REPORT

April 28, 2006
EWI Project No. 47961GTH
DoT Transaction Agreement No. DTRS56-05-T-0001

Innovative Welding Processes for Small to Medium Diameter Gas Transmission Pipelines

Task 7 Report
Productivity and Economic Analysis

Submitted to:

U.S. Department of Transportation
Research and Special Programs Administration
Washington, D.C.

MATERIALS JOINING TECHNOLOGY

Task 7 Report

Project No. 47961GTH
U.S. Dot OTA No. DTRS56-05-T-0001

on

Innovative Welding Processes for Small to Medium Diameter Gas Transmission Pipelines
Task 7 – Productivity and Economic Analysis

to

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April 28, 2006

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Executive Summary

On large-diameter tie-ins, and small- to medium-diameter pipelines, root side access is generally not provided due to cost constraints and equipment limitations. There is a technology gap to deploy high-strength materials on single-sided pipeline welding applications or provide cost-effective high integrity welding for deepwater applications.

Only advanced processes coupled with automation techniques have the potential to improve the robustness, quality, productivity, and integrity of single-sided pipeline root passes, and assure resistance to flaws through the use of in process monitoring and adaptive control techniques.

The project aimed to develop innovative welding processes and technologies for single-sided pipeline girth welding. Root pass welding techniques were emphasized since they have the greatest potential to improve pipeline integrity and facilitate the use of new and existing gas metal arc welding (GMAW) fill pass techniques. Advanced automation techniques were also used to improve weld quality, process control, and robustness. The objective of Task 7 was to examine the competing productivity and economic factors involved in selecting the appropriate technology for a particular pipeline project.

Based on the work reported here for GMAW procedure development on X80 pipe material, and laser or hybrid laser/GMAW work on X100, the following conclusions can be stated:

1. The GMAW process showing the most promise for high-speed mechanized root pass welding was the rotating electrode GMAW (GMAW-RE), known as Spin Arc.

2. Welding procedures were developed for welding in the 5G position using the double-down technique, but using only a single torch for the development work.

3. Welding speeds up to 1.5 m/min were used in the vertical down position, but the combination of pipe metallurgy, elongated teardrop weld pool shape, and the requirements of achieving full penetration with a reasonable throat thickness, consistently resulted in centerline solidification cracking.

4. The persistent cracking found with ER70S-6 and ER80S-D2 wires in the vertical-down position was solved using the ER90S-G Union NiMo80 wire, achieving an average root pass welding speed of 0.95 m/min.

- Flat position – Weld SA-134
    - Travel speed: 27.6 in./min (0.7 m/min)
    - Wire feed speed: 397 in./min
    - Welding current: 210 A
    - Arc voltage: 21.5 V
    - Wire feed speed/travel speed ratio: 14.4
    - Throat thickness: 5.6 mm.

- Vertical down – Weld SA-137
    - Travel speed: 46.3 in./min (1.2 m/min)
    - Wire feed speed: 552 in./min
    - Welding current: 254 A
    - Arc voltage: 22.1 V
    - Wire feed speed/travel speed ratio: 11.9
    - Throat thickness: 4.3 mm.

Trials were conducted with this wire to develop tolerance to root face mismatch and the results showed the procedure to be tolerant to 1.5 mm of mismatch with good penetration and root face profile, in both the flat and vertical-down positions.

5. For hybrid laser beam welding (LBW)/GMAW the speeds achieved easily exceed the objective of 1.5 m/min, and in fact it is possible to achieve 4-m/min welding speed with only 4-kW laser power, when used in a hybrid configuration with 5 kW of GMAW arc power. The productivity (and cost) of the overall welding system depends on the precise combination of laser power, arc power, and root throat thickness.

6. The economic case for using an 8-kW fiber laser and associated equipment versus the case for two GMAW-RE torches for the root pass needs to be considered. While the 6- to 8-mm throat thickness and travel speed achieved with the hybrid fiber laser/GMAW equipment is impressive, it must be borne in mind that the capital equipment cost of the laser/GMAW system is around $1M. This should be compared to a single torch GMAW system at a cost of about $505K for two systems which can produce a throat thickness for the root pass of 4 to 5.5 mm.

7. Ultimately the cost effectiveness of a mechanized pipe welding system depends on the pipe material and wall thickness, and the length of the pipeline in addition to the other items discussed here. There is nota single solution for all cases. Ultimately the ability to finish a project ahead of schedule with the concomitant cost savings for equipment rental and labor may be an overriding factor in determining which form of process and mechanization is the most cost effective.

Acknowledgements

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Legal Notice

1.0 Introduction

Pipelines will be an integral part of our energy distribution systems for the foreseeable future. It is predicted that natural gas consumption will double over the next 20 years. Operators are currently considering the installation of many tens of billions of dollars of pipeline infrastructure. In a number of cases, the cost of exporting the product will have a dominating influence on the viability of the upstream production facilities. These facilities will progress only if the industry can substantially reduce capital expenditure and improve design for pipeline integrity. Whether the application is an onshore gas transmission line or a deepwater pipeline, there is a need to constantly improve the productivity, quality, integrity, and reliability of pipeline girth welds to reduce construction costs. There is also a need for improved technologies suitable for the higher strength steels currently being developed. Furthermore, advanced welding technologies are currently only deployed on large-diameter pipelines where the costs of internal backing clamps or internal root welding machines can be justified. The vast majority of small- to medium-diameter pipelines (24 in. and less) are welded manually, which may be more cost-effective at present, but do not always provide the highest integrity pipeline and raise specific metallurgical concerns on pipelines exceeding the strength levels of Grade X70.

2.0 Technical Background

Increasing demand for gas will require major investment in new long-distance gas-transmission pipelines with significant expansion of existing infrastructure using shorter sections of small- and medium-diameter pipelines to extend and loop existing lines and increase capacity. Tie-in welds can also be very frequent due to ditch, river, road, and rail crossings as well as other topographical features and these are often the weak link in a system. Tie-in welding may represent 50% of the welding costs of some pipelines. Small- to medium-diameter and tie-in welds are typically performed using cellulosic welding techniques which are generally not suitable for pipelines over Grade X70 or corrosion-resistant alloys. A prerequisite for these applications is single-sided welding since internal welding machines and alignment tools are not practical. These will need to be constructed as economically as possible, but the trends toward higher operating pressures and higher strength steels require improved pipeline integrity through overmatching weld metals and better quality processes

High-strength pipeline materials (over X70) offer cost savings but are more sensitive to process variation to assure properties. The ideal welding process produces welds with good bead shape and fusion, matching or over-matching material properties, and is cost effective. There should be no cracks or flaws in the weld deposit. Cracking susceptibility increases as the hydrogen content, stress, and hardness of the microstructure increase. For high-strength pipelines, manual welding processes cannot meet the required combination of properties, diffusible hydrogen, and weld integrity to assure cracking resistance. Low-hydrogen automated welding processes are preferred to control microstructure to optimize strength and toughness on X70 and above. The overall productivity of a pipeline construction spread is usually controlled by the cycle time of the root pass welding operations. Internal welding machines have historically assured good root pass quality on high-strength pipelines. While welding speed is important, the costs of equipment and the time to align and setup the weld preparation are also important. On large-diameter tie-ins, and small- to medium-diameter pipelines, root side access is generally not provided due to cost constraints and equipment limitations. There is a technology gap to deploy high-strength materials on single-sided pipeline welding applications or provide cost-effective high integrity welding for deepwater applications.

Only advanced processes coupled with automation techniques have the potential to improve the robustness, quality, productivity, and integrity of single-sided pipeline root passes, and assure resistance to flaws through the use of in process monitoring and adaptive control techniques.

3.0 Objectives

The project aimed to develop innovative welding processes and technologies for single-sided pipeline girth welding. Root pass welding techniques were emphasized since they have the greatest potential to improve pipeline integrity and facilitate the use of new and existing gas metal arc welding (GMAW) fill pass techniques. Advanced automation techniques were used to improve weld quality, process control, and robustness.

4.0 Technical Approach

The project was broken down into the following tasks:

1. Task 1 – Development of Innovative Root Pass Welding Processes
2. Task 2 – Property Testing of Preferred Root Pass Welding Techniques
3. Task 3 – Improved Root Pass Techniques
4. Task 4 – Process Control Systems for Pipeline Girth Welding
5. Task 5 – Real-Time Quality Monitoring for the Detection of Welding Defects
6. Task 6 – Preferred Process/Technique Demonstration
7. Task 7 – Productivity and Economic Analysis
8. Task 8 – Final Report.

This report addresses the technical approach and results achieved in Task 7 – Productivity and Economic Analysis.

Throughout the research project, the potential productivity benefits of each process were analyzed and compared to competitive techniques to ensure that those techniques with the most potential benefit were developed.

A Pipeline Cost Calculator developed for PRCI allowing the use of GMAW procedures for root passes and fill passes was used to analyze costs of various pipeline welding root pass and fill pass technologies.

5.0 Results

The Pipeline Cost Calculator "PRCI Productivity and Economic Estimation Tool for Mechanised GMAW Welding of Pipelines" developed for PRCI was used to calculate costs for single-torch GMAW, tandem GMAW, and hybrid laser beam welding (LBW)/GMAW for three pipe sizes.

The Cost Calculator really only caters for GMAW procedures for root passes and fill passes, so is only partially useful to analyze costs of various pipeline welding root pass and fill pass technologies. However, it was used to give some indication of relative costs between different welding processes.

The cost calculator was used for four cases as noted below:

1. A baseline case for 52-in. pipe using internal root pass welding and dual-tandem GMAW fill.

2. A 24-in.-diameter pipeline using copper shoes for GMAW root pass (double down) and dual-tandem GMAW fill.

3. The LBW/GMAW external root pass case for 36in X80 pipe (single orbital head) with dual tandem GMAW fill.

4. The rotating electrode GMAW (GMAW-RE) external root pass case for 36-in. X80 pipe (double down) and dual-tandem GMAW fill.

The results are presented in Appendix A. Attention is drawn to a comparison of the data for the "joints per day" (JPD) average productivity (70% of theoretical maximum). This number was multiplied by a normalizing factor chosen to take into account the joint volume required to complete each joint for the different pipe diameters, based on the 36-in. pipe diameter, and expressed as JPDn. Based on this comparison, the following joint completion rates are derived.

1.	Baseline case for 52-in. pipe	(internal root)	99 JPD	148 JPDn
2.	24-in.-diameter pipeline	(copper shoes)	81 JPD	61 JPDn
3.	LBW/GMAW root pass case for 24-in. pipe	(external root)	112 JPD	84 JPDn
4.	GMAW-RE root pass case for 36-in. pipe	(external root)	74 JPD	74 JPDn

These numbers show internal root pass welding to be the most productive, appreciating that external root pass welding is required for smaller pipe sizes. For small pipe sizes the normalized results show both LBW/GMAW and GMAW-RE to be more productive that external roots on copper shoes. Of course, these “raw numbers” need to be put in the perspective of the overall cost of capital equipment cost differentials, especially for the LBW/GMAW case.

A useful summary of laser welding costs, comparing CO_2, Nd:YAG, fiber, and disc lasers was presented at ICALEO 2004.(1)

Present cost for IPG fiber lasers is as follows:

- 4-kW nominal power: $500,000
- 8-kW nominal power: $800,000

Laser costs are coming down a little, but not at a significant rate in real terms, especially for newer technology such as fiber lasers.

Other items that will be required include the following:

- Laser optics package (collimator and optics, no spares): $9,000
- Armored fiber optic delivery cable for fiber laser: $15,000
- Hybrid welding head: $60,000

Additional items which should be considered are:

- **Size of Equipment** – The amount of space the equipment takes up can be an issue. The fiber laser being about 1/5th the size is a plus.

- **Power Consumption** – The fiber laser is 25% electrically efficient.

- **Utilities** – The fiber laser only needs 480 V at 80 A (or less) which may be available already.

- **Cost of Diodes** – There is an expected life of 25,000 hr for the diodes in a fiber laser. There is a cost savings in materials and in labor for the change out which is summarized in Figure 1 and Ref. 1.

- **Laser Safety Enclosure** – The enclosure must assure eye safety for passing/proximate personnel. Black plastic paneling and laser-safe glass (for the 1.03/1.06-µm beam wavelength) must be used. The cost differential between a standard welding tent and a laser safe enclosure must be considered.

The productivity and economic trade-offs for faster welding speeds on pipeline girth welds need to be traded against the costs of weekly or monthly equipment rental required for each welding station on a pipe lay operation. For example:

- Trenching
- Crane to put next pipe in the trench
- Crane to put welding tent on the next joint
- The cost of welding contractor personnel and equipment based on the number of welding stations
- Any other equipment needed for such things as nondestructive evaluation (NDE) vehicle.

The benchmark is the typical total weekly or monthly equipment cost for a pipe spread using X80 pipe based on manual welding of the root and single-torch GMAW mechanized welding of the hot, fill, and cap passes using a double-down technique. X80 pipe from the Cheyenne Project was used in this project, so the number of welding stations and associated equipment rental costs for that project would be a useful benchmark too.

6.0 Discussion

High-speed pipe root pass welding increases the rate at which subsequent, hot fill, and cap passes need to be completed to keep up with the root pass process.

The aim was to achieve a welding speed of 1.5 m/min or better, so that the overall rate of pipeline welding is not restricted by the welding speed for the root pass. A fixed time is necessary to attach, align, and clamp a new section of pipe for welding, typically 2 to 3 min. Hence, there is there is little incentive to reduce the welding time below about 1 min. However, there is a very strong incentive to be able to make the pipe root weld from the outside of the pipe with mechanized welding, without using a copper backing bar inside the pipe, and to at least achieve a welding speed of 1.5 m/min.

The results are very significant in terms of their potential application to pipeline welding. Very high welding speeds of 1.5 m/min can be achieved with a large value of root face, up to 8 mm using hybrid LBW/GMAW for example. This outcome is desirable, since a high thickness root run reduces the number of subsequent fill passes. Extremely high weld speeds of 4 m/min can be achieved for low values of root face (0 and 1 mm).

To put these results in perspective, the time taken for a complete root run with one laser in a 24-in.-diameter pipe would be 77 sec at 1.5 m/min and 29 sec at 4 m/min. These values easily exceed those required to achieve optimum performance. A fixed time is necessary to attach, align, and clamp a new section of pipe for welding, typically 2 to 3 min and hence any welding speed in excess of 1.5 m/min will provide high productivity. The corresponding time for GMAW-RE using two torches in a double-down configuration at the 1. 9 m/min root pass completion rate (two torches at 0.95 m/min average speed) is 60 sec for a 24-in. pipe.

For Task 2, a high root face thickness of 6 mm was chosen, so that at least some of the laser weld would remain, and would be capable of influencing the mechanical property tests of the completed weld. This also allowed the weld to be completed in 19.5-mm pipe material in only four passes using the tandem GMAW process. The overall deposition rate of the process was high at 10.8 kg/hr (23.7 lb/hr).

Laser and laser hybrid root welds can be made with excellent weld quality and surface profile, together with very high productivity in X100 pipe material. Welds can be made with a 6-mm root throat thickness at 1.5 m/min and with a 4-mm throat thickness at 4 m/min. These welding speeds easily exceed the requirement for high productivity root welding, corresponding to a total root welding time of 77 and 29 sec, respectively, for a single laser head welding the root of a 24-

in. pipe. This would equate to 116 and 44 sec, respectively, for a 36-in.-diameter X80 pipe. Using two GMAW-RE heads for double-down welding at an average travel speed for each of 0.95 m/min would equate to a root pass welding times of 168 sec for a 36-in.-diameter pipe.

While the throat thickness and travel speed achieved with the hybrid fiber laser/GMAW equipment is impressive, it must be borne in mind that the capital equipment cost of the system is about $1M. This should be compared to two single-torch GMAW systems at a cost of about $50K.

The main outcome of the hybrid laser/GMAW work was that satisfactory laser and laser hybrid root welds can be made for a range of root face dimensions and welding conditions as follows:

- 18-degree preparation angle, 0-mm root face – welding speed of 4m/min at 4-kW laser power, and 5-kW arc power.

- 12-degree preparation angle, 1-mm root face – welding speed of 4 m/min at 5-kW laser power and 7.4-kW arc power.

- 45-degree preparation angle, 6-mm root face – welding speed of 1.5 m/min at 7.6-kW laser power.

- 45-degree preparation angle, 8-mm root face – welding speed of 1.4 m/min at 7.8-kW laser power.

The speeds achieved easily exceed the objective of 1.5 m/min and, in fact, it is possible to achieve 4-m/min welding speed with only 4-kW laser power. The productivity (and cost) of the overall welding system depends on the precise combination of laser power, arc power, and root throat thickness.

The use of laser root passes was shown to produce acceptable mechanical properties in X100 pipe material and can be extrapolated to X80 pipe. A 4-mm root face and a 4-m/min travel speed is recommended since one laser would be used to make the root pass, equivalent to 2-m/min travel speed with a two torch double-down procedure currently employed.

It was decided that a high weld root face of 6 mm should be used as basis for the GMAW fill weld to be made under Task 2, since this would provide a significant volume of laser melted weld metal, which could be evaluated during mechanical property testing.

Welding speed of 0.8 to 1.2 m/min for a single torch equates to 1.6 to 2.4 m/min for a double-down welding approach with one torch on each side of the joint. This compares favorably to the 1.4- to 4.0-m/min travel speed using laser or laser/GMAW with one torch when the comparative capital costs of the respective systems are considered. The system cost for an 8-kW fiber laser is about $1M whereas the cost for a dual-torch GMAW-RE system is less than $100K.

Although travel speeds of 1.3 m/min were achieved for the variable polarity GMAW (GMAW-VP) root pass on a closed root girth weld, feedback from industrial sponsors of the GSP was that the root face of 1 mm was too small based on the likelihood of damage in handling the pipe by crane and impacting the joint preparation on the section of pipe to which it was to be butted prior to fit-up in the pipe trench. A 1.6-mm (±0.2 mm) root face yielding a minimum of 1.4 mm was considered appropriate.

Interested parties at the DoT project kick-off meeting had agreed that a 1.0-mm root face, albeit small, could be considered with more careful pipe handling and fit-up. It was considered likely that more careful handling could be achieved for offshore fabrication, but unlikely for cross-country pipelines.

6.1 Commercialization

BP and TCPL are recognized leaders in pipeline technology and pipeline reliability and over the last 10 years have invested between them over $10M to assess, develop, and implement X100 pipelines. BP and TCPL have established an international R&D network of over 20 organizations to support them develop X100 pipeline technology. TCPL recently installed a small test loop from X100 pipe to gain experience with design, field construction, and operating practices. BP is currently evaluating X100 for the Alaskan Gas Pipeline Project.

Serimer-Dasa North America needs single-sided welding technology for building offshore pipelines where operating pressures and fatigue requirements demand smooth weld root profiles and high integrity. They have agreed to test and deploy the preferred welding processes if it can meet these quality objectives.

The optimized welding processes developed in this project will provide TCPL, BP, Serimer-Dasa and others with a robust method for small- to medium-diameter pipelines in the field. The process is available for immediate commercialization as Serimer-Dasa makes and leases welding systems and has agreed to commercialize and deploy the preferred process. Serimer-Dasa supplies onshore pipeline activities as well as deepwater installation contractors.

7.0 Conclusions from Pipe Root Pass Welding with GMAW-RE and LBW

Based on the work reported here for GMAW procedure development on X80 pipe material, and laser or hybrid laser/GMAW work on X100, the following conclusions can be stated:

1. The GMAW process showing the most promise for high-speed mechanized root pass welding was the GMAW-RE, known as Spin Arc.

2. Welding procedures were developed for welding in the 5G position using the double-down technique, but using only a single torch for the development work.

3. Welding speeds up to 1.5 m/min were used in the vertical down position, but the combination of pipe metallurgy, elongated teardrop weld pool shape, and the requirements of achieving full penetration with a reasonable throat thickness, consistently resulted in centerline solidification cracking.

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   - Flat position – Weld SA-134
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Trials were conducted with this wire to develop tolerance to root face mismatch and the results showed the procedure to be tolerant to 1.5 mm of mismatch with good penetration and root face profile, in both the flat and vertical-down positions.

5. For hybrid LBW/GMAW the speeds achieved easily exceed the objective of 1.5 m/min and, in fact, it is possible to achieve 4-m/min welding speed with only 4-kW laser power, when used in a hybrid configuration with 5 kW of GMAW arc power. The productivity (and cost) of the overall welding system depends on the precise combination of laser power, arc power, and root throat thickness.

6. The economic case for using an 8-kW fiber laser and associated equipment versus the case for two GMAW-RE torches for the root pass needs to be considered. While the 6- to 8-mm throat thickness and travel speed achieved with the hybrid fiber laser/GMAW equipment is impressive, it must be borne in mind that this requires 8-kW laser capability, and that the capital equipment cost of the laser alone is close to $1M. This should be compared to a single-torch GMAW system at a cost of about $50K, for a two torch double-down configuration, which can produce a throat thickness for the root pass of 4 to 5.5 mm.

7. Ultimately, the cost effectiveness of a mechanized pipe welding system depends on the pipe material and wall thickness, and the length of the pipeline in addition to the other items discussed here. There is nota single solution for all cases. Ultimately, the ability to finish a project ahead of schedule with the concomitant cost savings for equipment rental and labor may be an overriding factor in determining which form of process and mechanization is the most cost effective.

8.0 Recommendations

Based on the work and conclusions above, the GMAW-RE technique is recommended as the best for further work toward field deployment for root passes with GMAW in terms of economic grounds based on the high cost of the 8-kW fiber laser system.

9.0 Future Work

The following areas for future work are considered worthwhile:

1. Further development of hybrid laser/GMAW to weld out of position for 5G girth welding.

2. Further development of the pipeline cost calculator allowing the use of laser and laser/GMAW welding procedures for root passes and fill passes.

10.0 References

1. Ream, S., "Laser Welding Efficiency and Costs: CO_2, YAG, Fiber, and Disc", Proceedings of the 23rd International Congress on Applications of Lasers and Electro-Optics (ICALEO), San Francisco, CA (Oct. 4-7, 2004).

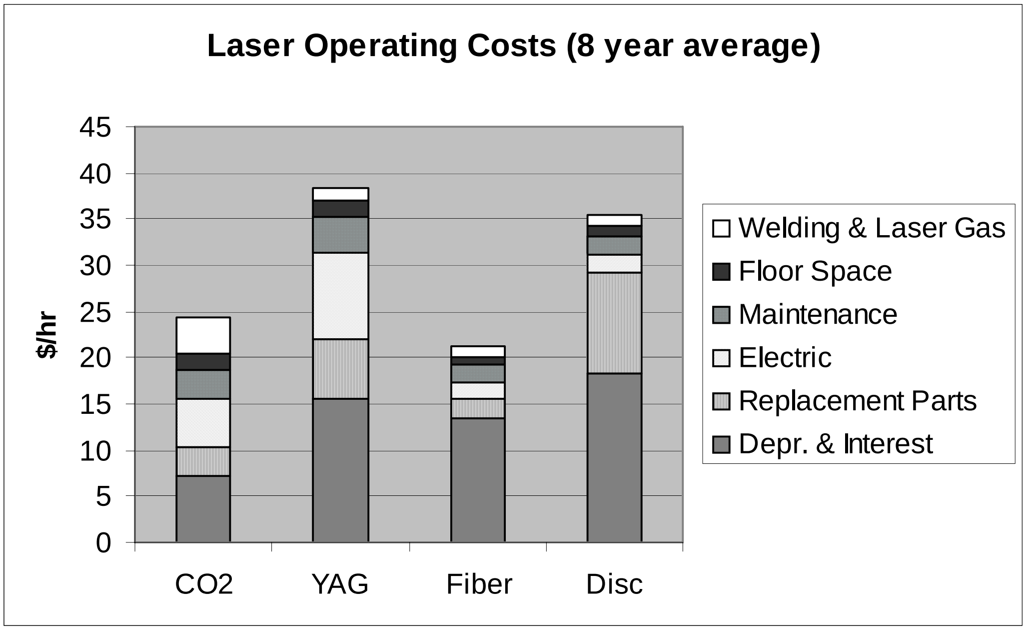

Figure 1. Laser Operating Cost Summary

Appendix A

Results from use of the PRCI Cost Calculator

Baseline Case

PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

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Summary 1

Pipeline Construction Type	Onshore

Pipeline Details

Pipeline Length	3200	km		
Pipeline Diameter	1321	mm	52	inch
Pipeline Wall Thickness	23	mm	0.906	inch
Pipe Unit Length	12.2	m	40	ft
Pipe Multi-Jointed?	double			
Total Number of Welds	131147.5			

Welding Process

Root Pass Method	Internal Welding Machine
Fill/Cap Pass Method	Dual Tandem-Wire External Bug

Number of Passes

Root	Hot	Fill	Cap
1	1	6	1

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PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

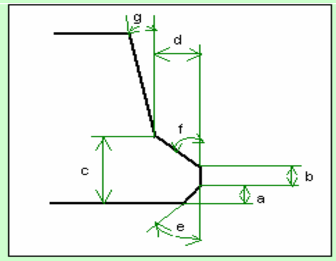
Cranfield UNIVERSITY

Summary 2

Joint Design

Values (distance in mm, angle in degree)	
a	1.3
b	1.3
c	5.9
d	3.3
e	37.5
f	45
g	5

Groove Area	**151**	mm^2
Groove Volume	**6.E+05**	mm^3
Weld Metal Weight / Weld	**4.9**	Kg



Welding Parameters

Run	Run 1	Run 2		Fill Run		Cap Run	
Pass	Root	Hot	Fill	Fill	Fill	Cap	Cap
Travel Speed (mm/min)	760	900	900	900	900	900	900
Wire Type							
Wire Diameter (mm)	0.9	1	1	1	1	1	1
Wire Feed Speed (mm/min)	9652	9500	8000	9500	8000	8200	8200
Wire Cost / Kg							
Total Weight of Wire (Kg)	46959	24053	20255	72160	60766	20762	20762
Total Cost of Wire				0			
Gas Mixture							
Gas Flow (L/min)	41	25	25	25	25	25	25
Gas Cost / L							
Total Volume of Gas (103 L)	39943	10267	10267	66733	30800	10267	10267
Total Cost of Gas				0			
Total Number of Runs	1	1		3		1	
Number of Bugs / Run	8	2		2		2	

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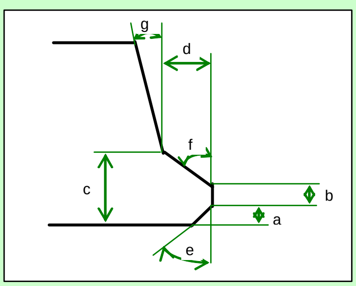

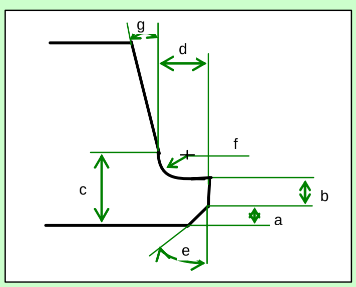

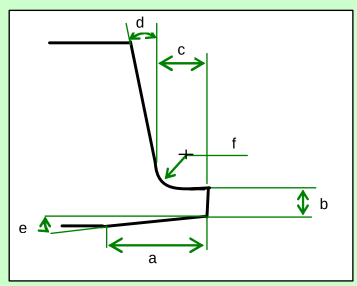

PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

Cranfield UNIVERSITY

Summary 2

Joint Design

Values (distance in mm, angle in degree	
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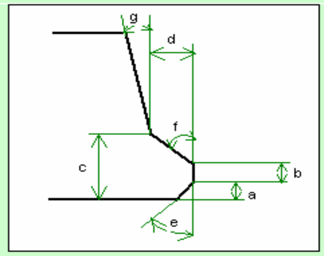
d	3.3
e	37.5
f	45
g	5



Groove Area	**151**	mm^2
Groove Volume	**625118**	mm^3
Weld Metal Weight / Weld	**4.9**	Kg

Welding Parameters

Run	Root Run	Hot/Fill Run				Fill Run				Cap Run			
Wire	1	1	2	1	2	1	2	1	2	1	2	1	2
Travel Speed (mm/min)	760	1300				1300				1300			
Wire Type													
Wire Diameter (mm)	0.9	1	1	1	1	1	1	1	1	1	1	1	1
Wire Feed Speed (mm/min)	9652	13000	13000	12000	12000	12000	12000	12000	12000	8000	8000	8000	8000
Wire Cost / Kg	0	0	0										
Total Weight of Wire (Kg)	46959	22798	22798	21045	21045	52611	52611	52611	52611	14030	14030	14030	14030
Total Cost of Wire	0												
Gas Mixture													
Gas Flow (L/min)	41	35	35	35	35	35	35	35	35	35	35	35	35
Gas Cost / L	0	0											
Total Volume of Gas (103 L)	39943	9956	9956	9956	9956	24889	24889	24889	24889	9956	9956	9956	9956
Total Cost of Gas	0												
Total Number of Runs	1	1				3				1			
Number of Bugs / Run	8	2				2				2			

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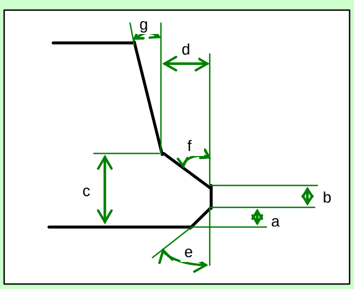

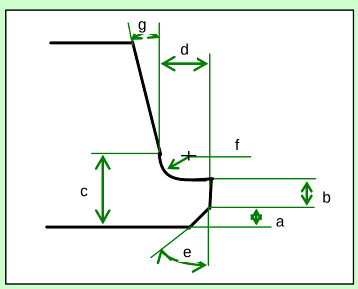

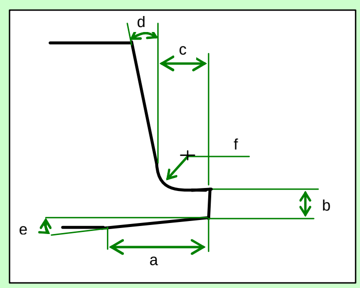

PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

Cranfield UNIVERSITY

Summary 3

Productivity Assessment

1st Welding Station (for indication only)

Constants	seconds	minutes
Pipe Alignment	60	1
Delay to Set Welding Heads	10	0.17
Move Up Time Duration	50	0.83
Additional Time (total)	120	2

Total number of welding stations	6

Following Welding Stations (for indication only)

Constants	seconds	minutes
Positoning of Shelter	5	0.08
Welders in Position	5	0.08
Shelter Back in Position	5	0.08
Move Up Time Duration	27	0.45
Delay Between Bugs	10	0.17
Additional Time (total)	52	0.86

Pay Day	10	hours	Non-Productive Time	2	hours	Net Productive Time	8	hours

Pass	Root	Hot/Fill	Fill	Cap
Welding Cycle time (min)	**1.37**	**1.6**	**1.6**	**1.6**
Additional Time (min)	**2**	**0.86**	**0.86**	**0.86**
Total Cycle Time (min)	**3.37**	**2.46**	**2.46**	**2.46**

	Joints/day	Project Duration (days)
Maximum Theoretical Productivity	**142**	**313**

	%	Joints/day	Project Duration (days)
Maximum Efficiency	77	**109**	**408**
Average Efficiency	70	**99**	**449**
Minimum Efficiency	63	**89**	**499**

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24-in. Pipe Girth Weld

PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

Summary 1

Pipeline Construction Type	Onshore

Pipeline Details

Pipeline Length	3200	km		
Pipeline Diameter	610	mm	24	inch
Pipeline Wall Thickness	28.5	mm	1.122	inch
Pipe Unit Length	12.2	m	40	ft
Pipe Multi-Jointed?	double			
Total Number of Welds	131147.5			

Welding Process

Root Pass Method	Copper Internal Line-Up Clamp
Fill/Cap Pass Method	Single Torch External Bug

Number of Passes

Root	Hot	Fill	Cap
1	1	7	1

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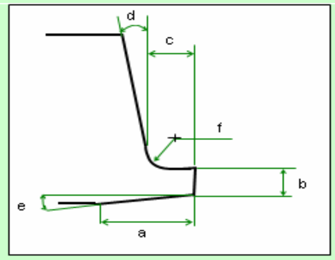
PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

Summary 2

Joint Design

Values (distance in mm, angle in degree)	
a	1.3
b	1.3
c	5.9
d	3.3
e	37.5
f	45
	0

Groove Area	151	mm^2
Groove Volume	3.E+05	mm^3
Weld Metal Weight / Weld	2.3	Kg



Welding Parameters

Pass	Root	Hot	1st Fill	ollowing Fil	Cap
Travel Speed (mm/min)	355	520	520	482	330
Wire Type					
Wire Diameter (mm)	1.2	1.2	1.2	1.2	1.2
Wire Feed Speed (mm/min)	4064	8382	8382	8382	8382
Wire Cost / Kg					
Total Weight of Wire (Kg)	51105	71830	71830	466116	113211
Total Cost of Wire			0		
Gas Mixture					
Gas Flow (L/min)	37	48	48	48	48
Gas Cost / L					
Total Volume of Gas (103 L)	52407	46332	46332	300653	73023
Total Cost of Gas			0		
Number of Stations / Pass	1	1	2	2	2
Total Number of Stations	1	1	2	12	2
Number of Bugs / Pass	2	2	2	2	2

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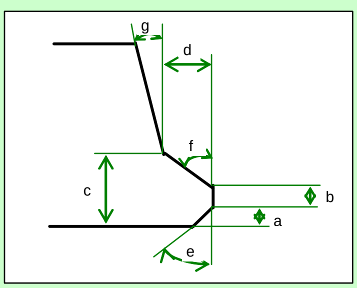
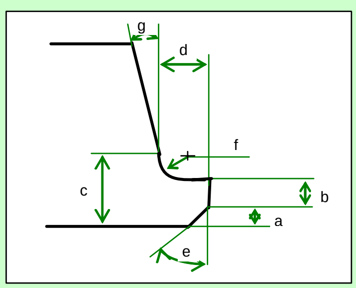
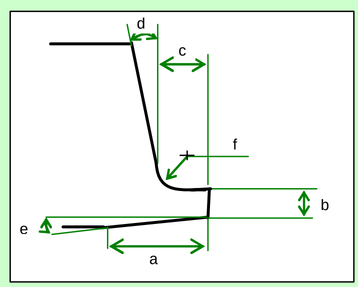






PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

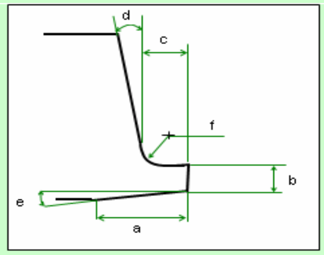
Cranfield UNIVERSITY

Summary 2

Joint Design

Values (distance in mm, angle in degree	
a	1.3
b	1.3
c	5.9
d	3.3
e	37.5
f	45
	0

Groove Area	**151**	mm^2
Groove Volume	**288662**	mm^3
Weld Metal Weight / Weld	**2.3**	Kg



Welding Parameters

Run	Root Run	Hot/Fill Run				Fill Run				Cap Run			
Wire	1	1	2	1	2	1	2	1	2	1	2	1	2
Travel Speed (mm/min)	760	1300				1300				1300			
Wire Type													
Wire Diameter (mm)	0.9	1	1	1	1	1	1	1	1	1	1	1	1
Wire Feed Speed (mm/min)	9652	13000	13000	12000	12000	12000	12000	12000	12000	8000	8000	8000	8000
Wire Cost / Kg	0	0	0										
Total Weight of Wire (Kg)	46959	22798	22798	21045	21045	52611	52611	52611	52611	14030	14030	14030	14030
Total Cost of Wire	0												
Gas Mixture													
Gas Flow (L/min)	41	35	35	35	35	35	35	35	35	35	35	35	35
Gas Cost / L	0	0											
Total Volume of Gas (103 L)	39943	9956	9956	9956	9956	24889	24889	24889	24889	9956	9956	9956	9956
Total Cost of Gas	0												
Total Number of Runs	1	1				3				1			
Number of Bugs / Run	8	2				2				2			

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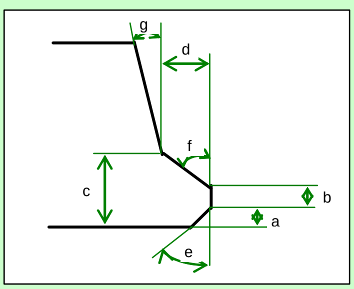

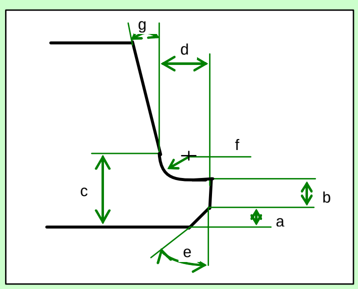

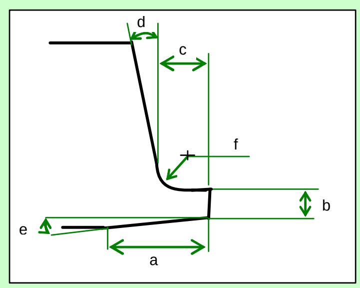

PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

Cranfield UNIVERSITY

Summary 3

Productivity Assessment

1st Welding Station (for indication only)

Constants	seconds	minutes
Pipe Alignment	60	1
Positoning of Shelter	5	0.08
Welders in Position	5	0.08
Shelter Back in Position	5	0.08
Move Up Time Duration	27	0.45
Delay Between Bugs	48	0.8
Additional Time (total)	150	2.49

Following Welding Stations (for indication only)

Constants	seconds	minutes
Positoning of Shelter	5	0.08
Welders in Position	5	0.08
Shelter Back in Position	5	0.08
Move Up Time Duration	27	0.45
Delay Between Bugs	48	0.8
Additional Time (total)	90	1.49

Total number of welding stations: 18

Pay Day: 10 hours — Non-Productive Time: 0 hours — Net Productive Time: 10 hours

Pass	Root	Hot Pass	1st Fill	ollowing Fil	Cap
Welding Cycle time (min)	**5.3**	**3.6**	**3.6**	**3.9**	**5.8**
Additional Time (min)	**2.49**	**1.49**	**1.49**	**1.49**	**1.49**
Total Cycle Time (min)	**7.79**	**5.09**	**2.55**	**2.7**	**3.65**

	Joints/day	Project Duration (days)
Maximum Theoretical Productivity	**77**	**3406**

	%	Joints/day	Project Duration (days)
Maximum Efficiency	77	**59**	**4446**
Average Efficiency	70	**54**	**4857**
Minimum Efficiency	63	**49**	**5353**

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36-in. Pipe Girth Weld Using LBW for the Root Pass

PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

Cranfield UNIVERSITY

Summary 1

Pipeline Construction Type	Onshore

Pipeline Details

Pipeline Length	3200	km		
Pipeline Diameter	610	mm	24	inch
Pipeline Wall Thickness	19.5	mm	0.768	inch
Pipe Unit Length	12.2	m	40	ft
Pipe Multi-Jointed?	double			
Total Number of Welds	131147.5			

Welding Process

Root Pass Method	Copper Internal Line-Up Clamp
Fill/Cap Pass Method	Tandem-Wire External Bug

Number of Passes

Root	Hot	Fill	Cap
1	1	2	1

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Cranfield University Welding Engineering Research Centre

PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

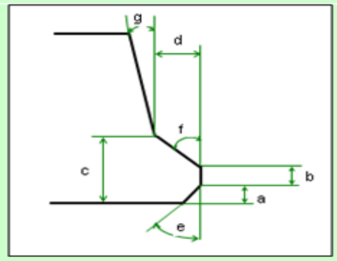
Cranfield UNIVERSITY

Summary 2

Joint Design

Values (distance in mm, angle in degree)	
a	1.3
b	1.3
c	5.9
d	3.3
e	37.5
f	45
g	5

Groove Area	**151**	mm^2
Groove Volume	**3.E+05**	mm^3
Weld Metal Weight / Weld	**2.3**	Kg



Welding Parameters

Pass	Root		Hot		Fill		Cap	
Wire	1	2	1	2	1	2	1	2
Travel Speed (mm/min)	1500		1500		1500		1500	
Wire Type								
Wire Diameter (mm)	1	1	1	1	1	1	1	1
Wire Feed Speed (mm/min)	14500	14500	14500	14500	14500	14500	14500	14500
Wire Cost / Kg								
Total Weight of Wire (Kg)	15007	15007	15007	15007	30014	30014	15007	15007
Total Cost of Wire	0							
Gas Mixture								
Gas Flow (L/min)	20	20	20	20	20	20	20	20
Gas Cost / L								
Total Volume of Gas (103 L)	3357	3357	3357	3357	6715	6715	3357	3357
Total Cost of Gas	0							
Total Number of Passes	1		1		1		1	
Number of Bugs / Pass	2		2		2		2	

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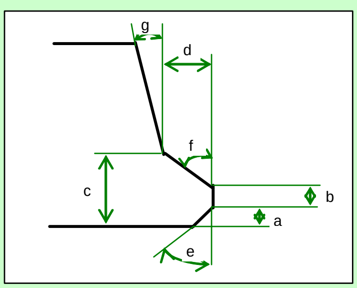
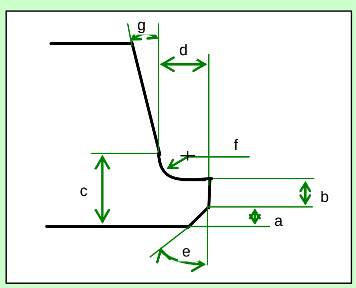
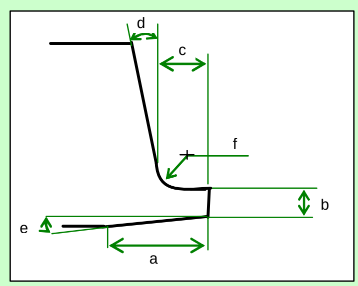






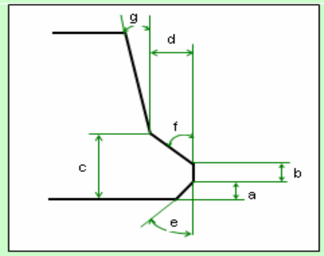
PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

Cranfield UNIVERSITY

Summary 2

Joint Design

Values (distance in mm, angle in degree	
a	1.3
b	1.3
c	5.9
d	3.3
e	37.5
f	45
g	5



Groove Area	**151**	mm^2
Groove Volume	**288662**	mm^3
Weld Metal Weight / Weld	**2.3**	Kg

Welding Parameters

Run	Root Run	Hot/Fill Run				Fill Run				Cap Run			
Wire	1	1	2	1	2	1	2	1	2	1	2	1	2
Travel Speed (mm/min)	760	1300				1300				1300			
Wire Type													
Wire Diameter (mm)	0.9	1	1	1	1	1	1	1	1	1	1	1	1
Wire Feed Speed (mm/min)	9652	13000	13000	12000	12000	12000	12000	12000	12000	8000	8000	8000	8000
Wire Cost / Kg	0	0	0										
Total Weight of Wire (Kg)	46959	22798	22798	21045	21045	52611	52611	52611	52611	14030	14030	14030	14030
Total Cost of Wire	0												
Gas Mixture													
Gas Flow (L/min)	41	35	35	35	35	35	35	35	35	35	35	35	35
Gas Cost / L	0	0											
Total Volume of Gas (103 L)	39943	9956	9956	9956	9956	24889	24889	24889	24889	9956	9956	9956	9956
Total Cost of Gas	0												
Total Number of Runs	1	1				3				1			
Number of Bugs / Run	8	2				2				2			

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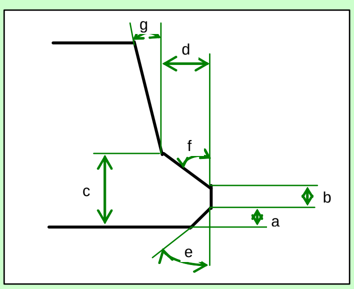

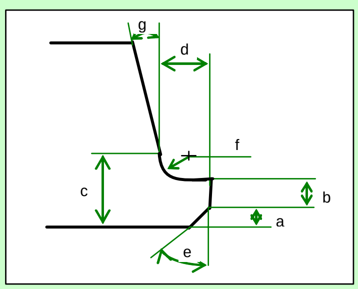

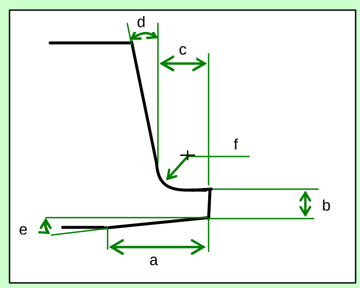

PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

Cranfield UNIVERSITY

Summary 3

Productivity Assessment

1st Welding Station (for indication only)

Constants	seconds	minutes
Pipe Alignment	60	1
Positoning of Shelter	5	0.08
Welders in Position	5	0.08
Shelter Back in Position	5	0.08
Move Up Time Duration	27	0.45
Delay Between Bugs	48	0.8
Additional Time (total)	150	2.49

Following Welding Stations (for indication only)

Constants	seconds	minutes
Positoning of Shelter	5	0.08
Welders in Position	5	0.08
Shelter Back in Position	5	0.08
Move Up Time Duration	27	0.45
Delay Between Bugs	48	0.8
Additional Time (total)	90	1.49

Total number of welding stations	4

Pay Day	10	hours
Non-Productive Time	0	hours
Net Productive Time	10	hours

Pass	Root	Hot	Fill	Cap
Welding Cycle time (min)	**1.27**	**1.27**	**1.27**	**1.27**
Additional Time (min)	**2.49**	**1.49**	**1.49**	**1.49**
Total Cycle Time (min)	**3.76**	**2.76**	**2.76**	**2.76**

	Joints/day	Project Duration (days)
Maximum Theoretical Productivity	**160**	**410**

	%	Joints/day	Project Duration (days)
Maximum Efficiency	77	**123**	**533**
Average Efficiency	70	**112**	**585**
Minimum Efficiency	63	**101**	**649**

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Cranfield University Welding Engineering Research Centre

36-in. Pipe Girth Weld Using GMAW-RE for the Root Pass

PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

Summary 1

Pipeline Construction Type	Onshore

Pipeline Details

Pipeline Length	3200	km		
Pipeline Diameter	914	mm	36	inch
Pipeline Wall Thickness	17	mm	0.669	inch
Pipe Unit Length	12.2	m	40	ft
Pipe Multi-Jointed?	double			
Total Number of Welds	131147.5			

Welding Process

Root Pass Method	Copper Internal Line-Up Clamp
Fill/Cap Pass Method	Tandem-Wire External Bug

Number of Passes

Root	Hot	Fill	Cap
1	1	2	1

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Cranfield University Welding Engineering Research Centre

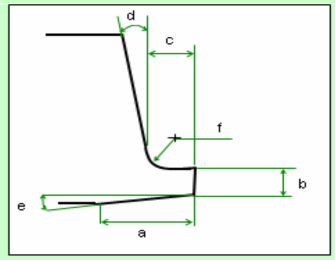
PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

Summary 2

Joint Design

Values (distance in mm, angle in degree)	
a	5
b	2.1
c	5.9
d	3.3
e	37.5
f	45
	0

Groove Area	151	mm^2
Groove Volume	4.E+05	mm^3
Weld Metal Weight / Weld	3.4	Kg



Welding Parameters

Pass	Root		Hot		Fill		Cap	
Wire	1	2	1	2	1	2	1	2
Travel Speed (mm/min)	900		1500		1500		1500	
Wire Type								
Wire Diameter (mm)	1	1	1	1	1	1	1	1
Wire Feed Speed (mm/min)	11607	11607	14500	14500	14500	14500	14500	14500
Wire Cost / Kg								
Total Weight of Wire (Kg)	30032	30032	22511	22511	45021	45021	22511	22511
Total Cost of Wire	0							
Gas Mixture								
Gas Flow (L/min)	20	20	20	20	20	20	20	20
Gas Cost / L								
Total Volume of Gas (103 L)	8393	8393	5036	5036	10072	10072	5036	5036
Total Cost of Gas	0							
Total Number of Passes	1		1		1		1	
Number of Bugs / Pass	2		2		2		2	

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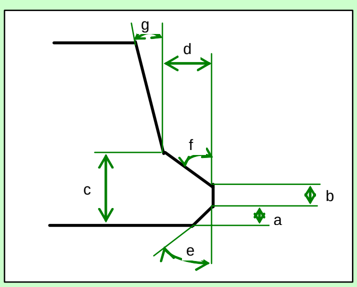
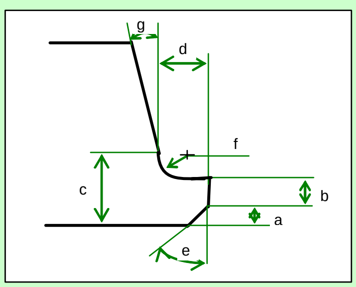
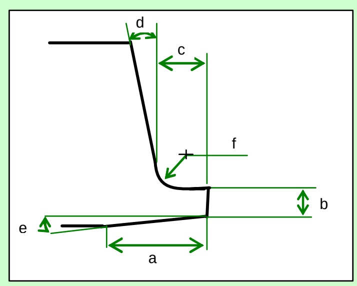






PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

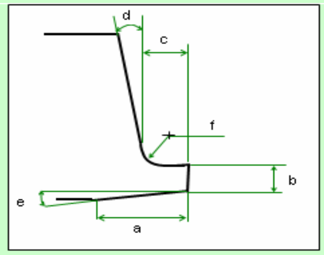
Cranfield UNIVERSITY

Summary 2

Joint Design

Values (distance in mm, angle in degree)	
a	5
b	2.1
c	5.9
d	3.3
e	37.5
f	45
	0

Groove Area	**151**	mm²
Groove Volume	**432519**	mm³
Weld Metal Weight / Weld	**3.4**	Kg



Welding Parameters

Run	Root Run	Hot/Fill Run				Fill Run				Cap Run			
Wire	1	1	2	1	2	1	2	1	2	1	2	1	2
Travel Speed (mm/min)	760	1300				1300				1300			
Wire Type													
Wire Diameter (mm)	0.9	1	1	1	1	1	1	1	1	1	1	1	1
Wire Feed Speed (mm/min)	9652	13000	13000	12000	12000	12000	12000	12000	12000	8000	8000	8000	8000
Wire Cost / Kg	0	0	0										
Total Weight of Wire (Kg)	46959	22798	22798	21045	21045	52611	52611	52611	52611	14030	14030	14030	14030
Total Cost of Wire	0												
Gas Mixture													
Gas Flow (L/min)	41	35	35	35	35	35	35	35	35	35	35	35	35
Gas Cost / L	0	0											
Total Volume of Gas (103 L)	39943	9956	9956	9956	9956	24889	24889	24889	24889	9956	9956	9956	9956
Total Cost of Gas	0												
Total Number of Runs	1	1				3				1			
Number of Bugs / Run	8	2				2				2			

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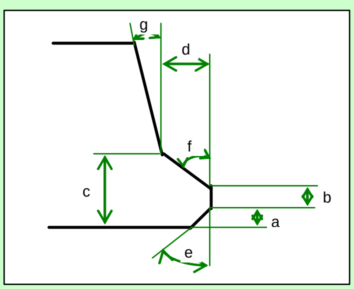

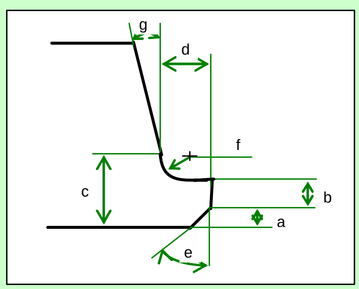

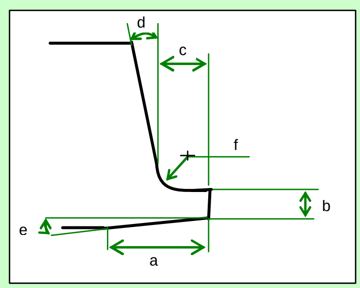

PRCI Productivity and Economic Estimation Tool For Mechanised GMAW Welding of Pipelines

Summary 3

Productivity Assessment

1st Welding Station (for indication only)

Constants	seconds	minutes
Pipe Alignment	60	1
Positoning of Shelter	5	0.08
Welders in Position	5	0.08
Shelter Back in Position	5	0.08
Move Up Time Duration	27	0.45
Delay Between Bugs	48	0.8
Additional Time (total)	150	2.49

Following Welding Stations (for indication only)

Constants	seconds	minutes
Positoning of Shelter	5	0.08
Welders in Position	5	0.08
Shelter Back in Position	5	0.08
Move Up Time Duration	27	0.45
Delay Between Bugs	48	0.8
Additional Time (total)	90	1.49

Total number of welding stations: 4

Pay Day: 10 hours | Non-Productive Time: 0 hours | Net Productive Time: 10 hours

Pass	Root	Hot	Fill	Cap
Welding Cycle time (min)	**3.19**	**1.91**	**1.91**	**1.91**
Additional Time (min)	**2.49**	**1.49**	**1.49**	**1.49**
Total Cycle Time (min)	**5.68**	**3.4**	**3.4**	**3.4**

	Joints/day	Project Duration (days)
Maximum Theoretical Productivity	**106**	**619**

	%	Joints/day	Project Duration (days)
Maximum Efficiency	77	**82**	**800**
Average Efficiency	70	**74**	**886**
Minimum Efficiency	63	**67**	**979**

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