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Prediction and Selection of the Best Process Parameters to Improve Toughness of Mild Steel Welded Joints

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Abstract

Poor combination of input process parameters has resulted in an innumerable amount of weld failure due to its negative influence on the microstructural and mechanical properties of the welded joints. To improve the welded joint, it is imperative that the material toughness be optimized. The aim of this study is to predict and enhance the toughness of mild steel welded joint using Response Surface Methodology (RSM). 10 mm mild steel plate was cut into 200 piece coupons measuring 27.5 × 10 × 10 mm for the experiment, after welding of the piece, 100 specimens of 55 × 10 × 10 mm were produced and the experiment was performed 20 times. Charpy impact tester was employed to measure the degree of toughness of the material, and results were analyzed using RSM. The results produced an optimum impact test of 275.514 joules at a desirability value of 95.6%. This optimum impact test was achieved through the use of current of 120.00 amp, voltage of 20.00 volt and gas flow rate of 12.00 L/min. The weld current was found to have a greater influence on the impact strength of the weldment as compared to voltage and gas flow rate at a moderate level.

Subject Areas

Material Experiment

Keywords

Impact, Weldment, Mild Steel, Specimen

1. Introduction

Toughness is usually regarded as the ability of materials to absorb energy before fracture, although, failure in welded materials can also arise from resonance (Etin-Osa and Achebo 2017) [1]. The toughness of a material is the amount of impact shock a material can withstand before failure which can be described graphically as the area under stress strain curve. The tougher a material, the better its ability to withstand sudden shock (Achebo and Odinikuku 2015) [2] and (Imhansoloeva *et al.*, 2018) [3]. Usually, the Izod and Charpy test are the most common method of measuring toughness of material. In welding, heat input that aids the joining of metals, can also cause a reduced toughness at welded joint, when an inexperience or poor combinations of process parameters are employed (Mallya and Srinivas 1989) [4], (Mistry, 2016) [5] and (Akande, 2016) [6]. This poor combination of input process parameters has resulted in an innumerable amount of weld failure due to its negative influence on the microstructural and mechanical properties of the welded joint (Etin-Osa and Etin-Osa, 2019) [1]. Mild steel is one of the cheapest metals in the market widely used because of its good microstructural and mechanical properties. It contains up to 0.2 percent carbon by weight and is often used in the building of ships, beams for buildings and bridges. The use of mild steel in production of desired construction and engineering structures can hardly be achieved without a joining process (Achebo, 2012) [7]. Quality and productivity play important role in today's manufacturing market, as it stresses the need for continuous improvement. Nowadays due to very stiff and cut throat competitive market conditions in manufacturing industries, quick failure of mild steel components are not tolerated, thereby necessitating the need to improve the toughness of the material. Usually, excessive or little heat input compromises the toughness of the welded joint. In other to achieve an optimum toughness, deliberate effort is put in place to identify the input process parameters which results in the best toughness (Achebo, 2011) [8]. In time past, numerical analysis of welded materials was carried out, solving by hand (Mallya and Srinivas, 1989) [4]. This procedure was very cumbersome as it took a lot of solving time with a higher error margin, but with the introduction of computer software to handle statistics, simulation, optimizations and predictions, welding operations can now be studies with in-depth knowledge of the causes of failure. Some researchers applied the try and error technique in weld optimization. This technique is time consuming and takes more experimentation, making it less economical. Our aim is to predict and improve the toughness of mild steel material, using the tungsten inert gas (TIG) welding process and response surface methodology.

2. Materials and Methods

2.1. Materials

This research work was conducted at the Department of Welding and fabrication technology, Petroleum Training Institute (PTI), Warri, Delta State, Nigeria. The Tungsten Inert Gas (TIG) welding method was adopted, thereafter, the samples from the welding process were subjected to impact test. **Table 1** presents the process parameters employed for the research. The selected input parameters have the upper (+) and lower limits (−). All the materials used in this research were purchased from a local vendor.

2.2. Weld Penetration Form Factor Measurement

The 10 mm mild steel plate was cut into 200 piecescouponsmeasuring 27.5 × 10 × 10 mm for the experiment, after welding of the piece, 100 specimens of 55 × 10 × 10 mm were produced, the experiment was performed twenty (20) times as presented in Table 2, using five (5) specimens per run. The welded specimen fits into the Charpy impact tester. The welded specimen was a rectangular shaped mild steel plate with measured dimension of 55 × 10 × 10 mm with a V-shaped notch, 2 mm deep, with 45 angle and 0.25 mm radius along the base cut in one side. The notch allows for a predetermined crack initiation location as shown in Figure 1.

3. Results and Discussion

3.1. Results

The study produced twenty experimental runs, each experimental run comprising the current, voltage and gas flow rate, used to join two pieces of mild steel plates measuring 55 mm × 10 mm × 10 mm. The impact test strength, was measured. The responses are shown in Table 2.

According to literature, the difference between the predicted and adjusted R^2 must be less than 0.2. In this research, a difference of 0.131 which is less than 0.2 was obtained in Table 3. The adequate Precision of 12.8046 which is used to measures the signal to noise ratio was obtained in our study. Literature states that the ratio should be greater than 4 to be desirable. Since the required condition for the fit statistics has been meet, the model can now be used to navigate the design space.

Table 1. Welding process parameters limits.

Process parameters	Unit	Symbol	Low (−)	High (+)
Welding Current	Amp	I	120	170
Welding Voltage	Volts	V	20	25
Gas Flow Rate	Lit/mill	F	12	14

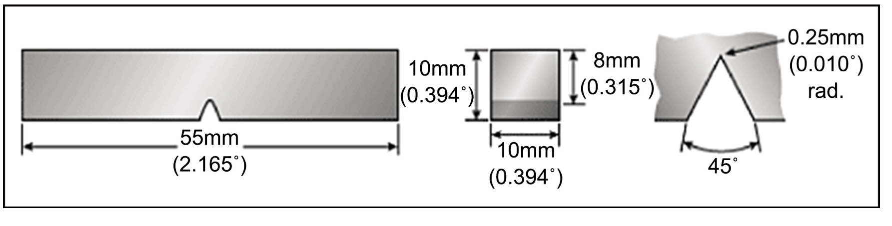

Figure 1. Charpy impact test specimen.

Table 2. Experimental result for the impact test.

Run	A: Welding Current	B: Welding Voltage	C: Gas Flow Rate	Impact Test
	Amp	Volts	Lit/mill	J
1	145	22.5	13	235.144
2	145	22.5	13	227.136
3	187.045	22.5	13	259.168
4	145	22.5	11.3182	257.712
5	170	20	12	234.416
6	145	18.2955	13	230.048
7	170	25	14	265.502
8	120	20	14	235.872
9	170	25	12	243.152
10	120	25	12	270.088
11	120	20	12	272.272
12	102.955	22.5	13	278.096
13	170	20	14	219.128
14	145	22.5	14.6818	232.232
15	145	22.5	13	230.776
16	*145*	*22.5*	*13*	*234.072*
17	145	26.7045	13	249.704
18	145	22.5	13	238.784
19	120	25	14	261.352
20	145	22.5	13	219.128

Table 3. Fit statistics for the impact test.

Std. Dev.	6.35	**R^2**	0.9354
Mean	244.69	**Adjusted R^2**	0.8773
C.V. %	2.59	**Predicted R^2**	0.7463
		Adeq Precision	12.8046

Table 4 presents the sum of squares which is a Type III—Partial, 16.10 was obtained as the Model F-value which describe a significant model. This means that there is only a 0.01% chance that an F-value this large manifest due to noise. The P-values less than 0.0500 shows that the model terms are significant. In this case A, B, C, AC, AB, BC, A^2 and C^2 obtained a P-val less than 0.05. This would increase the accuracy of our mathematical model in predicting the responses.

Table 4. ANOVA table for impact test.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5836.6	9	648.51	16.1	<0.0001	significant
A-Welding Current	873.47	1	873.47	21.68	0.0009	
B-Welding Voltage	909.73	1	909.73	22.58	0.0008	
C-Gas Flow Rate	479.55	1	479.55	11.9	0.0062	
AB	126.51	1	126.51	3.14	0.1068	
AC	340.57	1	340.57	8.45	0.0156	
BC	533.04	1	533.04	13.23	0.0046	
A^2	2399.52	1	2399.52	59.56	<0.0001	
B^2	107.94	1	107.94	2.68	0.1327	
C^2	296.85	1	296.85	7.37	0.0218	
Residual	402.85	10	40.28			
Lack of Fit	159.88	5	31.98	0.658	0.6714	not significant
Pure Error	242.97	5	48.59			
Cor Total	6239.45	19				

Based on the P-value obtained in Table 4, Equation (1) was mathematically modelled in terms of coded factors for predicting the impact test (IT). For minimal prediction error, more factors with P-value less than 5% should be included in the equation.

$$\begin{aligned} IT = 230.91 - 8.00A - 5.93B - 5.93C + 3.98AB + 6.52AC \\ + 8.16BC + 12.90A^2 + 2.74B^2 + 4.54C^2 \end{aligned} \quad (1)$$

where, A = voltage, B = current, C = gas flow rate.

The plot in Figure 2 was used to examine the reliability of future prediction based on the response obtained from the actual vs predicted impact. The blue square dots indicates the lowest limits of 219.128 joules while the red square dots, shows the maximum impact of 278.096 joules absorbed by the specimen.

The 3D surface plot was employed to examine the effect of the welding voltage and current on the impact absorption of mild steel specimen. At a gas flow rate of 13 L/min, the current and voltage could be varied to obtain the 3D surface plot architect presented in Figure 3. To target above the known predicted value, aim at the wine dot above the 3D mat while to predict below the known prediction value, aim at the dotted peach below.

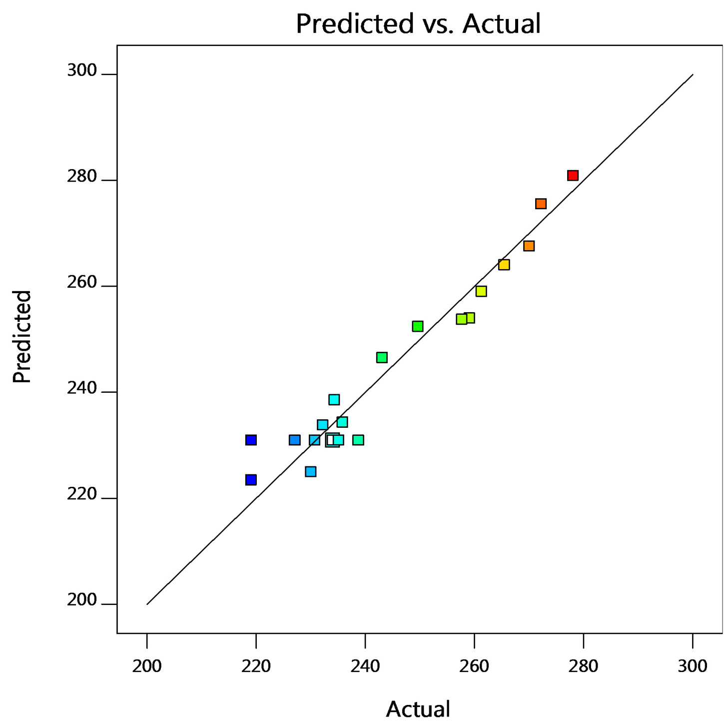

Figure 2. Reliability plot of observed versus predicted impact responses.

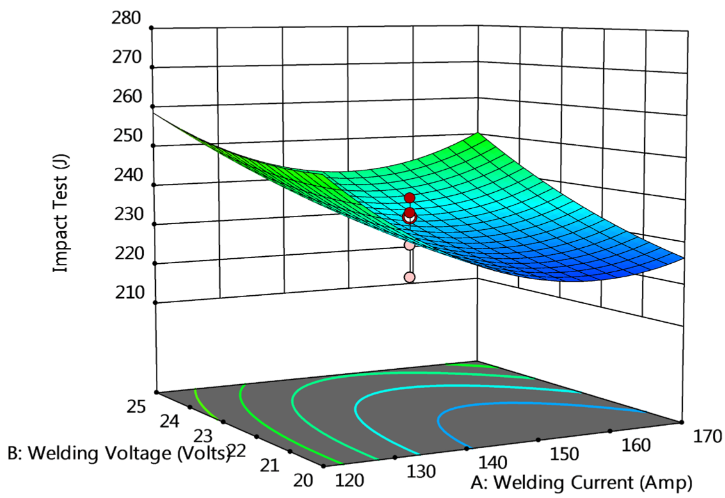

Figure 3. 3D surface plot for impact test.

The interphase in Figure 4 with the maximization target for the impact test, was employed to optimize the response. In the numerical optimization phase, design expert was instructed to maximize the impact test, while also determining the optimum value of voltage, current and gas flow rate.

Table 5 shows five (5) out of the eighteen (18) optimal solutions obtained from the settings made in Figure 4.

Finally, from the optimal solution, the contour plots showing the impact response variable of voltage and current at a gas flow rate of 12 L/min, against the optimized value of the input variable is presented in Figure 5.

Table 5. Optimal solutions of numerical optimization model.

Number	Welding Current	Welding Voltage	Gas Flow Rate	Impact Test	Desirability	
1	**120.000**	**20.000**	**12.000**	**275.514**	**0.956**	**Selected**
2	120.000	20.036	12.000	275.378	0.954	
3	120.010	20.000	12.007	275.285	0.952	
4	120.177	20.000	12.000	275.201	0.951	
5	120.000	20.119	12.000	275.069	0.949	

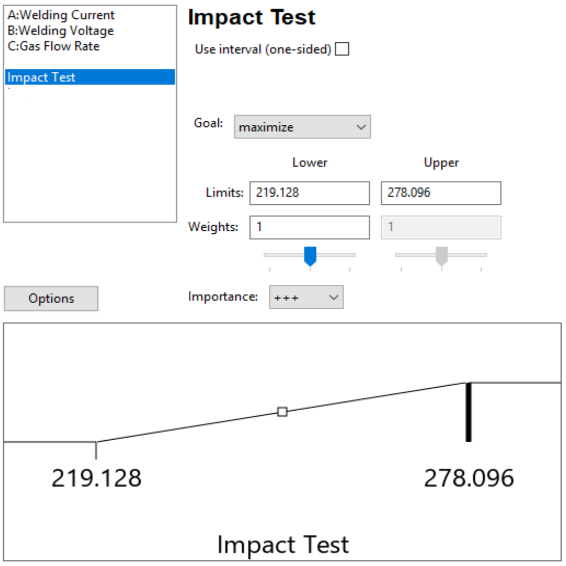

Figure 4. Interphase of numerical optimization of impact test.

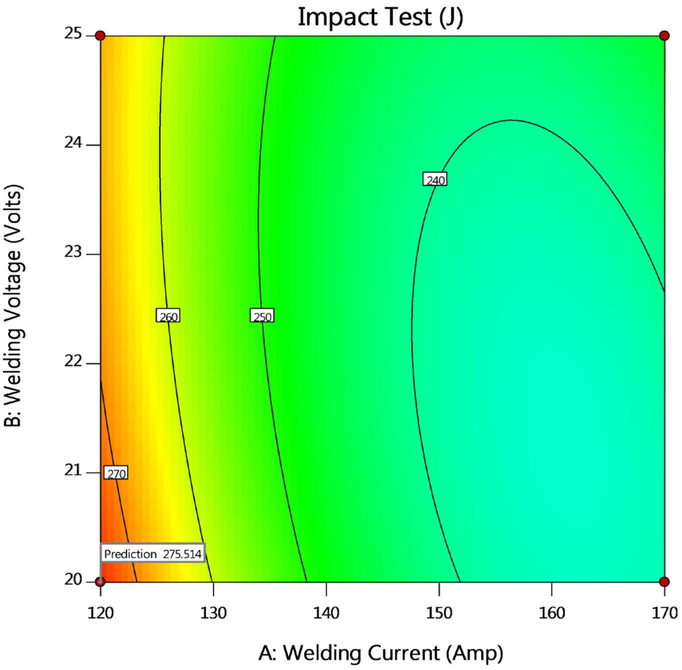

Figure 5. Predicting weld impact test using contour plot.

3.2. Discussion

The Fit Statistics for the Impact Test in Table 3, shows that The R^2 value of 0.9354, Predicted R^2 of 0.7463 and an Adjusted R^2 of 0.8773 were obtained. The difference between the predicted and adjusted R^2 of less than 0.2 was recorded, indicating a significant model. With an adequate Precision of 12.805, demonstrating a significant model. It meant that the mathematical model in Equation (1), can be employed to navigate the design space. In Figure 2, the reliability plotdeveloped was employed to compare the predicted response values obtained from using Equation (1) to that of the actual response. Based on the plot, it was observed that a positive linear relationship existed between the predicted and the actual response, with majority of the points clustering along the stright line. This indicates a good prediction model which can be employed for unknown prediction of the impact test. Figure 3 shows the 3D surface plot for the impact test with the lower impact test area denoted by the blue region and the green region representing the area with the highest impact strength. The 3D surface plot was used to determine the effect of current and voltage at a gas flow rate of 13 L/min on the impact test responses. From Figure 3, it was noticed that only current had a very strong effect on the response. Optimization was initiated using the interphase presented in Figure 4 with the lowest and highest impact of 219.128 and 278.096 being the optimization boundary space. Five (5) optimal results were selected as shown in Table 5 with the best having a current of 120.00 Amp, voltage of 20.00 volt and gas flow rate of 12.00 L/min, to produce a weld material with impact test of 275.514 joules at a desirability value of 95.6%. To further understand better, the effect of the process parameters on the response, Figure 5 was employed. This plot also known as the contour plot, shows that at a constant gas flow rate of 12 L/mm, quality weld can be achieved with voltage ranging between 20 - 25 volts, and a current range of about 120 - 125 amp, represented the red area on the plot in Figure 5. It shows that current has a significant effect on either increasing or reducing the material toughness. From the contour plot, it was noticed that lower current between 120 - 125 amp produced better impact test as compared with higher current input of 170 amp.

4. Conclusion

In this study a mathematical model for predicting impact test in Equation (1) has been developed with and an optimum impact test of 275.514 joules at a desirability value of 95.6%. This optimum impact test was achieved through the use of current of 120.00 amp, voltage of 20.00 volt and gas flow rate of 12.00 L/min. The weld current was found to have a great influence on the impact strength of the weldment as compared to voltage and gas flow rate at a moderate level.

Conflicts of Interest

The authors declare no conflicts of interest.

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