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The Effect of Metal Inert Gas Welding Parameters on the Weldability of Galvanised Steel

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Author's Contributions
This work was carried out by the author. The author has read and approved the revised manuscript.

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ABSTRACT

The Taguchi technique is employed to establish the optimal parameter for each tensile property of the weldments. The tensile properties determined are the ultimate tensile strength, the yield strength, and the percentage elongation, whereas the process parameter used is the welding current (A), welding voltage (B), and the gas flow rate (C). By applying the Taguchi method, the optimal process parameters for obtaining the weldment with better yield strength are $A_3B_1C_3$, whereas $A_3B_3C_3$ can produce the weldment for better elongation. These optimum process parameters have shown considerably improved signal-to-noise ratios over the current process parameters adapted by the welders.

1. Introduction

Welding is a major technique for joining two dissimilar (or similar) metals. Metal inert gas welding is an arc welding process where heat is produced for an arc between a consumable electrode and the workpiece [1]. The welding parameters are essential factors influencing productivity, quality, and the cost of the welded joints [2]. Weld bead penetration, shape, and size depend on several factors. The input constraints such as the arc voltage, welding current, and welding speed unambiguously affect the quality of a welded joint. Modifying these weld parameters and varying the structure of shielding gas, creates changes in penetration [3,4]. However, insufficient weld bead dimensions (e.g., shallow depth of penetration) can cause the failure of a welded structure [5].

The authors in [6], employed the Taguchi technique to define the optimum cutting constraints (feed rate, insert radius, and depth of cut) for the surface roughness. While analysing the performance characteristics using the signal-to-noise (S/N) ratio, orthogonal array, and analysis of variance. The authors observed that the design approach offers a simple, efficient, and orderly procedure for optimising the cutting constraints. The surface roughness enhancement of about 335% was attained. Yet, variations between actual and estimated signal-to-noise ratios are small for each parameter.

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In [7], the depth of penetration was estimated and optimised for arc welded plates. The simulated annealing approach was employed for optimising process parameters with the developed algorithm and source code implemented in MATLAB. The simulation results prove the effectiveness and accuracy of the developed model.

A methodical scheme based on the Taguchi design is utilised in [8] to verify the effects of different process parameters comprising welding current, weld and squeeze time, preheating current, and hold time on the tensile shear strength of the weld joint of galvanised steel. The study showed that the welding- time and current as highly effective factors, whereas hold time and squeeze time are less effective parameters.

The emphasis of the authors in [9], is on the application of the Taguchi technique for the reduction of weld undercuts in the welding process. The study established that the welding speed is the most significant input in minimising weld undercuts. In a more recent study [10], an effort was made to experimentally investigate the non-linear modelling of the plasma arc welding via a central composite design of experiments; considering different properties (including the percentage of elongation, ultimate tensile strength, flexural strength as well as the hardness of the weld joints) and, input parameters (weld speed, weld current, and gas flow rate) to examine the effect of these constraints on mechanical properties. The estimation accuracy is found to be in good agreement.

Analysis of the literature review suggests that the welding current and voltage, and shielding gas flow rate are essential welding parameters that influence the depth of penetration of a weld joint. In this paper, the effect of different welding process parameters on the weldability of galvanised steel specimens having a dimension of 50 mm x 40 mm 5 mm, welded by MIG is investigated.

2. Methods

The selection of the operation process parameter utilising the tensile properties takes the under-listed steps using the Taguchi method.

(a) The matrix design used to distribute and prepare the combinations of process parameters used for the study was established.
(b) These combinations of process parameters were used to make weldments of mild steel specimens.
(c) The mild steel test specimen was machined from the all-weld metal deposition and etched with sodium hydroxide.
(d) A Tensile test and Charpy impact machines were utilised to determine the tensile properties and impact strength of the weldment.
(e) The tensile properties obtained from each experimental run were recorded
(f) The signal-to-noise ratio was obtained for each tensile property.
(g) The optimum process parameters were established by adapting the higher the better criterion.
(h) The graph layout shows the relationship between the signal-to-noise ratios and different levels of the process parameter.
(i) Eventually, the analysis of variance (ANOVA) was processed to determine the contribution of each process parameter towards the improvement of the quality of the weldment.
(j) Lastly, a compressive analysis was done to compare the properties and improvements of the weldments made by the optimum and existing process parameters.

The following materials were used: a hammer, hacksaw, Tensile test machine, Chappy and Bord Hapert test machine, an electrode, arc welding machine, shield and workpiece (Fig. 1). The process control parameters considered are welding current (A), welding voltage (B), and shielding gas flow rate (C). Table 1 shows the process parameters and the different levels used. Thereafter, tensile tests were conducted on the weld deposits and the ultimate tensile strength (UTS), the yield strength (YS), and the percentage elongation (%Elong) were determined. In this study, the L_9 (3^2) orthogonal array which has 8 degrees of freedom was used. Nine experiments are expected to be carried out from the proposed L_9 orthogonal array. The experiment layout for the L_9 orthogonal array is expressed in Table 2.

Table 1. Process parameters and their levels.

Plate thickness (mm)	Electrode Diameter (mm)	Symbol	Process Parameter	Unit	Level 1	Level 2	Level 3
		A	Welding current	A	130	150	180
5	3.2	B	Welding voltage	V	12	15	19
		C	Gas flow rate	L/min	13	14	15

Table 2. Experimental layout using L_9 orthogonal array.

Exp. No.	Welding current (A)	Welding voltage (B)	Gas flow rate (C)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Fig. 1 Setup for (a) Chappy test machine, (b) electric arc welding machine, (c) tensile test machine, (d) grinding machine, and (e) workpiece.

To create a butt joint, two plates were tacked at the two ends along the width, with a constant root gap of 0.7 mm. Once the welding is over all the plates were cut by using a hacksaw, to the required shape for measuring the depth of penetration. The welding torch was mounted on a fixed arm of a portable gas-cutting machine, which can move at different known speeds. Copper-coated mild steel wire of 0.8 mm diameter was used in the experiment as the electrode. The wire was fed through the welding gun by a roller drive system. The shielding gas used was CO_2, supplied in a regulated manner at a constant flow rate and a constant pressure. The selection of the optimum process parameters utilising the tensile properties by applying the Taguchi method.

Each level in Table 1 was inserted in the appropriate level in Table 2 to generate the input parameters in Table 3, and each input parameter of the nine rows was used to make five weld deposits respectively which were machined into five standard specimens or conducting Tensile Tests. The average UTS, YS and %Elong values obtained from the tensile tests conducted are presented (Table 3).

The loss function of the large-the better-quality feature is therefore expressed as presented in equation (1) while the signal-to-noise (S/N) ratio is expressed in equation (2).

$$L_f=\left(\frac{1}{n}\sum_{i=0}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

$$\eta_j = 10 \log L_f \quad (2)$$

Where, n is the number of tests conducted and y_i, is the experimental value of the ι^{th} quality feature; L_f is the overall loss function and η is the S/N ratio [11].

3. Results and Discussion

3.1. Overall loss function and its signal-to-noise ratio

Table 3 shows the input-output process values for the tensile tests conducted in this study. The UTS of the welded structure in this study is in the category of the larger-the better-quality features. This is because the higher the values of UTS of the ductile mild steel welds, the better its quality level. Applying equations (1) and (2), the S/N ratio for each experiment of L_9 is obtained and summarised (Table 4).

Table 3. Input and output process parameters.

Experiment	Input parameters			Output parameters		
	Current	Voltage	Gas flow rate	UTS	YS	%Elong
1	130	12	13	268	236	7
2	130	15	14	240	224	5
3	130	19	15	320	296	20
4	150	12	14	310	282	15
5	150	15	15	280	263	18
6	150	19	13	225	208	12
7	180	12	15	370	356	25
8	180	19	13	258	242	9
9	180	19	14	336	312	22

Table 4. S/N ratios for the UTS measurements.

Experiment	S/N Ratios		
	UTS	YS	%Elong
1	48.5627	47.4582	16.9020
2.	47.8032	47.0050	13.9794
3	50.1030	49.4258	26.0206
4	49.8272	49.0050	23.5218
5	48.9432	48.3991	25.1055
6	47.0437	46.3613	21.5836
7	51.3640	51.0290	27.9588
8	48.2324	47.6763	19.0849
9	50.5268	49.8831	26.8485

3.2. Computing the signal-to-noise ratio of process parameters into their levels

From the L_9 layout in Table 2 and the corresponding values of S/N ratio welding process parameters were summarily arranged in their various levels as shown in Table 5.

Table 5. Summary of the welding process parameters and their levels.

	Symbol	Process Parameter	S/N Ratio (dB)			Total Mean	Max - Min
			Level 1	Level 2	Level 3		
UTS	A	Welding current	48.7566	48.6047	50.0411*	49.1341	1.4364
	B	Welding voltage	49.9180*	48.2599	49.2245		1.6581
	C	Gas flow rate	47.9463	49.3194	50.1367*		2.1904
YS	A	Welding current	47.9630	47.9218	49.5295*	48.4714	1.6077
	B	Welding voltage	49.1641*	47.6935	48.5567		1.4706
	C	Gas flow rate	47.1653	48.6310	49.6180*		2.4527
%Elong	A	Welding current	18.9673	23.4036	24.6307*	22.3339	5.6634
	B	Welding voltage	22.7942	19.3899	24.8179*		5.4277
	C	Gas flow rate	19.1902	21.4499	26.3616*		7.1714

** Indicates the optimal level based on the larger-the-better criterion*

It is seen (Table 5) that the optimum process parameters considered for the UTS are $A_3B_1C_3$, for YS, the optimum process parameters consist of $A_3B_1C_3$, whereas, for the percentage elongation, the optimum process parameters are $A_3B_3C_3$. The tensile properties of galvanised mild steel weldments were optimised by applying the Taguchi method. To a large extent, tensile properties define the ductile content of engineering material and ductility is a factor that measures the load-bearing capacity of the material. The tensile properties considered are the UTS, the YS and the %Elong. Each of these parameters is fiercely affected by the combination of the input parameters used by welders. Research has shown that an acceptable weld quality can mostly be determined by combining the selected process variables. Nine experimental runs were conducted. For each weld run, the tensile properties of the weldment were determined using the Avery tensometer. By applying the Taguchi method to the tensile results obtained, the signal-to-noise ratio was obtained (Table 4). Thereafter, the average signal-to-noise ratio in each level was arranged (Table 5) applying the larger the better criteria, the optimum signal-to-noise ratios were selected for each process parameter, and eventually for each tensile property. Fig. 2 shows the signal-to-noise ratio where the dotted lines indicate the value of the total average of the signal-to-noise ratios. It indicates the interactions between the levels of each process parameter.

The S/N ratio graph as shown in Fig 2 was drawn to illustrate the interactions between the levels of the process variables and the S/N ratios. The dashed line is the mean S/N ratio for each tensile property. From Fig. 2(a), it is seen that only points on $A_3B_1C_3$, are above the dashed line which indicates that they are the optimum parameters that could produce weldment of high UTS, which means weldment of better quality. For YS, as shown in Fig. 2(b), points $A_3B_1C_3$, are above the dashed line but B_3, is also above the dashed line but on a lesser magnitude than B_1, therefore since B_1, has a better chance than B_3, of producing the weldment that would give a desirable weld yield strength, B_1, is therefore selected over B_3. Considering percentage elongation in Fig 2 (c), it is observed that points $A_3B_3C_3$, are clearly above the dashed line; therefore, they are the combination of process parameters that would produce weldments with higher percentage elongation. Percentage elongation has been proven to be a dominant factor in determining the ductility of engineering material.

The ANOVA as a statistical tool (Table 6) can be employed to establish the level of the contribution of each process parameter to the overall enhancement of the quality and strength of the weld. The values in Table 6 were obtained from the following expressions:

$$S^2 = \Sigma(y_i^2) - \frac{(\Sigma y_i)^2}{n} . \quad (3)$$

Where y represents the result of each variable of the experiment, and n is the number of tests conducted.

$$O^2 = \frac{S^2}{DF} \quad (4)$$

Where DF = N – 1 and N is the number of observations.

$$\% \text{ Contribution} = \frac{S^2}{ST^2} \quad (5)$$

Where ST^2 is the total sum of squares.

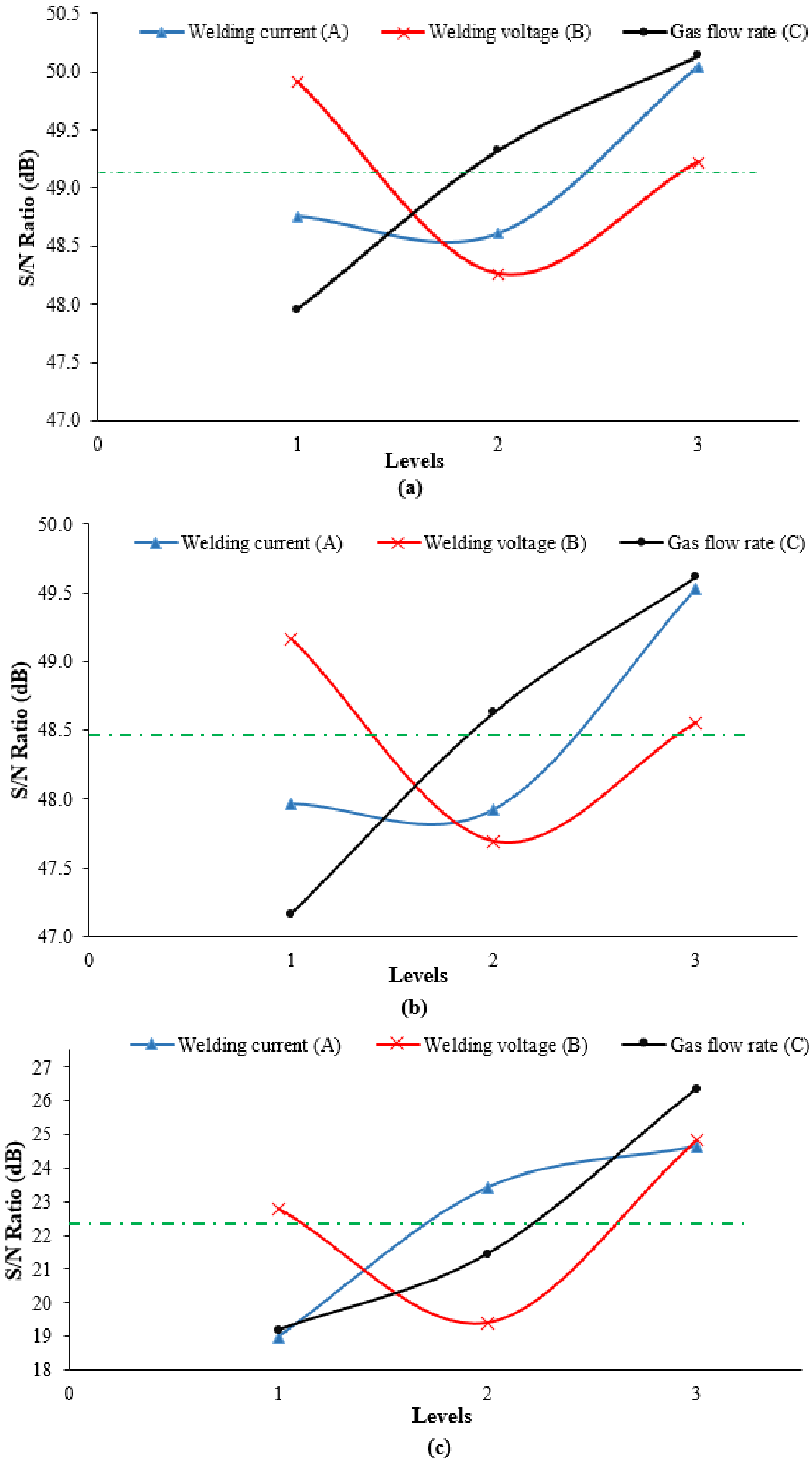

Fig. 2 Interactions between the levels of each process parameter (a) ultimate tensile strength, (b) yield strength, and (c) percentage elongation.

Table 6 ANOVA table.

Tensile property	Process Parameter	Notation	Degree of Freedom (DF)	Sum of Square (S^2)	Variance (O^2)	Contribution (%)
	Welding Current	A	2	1.2454	0.6227	24.5022
	Welding Voltage	B	2	1.3860	0.6935	27.2861
	Gas Flow Rate	C	2	2.4504	1.2252	48.2097
UTS	Error		2	0.0001	0.00005	
	Total		8	5.0828		
	Welding Current	A	2	1.6801	0.8401	28.8756
	Welding Voltage	B	2	1.0921	0.5461	18.7698
	Gas Flow Rate	C	2	3.0460	1.5230	52.3512
YS	Error		2	0.0002	0.0001	
	Total		8	5.8184		
%Elong	Welding Current	A	2	17.7536	8.8768	29.7439
	Welding Voltage	B	2	15.0478	7.5239	25.2107
	Gas Flow Rate	C	2	26.8867	13.4434	45.0453
	Error		2	0.0001	0.00005	
	Total		8	59.6882		

Considering the effect of the input process variables on the weldment UTS, it is observed (Table 6) that the gas flow rate contributed 48.2097% to an increase in the weldment UTS. The gas for the welding process is 80% Argon and 20% CO_2. This mixture of gas elements contains some alloying elements that contribute to strengthening the weldment thereby producing a high UTS. The welding voltage contributed about 27.2861% to the chances of the weldment having a higher and better UTS. This is followed by the welding current which contributed 24.5022%. The welding voltage and current contributions to the generation of arc heat for melting the workpiece and filler metal and influencing the heat-affected zones of the weldment. In considering the YS, the gas flow rate contributed the highest compared to the other process parameters. The gas flow rate contributed 52.8712%, the welding current contributed 28.8756% whereas, the welding voltage contributed 18.7698%. Their effects on the yield strength of the weldments are the same as that of the weldments with improved UTS. Also, the weldments with better % elongation were considered. Each of the process variables contributed to the production of the weldment with a better percentage of elongation (Table 6). Gas flow rate contributed 45.0453%; welding current contributed 29.7439% whereas, welding voltage contributed 25.2107% to improving the percentage elongation of the weldment.

3.3. Confirmation of tests

The enhancement in the performance characteristics of the welding process was predicted and verified. The signal-to-noise ratio was deduced by equation (6) using the optimal levels of the welding parameters. Equation (7) was used to obtain the results of experimental confirmation using optimal welding parameters and comparing it with existing/initial processes is shown in Table 7. The process parameters were validated by comparing the signal-to-noise ratio of the optimal process parameters to the existing process parameters. This was done by subjecting the weldments formed by applying these process parameters to the Charpy impact test to determine the extent to which the weldments can absorb impact load.

$$\text{F} - \text{ratio} = \frac{\sigma^2}{\sqrt{\sigma\ Error}} \tag{6}$$

$$\eta_i = \eta_m + \left(\sum_{i=1}^{n} \eta - \eta_m\right) \tag{7}$$

Where σ is the variance, η_m is the total mean of signal-to-noise, η_i is the mean of the signal-to-noise ratio at the optimal level and η is the number of main welding parameters that significantly affect the performance.

Table 7. Confirmation of experimental test result.

	Notation/Test	Optimum process parameter	Existing process parameters	Improvement in S/N ratio
UTS		**$A_3B_1C_3$**	**$A_2B_2C_1$**	
	S/N dB	51.8276	46.5427	5.2849
YS		**$A_3B_1C_3$**	**$A_2B_2C_1$**	
		51.3688	45.8378	5.5310
%Elong		**$A_3B_3C_3$**	**$A_2B_2C_1$**	
	S/N dB	31.1421	17.3159	13.8262
	Charpy impact testing, CVN Joules	246	178	

**CVN: Charpy V-notch*

It is observed (Table 7) that when considering the weldment with the good UTS, the optimum process parameters produced the weldments that have an S/N ratio of 5.2849dB over the weldment obtained by using the existent process parameters. When considering YS, the optimum process parameters produced weldments with S/N 5.5310dB over the weldments produced by applying the existent process variables. Also, when considering the percentage elongation, the optimum process parameters produced the weldments that have S/N 13.8262dB over that produced by applying the existing process parameters. The weldments produced by the optimal process constraints and the existent process parameters were subjected to the Charpy impact test and the weldment produced by using the optimum parameters absorb the impact energy of 246 Joules whereas, by utilising the existent parameters impact energy of 178 Joules was obtained. Therefore, from all indications, the Taguchi method has been used to successfully optimise the welding process parameters capable of producing weldments with improved UTS, YS and %Elong.

4. Conclusion

The Taguchi method has been utilised to successfully optimise the process parameters that were used to obtain improved tensile properties of mild steel weldments. Three output process parameters were considered UTS, YS and %Elong. These parameters are dominant in determining the ductile content of an engineering material's signal-to-noise ratio. The signal-to-noise ratio using the larger the better criteria was adopted for this study. Clustering these signal-to-noise ratios into their different levels the optimum process parameters which comprise welding voltage, welding current, and the gas flow rate was selected and the analysis of variance was done to assess the level of contribution made by each of the process parameters on the achievement of the weldments with improved UTS, YS and %Elong. From the analysis of variance, the gas flow rate which adds some alloying elements to the molten weld metal contributes most to the strength of the weldments thereby achieving better UTS, YS and %Elong.

Conflict of Interests

The author declares that there is no conflict of interest regarding the publication of this paper.

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