect of changing bevel angle and land height on the fusion zone geometry were investigated, as well as the effects of travel speed and laser-to-GMA welding head spacing[1]. A portion of the hybrid welded joints were subjected to mechanical and radiological tests. Finally, practical aspects of hybrid welding, such as welding over tack welds, overlap of weld start and stop (required for circumferential pipe welds), and root opening tolerance were also investigated.

Experimental Plan

A series of hybrid welds were performed using a combination of a Trumpf HLD4506 diode-pumped 4.5-kW Nd:YAG laser and a Lincoln PowerWave 455 STT GMAW power supply operated in constant voltage mode. Figure 3 shows the setup used to conduct the experiments at ARL Penn State. It should be noted that fully integrated hybrid welding heads are available from a variety of commercial vendors, but were not used for this project since the ability to easily and accurately modify processing conditions (such as separation distances and angles of the two processes) were of particular importance in this evaluation.

The welds were performed on mild steel butt joints (A36) using 70S-6 filler metal at a diameter of 0.045 in. (1.1 mm). In general, Ar-10% CO_2 shield gas was supplied through the GMAW welding head, though at larger laser-to-GMAW head separations an additional gas nozzle directed N_2 gas at the laser keyhole for plasma suppression and supplemental shielding. Experiments were performed

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[1] Note that "hybrid" welding can be defined in different ways. Throughout this paper, hybrid is meant to refer 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 (0.0–0.08 in.). In many of our experiments, the laser beam led the GMAW wire by 10 mm (0.39 in.) 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.

Table 1 — Evaluated Joint Geometries

Thickness	Lan Height	Included Bevel Angle
0.25 in. (6.4 mm)	0.0 in. (0.0 mm)	N/A
0.39 in. (10.0 mm)	0.12 in. (3.0 mm)	12 deg
0.39 in. (10.0 mm)	0.20 in. (5.0 mm)	20 deg
0.39 in. (10.0 mm)	0.20 in. (5.0 mm)	40 deg
0.39 in. (10.0 mm)	0.20 in. (5.0 mm)	60 deg
0.50 in. (12.7 mm)	0.35 in. (8.8 mm)	90 deg

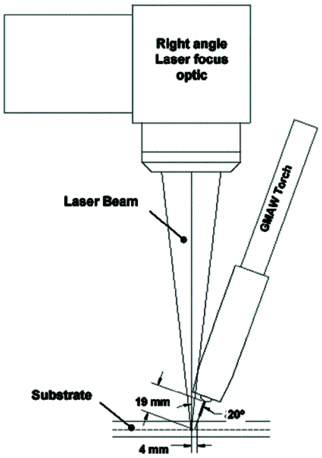

Fig. 6 — Sketch shows the hybrid configuration and the definition of laser-to-GMAW head spacing (note that the GMAW gas nozzle is modified to prevent clipping of the laser beam).

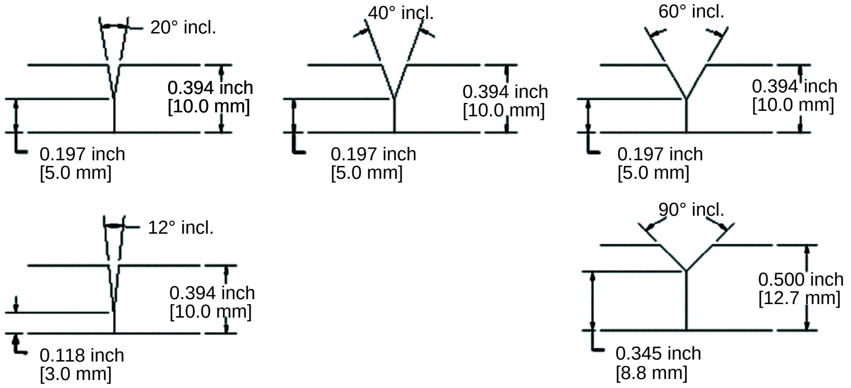

Fig. 4 — Joint configurations employed in this work.

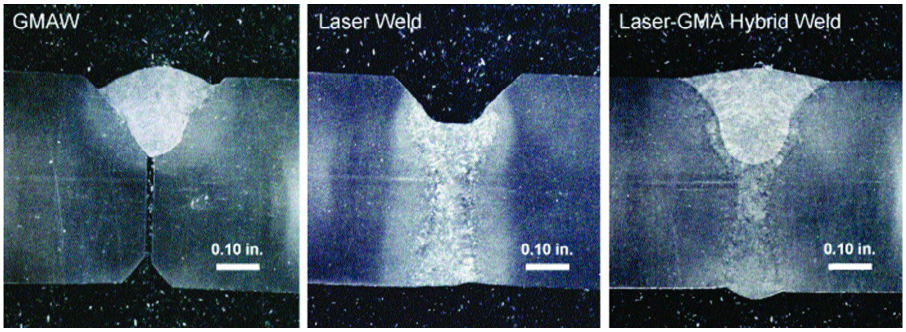

Fig. 5 — Three welds, 0.50-in. (12.7-mm) thick ASTM A-36/ABS Grade A steel plate, butt joint with 0.35-in. (8.8 mm) land and beveled with a 90-deg included angle and with an ⅛-in. (3.2-mm) chamfer at the root.

on a variety of butt joint configurations to investigate potential effects of variations in bevel angle and land height (Table 1 and Fig. 4). Figure 5 shows representative cross sections of welds made by the GMA, laser, and hybrid processes that were performed as part of the testing. The welds are shown side-by-side for comparison.

The schematic in Fig. 6 illustrates the configuration of the laser and GMAW welding head. In all experiments, the laser focus spot at the bottom of the joint, and the contact-tip-to-workpiece-distance (CTWD), measured from the bottom of the joint as shown, were held constant and the laser-to-GMAW head spacing was varied to observe its effect on process robustness, fusion zone geometry, and weld quality. Both laser-leading and GMA-leading configurations were investigated.

Experimental Results

A large number of processing parameters are available to affect the joining process when the LBW and GMAW processes are combined. Results of some experiments to investigate these complex relationships are presented below.

Effects of Laser-to-GMAW Head Spacing and Travel Speed

In a typical set of experiments, both laser-to-GMAW head spacing and travel speed were varied to observe the effect on fusion zone geometry — Fig. 7. In this case the thickness, land height, and included joint angle are 10 mm (0.39 in.), 3 mm (0.12 in.), and 12 deg, respectively. As travel speed is increased, the wire feed speed (WFS) is increased proportionally to maintain constant weld bead cross-sectional area, and voltage is varied accordingly. It has been widely reported that a synergistic effect occurs when the two processes are spaced near one another; however, as spacing is increased with this type of beveled butt joint, additional observations can be made.

For 20 in./min (0.5 m/min) travel speed, at both 2- and 4-mm (0.08- and 0.16-in.) spacing it appears that full penetration has been achieved and full mixing of the filler and base metals throughout the fusion zone has occurred. However, as is evident in the cross sections, significant backside melt-through was present in both cases resulting in unacceptable weld quality. A slight increase in spacing led to incomplete penetration, and there appear to be two separate solidification events as evidenced by the two distinct fusion zones.

As travel speed increases with close spacing, it appears that the reduced heat input per unit length prevents full pene-

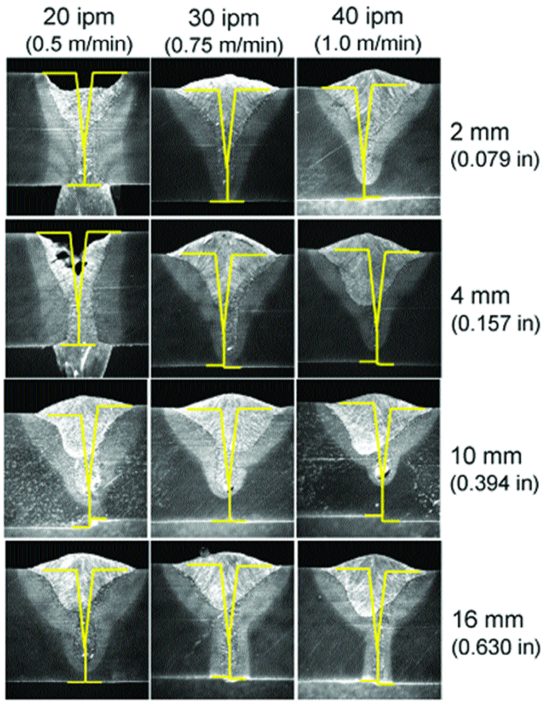

Fig. 7 — Macroscopic cross-sections illustrate effects of laser-to-GMAW head spacing and travel speed on fusion zone geometry.

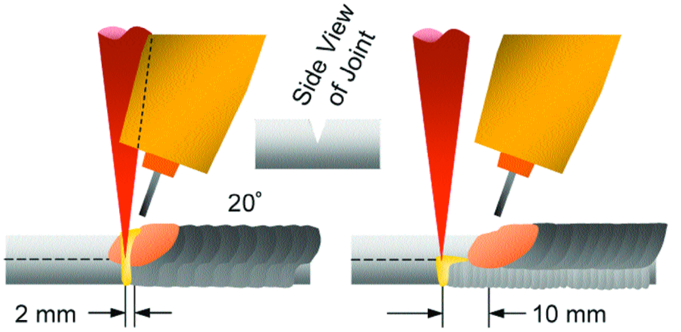

Fig. 8 — Illustrates how close spacing may cause the laser beam to interact with the GMAW pool, while increased spacing permits laser to directly irradiate the bottom of the joint.

tration. However, as laser-to-GMAW head spacing is increased to 16 mm (0.63 in.), complete joint penetration is observed to occur at much higher speeds. This seems to indicate that at higher speeds and greater laser-to-GMAW head spacing, the laser beam does not interact with the arc nor the material introduced by the GMAW process. In a separate experiment, autogenous laser welds achieved full penetration at both 30 and 40 in./min travel speed with no melting of the bevel side walls. Data at 20 in./min travel speed was not available; however, at 15 in./min full penetration was not achieved, seemingly due to melting of the bevel sidewalls, which absorbed energy and filled the joint with material.

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 molten material provided by the welding wire (which tends to flow slightly ahead of the wire). In this case, at slow travel speeds the combined process provides enough heat to result in full joint penetration, albeit accompanied by backside melt-through and unacceptable weld quality. As the spacing is increased to 10 mm (0.39 in.), the laser leads the GMAW weld pool by enough distance such that the laser beam irradiates the substrate directly, i.e., it no longer has to penetrate the molten weld pool (fed by the GMAW wire) that is filling the joint. This is illustrated in Fig. 8. It is noted that application of higher power laser systems may result in different operational regimes and trends at this thickness.

Other Observations

In addition to investigating the affects of laser-to-welding head spacing vs. travel speed, several other parameter interactions were studied. It was demonstrated that at these conditions with close spacing, the weld is very intolerant to small variations in travel speed, i.e. a 10% change in speed can result in either catastrophic blow-through or incomplete penetration. Experiments with larger separation, up to 16 mm (0.63 in.), perhaps more appropriately termed a tandem rather than hybrid weld, indicate that while interactions directly between the laser and arc are eliminated, the laser keyhole can provide full penetration of the land, and the added heat provided by the leading laser appears to help ensure complete sidewall fusion in narrow grooves. Additionally, experiments reveal that, given appropriate control of process parameters, hybrid laser-GMA welding can provide adequate penetration in practical aspects of pipe welding, such as welding through tack welds and weld overlap (Ref. 5).

Testing of Hybrid Laser-GMA Welded Joints

Through experimentation, a set of hybrid laser-GMAW processing conditions was found for welding 0.50-in. (12.7-mm) -thick A36 steel that produced a visually acceptable weld. The weld produced full penetration, desirable reinforcement on the top and bottom surfaces, and demonstrated an ability to compensate for some degree of weld joint misalignment — Fig. 9.

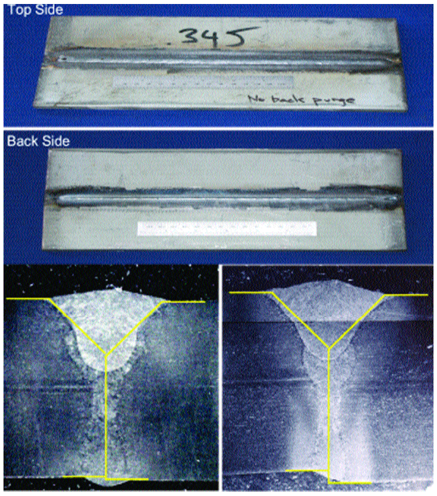

Fig. 9 — Hybrid welds used for mechanical and radiographic testing. Parameters are 0.5-in. (12.7-mm) -thick plate, 0.345 in. (8.8 mm) land, 90 deg included angle, 16 mm (0.63 in.) spacing, 10 in./min (0.25 m/min) travel speed, 200 in./min (5.1 m/min) wire feed speed.

Several of these welded samples were sent to a certified lab to undergo reduced-section tensile and bend testing (both face and root) according to ASME Section IX of the *Pressure Vessel Code* — Fig. 10. All tensile and bend tests passed. In all tensile tests, the failures occurred outside the weld heat-affected zone, indicating acceptable mechanical properties.

The welds were also subjected to radiographic testing in accordance with ASME Section IX — Fig. 11. Though the majority of the weld is porosity free, these

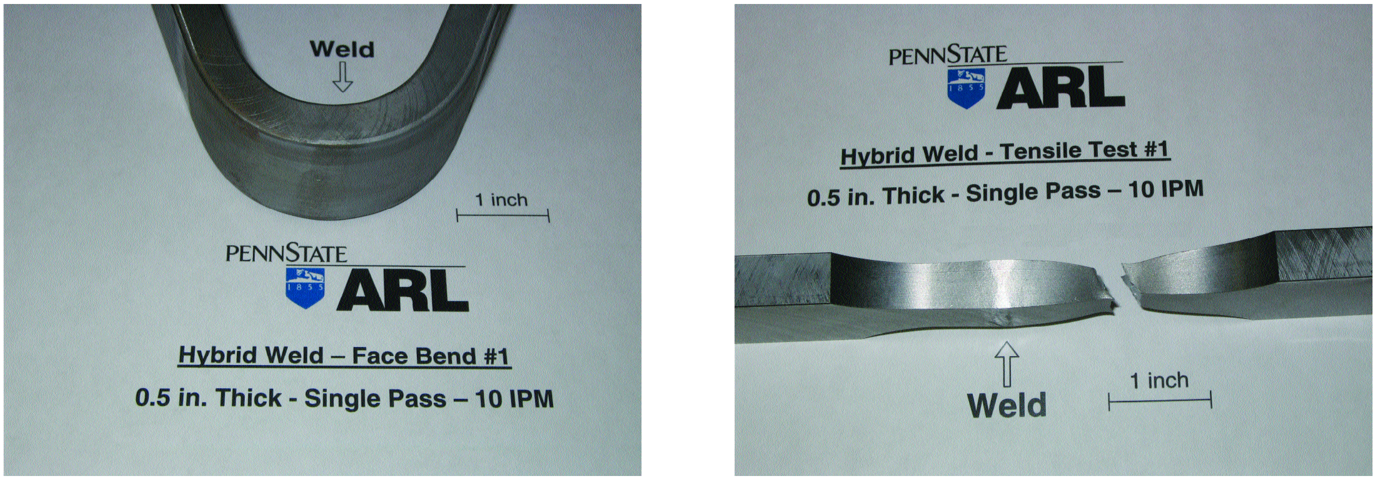

Fig. 10 — Mechanical testing of hybrid weld in 0.5-in.-thick mild steel indicated adequate mechanical properties.

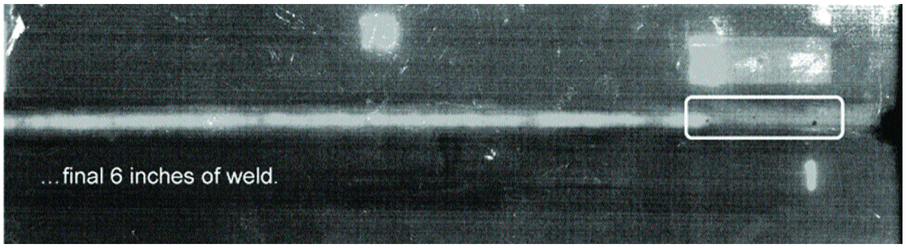

Fig. 11 — Radiographic testing of hybrid weld in 0.50-in. (12.7-mm) -thick mild steel reveals a small amount of porosity confined to regions near the end of the weld.

tests revealed a small degree of porosity near the beginning and end of the weld. Laser beam keyhole instability may be the cause. Ongoing investigations are being undertaken to determine the cause of this porosity and to eliminate it.

Based on the results of these tests, it is likely that with additional process optimization, porosity will be eliminated and hybrid welding can soon be successfully qualified for use in steel pipe welding in thicknesses up to 0.50 in. (12.7 mm).

Cost Analysis

To help determine potential savings in converting from conventional joining processes to a single-pass hybrid weld, a detailed study was undertaken to assess current practice in the shipyard (Ref. 6). 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 a P-2 open root joint over a range of pipe diameters is shown in Fig. 12. It was determined that for the P-2 joint the total process time is 102 min for 4-in. pipe, and up to 270 min for 30-in. pipe. The multipass conventional weld portion of the process contributes significantly to this time.

Based on this data, 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 welding wire consumption, hazardous fume emissions, and reduced total heat input for decreased distortion. Additionally, reducing the number of weld starts and stops and the total linear weld length provides fewer opportunities for defects. Comparing the fusion zones of hybrid and conventional welds, shown in Fig. 13, emphasizes these savings.

To evaluate cost effectiveness of the hybrid laser-GMAW process, time and material savings were calculated using the best available data. The analysis indicates that, for the same quantity of pipe welds, hybrid welding would require less than 600 man-hours annually vs. nearly 8500 man-hours annually using conventional multiple weld pass methods. The resultant annual savings are estimated to be $286,000 based on industry standard rates. An additional cost saving that was considered is the reduction in filler material consumption. The change in weld volume for GMAW/FCAW butt joint weld designs compared to these nonoptimized hybrid weld joint designs decreased welding wire consumption from more than 46,000 lb to less than 7000 lb, and is estimated to save $218,000 annually. Another factor that is considered is the daily consumable costs for such items as gas shielding cups and contact tips. Other consumables have been estimated at 10% of the yearly material costs. Reductions in weld fume emissions that are hazardous to workers and harmful to the environment are not considered, but are expected to be significant.

Summary

Experiments were conducted that demonstrated the ability of existing commercially available hybrid welding technology to weld up to 0.50-in. (12.7-mm) -thick ASTM A-36/ABS Grade A steel plate (similar in chemistry to A-53 pipe material) in a single pass. A portion of the welds were subjected to nondestructive radiographic testing (RT) and tensile and bend testing in accordance with Section IX of the ASME *Pressure Vessel Code*. Not all welds passed the RT test due to porosity near the start and end of the weld; however, it is believed that further process optimization will enable weld porosity to be eliminated. All welds passed tensile and bend tests, with all tensile failures occurring in the base material. Additional ongoing development of laser-GMAW is providing insight into the process that will aid in transitioning the technology into industrial applications.

Detailed time studies over an 11 week period at an actual pipe shop coupled with the welding data gathered during the project indicate that annual cost savings could be significant. Based on average industry rates, it is estimated that shipyards have the potential to generate more than $500,000 in annual operational cost savings should they implement a hybrid-GMA pipe welding system.

Other Applications for Hybrid Laser-GMA Welding

This investigation represents just one of many efforts worldwide to use high power laser-GMA hybrid welding for joining of

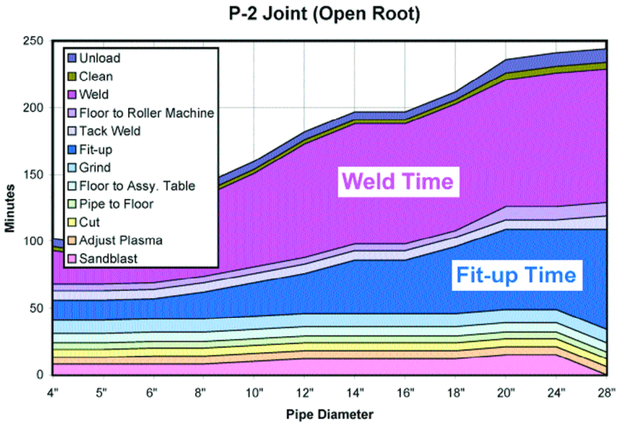

Fig. 12 — Plot of process times for entire conventional pipe joining process for P-2 open root joint.

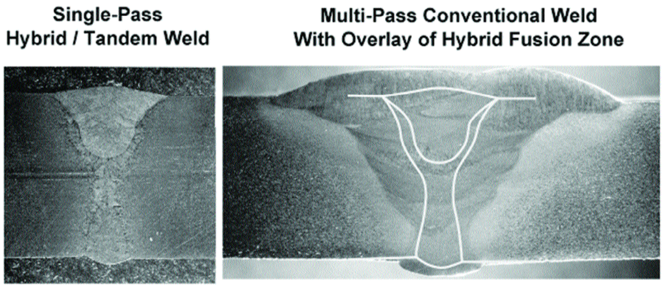

Fig. 13 — Macrosections comparing fusion zone of single-pass hybrid weld of 0.50-in. (12.7-mm) -thick plate vs. a multipass conventional weld.

thick sections in industrial applications.

In 1999, Meyer Werft shipyard in Papenburg, Germany, began investigating the potential to use high-power CO_2 laser-GMA welding for joining operations on their prefabricated deck panels and sidewalls. After a comprehensive test program, high-power laser-GMA hybrid welding was implemented in 2002 to join thick sections (Ref. 7). Around this same time, the domestic energy pipeline industry commissioned studies of hybrid laser-GMAW for pipeline girth welding (Ref. 8). This has been complemented by other pipeline investigations from research groups at Cranfield University, the University of Cambridge, TWI Ltd, the Bremen Institut für Angewandte Strahltechnik (BIAS), and others. The U.S. Navy is also taking interest, with ongoing investigations conducted at ARL Penn State and elsewhere to apply hybrid welding in a number of applications, such as reducing distortion in thin steel construction (Ref. 9). Recent efforts are directed at developing hybrid welding of the tee sections that serve as safety line tracks on submarines, and are soon expected to obtain U.S. Navy approval.

Though certainly not a comprehensive list of thick-section hybrid welding activities, they add to the evidence gathered in the present development effort in underlining the potential that industry and government see for this technology to generate substantial economic benefit. Continuing rapid improvements in high-power laser technology, and associated reductions in cost and size, will only serve to hasten the widespread industrial acceptance of high-power hybrid laser-GMA welding.

Acknowledgments

The authors gratefully acknowledge and thank Jay Tressler, Ed Good, Rob Crue, and Amish Shah of the ARL-PSU Laser Processing Division, who all contributed substantially to generating the data used in this study. Additional thanks go to Richard Martukanitz, Shawn Kelly, and James McDermott for many enlightening technical discussions. Finally, acknowledgment is given to the General Dynamics NASSCO for providing guidance, support, and several of the images used herein.

This material is based upon work supported by the National Shipbuilding Research Program, SP-7 Welding Committee and by the Office of Naval Research through the Center for National Shipbuilding Technology (CNST) under Contract No. N00014-03-C-0413, Subcontract No. 2005-352. CNST is administered by ATI, Charleston, S.C. 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.

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