Applied Research Laboratory

Technical Report

Laser Pipe Welding
Technology Evaluation and Cost Analysis

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For the:
National Shipbuilding and Research Program
SP-7 Welding Technology Panel
and
The Advanced Technology Institute

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14. ABSTRACT

Conventional pipe welding often requires multi-pass GMA or GTA welding of beveled joints. Significant cost savings are anticipated due to elimination of the multi-pass requirement by taking advantage of the deep penetration offered by keyhole laser and laser-GMA hybrid welding, which will enable direct, single-pass butt-welding of pipes with little or no bevel required. Experiments were run that demonstrated the ability of existing commercially available hybrid laser welding technology to weld up to 0.50 inch thick A53 steel plate in a single pass. Parameters were chosen based upon a review of the literature. A portion of the welds were subjected to radiographic testing and tensile and bend testing. All welds passed tensile and bend tests, with all tensile failures occurring in the base material. NASSCO provided a pipe shop product family analysis and specification review. This data, coupled with additional evidence gathered in the project, suggests that annual cost savings would be significant. Should a hybrid system be successfully implemented, annual operational cost savings at NASSCO are estimated to be $1.2M, resulting in an ROI of 3.5.

15. SUBJECT TERMS

Laser Welding, Pipe Welding, Hybrid Welding, Thick-Section Welding

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Executive Summary

Conventional pipe welding often requires multi-pass GMA or GTA welding of beveled joints. Significant cost savings are anticipated due to elimination of the multi-pass requirement by taking advantage of the deep penetration offered by keyhole laser and laser-GMA hybrid welding, which will enable direct, single-pass butt-welding of pipes with little or no bevel required. The ability to join pipes with a single deep penetration weld at higher travel speed can be expected to result in a significant reduction in processing time. Additional cost savings can be expected from reduced defects and inspection time due to the reduction in total length of the weld bead and reduced starts and stops, due to the reduction in the number of weld passes. A reduction in weld fumes and filler wire consumption can also be expected with single-pass laser-GMA hybrid welds, and is further enhanced through the smaller weld pool associated with laser beam welding, which results in reduced evaporation and generation of harmful fumes.

Experiments were run that demonstrated the ability of existing commercially available hybrid laser welding technology to weld up to 0.50 inch thick ASTM A-36 / ABS Grade A steel plate (similar in chemistry to A-53 pipe material) in a single pass. Parameters were chosen based upon a review of the literature. A portion of the welds were subjected to radiographic testing and tensile and bend testing. Not all welds passed the RT test, but in some cases porosity was limited and it is believed that further process optimization would deliver more consistent results. Possible sources of porosity are believed to be joint cleanliness, moisture, or laser keyhole instability. All welds passed tensile and bend tests, with all tensile failures occurring in the base material. NASSCO provided a pipe shop product family analysis and specification review. This data, coupled with additional evidence gathered in the project, suggests that annual cost savings would be significant. Should a hybrid system be successfully implemented, after two years annual operational cost savings at NASSCO are estimated to be more than $0.5M, resulting in a five-year ROI of 2.0.

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Introduction

In October 2003, the Applied Research Laboratory at the Pennsylvania State University (ARL Penn State) was chosen by the NSRP SP-7 Welding Technology Panel to lead an effort to evaluate some the latest laser welding technology as directly applied to shipyard pipe welding operations. National Steel and Shipbuilding Company (NASSCO) expressed support for this effort, and teamed with ARL Penn State to serve as a direct link from the applied research laboratory environment to a shipyard. The objectives were to perform experiments and testing to evaluate the technical applicability of the new processes, and to use actual shipyard data to evaluate the potential return on investment.

Conventional pipe welding often requires multi-pass FCAW, GMAW or GTAW welding of beveled joints. Significant cost savings are anticipated due to elimination of the multi-pass requirement by taking advantage of the deep penetration offered by keyhole laser and laser-GMA hybrid welding, which will enable direct, single-pass butt-welding of pipes with little or no bevel required[1]. Recent advances in laser welding technology promise to produce high quality, single-pass welds that have a significant beneficial impact in this application. The ability to join the pipes with a single deep penetration weld at higher travel speed can be expected to result in a significant reduction in processing time. Additional cost savings can be expected from reduced defects and inspection time due to the reduction in total length of the weld bead and reduced starts and stops, due to the reduction in the number of weld passes. A reduction in weld fumes and filler wire consumption can be expected with single-pass laser-GMA hybrid welds, and is further enhanced through the smaller weld pool associated with laser beam welding, which results in reduced evaporation and generation of harmful fumes.

[1] Note that "hybrid" welding can be defined in different ways. Throughout this report, "hybrid" is meant to refer to a laser weld and GMA weld taking place simultaneous in close proximity. It has been noted in the literature that "hybrid" often refers to laser and GMA wire impinging on the part within 1-2 mm. In many of our experiments, the laser led the GMA wire by 10 mm or more. It was suggested that "tandem" may be a better way to refer to welds that use this spacing. Though we have chosen not to use this terminology in our report, it is a noteworthy distinction.

This program was fashioned to determine the weld quality and return-on-investment (ROI) that a shipyard can expect by applying recent advances in laser welding technology to pipe welding during ship fabrication. The evaluation was accomplished by working with NASSCO to determine shipyard piping requirements, performing an abbreviated literature search on related laser pipe welding efforts, and performing experimental evaluation of recent laser welding technologies applicable to the requirements. Completion of these tasks enabled the team to provide solid evidence as to the applicability of the new processes, both from a technical and financial viewpoint.

Experiments were run that demonstrated the ability of existing commercially available hybrid laser welding technology to weld up to 0.50 inch 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 radiographic testing and tensile and bend testing. Not all welds passed the RT test (see Appendix H), but in some cases porosity was limited and it is believed that further process optimization would deliver more consistent results. Observed porosity was limited to the area of deep penetration associated with the laser keyhole. Possible sources of porosity are believed to be joint cleanliness, moisture, or laser keyhole instability. All welds passed tensile and bend tests, with all tensile failures occurring in the base material. Additionally, the evidence gathered in the project supports the belief that annual cost savings would be significant. In fact, should a hybrid system be successfully implemented, after two years it is estimated that more than $0.5M operational cost savings could be realized at NASSCO, resulting in a five-year ROI of 2.0.

Experiments

A series of experiments were designed to:

1. evaluate welding of the primary pipe material and range of piping material thickness used at NASSCO (see Appendix A and B). Similar information collected from other shipyards is in Appendix C,
2. develop autogenous laser and laser-GMA hybrid welding parameters based upon a brief literature review (see Appendix D), and some of the more promising data available for welding thick sections using high power lasers (see data in Appendix E), and
3. test the welds according to the Specification Review provided by NASSCO (see Appendix F).

The original experimental plan is shown in Appendix G. Due to variations in material thickness and other unforeseen conditions, it was not possible to conduct all of the planned experiments. However, modification to the original test plan was made during experimentation based upon sequential observations, resulting in the execution of more than 150 welds, many of them with one parameter varied in a single weld and with special joint designs (see lab notes also in Appendix G). Figure 1 shows the experimental setup used at ARL Penn State, designed using commercially available components, a Trumpf HLD4506 laser and a Lincoln Electric 455-STT welding power supply. It should be noted that fully integrated hybrid welding heads are available from 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 the evaluation. Figure 2 through Figure 6 show representative cross-sections of GMA, laser, and hybrid welds that were performed as part of the testing.

Note that the special joint design incorporates a 90^o included angle. Recently, researchers have reported that much smaller included angles can be utilized, which can be expected to result in faster travel speed, less filler material, and a better return-on-investment once processing conditions are optimized.

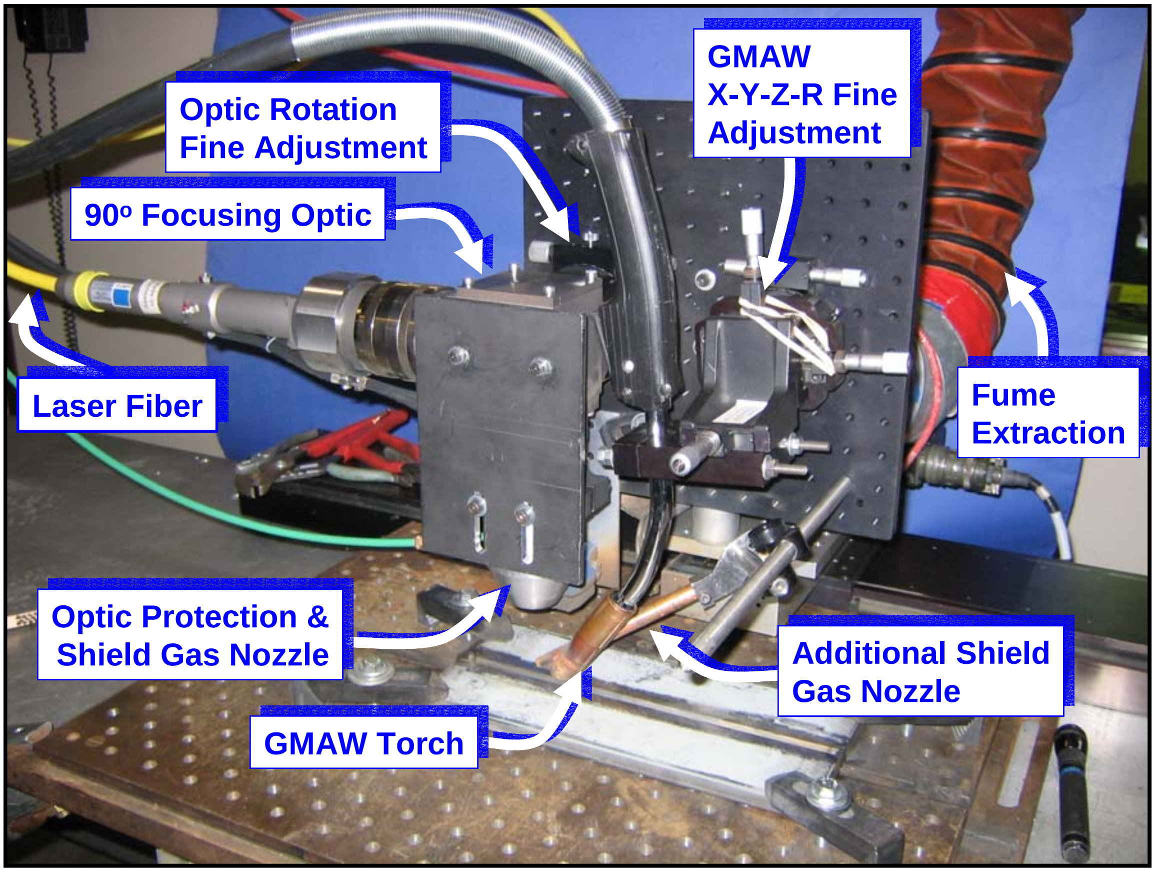

Figure 1. Experimental setup used to run experiments at ARL Penn State.

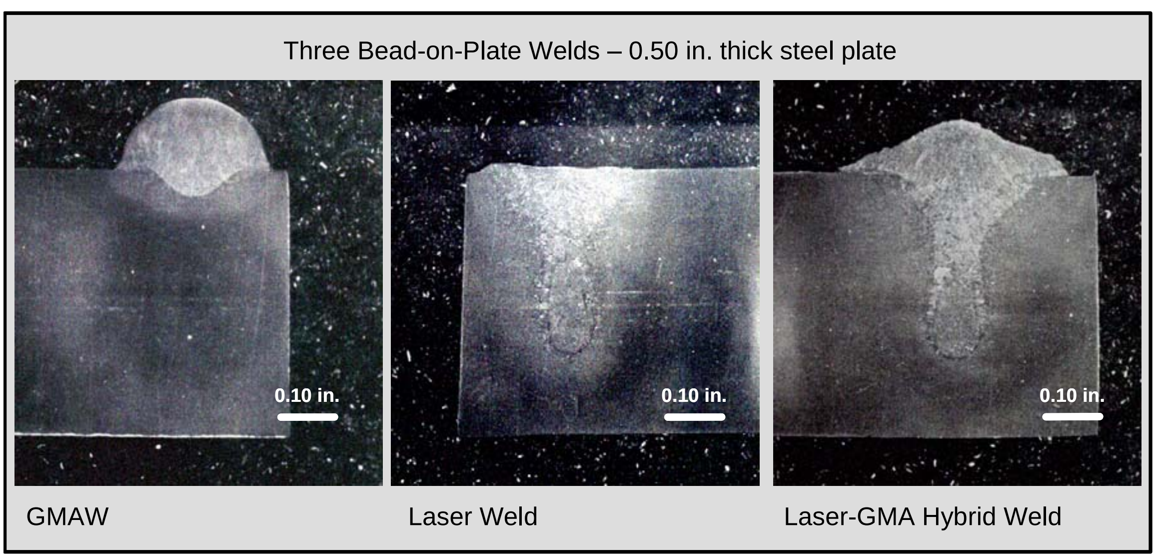

Figure 2. Three Bead-on-Plate Welds - 0.50 in. thick ASTM A-36 / ABS Grade A steel plate (similar in chemistry to A-53 pipe material).

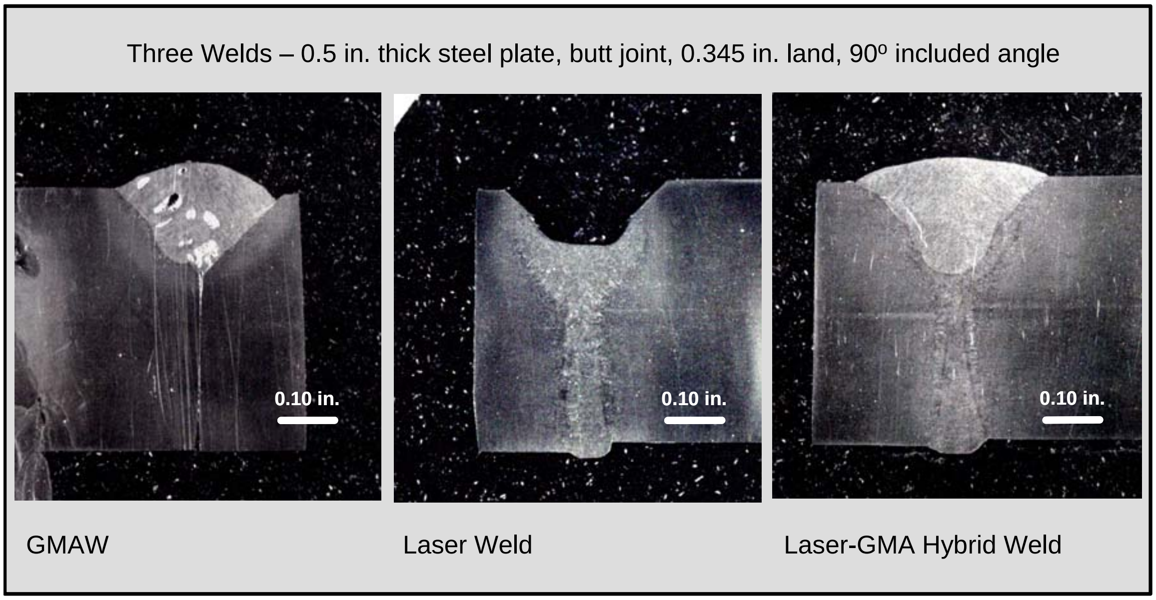

Figure 3. Three welds - 0.5 in. thick ASTM A-36 / ABS Grade A steel plate, butt joint with 0.345 in. land and beveled with a 90^o included angle.

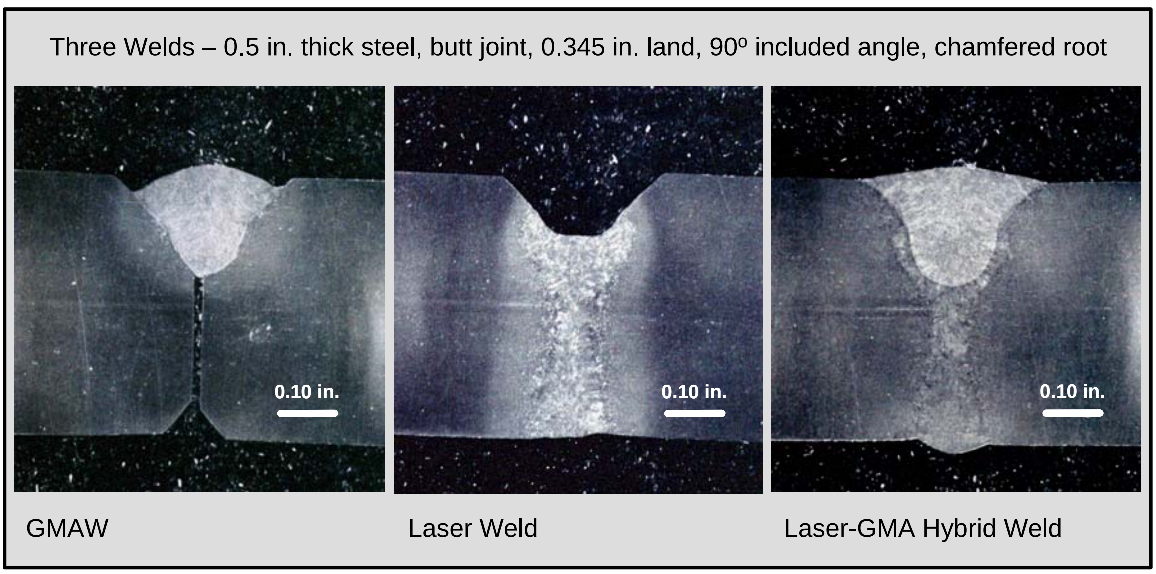

Figure 4. Three welds - 0.5 in. thick ASTM A-36 / ABS Grade A steel plate, butt joint with 0.345 in. land and beveled with a 90^o included angle and a 1/8 in. chamfer at the root.

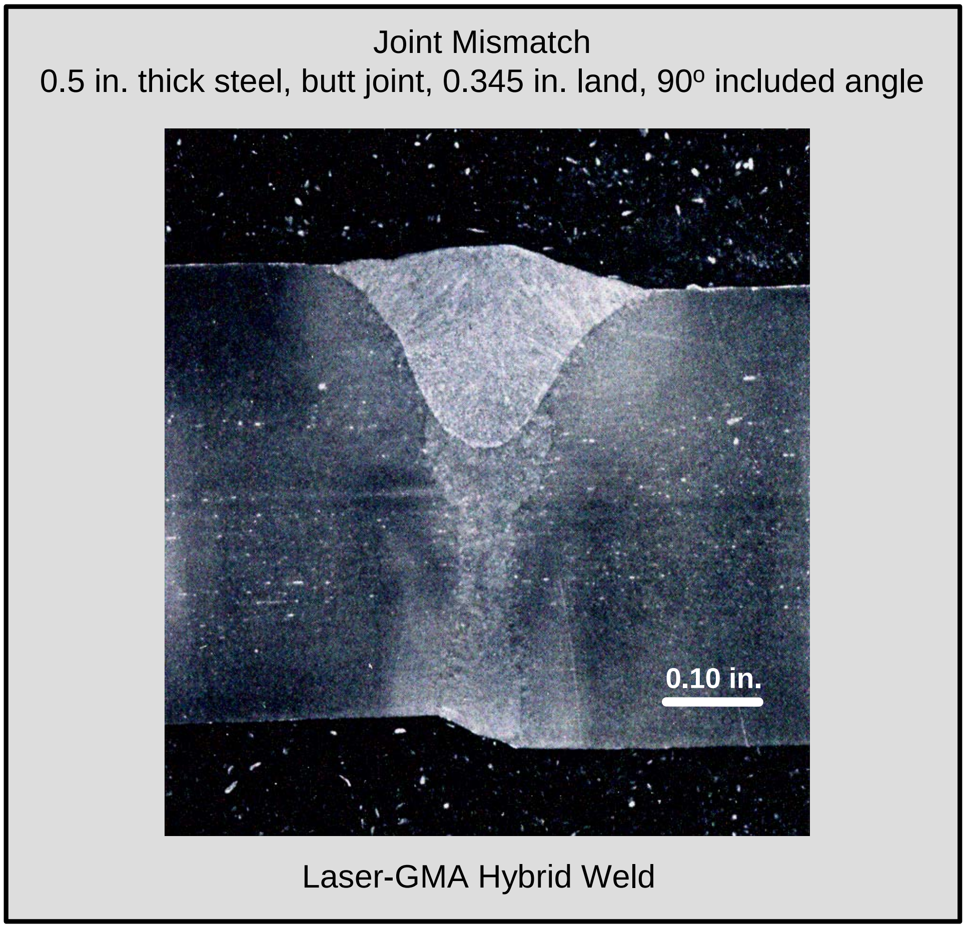

Figure 5. Demonstration of the ability of the process to accommodate joint mismatch.

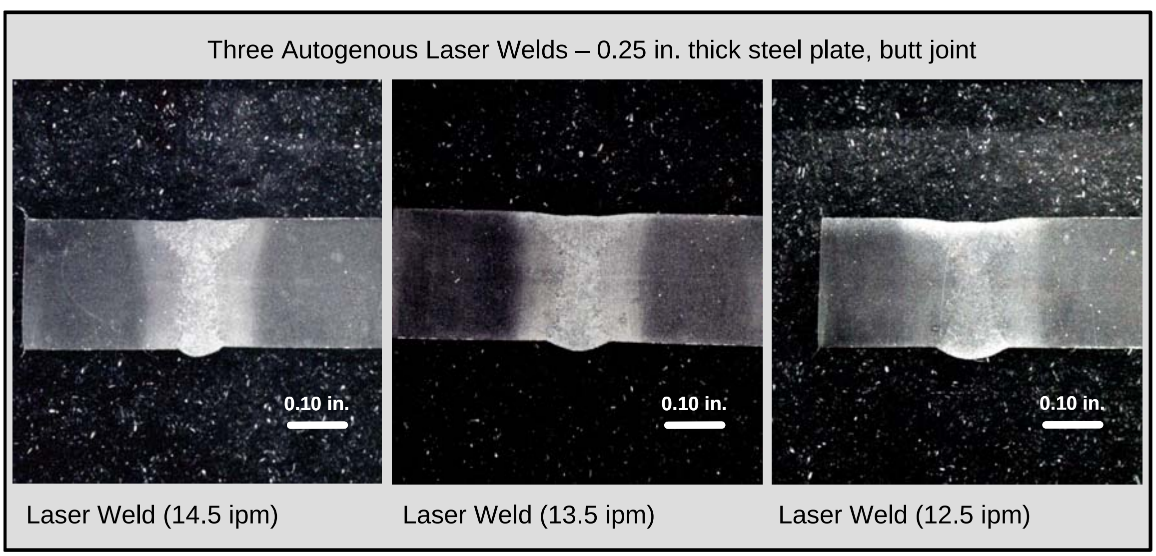

Figure 6. Three autogenous laser straight butt welds of 0.25 in. thick ASTM A-36 / ABS Grade A steel plate.

Based on the entire evaluation, four single-pass, full-penetration welds were chosen to be radiographically tested by a certified lab (see Figure 7):

- 0.25 inch thick – Autogenous laser weld, 2.6 kW laser power at the part, 14.5 ipm travel speed (No. AMT-1)
- 0.25 inch thick – Autogenous laser weld, 4.5 kW laser power at the part, 40 ipm travel speed (No. 104)
- 0.25 inch thick – Hybrid weld, 4.5 kW, 25.5 V, 500 ipm wire feed speed, 60 ipm travel speed (No. 118)
- 0.50 inch thick – Hybrid weld, 4.5 kW, 17.5 V, 317 ipm wire feed speed, 10 ipm travel speed (No. 79).

Note: No single-pass, autogenous laser welds were successfully performed in 0.50 in. thick material.

Figure 7. Photographs of representative hybrid welded samples.

The results of the radiographic testing are provided in detail in Appendix H. The autogenous laser beam welds passed inspection according to ASME Section IX of the "Pressure Vessel Code". The hybrid welds did not pass this specification due to evidence of porosity. It is believed that further process optimization could yield welds that consistently pass radiographic testing. Since welds were cleaned and tacked more than a week prior to welding, it is possible that porosity was due to improper cleaning procedures (some were ground while others were filed) and/or moisture being "wicked" into the prepared joint. Laser beam keyhole instability may also be the cause. This will be investigated in future work.

Three of these welded samples (No's AMT-1, 104, 79) were sent to a certified lab to undergo tensile and face and root bend testing according to ASME Section IX. Test results of photographs of all samples are in Appendix I. All samples passed, with tensile failures occurring in the base material.

Based on the results of these tests, it is highly probable that, with additional process optimization, laser and/or laser-GMA hybrid welding of A-53 steel can be successfully approved for use in pipe welding in thicknesses up to 0.50 inch.

Cost Analysis

For this initiative, we have used a modified ManTech[1] Return on Investment (ROI) methodology to calculate the ROI. This ROI is defined as the ratio of (a) the discounted cost avoidance realized by the proposed manufacturing methods over 5 years, to (b) the equipment and implementation costs for the proposed processing method. Modifications to this standard definition are included to account for (1) the funds required to implement a hybrid laser welding process including labor, material, equipment costs, and (2) a phase-in period in which first year savings are based on partial use of the new system. The operating cost savings is $505K/yr, resulting in a five year ROI of 2.0.

Manufacturing processes at NASSCO are labor intensive, requiring multiple weld passes to join piping. According to NASSCO, ¼ - ½ inch thick plates may require up to 5 weld passes to fill a butt joint. Currently, 25 man-years are expended annually in the pipe welding shop. This includes time to weld using various process methods (FCAW, GMAW-P, GTAW, GMAW-STT, SMAW, and silver braze), material handling, crane operation, bending pipe, and surface preparation before and after fabrication.

The ROI calculations were based on the two main welding processes utilized at NASSCO, GMAW and FCAW. The first objective was to evaluate the linear weld footage per weld type and pipe schedule to identify the actual man-hours required for “arc on” time. The actual linear weld footage was calculated based on the material consumption per weld type/ pipe schedule and the weld volume of a butt joint/fillet weld. We have estimated GMAW and FCAW processing consumes 46,580 lbs of filler material per year to weld 130,798 linear feet of Sch-40, Sch-80, and Sch-XS piping (Reference Attachment 1, Table2).

In order to accurately estimate the man-hours associated with NASSCO’s GMAW and FCAW “arc on” weld time, we used the linear weld footage per pipe schedule, taking into account the number of passes required to fill a butt joint and/or a fillet weld. Pipe welding activities such as material handling, crane operation, etc have been excluded from the return on investment

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[1] The objective of the Navy ManTech Program, managed by the Office of Naval Research (ONR) is to improve the affordability of Department of the Navy (DON) systems by engaging in manufacturing initiatives that address the entire weapon systems life-cycle and to transition that technology to the fleet.

calculation. Time required to perform these activities will be required regardless of the welding process method. From our analysis, we have estimated a 93% reduction in man-hours required to laser hybrid weld 130,798 linear feet of Sch-40, Sch-80, and Sch-XS compared to GMAW and FCAW ("arc on" weld time, only). Laser hybrid welding required 591 man-hours using a single weld pass method versus the GMAW and FCAW requiring 8,480 man-hours using a multiple weld pass method (Reference Attachment 1, Table 3). This resulted in annual savings of $286,700. (Reference Benefit Analysis Summary)

The second benefit considered was the filler material consumption for each welding process, calculated by weld schedule and weld type. The change in weld volume for GMAW/FCAW butt joint/fillet weld designs compared to laser hybrid weld joints/fillet weld designs decreased material consumption from 46,580 to 6,880 lbs. The reduction in filler material consumption and consumables saves $218,000 per year. (Reference Benefit Analysis Summary)

Additional costs involved with the implementation of a laser hybrid welding process at NASSCO include start up equipment and support costs. It is estimated that $871,285 is required for start-up equipment costs. (Reference Benefit Analysis Summary) This involves the purchase of a suitable laser, machining equipment, positioners, assembly hardware, etc. This amount is accounted for in the five year ROI calculation.

The ROI calculation also attempts to compensate for additional support required for operator and maintenance training, installation, travel, and marketing expenses. We have assumed an additional $159,000 will be applied to the implementation of hybrid welding at NASSCO to cover the estimated support costs. The associated engineering and development costs will be funded through the "Laser/GMA Hybrid Pipe Welding System" project, awarded under Center for Naval Shipbuilding Technology (CNST) Program and are therefore excluded from the benefit analysis.

Another factor to consider is the daily consumable processing costs such as gas shielding cups and contact tips. 'Other Consumables' have been estimated at 10% of the yearly material costs.

As noted above we have incorporated a phase in period in which first year savings are based on partial use of the new system. Generally, new processes do not achieve 100% utilization during the first year of implementation. The migration of shop practices from old to new requires time for learning to take place at all levels of an organization. To account for this, the first year projected savings is reduced by 40% and the second year savings reduced by 20%. After the second year, 100% utilization is assumed and accounted for accordingly in the ROI calculations. We believe that building a learning curve into the calculations results in a more accurate ROI.

Using the ROI methodology, modified as described above, we have calculated a return on investment of 2.0:1. (Reference Benefit Analysis Summary) This is a conservative estimate of the ROI, higher ROI's are possible if the optimal joint design is selected and all expected benefits of hybrid welding are realized.

Summary

Experiments were conducted that demonstrated the ability of existing commercially available hybrid laser welding technology to weld up to 0.50 inch 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 radiographic testing and tensile and bend testing. Not all welds passed the RT test (see Appendix H), but in some cases porosity was limited and it is believed that further process optimization would deliver more consistent results. Observed porosity was limited to the area of deep penetration associated with the laser keyhole. Possible sources of porosity are believed to be joint cleanliness, moisture, or laser keyhole instability. All welds passed tensile and bend tests, with all tensile failures occurring in the base material. Additionally, the evidence gathered in the project supports the belief that annual cost savings would be significant. In fact, should a hybrid system be successfully implemented, it is estimated that after two years more than $0.5M annual operational cost savings can be realized at NASSCO, resulting in a five-year ROI of 2.0.

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Appendix A – NASSCO Piping Process Storybook

1- Pipes received at NASSCO are stored by sizes near Gate 14

Pipe ready for plasma cutting at pipe shop

inside plasma cutting

Plasma cutting pipe exit

2- Pipes are cut to length in a plasma cutting cell

3- Pipe bending equipment for 12” 10” and 8” diameters if required

4- Pipes are then manually laid out and beveled by Oxy /Fuel gas cutting units

5- Weld end preparations are ground before fit up

6- Kits are established consisting of all parts for each pipe spool

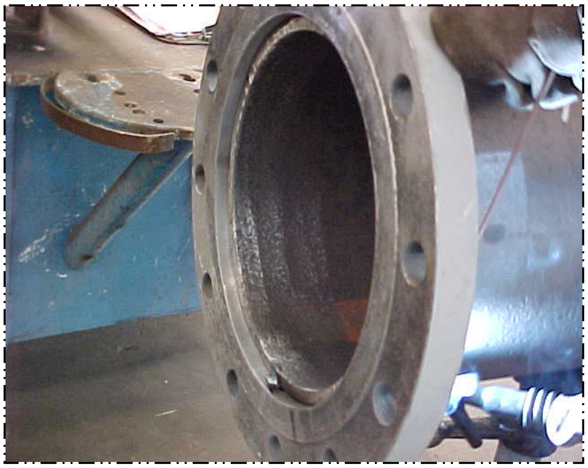
7- Designated fit up locations are used to assemble pipe spools

8- Basic fit up tools are squares and levels

9- Most pipe spools are tack welded with GTAW by welders

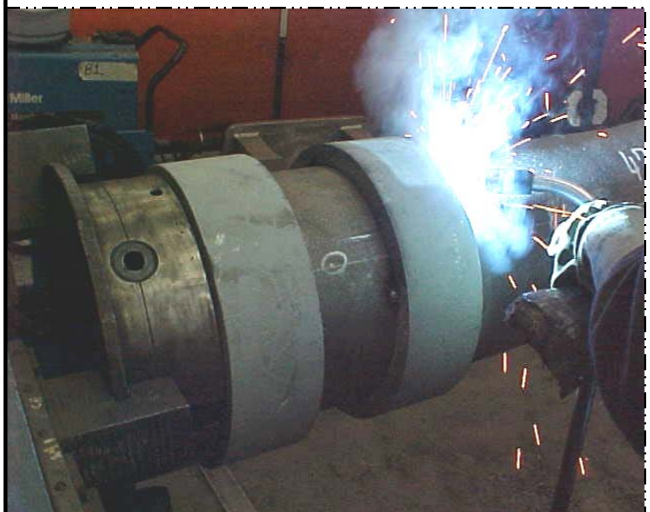
10- Spools are built to suite weld positioners for 1GR (roll-out)

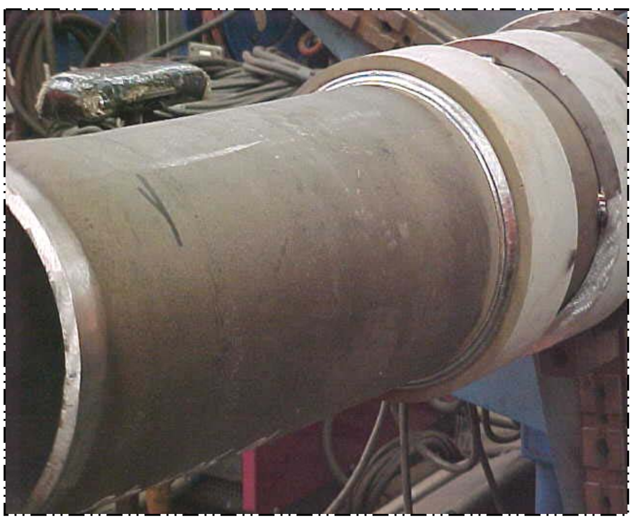
11- Sleeve type joints are shown P-13 and P-17



12- Slip on flanges shown are also tack welded before welding

13- All spools are moved to a welding roll-out station

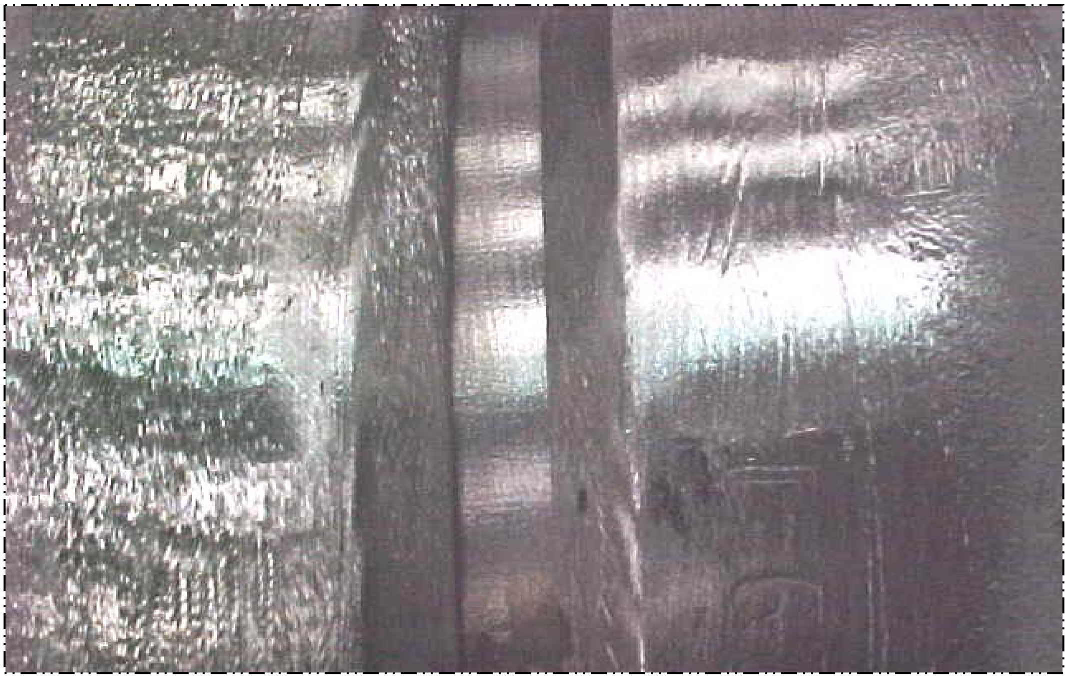




14- Some pipe spools are welded with FCAW semi-automatic

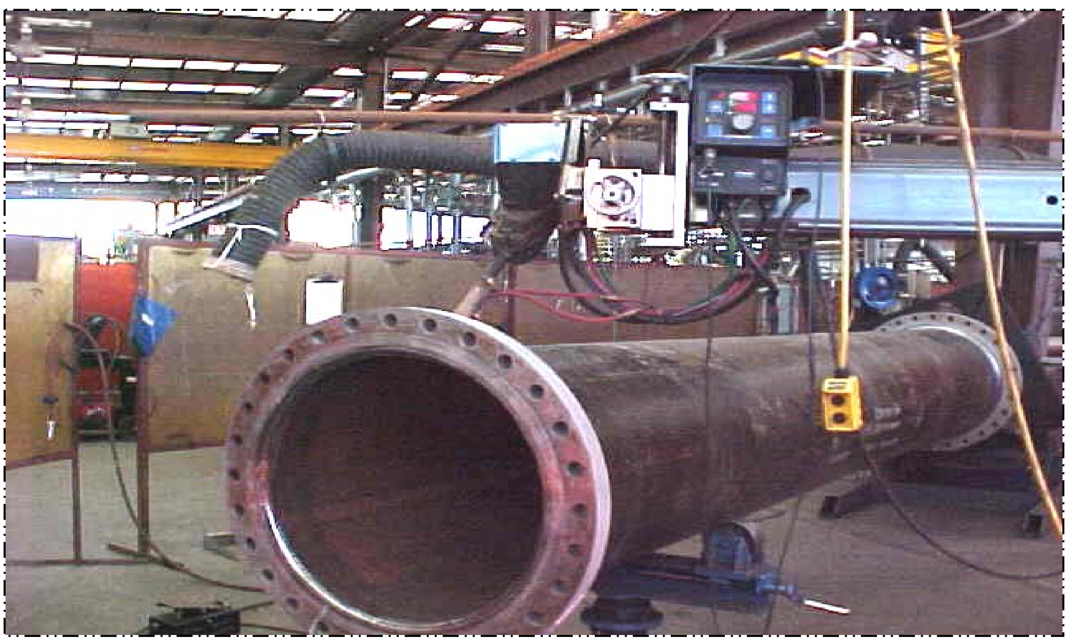
15- Some spools are prepared for open root butt joints. They are tacked for STT process.

16- Final weld out is performed by semi-automatic FCAW

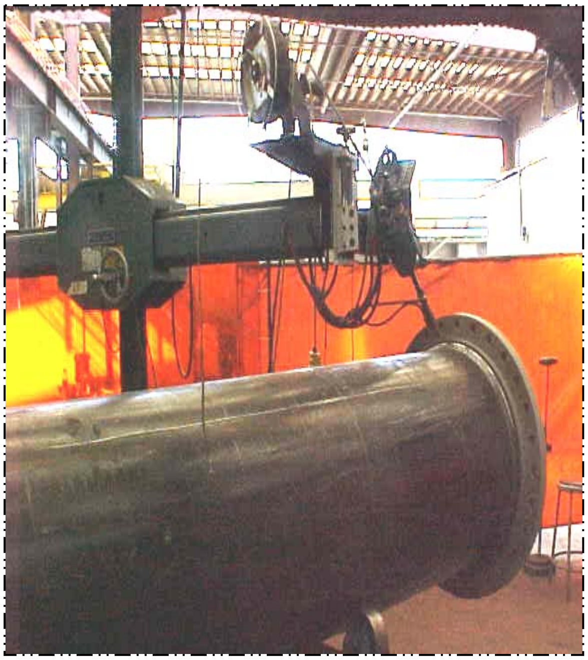


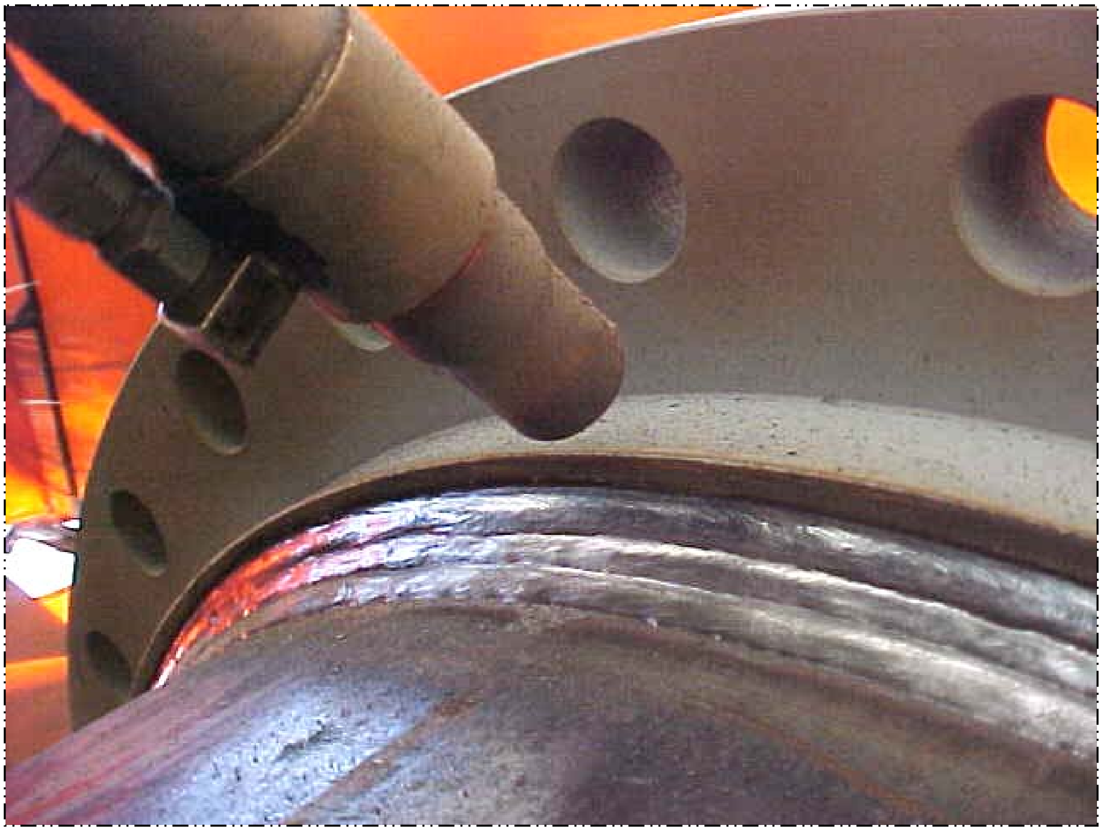
17- Some spools are fit with backing rings and are GTAW tack welded

18- Flanges for large diameter pipes are tacked welded with FCAW



19- Welding is completed at the manipulators using large diameter FCAW





20-Branch connections are also welded with semi-automatic FCAW

21- After VT inspection pipe spools are hydro tested and acid dipped for cleaning

22- Plastic covers are installed on all pipe ends for protection

23- Pipes are final sand blasted and painted inside and out if required

Appendix B – NASSCO Product Family Analysis

National Steel & Shipbuilding Research Project

LASER PIPE WELDING

<u>TASK 1 REPORT</u>
<u>Product Family Analysis</u>

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August 8, 2004

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1.0 Determine The Quantity Of Pipe Welding Performed

The NASSCO Pipe Shop tracks production by the number of pipe spools produced on a weekly basis. Each pipe spool is identified on a unique pipe spool sketch. These pipe spools can vary in size of pipe, length, complexity of bends (2 dimensional or 3 dimensional), the number of bends, the number of fittings and the number of weld joints. There has never been a need to track the production rate in any lower detail than the pipe spools.

The current project requires a more detailed breakdown of the pipe fabrication process. This data will be collected later in the project.

For the purpose of the laser welding project, the quantity of pipe welding performed in a shipyard (NASSCO being used as a typical commercial/military yard) can be stated using the following 2 metrics.

1. The average amount of welding filler material used per year in the pipe fabrication shop.
2. The average labor assigned to the pipe fabrication shop per year.

1.1 Welding Filler Materials

The main welding processes used at NASSCO in pipe fabrication, ranked from highest percentage usage to lowest, are:

FCAW
GMAW-P
GTAW
GMAW-STT
SMAW
Silver Braze

The type of material used in the pipe systems varies by system but is listed below ranked from the highest quantity to lowest.

Steel
CuNi
Stainless Steel
Copper

The average yearly consumption of weld filler material in the Pipe Shop is 50,000 lbs. of filler/year (41,580 lbs. of FCAW). This supports the construction of 1 ½ to 2 ships per year. The ships under construction were Tote Trailer Ships 255M length, BP Oil Tankers 287M length and T-AKE Support Ships 210M length.

1.2 Labor Assigned To The Pipe Shop

There are basically two trades or crafts assigned to the Pipe Shop; Pipe Fitters and Pipe Welders. These individuals perform all of the associated work, as well as pipe spool production. The associated work consists of material handling, crane operation, bending pipe, and surface preparation before and after fabrication, (not including final blasting and painting).

The number of production individuals working in the Pipe Shop vary constantly depending on the production scheduling in attempt to satisfy a JIT fabrication policy.

On an average the following manpower is used in the Pipe Shop for pipe spool fabrication.

30-35 Pipe Fitters	Average 33
20-30 Pipe Welders	Average 25

From these manning levels one can approximately calculate the quantity of pipe welding work performed.

Total	58 men/year	x	2000 hrs. =	116,000 hrs/yr.
Welding	25 men/year	x	2000 hrs. =	50,000 hrs/yr.

2.0 Pipe Estimates By Ship Type

In order to understand the quantity of pipe per vessel, the pipe systems must be separated into types of material. As previously stated the type of material used in pipe systems are as follows:

Steel
CuNi
Stainless Steel
Copper

The standard way to summarize pipe quantity per ship is by footage of pipe. Caution must be used when evaluating quantity of work based solely on footage. For example, the quantity of filler material and associated labor hours greatly increases with the thickness of material being processed. In addition, to a lesser extent, the quantity of work is influenced by the type of welded connections and the weld process.

For the following ship types the percentage of steel pipe is as follows:

SLNC	32% Steel
Tote	82% Steel
BP	61% Steel
T-AKE	50% Steel

This percentage breakdown directed the focus of this project to be steel pipe. It is acknowledged that laser welding is adaptable to all materials; however, the concentrated effort would be expended in the area that would result in the largest return on investment.

The pipe footage analysis shows that almost regardless of ship type the raw quantity of steel pipe is approximately 100,000 ft. to 120,000 ft. per ship.

3.0 Product Family

Detailed reports were analyzed to determine the quantity of pipe by pipe diameter and pipe schedule (or wall thickness). From these details the pipe product families can be broken as follows:

Diameter	Schedule	Percentage
0.5" – 10"	Sch-40	Largest quantity of footage 60%
0.5" – 10"	Sch-80	2nd largest quantity of footage 28%
10" – 30"	Sch-XS	3rd largest quantity of footage 12%

This analysis was performed for 3 ship types SLNC, Tote and BP with comparable results.

These are the three basic product families and relative quantities per ship for steel pipe.

4.0 Selection Of Target Family For Testing

The application for laser pipe welding was now focused on steel pipe. The types of joints that are most conducive to automation are those which shipyards identity as rollout joints. This refers to any pipe spool that can be welded in a 1GR (flat rolled) position. A weld positioner is used to rotate a pipe spool or a pipe spool section under a welding arc. The welding arc can be any arc weld process and can be hand held, mechanized or fully automatic.

All pipe spools are analyzed to maximize pipe rollout since this is the most economical method of fabrication. It is also the largest volume of work consuming the most filler material and labor. This is the targeted area to implement laser pipe welding.

In rollout welding of steel pipe the pipe diameters are further deselected to be 4" diameter and larger. A matrix was then established for the largest footage quantity based on product family further analyzing pipe wall thickness to determine the target family thickness for testing.

Diameter	Schedule	Quantity	Nominal Wall Thickness
4"	Sch-40	5,000 ft.	0.237"
	Sch-80	4,000 ft.	0.337"
6"	Sch-40	8,000 ft.	0.280"
	Sch-80	2,000 ft.	0.432"
10"-30"	Sch-XS	11,000 ft.	0.500"

With the low and high wall thickness defined, the laser technicians felt that process parameters could be interpolated. Therefore, the target family thickness for testing was selected to be 0.237" and 0.500".

5.0 Summary

This concludes the report of Task 1.

- The quantity of pipe welding has been determined
- The estimates of pipe by ship type has been provided
- The product family with quantity has been identified
- The target family thickness has been selected for testing

7.0 <u>Attachments</u>

1. NASSCO Response On Questionnaire

2. Pipe Footage By Ship Type

Note: Attachments are not included for general distribution and are considered NASSCO private information.

Appendix C – Shipyard Pipe Survey Questionnaire and Responses

12 November 2003

To: Paul Hebert, Northrop Grumman Newport News, paul.hebert@ngc.com
Pat Hoyt, NGSS / Avondale Operations, pmhoyt@ngc.com
Lee Kvidahl, Northrop Grumman Ship Systems, lee.kvidahl@ngc.com
Mike Ludwig, Bath Iron Works, michael.ludwig@biw.com
John Matthews, Electric Boat Corporation, jmatthew@ebmail.gdeb.com

From: Edward W. (Ted) Reutzel
ARL Penn State
ewr101@psu.edu
814-863-9891
814-863-1183 (fax)

Re: Questionnaire for Alternate Shipyards in support of NSRP SP-7 Panel Project, "Laser Pipe Welding"

Gentlemen,

The NSRP SP-7 Panel Project entitled "Laser Pipe Welding: Technology Evaluation, ROI" was recently funded. As part of the project, ARL Penn State is working closely with Nassco to perform a detailed ROI calculation based on using the latest laser welding technology to weld pipes. This calculation will be performed using production figures from Nassco.

To broaden the applicability of the effort, we have also been tasked to "…consult other shipyards in an attempt to more completely define the range of piping requirements across the industry". To this end, please fill in the attached matrix for your respective shipyard, and reply-email or fax to:

Ted Reutzel
Applied Research Laboratory, Penn State Univeristy
(814) 863-1183 (fax)

The intent of this survey is to provide a rough-order-of-magnitude estimate of these figures. Please **do not** spend appreciable time researching to producing exact results. If some of the requested data is company-sensitive, please provide only what you are permitted.

Don't hesitate to contact me by reply-email or phone (814-863-9891) if you have questions or wish to discuss any aspect of the project or this questionnaire. Thank you for sharing your time and experience to help make this project a success.

Sincerely,

Edward W. (Ted) Reutzel

Response from Shipyard #1

Provide the requested data for the three-to-five most often joined pipes.

Pipe Material	Pipe Diameter {inch} or {mm}	Pipe Wall Thickness {inch} or {mm}	Total Time to Join / Weld {min}	Approximate Percentage of Total Pipe Production
Carbon steel	10”, 12”, 14”	Sch. 40	10” – 10 hr 12” – 10 hr 14” – 12 hr	
Stainless steel	1/4”, 1/2”, 8”, 10”	Sch. 10	1/4” & 1/2” – 1 hr 8” – 2 hr 10” – 2-1/2 hr	
Copper nickel	6”, 8”, 10”	Sch. 10	6” – 1-1/2 hr 8” – 2 hr 10” – 2-1/2 hr	

Estimate the total cost spent on pipe welding each year.

Total Cost per Year
This information was not available.

Estimate the total time (man-year? other?) spent on pipe welding each year.

Total Time per Year
Proprietary Info

Response from Shipyard #2

Provide the requested data for the three-to-five most often joined pipes.

Pipe Material	Pipe Diameter {inch} or {mm}	Pipe Wall Thickness {inch} or {mm}	Total Time to Join / Weld {min}	Approximate Percentage of Total Pipe Production
SS type 304/304L	½” NPS	0.147”	60	15
SS type 304/304L	1 ¼’” NPS	0.140”	90	10
SS type 304/304L	1” NPS	0.179”	90	10
SS type 304/304L	1” NPS	0.133”	90	5
SS type 304/304L	3/4” NPS	0.154”	60	55

Estimate the total cost spent on pipe welding each year.

Total Cost per Year
> $1,000,000

Estimate the total time (man-year? other?) spent on pipe welding each year.

Total Time per Year
> 35 man years

Response from Shipyard #3

Responses from the shipyard came in two separate emails. Only the pertinent text is included.

Response #1

I can not complete your questionnaire. We are presently working 3 different contracts and the numbers are different for each. I can tell you that we work a lot of copper nickel, stainless steel and titanium. These are the top 3 materials, probably in this order. Mostly the diameters range from 1" to 4" with some very small being about 1/4" gauge lines and some being very large, 24" or greater. The wall thicknesses are typically thin being in the range of schedule 10-40.

I have no idea about how much is spent. These costs have to include direct labor, materials, overhead, capital costs, facility costs, etc. This would take a long research project to provide this number as requested. Similarly, the total time is based on the number of ships and in what stage of completion.

I understand your objective but I do not have the means or where with all to make it happen.

Response #2

I really can not do much with your questions. I know that we do a lot of stainless and copper nickel. A bit of steel and a smaller amount of titanium piping. The diameters range from gage tubing to 24". Mostly 2-6" is the larger population.

I have no idea on the time/joint because every joint size and material will be different. Similarly, the cost/ year is not in my easy reach. We employ about 200 pipe welders. However, we have a similar number of pipe fitters and other support personnel. How do you work these folks into your cost tables, if at all?

Obviously, I can not give you much help.

Appendix D – Literature Review

<u>Laser and Hybrid Methods for Welding Thick Steel</u>

Literature Survey

Elias Gwinn

Robert Crue

Edward Reutzel

Applied Research Laboratory

Penn State University

30 November 2004

Abstract

The focus of this paper is to provide a review of literature that details the recent efforts of researchers investigating and experimenting in the laser and hybrid laser arc welding area, in order to lay the groundwork for future experiments and to serve as a guide for those wishing to implement laser and laser-GMA hybrid welding of thick steel sections.

There are many things to consider in order to produce quality welds in thick steel sections. Process parameters such as the weld speed, filler wire, heat input, and shield gas all affect various aspects of the resultant weld, such as penetration depth, deformation, heat affected zone, cooling rate and material hardening characteristics, etc. There are currently many "conventional" welding systems being used in industry for thick-steel welding applications, the most prevalent being multi-pass arc welding, including Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), Flux-Core Arc Welding (FCAW) and Submerged Arc Welding (SAW). Due to the multi-pass nature of the welds, overall weld time is lengthy and incidence of weld defects can be high, due to the numerous starts and stops which are prone to defects.

This effort is focused on alternative welding techniques that could potentially produce thick section welds in a single pass, thus improving production rate and decreasing the likelihood for weld defects as compared to multi-pass techniques. The proposed solutions include high-power laser welding, and hybrid laser-arc welding. Both offer various advantages and disadvantages which are discussed herein.

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1. Introduction

For welding processes involving thick sections, a common industrial solution is currently multi-pass GTAW. This technique can produce high quality welds with the advantage of inherent equipment portability, thus enabling out-of-position welding with relative ease[5]. This flexibility, however, is at the expense of a relatively slow welding speed and the resultant low production rates. Additionally, since multiple passes are required to fill a large joint, there are many opportunities for generating weld defects, particularly during weld starts and stops.

When laser welding is employed in processes requiring deep penetration, CO_2 lasers have historically been the most common choice due to the availability of high output power (up to 20 kW or even 40 kW). CO_2 lasers generally offer excellent beam quality, which enables a high level of focusibilty, thus leading to high energy densities at the substrate which make high penetration depths possible. A weld the occurs in this manner is often referred to as operating in a keyhole regime. In this, case the high intensity laser energy generates enough heat to produce a metal vapor cavity, or keyhole, during welding, thus enabling high aspect ratio welds with significant penetration depths. Penetrations in the range of 15 to 20 mm can be produced at impressive welding velocities[5]. However, CO_2 laser beams operate in the far-infrared region of the electromagnetic spectrum, and thus have a relatively long wavelength (λ = 10.6 μm). This prevents the CO_2 laser beam from being transmissible[1] by fiber optic cables (the beam energy is absorbed in the fiber material), and thus so called "hard optics", or mirrors, are required to deliver the beam to the part. As such, industrial welding applications are limited because of the difficulty of beam transportation, and CO_2 lasers are not often used for out-of-position welding applications. Also, due to its long wavelength, CO_2 laser beam energy is subject to high levels of absorption within the plasma[2] plume that is generated above the keyhole during laser welding, causing the penetration depth to be significantly reduced[6]. This problem is exacerbated with increased laser power.

In contrast to CO_2 lasers, Nd:YAG lasers produce a beam in the near infrared (1.064 μm), and therefore can be delivered to the work piece via a fiber optic cable[5]. Using optical fibers and transmissive[1] optics, the Nd:YAG beam transportation and delivery proves to be quite flexible, thus enabling the use of standard robotics or low-cost manipulation systems. Additionally, Nd:YAG laser beams are not absorbed by the welding plasma[2] plume as much as CO_2 laser beams, thus letting more laser energy available to interact with and absorbed by the substrate. Nd:YAG lasers, however, have historically been limited by the relatively low output power, making deep penetration difficult. Recently, several laser suppliers have begun to offer Nd:YAG lasers producing powers up to 6 kW and higher.

There have been several studies undertaken in an attempt to bypass the processing limitations caused by welding with a relatively low power laser in order to create an efficient Nd:YAG laser welding system for welding processes requiring deep penetration. The literature reviewed within this paper includes an investigation of a non-autogenous (i.e. with added filler wire) system with up to 3 individual Nd:YAG lasers brought together at a common spot in order to achieve higher incident power[5].

Laser-arc hybrid welding systems have also been investigated to alleviate the limitations while maintaining some of the benefits of both arc and laser welding technologies. The quality and portability of the arc welder can coexist and complement the speed and penetration capabilities of the laser. The additional wire provided by the GMAW weld process can be used to bridge gaps normally impossible to effectively laser weld. The additional heat provided by an arc welding process can help to limit the cooling rate of an autogenous laser weld, thus reducing the likelihood of hot-cracking, centerline cracking, and the generation of brittle martensite. There is evidence to suggest that the additional heat can also help to alleviate porosity often found in deep penetration laser welds, by maintaining the molten pool long enough to permit buoyancy affects to remove solute gases.

When using an Nd:YAG laser arc hybrid welding system, the possibility of a high quality, high speed weld seems realistic, even for thick steel joints. Hybrid systems can be autogenous (such as with a supplemental TIG arc and no filler wire addition) or non-autogenous (such as with a GMAW system or GTA system with filler wire addition). Most documented studies focus on the addition of filler wire, since in many applications this provides the greatest benefit over an autogenous laser weld.

This remained of this paper is broken into three sections. The first provides background about GMAW welding and considerations when employing this conventional technique. This is used to provide contrast for the second section, which investigates high-power laser welding. Several related articles are reviewed and summarized, and the salient points are discussed. The third section discusses the marriage of these two process, known as laser-GMA hybrid welding. A variety of recent research and related publications is described and discussed. The report is concluded with a summary of the primary points to consider when attempting to implement these processes.

2. Gas Metal Arc Welding (GMAW)

General Discussion

GMAW is the preferred description of the process as it covers MIG welding, which uses an inert (non active) gas, and MAG welding which requires the use of an active gas (e.g. carbon dioxide, CO_2, and oxygen, O_2).

The process incorporates feeding a continuous, consumable electrode shielded by an externally supplied gas into a grounded metal substrate. This consumable electrode is guided by the welding gun which feeds electrical current to the weld wire and provides shielding gas to the local welding region. The welding power supply provides the energy to establish and maintain an arc and to melt the electrode, as well as controlling the flow of shield gas which provides the required protection from the ambient atmosphere to stabilize the arc and prevent oxidation. The contact tube of the welding torch is connected to the positive terminal of the power supply while the negative terminal is connected to the work piece. Welding current and Wire Feed Speed are generally set by the same control; with a constant voltage power supply, higher wire speeds results in higher amperages and vice-versa. Electrodes often consist of a bare wire to allow compatibility with parent plate. Metal powder and flux coated wires are also used with CO_2 shielding gas to allow high deposition rates and to improve weld metal quality.

The schematic of arc-welding is illustrated in Figure 1. The contact tube and workpiece shown would be integrated with an AC or DC power supply. An arc is created across the gap when the energized circuit and the electrode tip touches the work-piece and is withdrawn, yet still with in close contact.

An arc is an electric current flowing between two electrodes through an ionized column of gas. A negatively charged cathode and a positively charged anode create the intense heat of the welding arc. Negative and positive ions collide off each other in the plasma column at an accelerated rate, leading to extremely high temperatures.

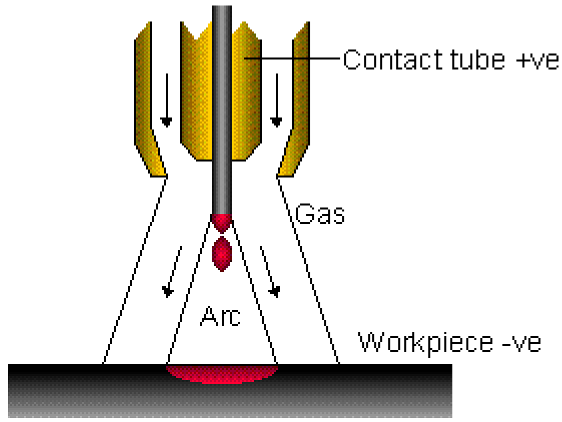


Figure 1. Arc Welding Schematic .

The arc produces a temperature of about 6500ºF at the tip. This heat melts both the base metal and the electrode, producing a pool of molten metal sometimes called a "weld puddle". The puddle solidifies behind the electrode as it is moved along the joint, resulting in a fusion bond. In constant voltage power supplies, the arc is self adjusting; any variation in the arc length made by the welder produces a change in the burn off rate of the electrode, and the arc re-establishes its original length.

In welding, the arc not only provides the heat needed to melt the electrode and the base metal, but under certain conditions must also supply the means to transport the molten metal from the tip of the electrode to the workpiece. Several mechanisms for metal transfer exist, such as globular mode and short circuiting mode. The primary metal transfer mechanism of interest for this project is the Spray Arc Transfer mechanism, which requires direct current and a positive electrode (DCEP). Using currents and voltages in the range 250-500 amps and 25-40 volts, the metal is transferred across the arc in the form of fine droplets in a spray. It is used for high deposition rate welds. Spray mode, due to the high current and voltages involved, is mainly used on thick materials in the flat position only; (except when welding aluminum, where spray transfer is used on all positions).

If an electrode is consumable, the tip melts under the heat of the arc and molten droplets are detached and are transported to the workpiece through the arc column. Any arc welding system in which the electrode is melted off and transferred to the workpiece is described as metal-arc. More of the heat developed by the arc is transferred to the weld pool with consumable electrodes (as compared to TIG welds with added filler wire). This produces higher thermal efficiencies and narrower heat-affected zones.

Since there must be an ionized path to conduct electricity across a gap, the mere switching on of the welding current with an electrically cold electrode mounted close to a metal workpiece will not start the arc. The arc must be *ignited*. This is caused by either supplying an initial voltage high enough to cause a breakdown discharge or by touching the electrode to the work and then withdrawing it as the contact area becomes heated.

Arc welding may be done with direct current (DC) with the electrode either positive or negative, or with alternating current (AC). The choice of current and polarity depends on the process, the type of electrode, the arc atmosphere, and the metal being welded.

The process can be applied to all commercial metals including carbon, low alloy steels, stainless steel and many important non-ferrous metals (aluminum, titanium, magnesium, nickel, and copper). The minimum sheet thickness is approximately is 0.5 mm while the maximum can be as high as 75 mm where multiple weld run are required for thicker sections. Due to the process being semiautomatic, relatively low operator skill is required compared to other welding processes.

Using an inverter power supply it is possible to produce pulsed arc (controlled spray transfer). This combines two power sources into one unit, one side supplies a back-ground current to keep the electrode in a molten condition, while the other unit produces pulses of higher current at regular intervals, which detach and accelerate the droplets of metal from the wire and accelerates them into the weld pool. This type of transfer enables out-of-position welding and higher deposition rates.

Process Variables

Weld penetration, bead geometry and overall weld quality can be controlled can be controlled by many variables such as the following:

- Welding current (electrode feed speed)
- Polarity
- Arc voltage (Arc length)
- Travel Speed
- Electrode extension
- Electrode orientation (trail or lead angle)
- Weld joint position
- Electrode diameter
- Shielding gas composition and flow rate

There are several benefits provided by GMAW welding that lead to a desire to marry the process to a laser welding process. Characteristics such as the ability to bridge wide root openings, low capital cost, and the formation of a relatively ductile microstructure (depending on the weld metal composition and cooling rate). Others include high deposition efficiency when used in spray transfer mode. With conventional GMAW. there is no slag that must be removed, and the use of a continuous electrode enables continuous, high-volume production. With the parameters properly set for the application, a high degree of mechanization or automation can often be employed, resulted in reduced labor costs. The welds are clean, high quality, and have good repeatability when utilized in with appropriate automation (i.e. robotic welders).

Unfortunately there are limitations to the process. Major limitations are the relatively slow weld travel speed and low penetration due to the fact that it is a conduction limited process. There is also a large potential for thermal distortion due to the high heat input involved. There is an ever-present danger of producing welds with a lack of fusion if the parameters and welding technique are not tightly controlled[11]. To weld thick sections, multi-pass welds are often required. These require numerous starts and stops, which are prone to weld defects.

3. High-Power Laser Welding

General Discussion

Laser welding of thick steel has several advantages over arc welding[5]. The main advantage is the deep penetration that is possible to achieve with lasers. High power CO_2 lasers can achieve up to 20 mm of penetration with a single pass. Another significant advantage is the high welding speeds that are achievable. The speeds are limited by the amount of penetration depth desired, but lasers can be three to four times as productive as arc welding. Also, there tends to be less distortion in the weld piece, due to the lower heat input and greater precision afforded by the laser compared to arc welding processes. Deep penetration welds are made via the so-called keyhole welding mechanism[6]. A keyhole is generated if the power density in the focused laser spot is high enough ($\sim 10^4$ W/mm^2) to cause melting and vaporization of the metal before significant quantities of heat are removed from the processing zone via thermal conduction. The keyhole essentially is a cylindrical cavity with molten walls that are kept from collapsing mainly by the vapor pressure inside the keyhole. Via the inverse Bremsstrahlung effect, a relationship between energy absorption and plasma, the vapor inside the keyhole is ionized and forms a plasma of ions and free electrons, which dramatically improves the energy coupling between the laser beam and the work piece.

To achieve deep penetration laser welds, however, it is usually necessary to weld at travel speeds of less than 1 m/min, at which speeds the process can be adversely affected by vapor and plasma[2] periodically escaping from the keyhole and forming a plume above it[6]. In the plume, the vapor and plasma[2] absorb and diffusely re-radiate some of the laser beam's energy. This can generally be seen in the weld by decreased penetration depth and widened top bead (which may lead to the so-called 'nail-head' or 'wine-glass' weld profile – see Figure 2 and Figure 3).

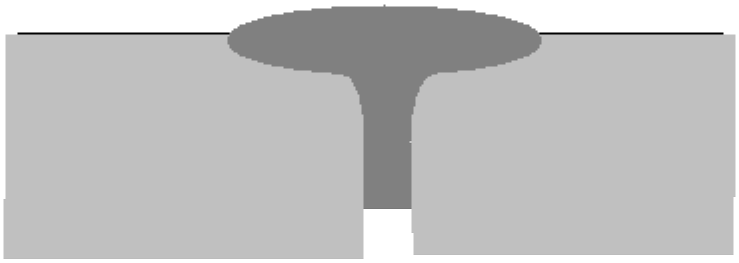
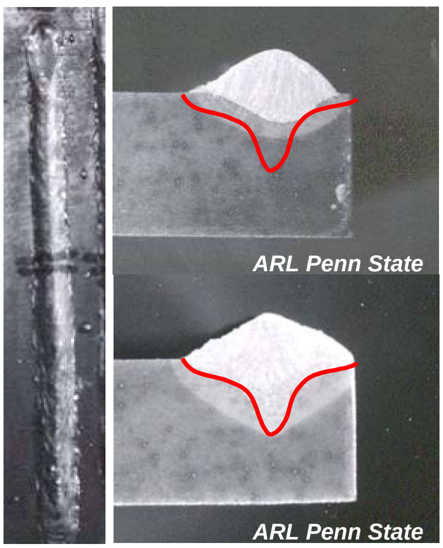


Figure 2. Decreased penetration and widened top bead due to plasma interference.



GMA Only
22 V, 215 ipm wire speed, 20 ipm travel speed, shield gas Ar/CO_2 @ 55 cfh

Laser – GMA Hybrid
2.6 kW Nd:YAG &
22 V, 215 ipm wire speed, 20 ipm travel speed, shield gas Ar/CO_2 @ 55 cfh

Figure 3. Penetration differences between arc and hybrid welding.

With CO_2 laser welding, this plasma plume is thought to be a partly-ionized gas plasma$_2$ consisting of ions, electrons and neutral atoms[6]. With Nd:YAG laser welding, it is thought to be merely a ‘hot gas’ or vapor plume consisting of neutral atoms only. This arises because the energy absorption coefficient for the inverse Bremsstrahlung effect is proportional to the square of the wavelength, which makes the plume more transparent to Nd:YAG (wavelength λ = 1.064 μm) than CO_2 laser light (wavelength λ = 10.6 μm). For that reason, there are differences in the most effective strategies for plume control measures for CO_2 vs. Nd:YAG laser welding. The plume control methods for Nd:YAG are addressed later in this paper.

High power Nd:YAG lasers (4 kW and higher) are now available[6]. Because of the low absorption of the Nd:YAG laser beam within the plume and the resulting higher efficiency of energy transfer to the substrate, coupled with the greater flexibility afforded the Nd:YAG laser due to the flexibility of the optical fiber beam delivery, Nd:YAG laser welding appears to be a more and more attractive solution. We will now further investigate research conducted using high power Nd:YAG.

Other Researchers' Results

Coste's Results:

Coste, et al, has explored the utilization of coupling up to three Nd:YAG lasers of up to 4 kW in each together to achieve a portable, non-autogenous, high-power laser welding process[5]. The experiments, which were performed on a cylindrical tube made of 316L steel with 60 mm thickness and external diameter of 400 mm, yielded 'very good' seam qualities for butt-welds of transverse and longitudinal sections (see Figure 4). The process, which was a multi-pass weld with added filler wire, was able to produce welds without evidence of porosity. The welding process was performed at a total 11 kW with 3 spots with 15 passes and cold wire speed of 10 m/min (except the root pass that used 8 kW, with a twin spot configuration and wire speed 1 m/min). The total welding time (laser switched on) required for producing the weld was typically 30 minutes.

Figure 4. a) Transverse section butt-weld; b) Longitudinal section butt-weld.

Weld Head and Filler Wire Configuration

Coste, et al, notes that for this regime of high penetration weld, an important enlargement of the metallic pool surface is observed, perpendicularly to the direction between the two spots (for both longitudinal and transverse twin spot beam configurations)[5]. This effect probably results from a very strong upwards hydrodynamic$_3$ flow induced along the keyhole walls by the drag forces due to the metallic vapor flow ejected from the keyhole.

Figure 5. a) Transverse beam configuration; b) Longitudinal beam configuration.

Therefore, as far as beam configuration is concerned, both longitudinal and transverse orientations have benefits[5]. In longitudinal (or tandem beam configuration), this perpendicular enlargement of the melt pool surface seems to improve the wetting ability of the groove walls (see Figure 5). On the other hand, by using a transverse configuration, a greater tolerance on the filler wire positioning can be obtained (compared to the usual wire-leading configuration – see Figure 5).

Coste, et al, has noted that, concerning filler wire orientation, there are some considerations that must be dealt with[5]. The usual configuration, in which the filler wire is inclined and the laser beam is perpendicular to the material surface, shows several drawbacks. First, for the wire-leading configuration, the wire intercepts the laser beam and perturbs the laser-substrate interaction, thus reducing the penetration of the root pass. If the wire is in trailing position, (the wire being sent into the rear of the melt pool), careful positioning is critical for quality welding and is difficult to achieve. Also, high wire speeds become difficult to achieve. This is likely due to the fact that there will be limited melting of the wire when it is being fed into the rear of the melt pool, and laser beam energy is primarily used for melting the substrate, rather than for melting of the wire.

These problems are strongly reduced if the wire is perpendicular to the surface with the use of an inclined incident beam[5]. Moreover, the use of a rather long focal length (300 mm or higher) gives the possibility of a limited angular inclination and this configuration becomes easily achievable. (However, a long focal length results in larger spot size[4], lower power density, and therefore, decreased penetration.) In this case, the perturbation of the beam by the wire is limited when the trailing position is adopted. This leads to various multiple laser beam configurations, in which each beam has a different purpose. For example, the first laser beam could be designated for penetration (higher power and smaller spot size[4]) and the second could be utilized for re-melting and finishing (decreased power and larger spot size[4]).

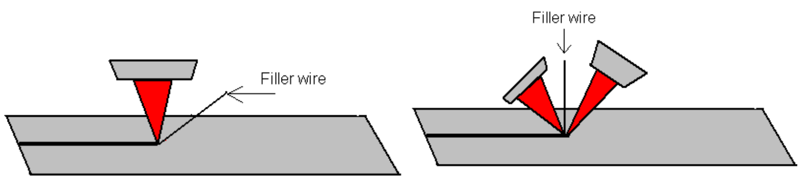


Figure 6. a) Angled filler wire and perpendicular laser beam, wire leading configuration; b) Angled laser beams (additional beam for melting) and perpendicular filler wire.

Another note from Coste, et al, is that the use of long focal lens for in-position welding can only be applied to down-hand position welding; for over head configuration it is no longer valid[5]. In over head position welding, the low level of penetration and the greater size of molten weld pool leads to a major instability of the weld pool (mainly its collapse) or to a loss of penetration. The use of a standard focal length (200 mm) that allows a smaller spot size[4] (0.6 mm diameter), a higher power density, and therefore a reasonable penetration (typically a several millimeters at 8 kW laser power at the reported weld speeds), leads to increased penetration for the root pass and also improved stability during welding. Coste, et al, adds that this likely results from an increased surface tension effect with the smaller weld pool. Coste suggests that an intermediate solution in which a 300 mm focal length is used could yield more desirable results. In this case, a 0.6 mm fiber diameter results in a focal spot of 0.9 mm.

Filler Wire

Coste, et al, also experimented with varying filler wire speed[5]. During a weld pass, the filler wire speed was increased from 7 to 8 m/min. The result, after any dynamic effects in changing wire speed has stabilized, was that laser energy transfer into the substrate seemed to decrease, as evidenced by a lack of full penetration. This is probably due to the fact that more of the laser's power was used to melt the filler wire rather than the weld piece. This effect is strongly correlated to the weld seam quality, as the level of porosity increases when the full penetration is no longer achieved.

Groove Geometry

An observation Coste, et al, make is that, during the filling passes, one generally observes a high angular deformation of these test pieces compared with conventional welding, even given the rather low thermal input and an efficient initial clamping of the test pieces[5]. Therefore, the initial configuration of the part to be welded and the weld groove itself must take into account some partial unavoidable closure leading to transverse angular deformation during the filling process (see Figure 7).

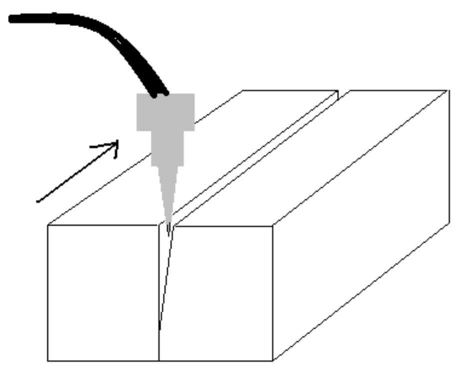


Figure 7. Groove geometry.

Gerritsen's Results:

Gerritsen, et al, also investigated the parameters involved in combining multiple Nd:YAG laser beams, though these welds were conducted without the addition of filler wire (i.e. they were autogenous)[6]. In these experiments, two C-Mn steels were used to weld test samples of 150 x 300 mm, with a thickness of 14 mm and 15 mm, respectively. Their compositions were as follows:

Table 1. Chemical compositions (in weight %) of the steels used in Gerritsen's experiments6.

Thickness	C	Mn	Si	Ni	Cr	Cu	Al	P	S
14 mm	0.12	1.28	0.009	0.019	0.015	0.014	0.036	0.015	0.005
15 mm	0.17	1.08	0.25	0.021	0.019	0.022	0.029	0.014	0.014

Laser Parameters

Laser powers (at the work piece) of 7.5 kW and 9 kW were achieved by using three Nd:YAG laser sources simultaneously[6]. Each laser was capable of an average continuous wave (CW) work piece power of 3.5 kW. The output from each laser was guided through a 0.6 mm core diameter fiber optic cable to a beam-combining unit. Inside this device, the output from all three fibers were focused onto the end of a single fiber optic cable of core diameter 1 mm, and this fiber optic cable transmitted the combined laser output to the focusing head, giving a laser power at the work piece of up to 10 kW. The focusing head, consisting of a re-collimating lens and focusing lens producing a focused spot of nominally 1.4 mm in diameter at a stand-off distance of 220 mm. The optics were protected from contamination and damage from weld spatter and fumes by three air knives, aligned below an anti-reflection-coated glass cover slide.

Gas Delivery Methods

The first set of experiments conducted by Gerritsen, et al, were partial-penetration welds in both types of steel at laser powers of 7.5 and 9 kW[6]. Firstly, to establish the most suitable plume control set-up, several different gas delivery systems were investigated. These tests were conducted using a 7.5 kW laser beam at a travel speed of 0.5 m/min; the steel used was the 14 mm thickness C-Mn steel. The commonly used co-axial shielding nozzle was also tested (at 9 kW).

After establishing the best performing delivery system, the influence of the process gas composition was evaluated[6]. Commonly used process gases were tested (helium, nitrogen, argon and carbon dioxide), as well as various mixtures (helium-nitrogen, helium-carbon dioxide, helium-oxygen, argon-oxygen) were studied. Again, the laser power used was 7.5 kW, and the travel speed 0.5 m/min. The steel used was the 14 mm thickness C-Mn steel.

Finally, the performance of the optimized set-up was further evaluated when attempting full penetration melt runs in the 14 mm thickness at 7.5 kW and in the 15 mm thickness steel at 9 kW of laser power[6].

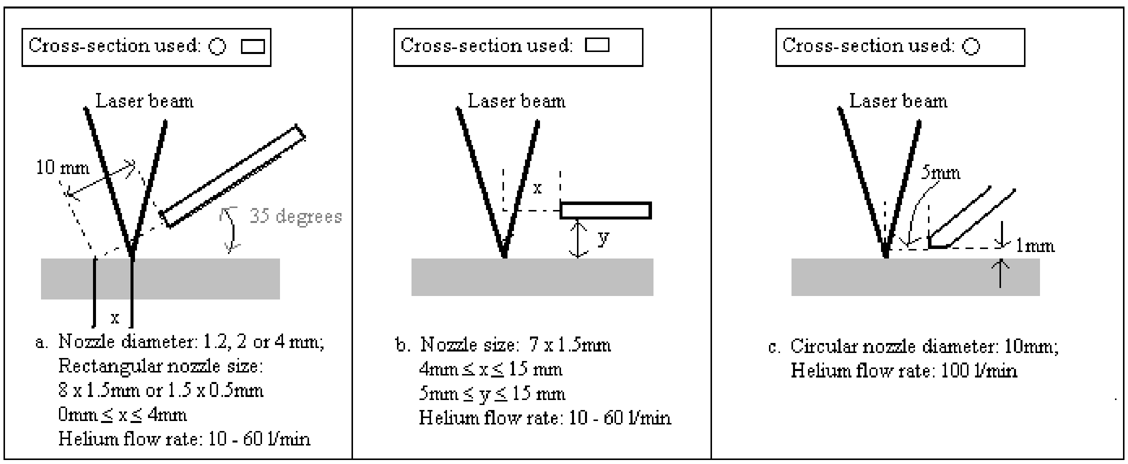


Figure 8. Investigated gas delivery systems for plume control: a) Angled jet; b) Horizontal jet; c) Angled jet with shaped nozzle6.

The set-up for these experiments are depicted in Figure 8[6]. The results of these experiments are as follows:

Circular cross-section angled jet:

Changes in the nozzle diameter, gas flow rate, or impingement position for a circular nozzle all had a significant effect on the weld bead geometry and penetration depth[6]. A series of observations from these experiments are noted:

- The deepest penetration depth observed was 12 mm. This was achieved with the following plume control parameters:
    - Nozzle diameter 2 mm, impingement position +1 mm, helium flow rate 30 l/min
    - Nozzle diameter 2 mm, impingement position +2 mm, helium flow rate 30 or 40 l/min
- Deep penetration melt runs were associated with a small plume and a smooth top bead. Radiographic examinations of these welds showed low levels of porosity. Additionally, the occurrence of short solidification cracks, although rare, was noted.
- When optimum parameters were not used, the penetration depth decreased to 8 mm and the plume was seen to significantly increase in size. The top bead of all low penetration melt runs showed a 'pulsing effect', which was also linked to extensive cracking.
- No melt runs of satisfactory penetration depth and weld quality were produced with the 1.2 mm or 4 mm diameter nozzles.

Rectangular cross-section angled jet:

A nozzle with a rectangular cross-section did not provide any improvement or increased tolerance to set-up, even though it was designed to spread the gas jet more widely and evenly across the interaction zone and thereby improve the tolerance to positioning[6]. In fact, within the range of parameters investigated, most melt runs exhibited a medium to large plume, a 'pulsing' or disturbed top bead and shallow penetrations.

Rectangular cross-section parallel jet:

A rectangular cross-section nozzle with its axis parallel to the work piece did not enable the production of a weld of acceptable quality over the range of parameters investigated[6]. Most welds exhibited a 'pulsing' top bead and relatively low penetration depths (8-10 mm). In these experiments, the position of the nozzle with respect to the work piece and the laser beam-material interaction point proved to be of little influence on the penetration depth. In addition, it was noticed that the weld shape and appearance were not directly linked to the visible plume size, as seen previously.

Circular cross-section angled jet with shaped nozzle:
Only two experiments were performed with this set-up, and neither experiment produced a melt run of acceptable quality[6]. Even the use of very high helium flow rates and gas bottle pressures did not allow control of the plume. Both melt runs exhibited pulsing top beads and small penetration depths.

Process Gases

The laser power used for the optimization of the gas parameters (mixture, flow rate, nozzle position, etc.) was 7.5 kW Nd:YAG laser beam at a travel speed of 0.5 m/min[6]. The experiments showed that, for every gas or mixture, the flow rate had a significant effect on the weld bead geometry and penetration depth.

The maximum penetration depth achieved was 12.5 mm with argon, nitrogen, carbon dioxide or a 90% helium-10% oxygen mixture[6]. The melt runs produced with these process gases exhibited low or acceptable porosity levels. Very short cracks (1 mm) were occasionally detected in some of the melt runs made with nitrogen. However, although not further investigated, this was not thought to be related to the process gas. It is interesting to note that the use of nitrogen did allow the plume to be controlled with this Nd:YAG system, whereas with high power CO_2 laser welding, it tends to give a very hot and fiery plume. This is likely due to the fact that the long wavelength of the CO_2 laser beam is absorbed in nitrogen, while the short Nd:YAG wavelength tends to pass through.

Argon was found to give the best overall results because it was most tolerant to set-up variations, is inert, and does not have an alloying effect[6]. It was therefore concluded that the optimum set of welding conditions, enabling a 12.5 mm penetration depth in C-Mn steel with an Nd:YAG laser power of 7.5 kW at a travel speed of 0.5/min, was as follows:

- Circular gas jet of diameter 2 mm;
- Jet oriented in line with the welding direction and trailing the beam at a 35^{o} angle to the work piece;
- 10 mm nozzle-to-work piece stand-off distance;
- Impingement point 2 mm ahead of the beam;
- Argon flow rate of 20 l/min

Ishide's Results

Another high-power Nd:YAG laser beam welding study was conducted by Ishide, et al[8]. In their investigation, an Nd:YAG laser was used for repair of nuclear power plant piping. Laser beam powers of 6kW to 10 kW were used to accomplish single-pass penetration of 15 mm to 20 mm in SUS 304 and carbon steel. Specifically, in continuous wave (CW) mode, the penetration depth of approximately 15 mm was obtained at 7.6 kW in laser power and 0.2 m/min travel speed. In pulse welding oscillation mode, 20 mm penetration depth was obtained at 6.6 kW average laser power (see Figure 9 for a schematic of the tube weld).

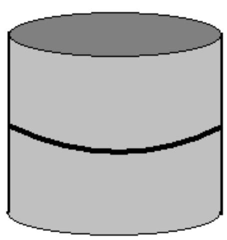


Figure 9. Ishide's tube weld.

<u>Laser Parameters</u>

Ishide, et al, noted that, though the pulse welding oscillation is advantageous in the low welding speed region being suitable for thick plates, with increasing welding speed, penetration for the pulse welding oscillation mode decreases[8]. This is considered to be due to the fact that the energy fluence per laser pulse decreases with the increasing speed.

The effects of pulse frequency and pulse-on time (duty cycle) on penetration depth were also studied[8]. When the pulse frequency and the pulse width were decreased at constant average laser power, the penetration depth increased. Depending on the welding speed, an optimal frequency existed. In this case, the welding speed which will be used in production is about 0.2 – 1.0 m/min, and the optimal frequency which maintains full penetration was determined to be more than 40 Hz. A pulse duty cycle of 40% to 50%, as opposed to longer duty cycles, makes the penetration deeper because the peak power in each pulse is higher. Above the 50% pulse duty, the penetration depth decreases because of the decreased peak power level in each pulse.

The final set of experiments they conducted utilized the 7 kW Nd:YAG laser to weld peripheral joints of piping and longitudinal joints of large vessels[8]. For Nd:YAG laser welding of piping of 20 mm thickness, all cases yielded satisfactory welds.

Zhao's Results

Porosity

Zhao's, et al, study of porosity in magnesium alloys demonstrated that weld porosity in laser beam welding in magnesium alloys is a major concern[7]. After laser welding, a significant increase in volume percent of porosity was observed in the fusion zone, as compared to the porosity of the base metal. The coalescence and expansion of small pre-existing pores due to heating and reduction of internal pressure is believed to have been the primary contributor to the porosity increase in the fusion zone.

The amount of porosity in the fusion zone was found to decrease with a decrease in heat input, i.e. decrease in laser power or increase in welding speed[7]. Porosity levels similar to that in the base metal could be obtained when heat input was low.

Pore formation has also been attributed to both hydrogen rejection from the solid phase during solidification, and to imperfect collapse of an unstable keyhole[7]. Turbulent flow in the weld pool has also been linked with porosity formation. Keyhole stability was found to play a major role in porosity formation during continuous-wave (CW) Nd:YAG laser beam welding of aluminum alloys 5182 and 5754.

Zhao, et al, demonstrated that the segregation of hydrogen from the solid phase played an insignificant role in the formation of large pores in the welds[7]. This may have to do with the specific hydrogen solubility in aluminum and magnesium. In the system studied, changes in porosity were attributed to heating, melting and pore coalescence, while the fast cooling rates may have limited the escape of gases compared to the fully melted alloy. Partial melting of the alloy resulted in significant increase in pore size and, more important, higher area-percent porosity than the base metal.

The transport of gas bubbles in a weld pool containing re-circulating liquid metal is complex, according to Zhao[7]. During welding, micrographs revealed that gas bubbles drifted with the flow of liquid metal and, at the same time, had a tendency to float upward due to buoyancy affects caused by the difference in the densities of the bulk liquid and the bubbles. Furthermore, the vigorous flow of weld metal promoted coalescence of bubbles. It is fair to expect that, due to the rapid thermal cycle, the pores formed in the fusion zone had little time to “float out” of the weld pool in a single welding thermal cycle. Therefore, small pores that require a long time for flotation due to small buoyancy could not be removed from the weld pool in time before the molten weld puddle solidified. If a second run of welding was performed, the pores in the fusion zone that are already much larger than the preexisting pores in the base metal had a second chance to float out of the weld pool, and observed porosity levels were reduced. Moreover, these pores could also coalesce to form even larger bubbles, thus increasing their buoyancy and therefore their opportunity to escape from the molten puddle prior to solidification. Thus, the use of multiple Nd:YAG lasers present some advantages for suppressing porosity[7]. It was found that well-controlled re-melting of the fusion zone led to removal of gas bubbles and reduced porosity in the fusion zone.

4. Laser-Arc Hybrid Welding

General Discussion

The laser-arc hybrid welding process presents many advantages over pure laser welding for thick steel welding. The benefits that both laser welding and arc welding bring are achievable when the two processes are coupled together[3]. For laser welding, these benefits include a higher welding speed and deeper penetration, as compared to conventional arc welding processes. For arc welding processes, one benefit compared to autogenous laser welding is that they produce a lower temperature gradient than laser welding, often resulting in improved material properties. They also offer an improved gap bridging ability, and provide transfer of filler metal by means of the arc, which can result in improved alloys in the weld region.

Several laser-arc combinations have been investigated. Tungsten Inert Gas (TIG or GTA), Metal Inert Gas and Metal Active Gas (MIG and MAG, respectively, or GMA) welds have each been investigated as the “arc” component of laser-arc hybrid welding systems. Currently, the most common laser-arc hybrid welding process in industry, according to Petring, et al, is using laser in conjunction with either MIG or MAG[1]. The process can be controlled in such a way that the MIG/MAG provides the appropriate amount of molten filler material to bridge the gap or fill the groove, while the laser is generating a vapor capillary (i.e. a keyhole) within the molten pool to ensure the desired welding penetration depth at high speed.

There have been a number of studies using both Nd:YAG and CO_2 lasers in hybrid welding processes, but Nd:YAG seems to be the current front-runner[1]. Its ability to be delivered by a fiber makes it easy to manipulate and retrofit into existing arc welding systems. Petring, et al, have noted that Nd:YAG laser radiation is less subject to detrimental interaction with the arc’s plasma, allowing use of shorter focal distance optics than CO_2 laser weld systems. Ishide, et al, also agrees that Nd:YAG laser is a better choice when compared to CO_2 lasers, noting that, because of absorption of the CO_2 beam in the plasma, expensive helium (He) shielding gas is needed to suppress the plasma in high power CO_2 applications if deep penetration is to be achieved (helium has a relatively high activation energy, and is therefore less prone than other shield gases to form a plasma)[2].

Hybrid processes have only recently (within the last five years) begun to be implemented in industry[1]. This is primarily due to the high cost of implementation, but can also be attributed to the lack of process information available. Most studies thus far have only investigated very specific parameters and applications of the process, but have not necessarily addressed a completely optimized system. Some of the results and parameters that have been researched are presented below.

Other Researchers' Results

Laser-arc hybrid welding systems in production have been successfully implemented since the year 2000 by Fraunhofer ILT[1]. The first system was used for welding cylinders and lids during the manufacture of oil tanks. The welding unit used consisted of a 5.7 kW CO_2 laser and a trailing MIG impulse arc, along with a water cooled head to permit continuous use. The material was 5 to 9 mm thick mild steel prepared by shear cut, resulting in a gap up to 1 mm, and the lids were joined with radial seams welded as butt joints to form the tank. The single-pass hybrid laser/MIG welding system was "ideal," according to Petring, et al. Another ILT system has been successfully utilized since 2002 for single-pass longitudinal joining of stainless steel tubes. This hybrid welding application was certified by Lloyd's Register in accordance with ASME Section IX Edition 2001 for single-pass longitudinal joining of stainless steel tubes with wall thicknesses between 2.4 and 14.4 mm. The welding speeds achieved at this pipe manufacturer are 10 times higher than the conventional welding process used before without the use of edge preparation.

Ishide, et al, performed MIG-Nd:YAG welding experiments in which a stable arc and a smooth bead were obtained easily compared with ordinary MIG processes, and it was possible to achieve the welding speed 2 m/min in 6 mm thick stainless steel using Ar shielding gas. Also, the same welding conditions approved successful in welding with joint gaps up to 1.5 mm. Thicknesses of 6 mm with a 2 mm gap, and 25 mm with a multi-pass weld schedule, were also achieved[2].

Ishide, et al, also performed TIG-Nd:YAG experiments in which they note that the occurrence of porosity is suppressed, in part because the diameter of the keyhole becomes larger and weld metal flow is promoted in the TIG-Nd:YAG welding, enabling discharge of porosity smoothly[2].

Sepold, et al, has noted a reduced temperature gradient with hybrid welding compared to pure laser beam welding[3]. This is a result of the additional heat supplied by the arc process, and helps achieve desirable hardness levels in the weld because of a reduced cooling rate. Efficiency advantages also include a reduction in welding time of 20-25% compared to conventional arc welding processes.

In a direct comparison between 7 kW CO_2 laser-only non-autogenous welding and the same power CO_2 laser coupled with an 8 kW MIG (welding 5 mm thick supermartensitic stainless steel), both processes were found to be industrially feasible and stable processes meeting quality demands despite some differences in their results (seam geometry, etc.)[3]. However, after X-ray testing 100% of all welds (according to DIN EN 25817 C), only hybrid welds did not show any unacceptable weld imperfections such as lack of fusion, cracks or pores, whereas the laser welds had some of these randomly distributed defects (total 1% of seam length welded).

The process can be controlled in such a way that the MIG/MAG component of the process provides the appropriate amount of molten filler material to bridge the gap or fill the groove, while the laser is generating a vapor capillary (keyhole) within the molten pool to ensure the desired welding depth at high speed[1]. The process combination increases the welding speed beyond the sum of the single speeds, and produces an increased regularity of the weld bead. Metallurgical property improvements are noted regarding hardness/toughness and diminished porosity due to the promoted escaping of gas out of the enlarged melt pool.

Pace's Results

<u>Process Parameters</u>

Pace, et al, have researched laser-arc hybrid welding as applied to joining of ultra high strength steels[8]. The hybrid method was researched to overcome challenges in joining these types of alloys with conventional welding techniques. For instance, the thermal cycle experienced during welding adversely affects the strength of the welded joint. Also, the manufacturing process of sheet steels produces distortion that causes joint fit-up problems that require a gap-tolerant joining process. A hybrid process was investigated in an attempt to achieve higher welding speeds, accommodate large fit-up tolerances, and introduce reduced heat input compared to traditional GMAW, while avoiding the extremely high cooling rates of laser welding.

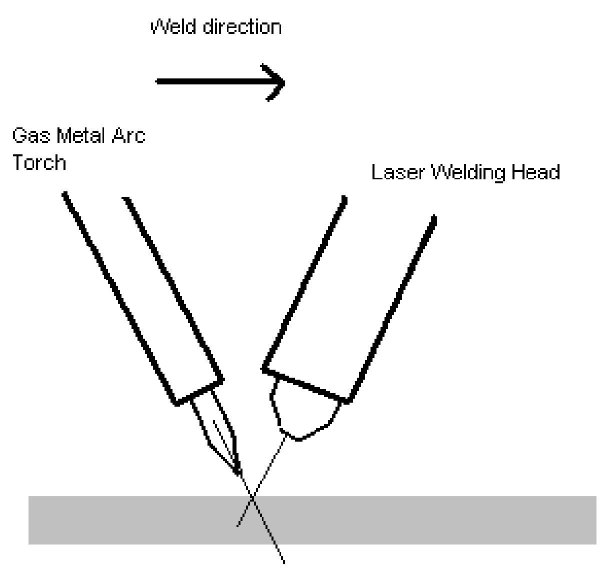


Figure 10. Pace's hybrid set-up.

The experimental setup used in Pace's study is illustrated below in Figure 10[8]. The weld head incorporates a protective lens and gas flow to protect the laser head from the gas metal arc spatter. All experiments were completed with the laser leading the gas metal arc torch.

The filler wire used was ESAB Spoolarc 120 (ER 120S-1) in 0.89 mm (0.035") diameter[8]. The laser welder was a CW Nd:YAG laser with optical fiber beam delivery and a maximum output power of 3.5 kW at the work piece. The shielding gas used for both processes was 98% Ar and 2% O_2.

Two different ultra high strength steels were selected to compare the different welding processes: ISPAT Inland's MartINsite M-190, a martensitic steel, and their DI-FORM 140T, a dual phase steel[8]. The weld joint investigated was a butt joint in the down-hand welding position. The experiments included a set of full penetration welds with laser welding, gas metal arc welding and the hybrid process to provide a comparison between the three processes.

A comparison of the cross sections for the three processes shows that the hybrid weld is in fact a blend of the two separate processes[8]. The cross section shows a much smaller heat-affected zone than the gas metal arc weld. There is also a small amount of reinforcement present which makes it superior for many designs both for improved aesthetics and mechanical properties. The cross sections show that the hybrid process combines the weld bead geometry benefits of the two parent processes. Similar results were found in experiments at ARL, and Figure 11 provides a representative illustration of this merging of processes.

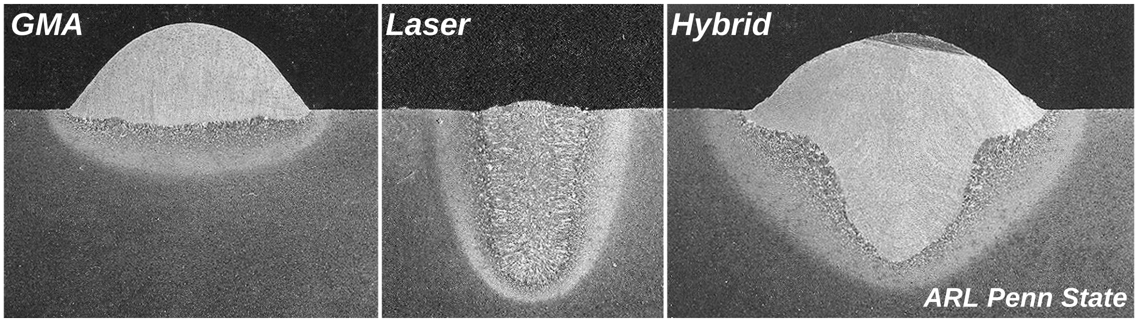


Figure 11. Cross sections illustrating the merging of laser and GMA welding processes.

The processes were also compared on evaluations of joint strength, joint ductility, gap tolerance and welding speed[8]. The results and discussion from these tests follow.

Joint Strength

Ultra high strength steels typically experience significant metallurgical degradation during welding[8]. This is caused by the large heat input from the welding process, which causes high peak temperatures and cooling rates that alter the microstructure of the base material in the heat-affected zone.

A hardness map was produced that showed that the heat-affected zone is severely softened compared to both the weld metal and base metal hardness levels[8]. The amount of the softening is directly related to the weld heat input. Mechanical tensile tests showed that the weld failed at the outer edge of the heat-affected zone in the region of lowest hardness, as revealed in the hardness map. This metallurgical degradation of the heat-affected zone is experienced with all welding processes for these ultra high strength steels. The greater the amount of heat added to the base metal by the welding process the more significant the effect[8].

In addition to the softening effect during welding, mechanical properties of the weld joint can also be related to the width of the heat-affected zone[8]. When less heat is added to the weld, the width of the heat-affected zone decreases, with the consequence that the joint cannot fully distribute the strain within the zone; higher mechanical strengths are

obtained as the strain is distributed outside the heat-affected zone into the stronger weld metal and base metal areas. This strengthened effect is known as “constraint.”
The experiments showed the martensitic steel to be more susceptible to degradation from welding than the dual phase steel[8]. Also, laser welds suffered the least amount of metallurgical degradation as exhibited by the high strength exhibited during the mechanical testing. GMA welding experienced the most degradation and exhibited the lowest strengths. The hybrid welds fall in between the two processes, as would be expected since it is a combination of the two.

Pace, et al, discusses the relationship between heat input and tensile strength[8]. Two relationships were graphed showing the effects of varying heat input two different ways: by varying the laser power with constant arc power and by varying the arc power with constant laser power. According to the data, varying the laser power while keeping the arc constant generated a plot with a much greater slope of strength vs. heat input. This shows that varying the energy supplied to the process by the laser produces a greater variation in strength than if that same energy were varied with the gas metal arc. According to Pace, et al, there could be several explanations for this phenomenon. First, increasing laser energy proportionately increases the energy density of the hybrid process. As energy is added to the gas metal arc process, the arc again becomes wider and the energy density is not increased proportionately. Second, the energy transfer efficiency of laser welding may exceed that of gas metal arc welding under these welding conditions. If this is the case, then adding a given amount of laser energy will result in more energy being absorbed into the weld than if the same amount of energy were added by the gas metal arc process.

Joint Ductility

The tests show that laser welds exhibit higher tensile strength, but also reduced ductility compared to the hybrid weld[8]. Ductility is the property of metals that allows them to be formed without fracturing. The higher ductility of the hybrid welds indicates superior formability as compared to the autogenous laser weld. This is expected since laser welds will produced a steeper thermal gradient, and therefore a faster cooling rate, leading to increased formation of martensite.

The micro-hardness tests show a reduction in hardness (relative to the base metal at each end of the traverse) in the heat-affected zones and peak hardness levels in the center weld metal region[8]. Tests also show that the hybrid weld exhibits lower weld metal hardness than the laser weld. This lower hardness leads to higher formability, with welds less likely to fracture during forming operations.

Welding Speed

The welding speed increases linearly with power input up to a point of diminishing returns beyond which a significant increase in power is required for an insignificant increase in weld speed, producing unacceptable welds[8]. The hybrid process exhibits welding speeds much higher than either of the parent processes. This is due to the higher power input gained by combining the two processes.

There are two trends present in the hybrid process that emulate the parent processes[8]. As gas metal arc power is increased with laser power held constant, the process behaves much like the parent gas metal arc welding process. It exhibits small increases in welding speed for increasing power input. On the other hand, as the laser energy is increased with the gas metal arc power held constant, the process behaves much like the parent laser welding process. It exhibits much higher increases in welding speeds with increasing power input. This leads to the conclusion that adding energy to the hybrid process with the laser is more effective at increasing welding speed than adding energy through the gas metal arc. Also, the slope of the speed vs. laser power with the hybrid process trend is much higher compared to the slope of that with the laser-only process trend. This demonstrates that adding a given amount of laser energy to the hybrid process yields a greater increase in welding speed than adding the same amount of energy to the laser process alone. This suggests some synergy between the two parent processes in the hybrid process creating a coupling effect that makes the laser energy more efficient in the hybrid process than by itself.

Gap Tolerance

To study the differences in gap bridging abilities for the three processes, a gap welding test was designed where two welding coupons were placed together with a gap set in one end as shown in Figure 12[8].

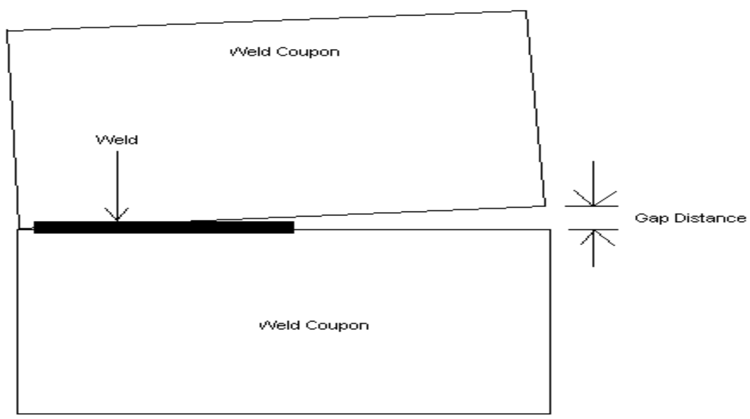


Figure 12. Gap-bridging test set-up.

This creates an increasing gap throughout the weld. Table 2 provides the results from the experiment.

Table 2. Experimental results for Pace's changing gap experiment.

Process	Maximum Gap Bridged
Laser Welding	0.35 mm (0.014”)
Hybrid Welding	0.81 mm (0.032”)
GMA Welding	0.86 mm (0.034”)

The results show that laser welding has the worst gap bridging abilities with gas metal arc welding able to bridge gaps over twice as wide[8]. Hybrid welding retains most of the bridging abilities of the gas metal arc welding. On the butt joint evaluated, the ability of the laser to bridge the gap is controlled by the diameter of the laser spot. As the gap widens, more and more energy is lost through the opening leaving less energy to melt the metal and bridge the gap. In gas metal arc welding, the gap bridging abilities seem to be mostly controlled by the diameter of the wire with the wire passing through the gap similar to laser welding. The diameter of wire used was 0.89mm (0.035”) which is very close to the bridge gap of 0.86mm). Since the combined hybrid process still utilizes the wire in the gas metal arc process it bridges gaps in a similar manner to gas metal arc welding. This indicates that the limit for gap bridging for both the hybrid and gas metal arc welding is approximately equal to the wire diameter.

It is important to note that the maximum gap bridged is NOT necessarily the maximum gap that the process is capable of welding[8]. In this experiment, the weld was started at the position in which there was no gap and welded over an increasing gap until it could no longer fuse the gap. This does not mean that the process, especially the laser process, could initiate in a gap of this size. Also, starting on a cold plate reduces melting of the exposed edges, which adds further difficulty gap bridging. The hybrid process and gas metal arc process should be able to start in gaps close to the maximum gap bridged because molten filler is being added which can bridge the gap. The laser process, on the other hand, would not be able to start in a gap near as large as the reported maximum gap bridged because there is no molten filler present when the laser is started.

Summery of Pace’s Results[8]

- The joint strength retention of hybrid welding is a compromise between gas metal arc’s low joint strengths and laser’s higher joint strengths.
- The higher ductility and decreased weld metal hardness produced by the hybrid process provides superior formability compared to the laser welding process.
- The gap bridging abilities of hybrid welding matches that of gas metal arc welding and more than twice that of laser welding for the conditions evaluated.
- The welding speed of hybrid welding is approximately 4 times greater than gas metal arc welding and 1.4 times greater than laser welding.

In addition to these quantifiable attributes, the hybrid process produces an aesthetically superior joint[8]. Furthermore, some materials experience solidification cracking problems when laser welded due to the extremely high cooling rates. Given the more moderate cooling rates of the hybrid process, solidification cracking could be eliminated.

Ishide's Results

Welding Head Configurations

According to Ishide, et al, the laser and arc can be arranged in series, as opposed to coaxially, if the welding direction does not need to be varied during the weld[2]. If this is the case, they recommend that the inclination of the arc should be as small as possible – in the range of 15^o to 30^o relative to the laser axis[1]. However, for any application involving materials with complicated shapes that would require changing welding direction, it may be desirable to arrange the laser and arc coaxially, which would necessarily require a special weld head.

In their experiments in welding SUS304 steel, the laser was initiated prior to the TIG arc. When the TIG arc was started, it was separate from the keyhole[2]. Immediately thereafter, however, the arc was 'pulled' in the direction of the laser keyhole and fixed there. They hypothesize that the arc is fixed at the beam irradiation point probably because a portion of the metal atoms in the laser weld plume are dissociated, or because an anode spot is generated by the laser. With the MIG arc, the penetration was observed to decrease if the arc and beam irradiation positions are completely unified, and the penetration increased when the beam is set at a point 2 mm forward or backward from the arc. He suggests that, when the arc and beam are unified, the laser energy is used in melting wire instead of the forming the keyhole. But if both laser beam and arc are separated by about 4 mm, penetration decreases again.

With the coaxial MIG-Nd:YAG welding, the beam is divided into two beams before being focused on the material at the spot at which the MIG wire is being fed[2]. This does not affect the shape of penetration both in the case of the focusing spot arranged transverse to welding direction and the case of the focusing spot arranged parallel to the welding direction.

Sepold's Results

In Sepold's investigation of a MIG:CO_2 hybrid welding process, he notes that the MIG arc stability is observed to be correlated to the CO_2 laser power[3]. When the laser was run at 4 kW, the arc voltage occasionally drops severely, and the current is very unstable. The arc was irregularly short-circuiting, resulting in spatter formation. When the laser power was raised to 9 kW, the arc was much more stable. In this paper, these and other power relationships are described through a series of equations. The effective arc power has the greatest influence on the variation coefficients of the arc voltage and current. Also, with higher current at higher voltages, the arc stability is increased while the mode of metal transfer shifts from short-circuiting transfer to spray transfer. However, he notes, the laser power also has a significant effect, significantly decreasing both variation coefficients for all arc powers. This is likely due to the fact the additional energy supplied by the laser contributes to stable melting.

The welding head has been subjected to severe production demands especially due to continuous welding times of several hours typical for pipe production from coil[3]. Thus, the torch has to be designed for extreme thermal loads resulting not only from the arc but from back-reflection of the laser beam, through the addition of a water cooling system.

<u>Shielding Gas</u>

Sepold notes that, for the MIG:CO_2 hybrid method, in order to avoid beam absorption or deflection effects with the CO_2 laser, helium or a mixture with high helium content may be preferred[3]. This is due to its high ionization potential suppressing such effects. (This may not be necessary with Nd:YAG laser systems.) Additionally, the MIG process usually requires an argon atmosphere and, if necessary, an admixture of active gases such as oxygen or carbon dioxide to facilitate arc ignition, stabilize the arc, and influence the seam geometry. An important note Sepold makes is that argon absorbs far-infrared radiation is known to cause CO_2 laser beam shielding effects, resulting in decreased interaction between the beam and the substrate, especially when applying higher laser powers. Therefore, the selection of an appropriate mixture of helium, argon and active gases must be established for a stable MIG:CO_2 hybrid process.

Filler wire

Sepold discusses the modes of metal transfer from the arc – namely, short-circuiting arc, semi-short circuiting arc, and spray transfer arc[3]. He concludes that due to its characteristic properties such as a high deposition efficiency and a generally spatter-free metal transfer, the spray transfer arc is appropriate for welds with high quality requirements at competitive cost and, thus, should be applied in CO_2-Laser GMA hybrid welding, too.

Fellman's Results

Shielding Gas

A gas composition for a MIG-CO_2 laser hybrid welding process, comprising helium, carbon dioxide, and argon, was experimentally optimized by Fellman[4]. The material used in the experiments run by Fellman, et al, was Rautaruukki's low-alloyed carbon steel RAEX 275 MC Laser, which is designed especially for laser cutting. Using a gas mixer, various concentrations of shielding gases, emitted from the gas nozzle of the MIG torch only, were tested. From the experiments, it was concluded that 40-50% helium content and 5-10% carbon-dioxide content is optimal. It is noted, however, that the helium content of 40-50% was enough for the 6 mm thick plates with which the experiments were conducted, but a higher helium content may be needed when a greater thickness is being welded. The helium inhibits the formation of plasma, which disturbs the penetration of the CO_2 laser (but was observed as not affecting the arc). When the helium content was raised above 50%, the stability of the process suffered, particularly due to the higher ionization potential of helium compared to argon, making the ignition of the arc more difficult and generating a more unstable arc. It also affected the penetration profile and appearance of the weld: the weld face became narrower, the root wider and the whole penetration profile smoother. These affects were also observed when the carbon dioxide content of the shield gas was raised. Carbon dioxide helps to stabilize the arc and reduces the surface tension of the weld pool, improving the fluidity of the weld and making the junction between the weld and the base metal smoother, in turn decreasing undercuts.

Some defects arose in Fellman's trials when there was an air gap in the joint, and when the carbon-dioxide content was low[4]. It was noticed that these conditions sometimes resulted in undercuts and root concavities, but the defects disappeared when the carbon-dioxide content was raised. Also, the porosity within the test-pieces was found to decrease as the helium or carbon dioxide content was raised.

It should be noted that, while Fellman's observations are especially valuable for MIG-CO_2 laser hybrid welding systems, they are not directly applicable to MIG-Nd:YAG laser hybrid welding systems, since Nd:YAG laser beams do not exhibit the same absorption characteristics in the plasma.

Travis' Results

Travis reports that a primary concern in industry is the ability to detect weld defects using real time monitoring methods. As defects propagate, production costs rise. For a system to be effective it must be reliable, flexible, and cost effective in high capacity non-clean environments. Travis states that there are various sensors for real time monitoring ranging from acoustic, plasma-based, optical (infrared, ultraviolet and x-ray), and electromagnetic. There are now commercial systems available that use different combinations of types of sensors (multiple sensor fusion).

If it is known that a particular signal value or trend corresponds to certain behaviors in the weld pool or surroundings, it is possible to use this signal to predict various characteristics of the weld. However, at this time no single sensor can reliable detect the full spectrum of the weld state. This is where the idea of multiple sensor fusion becomes important. Through the use of multiple sensors, the advantages of each individual sensor can be integrated together. Once there is sufficient evidence that a particular combination of signal outputs relates to a specific weld state, the data can be incorporated into a closed-loop feed back system. This system would evaluate the output and, if an undesirable signal occurs, the system would send a message to the welding controls in order to adjust the necessary parameters to overcome the problem.

Travis' system was designed using four sensors to detect various process characteristics during Laser-GMAW hybrid welding. Each of the sensors detected a different signal: current of the GMAW system, voltage of the GMAW system, infrared radiation, and ultraviolet radiation.

Process Sensing

The two main fundamental issues that must be addressed are the monitoring of the beam itself and the monitoring of the process. Several different approaches can be taken to gathering this information.

For beam sensing:

- optical sensors on the fiber optic delivery cable
- acoustical, thermal, and optical sensors on the guidance/focusing optics/mirrors

For process sensing:

- radiation, wavelength, size, position, stability, charge, refractive index, and acoustical noise sensors on the plasma/plume
- temperature, size, turbulence, waves, shape, penetration, and radiation sensors on the melt pool
- intensity and direction sensors on the reflected radiation
- temperature, composition, and acoustic noise sensors on the vapor in the keyhole
- temperature, stability, and position sensors on the keyhole
- direction, size, velocity, frequency, and quantity sensors on the sparks/spatter

Infra-red (IR) Sensing

Travis, *et al*, determined that weld quality could be determined by relating radiation output from the weld zone to the weld states. Quantum (photon) detectors can provide information on the temperature of the weld pool and the surrounding material. Through temperature monitoring it is possible to monitor features such as bead width and penetration.

Ultra-Violet (UV) Sensing

Understanding of ultra-violet sensing is very limited. This form of radiation ranges from 0.01 – 0.4 μm and can be associated with plasma formation. This is important because plasma formation plays such a large roll in keyhole dynamics this parameter can be expected to be affected with the addition of an arc system.

Arc Sensing

Detecting the process current and voltage can provide information about the arc process. Voltage probes, current transducers, isolation backplanes, and computers can be used to obtain current and voltage measurements.

Equipment Used

The following is a list of the equipment used for the sensing project:

- 3 kW Nd:YAG laser transmitted through fiber optic cable
- Powerwave 455/STT Lincoln Electric Welder (GMAW, 480 V 3 Phase)
- Magnum 400 Gooseneck Welding torch
- Hall Effect probe
- Signal conditioner
- 2 PDA 400 IR sensors
- Analog/Digital converter
- Resistors
- Various types of HSLA steel
- Air knives
- Oscilloscope
- PC with software including Labview and MATLAB

An arrangement of air knives were set up next to the lens and directly onto the fiber to prevent any damage to either of the two. The hybrid system was controlled by CNC code. A shield gas was fed through the GMAW welder in a 75% Argon / 25% CO_2 as well as feeding Argon with an additional cross jet.

The experimental set up can be seen in Figure 13 and Figure 14. Figure 13 shows the IR/UV sensor mounted below the GMAW torch. The air knife assembly is blue and silver colored mounted next to the black laser head. Figure 14 shows the video camera from reverse angle of the system.

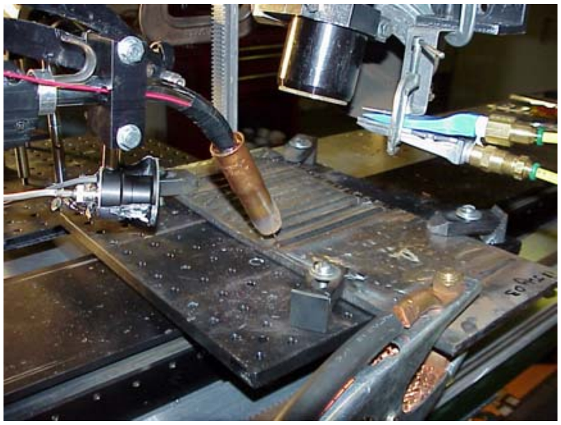


Figure 13. Monitoring system setup.

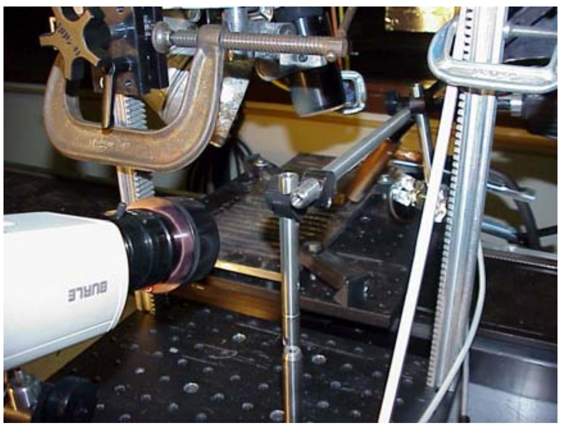


Figure 14. Reverse angle of setup.

<u>Sensing</u>

A total of four different signals were sensed during each weld; voltage across contact tip/work-piece distance, current through GMAW circuit, infrared emission, and ultraviolet emission. These four signals were collected by the respective sensors and sent through an A/D converter where LabView software acquired the digital signals. Examples of these signals can be seen in Figure 15 through Figure 16.

A voltmeter was connected in parallel with the GMAW torch system, one end on the torch end with the other on the base metal. Resistors had to be integrated into the wires leading to the A/D converter to drop the output voltage from the GMAW torch so as not to damage the equipment. These resistors decreased the voltage by a factor of approximately 10.

To sense current a CTL Hall Effect current sensor had to be used in conjunction with a CTA signal conditioner to produce the appropriate output. This sensor was placed around the GMAW torch positive cable.

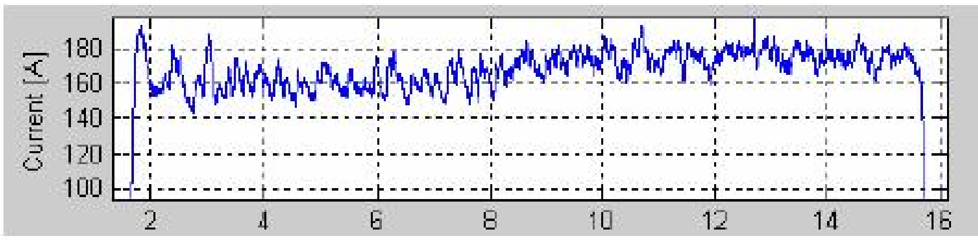


Figure 15. Current signal at 24V, 180IPM (4.572MPM).

Identical diode sensors were used for detecting the IR and UV signals. Unfortunately the sensors were more responsive to IR light, so in order to detect a UV signal a UV band pass filter was placed over one sensor and the gain was increased.

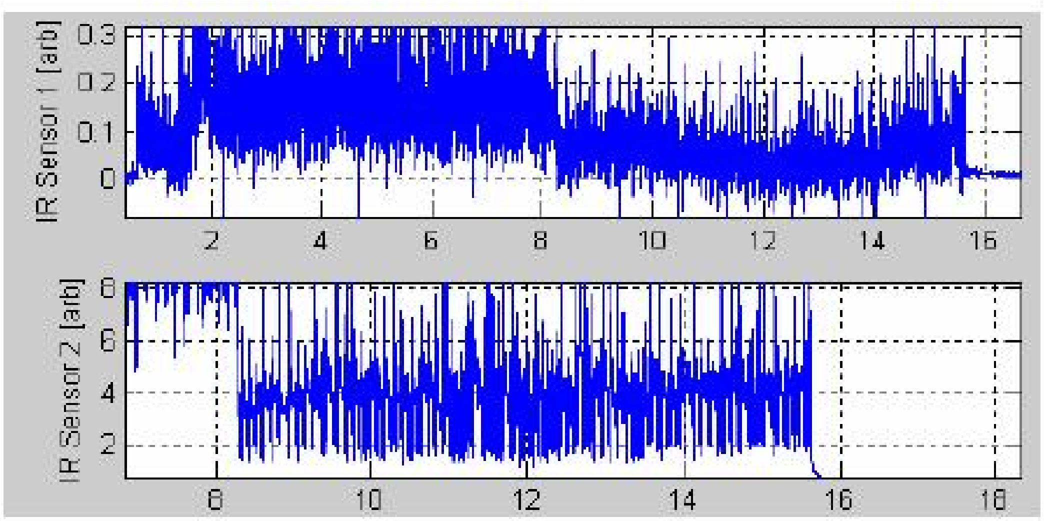


Figure 16. IR sensor on top, IR sensor with UV filter on bottom both at 24V, 180 IPM (4.572MPM).

Results

Welding

Initially Travis, *et al*, ran the process with GMAW alone to determine a weld bead profile at 180 IPM (4.572 MPM) wire feed speed, 10 IPM (0.254 MPM) travel speed and at two different voltages, 18 Volts and 24 Volts. From this it was determined that as voltage increases while wire feed rate remains constant, the bead profile widens while not increasing in height. Also with increasing voltage, penetration increases along with the heat affected zone. This can be seen in Figure 17.

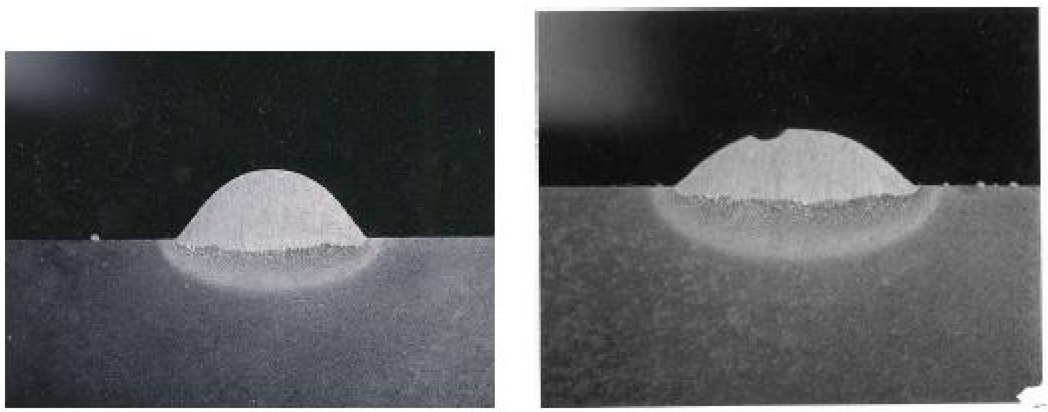


Figure 17. a) 18V, 180 IPM (4.572MPM), b) 24V, 180 IPM (4.572MPM).

Next the 3kW Nd:YAG laser was introduced to the system using an F2 focal length lens. This lens had a very short focal length and had a focused spot diameter of 0.024 inches. A test hybrid weld was then run at the same parameters as Figure 18. It was found, as seen in Figure 18, that the hybrid process has a widening and flattening effect on the weld bead when compared to GMAW.

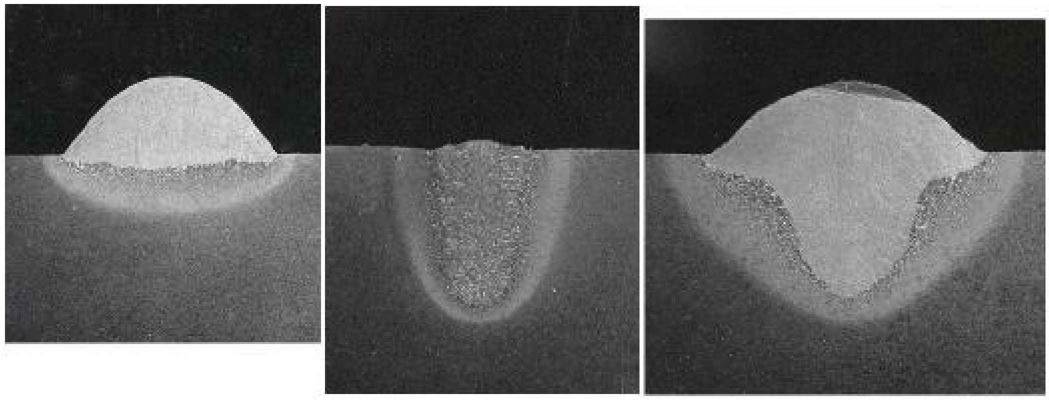


Figure 18. a) GMAW, b) 3 kW laser, c) Hybrid

It can be noted that hybrid weld is similar to a superposition of the GMAW and laser welds. Figure 19 shows a very acceptable and aesthetically pleasing weld cross section, but due to the close proximity of the lens while using the F2 focal length, it was not practical to continue using the F2 lens at the risk of damaging multiple cover glasses, the lens itself or possibly the fiber optic cable. To resolve this issue a F4 focal length lens was used. This allowed for less destruction of cover glasses, allowing for more welds per cover glass to be performed with less chance of catastrophic damage of other much more expensive laser system components. The down side to using the longer F4 focal length was that the beam spot size doubled to 0.050 inches, thus reducing the power density of the focused beam by a factor of four. A comparison of welds made with the F2 and F4 lens can be seen in Figure 19 and Figure 20.

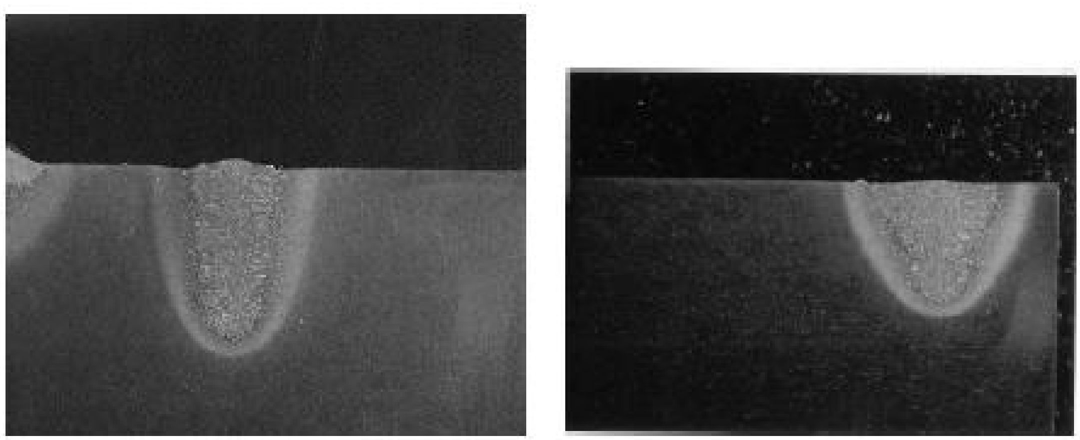


Figure 19. a) F2 lens laser weld, b) F4 lens laser weld.

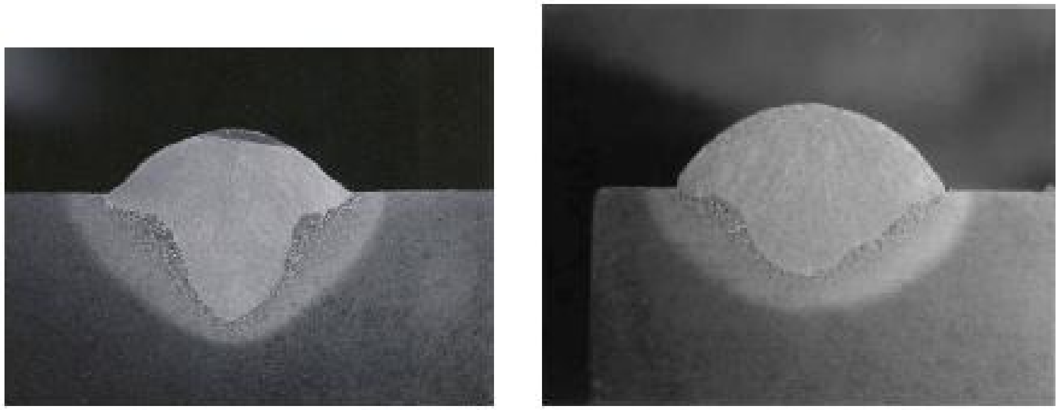


Figure 20. a) F2 hybrid weld, b) F4 hybrid weld.

Discussion

Sensing

Travis, *et al*, noted that most of the useful sensing data were based upon current, which is why not many other signals are included in his results. The GMAW power supply used was set at a constant voltage output so that any direct electrical changes were conveyed through the current signal. The IR and UV signals were very noisy and did not display suitable fluctuations or variations from which useful conclusions could be drawn, except in one case. When testing laser deactivation, the IR and UV signals showed significant effects.

Travis noted that one of the most significant findings during the sensing experiments was the increase of current when the laser was deactivated. To explain this, one theory is that the value of the current directly relates to penetration. This is because as arc length increases, as with high penetration, resistance also increases. Another theory is based on the beam interactions on the atomic level. A laser beam consists of photons that cause electrons to be stripped away when it impinges on a surface. These electrons are then absorbed directly into the beam by the Inverse Bremsstrahlung effect. It may be possible that the electrons flow across the arc and are directly absorbing photons from the beam therefore decreasing the current. The problem with this hypothesis is that if the laser is interacting in the weld zone, the extra energy supplied should decrease the resistance which from the electrical equation V = I*R (voltage = amperage * resistance) would mean that current would increase at a constant voltage.

Considering the physics of the arc, it can be divided into three regions at atmospheric pressure: the contraction, the high luminosity, and the space charge zone. The contraction zone is the transition region between the arc column and the space charge zone. It has a relatively low current density, compared to the space charge zone, which has a high current density. At the end of the transition region is the narrow high luminosity zone which has a high potential gradient that accelerates electrons away from the electrode surface and accelerates ions towards the metal surface. This space where the electrons and ions are accelerating must be kept free of collisions as the velocity or an electron or ion in the direction at right angles to the metal surface in this region depends on the energy it can acquire from the electric field. When the laser is introduced, it passes through the arc and induces multiple photon/electron collisions meaning that the energy provided by the laser must make a difference in the velocities of the electrons and ions therefore causing changes to the voltage and current in the GMAW process. As the electrons and ions gain enough energy by traveling through sufficient change in potential and are emitted, electron multiplication may take place. This is due to the ionizing collisions with the gas atoms that can occur. This multiplication leads to a large amount of electrons able to ionize at some distance from the cathode surface (metal surface). This causes the positive ions to form in large numbers in this area, which creates a strong positive space charge that leads to a voltage drop.

One thing that must be noted is that these are just theories. Due to the little understood nature of laser/arc interactions a verifiable explanation of the observed behavior is yet to be found. The main goal was to determine if it were possible to sense the presence of the laser during hybrid processes. Their data would appear to validate the claim that it is possible to sense a laser during the hybrid process.

IR and UV signals

Travis, *et al*, said “The decreasing values of IR and UV signals during the laser deactivation are two other promising changes that may be useful in sensing, The fact that both of these signals also increase with MIG voltage for both halves of the weld may make they suitable candidates for integrating with a current sensor for sensor multiplexing.” Although their results proved inconclusive for many tests, there is still promise that IR and UV signals could be used in the sensing process with further refinement.

Sensing laser position

A correlation between laser and GMAW separation distance and placement (either laser leading arc or arc leading laser) could be sensed to a point. When the laser trailed the arc, current signals decreased as separation distance decreased. This is suspected to be due to the laser penetration increasing arc length. This could explain why with the laser leading the arc, there was very little change in current relative to separation distance. Most likely this is because with the laser leading the electrode the path of least resistance is through the arc, which would lead to deeper weld penetration and a decrease in current. It should also be noted that there is the possibility that although with the laser leading, the current did not increase but the resistance could have been changing due to the interference of the laser.

Surface contaminants

Travis, *et al*, noted that it has already been proven that the current drops when an arc weld passes over a contaminated area. Their results only further supported the fact that surface contaminants can be sensed in both GMAW and hybrid processes.

Arc stabilization

A GMAW arc becomes unstable when the wire feed speed is too high for the voltage being supplied. This causes the electrode to make contact with the base metal causing short circuits and erratic responses. With the addition of a laser to an unstable GMAW process, Travis, *et al*, found that the laser was melting the electrode before it could make contact thus making the process less erratic or more stable.

Other comments

On a final note, it should be stated that the physics of arc and laser welding are both very complex and not completely understood. This makes it difficult to fully understand the physics of the two processes occurring simultaneously in the same space.

EWI-NJC Results

<u>Introduction</u>

The Edison Welding Institute (EWI) along with the Navy Joining Center (NJC) set out to perform a project to investigate hybrid laser welding. They compared autogenous laser welding with GMAW with hybrid laser/arc welding. The motivation for this endeavor is to be able to fabricate stiffener structures for ships.

Currently, hot rolled structural steel components are the most common stiffeners for general shipyard use. Because these stiffeners are being rolled in mass production, preferred dimensions may not be available, which results in the need to use larger and thicker stiffeners that add unnecessary weight. These stiffeners most often come from H beams that have one flange physically removed, which results in excessive generation of scrap and distorted T beams. Additionally, there are few high strength steels that are rolled into these necessary structural shapes.

An alternative to modifying these existing rolled structures is to fabricate them in a more specialized manner. The proposed approach uses only flat plate cut down to size and then welded to produce the necessary T beam. In the past, the process used to weld the structures has been arc welding. This has only been feasible in producing thick structures, which aren't prone to distortion by the relatively large amount of heat generated in conventional arc welding. Therefore, fabricating large quantities of thin structural components with arc welding becomes impractical because of distortion, fatigue, and mechanical performance. The thin structures require accurately controlled heat input, without which leads to out-of-shape beams that contribute to fit-up problems later in assembly. Fatigue also becomes an issue, as the weld surfaces can act as stress risers that decrease the structures strength and lifetime. Lastly the heat input of the arc welding process alters the microstructure of the metal and consequently alters the mechanical performance.

It is possible to produce structures such as these with an autogenous laser, however as stated in previous sections, laser welding has its benefits and drawbacks. The benefits of flexibility, low distortion, and high processing rates would indicate that it would be easy to fabricate difficult structures with minimal distortion at high processing rates. However, it is difficult in practice to achieve the required gap fit-up tolerances, typically less than 0.012inches (0.3mm). Dealing with this issue can be expected to result in lower production rates and higher operating and equipment costs than extrapolated form results achieved in a laboratory setting. Additionally, early work was performed on low carbon/low strength steels that tended to be "laser friendly". This is not true for the higher strength steels.

EWI-NJC stated that there has been success in Europe with hybrid welding, but it was not proven whether the approach would be compatible with the new alloys the U.S. Navy was considering. Their project was formulated to address this issue, with special attention to weld metal and HAZ hardness, weld joint toughness, and distortion.

The goals of the project were to:

1. Determine if hybrid welding could be used to join U.S. Navy materials and meet typical performance requirements.
2. Evaluate whether hybrid welding could be used under conditions that would be typical for shipyard applications
3. Compare the distortion developed by the hybrid welding process and compare to arc and laser welding.
4. Evaluate the ability and advantages of hybrid welding for the joining of common piping materials used in U.S. Navy ships.
5. Contrast the cost for using hybrid welding and determine what economical justification there may be to use the process.

Special focus was put on these materials:

- Plate materials
    - Alloys: DH-36 and HSLA-65
    - Thickness: 6.32 mm (0.25 in.) and 12.7 mm (0.50 in.)
    - Joint designs: Butt and Tee
    - Edge preparations: laser cut, machined, plasma cut

- Pipe materials
    - Alloys: Cu-Ni, carbon steel, stainless steel
    - Thickness: no greater than 9.53 mm (0.375 in.)
    - Edge preparations: machined

Three steps were taken in evaluating the hybrid performance.

1. Specimen fabrication: Standard test specimens were produced with material that was prepared by conventional means of laser cutting, plasma cutting, and machining. Typical filler metals were used on the alloys being welded and fit-up and fixturing was standard.

2. Weld evaluation: Upon completion of the welds, the specimens were inspected and evaluated on the following criteria:

- Type of defects (pores, cracks)
- Lack of penetration
- Undercuts
- Distortion
- Profile of weld (amount of reinforcement, bead profile)
- Metallurgy (microstructure)
- Mechanical Properties (Yield strength, Ultimate Tensile strength, Elongation)
- Hardness
- Toughness (Charpy V-Notch (CVN))
- Bend Tests

3. Process analysis: During fabrication, weld parameters were monitored to determine requisite costs that were associated with the weld process system. The parameters monitored were welding parameters, material preparation methods, alignment and fixturing methods, and other economic impact factors.

Discussion

Surface and Edge Preparation

Most of the material was received with a primer coating or was lightly corroded. The area to be welded was ground 25.4 mm (1 in.) on each side of the weld joint and wiped clean of any dust or particulate. A 6 kW CO_2 laser with transmissive optics and co-axial assist gas was used to cut edges. Machined edges were also produced, especially for the pipe joints and autogenous high powered laser welds. Light grinding was then used on the edges to remove any high points or loose material. In order to closely replicate shipyard procedures, this procedure was not performed with the goal of removing any oxide that may have formed on the cut surface. Plasma cut edges were assumed to be similar to or better than the laser cut surfaces in roughness, surface slag, squareness, etc. so only laser cut and machined edges were used in the trials.

Joint Configuration

The two joint configurations that were of interest were butt joints and tee joints. The butt joint was the most sensitive to laser welding, and if there were a gap between the plates or vertical mismatch the resulting weld would be of poor quality. This was because if the gap were sufficiently large, the laser would simply pass right through making no visible weld.

Fixturing and Positioning

The plates were GMAW tack welded to insure that they remained in consistent position. Some plates were fitted with preset gaps before tacking. The same occurred for the tee joint specimens. They were positioned and aligned for squareness, then clamped and tacked. Some tee specimens were also fitted with initial gaps and then tack welded.

For welding the paths were taught and interpolated by a robot for the Nd:YAG system and a CNC for the CO_2 system. For the tee specimens the flange was mostly positioned perpendicular to the horizontal plus 10º or 15º. The laser beam was then positioned to the web side of the joint equal to the distance of the focused spot size of approximately 0.60 mm (0.023 in.) with the GMAW head 45º between the web and flange and pointing forward 45º.

A similar procedure was used for tacking for the pipe specimens. The pipe specimens were then placed into a rotating chuck and held in the 1G-position. The laser was aligned approximately at 1 o'clock and the specimen was rotated. The rotation for the autogenous welds was in a vertical up motion while the hybrid welds were in a vertical down motion.

Hardware

Two laser systems were employed: a 6 kW CO_2 laser and a 4 kW Nd:YAG laser. The CO_2 laser used a reflective beam delivery system while the Nd:YAG laser used a fiber delivery system. The CO_2 laser and GMAW assembly was held stationary while the part was moved beneath it, while the Nd:YAG laser and GMAW assembly were attached to a robot and the part was fixed.

For this project, hybrid systems were developed instead of being commercially purchased. The hybrid systems were almost completely interchangeable between the CO_2 and Nd:YAG systems. A standard 450-amp direct current (DC) arc welding power supply system was used for both systems with a push-pull wire feed system. The GMAW torch was standard and able to feed both 1.14 mm (0.045 in.) and 0.89 mm (0.035 in.) wire. The torch also designed with positioners for X and Y adjustment along with a pivot for angle adjustment and a retractor extender for adjusting contact-tip-to-workpiece distance.

Process Development

Processing parameters were developed that examined the following:

- Plate material – DH-36 and HSLA-65
- 6.35 mm (0.25 in.) and 12.7 mm (0.50 in.) thick materials
- Piper materials – carbon steel, stainless steel, Cu-Ni
- Single pass (6.35 mm (0.25 in.)) and Two pass (12.7 mm (0.50 in.)) welds

- Butt and Tee joint configurations
- Machined and laser cut edge preparation

Most of the processing was accomplished at a wire deposition rate of 2.9 kg/hr (6.4 lb/hr). Variables for the hybrid welding process were:

- Voltage
- Current
- Welding speed
- Wire diameter
- Wire feed rate
- Torch angle
- Shielding gas, type and feed rate
- Location of focused laser spot
- Location of laser beam with respect to weld pool
- Angle(s) between laser beam, arch torch, and material being welded
- Direction of processing (laser leading or GMAW leading)
- Location of focus with respect to weld pool surface

Evaluation Guidelines

Although the guidelines used ("Guidelines for the Approval of CO_2 laser Welding") did not cover hybrid welding, many of the procedures addressed must have been accomplished for qualification of laser welding in commercial shipyards. Based on the guidelines, if a weld measured over 300 Vickers Hardness Number (VHN) the weld was to be noted. If the weld measured over 350 VHN the weld was not acceptable. For toughness it was assumed that for the hybrid process due to the addition of heat and filler metal to the weld that there should have been a positive impact. Distortion was measured by comparing the distortion of the post-tacked, pre-welded specimens to the uniform weld penetration post-welded specimens. Visual inspections were performed for penetration, porosity, cracks, and bead profile. If a weld visually appeared acceptable it was then radiographed for internal defect analysis and metallographically examined. The primary concern was to compare autogenous to hybrid welds.

Results

- Hybrid Processing
  - Hybrid hardware was successfully developed for laser welding with Nd:YAG and CO_2 lasers
  - Hybrid processing parameters were successfully developed for DH-36 and HSLA-65 alloys

- Processing Characteristics
  - The hybrid processing was superior to arc welding for the following reasons:
    - Hybrid welding could accomplish a full penetration weld through 6.35 mm (0.25 in.) plates at speeds at least 100% faster than arc welding
    - Hybrid could be achieved with machined and laser cut edges
    - The amount of distortion in the hybrid processing was at most equal to the GMAW process
  - The hybrid process had the following advantages over autogenous and autogenous with cold wire filler laser welding:
    - Hybrid processing can accommodate over 1.5 mm (0.060 in.) gaps in butt welds
    - Hybrid welding can be used with most laser, plasma and flame cut edges, which cannot be accomplished by autogenous laser welding
    - Hybrid welding can be used to produce fillet welds in tee structures that are no possible with autogenous laser welding
    - Hybrid welds were less likely to “miss” the joint than autogenous welding
    - Hybrid processing could either increase the penetration or processing speed versus autogenous welding by a factor of 15% to 50%

        - Hybrid welding has an advantage over cold wire filler laser welding in that it is less sensitive to wire alignment and heat is not lost to melting the wire, this results in higher processing speeds for the hybrid process

- Mechanical properties
    - The hybrid welds were found to have bend and tensile test results equal to those of GMAW
    - The hardness values for the HAZ and the weld metal averaged below 300 VHN
    - The CVN values for the hybrid welds were higher in comparison to the autogenous laser welds and in many cases were equal to the results for the GMAW welds

- Economic Justification
    - The advantages of the different lasers were the following:
        - 4 kW Nd:YAG laser was higher in cost than the 6 kW CO_2 laser but lower than the cost of a 14 kW CO_2 laser
        - the 4 kW Nd:YAG laser, because it can be fiver delivered, could use simple delivery systems which cannot be accomplished by CO_2 lasers
    - Based on an increase in processing speed alone, which may be double that of GMAW, this was enough to justify the use of hybrid processing
    - The use of hybrid processing could decrease the need for precision processing of weld joint edged. This would have an economic advantage over the beveling that would be required for the GMAW welds and the tight tolerance for joint fit up of the autogenous welds.
    - Based on pervious studies there are additional factors such as part fit-up and material savings to consider in the economic justification of whether to use the laser process
    - At least one European Shipyard, Meyer Werft in Germany, has justified going totally to hybrid laser welding for panel sheet and stiffener to sheet welding using 12 kW CO_2 lasers. This is being done with precision cut edges.

- Other observations
    - Hybrid welding is being examined by a number of potential users for welding thick section components. This includes industries involved in fabricating heavy section welds for construction equipment, and oil and gas pipelines.
    - There are also efforts underway in the automotive industry to use hybrid welding to address fit-up issues associated with stamped parts and to alloy weld metal for higher strength alloys
    - Hybrid processing has potential for use with other alloy welding where cooling rate and/or weld metal chemistry are factors

Conclusion

The use of hybrid welding may be the only approach for laser welding the Navy's high strength materials. This is based on part fit-up, mechanical properties, processing rates, and equipment costs. If most of the welding to be accomplished was less than 6.35 mm (0.25 in.) in thickness, the 4 kW Nd:YAG laser with hybrid would be the most economical based on equipment and processing costs. The use of a 6 kW CO_2 laser has the advantage of being able to cut and weld (hybrid) with the welding limitation being approximately 9.5 mm (0.375 in.).

5. Success of Hybrid Welding in Industry

Hybrid welding is an attractive solution to welding needs in many large industries such as automotive and shipbuilding. Due to the speed, accuracy, and automation abilities of hybrid welding, production speeds can be increased many times over. With hybrid welding, neither the precise fit up required of autogenous laser welding nor the multiple passes required of conventional arc welding are necessary. Hybrid welding can bridge gaps just as well as create much less distorting heat than standard arc welding, penetrate just as deep as laser welding, and still produce superior quality in the heat affected zone, weld geometry, weld chemistry, and weld strength.

Jos. L. Meyer BmbH Shipyard results

Manufacturing system and use

According to Meyer shipyard, laser arc hybrid welding can be used to drastically reduce production time as well as material consumption. Within the shipbuilding yard, Meyer had installed four multiaxis hybrid welders. The initial high cost of machinery and the higher costs of laser welding energy compared to traditional GMAW welding have been counterbalanced by the increase in welding speed, elimination of secondary operations and the reduction of filler metal consumption. This resulted in lower overall operating costs for Meyer.

Using traditional fabrication methods, the high heat used in joining of ship panels was sufficient to buckle, warp, and push the plates out of square. This resulted in the need to secondarily work the plates, flattening and filling large warp and shrinkage gaps. Meyer, in an effort to shorten build times, looked for a method that would allow prefabrication of 65 by 65 foot panels from 13 by 32.5 foot plates up to 5/8 inch thick. To achieve this with traditional GMAW processes, full penetration could not be achieved without multiple pass welds and distortion. The plates had to be welded halfway through and flipped to achieve full penetration without distortion.

Working with the Institute for Laser Technology in Aachen, Germany, Meyer sought to expand laser use into large plate production. Previous fabrication of I-core panels by use of laser welding yielded small shrinkage and good weld seam properties. Hermann Lembeck of Meyer set out to determine necessary parameters to achieve precise welds in large thick plate. It was found that in long welds, gaps distort up to a millimeter even with heavy clamping equipment, requiring filler metal to fill the gap. A sensing system was added to control wire feeding, compensating for gap changes by adding more or less filler wire. This helped to maintain welding speeds.

Through the use of lasers, Meyer was able to severely impact his processing times as well as costs. Weld speeds of 118.8 inches per minute (IPM) (2.5 – 3 meters per minute) (MPM) could be attained on plates up to ¼ inch (6mm) thick. The thicker 5/8 inch (15 mm) plate could be welded at speeds up to 47 IPM (1.2 MPM). The more accurate welding also led to less time spent flattening and fitting plates together, which Lembeck said he consider a significant advantage over the conventional methods. Due to the much smaller weld edge angle of the laser (6 degrees compared to 30 – 45 degrees for GMAW) filler wire consumption was reduced by 80%. “Welding procedures previously done largely by hand, or at best with certain mechanical aids such as tractors [robots], now are performed automatically. This saves us time and has improved quality. In general I would say that we have reformed the entire process of prefabrication,” said Lembeck.

6. Summary

The focus of this paper was to provide a review of literature that details the recent efforts of researchers investigating and experimenting in the laser and hybrid laser arc welding area. This effort provided a groundwork for designing the experiments performed in this project. It can also serve as a guide for those wishing to implement laser and laser-GMA hybrid welding of thick steel sections.

This project is focused on exploring alternative welding techniques that could potentially produce thick section welds in a single pass, thus improving production rate and decreasing the likelihood for weld defects as compared to multi-pass techniques. The proposed solutions include high-power laser welding, and hybrid laser-arc welding. Some of the general tips and rules-of-thumb offered by the various researchers reviewed in this report are outlined below in bullet form for easy reference.

High Power Laser Welding of Thick Sections

- CO_2 laser beams are absorbed in plasma escaping from the keyhole thus limiting the effective penetration, so high-ionization process gases, such as helium, are desired – this effect is not so pronounced with Nd:YAG laser beams
- Changes in nozzle shape, size, orientation and gas flow rate all affect penetration depth and weld bead geometry – 2 mm diameter nozzle is a good starting point
- Nitrogen may work with Nd:YAG laser beams, but not CO_2 laser beams – but may have an alloying effect
- Reported autogenous laser weld penetration is 15 mm for 7.6 kW Nd:YAG laser at 2 m/min travel speed
- Pulsing may offer certain advantages in process stability
- High thermal gradient associated with deep keyhole penetration can result in formation of brittle alloys and sometimes results in centerline cracking
- Welds can be autogenous (without wire) or with added wire, typically cold-fed

- There is some evidence that it is better to feed wire in perpendicularly to the surface, and incline the beam – less disturbance to weld pool and not as sensitive to positioning
- Increasing wire speed decreases penetration
- Long focal length, while offering benefits in system configuration, produces a larger spot size, leading to lower energy density and therefore decreased penetration and/or weld speed
- Long focal length may not work in overhead welding, due to large molten puddle
- Multiple beams can be employed in transverse or longitudinal configurations – transverse offers improved wetting of the gap walls
- Porosity may be due to coalescence of smaller pores found in the base metal
- Porosity can be reduced by decreasing the heat input per unit length
- In certain alloys, hydrogen dissolution may contribute to formation of pores
- Porosity may also be called by turbulent flow in the keyhole and keyhole collapse
- Gas bubbles formed tend to drift up due to buoyancy forces, so if a molten puddle last longer, it may provide time to gas bubbles to escape prior to solidification
- If porosity exists, it may be possible to use a second pass in order to further coalesce bubbles into large bubbles with a larger buoyant force
- Multiple lasers can be employed to help reduce porosity, since additional heat allows more time for bubbles to escape prior to solidification

Hybrid Welding

- Laser can be combined with GMA or GTA welding process, though GMA offers the added advantage of direct introduction of filler material
- Addition of filler material can result in beneficial alloying
- GMA welding wire can be used to bridge gaps
- Additional heat from either GMA or GTA welds can be used to reduce thermal gradients, resulting in less brittle heat affected zones and higher ductility

- Additional heat can also yield a larger and longer duration weld puddle, enabling pores and gas bubble adequate time to rise to the surface prior to solidification, resulting in decreased porosity
- Nd:YAG lasers offer advantage over CO_2 lasers of being fiber delivered, enabling easy retrofit into existing GMA workcells
- Nd:YAG lasers are less prone than CO_2 laser to be absorbed in low ionization energy GMA welding gases
- Helium and carbon dioxide shield gas mixtures can be used for effective CO_2 laser beam hybrid welding
- Voltage and current sensing can be effective in monitoring the laser-GMA hybrid welding process

References

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3. G. Sepold, C. Thomy, T. Seefeld, M. Schilf, F. Vollertsen, R. Hoffmann: CO_2-Laser GMA hybrid welding – aspects of research and industrial application. Proceedings of the Second International WLT-Conference on Lasers in Manufacturing. June 2003.

4. A. Fellman, P. Jernström, V. Kujanpää: CO_2-GMA Hybrid Welding of Carbon Steel – The Effect of Shielding Gas Composition (308), presented at ICALEO 2003.

5. F. Coste, F. Janin, L. Jones, R. Fabbro: Laser Welding Using Nd:YAG Lasers up to 12 kW Application to High Thickness Welding.

6. C. H. J. Gerritsen, C. A. Olivier: Optimization of Plasma/Plume Control for High Power Nd:YAG Laser Welding of 15mm Thickness C-Mn Steels. 6th International Trends in Welding Research Conference Proceedings, 15-19 April 2002, Pine Mountain, GA, ASM International, 2003.

7. H. Zhao, T. DebRoy: Pore Formation during Laser Beam Welding of Die-Cast Magnesium Alloy AM60B – Mechanism and Remedy. Welding Research Supplement, pp. 204-209-s. August, 2001.

8. T. Ishide, S. Tsubota, M. Nayama, Y. Shimokusu, T. Nagashima, K. Okimura. 10 kW Class YAG Laser Application for Heavy Components. High-Power Lasers in Manufacturing, Proceedings of SPIE Vol. 3888. 2000

9. D. P. Pace, K. L. Kenney, D. L. Galiher. Laser Assisted Arc Welding of Ultra High Strength Steels. 6th International Trends in Welding Research Conference Proceedings, ASM International. April 2002.

10. Tommi Jokinen, Miikka Karhu, Veli Kujanpää. Welding of Thick Austenitic Stainless Steel Using Nd:Yttrium-Aluminum-Garnet Laser with Filler Wire and Hybrid Process. Journal of Laser Applications, v. 15, # 4, pp. 220-224. Nov 2003.

11. Daniel Travis. Process Monitoring of Laser-Arc Hybrid Welding. Thesis report, September 18 2003.

12. Paul Denney, Larry Brown, Mike Fallara, and Brandon Shinn. EWI: Hybrid Welding of Ship Structures. Final Report Project No. 44522GTH, Jan 2003.

Appendix E – NSRP Panel Review Presentations

NOTE: Appendix E contains the full presentations from Project Updates presented at NSRP SP-7 Meetings in February and September 2004. It is believed that that some may find the figures and illustrations useful, though they have not been included in the body of the report.

Although in some cases, duplication of slides has occurred, the full presentation was nonetheless included for completeness.

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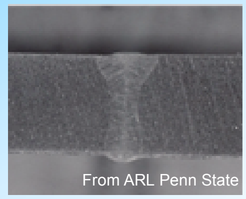
NSRP Laser Pipe Welding Investigation

Status Update



Mr. Ted Reutzel
Mr. Eli Gwinn
Mr. Jay Tressler
Applied Research Laboratory
Pennsylvania State University
Mr. Mike Sullivan
National Steel and Shipbuilding Company

Presented at:
NSRP SP-7 Meeting
Chattanooga, TN
February 2004

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Project Objective

Evaluate recent advances in laser welding technology applied to shipyard pipe welding.

- High-Power Nd:YAG (or Fiber Laser)
- Laser/GMA Hybrid Welding

Consider:

- Capability & Quality
- Cost

Outline

- Project Plan
- Shipyard Piping Survey
- Literature Survey
  - Autogenous High Power Laser
  - Hybrid Welding
- Weld Test Plan
- Other Considerations
- Summary

Project Plan

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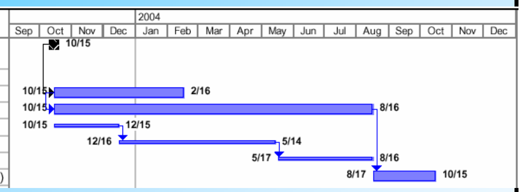
Project Plan

ID	Task Name
1	**NSRP Laser Pipe Welding**
2	**V. 1 - 28 Aug 2003**
3	1. Determine shipyard piping requirements (Nassco)
4	2. Conduct Weld Tests (ARL)
5	2.1. Perform Literature Survey
6	2.2. Produce Laser Welds
7	2.3. Perform NDT and Mechanical Tests
8	3.0 Detailed Cost Analysis and Final Report (Nassco & ARL)



- Task 1: Determine Piping Requirements (Feb 04)
- Task 2: Conduct Weld Test (Aug 04)
  - Perform Literature Survey (Dec 03)
  - Produce Laser Welds (May 04)
  - Perform NDT and Mechanical Testing (Aug 04)
- Task 3: Detailed ROI Calculation and Final Report

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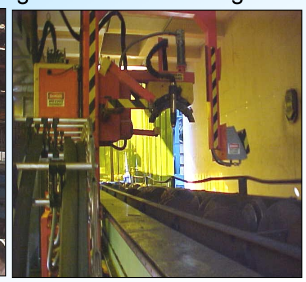
Shipyard Piping Survey

NASSCO

Pipes are Received

Cut to length in Plasma Cutting Cell



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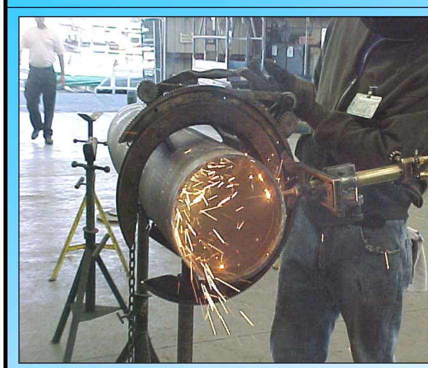
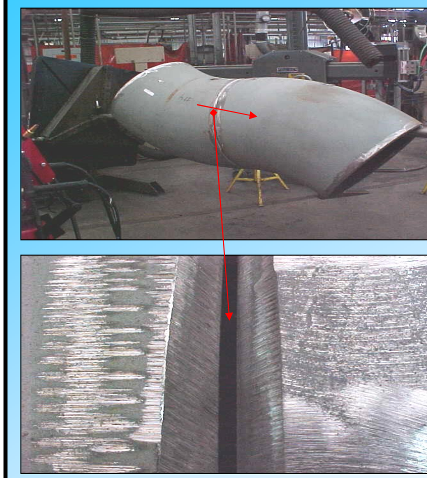
NASSCO



Beveled with Oxy-Fuel Gas Cutting Units

Weld ends are manually ground

NASSCO



Conventional processes require a gap.

<u>Not acceptable for laser processing</u>

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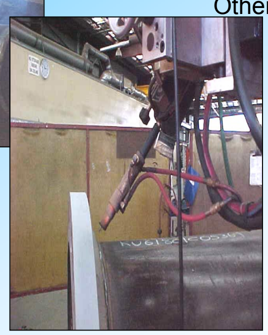
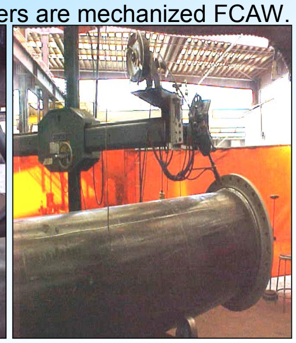
NASSCO

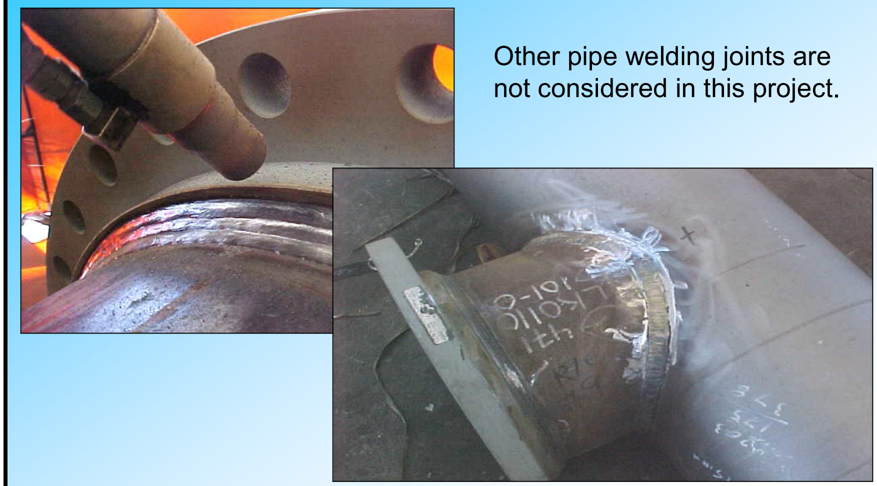
Some welds are manual semi-automatic FCAW

Others are mechanized FCAW.





NASSCO



Other pipe welding joints are not considered in this project.

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Questionnaire Responses

- Questionnaires sent to shipyards
  - Pipe joint specifications and processing time
  - Cost per year
  - Welding time per year
- Responses varied dramatically
  - Materials:
    - Stainless Steel – ¼ to 1 ½ in., 8 to 10 in., > 24 in.– 1 to 3+ hrs
    - Copper Nickel – 6 in. to 10 in. – 1-3 hrs
    - Carbon Steel – 10 in. to 14 in. – 10 to 12 hrs
    - Titanium
    - Wall thicknesses varied from 0.237 in. to 0.500 in.
  - 25 man-years to 200+ man-years

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Literature Survey

Literature Search

General Pipe Welding Information

1. P. A. Blomquist, W. G. Rhoads, J. T. Tressler, M. S. Brought, K. C. Meinert, Jr., D.H. Hardy: **Laser Welding of Piping Systems Screening Program**, October 30, 1996, ARL Technical Memorandum File No. 96-149.
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3. R. Thompson: **Evaluation of the Autogenous Automatic Gas Tungsten ARC Welding Process for Ship Tubing/Thin-Wall Piping Systems**, Mare Island Naval Shipyard Technical Report, Project 138-5-90, August 1994.

Hybrid Welding for Thick Sections – Processing Parameters

4. A. Fellman, P. Jernström, V. Kujanpää: **CO_2-GMA Hybrid Welding of Carbon Steel – The Effect of Shielding Gas Composition** (308), presented at ICALEO 2003.
5. T. Jokinen, M. Karhu, V. Kujanpää: **Welding of Thick Austenitic Stainless Steel Using Nd:YAG-Laser with Filler Wire and Hybrid Process**.
6. P. E. Denney, L. Brown, M. Fallara, B. Shinn: **Hybrid Welding of Ship Structures**, EWI final Report, January 27, 2003.
7. T. Jokinen, M. Karhu: **Narrow Gap Hybrid Welding of Thick Stainless Steel** (309), presented at ICALEO 2003.
8. D. Petring, C. Fuhrmann, N. Wolf, R. Poprawe: **Investigations and Applications of Laser-Arc Hybrid Welding from Thin Sheets up to Heavy Section Components**, presented at ICALEO 2003.
9. E. Schubert, B. Wedel, G. Köhler**: Influence of the Process Parameters on the Welding Results of Laser-GMA Welding**.
10. T. Jokinen, M. Karhu, V. Kujanpää: **Welding of thick austenitic stainless steel using Nd:yttrium-aluminum-garnet laser with filler wire and hybrid process**, *Journal of Laser Applications,* Volume 15, Number 4, November 2003. Edison Welding Institute: **Hybrid Laser Welding for Shipbuilding Applications** – Plan of Action and Milestones, TDL Reference No. TDL-00-04, NJC/EWI Project No. 44522GDE, December 12, 2000.

Incidentally, in steels, the Nd:YAG wavelength (1.06 microns) is absorbed almost twice as much as CO_2 wavelength (10.6 microns).

Also, CO_2 wavelength is absorbed more readily by the plasma, so choices for effective (and cost affective) shield gases are limited.

Literature Search

High Power Laser Welding for Thick Sections – Processing Parameters and Elimination of Porosity

1. F. Coste, F. Janin, L. Jones, R. Fabbro: **Laser Welding Using Nd:YAG Lasers up to 12 kW Application to High Thickness Welding**.
2. T. Ishide, S. Tsubota, M. Nayama, Y. Shimokusu, T. Nagashima, K. Okimura: **10 kW Class YAG Laser Application for Heavy Components**, Proceedings of SPIE Vol. 3888 (2000).
3. J. O. Milewski, M. B. Barbe: **Modeling and Analysis of Laser Melting within a Narrow Groove Weld Joint**, Supplement to the *Welding Journal*, April 1999.
4. A. Matsunawa, J. Kim, S. Katayama: **Porosity Formation in Laser Welding, Mechanisms and Suppression Methods**, Section G-ICALEO 1997.
5. H. Zhao, T. DebRoy: **Pore Formation during Laser Beam Welding of Die-Cast Magnesium Alloy AM60B-Mechanism and Remedy**, Supplement to the *Welding Journal*, August 2001.

Hybrid Welding in Industry and General Purpose

6. H. Staufer, M. Rührnößl, G. Miessbacher: **LaserHybrid Welding and LaserBrazing: State of the Art in Technology and Practice by the Examples of the Audi A8 and VW**-Phaeton, Fronius International GmbH, Weis – Austria.
7. C. Bagger, F. Olsen: **Comparison of Plasma, Metal Inactive Gas (MIG) and Tungsten Inactive Gas (TIG) Processes for Laser Hybrid Welding** (302), presented at ICALEO 2003.
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15. T. Ishide, Y. Hashimoto, T. Akada, T. Nagashima, S. Hamada: **The Latest YAG Laser Welding System Development of Hybrid YAG Laser Welding Technology**, Section A-ICAELO 1997.
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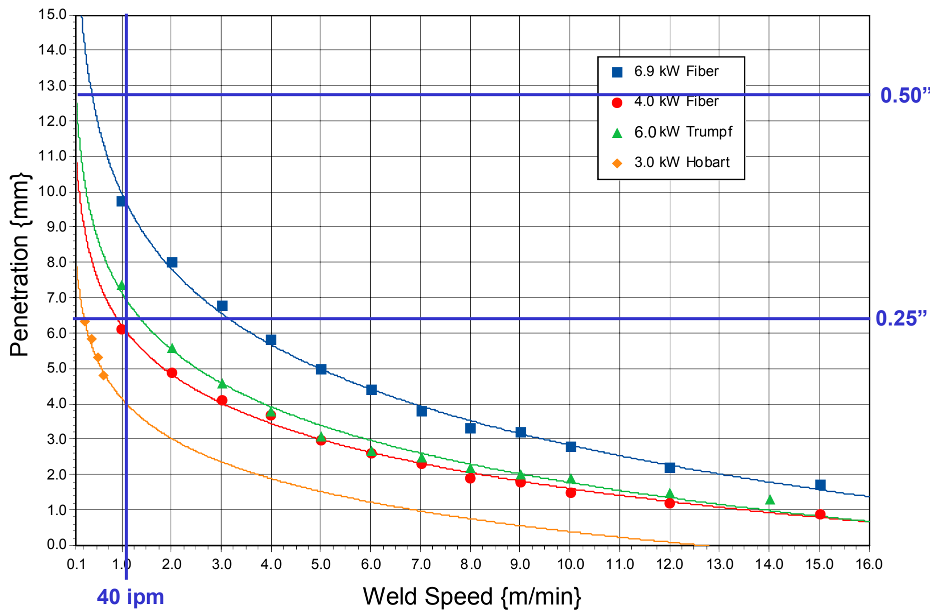
Autogenous High Power Laser Welds

Laser Comparison

Carbon Steel



Ballpark Prices

6.0 kW Trumpf HLD 4506 – Fiber Delivered
→ approx. **$680,000** (without chiller)

6.0 kW IPG Photonics Fiber Laser
→ approx. **$850,000** (air cooled)

10 kW IPG Photonics

Trumpf HL4006D

Trumpf Fiber & Welding Optics

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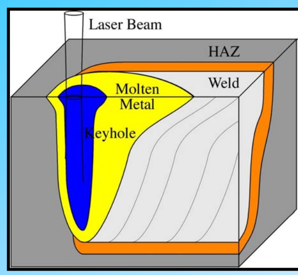
Thick Section Autogenous Laser



- Porosity
  - Contamination (oxygen, nitrogen, hydrogen)
  - Base material pore coalescence (castings)
  - Keyhole instability leading to collapse
- Preventing porosity
  - Manage contaminants
  - Shield Gas
  - Defocus beam
  - Weld faster to stabilize keyhole
  - Adjust angle to stabilize keyhole
  - Pulse shaping
  - Beam oscillation
  - More heat so porosity has time to escape

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Thick Section Autogenous Laser

- Mitsubishi Heavy Industries welded 20 mm thick stainless steel in 1 pass with 7.6 kW CW Nd:YAG
- With pulsing (frequency & duty cycle), they achieved 13 mm penetration with 4.5 kW Nd:YAG
- Multi-beam configurations can reduce porosity

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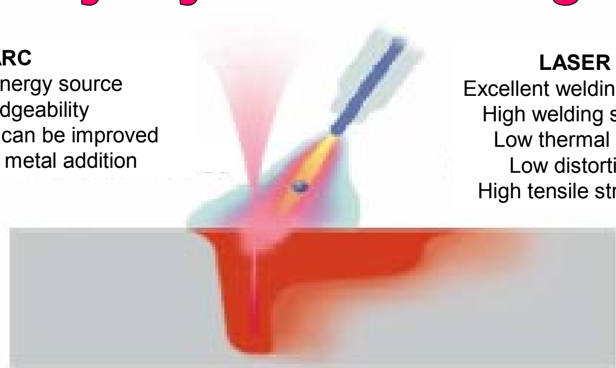
Hybrid Welds
Laser and GMAW

Why Hybrid Welding?

ARC
Low-cost energy source
Gap bridgeability
Microstructure can be improved
through filler metal addition

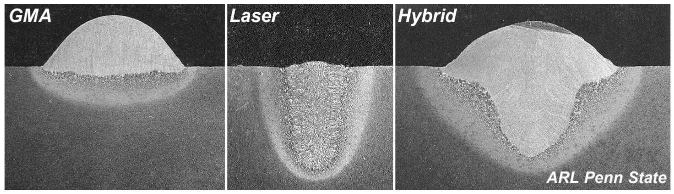
LASER
Excellent welding depth
High welding speed
Low thermal load
Low distortion
High tensile strength

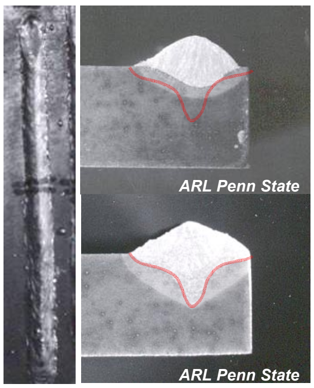


HYBRID PROCESS
High process stability, higher welding speed
Good flowing of the weld edges
Large seam volume
Good metallurgical properties

Figure was modified from an image obtained from Fronius website.

Deeper Penetration





GMA Only
22 V, 215 ipm wire speed, 20 ipm travel speed,
shield gas Ar/CO_2 @ 55 cfh

Laser – GMA Hybrid
2.6 kW Nd:YAG &
22 V, 215 ipm wire speed, 20 ipm travel speed,
shield gas Ar/CO_2 @ 55 cfh

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HighYAG Hybrid Welding Head
(auf Deutschland)

Kuka Hybrid Welding Head
(auf Deutschland)

Fronius Hybrid Welding Head
(auf Austria)

Fraunhofer ILT
(auf Deutschland)

Hybrid Head Design Considerations:

- Proper shield gas flow
- Prevent air entrainment
- Protect optics
- Heat management
- Adjustability
- Common head for improved accessibility

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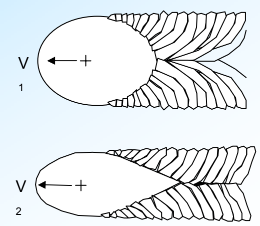
Hybrid Welding

- Much effort in Germany, Japan, China, elsewhere in Europe
  - Volkswagen (Phaeton door), Audi (A8 lateral roof frame), Meyer-Werft, Others
  - Lloyd's Register certified ILT hybrid for single-pass, longitudinal joining of stainless steel tubes with wall thickness ranging 2.4 mm to **14.4 mm** (2002)
  - Most related publications are from Europe and Asia
- Many process variations
  - Laser with GMA, GTA, plasma arc, induction
  - Addition of filler metal permits tailored metallurgy
  - Evidence that the additional heat has affect
    - Creates larger melt pool → Porosity reduction
    - Reduced cooling rate → Improved microsctructure
      → Reduced centerline cracking



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Hybrid Welding

- Many process variables
  - Process Gas
    - Arc stability, arc temperature, surface tension, laser energy absorption, laser plasma suppression, metal transfer mode, production cost
      → Ar-CO_2 and Ar-He mixtures are common
      → Spray mode to Short-Circuiting mode are recommended
  - Laser / GMAW geometry
    - Relative distance, leading vs. trailing, relative angle
      → Laser and arc leading are both common
      → 2 mm separation yields deeper penetration
      → Close angle (15° to 30°)
    - Joint geometry
      → Laser plasma stabilizes arc – possible to weld in narrow joint
  - "Normal" Process Parameters
    - GMAW – voltage, WFS, contact-tip-to-workpiece, travel speed
    - Laser – wavelength, power, focusing optics, travel speed, pulsing

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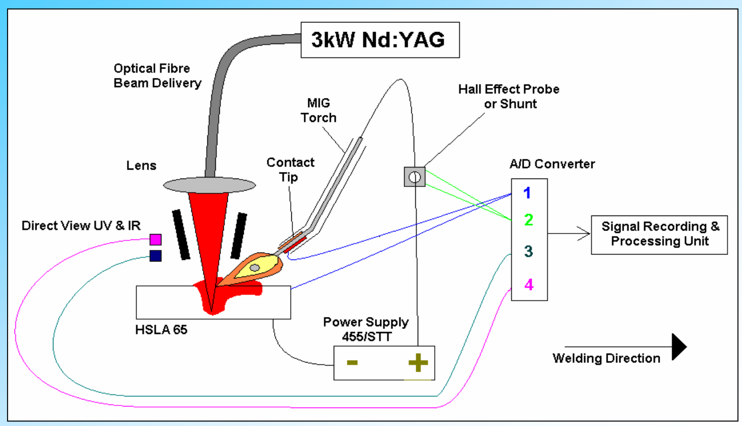
Hybrid Welding

Sensing for Quality Control



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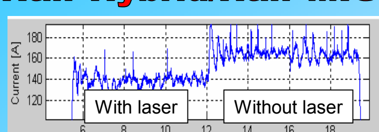
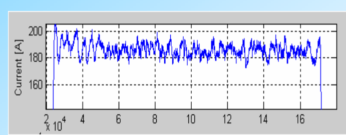
Hybrid Welding

Half Hybrid/Half MIG

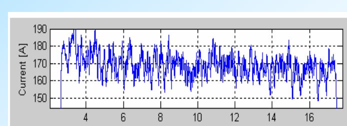


Sensing Alignment

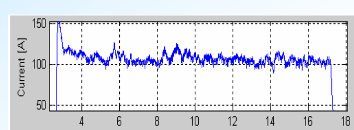
Laser
+ 2mm



Electrode
meets
He:Ne



Laser
- 2mm



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Test Plan

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Test Plan – Phased Approach

- Phase 1: Directed toward Qualification
  - *Goal is to lay the groundwork for process qualification*
- Phase 2: Test with Pipe Thickness Variations
- Phase 3: Test with Design Tolerances
  - Gap Variations
  - Joint Angularity

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Test Coupons – Phase I

- 2 Thickness Ranges
  - 0.237 inches
  - 0.500 inches
- 2 Joint Designs
  - Direct Butt Joint
  - Special Joint Preparation
- 2 Laser Welding Processes
  - IPG Photonics Fiber Laser @ 7 (or 10) kW or Trumpf Nd:YAG Laser @ 6 kW
  - **Hybrid** with Hobart ND:YAG @ 3 kW at ARL and with Trumpf Nd:YAG Laser @ 6 kW

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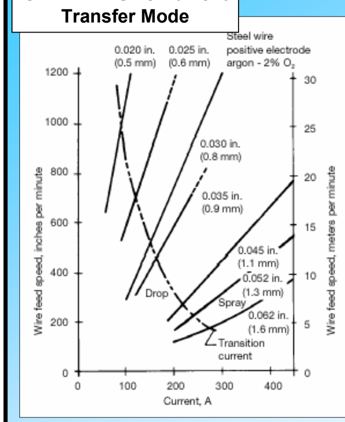
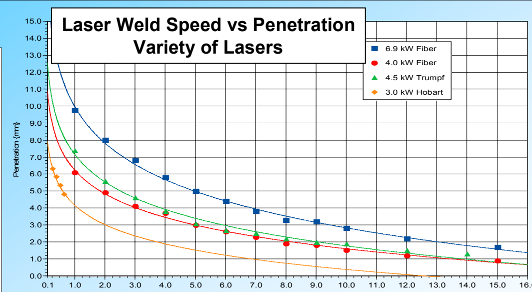
Designing Test Joint Geometries

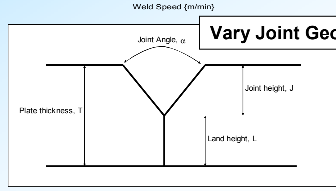
GMAW WFS vs Current Transfer Mode



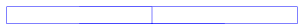
Laser Weld Speed vs Penetration Variety of Lasers



Vary Joint Geometry

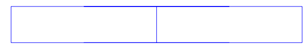


Joint Assemblies required for Parameter Development (to be joined at ARL Penn State)
Includes nominal processing parameters. (*dimensioned drawings on next page*)



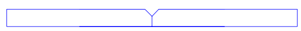
Joint A_{PD}

Joint Letter	A	
T	0.237	inch
L	0.237	inch
J	0	inch
a	0	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	12.8	ipm
4.5 kW Travel Speed	65.0	ipm
6.9 kW Travel Speed	141.2	ipm



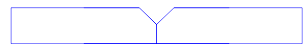
Joint D_{PD}

Joint Letter	D	
T	0.5	inch
L	0.5	inch
J	0	inch
a	0	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	0.2	ipm
4.5 kW Travel Speed	3.9	ipm
6.9 kW Travel Speed	16.6	ipm



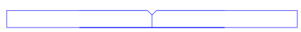
Joint B_{PD}

Joint Letter	B	
T	0.237	inch
L	0.142	inch
J	0.095	inch
a	90	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	54.1	ipm
2.6 kW Req'd Wire Feed Speed	507.25	ipm



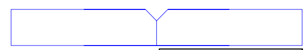
Joint E_{PD}

Joint Letter	E	
T	0.5	inch
L	0.263	inch
J	0.237	inch
a	90	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	8.6	ipm
2.6 kW Req'd Wire Feed Speed	502.91	ipm



Joint C_{PD}

Joint Letter	C	
T	0.237	inch
L	0.175	inch
J	0.062	inch
a	90	degrees
Wire Dia.	0.035	inch
4.5 kW Travel Speed	126.5	ipm
4.5 kW Req'd Wire Feed Speed	505.27	ipm



Joint F_{PD}

Joint Letter	F	
T	0.5	inch
L	0.345	inch
J	0.155	inch
a	90	degrees
Wire Dia.	0.035	inch
4.5 kW Travel Speed	20.4	ipm
4.5 kW Req'd Wire Feed Speed	509.67	ipm

Process Parameters

Autogenous Laser Weld Process Parameters

- Travel Speed
- Laser Angle
- Laser Focal Point
- Shield Gas
  - Composition
  - Flow Rate

If high porosity, may add supplemental heat source.

Additional Hybrid Weld Process Parameters

- Wire Speed
- Arc Voltage
- Wire Composition and Diameter
- Contact Tip to Workpiece Distance
- Electrode Orientation (lead, trail, angle)
- Distance between Laser and Wire

Parameter Variations

Thicknesses:	2
Processes:	2
Joint Designs:	2 (for ½”)
Laser to Torch Distance:	2
Contact Tip Distance:	2
Voltages:	3
Speeds:	5
Total Conditions:	**255**

Phase I Parameter Development

Sample No.	Thickness	Laser Process	Joint Prep	Laser to Torch Distance	Contact Tip to Workpiece Dist	Arc Voltage	Speed
1	1/4"	Autogenous	A	NA	NA	NA	Speed 1
	1/4"	Autogenous	A	NA	NA	NA	Speed 2
	1/4"	Autogenous	A	NA	NA	NA	Speed 3
	1/4"	Autogenous	A	NA	NA	NA	Speed 4
	1/4"	Autogenous	A	NA	NA	NA	Speed 5
2	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 1
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 2
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 3
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 4
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 5
3	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 1
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 2
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 3
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 4
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 5
4	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 1
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 2
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 3
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 4
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 5
5	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 1
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 2
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 3
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 4
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 5
6	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 1
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 2
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 3
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 4
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 5
7	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 1
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 2
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 3
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 4
	1/4"	Hybrid	A	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 5
8	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 1
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 2
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 3
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 4
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 5
9	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 1
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 2
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 3
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 4
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 5
10	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 1
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 2
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 3
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 4
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 5
11	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 1
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 2
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 3
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 4
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 5
12	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 1
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 2
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 3
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 4
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 5
13	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 1
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 2
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 3
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 4
	1/4"	Hybrid	A	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 5

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Testing

Phase I Mechanical Testing Matrix

Sample No.	Thickness	Laser Process	Joint Prep	Test
1	0.237 inch	2.6 kW Autogenous	A_{MT}	Tensile 1
	0.237 inch	2.6 kW Autogenous	A_{MT}	Tensile 2
	0.237 inch	2.6 kW Autogenous	A_{MT}	Bend 1
	0.237 inch	2.6 kW Autogenous	A_{MT}	Bend 2
2	0.237 inch	4.5 kW Autogenous	A_{MT}	Tensile 1
	0.237 inch	4.5 kW Autogenous	A_{MT}	Tensile 2
	0.237 inch	4.5 kW Autogenous	A_{MT}	Bend 1
	0.237 inch	4.5 kW Autogenous	A_{MT}	Bend 2
3	0.237 inch	2.6 kW Hybrid	B_{MT}	Tensile 1
	0.237 inch	2.6 kW Hybrid	B_{MT}	Tensile 2
	0.237 inch	2.6 kW Hybrid	B_{MT}	Bend 1
	0.237 inch	2.6 kW Hybrid	B_{MT}	Bend 2
4	0.237 inch	4.5 kW Hybrid	C_{MT}	Tensile 1
	0.237 inch	4.5 kW Hybrid	C_{MT}	Tensile 2
	0.237 inch	4.5 kW Hybrid	C_{MT}	Bend 1
	0.237 inch	4.5 kW Hybrid	C_{MT}	Bend 2
5	0.500 inch	4.5 kW Autogenous	D_{MT}	Tensile 1
	0.500 inch	4.5 kW Autogenous	D_{MT}	Tensile 2
	0.500 inch	4.5 kW Autogenous	D_{MT}	Bend 1
	0.500 inch	4.5 kW Autogenous	D_{MT}	Bend 2
6	0.500 inch	2.6 kW Hybrid	E_{MT}	Tensile 1
	0.500 inch	2.6 kW Hybrid	E_{MT}	Tensile 2
	0.500 inch	2.6 kW Hybrid	E_{MT}	Bend 1
	0.500 inch	2.6 kW Hybrid	E_{MT}	Bend 2
7	0.500 inch	4.5 kW Hybrid	F_{MT}	Tensile 1
	0.500 inch	4.5 kW Hybrid	F_{MT}	Tensile 2
	0.500 inch	4.5 kW Hybrid	F_{MT}	Bend 1
	0.500 inch	4.5 kW Hybrid	F_{MT}	Bend 2

- 2 Tensile
- 2 Side Bends
- Radiographic Testing

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Sample Delivery

- Coupons are being machined at NASSCO this week
- Expect welding can begin in April

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Other Considerations

Practical Considerations

- Rotary Positioner – velocity variation
- Gap tolerance
  - Ability to machine cost effectively
  - Ability to verify gap during production

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Velocity Variation

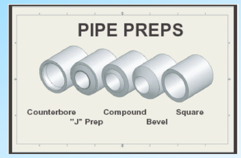
- POK-10 from All-Fab Corp ($14k)
  - 3,000 lb capacity
- POK-30 from All-Fab Corp ($22k)
  - 6,500 lb capacity
- +/- 1% velocity variation
- High precision units are available

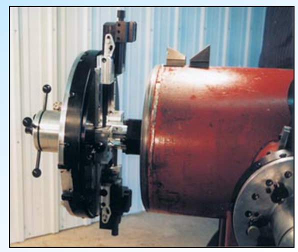
High precision rotary positioners from Orbit/FR website

Standard rotary positioners from All-Fab Corp website

Gap Tolerance - Machining

- D.L. Ricci is one supplier
- Custom edge geometry available
- Tolerance
  - Currently 0.010 inches tolerance on 36 inch pipe
  - They offered to work with us to improve tolerance
  - Cost $30k to $40k





Pipe Edge Prep Machine Tool from D.L.Ricci website

Laser bevel cutting by Prima (from Industrial Laser Solutions, Nov 03

Gap Tolerance - Measuring

- Capacitec gauge measures down to 0.009 inches
- Feeler Gauge
  - Wide ranges
  - Cheap & Easy

From Lee Valley Tools website

From Capacitec website

From Eastern Industries website

Summary

- Project is on-schedule
- Comprehensive piping survey conducted by NASSCO delivered
- Literature survey helping with process parameter selection
- Test Plan established – Test Coupons on the way
- Much activity in next few months

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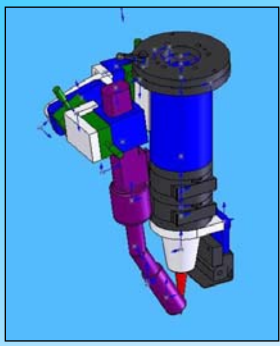
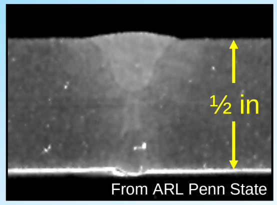
NSRP Laser Pipe Welding Investigation



Status Update



Mr. Ted Reutzel, Mr. Jay Tressler
Mr. Rob Crue, Mr. Eli Gwinn
Applied Research Laboratory
The Pennsylvania State University
Mr. Mike Sullivan
National Steel and Shipbuilding Company

Presented at:
NSRP SP-7 Meeting
Penn State University
16-17 September 2004

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Thanks!

For making the meeting arrangements:

Ms. Cindy Hull

For providing logistical and technical support (*usually on short notice*):

Dr. Rich Martukanitz, Mr. Jim McDermott, Mr. Ed Good, Mr. Chris Sills

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Project Objective

Evaluate recent advances in laser welding technology applied to shipyard pipe welding.

- High-Power Nd:YAG
- Laser/GMA Hybrid Welding

Consider:

- Capability & Quality
- Cost

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Outline

- Shipyard Piping Survey and Specification Review
- Literature Survey
- Weld Test Plan
- Testing
- Summary

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Shipyard Piping Survey

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NASSCO Deliverables

- NASSCO has delivered
  - Photographic record of material flow through pipe production
  - Material samples for weld testing
  - Task 1 Report: Product Family Analysis
  - Task 2 Report: Specification Review

NASSCO

Beveled with Oxy-Fuel Gas Cutting Units

Weld ends are manually ground

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NASSCO

Use of oxy-fuel cutters and manual grinding results in a poor gap tolerance

<u>Not acceptable for laser processing</u>

Nassco also uses machine-tool edge preparation (no pictures available)

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NASSCO

Some welds are manual FCAW

Others are semi-automated FCAW

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NASSCO Product Family Analysis

- Welding Process:
  - FCAW, GMAW-P, GTAW, GMAW-STT, SMAW, Braze
- Pipe Materials:
  - Steel, CuNi, Stainless Steel, Copper
- Thickness Range
  - Low – 0.237 in., High – 0.500 in.
- **Filler → 50,000 lbs/yr**
- **Labor**
  - **Pipe Fitters → 66,000 hrs/yr**
  - **Pipe Welders → 50,000 hrs/yr**
- **Steel Pipe per Ship → ~110,000 ft/ship**

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NASSCO Specification Review

- Testing Requirements – Pipe Butt Welds
  - Non-Destructive
    - Visual Testing – no cracks, excessive reinforcement, undercuts, lack of fusion, incomplete penetration
    - Radiographic Testing – no cracks, incomplete fusion or penetration
  - Destructive
    - Two reduced section tensile tests required
    - Four bend tests required
    - Charpy V Notch test not required
    - Macro Etch

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Literature Survey

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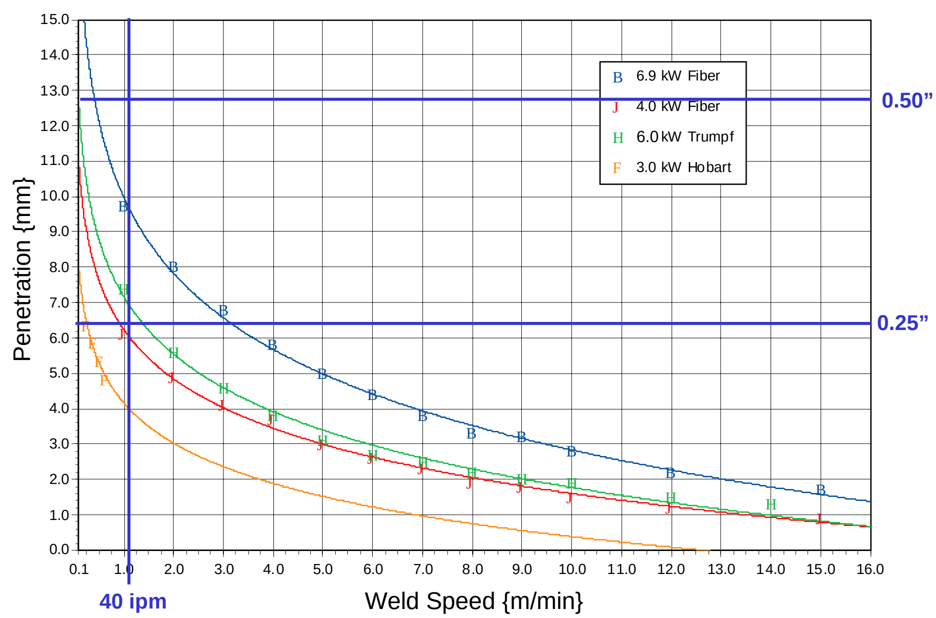
ARL Penn State Literature Review

- 30+ Articles were Reviewed
  - Laser & Hybrid Welding
  - Piping & Thick Sections
- 10+ Chosen for Inclusion
  - Addressed Practical Considerations
    - Gas, Head Configuration, Materials, Porosity, Gap, Joint Geometry, etc.
- Draft is Complete

Laser Comparison
Carbon Steel



Ballpark Prices

6.0 kW Trumpf HLD 4506 – Fiber Delivered

→ approx. **$680,000** (without chiller)

6.0 kW IPG Photonics Fiber Laser

→ approx. **$850,000** (air cooled)

Trumpf HL4006D

Trumpf Fiber & Welding Optics

10 kW IPG Photonics

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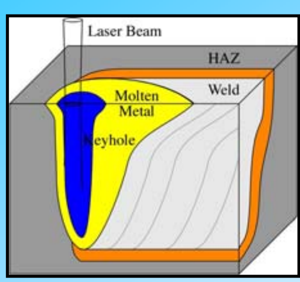
Thick Section Autogenous Laser



- Porosity
  - Contamination (oxygen, nitrogen, hydrogen)
  - Base material pore coalescence (castings)
  - Keyhole instability leading to collapse
- Preventing porosity
  - Manage contaminants
  - Shield Gas
  - Defocus beam
  - Weld faster to stabilize keyhole
  - Adjust angle to stabilize keyhole
  - Pulse shaping
  - Beam oscillation
  - More heat so porosity has time to escape

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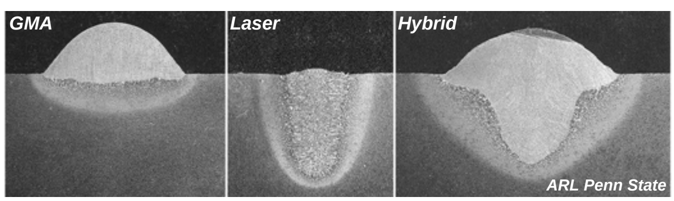
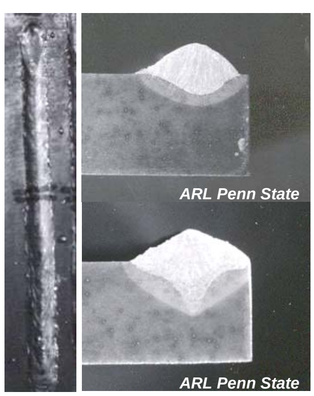
Hybrid Welds
Laser and GMAW

Deeper Penetration





GMA Only
22 V, 215 ipm wire speed, 20 ipm travel speed,
shield gas Ar/CO_2 @ 55 cfh

Laser – GMA Hybrid
2.6 kW Nd:YAG &
22 V, 215 ipm wire speed, 20 ipm travel speed,
shield gas Ar/CO_2 @ 55 cfh

Laser Processing Division

HighYAG Hybrid Welding Head
(Germany)

Kuka Hybrid Welding Head
(Germany)

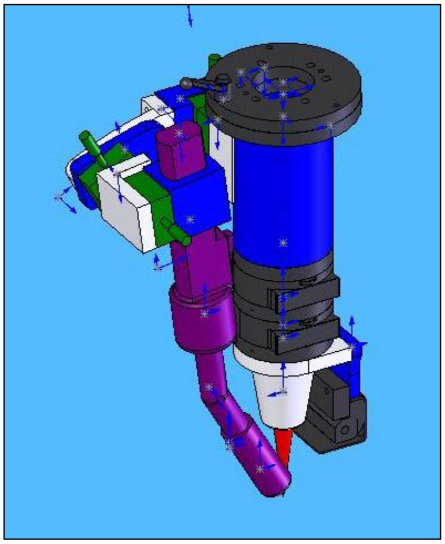
Fronius Hybrid Welding Head
(Austria)

Fraunhofer ILT
(Germany)

Hybrid Head Design Considerations:
- Proper shield gas flow
- Prevent air entrainment
- Protect optics
- Heat management
- Adjustability
- Common head for improved accessibility

Domestic Supplier

- Working with **Laser Mechanisms, Inc.** to develop an adjustable hybrid head.
- Laser Processing Consortium project
- Domestic Commercial Supplier



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Test Plan

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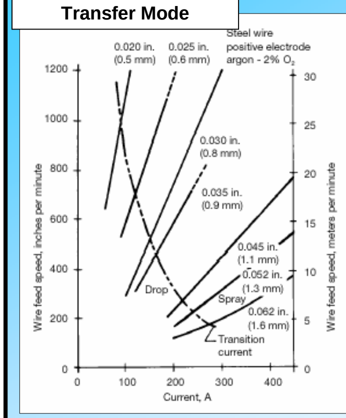
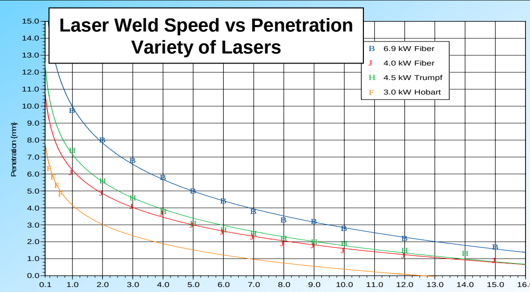
Designing Test Joint Geometries

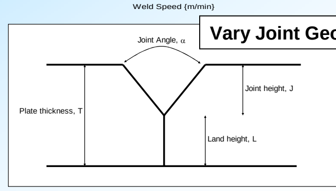
GMAW WFS vs Current Transfer Mode



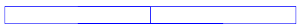
Laser Weld Speed vs Penetration Variety of Lasers



Vary Joint Geometry

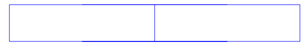


Joint Assemblies required for Parameter Development (to be joined at ARL Penn State)
Includes nominal processing parameters. (*dimensioned drawings on next page)*



Joint A_{PD}

Joint Letter	A	
T	0.237	inch
L	0.237	inch
J	0	inch
a	0	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	12.8	ipm
4.5 kW Travel Speed	65.0	ipm
6.9 kW Travel Speed	141.2	ipm

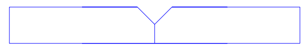


Joint D_{PD}

Joint Letter	D	
T	0.5	inch
L	0.5	inch
J	0	inch
a	0	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	0.2	ipm
4.5 kW Travel Speed	3.9	ipm
6.9 kW Travel Speed	16.6	ipm

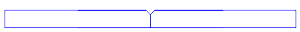
Joint B_{PD}

Joint Letter	B	
T	0.237	inch
L	0.142	inch
J	0.095	inch
a	90	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	54.1	ipm
2.6 kW Req'd Wire Feed Speed	507.25	ipm



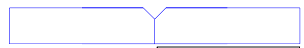
Joint E_{PD}

Joint Letter	E	
T	0.5	inch
L	0.263	inch
J	0.237	inch
a	90	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	8.6	ipm
2.6 kW Req'd Wire Feed Speed	502.91	ipm



Joint C_{PD}

Joint Letter	C	
T	0.237	inch
L	0.175	inch
J	0.062	inch
a	90	degrees
Wire Dia.	0.035	inch
4.5 kW Travel Speed	126.5	ipm
4.5 kW Req'd Wire Feed Speed	505.27	ipm



Joint F_{PD}

Joint Letter	F	
T	0.5	inch
L	0.345	inch
J	0.155	inch
a	90	degrees
Wire Dia.	0.035	inch
4.5 kW Travel Speed	20.4	ipm
4.5 kW Req'd Wire Feed Speed	509.67	ipm

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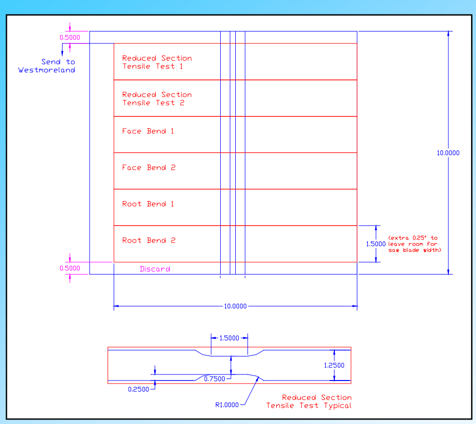
Planned Testing



- 2 Tensile
- 4 Side Bends
- Radiographic Testing

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Testing

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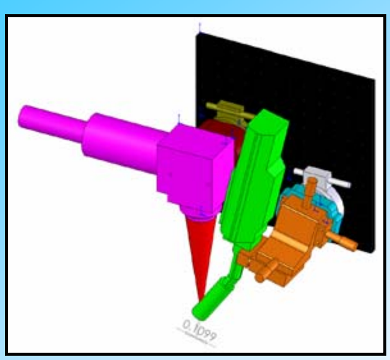
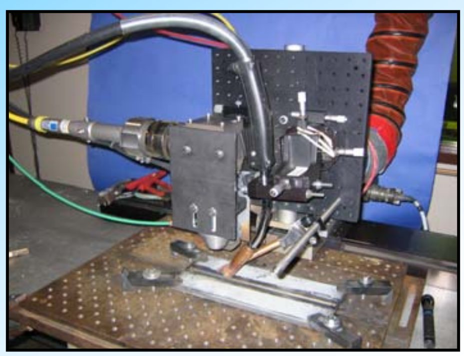
Experimental Set Up





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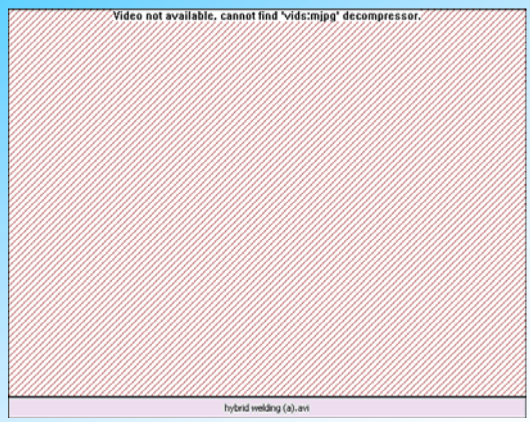
ARL Laser Processing Division

Video



PENNSTATE
ARL Laser Processing Division

Some Results

Weld ½" thick A36
With modified butt

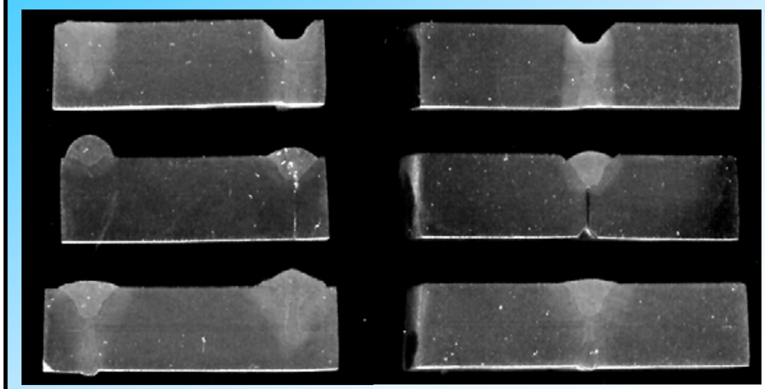
- 3" of laser only
- 5" of hybrid
- 3" of GMAW only

- 4500 W
- 17.5 v, 315 ipm WFS
- 10 ipm

PENNSTATE ARL Laser Processing Division

Some Results

Bead-On-Plate (1/2” thick)	0.345” land 90º bevel	0.345” land 90º bevel with backside chamfer	



Laser Only

GMAW Only

Hybrid Weld Single Pass

PENNSTATE ARL Laser Processing Division

Summary

- NASSCO has delivered:
  - Test Material
  - Product Family Analysis
  - Specification Review
- ARL Penn State has completed:
  - Draft Literature Review
  - Experimental Set Up & System Integration
  - Initial laser and hybrid weld testing
- Coming soon…
  - Mechanical Tests and final Cost Analysis

Appendix F – NASSCO Specification Review

National Steel & Shipbuilding Research Project

LASER PIPE WELDING

TASK 2 REPORT
Specification Review

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August 11, 2004

Table Of Contents

1.0 <u>Provide All Material Specifications</u>

Carbon steel pipe can be produced as welded pipe and as seamless pipe. For all conventional systems that permit the use of steel pipe, the pipe is purchased to two specifications. This applies to both commercial and non-combatant military ships.

ASTM A-53 / A-53M

Standard specification for pipe, steel, black and hot dipped, zinc coated, welded and seamless.

ASTM A-106

Standard specification for seamless carbon steel pipe for high temperature service.

2.0 <u>Determine Welding Procedure Requirements</u>

Many shipyards build to both commercial standards (ABS) and military standards. In addition, many regulatory agencies have accepted weld procedures qualified to other recognized standards.

2.1 ABS Welding Procedure Qualification Requirements

The details of ABS approval of welding procedures are found in ABS rules 2-4-3/5. The extent of the tests may vary depending on the intended application. The welding procedure demonstrates the fabricators capability in the application of the proposed filler metal to the base material. A pipe test weld assembly is to be welded and witnessed by the ABS surveyor.

2.1.1 Non-Destructive Tests Required

The details of the type of NDT tests are not specified for welding procedures per ABS Rules. However rules do exist for NDT requirements for production welds. Therefore, it is prudent to apply these same NDT requirements to the pipe weld test before machining specimens for mechanical testing.

NDT Test Required

1. VT

2. RT

VT Acceptance Requirements

1. Complete root penetration is required.

2. Welds are not allowed to contain unacceptable imperfections. All visible defects such as follows are to be repaired.

    - Cracks
    - Excessive weld reinforcements
    - Undercuts
    - Lack of fusion on surface
    - Incomplete penetration

RT Acceptance Requirements

- Any type of cracks or zones of incomplete fusion or penetration is unacceptable.

- Any elongated slag inclusion which has a length greater than ¼” for thicknesses less than or equal to ¾” is unacceptable.

- Rounded indications in excess of any recognized acceptance standard is unacceptable.

2.1.2 Mechanical/Destructive Tests Required

Pipe Butt Welds

1. Two reduced section tension tests are required. The details of the tension test specimen size are found in ABS Rules 2-4-3 Figure 4, for pipe butt joints.

2. For pipe butt joints, four bends tests are required. The details of the four bend tests are found in the ABS Rules 2-4-3, Figure 5, 6, 7. For material thickness 0.75” and under, two face and two root bends may be tested or four side bends may be substituted for material thickness over 3/8”.

3. Special tests such as all weld metal tension, charpy V notch are not required but may be performed for information.

4. In addition, 1 macro etch is normally performed and examined for defects.

Acceptance Requirements For Tension Tests

1. The tensile strength of each specimen, when it breaks in the weld, is not to be less than the minimum specified tensile strength of the base material.

2. The tensile strength of each specimen, when it breaks in the base material and the weld shows no signs of failure, is not to be less than 95% of the minimum specified tensile strength of the base material.

Acceptance Requirement For Bend Tests

1. After bending, the specimen is not to show any cracking or other open defect exceeding 1/8” on the convex side except at the corners.

2.2 Military Welding Procedure Qualification Requirements

Welding procedures for military class of ships require qualification in accordance with the rules detailed in the technical manual "Requirements for Welding and Brazing Procedure and Performance Qualification" S9074-AQ-GIB-010/248.

The required weld tests are to be performed and witnessed by an authorized representative. NAVSEA approval of procedure qualification data is required for special welding on P-1 applications. The application of the proposed procedure for laser welding of pipe joints (if intended to be used on P-1 systems) does require NAVSEA approval.

Two test welds are required to support the anticipated thickness to be used in production.

Pipe test assembly details are provided in Figure 3 of the Technical Manual. For our automatic process one test weld in the smallest and largest sizes (combination of diameter and thickness) is required.

To be welded in production:
Smallest 4" Sch-40 .237"
Largest 8" Sch-80 .500" (qualifies all diameters greater but wall thickness .550" max)

2.2.1 Non Destructive Tests Required

1. VT Acceptance standard, MIL-STD-2035 Class P-1

2. RT in accordance with MIL-STD-271, Acceptance standard, MIL-STD-2035 Class P-1

3. MT in accordance with MIL-STD-271, Acceptance standard, MIL-STD-2035 Class P-1

4. UT in accordance with MIL-STD-271, Acceptance standard, MIL-STD-2035 Class P-1

2.2.2 Mechanical/Destructive Tests Required

1. Transverse tensile test (2 tests) per AWS B 4.0

2. Guide bend (2 root, 2 face) per AWS B 4.0

3.0 Pipe Welding Production Requirements

The pipe fabrication shop processes pipe for all contracts at NASSCO. This includes New Construction and Repair for both commercial and military shipbuilding. The recognized fabrication documents that govern pipe fabrication are:

1. ABS Rules 2-4-4

2. Technical Publication - "Requirements for Fabrication Welding and Inspection, And Casting Inspection and Repair for Machinery, Piping and Pressure Vessels", S9074-AR-GIB-010/278.

3.1 ABS Requirements

Per ABS Rules 2-4-4/11.1, all pipe welds are to be VT inspected. All welded joints, including the root side wherever possible, are to be visually examined. All visible defects, such as cracks, excessive weld reinforcement, undercuts, lack of fusion on the surface, incomplete penetration where the inside is accessible, deficient size for fillet welds, etc. are to be repaired.

Butt joints require additional NDT depending on the pipe class. For Class I pipe systems any pipe diameter greater than 2 ½" or wall thicknesses greater than 3/8" shall be 100% RT examined. For Class II pipe systems any pipe diameter greater than 3 ½" shall be 10% RT examined.

3.1 Military Requirements

For Military pipe, production NDT requirements are detailed in the technical publication "Requirements for Fabrication Welding and Inspection, And Casting Inspection and Repair for Machinery, Piping and Pressure Vessels", S9074-AR-GIB-010/278.

For P-1 systems the following NDT is required:

1. VT final weld
   Acceptance standard MIL-STD-2035 Class P-1

2. MT/PT root layer or 5X VT
   Acceptance standard MIL-STD-2035 Class P-1

3. MT/PT final weld
   Acceptance standard MIL-STD-2035 Class P-1

4. RT final weld
   Acceptance standard MIL-STD-2035 Class P-1

For P-2 systems the following NDT is required:

1. VT final weld
   Acceptance standard MIL-STD-2035 Class P-2

2. MT/PT final weld
   (per component or shipbuilding specification)

3. RT final weld
   (per component or shipbuilding specification)

The attributes of the VT inspection criteria per MIL-STD-2035 are summarized below as well as other VT attributes of workmanship.

- No arc strikes
- No spatter
- No overlap
- No sharp ridges or irregularities
- No deep valleys
- No surface slag
- No areas of lack of penetration
- Welds to blend smoothly and gradually into base metal at the weld edges
- No concavity in root reinforcement
- Reinforcement convexity limits per diameter requirements
- Joint offset maximum limit per thickness
- No cracks
- No burn through
- Defect-free melt through
- No incomplete fusion
- Defect-free crater pits
- No oxidation
- No visible porosity
- Undercut limits per pipe class
- Re-entrant angle 90^{o} or greater or fab document requirement
- Correct fillet leg size
- Correct fillet contour

4.0 Steps For Processing Steel Pipe

The following 14 steps detail the activities involved during the fabrication of pipe spools at NASSCO. Photos of each step are included in Attachment 1.

1. Pipe is received at NASSCO steel yard and the certification documents are reviewed.

2. Pipe is temporarily stored by Gate 14 in the steel yard until required in the Pipe Shop. At the Pipe Shop, small diameter pipe 12" or less, is loaded into the pipe silo. Large diameter pipe is loaded directly in to the work cell.

3. All pipe 24 "and below is shot blasted in the automatic booth. Only the outside of the pipe is blasted not the inside. Larger pipe is blasted after fabrication is complete.

4. Pipe is then transferred to the plasma cutting room by conveyors. Plasma cutting is used on pipe diameter 6" to 30". Larger pipes are manually cut using oxy-fuel or plasma.

   - The plasma cutter uses nitrogen as the cutting gas.

   - Types of cuts capable are bevel cuts, straight cuts, and branch connections.

   - All cut pieces are manually marked for identification.

5. If a pipe requires bending it is then sent to one of the three pipe bending machines. The capability of the bending machines are 8" – 12" diameter pipe for the large bender and 4" – 8" diameter pipe for the medium bender, and 2 ½" – 8" diameter pipe for the small bender.

6. All miscellaneous holes not accomplished at the plasma cutting cell are manually laid out and manually cut.

7. All material for each spool sheet is collected and sorted into a Kit.

8. Designated stations are setup for fitting the pipe spool in accordance with the pipe spool sketch. The tools used are predominantly squares and levels. All weld joints are ground clean before fitting. Once the weld joint is fit the weld joint is tack welded. All joints are tack welded with the GTAW process except for flanges which are tack welded with FCAW.

9. All fit and tacked spools are moved to the weld out stations. The weld joints are welded as much as possible in the 1GR (flat rolled) position.

- In order to maximize roll-out welding (1GR) some spools are partially assembled for roll-out welding then additional pieces are fitted to complete the spool later.

- Open root butt joints are welded with the STT GMAW process for the root pass. The root gap is 3/32” to 1/8” with 45° included bevel angle. The weld is completed with FCAW.

- On systems that permit the use of backing rings a P-3 type joints is used. The root gap is ¼” with a 45° included bevel angle. The entire joint is welded with the FCAW process.

- Flange attachments to large diameter pipe are welded complete with large diameter flux-core wire. Flanges can be either butt welded or slip on type.

- Coupling sleeves P-13 or structural sleeves P-17 are welded with the FCAW process.

- Branch connections are full penetration welds completed with the FCAW process.

10. Visual inspection is performed on every weld joint by a certified VT inspector. Both the outside and the inside (where accessible) is inspected. Once all of the welds are accepted on the pipe spool the inspector signs his badge number on the spool identification tag fixed to the pipe spool.

11. If hydrostatic testing is required (Class 1 and Class 2 Pipe Systems) the spool is delivered to the testing area. Multiple spools are tested at the same time. This testing is performed on normally 8” diameter and below.

12. All pipe spools 12” diameter and below are cleaned in the caustic soda tanks for approximately 30 to 45 minutes followed by a rinse. This removes any oil or grease from the bending operation.

13. Final processing of the pipe spool is identified on the spool tag. This may be galvanize, paint, etc.

14. Completed pipe spools are kitted for installation.

5.0 Samples For Testing

ARL evaluated the target thickness determined in Task 1 and reviewed past testing to decide on the range of joint designs and plate thicknesses to be test welded. A matrix was developed where by all testing would encompass the range of possible parameter variations required to be tested to perform acceptable welds.

Two thicknesses were selected for testing .237" and .500".

Two bevel angles were selected for testing 0^o (square butt) and 45^o (90^o included).

Four root face dimensions were selected for testing:
- 0.142" and 0.175" for T = 0.237"
- 0.263" and 0.345" for T = 0.500"

Three hundred square feet of plate was sectioned for final machining of weld test samples.

Plate	150 sq. feet	¼" thickness
	150 sq. feet	½" thickness
	152 pcs. of	3" x 12" x .237"
	80 pcs. of	7" x 12" x .237"
	152 pcs. of	3" x 12" x .500"
	80 pcs. of	7" x 12" x .500"
Total	464 test pieces for 232 test butt joints.	

Pieces were beveled both sides. Therefore, 232 additional butt joints could be re-made without any re-machining.

Machining was completed on 3/22/04 and all samples were delivered to ARL Penn State for testing.

6.0 <u>Summary</u>

This concludes the report of Task 2.

- All material specifications ASTM-A-53 and A-106 have been provided.

- Welding procedure qualification requirements have been provided.

  1. ABS
     NDT – VT, RT
     Mechanical – 2 reduced section tension
     – 2 face, 2 root or 4 side bends
     – 1 macro

  2. Military
     NDT – VT, RT, UT, MT
     Mechanical – 2 transverse tensile tests
     – 2 face, 2 root or (4 side bends)

- Production requirements for pipe welds have been provided.

- Descriptions of current processes have been provided.

- Supplied weld test sample plates to ARL.

7.0 Attachments

1. Photos of 14 steps for processing steel pipe

2. ASTM A-53 / A-53M (hard copy only)

3. ASTM A-106 (hard copy only)

Appendix G – Initial Test Plan and Actual Lab Notes

NOTE: Appendix G contains the full text of the initial test plan, since the strategy in developing this plan may be considered useful by some. It should be noted, however, that very early on it was recognized that the plan did not produce the intended results. For this reasons, the initial test plan was not used. It is believed that the extrapolation used to estimated laser keyhole penetration was incorrect because it considered data from a flat plate only, while the experiments were performed with a beveled joint.

For the sake of completeness, the actual, hand-written experimental notes are also included.

NSRP Pipe Welding Panel Project

Test Coupon Requirements

Version 1.0
17 December 2003

The following pages outline the projected test coupon requirements necessary to complete parameter development and mechanical testing. Several extra coupons are included, to allow for experimental error.

The coupons are required to make butt joint assemblies made of flat plates representing the minimum and maximum range of pipe thicknesses used at Nassco. There are enough joints for a substantial effort in developing parameters and for performing mechanical testing for the following combinations of weld conditions:

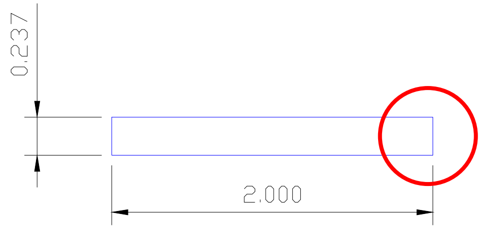
- 2.6 kW Hobart flashlamp-pumped Nd:YAG laser– autogenous weld
- 2.6 kW Laser / GMA hybrid weld
- 4.5 kW Trumpf diode-pumped Nd:YAG laser – autogenous weld
- 4.5 kW Laser/GMA hybrid weld

The current version does NOT specify plates to investigate mid-range thicknesses. It is anticipated that specification of mid-range thicknesses will take place a a later date.

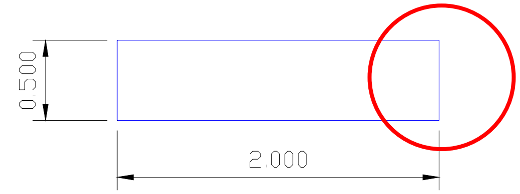
The document, “Joint Test Plan – Details – V1-0.pdf” contains detailed information about the proposed tests.

<u>Machined Test Coupons required to produce assemblies for Parameter Development</u>

(NOTE: All lengths are 12 inches into the page)

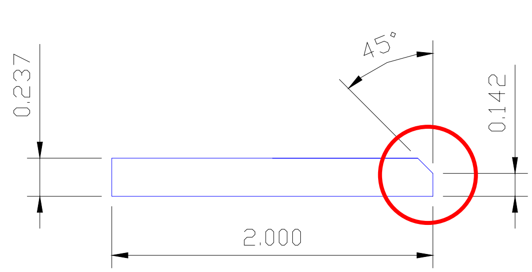


Joint A_{PD}:
Req'd Coupon Qty: **10**

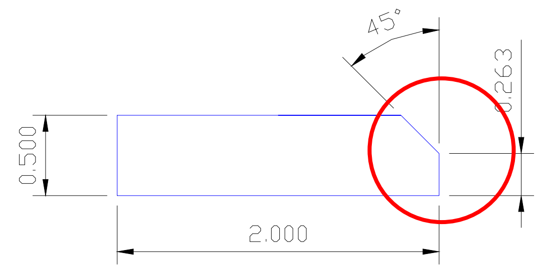


Joint D_{PD}:
Req'd Coupon Qty: **10**

<u>Tolerance Requirements:</u>
All "2.000" dimensions are +/- 0.100 inch
All other dimensions are +/- 0.005 inch

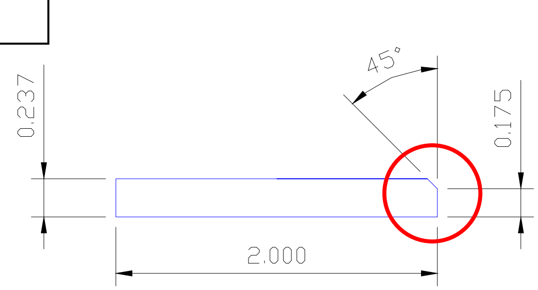


Joint B_{PD}:
Req'd Coupon Qty: **36**

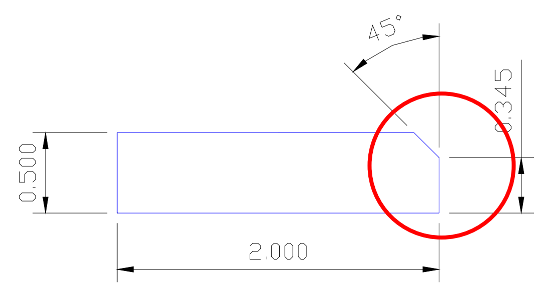


Joint E_{PD}:
Req'd Coupon Qty: **36**

<u>Note:</u>
Red Circled areas are the only that require machined surfaces. All other surfaces can be rough-cut.



Joint C_{PD}:
Req'd Coupon Qty: **30**

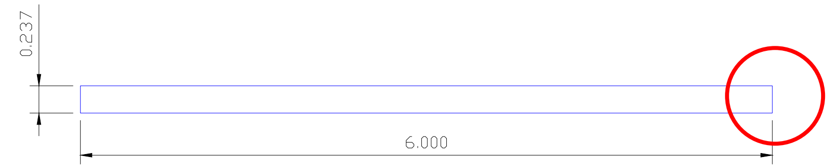


Joint F_{PD}:
Req'd Coupon Qty: **30**

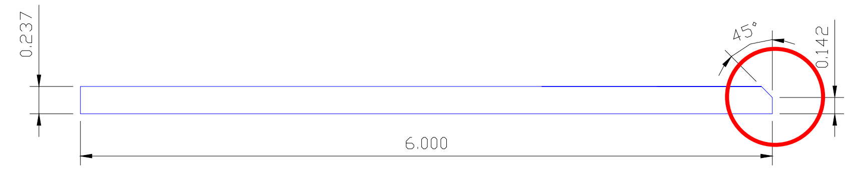
<u>Machined Test Coupons required to produce assemblies for Mechanical Testing</u>

(NOTE: All lengths are 12 inches into the page)

Joint A_{MT}:
Req'd Coupon Qty: **8**

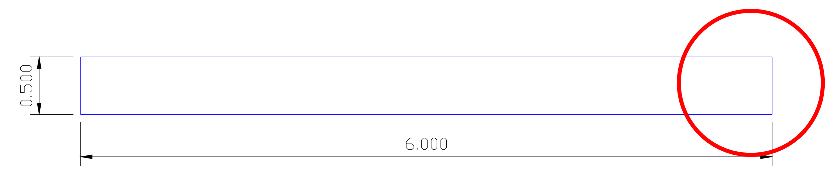


Joint B_{MT}:
Req'd Coupon Qty: **6**

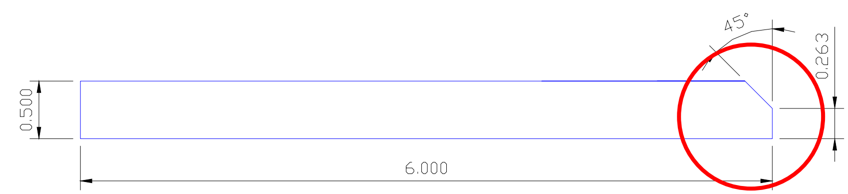


Joint C_{MT}:
Req'd Coupon Qty: **6**

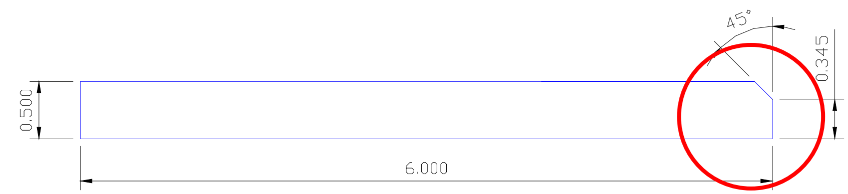
Joint D_{MT}:
Req'd Coupon Qty: **8**



Joint E_{MT}:
Req'd Coupon Qty: **6**



Joint F_{MT}:
Req'd Coupon Qty: **6**

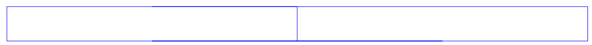


<u>Tolerance Requirements:</u>
All "6.000" dimensions are +/- 0.100 inch
All other dimensions are +/- 0.005 inch

<u>Note:</u>
Red Circled areas are the only that require machined surfaces. All other surfaces can be rough-cut.

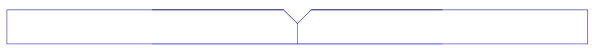
Joint Assemblies required for Parameter Development (to be joined at ARL Penn State)

Includes nominal processing parameters. (*dimensioned drawings on next page)*



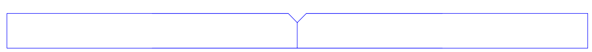
Joint A_{PD}

Joint Letter	A	
T	0.237	inch
L	0.237	inch
J	0	inch
a	0	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	12.8	ipm
4.5 kW Travel Speed	65.0	ipm
6.9 kW Travel Speed	141.2	ipm



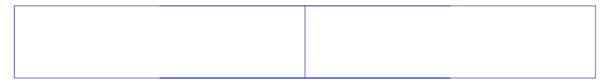
Joint B_{PD}

Joint Letter	B	
T	0.237	inch
L	0.142	inch
J	0.095	inch
a	90	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	54.1	ipm
2.6 kW Req'd Wire Feed Speed	507.25	ipm



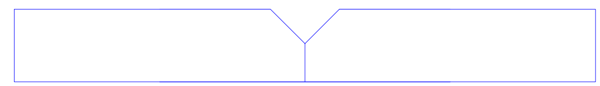
Joint C_{PD}

Joint Letter	C	
T	0.237	inch
L	0.175	inch
J	0.062	inch
a	90	degrees
Wire Dia.	0.035	inch
4.5 kW Travel Speed	126.5	ipm
4.5 kW Req'd Wire Feed Speed	505.27	ipm



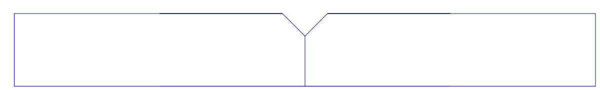
Joint D_{PD}

Joint Letter	D	
T	0.5	inch
L	0.5	inch
J	0	inch
a	0	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	0.2	ipm
4.5 kW Travel Speed	3.9	ipm
6.9 kW Travel Speed	16.6	ipm



Joint E_{PD}

Joint Letter	E	
T	0.5	inch
L	0.263	inch
J	0.237	inch
a	90	degrees
Wire Dia.	0.035	inch
2.6 kW Travel Speed	8.6	ipm
2.6 kW Req'd Wire Feed Speed	502.91	ipm

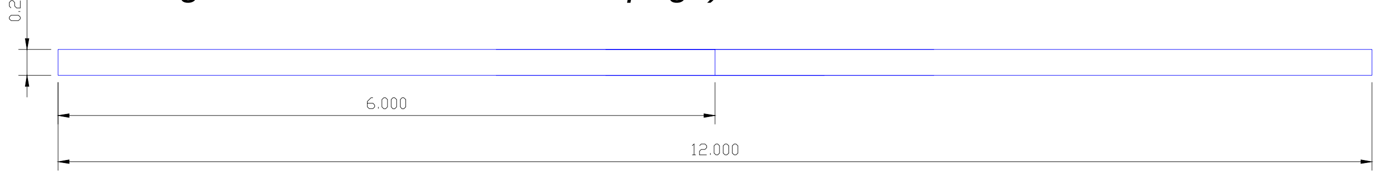


Joint F_{PD}

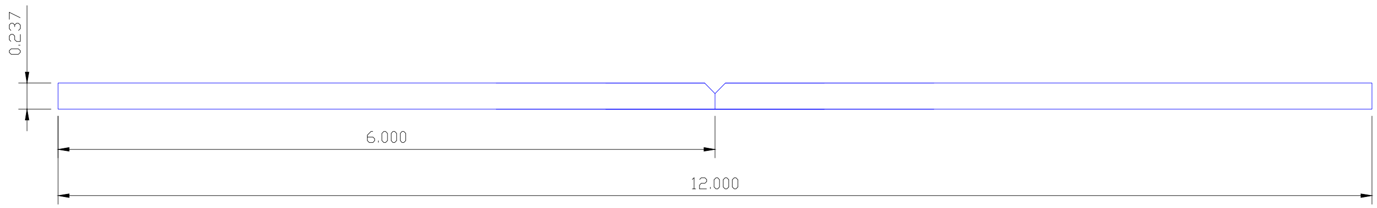
Joint Letter	F	
T	0.5	inch
L	0.345	inch
J	0.155	inch
a	90	degrees
Wire Dia.	0.035	inch
4.5 kW Travel Speed	20.4	ipm
4.5 kW Req'd Wire Feed Speed	509.67	ipm

Test Assemblies required for Mechanical Testing (to be joined at ARL Penn State)

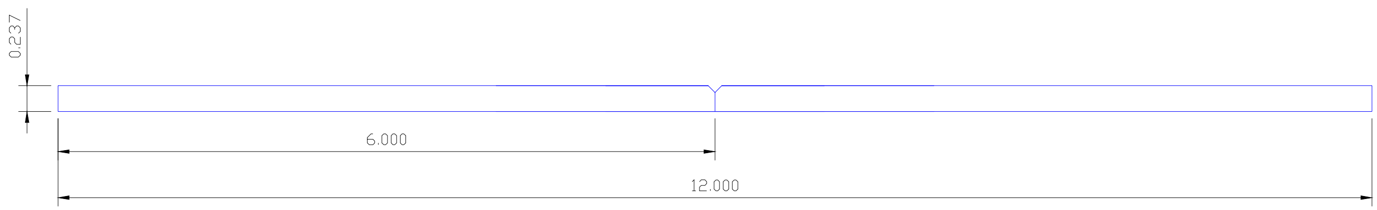
(NOTE: All lengths are 12 inches into the page)



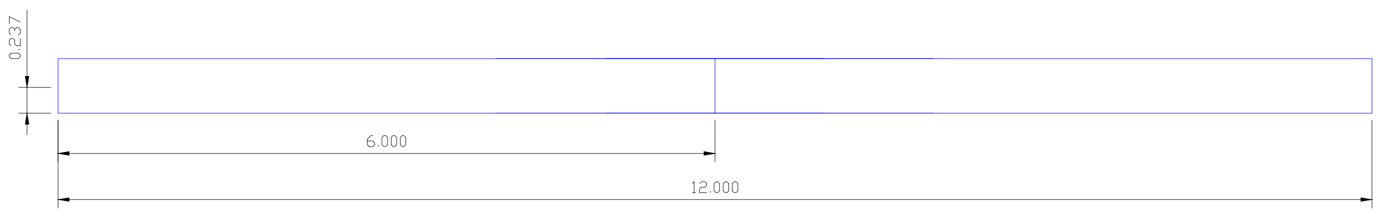
Test Joint **A**$_{MT}$



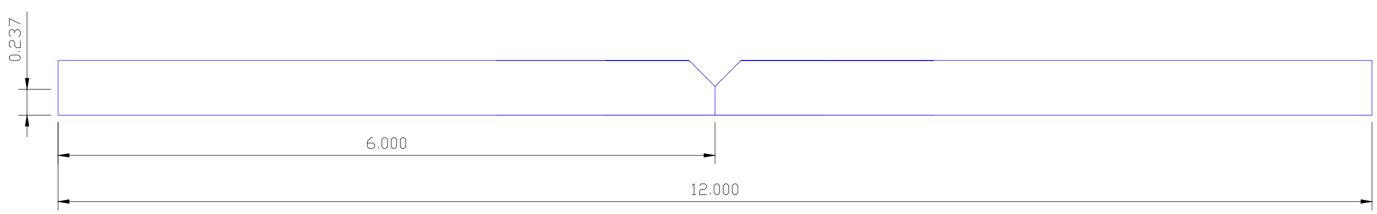
Test Joint **B**$_{MT}$



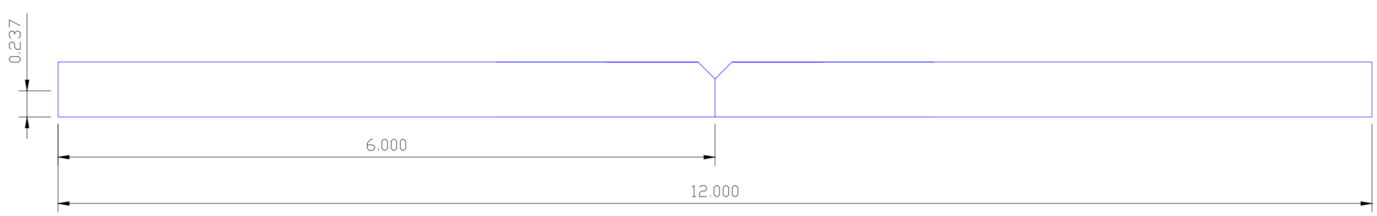
Test Joint **C**$_{MT}$



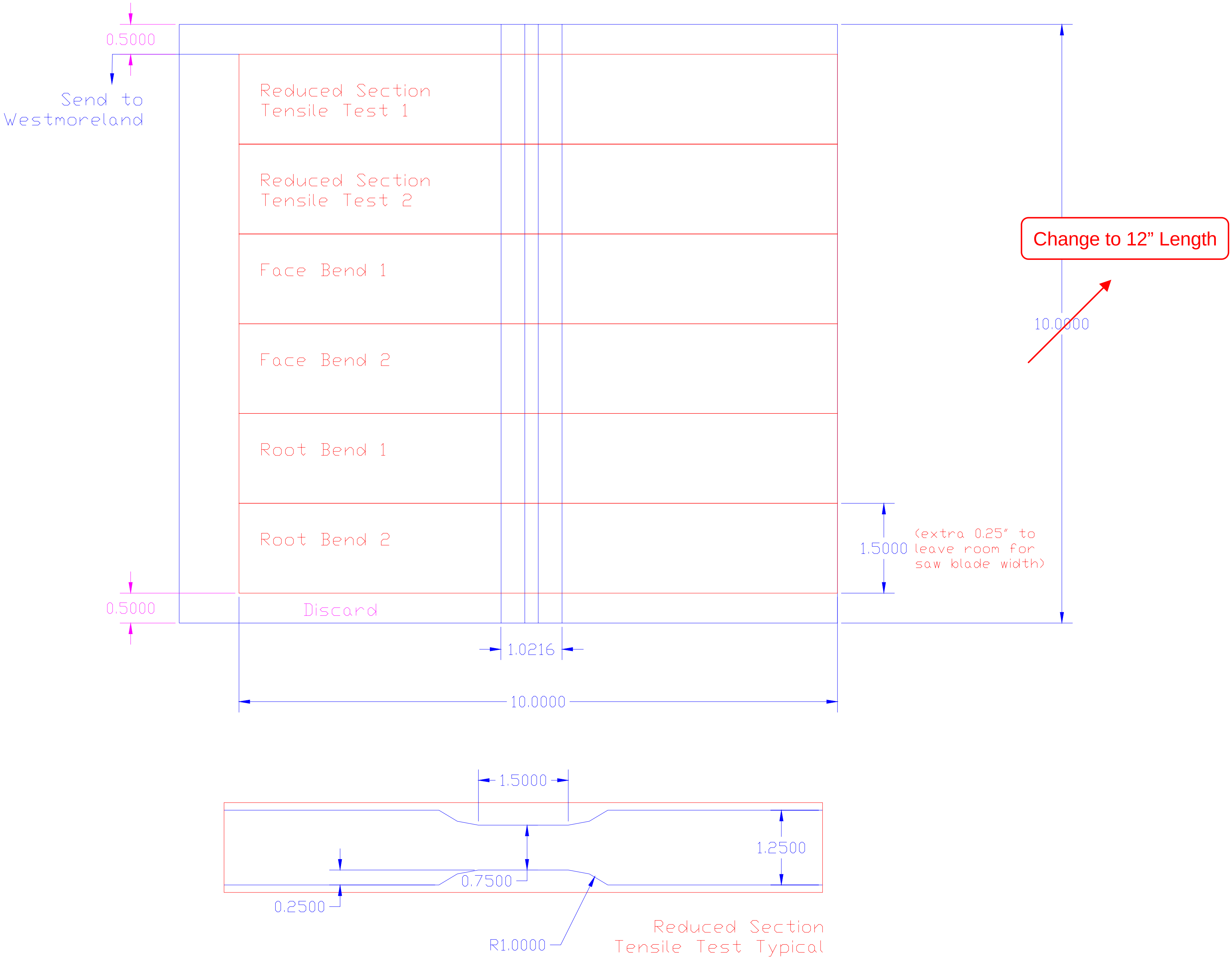
Test Joint **D**$_{MT}$



Test Joint **E**$_{MT}$



Test Joint **F**$_{MT}$



0.5000
Send to
Westmoreland
Reduced Section
Tensile Test 1
Reduced Section
Tensile Test 2
Face Bend 1
Face Bend 2
Root Bend 1
Root Bend 2
1.5000
(extra 0.25" to
leave room for
saw blade width)
0.5000
Discard
1.0216
10.0000
10.0000
Change to 12" Length
1.5000
1.2500
0.7500
0.2500
R1.0000
Reduced Section
Tensile Test Typical

Phase I Parameter Development

Sample No.	Thickness	Laser Process	Joint Prep	Laser to Torch Distance	Contact Tip to Workpiece Dist	Arc Voltage	Speed
1	0.237 inch	2.6 kW laser only	A_{PD}	NA	NA	NA	Speed 1
	0.237 inch	2.6 kW laser only	A_{PD}	NA	NA	NA	Speed 2
	0.237 inch	2.6 kW laser only	A_{PD}	NA	NA	NA	Speed 3
	0.237 inch	2.6 kW laser only	A_{PD}	NA	NA	NA	Speed 4
	0.237 inch	2.6 kW laser only	A_{PD}	NA	NA	NA	Speed 5
2	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 5
3	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 5
4	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 5
5	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 5
6	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 5
7	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 5
8	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 5
9	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 5
10	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 5
11	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 5
12	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 5
13	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 1
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 2
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 3
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 4
	0.237 inch	2.6 kW Hybrid	B_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 5

Sample No.	Thickness	Laser Process	Joint Prep	Laser to Torch Distance	Contact Tip to Workpiece Dist	Arc Voltage	Speed
14	0.237 inch	4.5 kW laser only	A_{PD}	NA	NA	NA	Speed 1
	0.237 inch	4.5 kW laser only	A_{PD}	NA	NA	NA	Speed 2
	0.237 inch	4.5 kW laser only	A_{PD}	NA	NA	NA	Speed 3
	0.237 inch	4.5 kW laser only	A_{PD}	NA	NA	NA	Speed 4
	0.237 inch	4.5 kW laser only	A_{PD}	NA	NA	NA	Speed 5
15	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 5
16	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 5
17	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 5
18	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 5
19	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 5
20	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 5
21	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 5
22	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 5
23	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 5
24	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 5
25	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 5
26	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 1
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 2
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 3
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 4
	0.237 inch	4.5 kW Hybrid	C_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 5

Phase I Parameter Development

Sample No.	Thickness	Laser Process	Joint Prep	Laser to Torch Distance	Contact Tip to Workpiece Dist	Arc Voltage	Speed
0	0.500 inch	2.6 kW laser only	D_{PD}	NA	NA	NA	NA
	0.500 inch	2.6 kW laser only	D_{PD}	NA	NA	NA	NA
	0.500 inch	2.6 kW laser only	D_{PD}	NA	NA	NA	NA
	0.500 inch	2.6 kW laser only	D_{PD}	NA	NA	NA	NA
	0.500 inch	2.6 kW laser only	D_{PD}	NA	NA	NA	NA
27	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 5
28	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 5
29	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 5
30	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 5
31	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 5
32	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 5
33	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 5
34	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 5
35	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 5
36	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 5
37	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 5
38	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 1
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 2
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 3
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 4
	0.500 inch	2.6 kW Hybrid	E_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 5

Phase I Parameter Development

Sample No.	Thickness	Laser Process	Joint Prep	Laser to Torch Distance	Contact Tip to Workpiece Dist	Arc Voltage	Speed
39	0.500 inch	4.5 kW laser only	D_{PD}	NA	NA	NA	Speed 1
	0.500 inch	4.5 kW laser only	D_{PD}	NA	NA	NA	Speed 2
	0.500 inch	4.5 kW laser only	D_{PD}	NA	NA	NA	Speed 3
	0.500 inch	4.5 kW laser only	D_{PD}	NA	NA	NA	Speed 4
	0.500 inch	4.5 kW laser only	D_{PD}	NA	NA	NA	Speed 5
40	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 1	Speed 5
41	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 2	Speed 5
42	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 1	Voltage 3	Speed 5
43	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 1	Speed 5
44	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 2	Speed 5
45	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 1	CT2WP Dist 2	Voltage 3	Speed 5
46	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 1	Speed 5
47	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 2	Speed 5
48	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 1	Voltage 3	Speed 5
49	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 1	Speed 5
50	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 2	Speed 5
51	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 1
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 2
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 3
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 4
	0.500 inch	4.5 kW Hybrid	F_{PD}	L2T Dist 2	CT2WP Dist 2	Voltage 3	Speed 5

Phase I Parameter Development

	Total	Required	Extra	
Joint A	**5**	2	3	(extra for practice)
Joint B	**18**	12	6	(3 extra for globular transfer at 3 voltages, and 3 extra for practice)
Joint C	**15**	12	3	(extra for practice)
Joint D	**5**	2	3	(extra for practice)
Joint E	**18**	12	6	(3 extra for globular transfer at 3 voltages, and 3 extra for practice)
Joint F	**15**	12	3	(extra for practice)

We can perhaps decrease number of tests by using a nominal voltage to select L2T Distance and CT2WP Distance…
So, perform the following experiments for each hybrid joint (instead of 12 experiments):

V1, L1, C1
V1, L1, C2
Choose C_optimal
V1, L2, C_optimal
Choose L_optimal
V2, L_optimal, C_optimal
V3, L_optimal, C_optimal

So, we've reduced 4 sets of 12 experiments each, to 4 sets of 5 experiments each...reduce from:

51 tests (or 51 + 24 = 65 joints)

to:

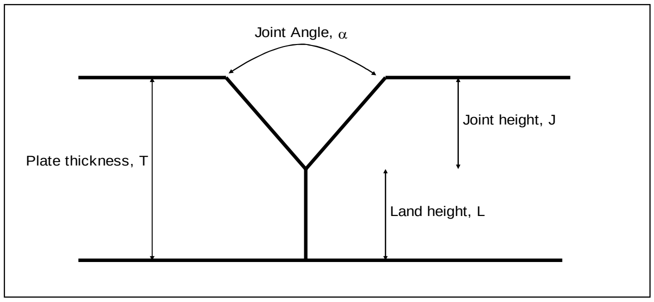
23 tests (or 23 + 24 = 47 joints)

Phase I Mechanical Testing Matrix

Sample No.	Thickness	Laser Process	Joint Prep	Test
1	0.237 inch	2.6 kW Autogenous	A_{MT}	Tensile 1
	0.237 inch	2.6 kW Autogenous	A_{MT}	Tensile 2
	0.237 inch	2.6 kW Autogenous	A_{MT}	Bend 1
	0.237 inch	2.6 kW Autogenous	A_{MT}	Bend 2
2	0.237 inch	4.5 kW Autogenous	A_{MT}	Tensile 1
	0.237 inch	4.5 kW Autogenous	A_{MT}	Tensile 2
	0.237 inch	4.5 kW Autogenous	A_{MT}	Bend 1
	0.237 inch	4.5 kW Autogenous	A_{MT}	Bend 2
3	0.237 inch	2.6 kW Hybrid	B_{MT}	Tensile 1
	0.237 inch	2.6 kW Hybrid	B_{MT}	Tensile 2
	0.237 inch	2.6 kW Hybrid	B_{MT}	Bend 1
	0.237 inch	2.6 kW Hybrid	B_{MT}	Bend 2
4	0.237 inch	4.5 kW Hybrid	C_{MT}	Tensile 1
	0.237 inch	4.5 kW Hybrid	C_{MT}	Tensile 2
	0.237 inch	4.5 kW Hybrid	C_{MT}	Bend 1
	0.237 inch	4.5 kW Hybrid	C_{MT}	Bend 2
5	0.500 inch	4.5 kW Autogenous	D_{MT}	Tensile 1
	0.500 inch	4.5 kW Autogenous	D_{MT}	Tensile 2
	0.500 inch	4.5 kW Autogenous	D_{MT}	Bend 1
	0.500 inch	4.5 kW Autogenous	D_{MT}	Bend 2
6	0.500 inch	2.6 kW Hybrid	E_{MT}	Tensile 1
	0.500 inch	2.6 kW Hybrid	E_{MT}	Tensile 2
	0.500 inch	2.6 kW Hybrid	E_{MT}	Bend 1
	0.500 inch	2.6 kW Hybrid	E_{MT}	Bend 2
7	0.500 inch	4.5 kW Hybrid	F_{MT}	Tensile 1
	0.500 inch	4.5 kW Hybrid	F_{MT}	Tensile 2
	0.500 inch	4.5 kW Hybrid	F_{MT}	Bend 1
	0.500 inch	4.5 kW Hybrid	F_{MT}	Bend 2

Phase I Mechanical Testing

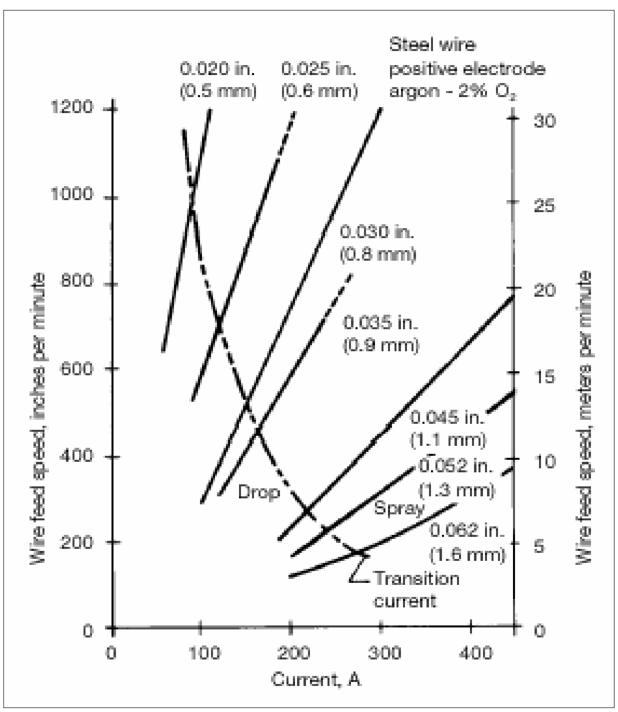
	Total	Required	Extra	
Joint A	**4**	2	2	(extra for practice)
Joint B	**3**	1	2	(extra for practice)
Joint C	**3**	1	2	(extra for practice)
Joint D	**3**	1	2	(extra for practice)
Joint E	**3**	1	2	(extra for practice)
Joint F	**3**	1	2	(extra for practice)



pipe dia	travel length
{in}	{in}
2	6.3
4	12.6
6	18.8
10	31.4

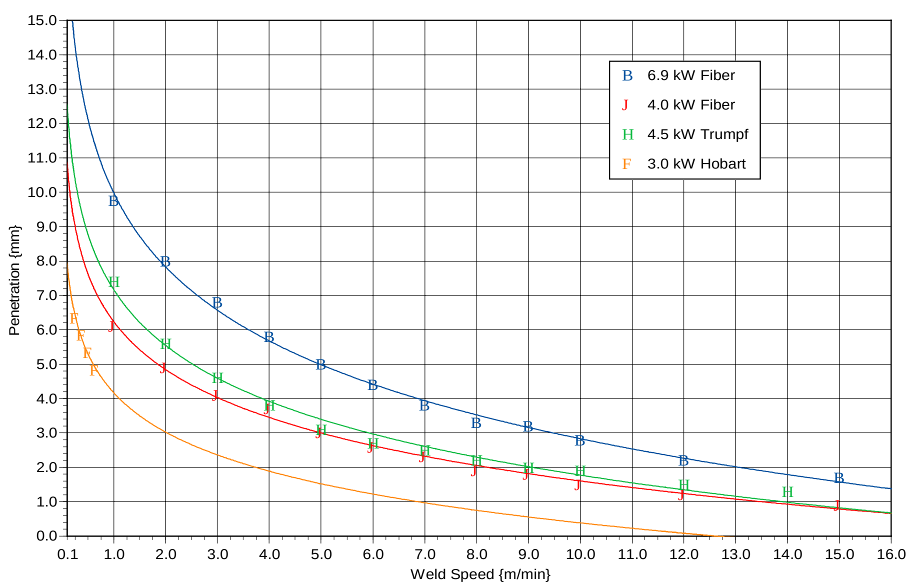
Blue - Calculated
Red - Table Look-Up

T	L	L	J	α	Req'd Reinfrcmnt	Wire Dia.	3kW Travel Speed	3 kW Req'd Wire Feed Speed	4.5kW Travel Speed	4.5 kW Req'd Wire Feed Speed	6.9 kW Travel Speed	6.9 kW Req'd Wire Feed Speed
{in}	{in}	{mm}	{in}	{degrees}	{in^2}	{in}	{ipm}	{ipm}	{ipm}	{ipm}	{ipm}	{ipm}
0.237	0.237	6.0198	0	0	0.0000	0.035	15.0	0.00	60.0	0.00	140	0.00
0.237	0.1745	4.4323	0.0625	90	0.0039	0.035	30.0	121.80	128.0	519.69	240	974.42
0.237	0.1745	4.4323	0.0625	30	0.0010	0.035	30.0	32.64	128.0	139.25	240	261.09
0.237	0.112	2.8448	0.125	90	0.0156	0.035	40.0	649.61	240.0	3897.67	440	7145.73
0.237	0.112	2.8448	0.125	30	0.0042	0.035	40.0	174.06	240.0	1044.38	440	1914.69
0.237	0.237	6.0198	0	0	0.0000	0.045	15.0	0.00	60.0	0.00	140	0.00
0.237	0.1745	4.4323	0.0625	90	0.0039	0.045	30.0	73.68	128.0	314.38	240	589.46
0.237	0.1745	4.4323	0.0625	30	0.0010	0.045	30.0	19.74	128.0	84.24	240	157.95
0.237	0.112	2.8448	0.125	90	0.0156	0.045	40.0	392.98	240.0	2357.85	440	4322.73
0.237	0.112	2.8448	0.125	30	0.0042	0.045	40.0	105.30	240.0	631.78	440	1158.27
0.5	0.5	12.7	0	0	0.0000	0.035	0.0	0.00	0.0	0.00	20	0.00
0.5	0.375	9.525	0.125	90	0.0156	0.035	0.0	0.00	12.0	194.88	50	812.02
0.5	0.375	9.525	0.125	30	0.0042	0.035	0.0	0.00	12.0	52.22	50	217.58
0.5	0.25	6.35	0.25	90	0.0625	0.035	10.0	649.61	56.0	3637.83	120	7795.34
0.5	0.25	6.35	0.25	30	0.0167	0.035	10.0	174.06	56.0	974.75	120	2088.76
0.5	0.5	12.7	0	0	0.0000	0.045	0.0	0.00	0.0	0.00	20	0.00
0.5	0.375	9.525	0.125	90	0.0156	0.045	0.0	0.00	12.0	117.89	50	491.22
0.5	0.375	9.525	0.125	30	0.0042	0.045	0.0	0.00	12.0	31.59	50	131.62
0.5	0.25	6.35	0.25	90	0.0625	0.045	10.0	392.98	56.0	2200.66	120	4715.70
0.5	0.25	6.35	0.25	30	0.0167	0.045	10.0	105.30	56.0	589.67	120	1263.57



T	L	L	J	α	Req'd Reinfrcmnt	Wire Dia.	3kW Travel Speed	3 kW Req'd Wire Feed Speed	4.5kW Travel Speed	4.5 kW Req'd Wire Feed Speed	6.9 kW Travel Speed	6.9 kW Req'd Wire Feed Speed
{in}	{in}	{mm}	{in}	{degrees}	{in^2}	{in}	{ipm}	{ipm}	{ipm}	{ipm}	{ipm}	{ipm}
0.237	0.237	6.0198	0	0	0.0000	0.035	15.0	0.00	60.0	0.00	140	0.00
0.237	0.1745	4.4323	0.0625	60	0.0023	0.035	30.0	70.32	128.0	300.04	240	562.58
0.237	0.1745	4.4323	0.0625	15	0.0005	0.035	30.0	16.04	128.0	68.42	240	128.28
0.237	0.112	2.8448	0.125	60	0.0090	0.035	40.0	375.05	240.0	2250.32	440	4125.59
0.237	0.112	2.8448	0.125	15	0.0021	0.035	40.0	85.52	240.0	513.14	440	940.75
0.237	0.237	6.0198	0	0	0.0000	0.045	15.0	0.00	60.0	0.00	140	0.00
0.237	0.1745	4.4323	0.0625	60	0.0023	0.045	30.0	42.54	128.0	181.51	240	340.33
0.237	0.1745	4.4323	0.0625	15	0.0005	0.045	30.0	9.70	128.0	41.39	240	77.60
0.237	0.112	2.8448	0.125	60	0.0090	0.045	40.0	226.88	240.0	1361.31	440	2495.73
0.237	0.112	2.8448	0.125	15	0.0021	0.045	40.0	51.74	240.0	310.42	440	569.10
0.5	0.5	12.7	0	0	0.0000	0.035	0.0	0.00	0.0	0.00	20	0.00
0.5	0.375	9.525	0.125	60	0.0090	0.035	0.0	0.00	12.0	112.52	50	468.82
0.5	0.375	9.525	0.125	15	0.0021	0.035	0.0	0.00	12.0	25.66	50	106.90
0.5	0.25	6.35	0.25	60	0.0361	0.035	10.0	375.05	56.0	2100.30	120	4500.64
0.5	0.25	6.35	0.25	15	0.0082	0.035	10.0	85.52	56.0	478.93	120	1026.28
0.5	0.5	12.7	0	0	0.0000	0.045	0.0	0.00	0.0	0.00	20	0.00
0.5	0.375	9.525	0.125	60	0.0090	0.045	0.0	0.00	12.0	68.07	50	283.61
0.5	0.375	9.525	0.125	15	0.0021	0.045	0.0	0.00	12.0	15.52	50	64.67
0.5	0.25	6.35	0.25	60	0.0361	0.045	10.0	226.88	56.0	1270.55	120	2722.61
0.5	0.25	6.35	0.25	15	0.0082	0.045	10.0	51.74	56.0	289.72	120	620.83

T	L	L	J	α	Req'd Reinfrcmnt	Wire Dia.	3kW Travel Speed	3 kW Req'd Wire Feed Speed	4.5kW Travel Speed	4.5 kW Req'd Wire Feed Speed	6.9 kW Travel Speed	6.9 kW Req'd Wire Feed Speed
{in}	{in}	{mm}	{in}	{degrees}	{in^2}	{in}	{ipm}	{ipm}	{ipm}	{ipm}	{ipm}	{ipm}
0.237	0.237	6.0198	0	0	0.0000	0.035	12.8	0.00	65.0	0.00	141.1857	
0.237	0.142	3.6068	0.095	90	0.0090	0.035	54.1	507.25	180.2	1690.26		
0.237	0.156	3.9624	0.081	120	0.0114	0.035	43.7	516.42	155.1	1831.48		
0.237	0.237	6.0198	0	0	0.0000	0.035	12.8	0.00	65.0	0.00	141.1857	
0.237	0.175	4.445	0.062	90	0.0038	0.035	32.8	130.91	126.5	505.27		
0.237	0.188	4.7752	0.049	90	0.0024	0.035	26.9	67.12	110.0	274.51	210.4963	525.30
0.237	0.187	4.7498	0.05	120	0.0043	0.035	27.3	122.91	111.2	500.41		
0.237	0.237	6.0198	0	0	0.0000	0.035	12.8	0.00	65.0	0.00	141.1857	
0.237	0.165	4.191	0.072	90	0.0052	0.035	38.1	205.49	140.8	758.58		
0.237	0.177	4.4958	0.06	120	0.0062	0.035	31.8	206.00	123.8	802.21		
0.237	0.237	6.0198	0	0	0.0000	0.035	12.8	0.00	65.0	0.00		
0.237	0.193	4.9022	0.044	90	0.0019	0.035	24.9	50.17	104.3	209.79		
0.237	0.202	5.1308	0.035	120	0.0021	0.035	21.7	47.96	94.7	208.75		
0.5	0.5	12.7	0	0	0.0000	0.035	0.2	0.00	3.9	0.00	16.55022	
0.5	0.239	6.0706	0.261	60	0.0393	0.035	12.4	506.93	63.6	2601.67		
0.5	0.263	6.6802	0.237	90	0.0562	0.035	8.6	502.91	49.2	2872.10		
0.5	0.286	7.2644	0.214	120	0.0793	0.035	6.1	500.88	38.4	3169.00		
0.5	0.5	12.7	0	0	0.0000	0.035	0.2	0.00	3.9	0.00	16.55022	
0.5	0.321	8.1534	0.179	60	0.0185	0.035	3.6	68.66	26.4	507.69		
0.5	0.345	8.763	0.155	90	0.0240	0.035	2.5	61.95	20.4	509.67		
0.5	0.39	9.906	0.11	90	0.0121	0.035	1.3	15.76	12.6	158.39	40.56859	510.21
0.5	0.368	9.3472	0.132	120	0.0302	0.035	1.7	54.88	15.9	500.22		
0.5	0.5	12.7	0	0	0.0000	0.035	0.2	0.00	3.9	0.00	16.55022	
0.5	0.277	7.0358	0.223	60	0.0287	0.035	7.0	207.84	42.3	1263.34		
0.5	0.321	8.1534	0.179	120	0.0555	0.035	3.6	205.99	26.4	1523.06		
0.5	0.5	12.7	0	0	0.0000	0.035	0.2	0.00	3.9	0.00	16.55022	
0.5	0.36	9.144	0.14	60	0.0113	0.035	2.0	23.23	17.4	204.37		
0.5	0.4	10.16	0.1	120	0.0173	0.035	1.1	19.38	11.3	203.66		



6.9 Fiber
x = -3.105 * ln(y) + 0.9981, R2 = 0.9963
y = 24.75 * exp(-0.3209 * x)

4.0 Fiber
x = -2.012 * ln(y) + 6.237, R2 = 0.9949
y = 22.03 * exp(-0.4944 * x)

4.5 Fiber
x = -2.342 * ln(y) + 7.165, R2 = 0.9894
y = 21.00 * exp (-0.4224 * x)

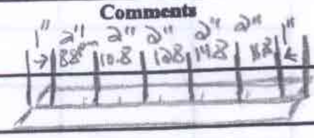
3.0 Fiber
x = -1.643 * ln(y) + 4.164, R2 = 0.9820
y = 11.86 * exp (-0.5977 * x)

y = travel speed {m/min}
x = penetration {mm}

Pennsylvania State University
Applied Research Laboratory
MSRF Facility
Nd:YAG Work Station

Date: 4/20/04 **Project#** 11771.11.01 **Sponsor** ______ **Operator** JJ.

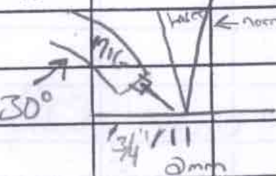
Material: A36 **Process:** butt welds

I.D.#	Laser Power	travel speed	Wire Type/speed	Powder Type	Powder Setting	Scanner Hz./in	Shielding gas	Focusing Optics	Comments
								@15°	1" 2" 2" 2" 2" 2" 1" 8.8 10.8 12.8 14.8 16.8 
4/20/04-1	2600 watts	8.8 - 10.8 - 12.8 - 14.8 - 16.8 IPM				3/8" ID nozzle @30°	70 CFH Ar leading	F2 focus ↓ .05"	|← 12" L →|
									cut up at 12.8 IPM (Pores) weld direction →
-2	"	16.8 - 14.8 - 12.8 - 10.8 - 8.8 IPM					"	"	cut up at 12.8 IPM Pores
-3	"	12.8				"	50 CFH Ar	"	Pores
-4	"	"					30 CFH Ar		No Pen
-5	"	"					15 CFH Ar		No Pen
-6	"	"				@20°	70 CFH Ar		Pores
-7	"	"				@30°	200 CFH He		Pores
-8	"	"				"	70 CFH N_2		Clean
-9	"	13				"	"		clean little undercut
-10	"	13.5 IPM				"	"		12" long weld
-11	"	11.5 - 12.5 - 13.5 - 14.5 - 15.5 IPM				"	"		
4/21/04-									
AMT-1	2600	14.5				"	70 CFH N_2	"	more pen at on 1st half
AMT-2	"	14.5					70 CFH Ar	"	spotty pen
AMT-3	"	12.5					" "		leveled little fill pen little undercut
AMT-4	"	14.5					70 CFH N_2		

Pennsylvania State University
Applied Research Laboratory
MSRF Facility
Nd:YAG Work Station

Date: 9-13-04 **Project#** 11771.11.01 **Sponsor**______ **Operator** JF.

Material: Steel 70S6 wire **Process:** butt welds hybrid

I.D.#	Laser Power	travel speed	MIG Wire Type/speed	Powder Type	Powder Setting	Scanner Hz./in	Shielding gas	Focusing Optics	Comments
1	4500	20 IPM	500 IPM 26 V				3/8" ID coaxial 70CFH Ar. 50CFH Ar mix MIG	200mm optics focus on surface	bead on plate
2	"	"	"				3/4" ID 70CFH Ar leading laser		
3	same as #1 with knife jet below nozzle								holes in weld
4	"	"	"	"	" "	"	" removed copper nozzle tip		looked clean
5	"	"	"	"		70CFH Ar coaxial + leading w/ knife jet			
						(20 coaxial)	stand-off wrong on laser 1-5		
6	"	"		Just Laser			both gas	focus ↓ 2mm	
7	"	"		Just MIG			"		
8	"	"		both			"		
9	"	"		both				focus on surface	
10	"	"		both		smaller leading nozzle 1/4" ID		focus 2mm ↓	
11	"	"		"		no leading gas		"	
12	"	"		"		90/10 gas on leading nozzle			
13	"	"		"		straight Ar on lead same as #10			
14	"	"		"	gas leading coaxial MIG			"	
15	"	"		"	"	"	MIG 4mm trailing beam		
16	4500	15-17.5-20-22.5-25 hybrid				70CFH Ar gas coaxial	70CFH Ar leading	MIG 90/10 Ar. 60CFH	Y=.345 v groove 5 speeds
				MIG	500 WS	26V			no pen
17	4500	12.5, 15, 17.5, 20, 22.5			500 WS	26V .035			no pen
18	"	10, 12.5, 15, 17.5, 20					MIG 5mm from beam Trail		

I.D.#	Laser Power	Travel Speed	Wire Type/Speed	Powder Type	Powder Setting	Scanner Hz./in	Shielding gas	Focusing Optics	Comments
19	4500	10, 12.5, 15 IPM	just Laser						no pen
20	"	7.5, 10, 12.5			1 cover lens			full Pen	.263 landing
21	4500	15	500 37V	focus at surface				045 wire	.263 Land
22	4500	20	500 35V	focus at 4mm in				045 wire	.345 Land
23	4500	20	500 35V	focus at 1mm				045	.345 Land
24	4500	20	400 32V	focus at 1mm				045 wire	
9/14									
25	4500	12.5, 15, 17.5, 20		just laser			coaxial 70 CFH leading 70 CFH	focus on surface	joint .263 → Y full Pen
26	"	20, 22.5, 25, 27.5							full Pen
27	"	27.5, 30, 32.5, 35							full Pen
28	"	35, 40, 45, 50							no Pen
29	"	10, 12.5, 15, 17.5			"	"	"	"	.345 land full Pen at 10
30	"	15	530 WS 37.5V	.045 7056	Hybrid		60 CFH 90/10 MIG 70 CFH coaxial 70 CFH leading	"	.263 land To Hot MIG blewthrough
31	"	15	530 WS 32V	"			"		blew thru
32	"	30	"						full Pen not enough fillet
33	"	22.5	800 IPM 40 V						too hot
34	"	"	800 WS 35V						" "
35	"	"	800 WS 30 V						" "
36	"	"	800 20V						" "
cover 37	"	10	170 WS 21 V	"	"		"	"	.263 land
38		15	230 23 V						Too Hot
39	"	10	170 WS 19V			MIG	6mm Trail Laser		Too much Pen
40	"	12.5	"				"		
41	"	"	"				"	Travel	MIG leading no Pen
42	"	"	"		MIG trailing		4mm from beam		no Pen
43	"	"	"		"	"	5mm		no Pen
44	"	"	"		"	"	6mm "		no Pen
45	"	10	"				2mm	joint → Y	over pen .263 land

I.D.#	Laser Power	Travel Speed	Wire Type/Speed	Powder Type	Powder Setting	Scanner Hz./ in	Shielding gas	Focusing Optics	Comments
46	4500	20 IPM	170 WS 19V	Hybrid		MIG 2mm from beam			.263 land Y
47	"	10 IPM	260 WS (.035 wire) 17.2V	Hybrid		65 Ar Coaxial + leading 50 Ar mix MIG Trail			.343 no Pen
48	"	8 IPM	260 18.5V						
"	"	"	230 16.5						
50	"	10 IPM	230V 17V		MIG Trailing beam by 16mm				full Pen
51	"	"	300 WS 17.5V						full Pen
52	"	12.5	"						no Pen
53	"	"				leading nozzle moved to side 70+CFH Ar			no Pen
54	"	10	"	add half of weld 312 WS		"	"	"	" nice full Pen 8" long run
55	"	"	"						filled back side MIG stuck
56	"	"	"					focus 1mm ↓	no Pen
57	"	"	"		MIG Trailing Laser 2mm			"	no Pen
58	"	"	"		"	"	"	focus ↑ 1mm	no Pen
59	"	"	"		"	"	7.5mm	"	no Pen
60	"	"	"		"	"	16mm	focus on Surface	
61	"	"	"			cross gas 70+CFH N2"		"	clear root Pores MIG
62	"	"	"		cross gas same side as MIG w/N2.				MIG 60CFH Mix nice
63	"	"	"						
9/15									
64	4500	10 IPM	300 WS 17.5V		MIG Trails laser beam ~16mm		60 CFH 90/10 Ar MIG Laser 70 CFH N2		70 CFH Coaxial 15 CFH N2 back shield focus on Surface
			no gas MIG						
65	same as 64								nice
66	Same		50 CFH He back shield						
67	Same				Laser/hybrid/MIG				
68	Same								
69	Same	but on	Top of plate						
70	4500	1,2,3,4,5		stop program burn thru					butt weld 1/2" Thick plate
71	"	2,2.5,3,3.5,4		"	"	"			" " "
72	"	3,3.5,4,4.5,5							" " "
73	"	10	300WS 17V	Hybrid full 11.5" weld					.343 land
74-77	"	"	"	"					Demos

I.D.#	Laser Power	Travel Speed	Wire Type/Speed	Powder Type	Powder Setting	Scanner Hz./in	Shielding gas	Focusing Optics	Comments
78	4500	10	hybrid	317 ws 17.5V			Same	Same	2-6x12 ropey back side
79	"	"	"				"	"	
80	"	4		laser only	1" long weld		70CFH N_2 Laser shield 70 CFH Ar coaxial		1/2 butt weld focus on surface Too Much Pen
81	"	5							Too much Pen
82	"	7.5							better no Pen
83	"	8.5							" "
84	"	9.5							" "
85	"	10.5							" "
86	"	6							Too much
87	"	6.5							"
88	"	7							"
89	"	7.5							3" long weld spotty pen
9/20 90	4500	20-25-30-35-40			Laser		70CFH N_2 - Laser shield 70 CFH Ar, coaxial		45° Angled Y .263" land 20 + 25 IPM full Pen
91	"	20	200 ws 16 V		hybrid		" 60CFH MIG 90/10 mix		Ugly MIG
92	"	"	250 WS 17 V						" "
93	"	"	317 WS 17.5 V						better
94	"	"	350 ws 17.5 V						not enough reinforcement
95	"	17.5 IPM	400 WS 17.5 V						better
96	"	"	400 WS 22 V						
97	"	"	450 WS 20 V						
98	"	"	500 20						
99	"	17.5	475 WS 20 V						11.5" run
9/23									
100	4500	20, 25, 30, 35, 40		Laser only			70 CFH N_2	focus on surface	1/4 butt welds All full Pen
101	"	40, 45, 50, 55, 60							lost Pen
102	"	35, 40, 45, 50, 55						1mm ↓	
– 103	"	35					"	focus on surface	full length weld for testing
– 104	"	40						"	" " " nice
105	"	80, 90, 100, 110, 120				all full Pen but	Thin		Y 1/4" plate .175 land
106		40, 50, 60, 70, 80							
107		"	"	"	"			focus on To surface	instead of land

I.D.#	Laser Power	Travel Speed	Wire Type/Speed	Powder Type	Powder Setting	Scanner Hz./ in	Shielding gas	Focusing Optics	Comments
108	4500	60	.035 7056	Hybrid	300ws 17.5 ✓	MIG	70CFH N2 60CFH Ar/O2 90/10	focus on surface	Y .175" land
109	''	''			350 18.5				
110	''	''			''				undercut back side
111	''	''			''			focus ↓ 4mm from surface	
112	''	''			400 21.5			''	
113	''	''			450 24.5			''	
114	''	''			500 25.5			''	
115	''	''			''			↓ 6mm	
116	''	''			''			''	longer
– 117	''	''			''			''	full length for testing
– 118	''	''			''			''	'' '' '' ''
119	''	10	''		317 17.5			focus @ Y	1/2 plate .345 land 2 spot welds in middle
9/24 120	''	''			''			''	Y .345 land Part is tight to 1/8" gap end
121	''	''			''			''	.345 land has 20° offset 0-1/8" gap end
122	''	''			''			''	.345 land 20° offset 0-1/8" gap
	11/9/04								
1	4500	80	.045 7056 160 wire	3mm	2500 RPM		70CFH Ar.	5 1/16"	1/4 plate .175" land
2	''	60	''						
3	''	40	''						
4	''	20	''						spotty pen big reinforcement
5	''	''	120	3mm		1500RPM		''	spotty
6	''	''	''	''		1000 RPM			
7	''	''	''	''		''	70CFH N2		
8	''	''	''	''		2000 RPM	''		
9	''	''	''	''		1000 RPM	''		0 Gap to 2mm GAP 12:15

Testing RobCine camera w/ hybrid welds

Pennsylvania State University
Applied Research Laboratory
MSRF Facility
Nd:YAG Work Station

Date: Sept 27, 2004 **Project#** N/A **Sponsor** N/A **Operator** Rob + Ted

Material: **Process:**

I.D.#	Laser Power	travel speed	Wire Type/speed	Powder Type	Powder Setting	Scanner Hz./in	Shielding gas	Focusing Optics	Comments
—	4500	10	WFS 317 V 17.5	5/8" standoff, N_2 laser assist					Time: 9:44 1/500 shutter shade 10
—	"	"	"		90/10 Ar/CO_2				9:50pm, 1/250 shutter
—	"	"	"						9:58 pm, 1/100 Shade
—									10:08 pm 1/10,000 3(?)
—									1/10,000 Shade 6(?)
—									10:23pm 1/4,000 shade 6(?)
—									10:26pm 1/2000 shade 4(?)
—									10:45pm 1/4,000 shade 8(?)
—									10:50pm 1/2,000 shade 8(?)
—									10:54pm 1/1,000 shade 8(?)
—									10:56 pm 1/500 shade 8(?)
123	4500	20	WFS 317 V 17.5	5/8" standoff, 16mm separation, laser lead					11:11 1/1,000 shade 8
124	4500	20	WFS 500 V 26.9						11:14 " "
125	"	"	"						11:19 1/2,000 "
126	"	~~40~~ 20	"						11:24 1/4,000
127	"	40	"						11:27 1/4,000
128	"	"	"	No N_2 assist gas.					11:34 1/4,000
129	"	"	"	No N_2, 16mm spacing, laser lead					11:59 1/4,000
130	"								12:02 1/2,000
131	"	"	"		10mm spacing				12:12 1/2,000
132					5mm				12:20 1/2000
133					3mm				12:25 1/2,000
134					1mm				12:32 1/2000
135	4500	40	WFS 500 V 26.9		1mm				1:04 1/2000
136	"	"	V 24.9		"				1:07

I.D.#	Laser Power	Wire ~~Travel~~ Speed	Travel ~~Wire~~ Type/Speed	Powder Type	Powder Setting	Scanner Hz./ in	Shielding gas	Focusing Optics	Comments
137	4500	WFS500 V22.9	40ipm	1mm spacing					1:10pm 1/2000
138	"	v28.9		"					
139		v30.9							1:19

Appendix H – Radiographic Test Results

RNDT, Inc. Nondestructive Testing Services ♦ 228 Maple Ave. ♦ Johnstown, PA 15901 ♦ 814-535-5448

RADIOGRAPHIC EXAMINATION REPORT FORM

Customer	Specification	Acceptance Standard	NDE Procedure No.
Penn State University - ARL P.O. Box 30, N. Atherton St State College, PA 16804	ASME Section IX: 2001 Ed.	ASME Section IX QW-191.2.2	RNDT-RT-1001V, Rev. 0

Part Name	Part Thickness	Drawing Number	Material
WPQ plates	0.250"	na	C/S Alloy

Radiation Source	Curies	Kv	Ma	Focal Spot Size	Technique Used	Focal Film Distance	Exposure Time
X-Ray	na	150	3	3 mm	SWE/SWV	42"	1.8 minutes

Film Type	Film Size	Film Technique	Penetrameter Type	Material	Penetrameter Location	Penetrameter Size	Shim Thickness
Agfa D5	7" X 17"	Single	ASME SE-1025	Stainless Steel	Source Side	12 (2)	0.062" & none

Film Processing	Intensifying Screens	Front	Center	Back	Radiographer	Film Reviewer
Automatic 6@84	Pb	0.005"	na	0.005"	Terry Mattes	Fred Raco, Jr.

Item Identification	View	Incomplete Penetration	Incomplete Fusion	Root Condition	Slag Inclusion	Porosity	Undercut	Tungsten Inclusion	Crack	Burn Through	Other-See Remarks	Film Artifact	Density-Weld	Density-Pene	Accept	Reject	Remarks
#118, Hybrid, 0.25"T	0 - 1	X				X										X	
0.175" land, 4500 W																	
60 IPM TS																	
500 IPM WFS																	
25.5 V																	
#104, 0.25"T	0 - 1														X		
Butt, 4500 W																	
40 IPM TS																	
Autogenous																	
AMT-1, 0.25"T	0 - 1														X		
Butt, 2600 W																	
14.5 IPM TS																	
Autogenous																	

Signature: Fred Raco, Jr. NDT Inspector III SNT-TC-1A Level

Date: 30-Sep-04

P.O. Number 917265

Job Number J4-1220

RNDT, Inc. Nondestructive Testing Services ♦ 228 Maple Ave. ♦ Johnstown, PA 15901 ♦ 814-535-5448

RADIOGRAPHIC EXAMINATION REPORT FORM

Customer Penn State University - ARL P.O. Box 30, N. Atherton St State College, PA 16804	**Specification** ASME Section IX: 2001 Ed.	**Acceptance Standard** ASME Section IX QW-191.2.2	**NDE Procedure No.** RNDT-RT-1001V, Rev. 0
	Part Name WPQ plates	**Part Thickness** 0.500"	**Drawing Number** na
			Material C/S Alloy

Radiation Source	**Curies**	**Kv**	**Ma**	**Focal Spot Size**	**Technique Used**	**Focal Film Distance**	**Exposure Time**
X-Ray	na	200	3	3 mm	SWE/SWV	42"	2.0 minutes

Film Type	**Film Size**	**Film Technique**	**Penetrameter Type**	**Material**	**Penetrameter Location**	**Penetrameter Size**	**Shim Thickness**
Agfa D5	7" X 17"	Single	ASME SE-1025	Stainless Steel	Source Side	17 (2)	0.062" & none

Film Processing	**Intensifying Screens**	**Front**	**Center**	**Back**	**Radiographer**	**Film Reviewer**
Automatic 6@84	Pb	0.005"	na	0.005"	Terry Mattes	Fred Raco, Jr.

Item Identification	View	Incomplete Penetration	Incomplete Fusion	Root Condition	Slag Inclusion	Porosity	Undercut	Tungsten Inclusion	Crack	Burn Through	Other-See Remarks	Film Artifact	Density-Weld	Density-Pene	Accept	Reject	Remarks
#79, Hybrid, 0.50T	0 - 1					X										X	
0.345 land, 4500 W																	
10 IPM TS																	
317 IPM WFS																	
17.5 V																	

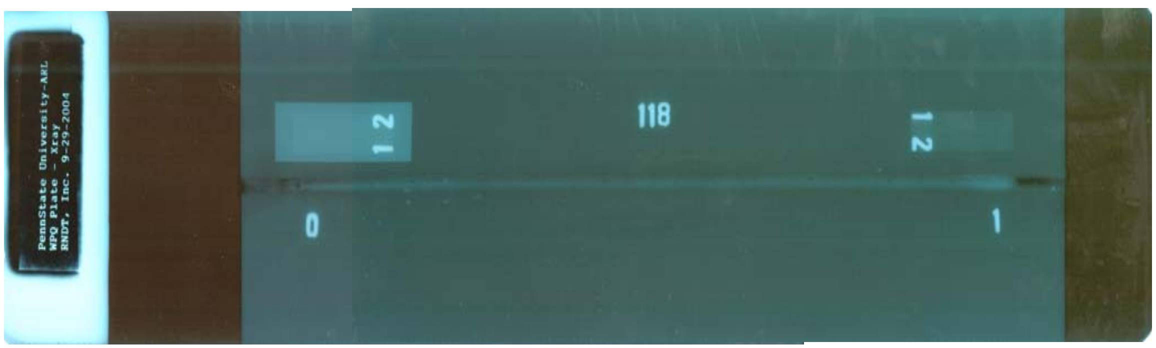
Signature: Fred E Raco Jr. III
NDT Inspector SNT-TC-1A Level

Date: 30-Sep-04

P.O. Number 917265

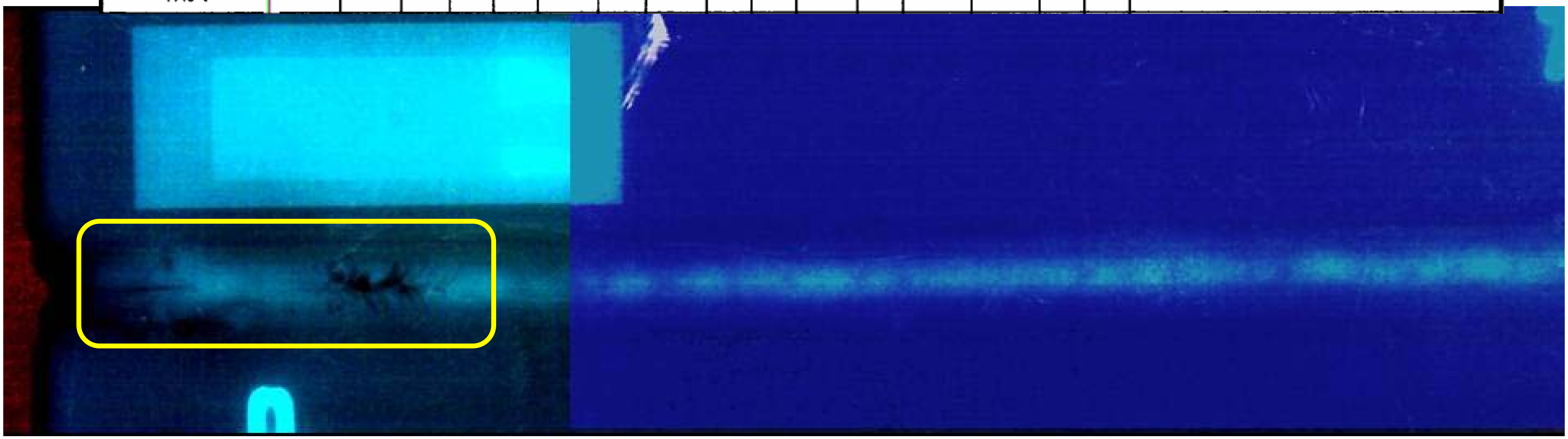
Job Number J4-1220

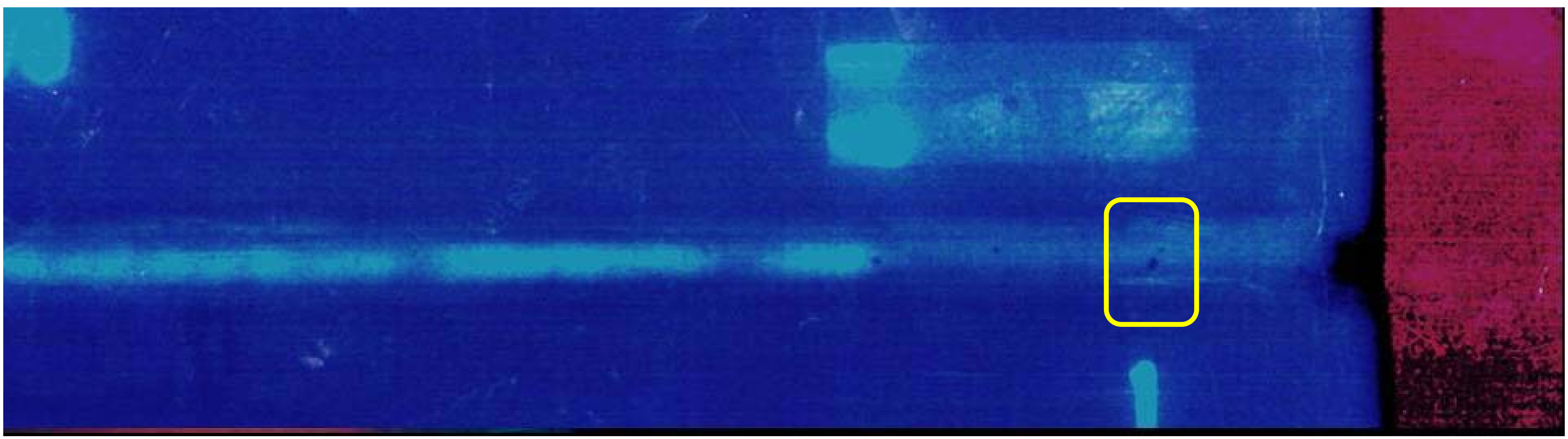
Raw Scanned
X-Ray Images



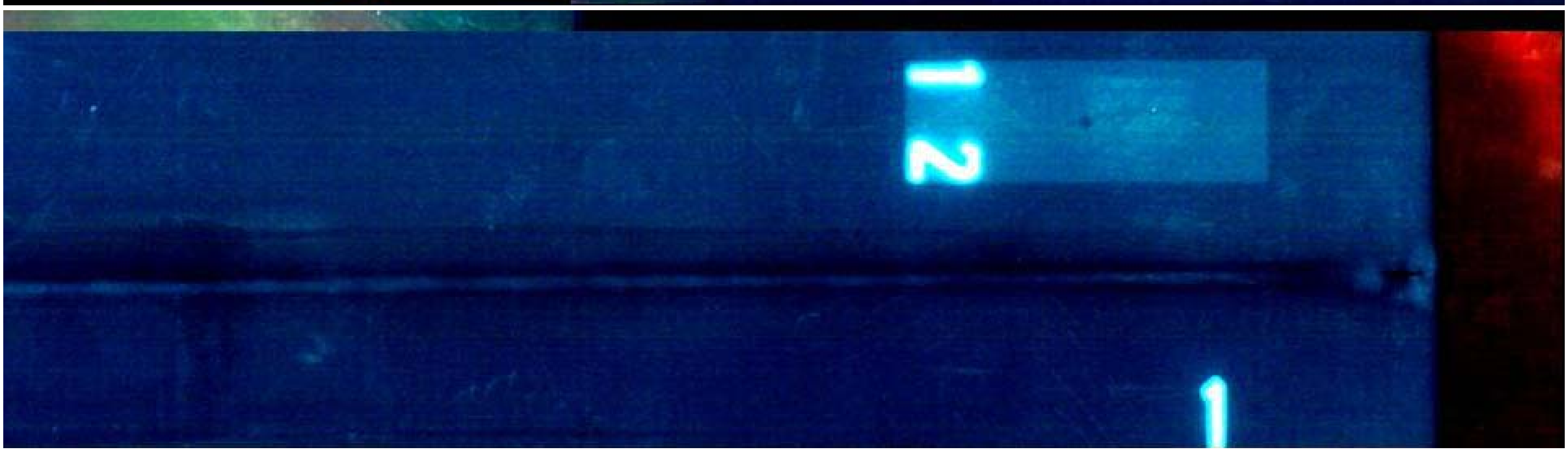
Magnified,
False-Color
X-Ray Images
Follow on Remaining
Slides

Item Identification	View	Incomplete Penetration	Incomplete Fusion	Root Condition	Slag Inclusion	Porosity	Undercut	Tungsten Inclusion	Crack	Burn Through	Other-See Remarks	Film Artifact	Density-Weld	Density-Pene	Accept	Reject	Remarks
#79, Hybrid, 0.50T	0 - 1					X										X	
0.345 land, 4500 W																	
10 IPM TS																	
317 IPM WFS																	
17.5 V																	

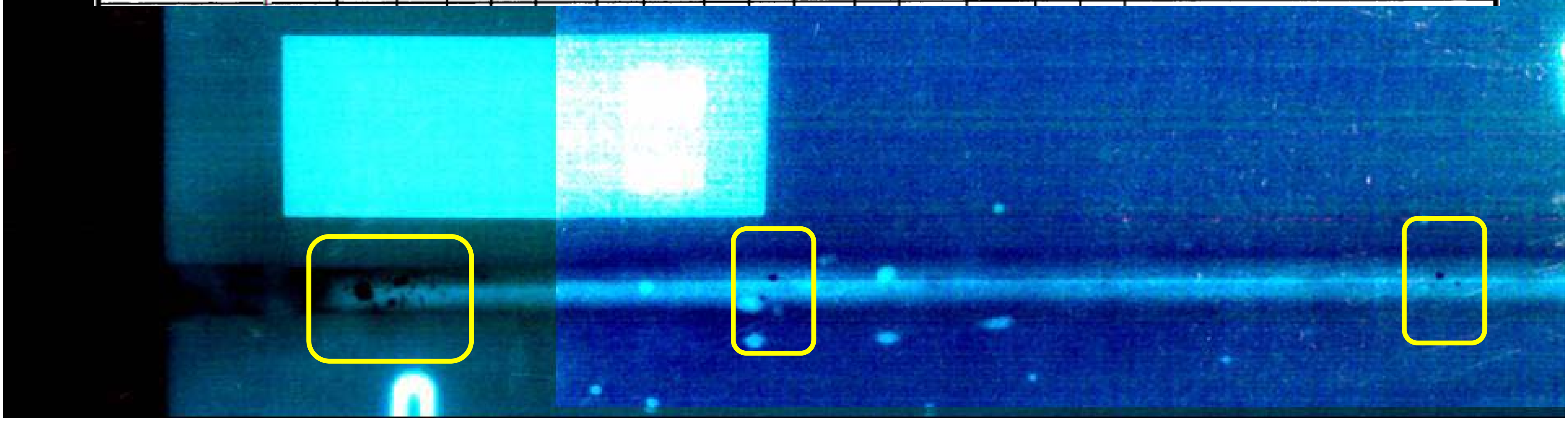


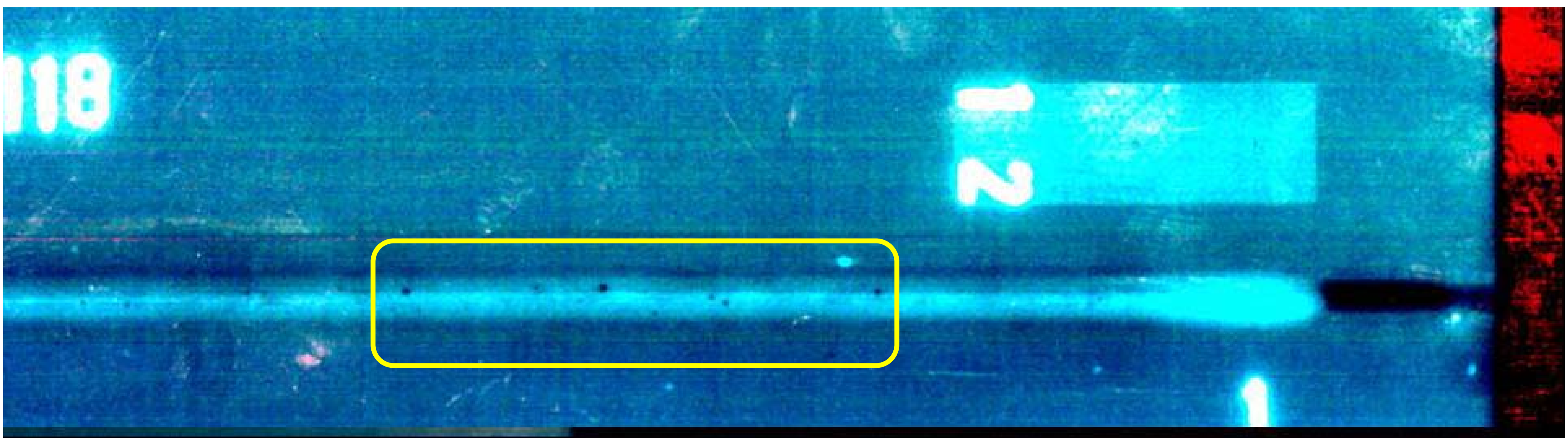


Item Identification	View	Incomplete Penetration	Incomplete Fusion	Root Condition	Slag Inclusion	Porosity	Undercut	Tungsten Inclusion	Crack	Burn Through	Other-See Remarks	Film Artifact	Density-Weld	Density-Pene	Accept	Reject	Remarks
#104, 0.25"T	0 - 1														X		
Butt, 4500 W																	
40 IPM TS																	
Autogenous																	

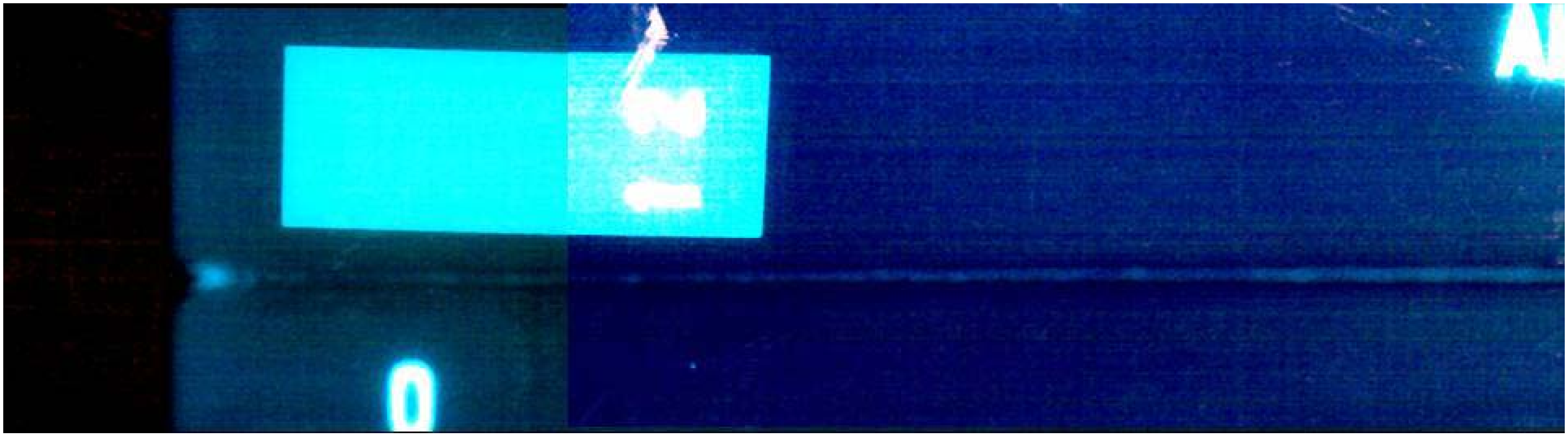


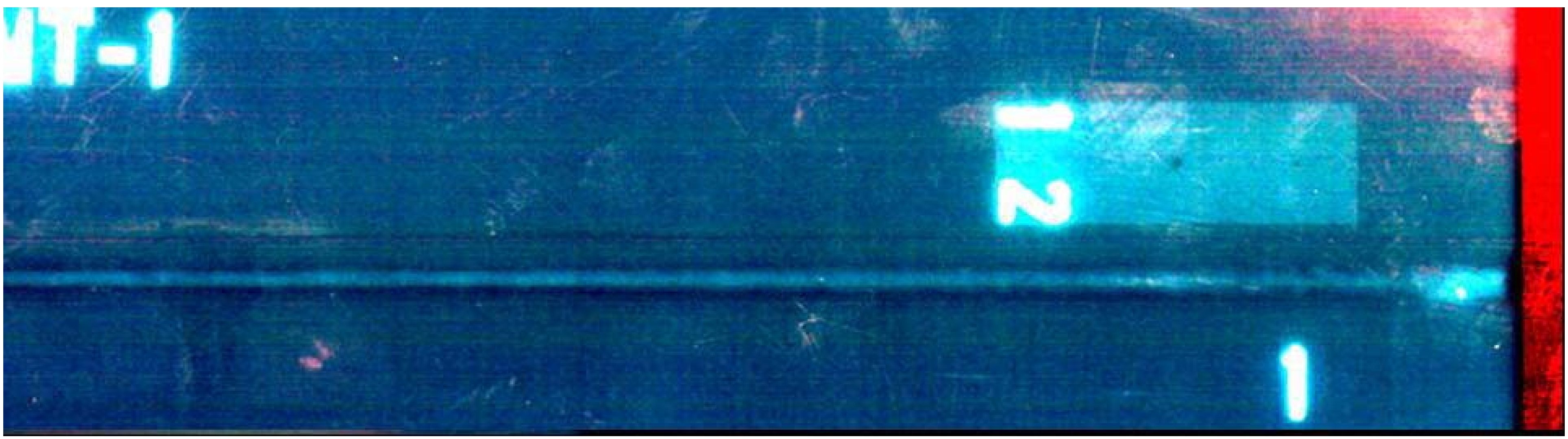
Item Identification	View	Incomplete Penetration	Incomplete Fusion	Root Condition	Slag Inclusion	Porosity	Undercut	Tungsten Inclusion	Crack	Burn Through	Other-See Remarks	Film Artifact	Density-Weld	Density-Pene	Accept	Reject	Remarks
#118, Hybrid, 0.25"T	0 - 1	X				X										X	
0.175" land, 4500 W																	
60 IPM TS																	
500 IPM WFS																	
25.5 V																	

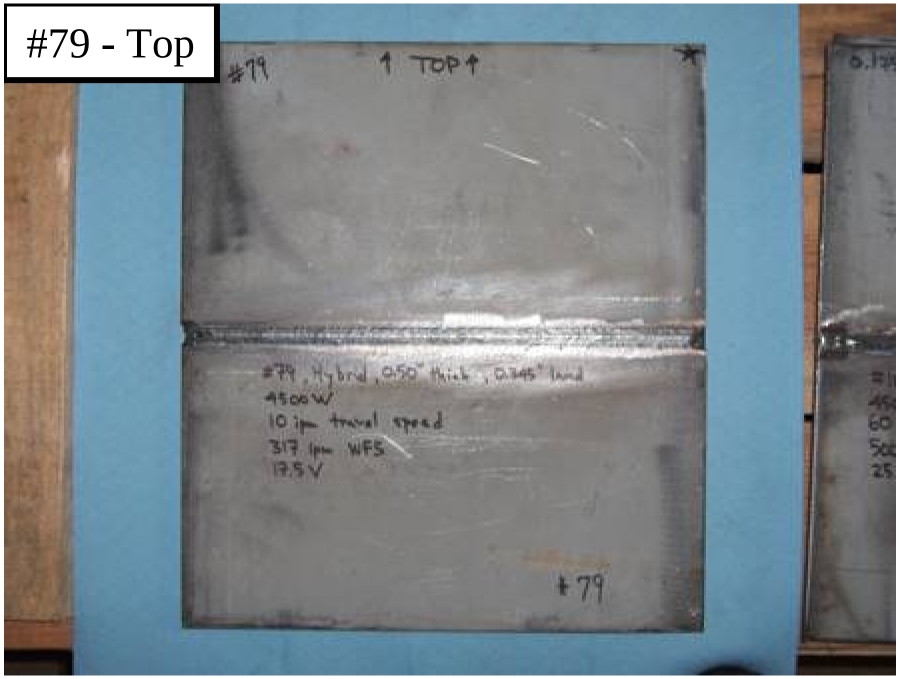


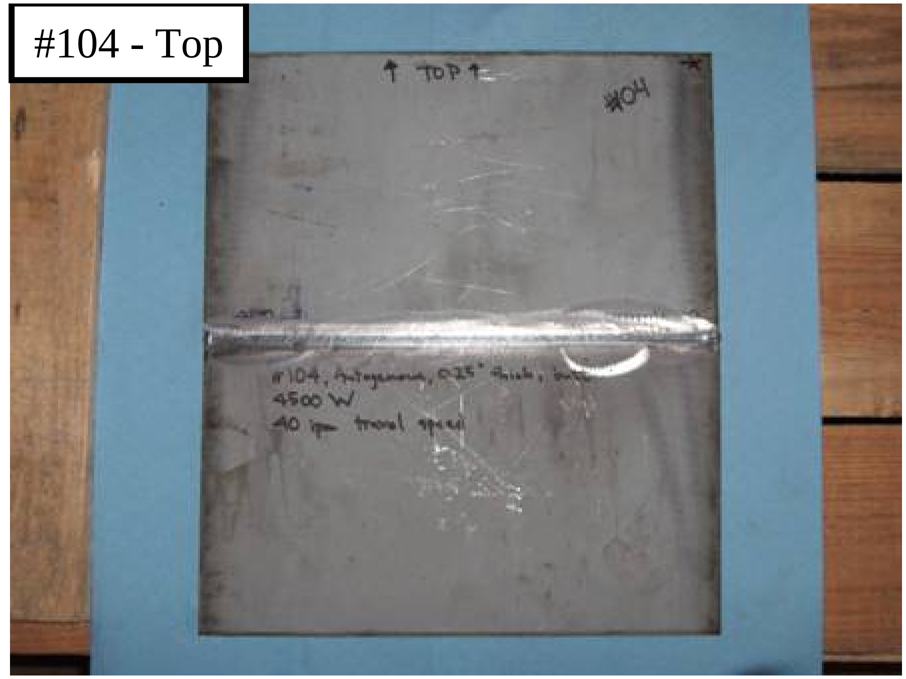


Item Identification	View	Incomplete Penetration	Incomplete Fusion	Root Condition	Slag Inclusion	Porosity	Undercut	Tungsten Inclusion	Crack	Burn Through	Other-See Remarks	Film Artifact	Density-Weld	Density-Pene	Accept	Reject	Remarks
AMT-1, 0.25"T	0 - 1														X		
Butt, 2600 W																	
14.5 IPM TS																	
Autogenous																	






#79 - Top
↑ TOP ↑
#79
4500W
10 ipm travel speed
317 ipm WFS
17.5V
#79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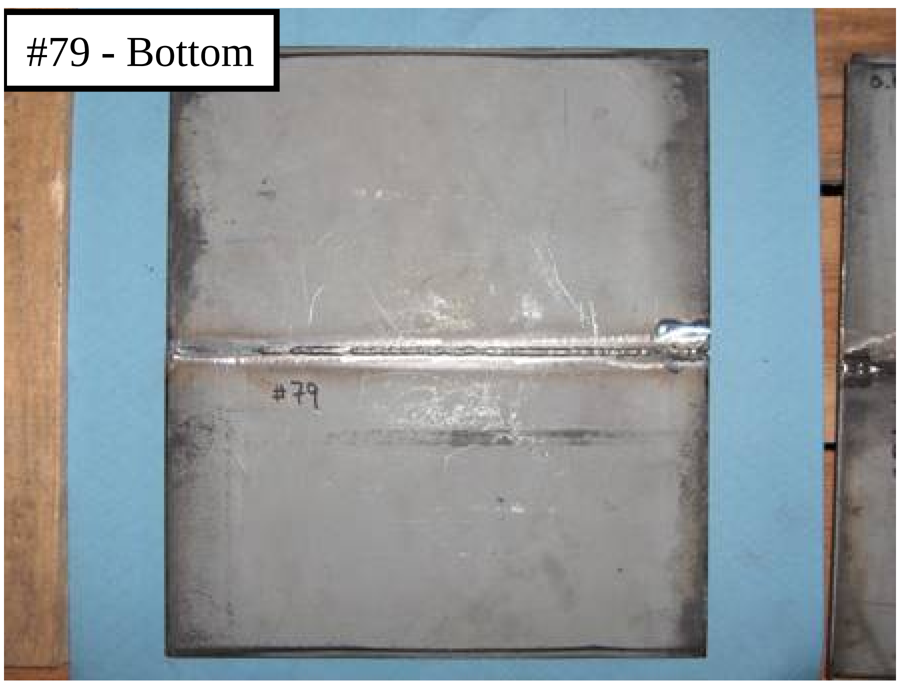
↑ TOP ↑
#104
4500 W
40 ipm travel speed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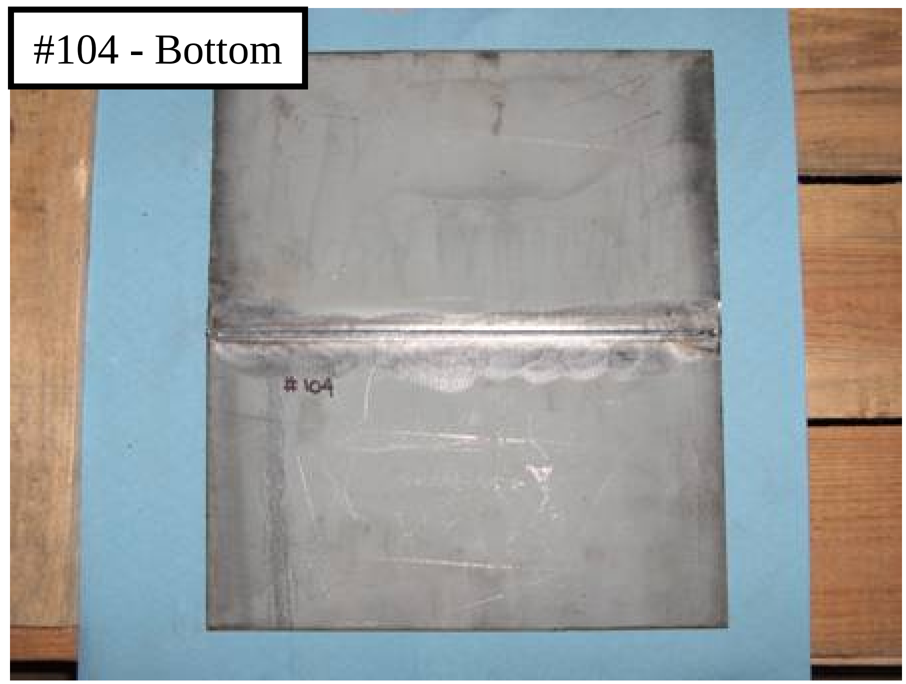
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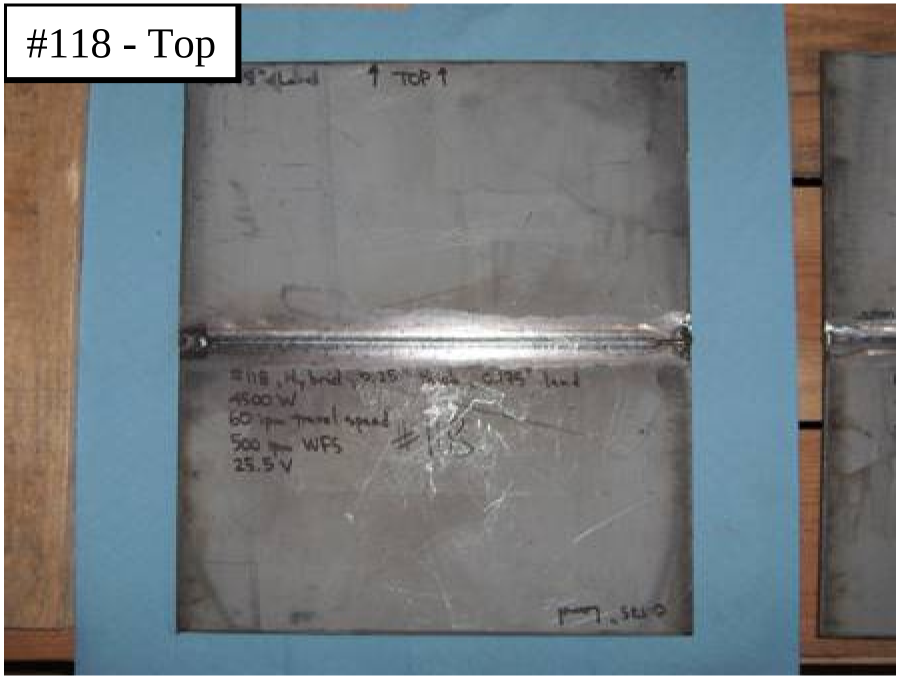

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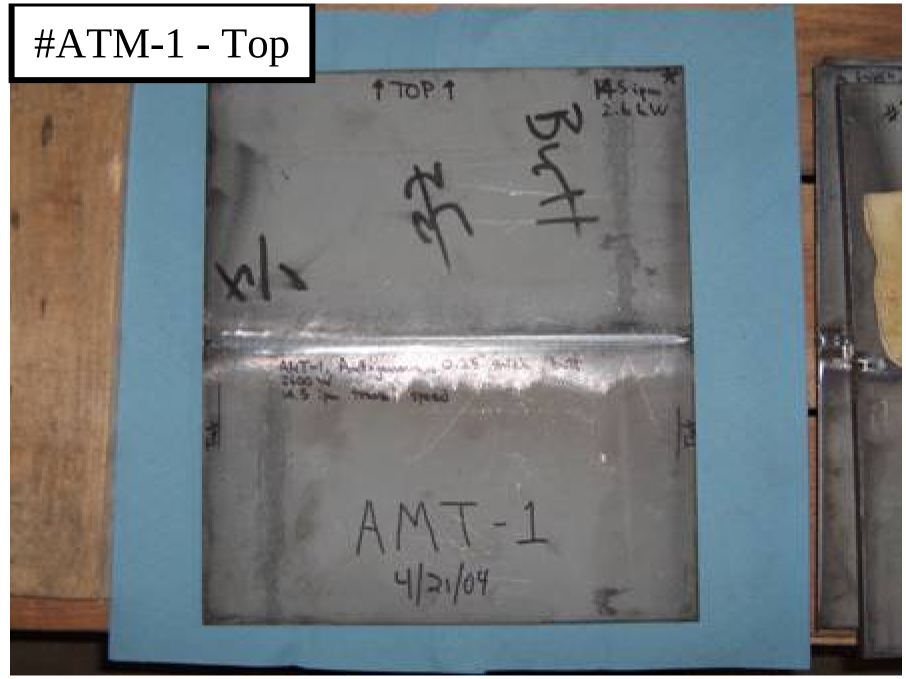

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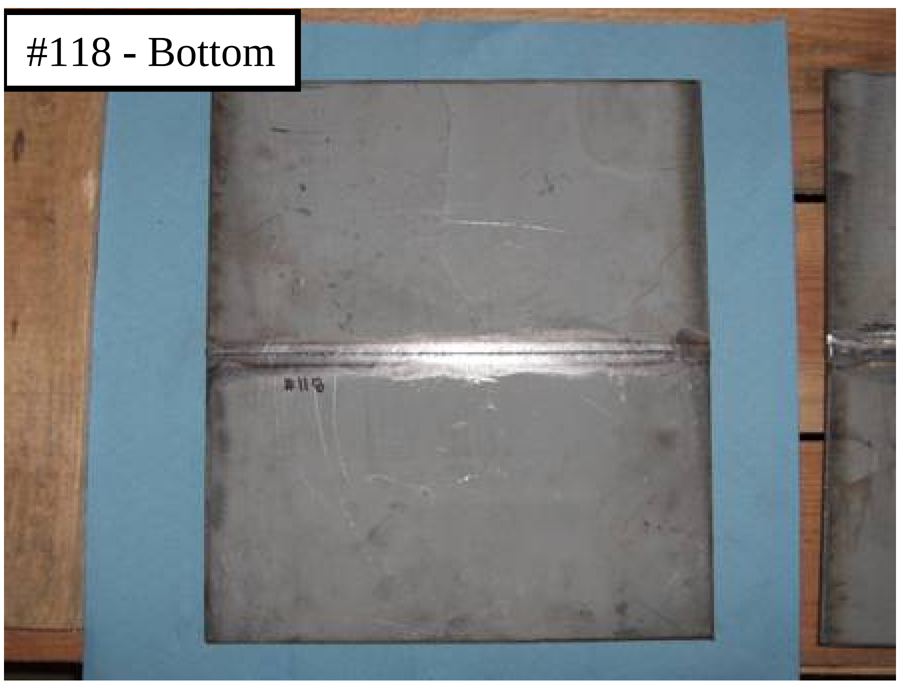

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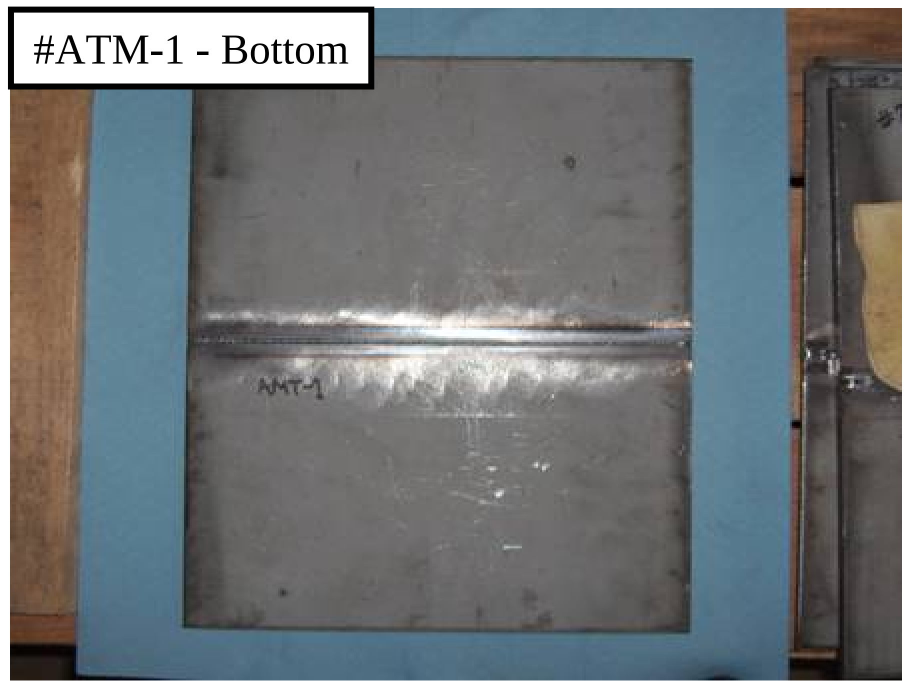

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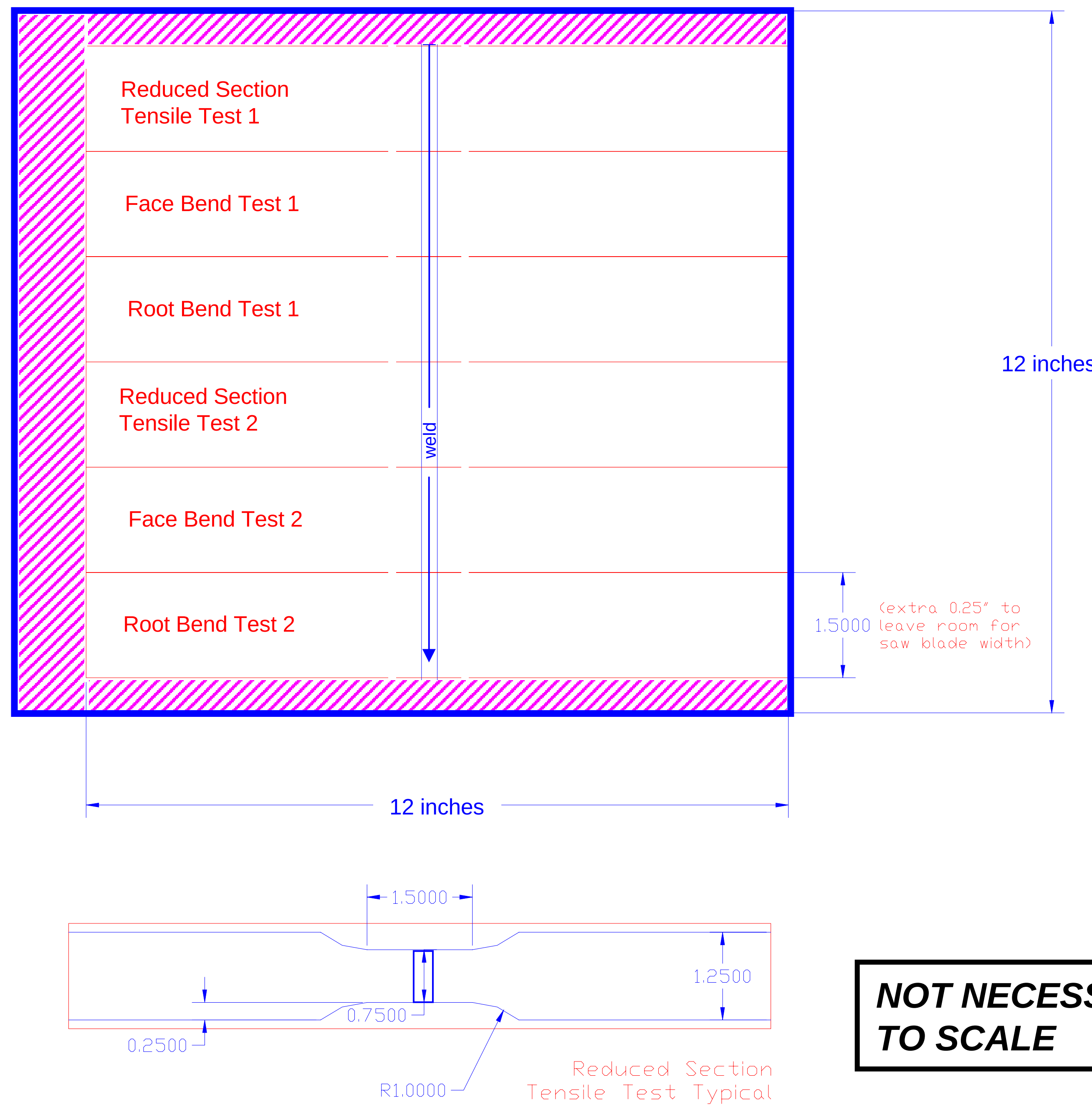
Appendix I – Tensile and Bend Test Results



NOT NECESSARILY TO SCALE

Westmoreland Mechanical Testing & Research, Inc.
P.O. Box 388
Old Route 30, Westmoreland Drive
Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 724-537-3131 Fax: 724-537-3151
Website: www.wmtr.com
WMT&R is a technical leader in the material testing industry.

BEND TEST CERTIFICATION

ARL Penn State
Rear, Research Building West
North Atherton Street
State College, PA 16804

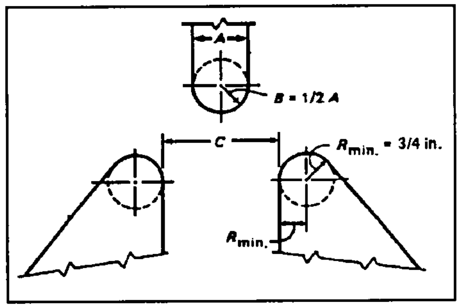
WMT&R Report No.	4-34144
P.O. No.	---
Date	10/21/2004
Page No.	B1 of 2

Mr. Ted Reutzel

P.Q.R. Number:	---
Material Thickness:	---
Specimen Thickness:	.22"
P-Number:	---

Material: Steel Specification: ASME Section IX 1998 w/2001 Addenda

Specimen No.	Type of Bend	Direction	Results	Test Log No.
104-FB1	Face	Long.	Acceptable	A97111
104-FB2	Face	Long.	Acceptable	A97112
AMT-1-FB1	Face	Long.	Acceptable	A97115
AMT-1-FB2	Face	Long.	Acceptable	A97116
104-RB1	Root	Long.	Acceptable	A97117
104-RB2	Root	Long.	Acceptable	A97118
AMT-1-RB1	Root	Long.	Acceptable	A97121
AMT-1-RB2	Root	Long.	Acceptable	A97122



Jig Dimensions	
A =	.88"
B =	.44"
C =	1.445"

Comments:
All machining, testing, and inspections were performed in accordance with the WMT&R Quality Assurance Manual Rev. 9, dated 4/1/2000.
WMT&R Quote No. QN241208
Shipping Order No. 20956A

Mark A. Stape, Tensile Foreperson

10/21/04
10/21/2004

Accredited Nadcap Materials Testing Laboratory

KNOWINGLY OR WILLFULLY FALSIFYING OR CONCEALING A MATERIAL FACT ON THIS FORM, OR MAKING FALSE, FICTITIOUS OR FRAUDULENT STATEMENTS OR REPRESENTATIONS HEREIN COULD CONSTITUTE A FELONY PUNISHABLE UNDER FEDERAL STATUTES.

A2LA ACCREDITED 621-01 & 621-02

Westmoreland Mechanical Testing & Research, Inc.
P.O. Box 388
Old Route 30, Westmoreland Drive
Youngstown, Pa. 15696-0388 U.S.A.
Telephone: 724-537-3131 Fax: 724-537-3151
Website: www.wmtr.com
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BEND TEST CERTIFICATION

ARL Penn State
Rear, Research Building West
North Atherton Street
State College, PA 16804

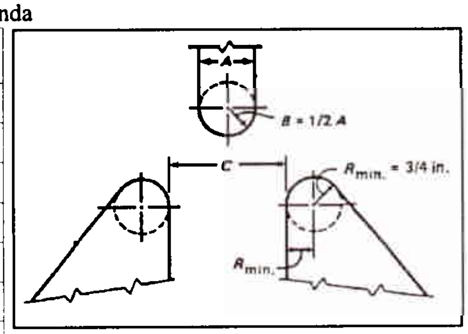
WMT&R Report No. 4-34144
P.O. No. ---
Date 10/21/2004
Page No. B2 of 2

Mr. Ted Reutzel

P.Q.R. Number: ---
Material Thickness: ---
Specimen Thickness: .50"
P-Number: ---

Material: Steel Specification: ASME Section IX 1998 w/2001 Addenda

Specimen No.	Type of Bend	Direction	Results	Test Log No.
79-FB1	Face	Long.	Acceptable	A97113
79-FB2	Face	Long.	Acceptable	A97114
79-RB1	Root	Long.	Acceptable	A97119
79-RB2	Root	Long.	Acceptable	A97120



Jig Dimensions	
A =	2.0"
B =	1.0"
C =	3.125"

Comments:

All machining, testing, and inspections were performed in accordance with the WMT&R Quality Assurance Manual Rev. 9, dated 4/1/2000.

WMT&R Quote No. QN241208

Shipping Order No. 20956A

Mark A. Stape, Tensile Foreperson

10/21/04

10/21/2004

Accredited Nadcap Materials Testing Laboratory

A2LA ACCREDITED 621-01 & 621-02

Westmoreland Mechanical Testing & Research, Inc.
P.O. Box 388
Westmoreland Drive
Youngstown, PA 15696-0388 U.S.A.
Telephone: 724-537-3131 Fax: 724-537-3151
Website: www.wmtr.com
WMT&R is a technical leader in the material testing industry.

ACCREDITED 621-01 & 621-02

Accredited Nadcap Materials Testing Laboratory

October 23, 2004

CERTIFICATION

Section 1 of 1

WMT&R Report No. 4-34144
WMTR Quote No. QN241208
Shipping Order No. 20956A

ARL Penn State
Rear Research Building West
North Atherton Street
State College, PA 16804

Attention: Ted Reutzel

Subject: All processes, performed upon the material as received, were conducted at WMT&R, Inc. in accordance with the WMT&R Quality Assurance Manual, Rev. 9, dated 4/1/2000.
The following tests were performed on this order: TENSILE, FACE BEND and ROOT BEND

TENSILE RESULTS: ASTM E8-04
SPEED OF TESTING: 0.0050 in./in./min., 0.0500 in./min./in.
MATERIAL: A53 Steel
DISPOSITION: Report

Specimen ID	TestLog Number	Temp.	UTS KSI	0.2% YS KSI	Modulus MSI	Ult. Load LBS	0.2% YLD. LBS	Orig. Width (in.)	Orig. Thick (in)	Orig. Area (Sq. In.)	Failure Location/Type	Machine Number	A/U/R
104-T1	A97105	Room	71.3	41.1	17.3	11060	6373	0.7501	0.2068	0.15512068	BASE/DUCTILE	M10	R
104-T2	A97106	Room	72.0	37.5	10.7	11500	5981	0.7502	0.2128	0.15964256	BASE/DUCTILE	M10	R
79-T1	A97107	Room	69.8	42.8	16.3	24670	15140	0.7526	0.4698	0.35357148	BASE/DUCTILE	M10	R
79-T2	A97108	Room	69.3	40.2	15.1	24990	14500	0.7522	0.4791	0.36037902	BASE/DUCTILE	M10	R
AMT-1-T1	A97109	Room	71.6	42.4	12.1	11440	6780	0.7508	0.2128	0.15977024	BASE/DUCTILE	M10	R
AMT-1-T2	A97110	Room	71.6	34.9	9.9	9750	4757	0.7504	0.1814	0.13612256	BASE/DUCTILE	M10	R

A/U/R: A=ACCEPTABLE, U=UNACCEPTABLE, R=REPORT

Roy E. Starr/Mark A. Stape
____ Technical Services Manager/____ Tensile Foreperson

10/23/04
October 23, 2004

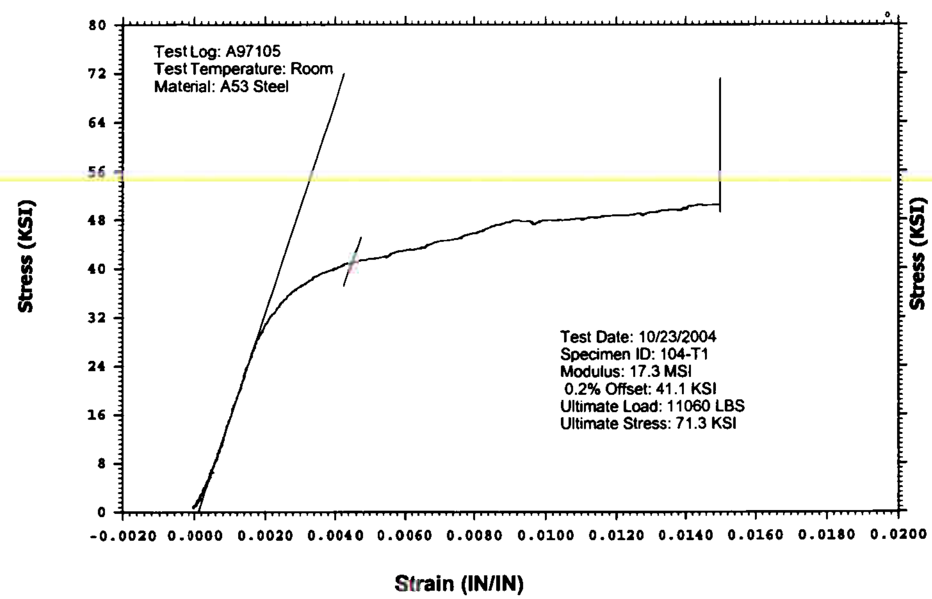
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

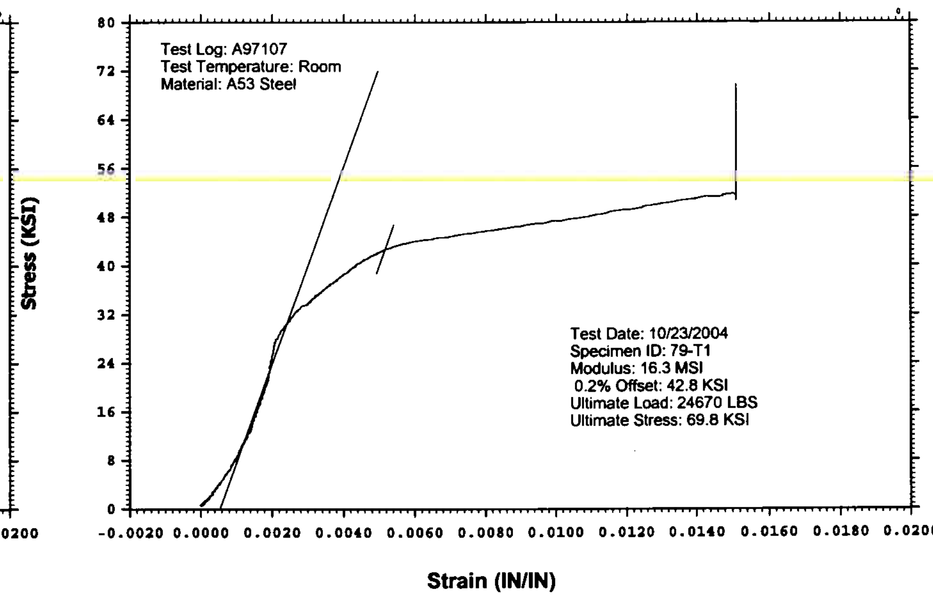
Stress vs. Strain

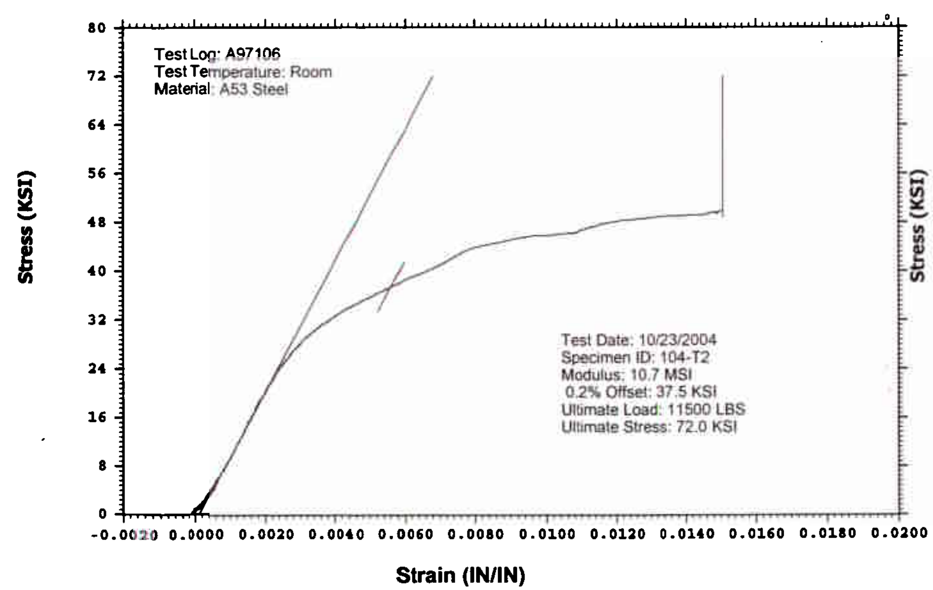
Phone: (724)537-3131

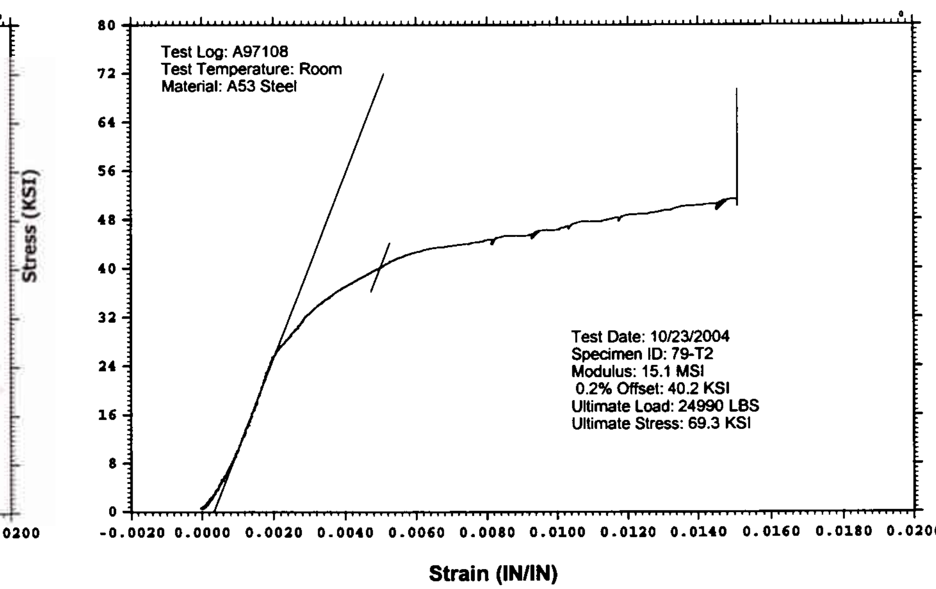
Customer: ARL Penn State
WMT&R Report: 4-34144

WMTR Quote No.: QN241208
Shipping Order No.: 20956A









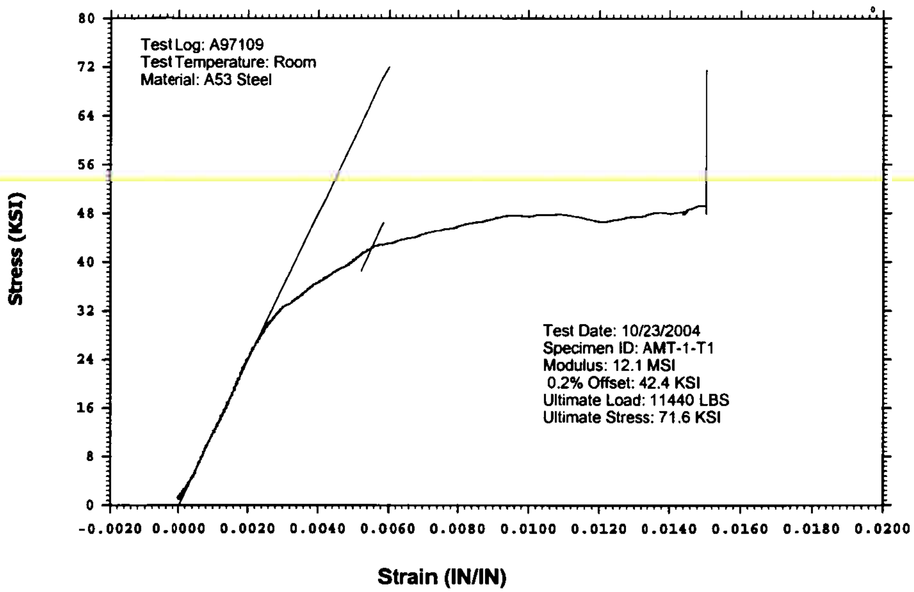
WESTMORELAND MECHANICAL TESTING & RESEARCH, Inc

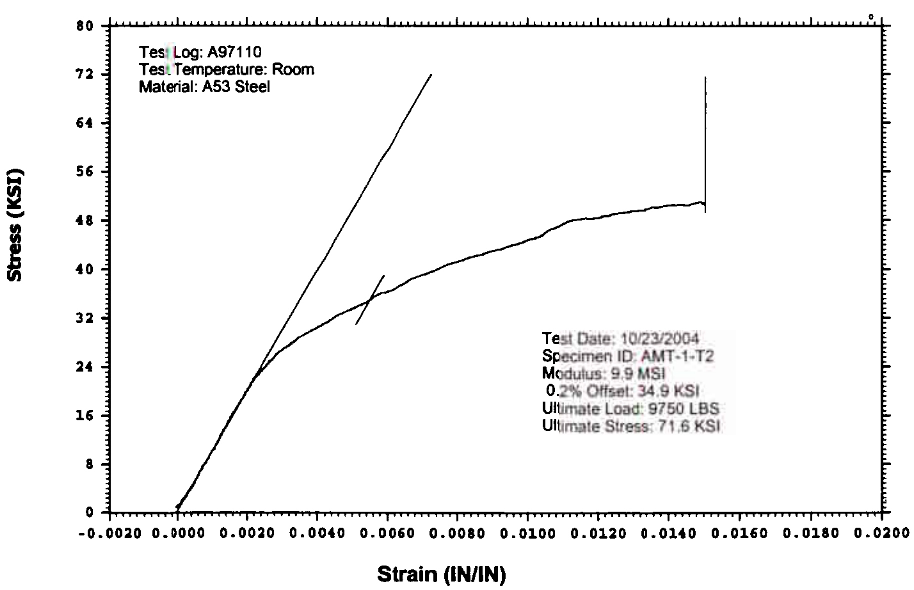
Stress vs. Strain

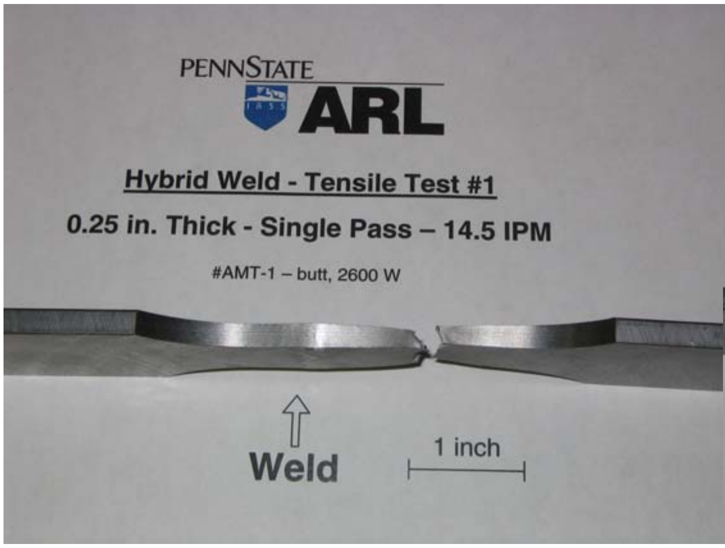
Phone: (724)537-3131

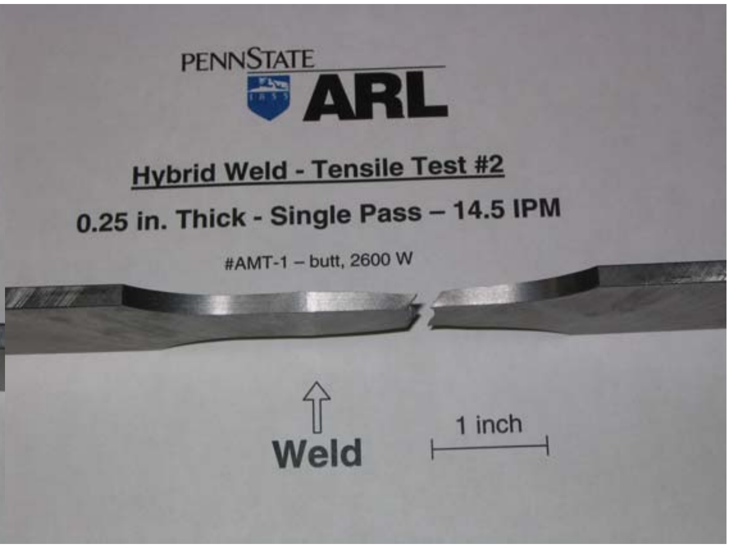
Customer: ARL Penn State
WMT&R Report: 4-34144

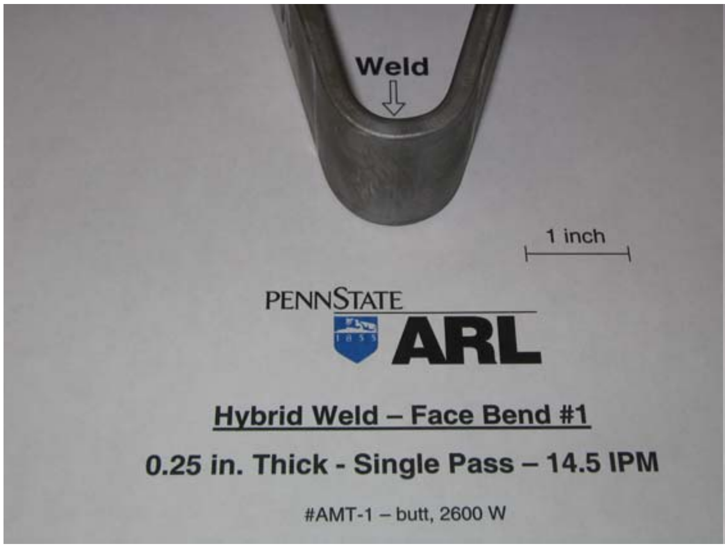
WMTR Quote No.: QN241208
Shipping Order No.: 20956A

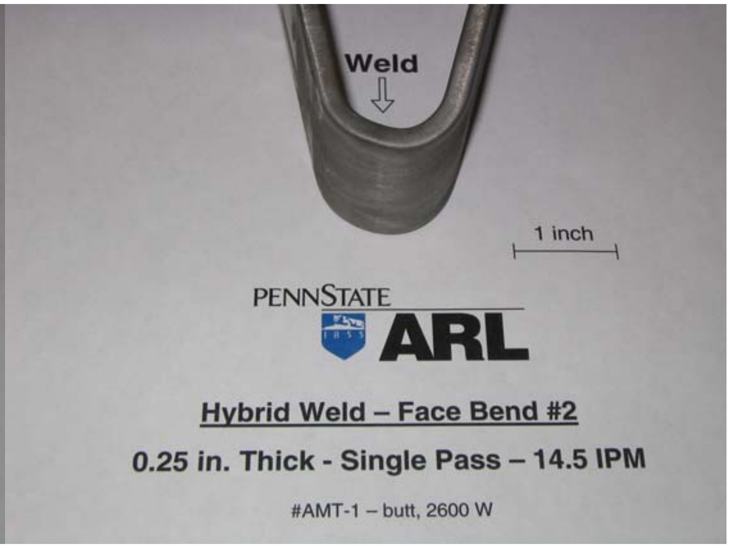





PENNSTATE
ARL
Hybrid Weld - Tensile Test #1
0.25 in. Thick - Single Pass – 14.5 IPM
#AMT-1 – butt, 2600 W
Weld
1 inch


PENNSTATE
ARL
Hybrid Weld - Tensile Test #2
0.25 in. Thick - Single Pass – 14.5 IPM
#AMT-1 – butt, 2600 W
Weld
1 inch


Weld
1 inch
PENNSTATE
ARL
Hybrid Weld – Face Bend #1
0.25 in. Thick - Single Pass – 14.5 IPM
#AMT-1 – butt, 2600 W


Weld
1 inch
PENNSTATE
ARL
Hybrid Weld – Face Bend #2
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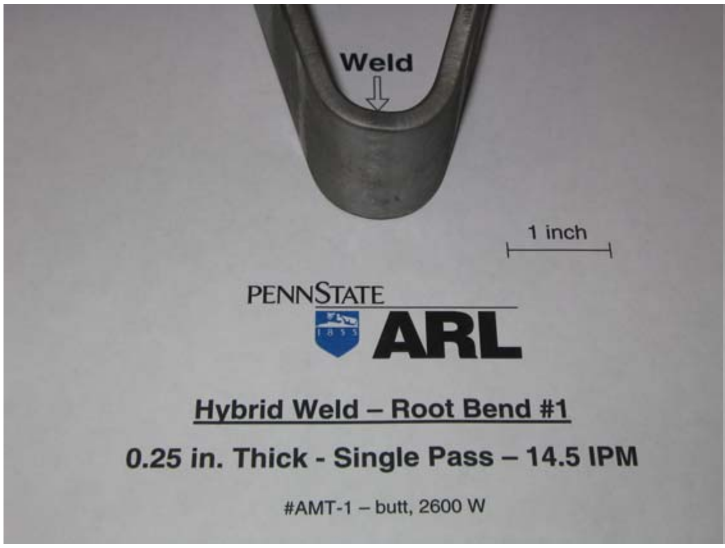
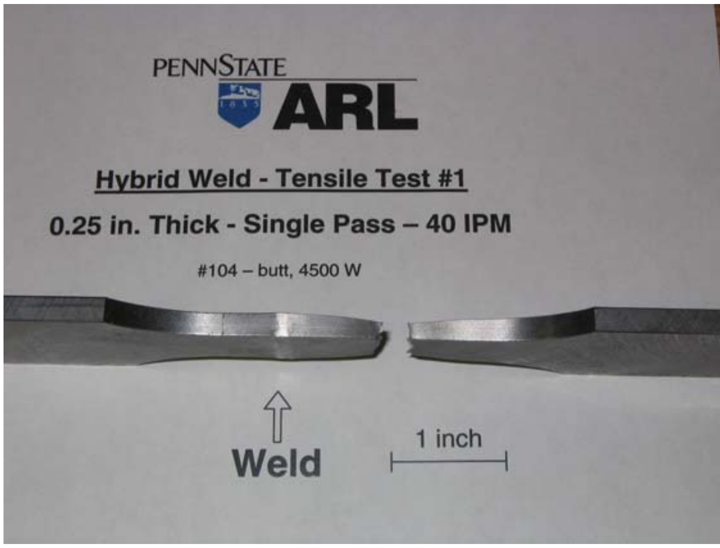
#AMT-1 – butt, 2600 W


Weld
1 inch
PENNSTATE
ARL
Hybrid Weld – Root Bend #1
0.25 in. Thick - Single Pass – 14.5 IPM
#AMT-1 – butt, 2600 W


Weld
1 inch
PENNSTATE
ARL
Hybrid Weld – Root Bend #2
0.25 in. Thick - Single Pass – 14.5 IPM
#AMT-1 – butt, 2600 W


PENNSTATE
ARL
Hybrid Weld - Tensile Test #1
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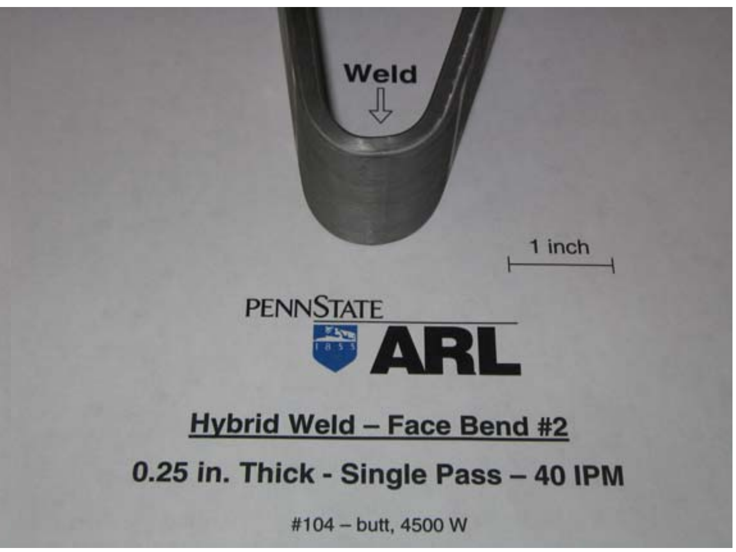
#104 – butt, 4500 W
Weld
1 inch


PENNSTATE
ARL
Hybrid Weld - Tensile Test #2
0.25 in. Thick - Single Pass – 40 IPM
#104 – butt, 4500 W
Weld
1 inch


Weld
1 inch
PENNSTATE
ARL
Hybrid Weld – Face Bend #1
0.25 in. Thick - Single Pass – 40 IPM
#104 – butt, 4500 W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PENNSTATE
ARL
Hybrid Weld – Face Bend #2
0.25 in. Thick - Single Pass – 40 IPM
#104 – butt, 4500 W


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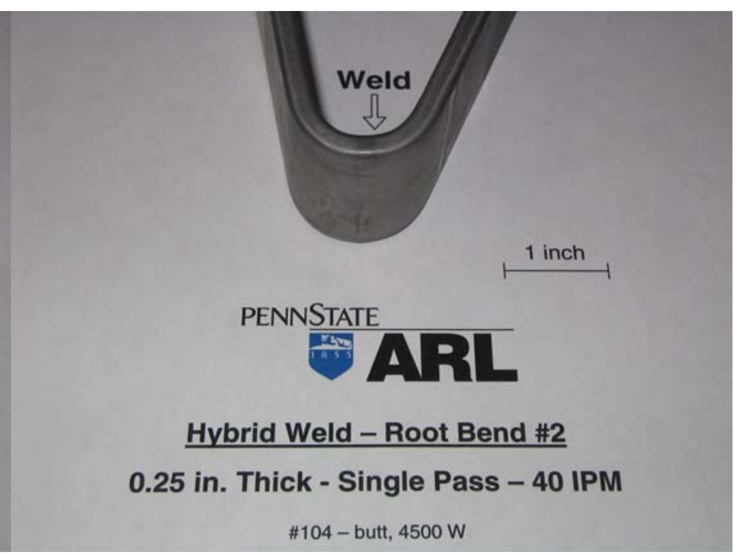
1 inch
PENNSTATE
ARL
Hybrid Weld – Root Bend #1
0.25 in. Thick - Single Pass – 40 IPM
#104 – butt, 4500 W


Weld
1 inch
PENNSTATE
ARL
Hybrid Weld – Root Bend #2
0.25 in. Thick - Single Pass – 40 IPM
#104 – butt, 4500 W

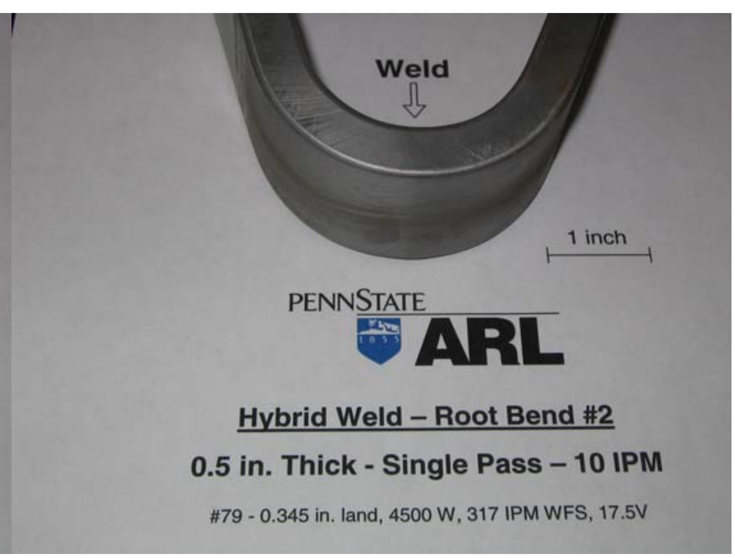

PENNSTATE
ARL
Hybrid Weld - Tensile Test #1
0.5 in. Thick - Single Pass – 10 IPM
#79 - 0.345 in. land, 4500 W, 317 IPM WFS, 17.5V
Weld
1 inch


PENNSTATE
ARL
Hybrid Weld - Tensile Test #2
0.5 in. Thick - Single Pass – 10 IPM
#79 - 0.345 in. land, 4500 W, 317 IPM WFS, 17.5V
Weld
1 inch


Weld
1 inch
PENNSTATE
ARL
Hybrid Weld – Face Bend #1
0.5 in. Thick - Single Pass – 10 IPM
#79 - 0.345 in. land, 4500 W, 317 IPM WFS, 17.5V


Weld
1 inch
PENNSTATE
ARL
Hybrid Weld – Face Bend #2
0.5 in. Thick - Single Pass – 10 IPM
#79 - 0.345 in. land, 4500 W, 317 IPM WFS, 17.5V


Weld
1 inch
PENNSTATE
ARL
Hybrid Weld – Root Bend #1
0.5 in. Thick - Single Pass – 10 IPM
#79 - 0.345 in. land, 4500 W, 317 IPM WFS, 17.5V


Weld
1 inch
PENNSTATE
ARL
Hybrid Weld – Root Bend #2
0.5 in. Thick - Single Pass – 10 IPM
#79 - 0.345 in. land, 4500 W, 317 IPM WFS, 17.5V

Appendix J – Cost Analysis and ROI calculations

Benefits Analysis / Business Case

For this initiative, we have used a modified ManTech[1] Return on Investment (ROI) methodology to calculate the ROI. This ROI is defined as the ratio of (a) the discounted cost avoidance realized by the proposed manufacturing methods over 5 years, to (b) the equipment and implementation costs for the proposed processing method. Modifications to this standard definition are included to account for (1) the funds required to implement a hybrid laser welding process including labor, material, equipment costs, and (2) a phase-in period in which first year savings are based on partial use of the new system. The operating cost savings is $505K/yr, resulting in a five year ROI of 2.0.

Manufacturing processes at NASSCO are labor intensive, requiring multiple weld passes to join piping. According to NASSCO, ¼ - ½ inch thick plates may require up to 5 weld passes to fill a butt joint. Currently, 25 man-years are expended annually in the pipe welding shop. This includes time to weld using various process methods (FCAW, GMAW-P, GTAW, GMAW-STT, SMAW, and silver braze), material handling, crane operation, bending pipe, and surface preparation before and after fabrication.

The ROI calculations were based on the two main welding processes utilized at NASSCO, GMAW and FCAW. The first objective was to evaluate the linear weld footage per weld type and pipe schedule to identify the actual man-hours required for "arc on" time. The actual linear weld footage was calculated based on the material consumption per weld type/ pipe schedule and the weld volume of a butt joint/fillet weld. We have estimated GMAW and FCAW processing consumes 46,580 lbs of filler material per year to weld 130,798 linear feet of Sch-40, Sch-80, and Sch-XS piping (Reference Attachment 1, Table2).

In order to accurately estimate the man-hours associated with NASSCO's GMAW and FCAW "arc on" weld time, we used the linear weld footage per pipe schedule, taking into account the number of passes required to fill a butt joint and/or a fillet weld. Pipe welding activities such as material handling, crane operation, etc have been excluded from the return on investment calculation. Time required to perform these activities will be required regardless of the welding process method. From our analysis, we have estimated a 93% reduction in man-hours required to laser hybrid weld 130,798 linear feet of Sch-40, Sch-80, and Sch-XS compared to GMAW and FCAW ("arc on" weld time, only). Laser hybrid welding required 591 man-hours using a single weld pass method versus the GMAW and FCAW requiring 8,480 man-hours using a multiple weld pass method (Reference Attachment 1, Table 3). This resulted in annual savings of $286,700. (Reference Benefit Analysis Summary)

The second benefit considered was the filler material consumption for each welding process, calculated by weld schedule and weld type. The change in weld volume for GMAW/FCAW butt joint/fillet weld designs compared to laser hybrid weld joints/fillet weld designs decreased material consumption from 46,580 to 6,880 lbs. The reduction in filler material consumption and consumables saves $218,000 per year. (Reference Benefit Analysis Summary)

Additional costs involved with the implementation of a laser hybrid welding process at NASSCO include start up equipment and support costs. It is estimated that $871,285 is required for start-up equipment costs. (Reference Benefit Analysis Summary) This involves the purchase of a suitable laser, machining equipment, positioners, assembly hardware, etc. This amount is accounted for in the five year ROI calculation.

[1] The objective of the Navy ManTech Program, managed by the Office of Naval Research (ONR) is to improve the affordability of Department of the Navy (DON) systems by engaging in manufacturing initiatives that address the entire weapon systems life-cycle and to transition that technology to the fleet.

The ROI calculation also attempts to compensate for additional support required for operator and maintenance training, installation, travel, and marketing expenses. We have assumed an additional $159,000 will be applied to the implementation of hybrid welding at NASSCO to cover the estimated support costs. The associated engineering and development costs will be funded through the "Laser/GMA Hybrid Pipe Welding System" project, awarded under Center for Naval Shipbuilding Technology (CNST) Program and are therefore excluded from the benefit analysis.

Another factor to consider is the daily consumable processing costs such as gas shielding cups and contact tips. ‘Other Consumables’ have been estimated at 10% of the yearly material costs.

As noted above we have incorporated a phase in period in which first year savings are based on partial use of the new system. Generally, new processes do not achieve 100% utilization during the first year of implementation. The migration of shop practices from old to new requires time for learning to take place at all levels of an organization. To account for this, the first year projected savings is reduced by 40% and the second year savings reduced by 20%. After the second year, 100% utilization is assumed and accounted for accordingly in the ROI calculations. We believe that building a learning curve into the calculations results in a more accurate ROI.

Using the ROI methodology, modified as described above, we have calculated a return on investment of 2.0:1. (Reference Benefit Analysis Summary) This is a conservative estimate of the ROI, higher ROI’s are possible if the optimal joint design is selected and all expected benefits of hybrid welding are realized.

Benefit Analysis Summary

Hybrid Welding of Pipes at NASSCO

Current Manufacturing Processes GMAW/FCAW			
Operating Costs:	GMAW	FCAW	Cost
Hours "arc on" Pipe Welding *(Reference Attachment 1, Section 3)*	955 hrs/yr	7,525 hrs/yr	$308,162
Estimated Materials *(Reference Attachment 1, Section 1)*	5,000 lbs/yr	41,580 lbs/yr	$232,900
Other Consumables *(Estimated 10% of Material Costs)*			$23,290
Total			**$564,352**

Proposed Manufacturing Process - Laser Hybrid Welding (including non recurring first year costs)			
Operating Costs:	Laser Hybrid Welding		Cost
Hours Pipe Welding *(Reference Attachment 1, Section 3)*		591 hrs/yr	$21,461
Estimated Materials *(Reference Attachment 1, Section 4)*		6,880 lbs/yr	$34,402
Other Consumables *(Estimated 10% of Material Costs)*			$3,440
		Subtotal	**$59,303**
Laser Hybrid Equipment Costs: (Reference Table 1)		***Subtotal***	**$871,285**
Implementation Costs: (Reference Table 2)		***Subtotal***	**$159,000**

Present Value ROI						
Laser Hybrid Processing						
Project Year	Current Method	Proposed Method	Cost Avoidance (b-a)	Discount Factor	System Utilization	Present Value Cost Avoidance
1	$564,352	$59,303	$505,049	0.975	60%	$295,453
2	$564,352	$59,303	$505,049	0.950	80%	$383,837
3	$564,352	$59,303	$505,049	0.926	100%	$467,675
4	$564,352	$59,303	$505,049	0.901	100%	$455,049
5	$564,352	$59,303	$505,049	0.875	100%	$441,918
Total Present Value Savings						**$2,043,932**
Laser Hybrid Equipment + Implementation Costs ***(Reference Table 1 and Table 2)***						**$1,030,285**
PV ROI:	**2.0 :1**					

Table 1: Laser Hybrid Equipment Costs

Equipment to clamp pipe sections	$10,500
Assembly, Hardware, Wiring, Outlets	$5,250
Tracking system	$57,500
Precision 2 Axis Slides to Mount to Robot	$23,100
Machining Equipment	$38,905
Positioner	$43,050
Manipulator	$13,388
Hybrid Weld Head and GMA System	$49,593
Laser	$630,000
Total	**$871,285**

Table 2: Implementation Costs

Operating Training	$ 20,000
Maintenance Training	$ 20,000
Installation	$ 69,000
Marketing/Travel	$ 50,000
Total	**$ 159,000**

Assumptions:

Please reference Attachment 1 and 2 for assumptions used to estimate hours pipe welding and consumed material
Implementation Cost: $159, 000
Laser Hybrid and Equipment Start Up Costs: $871,285 (9)
First Year utilization of hybrid system is 60% (8)
Second year utilization of hybrid system is 80%(8)
Third, fourth, and fifth year implementation at 100%(8)
Burdened Labor Cost = $36.34/hour (10)
Burdened wire Cost = $5.0/lbs (10)

ATTACHMENT 1

1) Estimated NASSCO Material Consumption per Weld Joint and Pipe Schedule

Data:

- NASSCO yearly material consumption is 50,000 lbs/yr for FCAW, GMAW-P, GTAW, GMAW-STT, SMAW, Silver Braze (1)
  - FCAW welding process consumes 41,580 lbs/yr.
  - The consumed weld filler supports the construction of 1 ½ to 2 ships per year.
- There are three basic pipe product families used to build a ship. The three basic pipe product families and their relative quantities per ship (SLNC, Tote, and BP) are as follows: (1)

Diameter	Schedule	Avg Wall Thickness	% of pipe footage
0.5" – 10"	Sch-40	0.250	60%
0.5" – 10"	Sch-80	0.375	28%
10" – 30"	Sch-XS	0.500	12%

Assumptions:

- 10% of the 50,000 lb of consumed material was used for GMAW processing
- % of pipe footage per schedule is equal to the % of material consumed per pipe schedule
- Butt joint and fillet weld were assumed equal

The two primary welding processes used at NASCCO are FCAW and GMAW. (1) On average, the FCAW welding process consumes 41,580 lbs/yr of filler material to weld Sch-40, Sch-80, and Sch-XS piping for SLNC, Tote, and BP ships.

We have assumed 5,000 lbs/yr of material is consumed during the GMAW welding process. The amount of consumed material per pipe schedule was then calculated by multiplying the % of pipe footage times the average lbs of material consumed per year. See Table 1 for FCAW and GMAW estimated yearly material consumption per weld joint and pipe schedule.

Table 1: GMAW/FCAW material consumption for Sch-40, Sch-80, and Sch-XS

Schedule	Avg Wall Thickness (in)	*Weld Type*	% of pipe footage	GMAW Assumed Material Consumption	FCAW Assumed Material Consumption
Sch-40	0.250	*Butt Joint / Fillet Weld*	60%	3,000	24,948
Sch-80	0.375	*Butt Joint / Fillet Weld*	28%	1,400	11,642
Sch-XS	0.500	*Butt Joint / Fillet Weld*	12%	600	4,990
Total				***5,000***	***41,580***

With known yearly material consumption, we can now estimate the linear weld footage for the GMAW and FCAW process methods for each pipe schedule. This information is necessary to determine cost savings due to reduced "arc on" weld time and material consumption with the laser hybrid welding methods.

2) Linear Weld Footage per Pipe Schedule

Data:

- FCAW welding process consumes 41,580 lbs/yr of filler material [1]

Assumptions:

- Material consumed per pipe schedule: *[Refer to Table 1]*

Schedule	GMAW	FCAW
Sch-40	3,000	24,948
Sch-80	1,400	11,642
Sch-XS	600	4,990

- GMAW Deposition Efficiency is 95% [2]
- FCAW Deposition Efficiency is 90% [2]
- Steel Weight (Density) of filler material is 0.283 lbs/in^3 [3]
- Butt joint and fillet weld volumes were assumed equal
- GMAW/FCAW Weld Volume[4]: *[Refer to Attach. 2 for weld volume parameters and calculation methods]*
  - 0.250” plate = 0.881 in^3 /ft
  - 0.375” plate = 1.79 in^3 /ft
  - 0.500” plate = 3.01 in^3 /ft

The linear feet welded for the FCAW and GMAW processes were calculated based on the pounds of consumed material, deposition efficiency, volume of the weld, and the weight of steel material.

The linear feet of weld (L) calculation used for analysis is as follows [6]:

$$L = P*E/W$$

Where:
L = Length of weld (ft)
P = Pounds of electrode or wire required
E = Deposition Efficiency
W = Volume of Weld x weight of steel = Weight per foot of a weld

For Example, the steel pipe weld length of Sch-40 GMAW Butt joint/fillet weld can be calculated as follows:

$$L = \frac{\overbrace{[(60\%\text{ pipe footage} * 5{,}000\text{ lbs})]}^{P} * \overbrace{95\%\text{ Efficiency}}^{E}}{\underbrace{(0.881\text{ in}^3/\text{ft}) \quad \text{X} \quad 0.283\text{ lb/in3}}_{W}}$$

L = 11,431 ft

Refer to Table 2 for the GMAW/FCAW weld volume and linear weld footage calculations per pipe schedule.

Table 2: GMAW/FCAW Linear Weld Footage Calculations

GMAW Linear Weld Footage Calculations by Schedule Type

Schedule	Plate Thickness	Weld Type	Pounds Weld Filler Consumed per Year	Deposition Efficiency	Weld Volume	Weight of Material	Weight/foot of weld (W = Weld Volume * Weight of Material)	Linear Weld Footage L = P*E/W
			lbs.	%	in3	lbs/in3	lbs./ft	ft
Sch 40	**0.250**	**Butt Joint/Fillet Weld**	3,000	0.95	0.88	0.283	0.249	11,431
Sch 80	**0.375**	**Butt Joint/Fillet Weld**	1,400	0.95	1.79	0.283	0.506	2,625
Sch XS	**0.500**	**Butt Joint/Fillet Weld**	600	0.95	3.01	0.283	0.851	669
Total			**5,000**					**14,725**

FCAW Linear Weld Footage Calculations by Schedule Type

Schedule	Plate Thickness	Weld Type	Pounds Weld Filler Consumed per Year	Deposition Efficiency	Weld Volume	Weight of Material	Weight/foot of weld (W = Weld Volume * Weight of Material)	Linear Weld Footage L = P*E/W
			lbs.	%	in3	lbs/in3	lbs./ft	ft
Sch 40	**0.250**	**Butt Joint/Fillet Weld**	24,948	0.90	0.88	0.283	0.249	90,108
Sch 80	**0.375**	**Butt Joint/Fillet Weld**	11,642	0.90	1.79	0.283	0.506	20,690
Sch XS	**0.500**	**Butt Joint/Fillet Weld**	4,990	0.90	3.01	0.283	0.851	5,275
Total			**41,580**					**116,073**

Total GMAW +FCAW	**46,580**		**130,798**

From Table 2, GMAW and FCAW processing consumes 46,580 lbs of filler material to conventionally join 130,798 ft/year to of Sch-40, Sch-80, and Sch-XS piping.

3) Man-hours expended to conventionally join Sch-40, Sch-80, and Sch-XS piping

Data:

- ½" thick pipe requires 3-5 passes at 5-10 ipm [7] (0.417 – 0.833 fpm)
- ¼" thick pipe requires 2 passes at 5-10 ipm [7] (0.417 – 0.833 fpm)

Assumptions:

- NASSCO linear weld footage per year is 130,798 ft for GMAW/FCAW weld processes *[Reference Table 2]*
- GMAW/FCAW Weld Speed
  - 0.500" thick pipe requires 4 passes at 7 ipm (0.583 fpm)
  - 0.375" thick pipe requires 3 passes at 7 ipm (0.583 fpm)
  - 0.250" thick pipe requires 2 passes at 7 ipm (0.583 fpm)
- Laser Hybrid Weld Speed
  - 0.500" thick pipe requires a single pass at 10 ipm (5.000 fpm)
  - 0.375" thick pipe requires a single pass at 35 ipm (2.917 fpm)
  - 0.250" thick pipe requires a single pass at 60 ipm (0.833 fpm)

The estimated linear weld footage found in Table 2 was then used to calculate the man-hours required to weld 130,798 ft of Sch 40, Sch-80, and Sch-XS piping.

To calculate the man-hours associated with GMAW and FCAW welding at NASSCO, we need to take into account the linear weld footage as well as the number of passes required to fill a butt joint and/or a fillet weld. The linear weld footage estimated in Table 2, divided by weld speed per pass resulted in the actual time a pipe welder welded.

Refer to Table 3 for NASSCO GMAW/FCAW and Laser Hybrid man-hours required to complete 130,798 ft of Sch-40, Sch-80, and Sch XS butt joint and fillet welds.

Table 3: Man-hours welding per pipe schedule

GMAW Man-hours welding per pipe schedule

Schedule	Plate Thickness	Weld Type	Linear Weld Footage (ft)	Speed (fpm)	Number of passes required	Time to Weld (minutes)	Time to Weld (hours)
Sch 40	0.250	Butt Joint/Fillet Weld	11,431	0.583	2	39,192	653
Sch 80	0.375	Butt Joint/Fillet Weld	2,625	0.583	3	13,500	225
Sch XS	0.500	Butt Joint/Fillet Weld	669	0.583	4	4,587	76
Total			**14,725**				**955**

FCAW Man-hours welding per pipe schedule

Schedule	Plate Thickness	Weld Type	Linear Weld Footage (ft)	Speed (fpm)	Number of passes required	Time to Weld (minutes)	Time to Weld (hours)
Sch 40	0.250	Butt Joint/Fillet Weld	90,108	0.583	2	308,941	5,149
Sch 80	0.375	Butt Joint/Fillet Weld	20,690	0.583	3	106,407	1,773
Sch XS	0.500	Butt Joint/Fillet Weld	5,275	0.583	4	36,170	603
Total			**116,073**				**7,525**

Total Linear Weld Footage (ft) (GMAW + FCAW): **130,798** **Total Time to Weld (GMAW + FCAW):** **8,480**

Laser Hybrid Man-hours welding per pipe schedule

Schedule	Plate Thickness	Weld Type	Linear Weld Footage (ft)	Speed (fpm)	Number of passes required	Time to Weld (minutes)	Time to Weld (hours)
Sch 40	0.250	Butt Joint/Fillet Weld	101,539	5.000	1	20,308	338
Sch 80	0.375	Butt Joint/Fillet Weld	23,315	2.917	1	7,994	133
Sch XS	0.500	Butt Joint/Fillet Weld	5,944	0.833	1	7,133	119
Total			**130,798**				**591**

From Table 3, we have concluded a 90% reduction in man-hours required to GMAW and FCAW weld 130,798 linear feet of Sch-40-Sch-80, and Sch-XS piping using the laser hybrid welding method.

4) Laser Hybrid Welding Material Consumption

Assumptions:

- NASSCO linear weld footage per year is 130,798 ft for GMAW/FCAW weld processes [Reference Table 3]
  - Sch 40 – 101,545 ft of weld
  - Sch 80 – 23,315 ft of weld
  - Sch-XS – 5,944 ft of weld
  - Butt joint and fillet weld volumes were assumed equal
  - Laser Hybrid Butt Joint/Fillet Weld Volume [5] – *Refer to Attach 2 for joint parameters and volume calculation methods*
    - 0.250” plate = 0.140 in^3 /ft
    - 0.375” plate = 0.304 in^3 /ft
    - 0.500” plate = 0.521 in^3 /ft
- Laser Hybrid Welding Deposition Efficiency is 100%
- Steel weight (density) of filler material is 0.283 lbs/in^3 [3]

The second benefit considered was the reduction in material costs for laser hybrid welding methods compared to the GMAW and FCAW welding. The difference in consumed material is due to the change in weld volume. As shown in Table 2, the estimated weld volume for the GMAW and FCAW butt joint and fillet welds were 0.881 in^3, 1.79 in^3, and 3.01 in^3 for Sch-40, Sch-80, and Sch-XS piping respectively.

To calculate the estimated material consumption for the laser hybrid welding process we can rearrange the formula used in section 2 [6] and solve for P = pounds of material.

P = L*W/E   Where: P = Pounds of electrode or wire required
L = Length of weld (ft)
W = Volume of Weld x weight of steel = Weight per foot of a weld
E = Deposition Efficiency

Refer to Table 4 and 5 for estimated GMAW, FCAW, and Laser Hybrid Material Consumption.

Table 4: Laser hybrid welding Material Consumption

Schedule	Plate Thickness	Weld Type	L = Total NASSCO Linear Weld Footage GMAW + FCAW	Laser Hybrid Weld Volume	Weight of Material	W = Laser Hybrid Weight/ft of weld	E = Deposition Efficiency	P = Pounds of Material
Sch-40	0.250	Butt/Fillet Welds	101,545	0.139	0.283	0.039	100%	3,998
Sch-80	0.375	Butt/Fillet Welds	23,315	0.304	0.283	0.086	100%	2,006
Sch-XS	0.500	Butt/Fillet Welds	5,944	0.521	0.283	0.147	100%	876
Total			**130,805**					**6,880**

Table 5: GMAW, FCAW, and Laser Hybrid Material Consumption per pipe schedule

Schedule	Plate Thickness (in)	Weld Type	% of pipe footage	GMAW Assumed Material Consumption	FCAW Assumed Material Consumption	Laser Hybrid Estimated Material Consumption to complete GMAW/FCAW butt joint/fillet welds
Sch-40	0.250	Butt Joint / Fillet Weld	60%	3,000	24,948	3,998
Sch-80	0.375	Butt Joint / Fillet Weld	28%	1,400	11,642	2,006
Sch-XS	0.500	Butt Joint / Fillet Weld	12%	600	4,990	876
Total				5,000	41,580	6,880

References:

1) Task 1 Report Product Family Analysis, August 8, 2004
2) GMAW and FCAW deposition efficiencies – Website: www.postle.com
3) A 106 carbon steel density physical properties – Website: **http://www.suppliersonline.com/Research/Property/result.asp?FamilyID=4&MetalID=951&Chemical=1&Physical=1&Mechanical=1**
4) FCAW and GMAW Butt Joint Parameters - Section IX Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators, 1995 Edition, July 1, 1995
5) NSRP Pipe Welding Panel Project Test Coupon Requirements, 17 December 2003
6) Linear Weld Footage formula – Website: www.esabna.com/EUWeb/FM_handbook/577fm8_2.htm
7) NASSCO welding rates – Conversation between Edward Reutzel and Michael Sullivan, 17 Sept 2004
8) Volume 1: Technical Proposal Laser/GMA Hybrid Pipe Welding System, Benefit Analysis/Business Case, June 17, 2004
9) Volume 1: Technical Proposal Laser/GMA Hybrid Pipe Welding System, CNST Material/Equipment, June 17, 2004. Assumed 5% Burden Cost.
10) Labor cost = $18.17/hour; Wire cost = $2.0 – 3.0/lb – Email dated 10 Jan 2005 sent from James Perry, NASSCO, to Ted Reutzel; Burden Cost for labor and wire are equal to 2 X the rate – Per correspondence between Mike Sullivan and Ted Reutzel 11 Jan 05

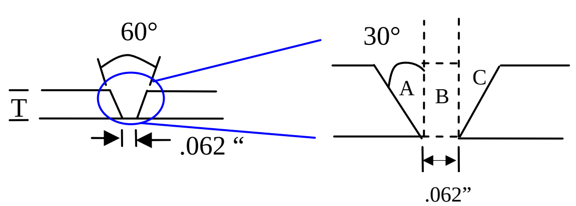
ATTACHMENT 2

The following figures show the method in which the weld volume was calculated for GMAW, FCAW, and laser hybrid butt joints and fillet welds. The butt joint parameters used to calculate the GMAW/FCAW weld volume was a 60° joint with T/2 gap, where T = the plate thickness. [4]

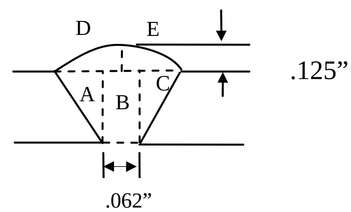
Note: Drawings are not to scale

GMAW/FCAW Weld Volume Calculations:

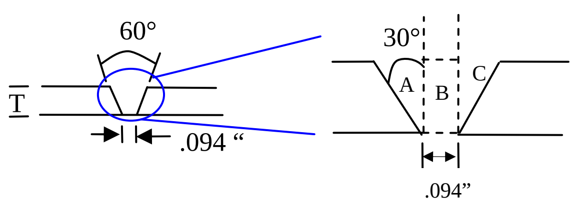
Sch-40 Butt Joint Weld, where T = 0.250”



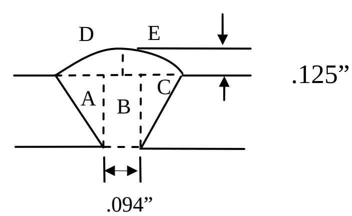
Excess Weld Volume



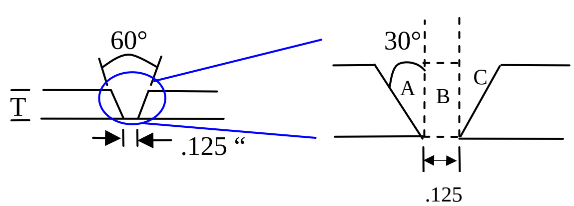
Sch-80 Butt Joint Weld, where T = 0.375”



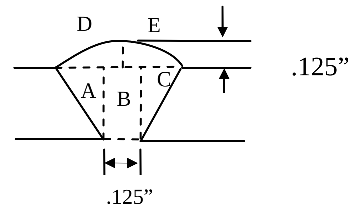
Excess Weld Volume



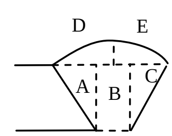
Sch-XS Butt Joint Weld, where T = 0.500”



Excess Weld Volume



Example Butt Joint Volume Calculation, where T = 0.500”:

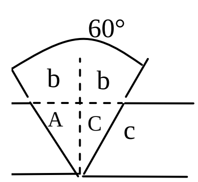


Equilateral Triangle:
c = 2b

Therefore, $a^2 + b^2 = (2b)^2$
where: a = (Sqrt 3) * b
b = a / (Sqrt 3)

Given a = 0.500”
Then b = 0.2886

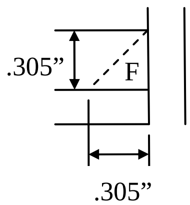
Equilateral Triangle:



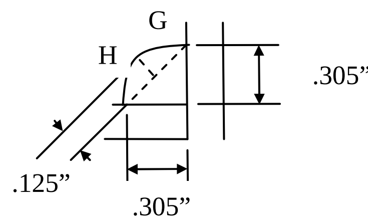
V = ½ base * height * 12 (in)
$V_A = V_C$ = ½ b * a * 12
½ (.2886 * .500) * 12 = 0.865 in^3
V_B = l * w * h
= 12” * 0.125”* 0.500” 0.750 in^3
$V_D = V_E$ = ½ b * h * 12
= ½ (b + ½ * .125) * .125 * 12 = .263 in^3
$V_W = V_A + V_B + V_C + V_D + V_E = 3.01 in^3$

The fillet weld parameters were estimated based on the butt joint weld volume. The volume of a fillet weld was assumed equivalent to that of a butt joint for calculating labor costs and material consumption. The GMAW/FCAW weld parameters have been estimated accordingly.

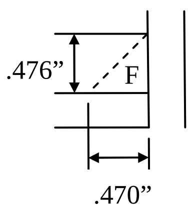
Sch-40 Fillet Weld



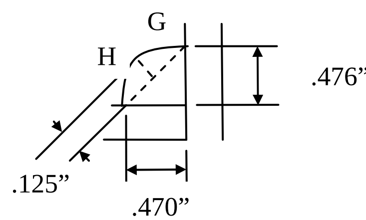
Sch-40 Excess Volume Fillet Weld



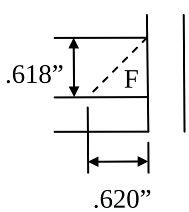
Sch-80 Fillet Weld



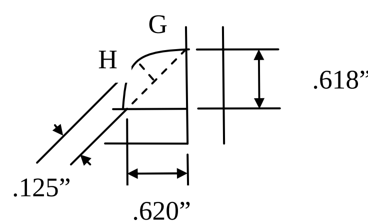
Sch-80 Excess Volume Fillet Weld



Sch-XS Fillet Weld



Sch-XS Excess Volume Fillet Weld



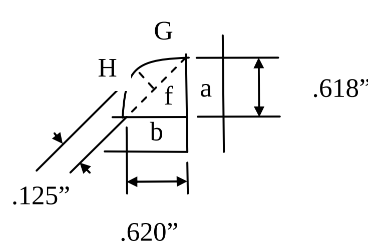
Example Fillet Weld Volume Calculation where T = 0.500”

V_F = ½ (.618 * .620) * 12 = 2.30 in^3

f = SQRT($a^2 + b^2$)
= SQRT ($0.618^2 + 0.620^2$) = .876 in^3

$V_G = V_H$ = ½ ((0.5*0.8754) * .125) * 12 = .328 in^3

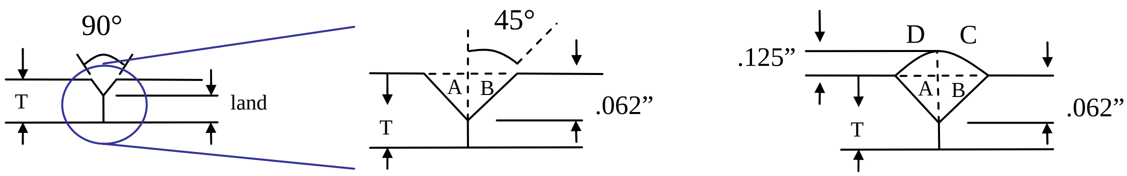
$V_{FW} = V_F + V_G + V_H$ = 3.01 in^3



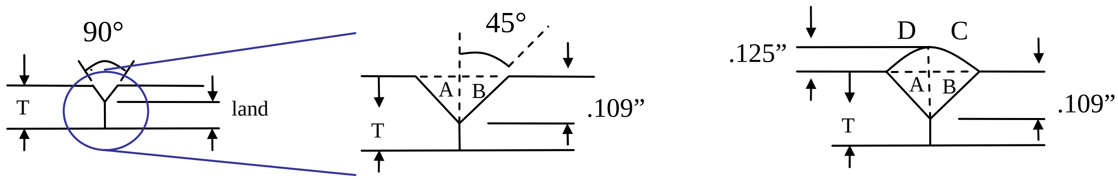
Hybrid Laser Weld Volume Calculations

The butt weld joint parameters used to calculate man-hours expended in the pipe shop and material consumption were based on the test coupon requirements[5]. Please note the parameters do not represent the optimal joint design, resulting in a conservative return on investment. An improved design would further reduce welding man-hours as well as the yearly material consumption for laser hybrid welding.

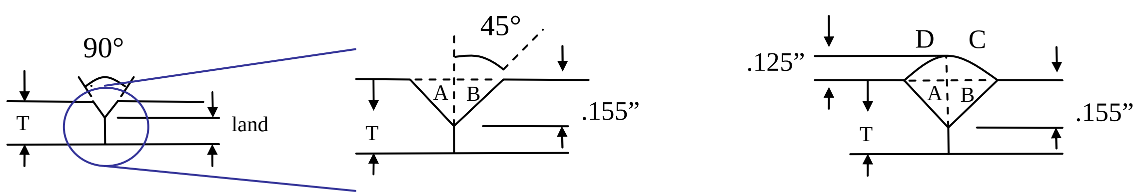
Sch-40 Butt Joint Weld, where T = 0.25” — Sch-40 Excess Volume Weld



Sch-80 Butt Joint Weld, where T = 0.375” — Sch-80 Excess Volume Weld



Sch-XS Butt Joint Weld, where T = 0.50 — Sch-XS Excess Volume Weld



Example Butt Joint Weld Volume

Isosceles Triangle, Therefore a = b

V = ½ base * height * 12 (in)

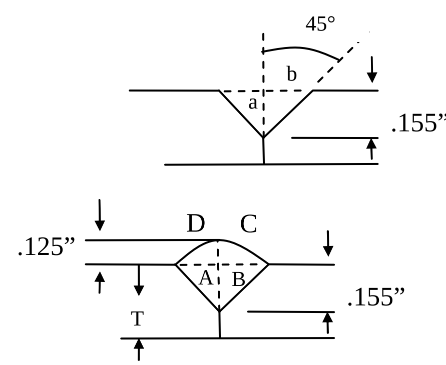
$V_A = V_B = \frac{1}{2}\ \ b\ *\ a\ * 12$

$\frac{1}{2}(.155 * .155) * 12 = 0.144\ in^3$

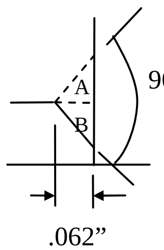
$V_C = V_D = \frac{1}{2}\ \ b\ *\ h\ * 12$

$= \frac{1}{2}\ \ .155 *\ .125 * 12 = .116\ in^3$

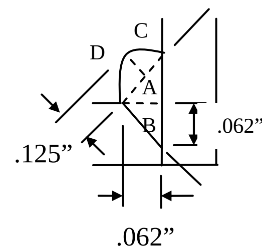
$V_W = V_A + V_B + V_C + V_D = .5205\ in^3$



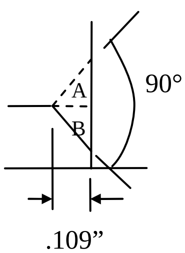
Sch-40 Fillet Weld



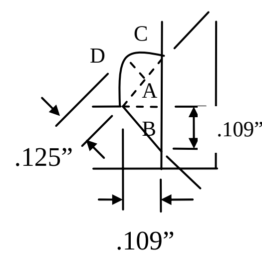
Schedule-40 Excess Volume Weld



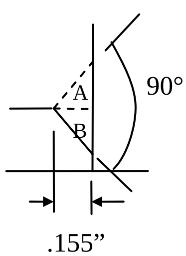
Sch-80 Fillet Weld



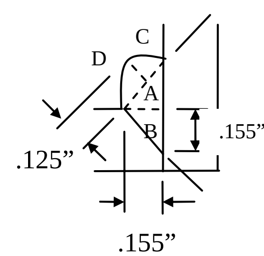
Schedule-80 Excess Volume Weld



Sch-XS Fillet Weld



Schedule-XS Excess Volume



Example Laser Hybrid Weld Volume Calculation, where T = 0.500”

Note: The volume of a laser hybrid fillet weld was assumed equivalent to that of the butt joint weld.

Isosceles Triangle, Therefore a = b

V = ½ base * height * 12 (in)

$V_A = V_B = ½ \quad b \quad * \quad a \quad * 12$

$½ (.155 * .155) * 12 = 0.144 \text{ in}^3$

$V_C = V_D = ½ \quad b \quad * \quad h \quad * \quad 12$

$= ½ \quad .155 * .125 * \quad 12 = .116 \text{ in}^3$

$V_W = V_A + V_B + V_C + V_D = .5205 \text{ in}^3$

Appendix K – NASSCO Data Collection on Current Pipe Fabrication Costs and Data Required to Support ROI

National Steel & Shipbuilding Research Project

LASER PIPE WELDING

TASK 3 and 4 REPORT
Data Collection on Current Pipe Fabrication Costs
Data Required to Support ROI

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November 30, 2004

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1.0 Provide The Number Of Steel Pipe Spools Produced Per Week

Attachment 1 provides all of the required data.

Data was collected for 11 weeks and analyzed to provide the following detailed information.

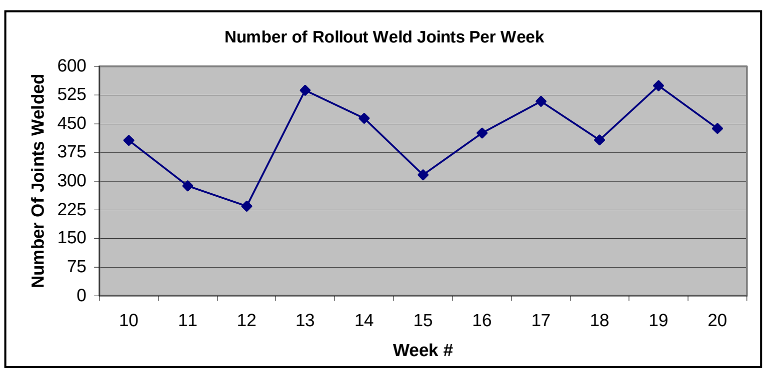
- The number of welded steel pipe spools per week
- The total number of welded steel joints per week
- The number of welded steel joints produced in the rollout stations
- The number of welded steel joints produced in the manual welding stations
- The number of welded steel joints by diameter and by weld joint design type
- The pipe spool length
- The average length of raw pipe per weld joint (not weld length)

The following table summarizes the number of roll out welded steel joints welded per week. This is critical to the laser project since this is the primary type of weld joints that is targeted for laser welding. Over the 11 week period the average number of steel roll out weld joints per week is 416 weld joints.

The weekly data sheets are found in Attachment 1 "NASSCO Pipe Shop Steel Spools Per Week"

Number of Weld Joints Per Week
For Rollout 4" Diameter And Greater

Wk #	
10	407
11	287
12	234
13	538
14	464
15	316
16	426
17	509
18	408
19	549
20	438
	4576
Average	**416**



2.0 Time Study The Current Pipe Fabrication Process

The time study was divided into two distinct groups:

- Pipe Joint Fit Up Time
- Pipe Joint Weld Time

Within each group the miscellaneous work performed by that trade organization is included and separately identified and recorded.

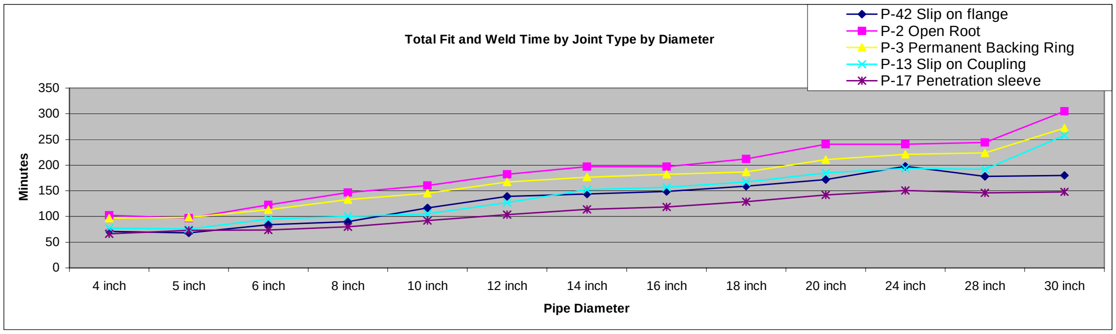
The following table details the pipe joint fit up time, the pipe joint weld time and the total time by each type of weld joint for each diameter of steel pipe.

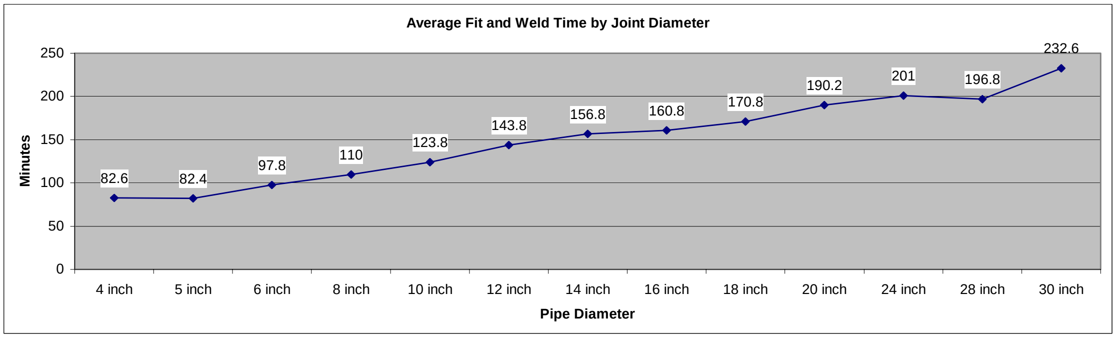
PIPE FABRICATION TIME STUDY ANALYSIS
NASSCO WELDING ENGINEERING

PIPE JOINT FIT UP TIME (MINUTES)													
JOINT TYPE // PIPE DIAMETER	4 inch	5 inch	6 inch	8 inch	10 inch	12 inch	14 inch	16 inch	18 inch	20 inch	24 inch	28 inch	30 inch
PIPE WALL SIZE (SCHEDLUE)	80	80	80	80	XS	XS	XS	XS	XS	XS	XS	XS	XS
P-42 Slip on flange	37	39	45	46	58	65	70	70	75	83	93	73	75
P-2 Open Root	63	63	64	69	76	83	93	93	103	116	116	119	180
P-3 Permanent Backing Ring	58	59	59	64	71	78	83	83	88	96	106	109	157
P-13 Slip on Coupling	48	47	56	56	61	63	73	73	78	86	86	84	140
P-17 Penetration sleeve	37	39	40	46	53	55	65	65	70	78	78	73	75
PIPE JOINT WELD TIME (MINUTES)													
JOINT TYPE // PIPE DIAMETER	4 inch	5 inch	6 inch	8 inch	10 inch	12 inch	14 inch	16 inch	18 inch	20 inch	24 inch	28 inch	30 inch
PIPE WALL SIZE (SCHEDLUE)	80	80	80	80	XS	XS	XS	XS	XS	XS	XS	XS	XS
P-42 Slip on flange	34	29	39	44	59	74	74	79	84	89	105	105	105
P-2 Open Root	39	34	59	78	84	99	104	104	109	125	125	125	125
P-3 Permanent Backing Ring	39	39	54	69	74	89	94	99	99	115	115	115	115
P-13 Slip on Coupling	29	29	39	44	44	64	79	84	89	99	108	108	118
P-17 Penetration sleeve	29	34	34	34	39	49	49	54	59	64	73	73	73
PIPE JOINT TOTAL TIME (MINUTES)													
JOINT TYPE // PIPE DIAMETER	4 inch	5 inch	6 inch	8 inch	10 inch	12 inch	14 inch	16 inch	18 inch	20 inch	24 inch	28 inch	30 inch
PIPE WALL SIZE (SCHEDLUE)	80	80	80	80	XS	XS	XS	XS	XS	XS	XS	XS	XS
P-42 Slip on flange	71	68	84	90	117	139	144	149	159	172	198	178	180
P-2 Open Root	102	97	123	147	160	182	197	197	212	241	241	244	305
P-3 Permanent Backing Ring	97	98	113	133	145	167	177	182	187	211	221	224	272
P-13 Slip on Coupling	77	76	95	100	105	127	152	157	167	185	194	192	258
P-17 Penetration sleeve	66	73	74	80	92	104	114	119	129	142	151	146	148
AVERAGE JOINT TIME PER DIAMETER	82.6	82.4	97.8	110	123.8	143.8	156.8	160.8	170.8	190.2	201	196.8	232.6

An analysis was also performed to identify the average total cost per weld joint type. The results identify which type of weld joints are more costly to produce. The weld size requirements are for commercial weld sizes per ABS requirements. The results are as follows from the most costly to the least costly:

- P-2 Open root
- P-3 Permanent backing ring
- P-13 Slip on coupling
- P-42 Slip on flange
- P-17 Penetration sleeve





The details of the time study are found in the attachments
Attachment 2 Pipe Joint Fit Up Time
Attachment 3 Pipe Joint Weld Time

3.0 Data To Assist In ROI Calculation

The table in Section 2.0 does not show significant differences in the cost to fit and weld different joint types as compared to the cost to fit and weld different pipe diameters. Therefore we can determine the average fit and weld time for each pipe diameter that will include all weld joint types.

From the previous data the average number of weld joints per week, by pipe diameter, can be calculated based on the representative 11 week sample.

This data has been collected for the conventional current weld process:

- STT / GMAW or GTAW for the open butt root pass
- FCAW fill and cover for butt joints
- FCAW for fillet weld type joints

Estimates can be made for each of the detailed steps described in the time study for the laser welding process. Assumptions can be made for both the fit and weld times. As the project continues, accurate real data can be collected to ascertain the correct production costs. Information such as weld joint preparation or machining time can be validated with test joints and the sample spread sheet values can be simply modified to establish the true ROI.

For now the following table shows the current cost and the fields for the laser process with fields to show the direct savings.

WELD JOINTS	WK #10	WK #11	WK #12	WK #13	WK #14	WK #15	WK #16	WK #17	WK #18	WK #19	WK #20	Average #	Current	Current	Current	Laser	Savings (Joints)	Savings
PIPE DIAMETER	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Joint/WK/ Size	Average of Min./Joints	Hrs./Joint Type Per Wk	% of Hrs./Joint Type Per Wk	Average of Hrs./Joints	Average of Hrs./Joints	Per Week
4"	117	56	46	159	87	56	93	69	148	130	98	96	83	133	14%	*	*	*
5"	14	4	2	0	61	13	3	5	1	23	8	12	82	17	2%	*	*	*
6"	114	55	38	118	58	76	131	108	84	190	143	101	98	165	18%	*	*	*
8"	54	41	38	88	72	70	65	112	79	58	99	71	110	129	14%	*	*	*
10"	42	67	8	62	144	41	64	137	60	107	82	74	124	153	17%	*	*	*
12"	29	8	21	10	9	39	13	27	20	22	17	20	144	47	5%	*	*	*
14"	0	0	10	31	20	5	2	4	0	0	0	7	157	17	2%	*	*	*
16"	16	42	40	11	15	13	18	25	14	16	13	20	161	54	6%	*	*	*
18"	18	24	11	13	16	9	44	21	29	19	12	20	171	56	6%	*	*	*
20"	14	3	7	46	9	7	29	21	5	0	8	14	190	43	5%	*	*	*
22"	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	*	*	*
24"	0	28	24	28	8	3	17	15	0	6	11	13	201	43	5%	*	*	*
28"	4	0	22	23	12	0	0	13	11	10	0	9	197	28	3%	*	*	*
30"	0	0	22	21	7	0	0	0	14	28	4	9	233	34	4%	*	*	*
JOINTS PER WK	452	328	289	610	518	332	484	557	465	609	495	467		918 Hours	100%	*	*	*
																	Total Savings/Wk.	*
																	Hrs Saved/Yr.	*

4.0 Summary

This concludes the report of Task 3 and 4.

- Provide the number of steel pipe spools produced per week
- Time Study the Current Pipe Fabrication Process
- Provide Data to Assist in ROI Calculation

4.0 Attachments

Attachment 1 NASSCO Pipe Shop Steel Spools Per Week
Attachment 2 Pipe Joint Fit Up Time
Attachment 3 Pipe Joint Weld Time

Attachment 1
NASSCO Pipe Shop Steel Spools Per Week

NASSCO PIPE SHOP STEEL SPOOLS PER WEEK

WEEK 10, 2004														
WELD JOINTS			**BUTT JOINT**	**BUTT JOINT**	**BUTT JOINT**	**SLEEVE**	**SLEEVE**	**FLANGE**	**FLANGE**	**STRUCTURAL**	**BRANCH**	**TOTAL**	**SPOOL**	**Average**
PIPE DIAMETER/SCH.			**OPEN ROOT SST**	**GTAW CONSUMABLE**	**BACKING RINGS**	**SOCKET P-14**	**SLIP-ON P-13**	**SLIP-0N P-42**	**SOCKET P-15**	**P-17**	**CONN.**	**JOINTS**	**LENGTH MM**	**length/joint**
4"	40		11	0	39	0	1	54	0	0	4	109	49,252	451.9
	80		1	0	0	0	0	6	0	0	1	8	3,537	442.1
5"	40				4			10				14	7,169	512.1
	80													
6"	40		8		29		5	54		1	3	100	9,494	94.9
	80				1			10			3	14	6,181	441.5
8"	40		15		3		1	22		2	3	46	21,616	469.9
	80							6		2		8	22,653	2,831.6
10"	40				7		1	10		1		19	10,856	571.4
	80							4				4	4,575	1,143.8
	0.375													
	0.5				4			12		3		19	7,055	371.3
12"	40													
	0.375				6			12				18	13,374	743.0
	0.5				5			6				11	3,501	318.3
14"	0.375													
	0.5													
16"	10													
	0.375							4		1		5	878	175.6
	0.5				7			2		2		11	15,321	1,392.8
18"	10												500	
	0.375							2				2		-
	0.5				4			12				16	7,104	444.0
20"	XS.812							2		1		3	681	227.0
	0.375													
	0.5							10			1	11	1,038	94.4
22"	10													
24"	10													
	40													
	0.375													
	0.5													
28"	0.5							4				4	6,121	1,530.3
30"	0.375													
	0.5													
TOTAL SPOOLS		**110**												
JOINTS PER WEEK		**422**	35	0	109	0	8	242	0	13	15	**422**	**190,906**	**452.4**
ROLL OUT		**407**												
MANUAL		**15**												

WELDING ENGINEERING MARCH 18, 2004

NASSCO PIPE SHOP STEEL SPOOLS PER WEEK

WEEK 11, 2004														
WELD JOINTS			**BUTT JOINT**	**BUTT JOINT**	**BUTT JOINT**	**SLEEVE**	**SLEEVE**	**FLANGE**	**FLANGE**	**STRUCTURAL**	**BRANCH**	**TOTAL**	**SPOOL**	**Average**
PIPE DIAMETER/SCH.			**OPEN ROOT SST**	**GTAW CONSUMABLE**	**BACKING RINGS**	**SOCKET P-14**	**SLIP-ON P-13**	**SLIP-0N P-42**	**SOCKET P-15**	**P-17**	**CONN.**	**JOINTS**	**LENGTH MM**	**length/joint**
4"	40		1		7		2	12		3		25	26,160	1,046.4
	80		1		2			28				31	21,919	707.1
5"	40		2					2				4	4,382	1,095.5
	80													
6"	40		3		28			22			2	55	32,988	599.8
	80													
8"	40				3			8			1	12	14,980	1,248.3
	80				2			22		5		29	7,711	265.9
10"	40				1							1	6,148	6,148.0
	80							4				4	4,575	1,143.8
	0.375													
	0.5				20		4	30		8		62	35,007	564.6
12"	40													
	0.375							4				4	893	223.3
	0.5							4				4	3,081	770.3
14"	0.375													
	0.5													
16"	10				2			2				4	1,067	266.8
	0.375							6		3		9	810	90.0
	0.5				8		1	16		1	3	29	11,527	397.5
18"	10													
	0.375													
	0.5				3			18		2	1	24	5,769	240.4
20"	XS.812													
	0.375													
	0.5				1			2				3	2,884	961.3
22"	10													
24"	10				1							1	6,000	6,000.0
	40													
	0.375							2		2		4	6,768	1,692.0
	0.5		5		3			8		7		23	10,479	455.6
28"	0.5													
30"	0.375													
	0.5													
TOTAL SPOOLS		**78**												
JOINTS PER WEEK		**328**	12		81		7	190		31	7	**328**	**203,148**	**619.4**
ROLL OUT		**287**												
MANUAL		**41**												

NASSCO PIPE SHOP STEEL SPOOLS PER WEEK

WEEK 12, 2004														
WELD JOINTS			**BUTT JOINT**	**BUTT JOINT**	**BUTT JOINT**	**SLEEVE**	**SLEEVE**	**FLANGE**	**FLANGE**	**STRUCTURAL**	**BRANCH**	**TOTAL**	**SPOOL**	**Average**
PIPE DIAMETER/SCH.			**OPEN ROOT SST**	**GTAW CONSUMABLE**	**BACKING RINGS**	**SOCKET P-14**	**SLIP-ON P-13**	**SLIP-0N P-42**	**SOCKET P-15**	**P-17**	**CONN.**	**JOINTS**	**LENGTH MM**	**length/joint**
4"	40				4			16	1		1	22	16,044	729.3
	80		2				2	20				24	17,443	726.8
5"	40							2				2	8,196	4,098.0
	80													
6"	40				2		3	8		2	1	16	17,017	1,063.6
	80				2			18		2		22	7,459	339.0
8"	40							6		2		8	2,714	339.3
	80				11		11	6		2		30	11,786	392.9
10"	40		2		4								5,681	
	80													
	0.375													
	0.5				1			5		2		8	3,893	486.6
12"	40													
	0.375							2				2	3,982	1,991.0
	0.5		1		3			14			1	19	11,898	626.2
14"	0.375													
	0.5		3		4		1	2				10	10,703	1,070.3
16"	10													
	0.375			2				2			1	5	1,175	235.0
	0.5		3		8			18			6	35	16,702	477.2
18"	10													
	0.375													
	0.5			2				8			1	11	2,862	260.2
20"	XS.812													
	0.375													
	0.5							6			1	7	2,073	296.1
22"	10													
24"	10													
	40													
	0.375		1		3			2		2		8	9,049	1,131.1
	0.5				5			8		2	1	16	14,813	925.8
28"	0.5							20			2	22	6,908	314.0
30"	0.375													
	0.5							20			2	22	47,918	2,178.1
TOTAL SPOOLS		**73**												
JOINTS PER WEEK		**289**	12	4	47		17	183		14	17	**289**	**218,316**	**729.3**
ROLL OUT		**234**												
MANUAL		**55**												

WELDING ENGINEERING MARCH 18, 2004

NASSCO PIPE SHOP STEEL SPOOLS PER WEEK

WEEK 13, 2004														
WELD JOINTS			**BUTT JOINT**	**BUTT JOINT**	**BUTT JOINT**	**SLEEVE**	**SLEEVE**	**FLANGE**	**FLANGE**	**STRUCTURAL**	**BRANCH**	**TOTAL**	**SPOOL**	**Average**
PIPE DIAMETER/SCH.			**OPEN ROOT SST**	**GTAW CONSUMABLE**	**BACKING RINGS**	**SOCKET P-14**	**SLIP-ON P-13**	**SLIP-0N P-42**	**SOCKET P-15**	**P-17**	**CONN.**	**JOINTS**	**LENGTH MM**	**length/joint**
4"	40				3		3	52			1	59	73,329	1,242.9
	80		5		6		1	80		5	3	100	55,829	558.3
5"	40													
	80													
6"	40				13		33	50			2	98	77,586	791.7
	80							20				20	14,567	728.4
8"	40				15		4	20		1	3	43	35,928	835.5
	80		2		16		5	22				45	35,707	793.5
10"	40		4		2		1	6			4	17	17,177	1,010.4
	80							4		1		5	825	165.0
	0.375													
	0.5		3		8		6	18		2	3	40	37,897	947.4
12"	40													
	0.375				2		4	4				10	9,524	952.4
	0.5													
14"	0.375													
	0.5		3		6		4	18				31	30,071	970.0
16"	10													
	0.375							2		1		3	378	126.0
	0.5						2	4		2		8	7,426	928.3
18"	10													
	0.375													
	0.5		6					6			1	13	8,876	682.8
20"	XS.812													
	0.375							4			1	5	1,811	362.2
	0.5		8					28			5	41	26,848	654.8
22"	10													
24"	10													
	40													
	0.375													
	0.5		**3**					13		3	9	28	22,175	792.0
28"	0.5		5					14			4	23	11,160	485.2
30"	0.375													
	0.5							16			5	21	21,166	1,007.9
TOTAL SPOOLS		**151**												
JOINTS PER WEEK		**610**	39		71		63	381		15	41	**610**	**488,280**	**800.5**
ROLL OUT		**538**												
MANUAL		**72**												

WELDING ENGINEERING MARCH 18, 2004

NASSCO PIPE SHOP STEEL SPOOLS PER WEEK

WEEK 14, 2004														
WELD JOINTS			**BUTT JOINT**	**BUTT JOINT**	**BUTT JOINT**	**SLEEVE**	**SLEEVE**	**FLANGE**	**FLANGE**	**STRUCTURAL**	**BRANCH**	**TOTAL**	**SPOOL**	**Average**
PIPE DIAMETER/SCH.			**OPEN ROOT SST**	**GTAW CONSUMABLE**	**BACKING RINGS**	**SOCKET P-14**	**SLIP-ON P-13**	**SLIP-0N P-42**	**SOCKET P-15**	**P-17**	**CONN.**	**JOINTS**	**LENGTH MM**	**length/joint**
4"	40		2		8		6	26		1	2	45	91,446	2,032.1
	80		2		1			34		5		42	77,351	1,841.7
5"	40				4			54				58	11,390	196.4
	80						1	2				3	6,104	2,034.7
6"	40				15		5	26		1	1	48	36,805	766.8
	80						1	8		1		10	11,608	1,160.8
8"	40		4		8		3	8			2	25	14,294	571.8
	80		4		1		9	31		2		47	33,202	706.4
10"	40		4				4	6		1		15	23,967	1,597.8
	80													
	0.375													
	0.5		4		18		11	88		6	2	129	71,471	554.0
12"	40													
	0.375													
	0.5				1			8				9	4,863	540.3
14"	0.375													
	0.5				14		6					20	16,674	833.7
16"	10													
	0.375													
	0.5							12			3	15	7,039	469.3
18"	10													
	0.375													
	0.5		4		6			6				16	13,861	866.3
20"	XS.812													
	0.375		6					2		1		9	4,295	477.2
	0.5													
22"	10													
24"	10													
	40													
	0.375													
	0.5							6		2		8	3,965	495.6
28"	0.5							12				12	29,876	2,489.7
30"	0.375													
	0.5							4			3	7	7,572	1,081.7
TOTAL SPOOLS		**159**												
JOINTS PER WEEK		**518**	30		76		46	333		20	13	**518**	**465,783**	**899.2**
ROLL OUT		**464**												
MANUAL		**54**												

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NASSCO PIPE SHOP STEEL SPOOLS PER WEEK

WEEK 15, 2004														
WELD JOINTS			**BUTT JOINT**	**BUTT JOINT**	**BUTT JOINT**	**SLEEVE**	**SLEEVE**	**FLANGE**	**FLANGE**	**STRUCTURAL**	**BRANCH**	**TOTAL**	**SPOOL**	**Average**
PIPE DIAMETER/SCH.			**OPEN ROOT SST**	**GTAW CONSUMABLE**	**BACKING RINGS**	**SOCKET P-14**	**SLIP-ON P-13**	**SLIP-0N P-42**	**SOCKET P-15**	**P-17**	**CONN.**	**JOINTS**	**LENGTH MM**	**length/joint**
4"	40				2		2	19			1	24	17,759	740.0
	80				5		1	24		2		32	17,813	556.7
5"	40				6			7				13	8,853	681.0
	80													
6"	40				14		7	43				64	55,818	872.2
	80				2		1	6		1	2	12	4,981	415.1
8"	40		1		2		1	32		2	1	39	14,933	382.9
	80				6		5	17		2	1	31	11,742	378.8
10"	40				6		2	2				10	4,714	471.4
	80													
	0.375													
	0.5				4		2	20			5	31	7,325	236.3
12"	40													
	0.375				2			22				24	3,074	128.1
	0.5				4			10			1	15	6,347	423.1
14"	0.375													
	0.5							4		1		5	1,237	247.4
16"	10													
	0.375													
	0.5				1			10			2	13	7,652	588.6
18"	10													
	0.375													
	0.5							8		1		9	1,489	165.4
20"	XS.812													
	0.375													
	0.5		1		2			2			2	7	10,101	1,443.0
22"	10													
24"	10													
	40													
	0.375													
	0.5							2			1	3	2,034	678.0
28"	0.5													
30"	0.375													
	0.5													
TOTAL SPOOLS		**106**												
JOINTS PER WEEK		**332**	2		56		21	228		9	16	**332**	**175,872**	**529.7**
ROLL OUT		**316**												
MANUAL		**16**												

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NASSCO PIPE SHOP STEEL SPOOLS PER WEEK

WEEK 16, 2004														
WELD JOINTS			BUTT JOINT	BUTT JOINT	BUTT JOINT	SLEEVE	SLEEVE	FLANGE	FLANGE	STRUCTURAL	BRANCH	TOTAL	SPOOL	Average
PIPE DIAMETER/SCH.			OPEN ROOT SST	GTAW CONSUMABLE	BACKING RINGS	SOCKET P-14	SLIP-ON P-13	SLIP-0N P-42	SOCKET P-15	P-17	CONN.	JOINTS	LENGTH MM	length/joint
4"	40				8			36		4	3	51	32,666	640.5
	80				3		2	32		5		42	23,915	569.4
5"	40		1		1			1				3	3,330	1,110.0
	80													
6"	40		3		37		6	64		2	2	114	77,113	676.4
	80						3	14				17	20,020	1,177.6
8"	40				17		4	12			6	39	38,374	983.9
	80		4		10		6	4		2		26	29,105	1,119.4
10"	40				9		1	2				12		
	80													
	0.375													
	0.5		5		8		10	28		1		52	50,334	968.0
12"	40													
	0.375						1	2				3	1,317	439.0
	0.5				4			6				10	2,107	210.7
14"	0.375													
	0.5							2				2	5,370	2,685.0
16"	10													
	0.375		3					4				7	2,442	348.9
	0.5				5			4			2	11	8,810	800.9
18"	10													
	0.375				6			6				12	6,364	530.3
	0.5		6					24			2	32	14,645	457.7
20"	XS.812													
	0.375		5				1	10			3	19	13,886	730.8
	0.5		1		2			4			3	10	1,578	157.8
22"	10													
24"	10													
	40													
	0.375		3					6			1	10	7,608	760.8
	0.5				4			2		1		7	3,517	502.4
28"	0.5													
30"	0.375													
	0.5													
36"	0.375		2					2			1	5	4,962	992.4
TOTAL SPOOLS		142												
JOINTS PER WEEK		484	33		114		34	265		15	23	484	347,463	717.9
ROLL OUT		426												
MANUAL		58												

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NASSCO PIPE SHOP STEEL SPOOLS PER WEEK

WEEK 17, 2004														
WELD JOINTS			BUTT JOINT	BUTT JOINT	BUTT JOINT	SLEEVE	SLEEVE	FLANGE	FLANGE	STRUCTURAL	BRANCH	TOTAL	SPOOL	Average
PIPE DIAMETER/SCH.			OPEN ROOT SST	GTAW CONSUMABLE	BACKING RINGS	SOCKET P-14	SLIP-ON P-13	SLIP-0N P-42	SOCKET P-15	P-17	CONN.	JOINTS	LENGTH MM	length/joint
4"	40				4		1	43		4		52	36,367	699.4
	80				1		1	14		1		17	15,431	907.7
5"	40				1			4				5	4,028	805.6
	80													
6"	40		2		38		5	56		1	1	103	48,549	471.3
	80						1	4				5	5,886	1,177.2
8"	40				7		3	12		1	1	24	13,284	553.5
	80		10		24		6	47			1	88	71,523	812.8
10"	40						4	4				8	17,531	2,191.4
	80													
	0.375							2				2	3,722	1,861.0
	0.5		7		38		17	55		10		127	89,639	705.8
12"	40													
	0.375							12				12	1,420	118.3
	0.5		2		4		1	6			2	15	7,693	512.9
14"	0.375													
	0.5							4				4	777	194.3
16"	10													
	0.375													
	0.5				8			16			1	25	8,566	342.6
18"	10													
	0.375							1				1	3,134	3,134.0
	0.5		2		2			14		1	1	20	9,021	451.1
20"	XS.812													
	0.375		5		4			6		2		17	7,348	432.2
	0.5							4				4	1,536	384.0
22"	10													
24"	10													
	40													
	0.375													
	0.5				5			6		2	2	15	10,111	674.1
28"	0.5							12		1		13	8,714	670.3
30"	0.375													
	0.5													
TOTAL SPOOLS		162												
JOINTS PER WEEK		557	28		136		39	322		23	9	557	364,280	654.0
ROLL OUT		509												
MANUAL		48												

WELDING ENGINEERING MARCH 18, 2004

NASSCO PIPE SHOP STEEL SPOOLS PER WEEK

WEEK 18, 2004														
WELD JOINTS			**BUTT JOINT**	**BUTT JOINT**	**BUTT JOINT**	**SLEEVE**	**SLEEVE**	**FLANGE**	**FLANGE**	**STRUCTURAL**	**BRANCH**	**TOTAL**	**SPOOL**	**Average**
PIPE DIAMETER/SCH.			**OPEN ROOT SST**	**GTAW CONSUMABLE**	**BACKING RINGS**	**SOCKET P-14**	**SLIP-ON P-13**	**SLIP-0N P-42**	**SOCKET P-15**	**P-17**	**CONN.**	**JOINTS**	**LENGTH MM**	**length/joint**
4"	40				18		3	73		1	2	97	62,905	648.5
	80				1			46		4		51	44,885	880.1
5"	40				1							1	1,023	1,023.0
	80													
6"	40				27		3	31			3	64	38,707	604.8
	80				2		1	10		4	3	20	11,442	572.1
8"	40		6		3		1	40		3	1	54	16,553	306.5
	80		2		9		4	8		2		25	20,720	828.8
10"	40				1			4			3	8	5,085	635.6
	80												3,571	
	0.375													
	0.5				9		5	35		3		52	37,634	723.7
12"	40													
	0.375							6				6	710	118.3
	0.5				5		2	4			3	14	8,402	600.1
14"	0.375													
	0.5													
16"	10													
	0.375													
	0.5				8		3			3		14	7,908	564.9
18"	10													
	0.375				5		3	2				10	8,321	832.1
	0.5		4		4		1	10				19	7,421	390.6
20"	XS.812													
	0.375													
	0.5							4		1		5	1,353	270.6
22"	10													
24"	10													
	40													
	0.375													
	0.5													
28"	0.5							10			1	11	12,178	1,107.1
30"	0.375													
	0.5							14				14	29,347	2,096.2
TOTAL SPOOLS		**143**												
JOINTS PER WEEK		**465**	12		93		26	297		21	16	**465**	**318,165**	**684.2**
ROLL OUT		**408**												
MANUAL		**57**												

WELDING ENGINEERING MARCH 18, 2004

NASSCO PIPE SHOP STEEL SPOOLS PER WEEK

WEEK 19, 2004														
WELD JOINTS			BUTT JOINT	BUTT JOINT	BUTT JOINT	SLEEVE	SLEEVE	FLANGE	FLANGE	STRUCTURAL	BRANCH	TOTAL	SPOOL	Average
PIPE DIAMETER/SCH.			OPEN ROOT SST	GTAW CONSUMABLE	BACKING RINGS	SOCKET P-14	SLIP-ON P-13	SLIP-0N P-42	SOCKET P-15	P-17	CONN.	JOINTS	LENGTH MM	length/joint
4"	40				26		5	78			8	117	56,377	481.9
	80		1				1	10			1	13	10,954	842.6
5"	40		1		4			18				23	8,067	350.7
	80													
6"	40		3		24		7	97		1	5	137	60,704	443.1
	80				6		6	36		3	2	53	35,866	676.7
8"	40		6		8		1	8			1	24	18,245	760.2
	80				8		7	19				34	13,891	408.6
10"	40				10		5	24			1	40	16,660	416.5
	80													
	0.375													
	0.5		3		13		13	34			4	67	44,854	669.5
12"	40													
	0.375				8			6				14	4,811	343.6
	0.5				1			6			1	8	5,484	685.5
14"	0.375													
	0.5													
16"	10													
	0.375		4					4				8	2,547	318.4
	0.5		4					4				8	1,165	145.6
18"	10													
	0.375													
	0.5							18		1		19	10,687	562.5
20"	XS.812													
	0.375													
	0.5													
22"	10													
24"	10													
	40													
	0.375													
	0.5		2					4				6	4,302	717.0
28"	0.5		2					8				10	11,097	1,109.7
30"	0.375												6121	
	0.5							22		1	5	28	28,176	1,006.3
TOTAL SPOOLS		163												
JOINTS PER WEEK		609	26		108		45	396		6	28	609	340,008	558.3
ROLL OUT		549												
MANUAL		60												

WELDING ENGINEERING MARCH 18, 2004

NASSCO PIPE SHOP STEEL SPOOLS PER WEEK

WEEK 20, 2004														
WELD JOINTS			BUTT JOINT	BUTT JOINT	BUTT JOINT	SLEEVE	SLEEVE	FLANGE	FLANGE	STRUCTURAL	BRANCH	TOTAL	SPOOL	Average
PIPE DIAMETER/SCH.			OPEN ROOT SST	GTAW CONSUMABLE	BACKING RINGS	SOCKET P-14	SLIP-ON P-13	SLIP-0N P-42	SOCKET P-15	P-17	CONN.	JOINTS	LENGTH MM	length/joint
4"	40				11		3	48		2	3	67	24,535	366.2
	80		2				4	24		1		31	19,200	619.4
5"	40							8				8	1,203	150.4
	80													
6"	40		13		36		2	54			1	106	42,443	400.4
	80		1		2			32		2		37	21,920	592.4
8"	40		9		22			24		2	1	58	22,986	396.3
	80				6		7	26		1	1	41	36,810	897.8
10"	40		1		1		1	8		1	3	15	8,996	599.7
	80													
	0.375													
	0.5		8		9		1	44		4	1	67	30,545	455.9
12"	40													
	0.375				1			2				3	5,106	1,702.0
	0.5				3		2	6		1	2	14	13,499	964.2
14"	0.375													
	0.5													
16"	10													
	0.375													
	0.5				7			6				13	6,907	531.3
18"	10													
	0.375													
	0.5		4					8				12	5,988	499.0
20"	XS.812													
	0.375							8				8	1,000	125.0
	0.5													
22"	10													
24"	10													
	40							2		1		3	441	147.0
	0.375							2				2	238	119.0
	0.5							6				6	3,640	606.7
28"	0.5													
30"	0.375							4				4	5,913	1,478.3
	0.5													
TOTAL SPOOLS		130												
JOINTS PER WEEK		495	38		98		20	312		15	12	495	251,370	507.8
ROLL OUT		438												
MANUAL		57												

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Attachment 2
Pipe Joint Fit-Up Time

PIPE JOINT FIT-UP TIME AVERAGE

4" Steel pipe sch.80 slip-on flange P42 joint		**Penetration sleeve P-17 joint**
Steel 4 " sch 80 wall, 20' (6000 mm) in length takes approx. 6 minutes for sandblast	6 min.	6 min.
5" minutes approx. to adjust the plasma cutting machine	5	5
Stright cut approx. 2 to 3 min.	3	3
To move pipe to floor after has been cut 2 to 3 min.	3	3
To pick up pipe from the floor and move to assy table 5 min.	5	5
Grinding pipe and flange 5 min.	5	5
To fit-up 4" slip-on flange	5	5
To tack weld flange.	5	5
	37 min.	**37 min.**
4" Steel pipe open root P-2 joint		
8 minutes to sandblast	8 min.	
5 min. to adjust plasma	5	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
10 to 15 min. to fit- up open root butt joint	15	
5 to 7 min. to weld tack joint	7	
	63 min.	
4" Steel pipe butt joint with permanent backing ring P-3 joint		
8 minutes to sandblast	8 min.	
5 min. to adjust plasma	5	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
10 min. to fit-up	10	
5 to 7 min. to weld tack joint	7	
	58 min.	
4" Steel pipe Slip- on coupling P-13 joint		
8 minutes to sandblast	8 min.	
5 min. to adjust plasma	5	
6 min. to cut pipe	6	
3 to 5 min. to move pipe to the floor near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy. table	7	
5 min. to grind both sides of piping	5	
Fit up coupling to pipe	5	
5 to 7 min. to weld tack joint	7	
	48 min.	

PIPE JOINT FIT-UP TIME AVERAGE

5" Pipe sch.80 slip-on flange P42 joint		**Penetration sleeve P-17 joint**
Steel 5 " sch. 80 wall, 20' (6000 mm) in length takes approx. 8 minutes for sandblast	8	8
5" minutes approx. to adjust the plasma cutting machine	5	5
Stright cut approx. 2 to 3 min.	3	3
To move pipe to floor after has been cut 2 to 3 min.	3	3
To pick up pipe from the floor and move to assy table 5 min.	5	5
Grinding pipe and flange 5 min.	5	5
To fit-up 4" pipe and flange	5	5
To tack weld 5 min..	5	5
	39 min. approx.	**39 min. approx.**
5" Steel pipe open root P-2 joint		
8 minutes to sandblast	8 min.	
5 min. to adjust plasma	5	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
10 to 15 min. to fit up butt joint	15	
5 to 7 min. to weld tack joint	7	
	63 min.	
5" Steel pipe butt joint with permanent backing ring P-3 joint		
8 minutes to sandblast	8 min.	
5 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
10 to 15 min. to fit up butt joint with backing ring	10	
5 to 7 min. to weld tack joint	7	
	59 min.	
5" Steel pipe Slip- on coupling P-13 joint		
8 minutes to sandblast	8 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
10 to 15 min. to fit up	5	
5 to 7 min. to weld tack joint	7	
	47 min	

PIPE JOINT FIT-UP TIME AVERAGE

6" Slip-on flange P42 joint		**Penetration sleeve P-17 joint**
Steel 6 " sch 80 wall, 20' (6000 mm) in length takes approx. 8 minutes for sandblast	8 min.	8 min.
5" minutes approx. to adjust the plasma cutting machine	5	5
Stright cut approx. 2 to 3 min.	3	3
To move pipe to floor after has been cut 2 to 3 min.	3	3
To pick up pipe from the floor and move to assy table 6 min.	6	6
Grinding pipe and flange	5	5
To fit-up 5 " slip on flange	10	5
To tack weld pipe to flange	5	5
	45 min.	**40 min.**
6" Steel pipe open root P-2 joint		
8 minutes to sandblast	8 min.	
6min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
15 to 20 min to fit up butt joint	15	
5 to 7 min. to weld tack joint	7	
	64 min.	
6" Steel pipe butt joint with permanent backing ring P-3 joint		
8 minutes to sandblast	8 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
15 to 20 min to fit up butt joint	10	
5 to 7 min. to weld tack joint	7 min.	
	59 min.	
6" Steel pipe Slip- on coupling P-13 joint		
8 minutes to sandblast	8 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy. table	7	
5 to 10 min. to grind both sides of piping	10	
7 min to fit up pipe and coupling	7	
5 to 7 min. to weld tack joint	7 min.	
	56 min.	

PIPE JOINT FIT-UP TIME AVERAGE

8" Slip-on flange P42 joint		**Penetration sleeve P-17 joint**
Steel 8 " sch. 80 wall, 20' (6000 mm) in length takes approx. 8 minutes for sandblast	8 min.	8 min.
5" minutes approx. to adjust the plasma cutting machine	5	5
Stright cut approx. 2 to 3 min.	3	3
To move pipe to floor after has been cut 2 to 3 min.	3	3
To pick up pipe from the floor and move to assy table 5 min.	5	5
Grinding pipe and flange 5 to 10 min.	10	10
To fit-up 6" slip-on flange and piping 5 to 7 min.	7	7
To tack weld sleeve to pipe 5 to 7 min.	5	5
	46 min.	**46 min.**
8" Steel pipe open root P-2 joint		
8 minutes to sandblast	8 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
15 to 20 min. to fit- up butt joint	20	
5 to 7 min. to weld tack joint	7 min.	
	69 min.	
8" Steel pipe butt joint with permanent backing ring P-3 joint		
8 minutes to sandblast	8 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
15 to 20 min. to fit- up butt joint	15	
5 to 7 min. to weld tack joint	7	
	64 min.	
8" Steel pipe Slip- on coupling P-13 joint		
8 minutes to sandblast	8 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
7 min. to fit- up coupling	7	
5 to 7 min. to weld tack joint	7	
	56 min.	

PIPE JOINT FIT-UP TIME AVERAGE

10"Slip-on flange P42 joint		**Penetration sleeve P-17 joint**
Steel 10" .500 wall, 20' (6000 mm) in length takes approx. 10 minutes for sandblast	10 min.	10
5" minutes approx. to adjust the plasma cutting machine	5 min.	5
Stright cut approx. 2 to 3 min.	3 min.	3
To move pipe to floor after has been cut 2 to 3 min.	3 min.	3
To pick up pipe from the floor and move to assy table 5 min.	5 min.	5
Grinding pipe and 5 to 10 min.	10 min.	10
To fit-up 8" slip-on flange	15min.	10
To tack weld flange to pipe	7 min.	7
	58 min.	**53 min.**
10" .500 wall steel pipe open root P-2 joint		
10 minutes to sandblast	10 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
20 to25 min. to fit- up butt joint	25	
5 to 7 min. to weld tack joint	7 min.	
	76 min.	
10" Steel pipe .500 wall butt joing with permanent backing ring P-3 joint		
10 minutes to sandblast	10 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
15 to20 min. to fit- up butt joint	20	
5 to 7 min. to weld tack joint	7 min.	
	71 min.	
10" Steel pipe Slip- on coupling P-13 joint		
10 minutes to sandblast	10min.	
6 min. to adjust plasma	6	
6 min. to cut pipe	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
10 min. to fit- up coupling	10	
5 to 7 min. to weld tack joint	7 min.	
	61 min.	

PIPE JOINT FIT-UP TIME AVERAGE

12" .500 wall Slip-on flange P42 joint		**Penetration sleeve P-17 joint**
Steel 12" .500 wall, 20' (6000 mm) in length takes approx. 10 to 12 minutes for sandblast	12 min.	12
5" minutes approx. to adjust the plasma cutting machine	5 min.	5
Stright cut approx. 2 to 3 min.	3 min.	3
To move pipe to floor after has been cut 2 to 3 min.	3 min.	3
To pick up pipe from the floor and move to assy table 5 min.	5 min.	5
Grinding pipe and flange 5 to 10 min.	10 min.	10
To fit-up 12" slip-on flange and piping 15 to 20 min.	20 min.	10
To tack weld coupling to pipe 5 to 7 min.	7 min.	7
	65 min.	**55 min.**
12" .500 wall Steel pipe open root P-2 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
25 to 30 min. to fit- up butt joint	30	
5 to 7 min. to weld tack joint	7 min.	
	83 min.	
12" Steel pipe .500 wall butt joing with permanent backing ring P-3 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
25 to 30 min. to fit- up butt joint	25	
5 to 7 min. to weld tack joint	7	
	78 min.	
12" Steel pipe .500 wall slip- on coupling P-13 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
10 min. to fit- up	10	
5 to 7 min. to weld tack joint	7	
	63 min.	

PIPE JOINT FIT-UP TIME AVERAGE

14" Slip-on flange .500 wall P42 joint		**Penetration sleeve P-17 joint**
Steel 14" .500 wall, 20' (6000 mm) in length takes approx. 10 to 12 minutes for sandblast	12 min.	12 min.
5" minutes approx. to adjust the plasma cutting machine	5	5
Stright cut approx. 2 to 3 min.	3	3
To move pipe to floor after has been cut 2 to 3 min.	3	3
To pick up pipe from the floor and move to assy table 5 min.	5	5
Grinding pipe and flange 5 to 10 min.	10	10
To fit-up 14" slip-on flange and piping 20 to 25min.	25	20
To tack weld coupling to pipe 5 to 7 min.	7	7
	70 min.	**65 min.**
14" Steel pipe .500 wall open root P-2 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
30 to 35 min. to fit up butt joint	40	
5 to 7 min. to weld tack joint	7 min.	
	93 min.	
14" Steel pipe .500 wall butt joing with permanent backing ring P-3 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
30 to 35 min. to fit up butt joint with permanent ring	30	
5 to 7 min. to weld tack joint	7	
	83 min.	
14" Steel pipe .500 wall slip- on coupling P-13 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
20 min. to fit up	20	
5 to 7 min. to weld tack joint	7 min.	
	73 min.	

PIPE JOINT FIT-UP TIME AVERAGE

16" Slip-on flange .500 wall P42 joint		**Penetration sleeve P-17 joint**
Steel 16" .500 wall, 20' (6000 mm) in length takes approx. 10 to 12 minutes for sandblast	12 min.	12 min.
5" minutes approx. to adjust the plasma cutting machine	5	5
Stright cut approx. 2 to 3 min.	3	3
To move pipe to floor after has been cut 2 to 3 min.	3	3
To pick up pipe from the floor and move to assy table 5 min.	5	5
Grinding pipe 5 to 10 min.	10	10
To fit-up 16" slip-on flange and pipe 15 to 25 min.	25	20
To tack weld flange with pipe 5 to 7 min.	7	7
	70 min.	**65 min.**
16" Steel pipe .500 wall open root P-2 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
30 to 35 min. to fit- up	40	
5 to 7 min. to weld tack joint	7 min.	
	93 min.	
16" Steel pipe .500 wall but joint with permanent backing ring P-3 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
25 to30 min. to fit- up butt with permanent backing ring	30	
5 to 7 min. to weld tack joint	7	
	83 min.	
16" Steel pipe .500 wall slip- on coupling P-13 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
15 to20 min. to fit- up	20	
5 to 7 min. to weld tack joint	7 min.	
	73 min.	

PIPE JOINT FIT-UP TIME AVERAGE

18" Slip-on flange .500 wall P42 joint		**Penetration sleeve P-17 joint**
Steel 18" .500 wall, 20' (6000 mm) in length takes approx. 10 to 12 minutes for sandblast	12 min.	12 min.
5" minutes approx. to adjust the plasma cutting machine	5	5
Stright cut approx. 2 to 3 min.	3	3
To move pipe to floor after has been cut 2 to 3 min.	3	3
To pick up pipe from the floor and move to assy table 5 min.	5	5
Grinding pipe and flange 5 to 10 min.	10	10
To fit-up 18" slip-on flange and piping 25 to 30 min.	30	25
To tack weld flange to pipe 5 to 7 min.	7	7
	75 min.	**70 min.**
18" Steel pipe .500 wall open root P-2 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
45 to 50 min. to fit- up butt joint	50	
5 to 7 min. to weld tack joint	7 min.	
	103 min.	
18" Steel pipe .500 wall butt joint with permanent backing ring P-3 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
35 to 40 min. to fit- up butt joint	40	
5 to 7 min. to weld tack joint	7 min.	
	88 min.	
18" Steel pipe .500 wall slip- on coupling P-13 joint		
12 minutes to sandblast	12 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
20 to25 min. to fit- up	25	
5 to 7 min. to weld tack joint	7 min.	
	78 min.	

PIPE JOINT FIT-UP TIME AVERAGE

20" Slip-on flange .500 wall P42 joint		**Penetration sleeve P-17 joint**
Steel 20" .500 wall, 20' (6000 mm) in length takes approx. 110 to 15 minutes for sandblast	15	15
5" minutes approx. to adjust the plasma cutting machine	5	5
Stright cut approx. 2 to 3 min.	3	3
To move pipe to floor after has been cut 2 to 3 min.	3	3
To pick up pipe from the floor and move to assy table 5 min.	5	5
Grinding pipe and flange 5 to 10 min.	10	10
To fit-up 20" slip-on flange and piping 30 to 35 min.	35	30
To tack weld flange to pipe 5 to 7 min.	7	7
	83 min.	**78 min.**
20" Steel pipe .500 wall open root P-2 joint		
15 minutes to sandblast	15 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	**Fit-up 20 " saddle 20 to 30 minutes approx.**
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
55 to 60 min. to fit- up butt joint	60	
5 to 7 min. to weld tack joint	7	
	116 min.	
20" Steel pipe .500 wall butt joint with permanent backing ring P-3 joint		
15 minutes to sandblast	15 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
55 to 60 min. to fit- up butt joint	60	
5 to 7 min. to weld tack joint	7	
	96 min.	
20" Steel pipe .500 wall slip- on coupling P-13 joint		
15 minutes to sandblast	15 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
25 to 30 min. to fit- up	30	
5 to 7 min. to weld tack joint	7	
	86 min.	

PIPE JOINT FIT-UP TIME AVERAGE

24" Slip-on flange .500 wall P42 joint		**Penetration sleeve P-17 joint**
Steel 24" .500 wall, 20' (6000 mm) in length takes approx. 10 t015 minutes for sandblast	15 min.	15 min.
5" minutes approx. to adjust the plasma cutting machine	5	5
Stright cut approx. 2 to 3 min.	3	3
To move pipe to floor after has been cut 2 to 3 min.	3	3
To pick up pipe from the floor and move to assy table 5 min.	5	5
Grinding pipe and flange 5 to 10 min.	10	10
To fit-up 24" slip-on flange and piping 40 to 45 min.	45	30
To tack weld flange to pipe 5 to 7 min.	7	7
	93 min.	**78 min.**
24" Steel pipe .500 wall open root P-2 joint		
15 minutes to sandblast	15 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
55 to 60 min. to fit-up butt joint	60	
5 to 7 min. to weld tack joint	7	
	116 min.	
24" Steel pipe .500 wall butt joint with permanent backing ring P-3 joint		
15 minutes to sandblast	15 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
35 to 40 min. to fit-up butt joint	40	
5 to 7 min. to weld tack joint	7	
	106 min.	
24" Steel pipe .500 wall slip- on coupling P-13 joint		
15 minutes to sandblast	15 min.	
6 min. to adjust plasma	6	
6 min. to cut pipe	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
25 to 30 min. to fit-up	30	
5 to 7 min. to weld tack joint	7	
	86 min.	
Note: 24" in diameter is the biggest inside the sand blast machine		

PIPE JOINT FIT-UP TIME AVERAGE

28" Slip-on flange .500 wall P42 joint		**Penetration sleeve P-17 joint**
5" minutes approx. to adjust the plasma cutting machine	5	5
Stright cut approx. 2 to 3 min.	3	3
To move pipe to floor after has been cut 2 to 3 min.	3	3
To pick up pipe from the floor and move to assy table 5 min.	5	5
Grinding pipe and flange 5 to 10 min.	10	10
To fit-up 28" slip-on flange and piping 40 min.	40	40
To tack weld flange to pipe 5 to 7 min.	7	7
	73 min.	**73 min.**
28" Steel pipe .500 wall open root P-2 joint		
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
60 to 75 min. to fit- up butt joint	75	
5 to 10 min. to weld tack joint	10	
	119 min.	
28" steel pipe .500 wall butt joint with permanent backing ring P-3 joint		
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
60 to 65 min. to fit- up butt joint	65	
5 to 10 min. to weld tack joint	10	
	109 min.	
28" Steel pipe .500 wall slip- on coupling P-13 joint		
6 min. to adjust plasma	6	
6 min. to cut pipe with bevel both sides	6	
3 to 5 min. to move pipe to the floo near to the assy. area	5	
5 to 7 min. to transfer pipe to the assy table	7	
5 to 10 min. to grind both sides of piping	10	
35 to 40 min. to fit- up	40	
5 to 10 min. to weld tack joint	10	
	84 min.	
Note: 28" Piping is sandblast and paint after fit- up and welding is complete		

PIPE JOINT FIT-UP TIME AVERAGE

30" Slip-on flange .500 wall P42 joint		**Penetration sleeve P-17 joint**	
Set pipe length in position for fit up on top of pipe stands 5 to 10 min.	10 min.	10 min.	
To grind pipe and flange 10 to 15 min.	15	15	
To fit 30" flange and pipe 35 to40 min.	40	40	
5 to 10 min to tack weld flange to pipe	10	10	
	75 min.	**75 min.**	
30" Steel pipe .500 wall open root P-2 joint			
10 TO 15 min. to set piping over pipe stands	15		
Install and adjust manual circular torch 10 to 15 min.	15		
To cut bevel both sides 30 to 35 min.	35		
Removing circular torch equipment 5 min.	5		
Grinding clean both ends of pipe 20 min.	20		
Fit-up butt joint 70 to 80 min.	80		
To tack weld butt pipe 5 to 7 min.	10		
	180 min.		
Steel 30" .500 wall butt joint with permanent backing ring P-3 joint		**Cutting pipe bevels with plasma machine**	
10 TO 15 min. to set piping over pipe stands	15	Adjust plasma 6 min.	6
Install and adjust manual circular torch 10 to 15 min.	15	Bevel pipe both sides 6. min.	6
To cut bevel both sides 30 to 35 min.	35	To move pipe to floor after has been cut 2 to 3 min.	3
Removing circular torch equipment 5 min.	5	To pick up pipe from floor and move to assy area	5
Grinding clean both ends of pipe 20 min.	20	Pick up pipe and set over pipe stands	10
Fit-up butt joint 55 to 60 min.	60	Grinding pipe both ends 5 to 7 min.	7
To tack weld butt pipe 5 to 10 min.	7	Fit-up butt joint with permanent backing ring	60
	157 min.	Tack weld butt joint	10
30" Steel pipe .500 wall slip- on coupling P-13 joint			**107 min.**
10 TO 15 min. to set piping over pipe stands	15		
Install and adjust manual circular torch 10 to 15 min.	15		
To strigth cut 25 to 35	35		
Removing circular torch equipment 5 min.	5		
Grinding clean both ends of pipe 20 min.	20		
Fit-up joint 35 t0 40 min.	40		
To tack weld 5 to 10 min.	10		
	140 min.		
Note: 30" Piping is sandblast and paint after fit- up and welding is complete			
30" in diameter is the biggest inside the plasma cutting machine			

Attachment 3

Pipe Joint Weld Time

PIPE JOINT WELD TIME AVERAGE

4" Slip-on flange P-42	**Sch-80**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld flange to pipe	20 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	34 min.
4" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	25 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	39 min.
4" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	25 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	39 min.
4" Slip-on coupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	15 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	29 min.
4" P-17 joint penetration sleeve	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	15min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	29 min.

PIPE JOINT WELD TIME AVERAGE

5" Slip on flange P-42	**Sch. 80**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld flange to pipe	15min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	29 min.
5" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	20 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	34 min.
5" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	25 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	39 min.
5"Sleeve slip- on coupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	15 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	29 min.
5" P-17 joint penetration sleeve	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Wel coupling to pipe	20 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	34 min.

PIPE JOINT WELD TIME AVERAGE

6" Slip on flange P-42	**Sch.80**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld flange to pipe	25 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	39 min.
6" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	45 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	59 min.
6" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	45 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	54 min.
6" Sleeve slip-on coupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	25 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	39 min.
6" P-17 joint penetration sleeve	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	20min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	34 min.

PIPE JOINT WELD TIME AVERAGE

8" Slip-on flange P-42	**Sch. 80**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld flange to pipe	30 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	44 min.
8" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	60 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	78 min.
8" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	55 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	69 min.
8" Slip-on sleeve coupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	30 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	44 min.
8" P-17 joint penetration sleeve	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	20 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	34 min.

PIPE JOINT WELD TIME AVERAGE

10" Slip-on flange P-42	**.500 wall**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld flange to pipe	45 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	59 min.
10" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	70 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	84 min.
10" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	60 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	74 min.
10"Slip-on sleeve coupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	30 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	44 min.
10" P-17 joint penetration sleeve	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	25 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	39 min.

PIPE JOINT WELD TIME AVERAGE

12" Slip-on flange P-42	**.500 wall**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld flange to pipe	60 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	74 min.
12" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	85 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	99 min.
12" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	75 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	89 min.
12" Slip-on coupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	50 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
12" P-17 joint penetration sleeve	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	35 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	49 min.

PIPE JOINT WELD TIME AVERAGE

14" Slip-on flange P-42	**.500 wall**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld flange to pipe	60min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	74 min.
14" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	90 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	104 min.
14" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	85 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	94 min.
14" Slip- on coupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	65 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	79 min.
14" P-17 joint penetration sleeve	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	35 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	49 min.

PIPE JOINT WELD TIME AVERAGE

16" Slip-on flange P-42	**.500 wall**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld flange to pipe	65 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	79 min.
16" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	90 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	104 min.
16" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	85 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
16" Slip-on coupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	70 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	84 min.
16" P-17 joint penetration sleeve	5 min.
Pick-up pipe spool from the floor with the crane and install it in the roller machine	40 min.
Weld coupling to pipe	3 min.
clean pipe joint	6 min.
V T pipe joint and unload spool from roller	**54 min.**

PIPE JOINT WELD TIME AVERAGE

18" Slip-on flange P-42	**.500 wall**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld flange to pipe	70 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	84 min.
18" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	95 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	109 min.
18" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld pipe joint	85 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	99 min.
18" Slip-on coupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	75 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	89 min.
18" P-17 joint penetration sleeve	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	5 min.
Weld coupling to pipe	45 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	6 min.
	59 min.

PIPE JOINT WELD TIME AVERAGE

20" Slip-on flange P-42	**.500 wall**	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.	
Weld flange to pipe	70 min.	
clean pipe joint	3 min.	
V T pipe joint and unload spool from roller	6 min.	
	89 min.	
20" Open root butt joint P-2		
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.	
Weld pipe joint	95 min.	
clean pipe joint	5 min.	
V T pipe joint and unload spool from roller	10 min.	
	125 min.	
20" Butt joint with permanent backing ring P-3		**Welding 20" saddle full penetration takes approx. 3 hours**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.	
Weld pipe joint	90 min.	
clean pipe joint	5 min.	
V T pipe joint and unload spool from roller	10 min.	
	115 min.	
20" Slip-on coupling P-13 joint		
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.	
Weld coupling to pipe	80min.	
clean pipe joint	3 min.	
V T pipe joint and unload spool from roller	6 min.	
	99 min.	
20" P-17 joint penetration sleeve		
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10min.	
Weld coupling to pipe	50 min.	
clean pipe joint	3 min.	
V T pipe joint and unload spool from roller	6 min.	
	64 min.	

PIPE JOINT WELD TIME AVERAGE

24" Slip-on flange P-42	**.500 wall**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld flange to pipe	80 min.
clean pipe joint	5 min.
V T pipe joint and unload spool from roller	10 min.
	105 min.
24" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld pipe joint	100 min.
clean pipe joint	5 min.
V T pipe joint and unload spool from roller	10 min.
	125 min.
24" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld pipe joint	90 min.
clean pipe joint	5 min.
V T pipe joint and unload spool from roller	10 min.
	115 min.
24" Slip-oncoupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld coupling to pipe	85 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	10min.
	108 min.
24" P-17 joint penetration sleeve	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld coupling to pipe	50 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	10 min.
	73 min.

PIPE JOINT WELD TIME AVERAGE

28" Slip-on flange P-42	**.500 wall**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld flange to pipe	80 min.
clean pipe joint	5 min.
V T pipe joint and unload spool from roller	10 min.
	105 min.
28" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld pipe joint	100 min.
clean pipe joint	5 min.
V T pipe joint and unload spool from roller	10 min.
	125 min.
28" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld pipe joint	90 min.
clean pipe joint	5 min.
V T pipe joint and unload spool from roller	10 min.
	115 min.
28" Slip-on coupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld coupling to pipe	85 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	10min.
	108 min.
28" P-17 joint penetration sleeve	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld coupling to pipe	50 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	10 min.
	73 min.
Note: 28" Piping is sandblast and paint after fit- up and welding are complete	

PIPE JOINT WELD TIME AVERAGE

30" Slip-on flange P-42	**.500 wall**
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld flange to pipe	80 min.
clean pipe joint	5 min.
V T pipe joint and unload spool from roller	10 min.
	105 min.
30" Open root butt joint P-2	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld pipe joint	100 min.
clean pipe joint	5 min.
V T pipe joint and unload spool from roller	10 min.
	125 min.
30" Butt joint with permanent backing ring P-3	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld pipe joint	90 min.
clean pipe joint	5 min.
V T pipe joint and unload spool from roller	10 min.
	115 min.
30" Steel pipe slip-on coupling P-13 joint	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld coupling to pipe	85 min.
clean pipe joint	5 min.
V T pipe joint and unload spool from roller	10min.
	118 min.
30" P-17 joint penetration sleeve	
Pick-up pipe spool from the floor with the crane and install it in the roller machine	10 min.
Weld coupling to pipe	50 min.
clean pipe joint	3 min.
V T pipe joint and unload spool from roller	10 min.
	73 min.
Note: 30" Piping is sandblast and paint after fit- up and welding is complete	

AVERAGE DIAMETER SIZE OF JOINTS WELDED

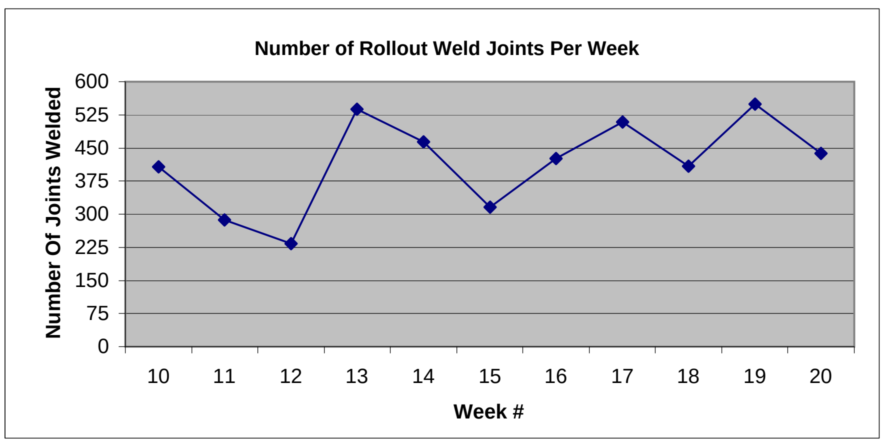
WELD JOINTS	WK #10	WK #11	WK #12	WK #13	WK #14	WK #15	WK #16	WK #17	WK #18	WK #19	WK #20	Average #	Current	Current	Current	Laser	Savings (Joints)	Savings
PIPE DIAMETER	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Total Joints	Joint/WK/ Size	Average of Min./Joints	Hrs./Joint Type Per Wk	% of Hrs./Joint Type Per Wk	Average of Hrs./Joints	Average of Hrs./Joints	Per Week
4"	117	56	46	159	87	56	93	69	148	130	98	96	83	133	14%	*	*	*
5"	14	4	2	0	61	13	3	5	1	23	8	12	82	17	2%	*	*	*
6"	114	55	38	118	58	76	131	108	84	190	143	101	98	165	18%	*	*	*
8"	54	41	38	88	72	70	65	112	79	58	99	71	110	129	14%	*	*	*
10"	42	67	8	62	144	41	64	137	60	107	82	74	124	153	17%	*	*	*
12"	29	8	21	10	9	39	13	27	20	22	17	20	144	47	5%	*	*	*
14"	0	0	10	31	20	5	2	4	0	0	0	7	157	17	2%	*	*	*
16"	16	42	40	11	15	13	18	25	14	16	13	20	161	54	6%	*	*	*
18"	18	24	11	13	16	9	44	21	29	19	12	20	171	56	6%	*	*	*
20"	14	3	7	46	9	7	29	21	5	0	8	14	190	43	5%	*	*	*
22"	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%	*	*	*
24"	0	28	24	28	8	3	17	15	0	6	11	13	201	43	5%	*	*	*
28"	4	0	22	23	12	0	0	13	11	10	0	9	197	28	3%	*	*	*
30"	0	0	22	21	7	0	0	0	14	28	4	9	233	34	4%	*	*	*
JOINTS PER WK	452	328	289	610	518	332	484	557	465	609	495	467		918 Hours	100%	*	*	*
																	Total Savings/Wk.	*
																	Hrs Saved/Yr.	*

Green = minutes
Blue = hours

Number of Weld Joints Per Week For Rollout 4" Diameter And Greater

Wk #	
#	407
#	287
#	234
#	538
#	464
#	316
#	426
#	509
#	408
#	549
#	438
	4576

Average 416



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