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IDENTIFICATION OF KEY GMAW FILLET WELD PARAMETERS AND INTERACTIONS USING ARTIFICIAL NEURAL NETWORKS

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Abstract

Fillet welds are one of the most commonly used weld joints but one of the most difficult to weld consistently. This paper presents a technique using Artificial Neural Networks (ANN) to identify the key Gas Metal Arc Welding (GMAW) fillet weld parameters and interactions that impact on the resultant geometry, when using a metal cored wire. The input parameters to the model were current, voltage, travel speed; gun angle and travel angle and the outputs of the model were penetration and leg length. The model was in good agreement with experimental data collected and the subsequent sensitivity analysis showed that current was the most influential parameter in determining penetration and that travel speed, followed closely by current and voltage were most influential in determining the leg length. The paper also concludes that a 'pushing' travel angle is preferred when trying to control the resultant geometry mainly because both the resultant leg length and penetration appear to be less sensitive to changes in heat input.

Introduction

Presently there is no economic technology available to accurately measure the actual internal geometry of a fillet weld without destructively testing the work piece. The external geometry of a fillet weld can be measured easily using specifically designed gauges, but the internal characteristics, such as penetration cannot be measured as easily. Penetration is critical in determining the structural integrity of a fillet weld to ensure that the axis between the bar and the plate is effectively 'cut'. In order to guarantee satisfactory penetration and weld geometry it is imperative that a high level of control of the welding parameters can be demonstrated. Over the years there have been numerous studies [1, 3 & 4] proving that the ability to predict weld geometry is related to the level of control of the parameters. Miller [1] reported that tight control of electrode placement; fit-up, welding position and welding procedures are required to ensure repeatability. Initial investigations would seem to indicate that increasing stick out increases spatter but reduces penetration and the width of the weld bead. There are also studies [12,22] which demonstrate that alternating the shielding gas can have a positive effect on the level of weld penetration whilst reducing leg length and also that the shielding gas flow rate can be reduced substantially without impacting the overall coverage and quality of the weld. Tham et al [3] also demonstrated the correlation between the welding parameters and the resultant bead geometry.

Welder	**Current (A)**	**Volts (V)**	**Heat Input (kJ/mm)** **Assumed average travel speed 400mm/min**
1	204	20.8	0.636
5	224	22.1	0.743
6	238	19.8	0.707
7	236	22	0.779
8	212	21.5	0.684
10	234	22.9	0.804
12	240	24.8	0.893
15	229	24.4	0.838
18	224	22.8	0.766
19	215	24.6	0.793
Average	225.6	22.57	0.764

Min	204	19.8	0.636
Max	240	24.8	0.893
Variation (%)	15.0%	20.2%	28.7%

Table 1: Variation in parameter settings for manual welding

Table 1 shows the results of a short study of a number of welders showing the parameters they used to complete a series of downhand fillet welds. The variation seen in this study highlights that even within a group of experienced welders there is a high level of variation of the input parameter settings for a relatively simple fillet weld arrangement. There have been numerous papers written and studies undertaken on the subject of controlling GMAW weld parameters and resultant geometry however as figure 1 shows, the large number of input parameters and variables (this list is indicative not exhaustive) makes it extremely challenging to understand exactly what impact the variation each of the inputs (and their interactions with each other) has on the resultant fillet weld. The impact of this variation will be discussed later. However, in order to maintain consistent quality fillet welds it is critical to understand the extent to which each of these input parameters (and their interactions) affect the resultant outputs. Furthermore if a robust process control model can be developed that can demonstrate tight control of the parameters and interactions that affect the joint geometry, then confidence can be increased that sufficient penetration and leg length is being achieved whilst heat input and distortion is minimised. This paper details the 1st stage of a wider scope of work which will focus on understanding how the input parameters in figure 1 interact and impact the resultant fillet weld geometry. One of the key goals of this research is ultimately to provide guidance on parameter control to ensure that all automated welding is carried out consistently. This paper however will deal specifically with understanding the impact and interactions the following parameters: current voltage, travel speed, travel angle and gun angle, have on the resultant fillet weld geometry (leg length and penetration).

There are many sources of guidance on input parameter selection for GMAW, in both academic and industrial publications. However on closer inspection the wealth of guidance on offer can be confusing and at times contradictory. The following examples, taken from a mixture of supplier's websites, technical documentation and academic publications, highlight the level of variation and the complexities involved in trying to identify exactly what the optimum gun and travel angles are for GMAW fillet welding. Miller Electric [6] advise that a 'pushing' (+ve) travel angle produces less penetration and a flatter bead (so conversely a 'pulling' (-ve) travel angle produces a deeper/narrower bead). Miller Electric [6] also advises using a travel angle of 5°-15° because increasing to greater than 20°-25° creates more spatter, less penetration and is consequently less stable. Similar advice can be found from Esab's online handbook where a backhand (pulling) technique is recommended to reduce spatter and produce a more stable arc. Esab also advise that a backhand technique increases penetration and bead width, whereas a forehand (pushing) technique reduces the penetration and bead width of the resultant weld. BOC [7] advises that for metal cored GMAW the travel angle should be 20°-30° (pushing). Harwig [8] advises that higher deposition rates can be achieved with a 15° 'pushing' travel angle, Bhattacharya [9] advises that in general 'pushing' reduces deposition efficiency, however Lincoln Electric [10] advise using a 'pulling' angle of between 20°-30°. The range of gun angles also varies depending on what publication is being referred to. Lincoln Electric [10] recommends using a gun angle of less than 45° and BOC [7] a gun angle range of 30°-40°. Tham et al [3] also conducted investigations using a fixed gun angle of 45°. The experiments detailed within this paper, with the aid of an ANN model aim to try and provide some clarity as to what guidance can be confidently applied to GMAW mild steel fillet joints (6mm).

Artificial Neural Networks (ANNs) are computing systems consisting of a collection of interconnected processing elements which are able to represent complex interactions between process inputs and outputs, such as that shown for fillet welding. During the model development a number of different network topologies were assessed including Multilayer Perceptron (MLP), Generalised Feed Forward (GFF) and Probabilistic Neural Network (PNN). As part of the model development the software produced a report comparing the accuracy of the different various network topologies. This report concluded that a Multi-Layer Perceptron (MLP) Model, with 5 inputs, 2 hidden layers and 3 output layers was the most accurate model and so was selected. ANN's can be used to predict the outputs to a process as long as sufficient data is created and fed in to train the model. The ANN can identify patterns, trends and interactions that are too complex to be detected by other existing methods and technologies. Bhadeshia [19] suggests that ANN's are ideal for determining welding process parameters such as penetration. ANN's which could accurately predict the penetration and internal geometry of a fillet joint would provide a great benefit by greatly reducing the cost (material and labour) or trialling and testing new welding procedures and processes.

The main benefits that ANN's provide are:

- They do not require any predefined relationship between the variables to be understood
- They allow patterns, trends and interactions to be identified that otherwise would be impossible to detect.
- They work well when there are a large number of diverse variables to analyse.
- They can be used and applied to a variety of problems (not specific to thermo-mechanical engineering related processes)
- They can be used to process symbolic data as well as numeric data.

There are however some important limitations in using MLP ANN models that need to be understood.

- They do not explain why patterns and/or interactions exist so it requires analyses and interpretation of the results
- They may not always find the optimal solution

- The model development requires an element of trial and error (trying different network topologies, iterations, number of layers…etc.) in order to try and create the most accurate model.

There are numerous examples of ANN's that have been developed to predict GMAW fillet weld geometries. [11-18] provide examples of ANN's that have been successfully developed using a subset of the input and output parameters shown in Figure 1. However there are no publications that investigate the impact of both travel angle and the gun angle (and their interactions) have on the resultant fillet weld geometry (horizontal leg length, vertical leg length and penetration). This paper will use ANNs to analyse the relationship/impact that the current, voltage, travel speed, torch travel angle and gun angle have on the resultant fillet weld geometry (leg length and penetration). It will also analyse if the interactions between these input parameters are significant in influencing the resultant weld geometry.

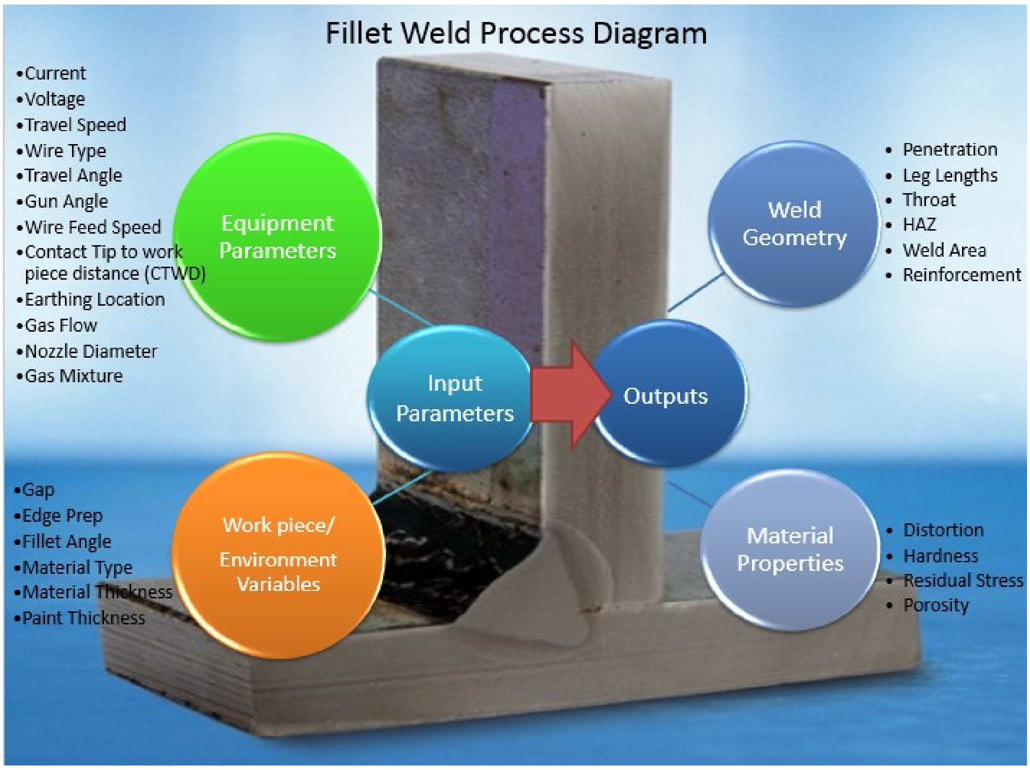


Figure 1: Fillet Weld Inputs and Outputs

Experimental Procedure

In total 97 test plates were welded on the rig (figure 2) at Strathclyde University using a customised jig to set the gun and travel angle. The jig was designed to allow the torch (gun) angle (figure 3) to be set at 5° increments from 35° - 50° relative to the horizontal base plate. The jig also allowed the torch travel angle (figure 4) to be set a 15° increments from -30°to +30° relative to the direction of travel.

Figure 2: Image of Welding Rig

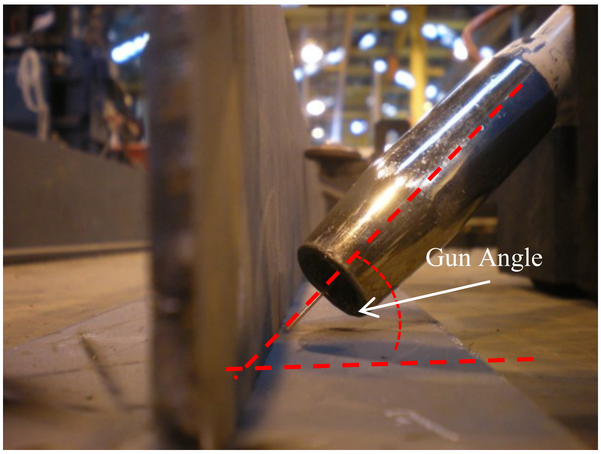


Figure 3: Diagram showing gun angle orientation

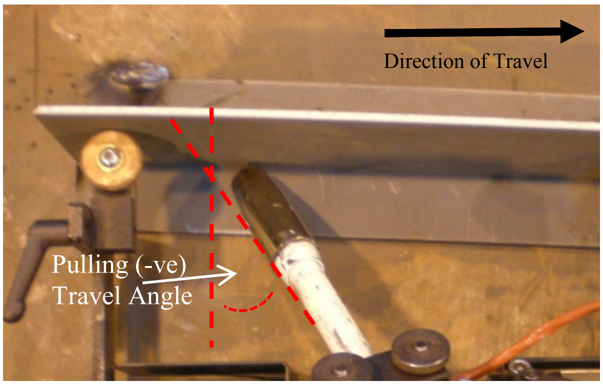


Figure 4: Diagram showing travel angle orientation

Each test piece consisted of two (100mm x 500mm x 6mm) primed DH36 grade steel test plates tack welded together at 90° to form a T-Joint. Magnetic aids were used to set the 90° fillet angle. Primed plates were used to best replicate production conditions and all the experimental plates were cut from the same primed steel plate in order to minimise the potential impact of the primer during the experiments. The impact of primer as a welding variable is out with the scope of this paper, however further investigation is planned to understand what impact the primer has on the stability of the arc and the resultant geometry. The welding process used was gas metal arc welding (GMAW) performed using 1mm diameter (NST MC-1) metal cored welding wire fed through a stationery straight necked torch suspended above the moving test piece. A pre-calibrated Portable Arc Monitoring System (PAMS) was connected to the equipment during the experiments to obtain accurate readings for the arc voltage and current.

Gun Angle (°)	35,40,45,50	Controlled using pre-set jig, checked and measured using magnetic inclinometer
Travel Angle(°)	-30, -15, 0, 15, 30	Controlled using pre-set jig (ve travel angle = pull, +ve travel angle = push)
Travel Speed (mm/min)	300,400, 500	Set using Matlab software connected to Welding Rig. Calibrated prior to each test run
Voltage (V)	21,24,26	Controlled using Miller Power Source and measured on calibrated PAMS unit
Current (A)	170, 220, 270	
Contact Tip to work distance (CTWD) (mm)	15	
Gap (mm)	0	
Wire Type	MC-1 (metal cored)	
Material	DH36 Mild Steel Primed Plate – Interplate 855 Grey	
Gas Flow (l/min)	18 l/min Measured using calibrated gas flow meter	
Shielding Gas	BOC Specshield 20% CO_2 / 80% Argon	
Nozzle Dia (mm)	16mm	
Plate Thickness (mm)	6mm	

Table 2: Experimental Parameters

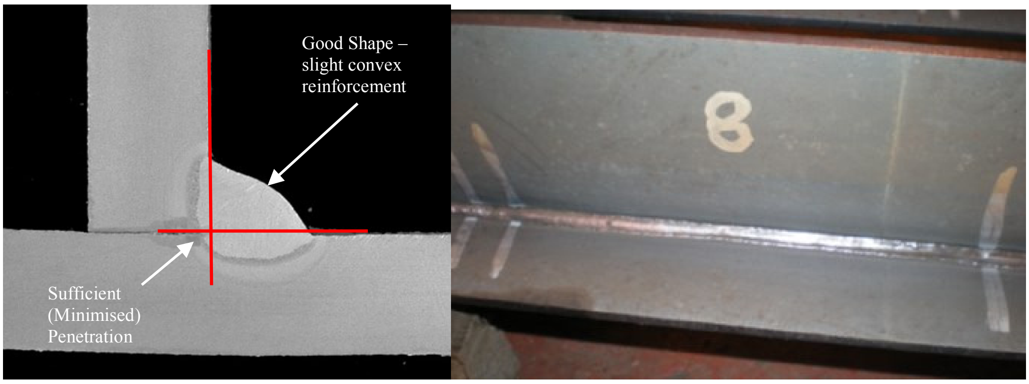


Figure 5: Macro image and photograph of acceptable fillet weld profile

All test pieces were single side welded in the downhand (2F) position. Table 2 shows the parameters that were varied and kept constant during the experiments. Once welded the test pieces were cut and macrographed (figure 5) so that the internal geometry of the weld could be photographed and then measured. Imaging software (ImageJ) was then used to measure the leg length and penetration, as identified below, from each sample. The weld geometry characteristics (figure 6) defined above were then reviewed against a combination of Lloyds' Register rules and regulations for Naval Ships [21] and local shipyard guidelines to assess whether or not they could be categorised as acceptable or not.

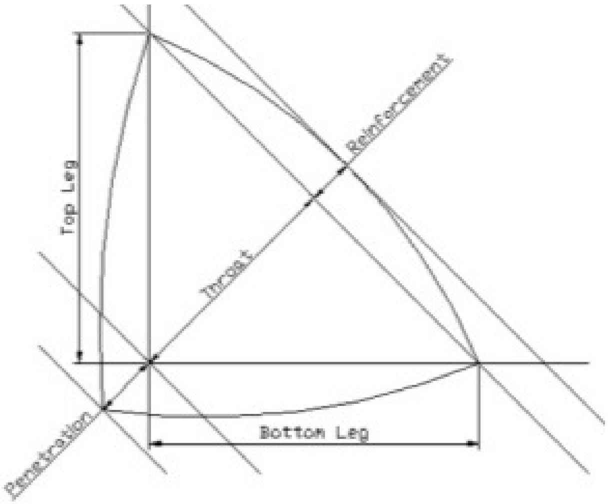
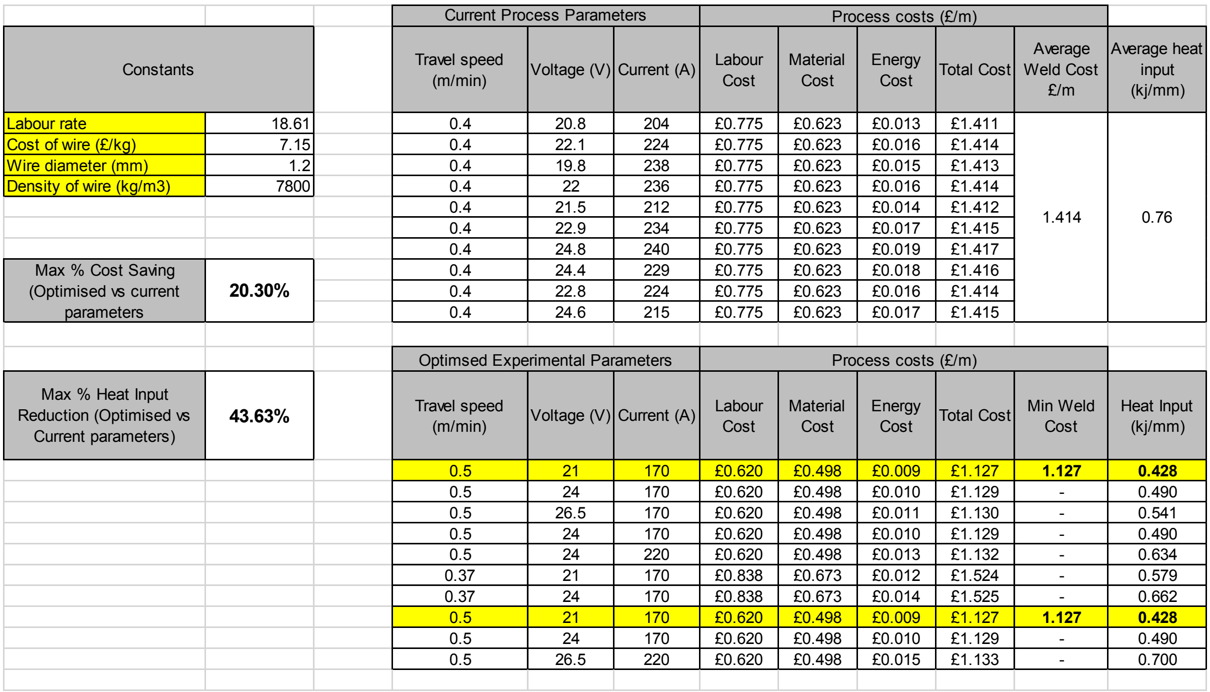


Figure 6: Key Fillet Weld Geometry

Results

Comparing the experimental results against the settings detailed in table 1 indicated that this level of parameter variation can cause the leg length and penetration of the resultant weld to vary by approximately 20% and 80% respectively. A simple cost model analysis (table 3) also highlighted that the fillet weld cost (labour + material) could be reduced by approximately 20% and the heat input by 44% simply by selecting and maintaining tight control of an optimal set of parameters. This 20% cost saving does not take into consideration any subsequent distortion related costs (i.e. Additional fairing, heat damage, rework….), so in real life production the cost savings associated with maintaining tight control of welding parameters could be much higher.



Constants	
Labour rate	18.61
Cost of wire (£/kg)	7.15
Wire diameter (mm)	1.2
Density of wire (kg/m3)	7800
Max % Cost Saving (Optimised vs current parameters	**20.30%**
Max % Heat Input Reduction (Optimised vs Current parameters)	**43.63%**

Current Process Parameters			Process costs (£/m)					
Travel speed (m/min)	Voltage (V)	Current (A)	Labour Cost	Material Cost	Energy Cost	Total Cost	Average Weld Cost £/m	Average heat input (kj/mm)
0.4	20.8	204	£0.775	£0.623	£0.013	£1.411	1.414	0.76
0.4	22.1	224	£0.775	£0.623	£0.016	£1.414		
0.4	19.8	238	£0.775	£0.623	£0.015	£1.413		
0.4	22	236	£0.775	£0.623	£0.016	£1.414		
0.4	21.5	212	£0.775	£0.623	£0.014	£1.412		
0.4	22.9	234	£0.775	£0.623	£0.017	£1.415		
0.4	24.8	240	£0.775	£0.623	£0.019	£1.417		
0.4	24.4	229	£0.775	£0.623	£0.018	£1.416		
0.4	22.8	224	£0.775	£0.623	£0.016	£1.414		
0.4	24.6	215	£0.775	£0.623	£0.017	£1.415		

Optimsed Experimental Parameters			Process costs (£/m)					
Travel speed (m/min)	Voltage (V)	Current (A)	Labour Cost	Material Cost	Energy Cost	Total Cost	Min Weld Cost	Heat Input (kj/mm)
0.5	21	170	£0.620	£0.498	£0.009	£1.127	**1.127**	**0.428**
0.5	24	170	£0.620	£0.498	£0.010	£1.129	-	0.490
0.5	26.5	170	£0.620	£0.498	£0.011	£1.130	-	0.541
0.5	24	170	£0.620	£0.498	£0.010	£1.129	-	0.490
0.5	24	220	£0.620	£0.498	£0.013	£1.132	-	0.634
0.37	21	170	£0.838	£0.673	£0.012	£1.524	-	0.579
0.37	24	170	£0.838	£0.673	£0.014	£1.525	-	0.662
0.5	21	170	£0.620	£0.498	£0.009	£1.127	**1.127**	**0.428**
0.5	24	170	£0.620	£0.498	£0.010	£1.129	-	0.490
0.5	26.5	220	£0.620	£0.498	£0.015	£1.133	-	0.700

Table 3: Fillet Weld Cost Model

ANN Model Development

Neurosolutions for Excel was used to develop the Artificial Neural Network (ANN). A total of 97 test pieces were analysed in order to develop the model. 72 samples were used to train the model and 25 for cross validating and testing the model. The input variables to the model were current, voltage, travel speed, travel angle and gun angle. The desired 'output' variables to the model were penetration, vertical leg length and horizontal leg length. The model was run 3 times in order to ensure acceptable levels of repeatability. The analysis concluded that a Multi-Layer Perceptron Model with 5 inputs (current, voltage, travel speed, gun angle and travel angle), 2 hidden layers and 3 output layers (horizontal leg length, vertical leg length and penetration) was the most accurate model and so was selected. Once the model had been trained and tested its ability to predict fillet weld leg length and penetration given input values for current, voltage, travel speed, gun angle and travel angle was further validated with some additional experimental data. Figure 7 shows the results of this validation. The results showed good overall agreement between the predicted and the actual outputs for both the vertical and horizontal leg length. There was also reasonable agreement between the predicted and actual outputs for penetration, however this would be expected due to the higher % error in measuring the relatively small sizes of penetration.

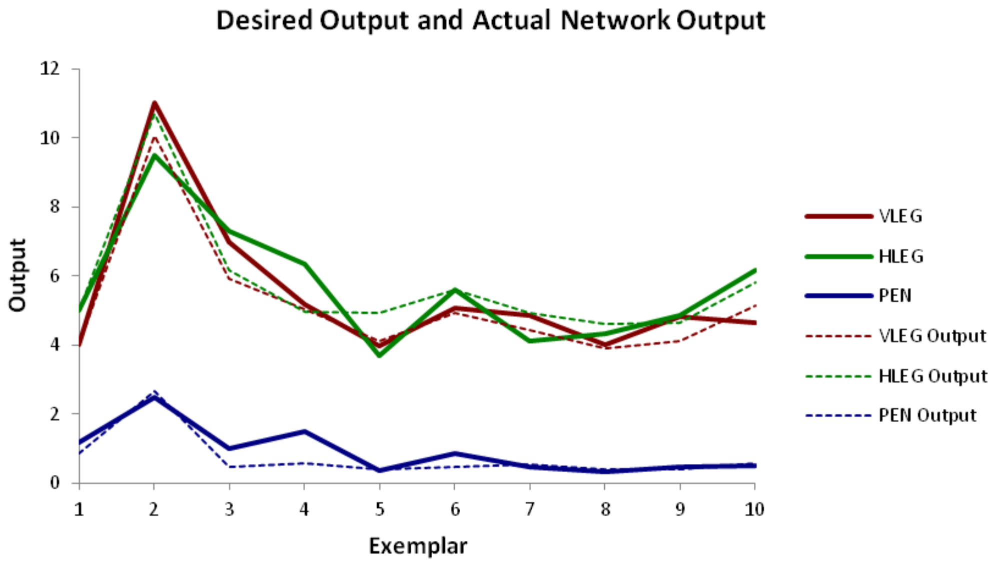


Figure 7: ANN Model Results (Actual vs. Predicted)

Sensitivity Analysis – Main Effects and Interaction

Once the ANN model had been trained and tested a sensitivity analysis was conducted using Neurosolutions for Excel. The results of the sensitivity analysis are shown in figure 8. The analysis indicates that **current** was the most influential parameter in determining the penetration of the fillet weld and that the **travel speed** was the most influential parameter in determining the vertical and horizontal leg lengths. The analysis also shows the travel angle and the gun angle are not insignificant in determining the vertical and horizontal leg lengths as single variables. This confirms the results of further sensitivity analysis of the variables and their interactions, and will be discussed in a later section.

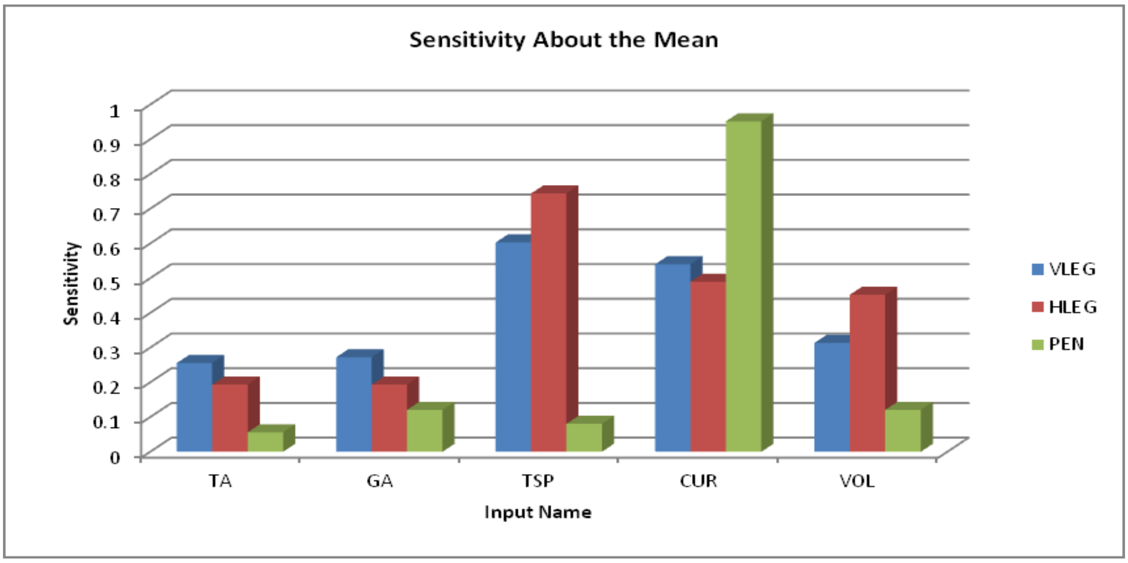


Figure 8: Results of ANN Sensitivity Analysis

Following the results of the ANN model, an Analysis of Variance (ANOVA) study was carried out in order to determine if any of the interactions between the input variables are significant in predicting the penetration and leg length of the resultant fillet weld. This analysis highlighted that current was the most influential parameter in determining the penetration of the fillet weld. This seems to support the results of the ANN sensitivity analysis. The analysis also concluded that the 3 way interaction between the gun angle, travel angle and current and the 2 way interaction between the travel angle and current were both significant in determining fillet weld geometry. The analysis also highlighted that the 2 way interaction between travel speed and travel angle was the most influential in determining the leg length, followed closely by travel speed. The dominance of travel speed in these results again reinforce the results from the ANN sensitivity analysis (figure 8), that travel speed was the most influential factor. Travel speed is one of the key factors in determining the amount of filler material that is deposited at each position across the length of the weld, so it is logical that the angle of deposition (travel angle) and the volume of filler material deposited per unit length are the most influential factors in determining the leg length. The significance of the travel speed in determining GMAW geometry reflects favourably with the data reported by Campbell et al [11] when developing an ANN model to predict GMAW weld geometry.

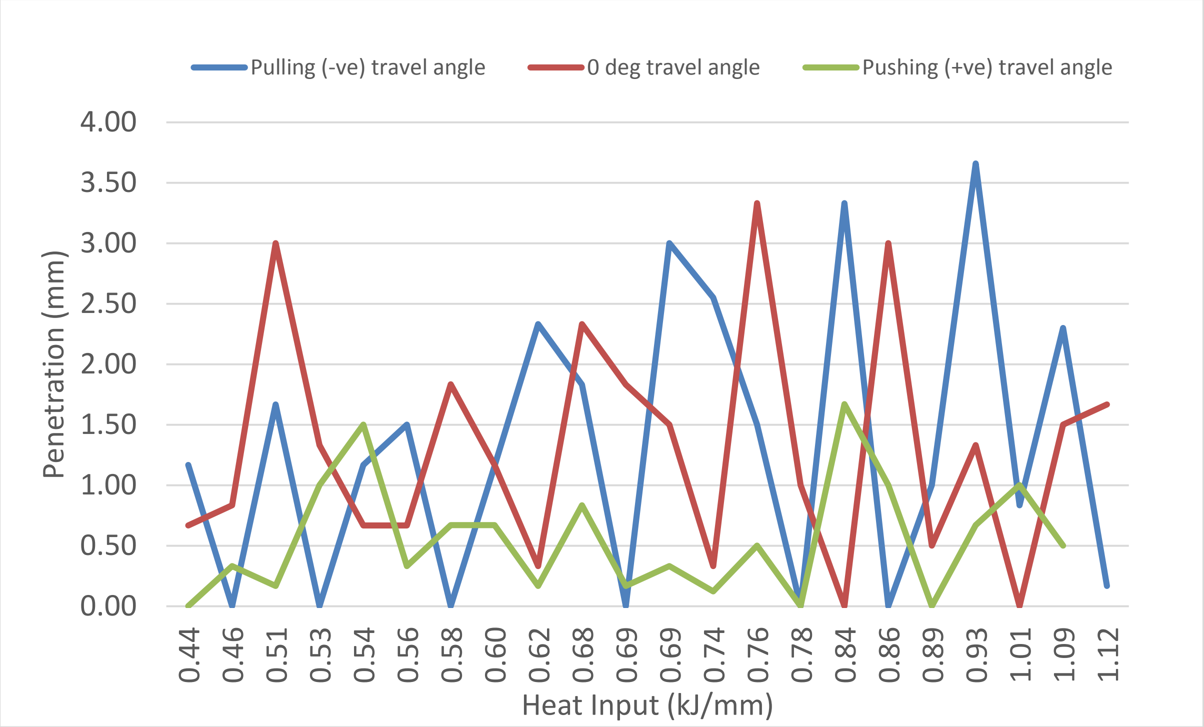


Figure 9: Graph showing impact of varying travel angle has on penetration

Further analysis of the experimental data shows that a pushing (+ve) travel angle improves the consistency of the resultant penetration (figure 9) and leg length, regardless of the heat input. The results also show that for pulling (-ve) and neutral travel angles the leg length increases proportionally with the heat input, however for pushing (+ve) travel angles the resultant leg length is less sensitive to increases in heat input. Figure 10 also shows that a pushing (+ve) travel angle reduced the variation between the resultant horizontal and vertical leg lengths compared to when the torch is being pulled (-ve). This would be in line with industrial supplier guidance which advocates ‘pushing’ when using

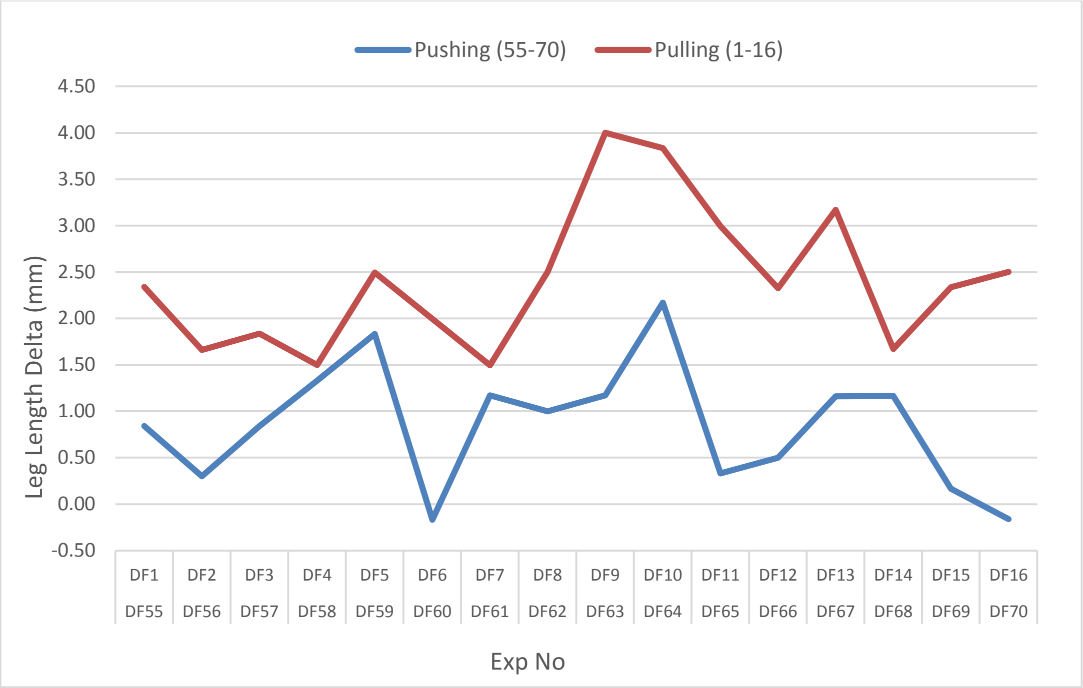


Figure 10: Graph showing the effect that changing the travel angle (from push to pull) has on the difference between the resultant horizontal and vertical leg lengths

metal cored wires as recommended by BOC [7] on lighter gauge material. An improved coverage of shielding gas, caused by the ‘pushing’ travel angle’ may also be one of the main contributing factors towards the observed reduced variation in leg length and penetration. A similar analysis was conducted on the impact that the gun angle has on the penetration and leg length of a fillet weld. The results show that the gun angle seems to have no significant impact on the leg length of the resultant weld; however the variation in penetration of the welds conducted with a gun angle of 50° appeared to be slightly more stable than at 40° and 45°. The experimental results also demonstrated that on average a ‘pushing’ travel angle produces less penetration and a flatter weld bead. Conversely the ‘pulling’ experiments produced a fillet weld with a more rounded reinforcement. This supports the technological stance put forward by Miller Electric [6]. The results also show that ANN software can be used to create a model which can accurately predict fillet weld geometry given a range of input parameters. The results of the sensitivity analysis and the assessment of the interactions were also in broad agreement, that current is the most influential factor when determining **penetration** and that travel speed and current are both influential factors in determining **leg length**. The effect and interaction analysis also identified that there are a number of interactions between the input parameters that are significant in determining both the penetration and leg length of the fillet weld. Further studies will be required to assess the aforementioned interactions in more detail and understand how the constituent input parameters affect the geometry via the interaction.

Conclusions

This study has confirmed, using an ANN Model, the impact that key GMAW input parameters have on the resultant penetration and leg length of a fillet weld. Based on the results of this work we can draw the following conclusions:

- Current is the most significant factor in determining penetration.
- Both travel speed and current are significant in determining the leg length.
- A ‘pushing’ travel angle produces a more consistent level of penetration and leg length that are less sensitive to variations in heat input.
- An optimised set of parameters can generate cost savings of approximately 20% and a reduction in heat input of 40% for a GMAW fillet weld.

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Keywords

Artificial Neural Networks (ANN)
Fillet Welding
Design of Experiments (DOE)
GMAW
Travel Angle
Gun Angle
Penetration
Leg Length

References

1. **Miller, D.K**. 1998. Consider penetration when determining fillet weld size. Welding Innovation 1998, Vol XV, No.1, pp.20-22.

2. **Welding Technology Institute of Australia,** 2006. A Guide for Welding, Assessment and Inspection of Fillet Welding, May 2006

3. Tham, G., Yaakub, M.Y., Abas, S.K., Manurung, Y., Jalil, B.A., 2012. Predicting the GMAW 3F T-Fillet Geometry and its Welding Patameter. Procedia Engineering, International Symposium on Robotics and Intelligent Sensors, vol.41, 2012, pp1794-1799. DOI:10.1016/j.proeng.2012.07.385

4. **Beckett, S., MacPherson, M.J., McPherson, N.A**. 2011. Improved Welding Control of Automated Fillet Welding for Ship Structures Using Artificial Neural Networks (ANN). Presented at JOM 16 Conference, May 2011, HelsingØr.

5. Lightfoot, M.P., Bruce, G.J., McPherson, N.A., Woods, K. 2005. The Application of Artificial Neural Networks to Weld-Induced Deformation in Ship Plate. Supplement to the Welding Journal, February 2005, pp23s-26s.

6. Miller Electric Mfg. Co, Guidelines for Gas Metal Arc Welding (GMAW), 2012-04

7. **BOC**, Fundamentals of flux and Metal Cored Arc Welding, Section 8: Consumables (2007), pp322-325.

8. Harwig, D. 2000. Arc Wise – Optimisation, Productivity and Quality in Arc Welding, Materials Joining Technology Newsletter, vol.13, no 2.

9. Pal, K., Bhattacharya, S., Pal, S.K. 2010, Multisensor-based monitoring of weld deposition and plate distortion for various torch angles in pulsed MIG welding, Int J Adv Manuf Technol (2010) 50:543-556

10. Lincoln Electric, Innershield Welding Guide, Publication C3.2400, Issue Date 02/11, pp21-31

11. Campbell, S.W., Galloway, A.M., McPherson, N.A. 2012. Artificial Neural Network Prediction of Weld Geometry performed using GMAW with Alternating Shielding Gases. Welding Journal, vol.91, no.6. June 2012. Supplement: Welding Research. Pp.174s-181s, ISSN: 0043-2296

12. Dadgar Asl, Y., Mostafa, N.B., Panahizadeh, V., Seyedkashi, S.M.H. 2011. Prediction of Weld Penetration in FCAW of HSLA Steel using Artificial Neural Networks. AIP Conf.Proc.1315,884 (2011).DOI: 10.1063/1.3552564.

13. Moon, H., Na, S. 1997. Optimum Design Based on Mathematical Model and Neural Network to Predict Weld Parameters for Fillet Joints. Journal of Manufacturing Systems. 01/1997; 16(1):13-23. DOI: 10.1016/S0278-6125(97)88402-6

14. Andersen, K., Cook, G., Karsai, G., Ramaswamy, K. 1990. Artificial Neural Networks Applied to Arc Welding Process Modeling and Control. IEEE Transactions on Industry Applications. 10/1990; 26(5):824 - 830. DOI: 10.1109/28.60056

15. Nagesh, D.S., Datta, G.L.2002. Prediction of Weld Bead Geometry and Penetration in shielded metal-arc welding using artificial neural networks. Journal of Materials Processing Technology, vol.123, no.2.pp303-312, April 2002 DOI:10.1016/S0924-0136(02)00101-2

16. Nagesh, D.S., Datta, G.L.2008. Modeling of fillet welded joint of GMAW process: integrated approach using DOE, ANN and GA. International Journal for Interactive Design and Manufacturing (IJIDeM) 07/2008; 2(3):127-136. DOI: 10.1007/s12008-008-0042-8

17. Kumar, A., Debroy, T. 2007. Tailoring Fillet Weld Geometry Using a Genetic Algorithm and a Neural Network Trained with Convective Heat Flow Calculations. Welding Journal, vol.86, no.1. January 2007, pp.26-33

18. Chan, B., Pacey, J., Bibby, M. 1998. Modelling Gas Metal Arc Weld Geometry Using Artificial Neural Network Technology. Canadian Metallurgical Quarterly, vol.38, no.1. January 1999. Pp43-51. DOI:10.1016/S0008-4433(98)00037-8

19. Bhadeshia, H.K.D.H. 1999. Neural Networks in Materials Science. ISIJ International, Vol. 39 (1999), No. 10, pp, 966-979

20. Kim, I.S., Son, J.S., Park, C.E., Kim, I.J., Kim, H.H.2005. An investigation into an intelligent system for predicting bead geometry in GMA Welding process. Journal of Materials Processing Technology, vol.159, no.1. January 2005, pp113-118

21. **Lloyds' Register**, Rules and Regulations for the classification of Naval Ships, Jan 2011, Volume 1, Part 6, Chapter 6, Section 4, pp11-17.

22. Campbell, S.W., Galloway, A.M., McPherson, N.A. 2013. GMAW Shielding Gas Flow Optimisation by Refinement of Nozzle Geometry. 8th Pacific Rim International Congress on Advanced Materials and Processing, 2013-08-04 – 2013-08-09, Hawaii.