

# EXPERIENCE WITH SHIPYARD INSTALLATION OF A HYBRID PIPE WELDING SYSTEM

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## Abstract

Laser-Gas Metal Arc (GMA) hybrid welding is fast making the transition from laboratory to production, in industries as diverse as shipbuilding to automobile manufacture. For the past 3 years, our team has striven to both develop a hybrid welding process for steel pipe, and to specify, build, and install a hybrid pipe welding system in a General Dynamics NASSCO shipyard. In March 2007, the system was successfully installed into the shipyard. This work presents a summary of our continued experimental explorations into various practical aspects of hybrid welding, discusses the system design, and provides an overview of the installation of the system into the shipyard. Test results are presented, as well as lessons learned throughout the project.

## 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 [1,2], but only recently has laser-GMA hybrid welding begun to be utilized in industrial applications. Hybrid laser-GMA welding has demonstrated an ability overcome some of the shortcomings both of standalone laser welding, such as lack of filler wire addition for reinforcement, and of standalone GMA welding processes, such as inability to achieve full penetration in thick sections. One of the benefits of the process is that the reduced heat required for joining plate using hybrid laser-GMA welding has shown to be beneficial in reducing distortion in panel welds and fillet welds, thus reducing overall production costs through reduction in any required post process distortion correction [3]. Hybrid laser-GMA welding can also reduce costs simply by reducing the number of required welding passes necessary to join thick sections, such as pipe commonly used in ship piping systems [4].

In December 2004, a project to develop and implement a hybrid laser-GMA pipe welding system was initiated. Throughout the development of the processing parameters and the system design, interim results have been presented through various conference and publications [5,6]. In March 2007, the final system

was delivered to General Dynamics NASSCO shipyard for use in their pipe welding shop. This paper discusses results of recent experiments to optimize process parameter experiments, and discusses some of the details of the final system as well as lessons learned during implementation for production.

## 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 1 illustrates a current joining technique employed at the National Steel and Shipbuilding Company (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 1. Photograph of the conventional pipe welding process.**

Producing an adequate joint requires the execution of multiple weld passes. Figure 2 shows a cross section of a conventional multiple-pass weld.

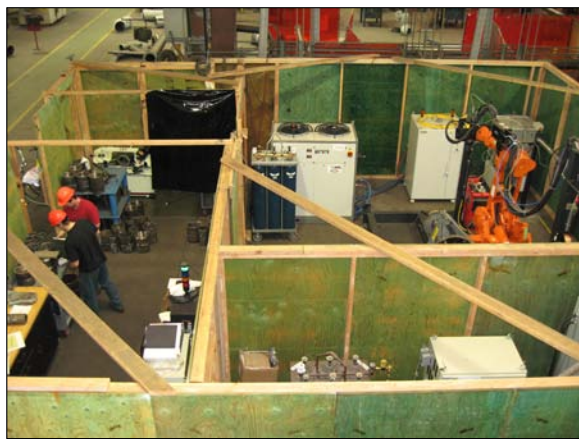


**Figure 2. Cross section of conventional multipass pipe weld with 12.7 mm (0.5 in) thickness.**

There are a number of advantages if a single-pass hybrid weld can be used for this application. Reducing the number of weld starts and stops results in fewer opportunities for defects. An automated hybrid process also promises more consistency by reducing process variation. In addition to potential improvements in weld quality and consistency, a single-pass hybrid welding process could also yield significant time and cost savings. Joining pipes using conventional GMA pipe welding requires 2–7 passes at 5–10 ipm weld travel speed. A single-pass hybrid weld at increased travel speed, say 30 ipm, promises to deliver significantly faster processing times, joining the pipe between 6 and 42 times faster, along with the attendant reduction in production costs.

### Hybrid Pipe Welding System Implementation

To realize these savings, detailed system specifications were drawn up for a hybrid pipe welding system capable of joining many of the pipe spools (or pipe assemblies) that are currently joined in the pipe shop with a semi-permanent plywood enclosure. Wolf Robotics design was selected and they integrated the system, which is shown installed at GD NASSCO in Figure 3. The figure shows a bird's eye view of the system installed in the pipe shop; the operator area and pipe preparation and staging area are on the left side, the robot welding area is on the top-right, and additional storage is on the bottom-right. Note that the ceiling was intentionally left off and entryways do not have headers in order to accommodate overhead crane access for positioning large pipe spools.



**Figure 3. Bird's eye view of the hybrid pipe welding system installed in GD NASSCO's pipe shop.**

The integrated system includes a 7 kW IPG Photonics fiber laser (YLR-7000), a Fronius pulsed synergic GMAW power supply (Transpulse Synergic 50000MV 500A supply with integrated FK 4000 cooling unit), an

ABB 6-axis articulated arm robot (IRB 4400 with M2000 robot controller) coupled to a large rotary positioner serving as the 7<sup>th</sup> robot axis, a ServoRobot seam tracking system (Rafal-SSO 3-d laser vision camera coupled with a Pilot-LW control box linked to both y- and z-axis linear stages with 30mm stroke), and the customized Wolf Cell Controller, to provide an easy-to-use user interface and communications and control of all system components.

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 specify and store all process parameters for each weld, simple user interface and operation, and others.

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 4). 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 4. Photograph showing the operator jogging the robot to teach the approximate joint location.**

### Process Parameter Experiments

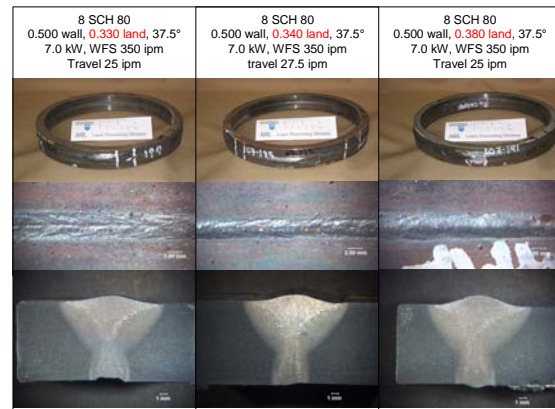
Substantial effort to develop hybrid welding process parameters for various thicknesses of flat steel plate was undertaken prior to completion of the hybrid pipe welding system. However, once the pipe welding system was available, additional process parameter evaluations on pipe were required to help ensure a robust process and to learn of other process variations by the transition from welding plate to pipe. A portion of the more important experimental results are presented below.

Unless otherwise noted, in all experiments the weld was performed in a 1G horizontal rolled position. The seam tracker was 25 mm ahead of the 200 mm focal length laser beam, which was 25 mm ahead of the GMAW torch.<sup>1</sup> The laser impinged the pipe 35 mm ahead of top-dead-center, in order to produce a flatter and smoother topside reinforcement. Additionally, the pipes were fit and tack welded with 20–25 mm long autogenous GTAW tack welds, i.e. without filler wire addition, in order to ensure a consistent volume of material for the laser penetration. The pipe was

<sup>1</sup> Separating the laser-to-GMAW torch, as in subject configuration, is sometimes referred to as tandem laser-GMA welding rather than hybrid laser-GMA welding, and enables the use of an argon plasma suppression nozzle without detrimental affect to the GMAW shielding gas.

specified according to ASTM A53, the GMAW filler wire was 1.1 mm (0.045 inch) diameter ER70S-6, and the GMAW shield gas was Ar-10%CO<sub>2</sub>. The pipe diameter and wall thickness, i.e. pipe schedule, are noted, and two 150 mm (6 inch) lengths were joined for the experiments (though only a 25 mm wide section cut around the weld is shown).

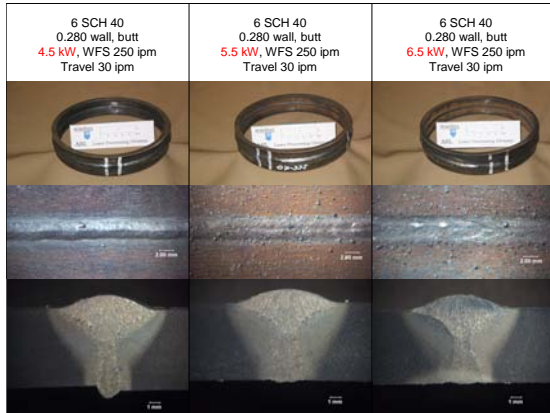
In the first experiment, involving 8 inch SCH 80 pipe, substantially the same processing conditions and joint bevel angle were used in each case, and variation in land height was investigated. All three land heights produced acceptable topside and bottomsides weld beads, though the small land height exhibits slight undesirable undercut at the root. This is because the vapor keyhole has fully penetrated, resulting in expulsion of molten material through the root into the inside of the pipe. In contrast, the larger land heights produce excellent rootside reinforcement, and though full penetration is achieved, seemingly the vapor keyhole does not fully penetrate and so surface tension forces act to maintain the rootside reinforcement -- the vapor keyhole does not cause material expulsion through the root. In the case of small land height, the laser energy per unit volume seemingly exceeds that required to melt the volume of material that must be melted to achieve full penetration.



**Figure 5. Investigation of varying land height. The welded pipe is shown, with close-ups of the rootside reinforcement and macro sections.**

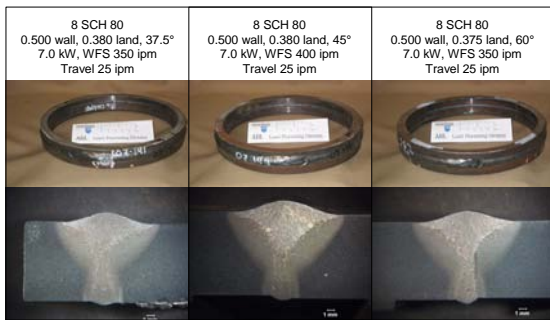
In the second experiment, involving 6 inch SCH 40 pipe, the same processing conditions and joint geometry were used in each case, and variation in laser power was investigated. Again, all three exhibit acceptable topside and rootside reinforcement, but the two higher power conditions result in slight undesirable undercut at the root. This is again caused by full penetration of the vapor keyhole and expulsion of material through the root. Evidence of this is readily observable in the form of small beads of metal which come from the opposite side of the pipe interior.

Again, the laser energy seems to be higher than necessary to melt the correct amount of material. These last two experiments suggest that a simple way to ensure a robust process would be “overpowering” the process, i.e. providing more laser energy than is necessary to melt just the minimum amount of material to achieve full penetration. It is likely that this may not be the case for other alloy systems.



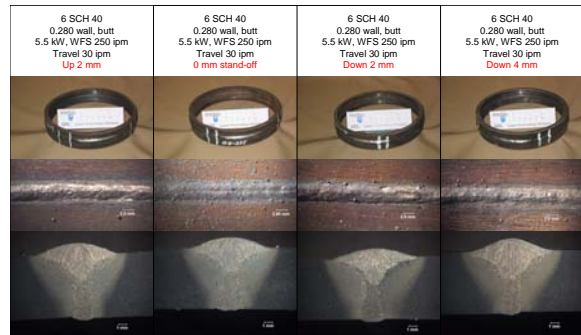
**Figure 6. Investigation of varying laser power. The welded pipe is shown, with close-ups of the rootside reinforcement and macro sections.**

In the third experiment, involving 8 inch SCH 80 pipe, substantially the same processing conditions and land height were used in each case, but the bevel angle was varied. In past work, variations in bevel angle have been known to occasionally result in changing melt characteristics, e.g. melting of the bevel sidewall, with attendant variability in penetration characteristics. Additionally, wider bevels will require additional material to adequately fill the joint. Given this, it is unexpected that all three bevel angles produce comparable, high quality weld beads, though that is what is observed in this case. This is likely due to the relatively small proportion of the bevel relative to the overall wall thickness, so that the fill volume varies little with respect to the volume of the added filler material.



**Figure 7. Investigation of varying bevel angle. The welded pipe is shown, with macro sections.**

In the fourth experiment, involving 6 inch SCH 40 pipe, the same processing conditions and joint geometry were used in each case, but the laser stand-off was varied. The nominal stand-off places the focal point of the beam squarely at the surface of the pipe (or on the bottom of the bevel, when bevels are used in thick wall pipe). In this case, when beam irradiance is at a maximum at the surface, full penetration of the vapour keyhole and resultant material expulsion is evident in the backside reinforcement. However, taking the laser beam slightly out of focus seems to reduce the irradiance such that full vapour keyhole penetration is not realized, with the resultant improved rootside reinforcement geometry.



**Figure 8. Investigation of varying laser stand-off. The welded pipe is shown, along with close-ups of backside reinforcement and macro sections.**

### Process Gas Management

Management of process gases is an important part of developing a practical hybrid welding system and refers to the gas and air knives, jets, and nozzles used to control the gas, plasma, and spatter generated during the welding process. These gases must not negatively impact the GMAW shielding gas, which provides numerous functions required for adequate weld bead quality, and cannot be substantially disturbed. The effectiveness of the design is evaluated based on its ability to perform two main functions: plasma suppression and spatter control.

### Plasma Suppression

A primary function of the gas management design is to suppress the plasma and gas plumes that are formed in the keyhole during laser welding. The plasma and gas plumes are generally directed by the keyhole directly along the laser beam path. This plasma absorbs and refracts the laser energy, and can result in substantial losses in the amount of laser energy available for welding, leading to a reduction in weld penetration. Plasma suppression gas has long been utilized for CO<sub>2</sub> laser beams, which operate at 10.6 μm in the far

infrared portion of the electromagnetic spectrum and are known to be strongly absorbed in plasma. However, historically plasma suppression for lasers operating at 3 kW or less in the near infrared, i.e. Nd:YAG at 1062 nm, is often not considered important, since absorption by the plasma at the shorter wavelength is much reduced. However, we found that at the high powers provided by the 7 kW fiber laser, plasma suppression at these wavelengths did produce a noticeable increase in penetration.

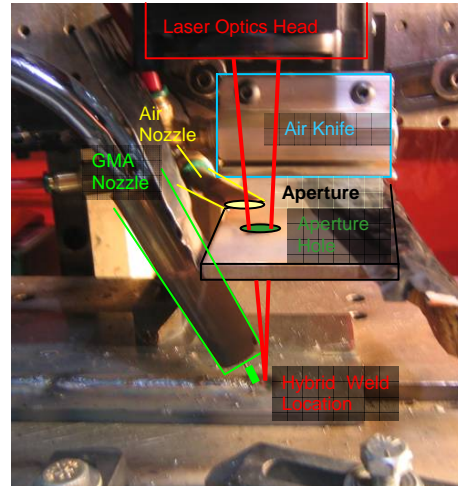
To limit effects of the energy-absorbing plasma plume the plasma suppression gas should incorporate an element to blow the plasma and gas plumes out of the path of the laser beam. This element should be close to the work piece to limit the size of the plasma and gas plumes, as shorter plasma and gas plumes will absorb less laser energy. It is also important that this element use a gas which is not conducive to plasma formation and which does not have negative effects on the weld quality such as oxidation or porosity. A simple solution, implemented in the plasma suppression design used in this hybrid welding system, is a gas nozzle or jet aimed roughly perpendicular to the plasma and gas plumes a short distance above the work piece, utilizing argon gas (with high ionization potential), and aimed so as not to disturb the GMAW shield gas.

### Spatter Control

The second function of the gas management system is to protect the laser optics from being damaged by the spatter produced during the welding process. The laser optics are protected by a cover glass but if spatter sticks to the cover glass, the laser beam will heat the spatter until the cover glass is damaged and must be replaced. Frequent replacement of cover glasses can be costly, but a ruined cover glass during a weld will likely result in an unacceptable weld, wasting both time and material. For these reasons it is important that the spatter control system limit the amount of weld spatter reaching the laser optics.

### Gas Management Experiments

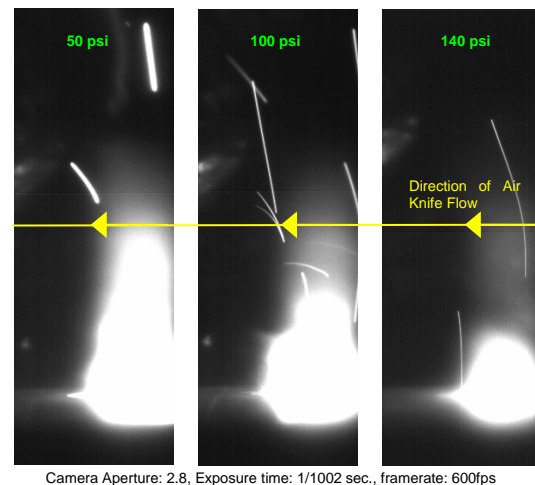
Several elements may be used in a spatter control design to prevent damage to the laser optics. Air knives, nozzles, and jets are used to deflect the trajectory of the spatter away from the optics. Also, one or multiple apertures may be used to keep a majority of the spatter from coming near the optics. Figure 9 shows one example of such a set up using a simple aperture made by drilling a 0.25 inch aluminium plate, an air knife, and a nozzle made by flattening a copper tube. In this photograph, the air nozzle and air knife air directed toward the observer.



**Figure 9. Experimental setup for evaluation of gas management designs.**

A series of experiments were conducted using the basic gas management design shown in Figure 9 varying the positioning of the air knife, using nozzles above, below, or above and below the aperture, and varying the air pressure to each element. A Mikrotron 1302 high speed digital camera, viewing the processing area from the right side of the figure, was used to record the performance of each configuration.

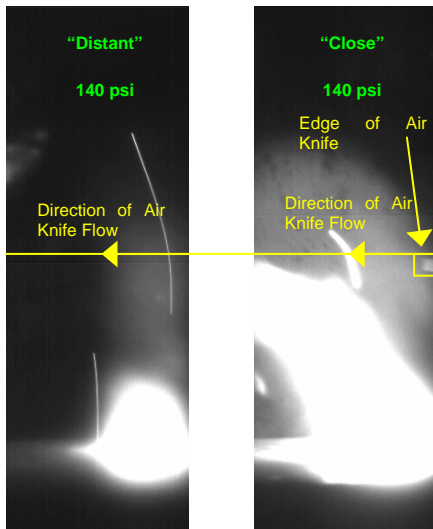
Figure 10 shows the effect of varying the air pressure through the air knife. The yellow line designates the direction of air flow from the air knife (right to left). As the increasing air pressure leads to increased air velocity, helping to deflect spatter. Also, the white gas plume coming through the aperture decreased in height as the air pressure was increased since the air jet spreads along a wider path as it travels away from the air knife.



Camera Aperture: 2.8, Exposure time: 1/1002 sec., framerate: 600fps

**Figure 10. Gas management with varying air pressure.**

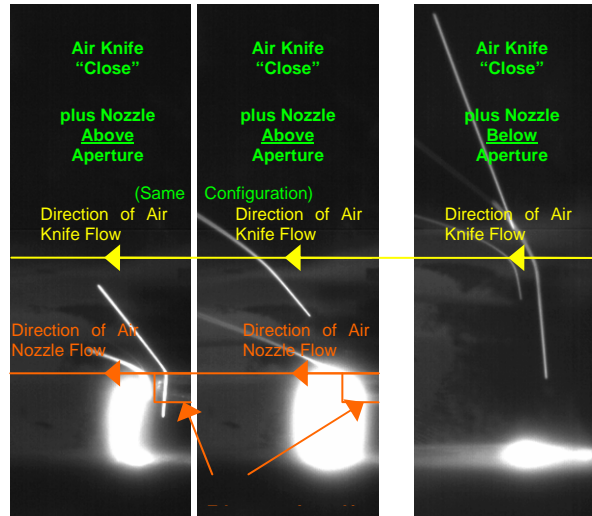
Figure 11 shows the effect of varying the distance from the gas nozzle to the aperture hole. When the air knife is positioned closer to the aperture hole (right side of figure) the air is travelling at a higher velocity, and is thus more effective in deflecting the trajectory of spatter and the gas plume. When the air knife is at a more distant position from the aperture hole (left side of figure), the air jet has spread out, providing a wider area of coverage and affecting the gas plume at a lower height, but the resultant reduction in gas velocity diminishes its ability to deflect the heavier spatter particles.



Camera Aperture: 2.8, Exposure time: 1/1002 sec., framerate: 600fps

**Figure 11. Air knife at varying distance from aperture hole.**

Figure 13 shows the result of using an air nozzle in combination with an air knife. The left and middle pictures feature an air nozzle, with orange arrows indicating the patten of air flow, above the aperture but below the air knife, with yellow arrows indicating air flow from the air knife. The air nozzle produces a higher velocity flow of air which can be clearly seen in the drastic change of trajectory of spatter as it crosses the path of the air nozzle. The middle picture is useful in comparing the impact of the air nozzle versus the air knife in deflecting spatter with the high velocity air nozzle clearly resulting in a greater change in the spatter trajectory. The right picture shows the effect of placing the air nozzle below the aperture which limited the height of the gas plume, which no longer passed through the aperture hole, but did not significantly limit the amount of spatter which travelled upward toward the air knife.



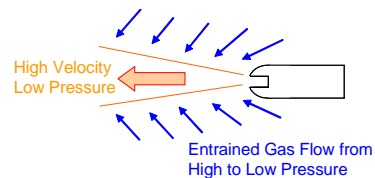
Camera Aperture: 2.8, Exposure time: 1/1002 sec., framerate: 600fps

**Figure 13. Air knife in combination with air nozzle above versus below aperture.**

Based on the motion of spatter in individual frames of the high speed video and the exposure time of each frame the spatter travelling above the aperture has an estimated velocity of 25 m/sec.

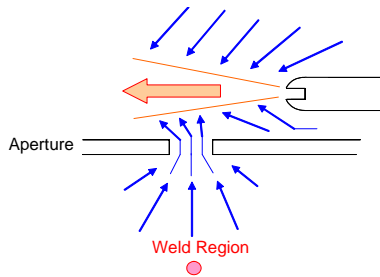
#### Gas Flow Management

Another important factor to consider in gas flow design is the management of the gas flow caused by the gas and air knives, jets, and nozzles. A high velocity gas jet creates a pressure drop which causes the surrounding air to flow toward the gas jet as displayed in Figure 14.



**Figure 14. Gas flow induced by pressure drop at high velocity gas jet.**

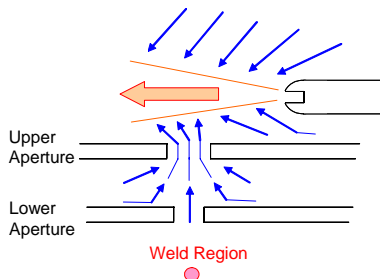
During welding experiments the pressure drop caused by the high velocity air nozzle above the aperture was large enough to draw a significant volume of air through the aperture hole as shown in Figure 15.



**Figure 15. Gas flow near weld region with single aperture.**

A string can be placed near the region of interest in order to roughly gauge the gas flow and turbulence in the region. This simple string test was used to verify that there was indeed disturbance in the air around the weld region. This disturbance affected the GMAW shield gas, necessarily located below the aperture hole, with a resultant negative impact on weld quality and increase in surface porosity.

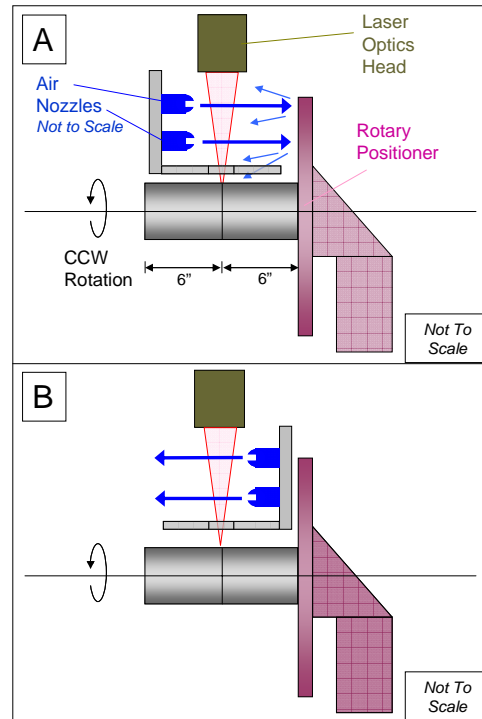
The solution to this problem was to use two apertures. The pressure drop created by the air nozzle pulled air through the upper aperture hole. However, the lower aperture, with a smaller aperture hole, limited the air drawn upward from the weld region. Instead, most of the air travelling through the upper aperture hole was drawn from between the two apertures, as shown in Figure 16. This prevented disturbance of the gases in the weld region and maintained weld quality.



**Figure 16. Gas flow near weld region with both an upper and lower aperture.**

It is also important to make sure that the high velocity gas or air jets used for plasma suppression or spatter control are not deflected by any object in its path back into the GMA weld region. This requires ensuring that the jet is aimed high enough above the aperture hole so that no air is deflected downward by the edge of the aperture hole, and also aiming the jet away from any other objects which could deflect it down toward the weld region. For example, when the air knife assembly was installed on the hybrid welding system at ARL Penn State for the initial pipe welding experiments, the high velocity air jets deflected off of the rotary positioner which disrupted the flow of shield

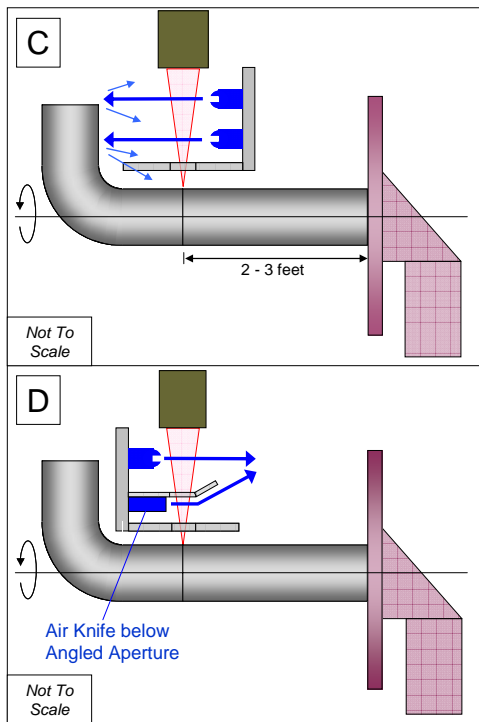
gases in the weld region, as shown in configuration A in Figure 17. The dark blue arrows represent the air flow from the air nozzles and the light blue arrows represent the flow deflected by the rotary positioner. The obvious solution was to aim the air knife assembly in the opposite direction, away from the rotary positioner as shown in configuration B.



**Figure 17. Gas flow management during pipe welding at ARL Penn State.**

However, when the pipe welding system was installed at GD NASSCO shipyard and production pipe assemblies were welded, a different gas deflection issue was encountered. The high velocity gas jet was deflected by elbow joints, as shown in configuration C in Figure 18, such that shield gas flow in the weld region was again disrupted. Due to the position of the seam tracking camera being immediately ahead of the laser, and the laser begin ahead of the GMAW torch relative to the weld travel direction (and also relative to the view given in the figure) the air knife assembly could only be aimed parallel to the pipe axis toward or away from the rotary positioner (corresponding to right and left in the figure). Fortunately, the straight pipe sections used in production welds at NASSCO shipyard were significantly longer, >600 mm (2 feet), than the 150 mm (6 inch) sections used during parameter development at ARL Penn State, which allowed more room to direct the high velocity air jet so as to not be deflected by the rotary positioner. The solution was to replace the lower air nozzle with a ServoRobot air knife which incorporated an aperture

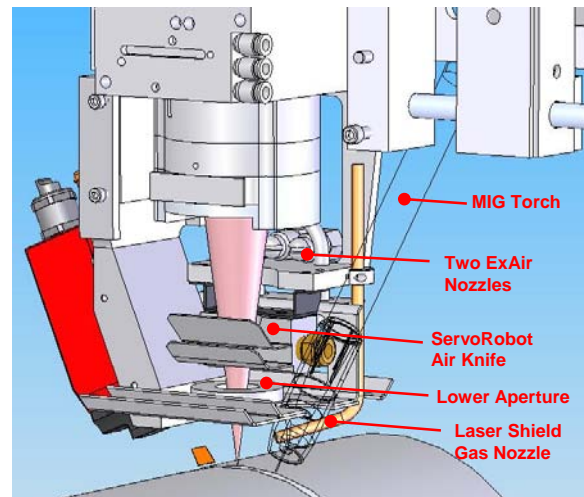
with an upward angled lip. The air jet closely follows the aperture and angled tip, and was successfully directed upward, above the rotary positioner, as shown in configuration D.



**Figure 18. Gas flow management during pipe welding at GD NASSCO shipyard.**

The final air knife design, shown in Figure 19, took into account all of the factors previously discussed and the lessons learned while welding at Penn State ARL and NASSCO shipyard. This design features a simple gas nozzle aimed perpendicular to the laser beam just above the weld region using argon gas to suppress the plasma and gas plumes and slightly deflect spatter. An air knife and two air nozzles are employed above the apertures for spatter control. The air from the air knife is directed upward by the lower of two angled apertures and thus does result in disturbance to the GMAW shield gas. The aperture below the air knife was sufficient to ensure that the air flow did not disrupt the laser shield gas near the weld region and was effective in stopping the upward motion of most of the spatter. Above the air knife two ExAir high velocity air nozzles were used for additional spatter control needed to deflect the spatter travelling at the highest velocities. They were placed side by side to cover the full width of the possible trajectory of spatter travelling upward through the aperture holes of the three apertures. The significant air flow caused by the high velocity air jets from these nozzles was directed by the three apertures such that shield gases in the weld region were not disrupted. For the same reason the

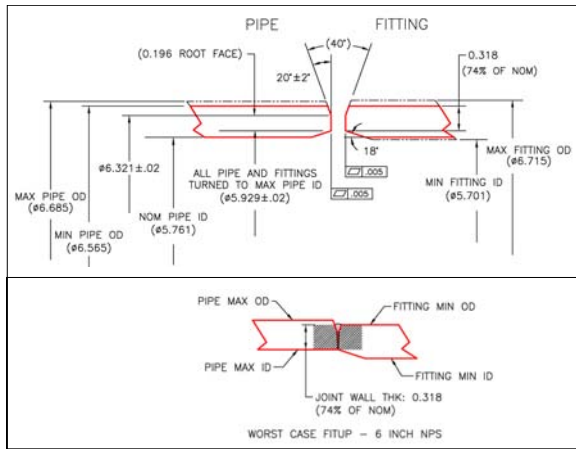
nozzles were placed above the air knife to give a greater distance between the nozzles and the weld region.



**Figure 19. Final gas management system design.**

### Wall Thickness Variations and Edge Preparation

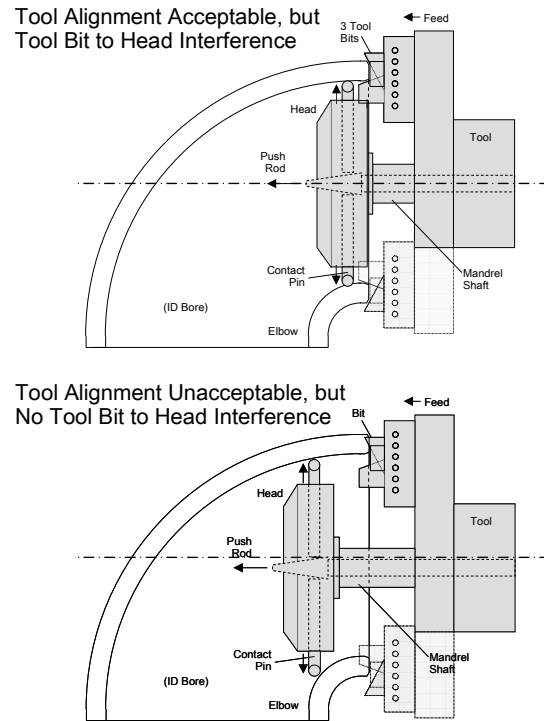
Laser welding with optimal penetration characteristics and rootside reinforcement geometry is very sensitive to variations in wall thickness. If the process is optimized for a given wall thickness and the thickness increases, lack of penetration may result. If the thickness decreases, the vapour keyhole may fully penetrate leading to material expulsion at the root. Unfortunately, existing ASTM A53 specifications for pipe and ASME B16.9 specifications for fittings allow for substantial variations in wall thickness. As such, it was determined early on that machining of pipe edges, both inside and outside diameter might be necessary. This would serve to ensure a constant land height, and hence volume of material, for the laser to melt and penetrate. Figure 20 illustrates the potential joint mismatch that can result using pipes that actually meet the specifications, and how edge preparation can ensure that a constant joint geometry is presented to the laser beam. Though additional expense for machining is required to ensure consistent joint geometry, unless suppliers can provide materials with tighter tolerances, the edge preparation is believed to be necessary to guarantee consistent weld quality.



**Figure 20. Illustration of potential wall thickness variations, and how machining of edges can ensure a consistent joint presentation to the laser beam.**

Fortunately, several manufacturers supply portable tools for that can provide the required edge preparation for pipes and elbows. Regrettably, however, it was determined that the elbow mandrels, which would work fine if merely facing and machining the outside diameter of elbows, do not work when machining of the inside diameter is required. The standard position of the mandrel within the elbow would cause interference with the inside diameter tool bit, so the mandrel must be extend further into the elbow. This, in turn, results in misalignment with the center of the pipe opening, and unacceptable edge machining. This is illustrated in Figure 21. Though modules that allow the tool bits to track the inside diameter are available, and would indeed provide a consistent land height, there is potential for eccentricity of pipe and fittings to result in unacceptable mismatch. As such, to date all fittings used in preliminary production runs are prepared in a machine shop.

Another item of note related to edge preparation is that standard fittings come with a pre-machined bevelled edge, the length of which is considered in design of pipe spools. In order to provide the required joint geometry and land height, this bevel must be machined off, thus reducing the length of the fitting by a non-negligible amount. This must be compensated for either by using sliding collars or fittings downstream of the machined fitting or by lengthening pipe sections are required. If the production volume is high enough, it is likely that it would be economically viable for suppliers to provide fittings that have the required dimensional tolerance, thus eliminating the need for pre-weld machining operations.



**Figure 21. Illustration of inability to adequately machine the inside pipe diameter with existing pipe edge preparation tools.**

### Test Production Run

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 test 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 22, and the results of the time study are presented in Table 1.

The time to load, teach, and weld 10 joints averages under 7 minutes per weld. This substantial improvement over conventional techniques can be attributed to the ease in utilizing the system due to simple user interface and the automatic seam tracking, as well as to the substantial improvement in weld time due to the higher travel speeds and reduced number of weld passes realized with the hybrid welding process.



**Figure 22. Photograph of pipes joined with a hybrid laser-GMA weld for the small production test run time study.**

Table 1. Results of the 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 m 40 s

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

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.

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