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Experimental Evaluation of the Optimal Strength and Fatigue Life of a Gas Tungsten Arc Welded Joints Using RSM and GA.

[1]S. O. Sada, [2]J. Achebo and [2]J. Osarenwinda

[1]Department of Mechanical and Production Engineering, Faculty of Engineering, Delta State University, Oleh Campus, Nigeria.
[2]Department of Production Engineering, Faculty of Engineering, University of Benin. Benin City, Nigeria.
sosada@delsu.edu.ng

Research Article

Abstract

Research has shown that fatigue failure is a major concerned for manufacturers, as it has been recorded that a good percentage of manufactured products and structures, especially those with welded joints, tend to fail as a result of being subjected to loads, often beyond their designed capacity. This study explores the application of optimization techniques such as Response Surface Methodology (RSM) and Genetic Algorithm (GA) in determining the optimal Impact Strength, tensile strength and Fatigue Life of a Gas tungsten arc welded plate with the aim of ascertaining the optimal fatigue life and strength of the weld. With the application of both techniques, this study obtained the most adequate optimal process parameter with the GA recording the most accurate performance. The RSM recorded optimal Impact Strength, tensile strength and Fatigue Life values of 576.609N/mm2, 491.462N/mm2 and 288306cycles respectively, while the GA recorded optimal impact strength, tensile strength, and fatigue life values of 587.25N/mm2, 489.81N/mm2 and 299635.0 respectively at the 119 iteration. Confirmatory test performed using the optimal values revealed that the GA technique had the most accurate performance with a percentage error of 3% compared to the RSM results which recorded an error of 11%.

Keywords: Fatigue Life, Tensile Strength, Impact Strength, Genetic Algorithm

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1. Introduction

Welding is one of the predominant process of joining employed in the construction and manufacturing industries, a good number of the welding processes has been designed to suit different structures and components utilized in these industries. The reliability of these structures is dependent on obtaining a welded joint free from defects and possessing sufficient static and fatigue strengths. However, the welds in most of these structures, are very critical areas prone to mechanical and or metallurgical failures arising from several complex interaction which the design is subjected to either during fabrication or application stages which invariably affects the fatigue life (Khurshid, 2017). In many cases, failure commences at the welded joints basically due to the disparity in strength between the weld area and the parent metal in addition to other related unknown properties (Gagg 2005). Therefore, it is important that accurate methods are established during the design stages of the welding process, to enhance the performance of machines and structures against fatigue failures.

Research has shown that several factors such material thickness, residual stress, environmental effects and discontinuities have a magnitude of effects on the fatigue properties of welded structures (Ngiam, 2007), with each of them recording difference in their influence. According to Chaudhari and Belkar, (2014) discontinuities which create potential nests for localized stress concentration poses the greatest challenge to fatigue properties. These feature according to Stenberg et al (2012) comprises weld toe transition radius, as well as weld penetration, the inner lack of fusion, undercut, cold lap size, porosity and joint misalignment etc. A study conducted by Sanders and Lawrence (1997) on the effect of lack of fusion (LOF) and lack of penetration (LOP) on the fatigue behavior of a double-V aluminum alloy weld, shows that the fatigue life of a weld is seriously affected by defects due to lack of penetration. Lee *et al.* (2009) in his study of the influence of weld joint geometry on fatigue resistance using cruciform-shaped specimens, reported that increase in the weld flank angle and toe resulted in a gradual increase in the resistance to fatigue. Boukharouba, *et. al.* (1999) also in his study on the effect of stress concentration factor on weld geometry based on experimental and finite element methods result reported that a decrease in the fatigue life of welded joints was observed.

In improving the design of the welded joints against fatigue, three different local approaches (the notch stress or strain approach, elastic structural stress or strain approach and the fracture mechanics approach) has been reported (Radaj 1996). Balasubramanian and Guha (1999), reported that with result obtained from the elastic structural stress or strain approach, the optimal fatigue life of a welded jointed can be determined through the application of improved optimization techniques. A few studies have been performed using non-conventional techniques (Karupanan *et al.,* 2014). Generally, optimization process comprises of two main methods; classical and statistical methods. The classical method which involves the system of alternating one of the independent variables while others are kept fixed is popularly referred as the 'One-factor-at-a-time' (OFAT) method. One major drawback of the classical method is the inability to guarantee determination of optimal process conditions as well as study the model terms interactions, which makes it unreliable and inaccurate (Sada 2018). On the hand, with data obtained from experimental test, the statistical optimization method is capable of overcoming limitations associated with the classical method by making use of data obtained from experimental procedures in determining empirical models with which optimal conditions can be determined. It has been proven to be very useful for experimental design, model building, and evaluation of process parameter effect as well as analysis necessary in determining optimal process parameters. Statistical methods can be categorized into two; design of experiment and Iterative mathematical search techniques. The design of experiment comprises the Factorial method, Taguchi method, and Response surface design methodology (RSM) while Iterative mathematical search techniques, such as linear programming (LP), non-linear programming (NLP), and dynamic programming (DP) algorithms (Modenesi et al., 1999).

This study explores the adequacy of the Response Surface Methodology (RSM) one of the techniques applied in statistical optimization method which captures the interactive effect of model terms, along with genetic Algorithm (GA) approach, in determining optimal static and fatigue strength of a welded joint based on elastic structural stress or strain approach.

2. Methodology

Materials: A mild steel plate of 6mm thickness was selected as specimen for the experiment, alongside 100% Argon gas (EN ISO 14175−M21−ArC−18) as the shielding gas and a wire union X96 (EN ISO 16834−A−G Mn4Ni2, 5CrMo) filler metal.

Methods: In performing the welding experiment, process parameters and their ranges as tabulated in Table 1, were selected for the experiment based on the knowledge from previous studies (sada 2018) on weld input parameters related to weld discontinuities.

Furthermore, one of the response surface design known as the central composite design (CCD) was employed in developing a four factor experimental matrix comprising 30 experimental run using Design Expert V.12, according to the selected process as shown in Table 2.

Table 1: Process Parameters and their Ranges

Parameters	Weld Current (Amp)	Arc Voltage (volts)	Gas Flow Rate (lit/min)	Filler Rod (mm)
Range	140 -200	15-25	2.4-3.2	20-24

Table 2: Three Level CCD Experimental Matrix

Exp No	Weld Current (Amp)	Arc Voltage (volts)	Gas Flow Rate (lit/min)	Filler Rod (mm)
1	200	15	24	2.4
2	200	15	24	3.2
3	200	15	20	3.2
4	170	20	18	2.8
5	140	15	24	2.4
6	230	20	22	2.8
7	170	20	22	2.8
8	170	20	26	2.8
9	110	20	22	2.8
10	200	15	20	2.4
11	140	15	24	3.2
12	200	25	20	3.2
13	170	10	22	2.8
14	200	25	20	2.4
15	170	20	22	2.8
16	200	25	24	3.2
17	170	30	22	2.8
18	140	15	20	3.2
19	140	25	20	2.4
20	140	15	20	2.4
21	140	25	24	2.4
22	170	20	22	2.8
23	170	20	22	3.6
24	170	20	22	2.8
25	170	20	22	2.8
26	200	25	24	2.4
27	140	25	24	3.2
28	140	25	20	3.2
29	170	20	22	2.8
30	170	20	22	2.0

With the use of the gas tungsten arc welding (GTAW) process the experimental run was applied individually to each coupons which had earlier been designed to a V-shaped butt joint. Figure 1 shows a pictorial view of the connected weld geometry before welding.

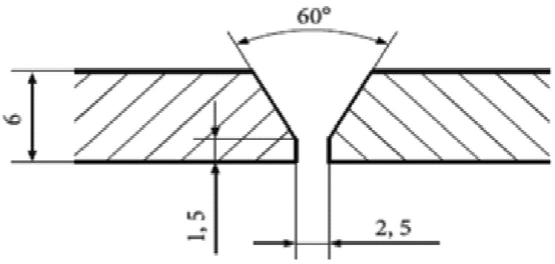


Figure 1: Geometry of welded elements prior to the implementation of joints

Test Specimen Preparation**:** Flat samples representing the test specimens were prepared on the basis of standard ASTM E606-4 from the welded plate as shown in Figure 2. For the purpose of obtaining specific properties of the welded material, as well as the stress-strain curves, the the cross sectional area of the welded plates grinded and polished to mirror finishing form, using 1 mm diamond paste. Thereafter tensile test were carried out according to EN ISO 6892-1:2009 (British Standard: Metallic materials tensile test) at ambient temperature with the aid of the Instron 3369 testing device (Instron 3369 device specification: 0.05 to 500 mm/min speed range and 50KN maximum capacity). The testing machine with extensometer attached, was set in displacement control loading mode, and each samples was loaded at a speed of 5 mm/min.

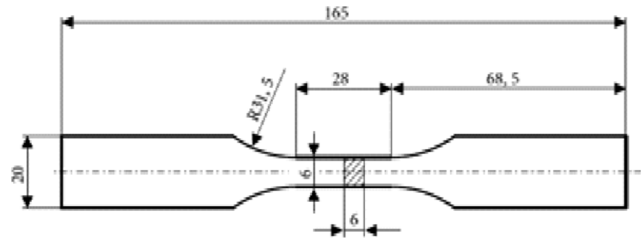


Figure 2: Geometry of tensile test specimen (EN ISO 6892-1:2009)

Figure 2 shows the geometry of the test sample, dimensioned as follows; overall length 165 mm, grip length 68.5 mm, reduced section 28 mm, material thickness 6.5 mm thickness.

2.1 Fatigue Life of a Component

The fatigue life of a structural component is a representation of the number of load cycles required for a fatigue crack to initiate and propagate to a critical size. It involves the following three stages; crack initiation, crack growth and rapid fracture (Berkovis, et. al., 1998). As the crack propagates to a certain point, fracture toughness is exceeded leading to rapid fracture of the cross-section of the material, a stage referred to as fatigue failure (Schijve, 2003). This process in fatig ue design involves two types of load history (Berkovis, *et. al.*, 1998); the constant-amplitude cyclic load (Figure 3) which occurs normally in the laboratory during fatigue testing and the variable–amplitude loading. The constant-amplitude loading involves the following parameters; stress range, stress amplitude, mean stress, stress ratio (Lu & Makelainen, 2003).

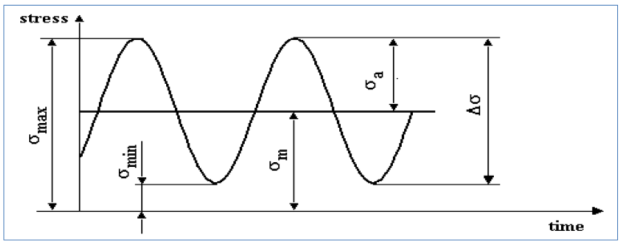


Figure 3: Constant-amplitude loading Nomenclature (Lu & Makelainen, 2003)

The variable–amplitude loading (Figure 4) in contract to the constant amplitude loading has complex analytical function representation. Based on statistical data, the variable–amplitude loading accounts for 80% of structural fatigue failure (Lu & Makelainen, 2003). Techniques such as short time Fourier transform and wavelet methods are example of methods which have been applied to idealize this load closer to laboratory load.

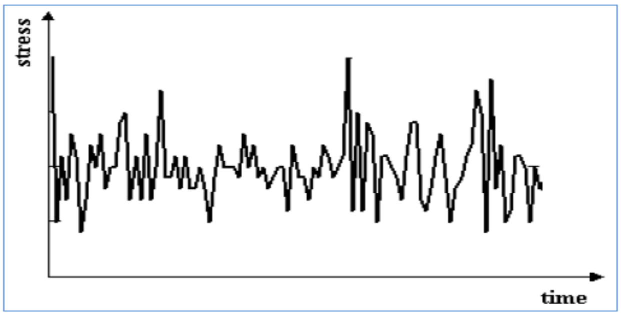


Figure 4: Variable amplitude loading (Lu & Makelainen, 2003)

2.2 Experimental Fatigue Testing

The constant amplitude uniaxial loading which is mostly used for fatigue testing of welded joints was employing in carrying out the test under low-cycle fatigue (LCF), using an Instron 8808 hydraulic fatigue testing machine equipped with a dynamic extensometer having a 50cm gauge length. The experiments was performed on all specimens under a control load condition subjected to tensile load cycled sinusoidally at 1 Hz frequency, with loading direction observed transverse to the weld direction. The number of cycles were recorded when the displacement limit was triggered at a failure criterion of complete rapture. The results obtained including the tensile test were recorded and tabulated as shown in Table 1.

2.3 Process optimization

Second-order polynomial which has a general form as presented in Equation 1, was employed in fitting the response variable in order to obtain a correlation between the response and independent variables, with the aid of the statistical software Design Expert, the second-order polynomial coefficients were calculated and analyzed.

$$y = \beta_o + \sum_{i=1}^{k} \beta_{ij} x_i^2 + \sum_{j=1}^{k} \beta_{ij} x_i^2 + \sum\sum \beta_i x_i x_j + \varepsilon \quad for\ i < j \qquad (1)$$

Where, y represents the response, β_o the intercept, β_i the linear coefficient, β_{ij} the quadratic coefficient, β_{ii} is the linear-by-linear interaction between the regression coefficients x_i and x_j and x_i, x_j the input variables.

Statistical analysis of the model was performed to evaluate the analysis of variance (ANOVA), for each of the responses to determine the overall model significance. This analysis comprises of Fisher's F test (overall model significance), its correlation coefficient R, determination coefficient R^2 which is a measure of the goodness of fit of regression model.

2.4 Optimization using genetic algorithm

The basic concept of Genetic Algorithm (GA) involves encoding a potential solution to a problem to fit a series of parameters. Each set of parameter value is referred to as the genome of an individual solution. The GA technique is based survival of the fittest among different individuals over consecutive generation consisting of a population of individuals, which are generated randomly (Asokan *et al.* 2005). In every generation the individuals are decoded according to a fitness function in the current population and chromosomes with the highest population fitness are selected for mating. New genes which replaces the earlier ones in a new generation are produced through the exchange of each parameter, thus creating a set of current population. The iteration process is terminated at the completion of a maximum number of generations or at the attainment of a suitable result (Palaniswamy *et al.* 2007).

Using GA solver of the MAtlab 2015a, the optimization of the responses was performed with the consideration of the following parameters; 100 population size, (RX) Mutation function, 2 elite counts and (PMX) Crossover function. The computation of the GA) process utilizes the steps below (Sada, 2020).

(1) Initial creation of 100 random initial combinations through the selection of process variables and the estimated fitness value.

2) Computation of a combination of new population through the application of the GA biological progression method as enumerated in steps a-c below.
   (a) Using the Rolette wheel selection algorithm determine the best fitness value for the proper process parameter combination.
   (b) Consider as elite the combinations possessing the slightest fitness value.
   (c) Generate offspring generation based on the considered mutation and Crossover combination.

3. Results and Discussion

The result of the impact strength, tensile strength and the fatigue life of the weld is presented below in Table 3.

Table 3: Result of Test Performed on Welded Joint

Exp Run	IMPACT Strength N/mm^2	TENSILE Strength (J)	Fatigue Life (No of cycles)
1	481.5	560.3	282000
2	496.3	580.5	289111
3	486.4	454.3	281900
4	495.9	440.6	281000
5	496.3	594.2	268900
6	476.2	571.1	279500
7	496.8	581.3	295000
8	501.0	583.6	285000
9	485.9	621.6	276000
10	473.4	504.2	283100
11	472.3	562.3	283000
12	490.0	526.4	279000
13	450.3	513.8	278200
14	485.0	553.8	277000
15	488.7	600.5	286000
16	469.6	637.0	279500
17	480.3	577.6	283200
18	446.3	505.7	279000
19	504.0	587.3	275100
20	476.1	601.5	269900
21	492.3	573.6	274800
22	488.1	570.6	285300
23	477.8	543.2	284500
24	489.0	572.3	299800
25	485.0	546.4	296200
26	457.7	583.8	280700
27	472.3	561.8	284700
28	482.1	500.1	281000
29	486.3	587.0	288600
30	485.2	544.9	275700

Analysis of variance (ANOVA) as presented in Table 4, 5 & 6 was employed to determine the model signification. With results obtained as evident in the Fishers test, the quadratic regression model demonstrates a highly significant model, haven recorded a very high probability value ($p<0.001$) for each of the responses.

Table 4: ANOVA for Tensile Strength

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	5045.05	14	360.36	14.36	<0.0001	Significant
A-Weld Current	18.73	1	18.73	0.7461	0.0013	
B-Weld Voltage	296.81	1	296.81	11.83	0.0037	
C-Gas Flow Rate	1.13	1	1.13	0.0449	0.8351	
D-Filler Rod	180.40	1	180.40	7.19	0.0171	
AB	564.06	1	564.06	22.47	0.0003	
AC	184.96	1	184.96	7.37	0.0160	
AD	1232.01	1	1232.01	49.09	<0.0001	
BC	1112.22	1	1112.22	44.31	<0.0001	
Residual	376.49	15	29.15			
Lack of Fit	291.46	10	17.01	1.71	0.2871	not significant
Pure Error	85.03	5	0.1029			
Cor Total	5421.54	29				

Table 5: ANOVA for Impact Strength

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	53553.12	14	3825.22	14.25	<0.0001	Significant
A-Weld Current	1460.16	1	1460.16	5.44	0.0340	
B-Weld Voltage	3465.61	1	3465.61	12.91	0.0027	
C-Gas Flow Rate	20779.93	1	20779.93	77.43	<0.0001	
D-Filler Rod	2281.50	1	2281.50	8.50	0.0107	
AB	3678.42	1	3678.42	13.71	0.0021	
AC	3180.96	1	3180.96	11.85	0.0036	
AD	3102.49	1	3102.49	11.56	0.0040	
Residual	57578.71	15	268.37			
Lack of Fit	2357.97	10	235.80	1.71	0.2871	not significant
Pure Error	1667.62	5	333.52			
Cor Total	5421.54	29				

Table 6: ANOVA for Fatigue Life

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.171E+09	14	8.367E+07	5.46	0.0012	Significant
A-Weld Current	7.672E+07	1	7.672E+07	5.01	0.0408	
B-Weld Voltage	9.959E+05	1	9.959E+05	0.0650	0.8022	
C-Gas Flow Rate	2.544E+07	1	2.544E+07	1.66	0.0071	
D-Filler Rod	1.670E+08	1	1.670E+05	10.90	0.0048	
AB	7.530E+07	1	7.530E+07	4.91	0.0425	
Residual	2.298E+08	15	1.523E+07			
Lack of Fit	5.012E+07	10	5.012E+06	0.1394	0.9957	not significant
Pure Error	1.797E+08	5	3.595E+07			
Cor Total	1.401E+09	29				

Among the four variables tested, weld current, arc voltage and filler rod size had the most significant effect on the model based on their p values (p<0.001). However, despite their positive effects, they exhibited a negative interactive effect on the model.

3.1 Mathematical Model

The mathematical model relating the responses with the independent process variables, A, B, C and D signifying the weld current, arc voltage, gas flow rate, and filler rod size respectively have been represented by the second order polynomial equations given in equations 2, 3 and 4 respectively.

$$\boldsymbol{Impact\ Strength} = 1429.010 - 12.959A - 5.542B + 82.617C - 524.354D + 0.101AB + 0.235AC + 1.160AD - 0.268BC + 2.631BD + 22.656CD + 0.007A^2 - 0.267B^2 - 3.771C^2 - 44.349D^2 \quad (2)$$

$$\textbf{Tensile Strength} = 194.770 + 0.804A + 35.554B - 0.500C - 85.895D - 0.0395AB - 0.056AC + 0.731AD - 0.834BC + 0.031BD + 1.281CD - 0.002A^2 - 0.247B^2 + 0.530C^2 - 13.229D^2 \quad (3)$$

$$\textbf{Fatigue Life} = -4.284E05 + 2127.452A + 8540.062B + 23174.114C + 1.276D - 14.462AB + 4.074AC - 168.172AD - 9.444BC - 390.969BD + 1102.421CD - 4.109A^2 - 118.454B^2 - 596.586C^2 - 19445.898D^2 \quad (4)$$

Result from the goodness of fit statistical analysis of the regression model reports, R^2 (determination of coefficient) value of 93.06% was obtained for the tensile strength, 93.01% for the impact strength and 83.6% for the fatigue life. To validate the results of R^2 values obtained, a comparison was made between the R^2 values and adj. R^2, an acceptable range of 0.02 was obtained as difference between the parameters, an indication that the model is a good predictor of the responses. In addition to the above results recorded, the developed models was used in carrying out prediction of the responses. A plot of the predicted results against the experimental results obtained earlier as shown in Figure 6, shows the error is uniformly distributed.

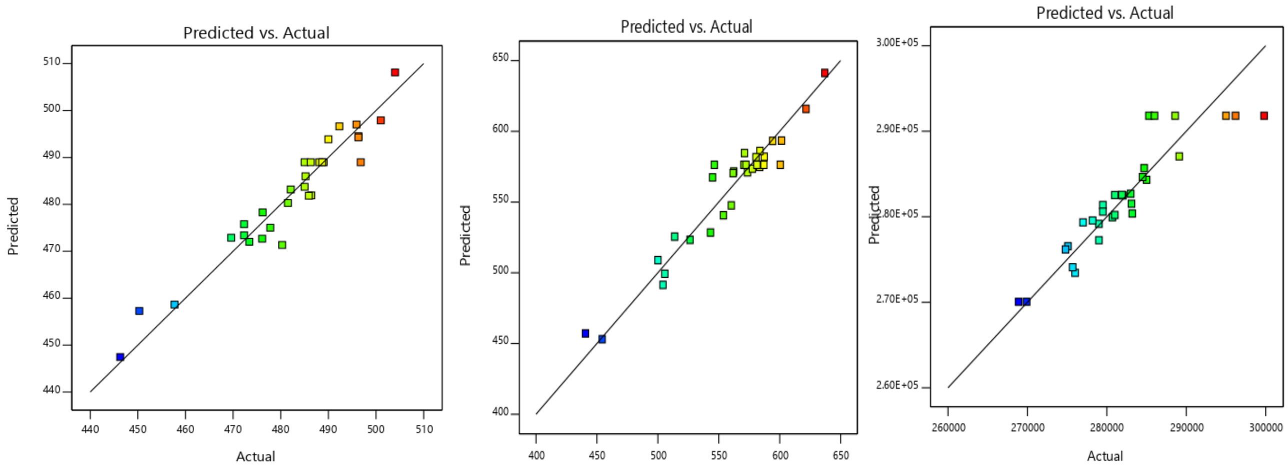


Figure 5: Observed versus Predicted Values for the Responses

Surface Response of Combined Parameters against the Responses

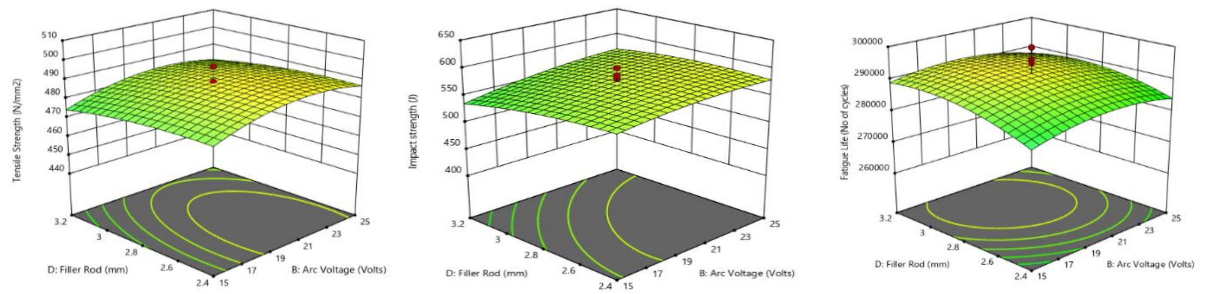


Figure 6: Effect of Arc Voltage and Filler Rod on the Tensile Strength

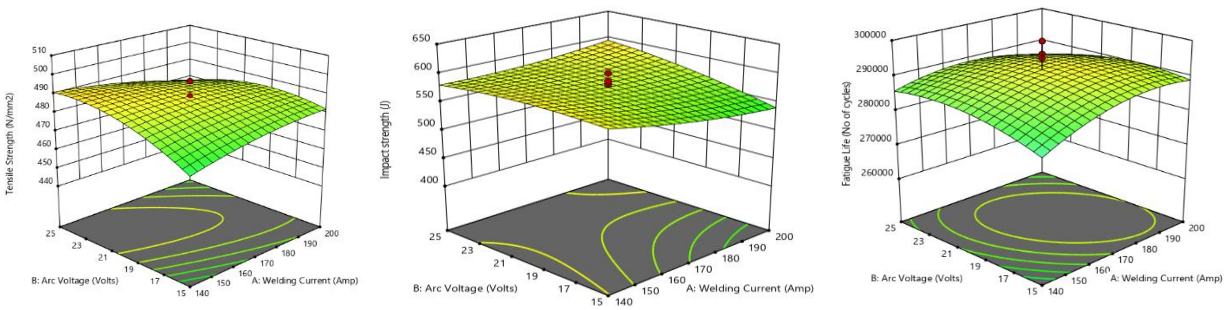


Figure 7: Effect of Weld current and Arc Voltage on the Tensile Strength

As shown in figures 5, 6 & 7 respectively, the variation of the process parameters (weld current and arc voltage) remarkably affected the responses of the material. The same observations were reported for the combined effect of arc voltage and filler rod. As the parameters were increased, the tensile strength displayed a corresponding increase up to a certain point where further increase resulted in a decrease, this collaborates the finding of (Sada 2018) who observed that further increase in current and voltage resulted in decreased mechanical properties.

As observed in figure 8 & 9 respectively, no remarkable effect was observed in the variation of gas flow rate/filler rod and weld current on the responses except for the fatigue life, where an increased in the current resulted in a decline.

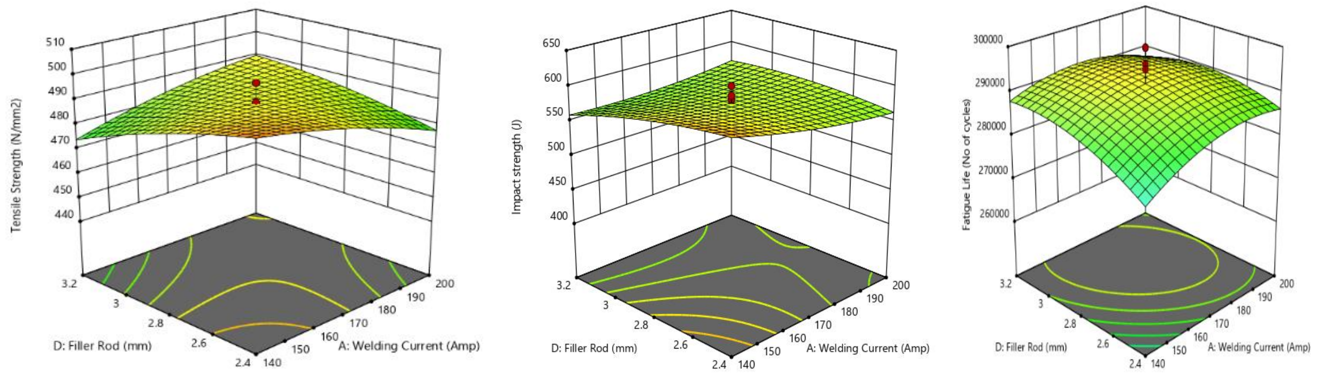


Figure 8: Effect of Weld Current and Filler Rod on the Impact Strength

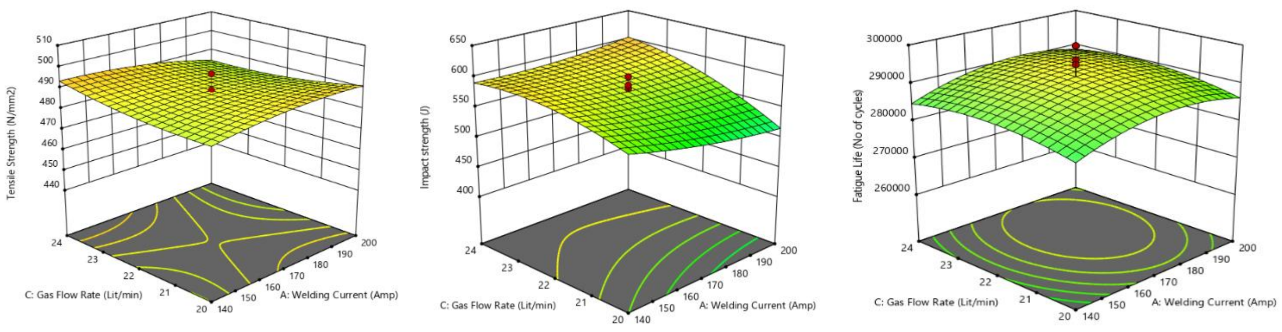


Figure 9: Effect of Weld Current and Gas Flow Rate on the Impact Strength

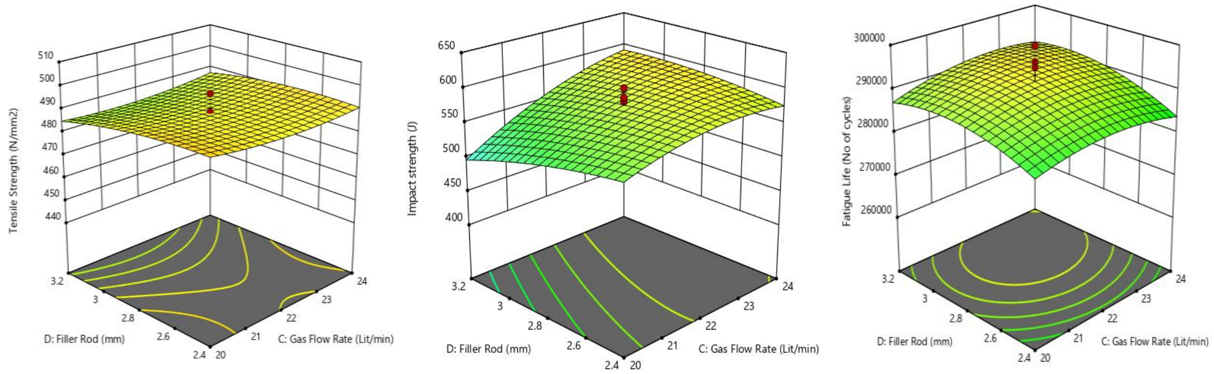


Figure 10: Effect of Gas Flow Rate and Filler Rod on the Impact Strength

3.2 Numerical Optimization

Design expert software was used in performing the numerical optimization of the responses in order to ascertain the desirability of the overall model. With the software set at maximize for the responses, optimal tensile strength of 491.462N/mm^2, impact strength of 576.609N/mm^2, and fatigue life of 288306cycles was observed at a current of 200.00amp, voltage 15.00volt, gas flow rate 24.00l/min and filler rod 2.93mm at desirability value observed at 0.811.

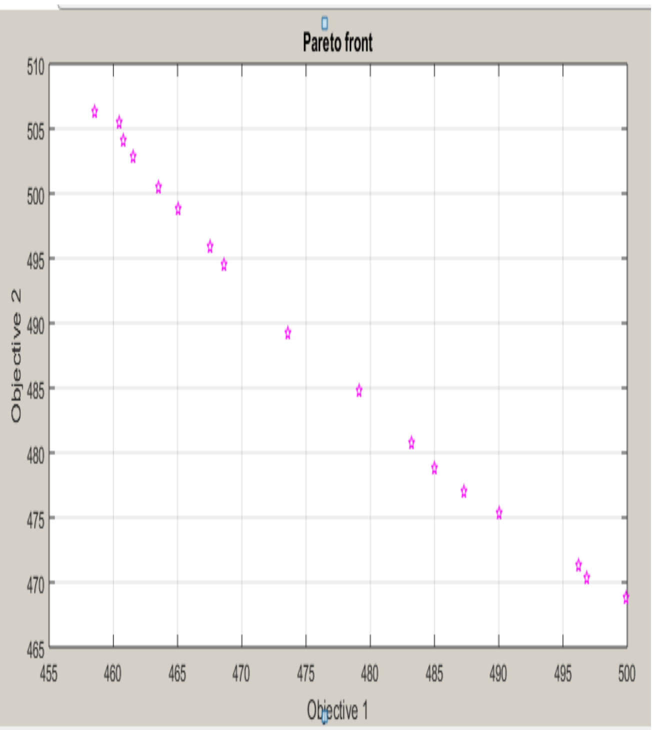
3.3 Genetic Algorithm

The optimization of the responses using Genetic Algorithm was applied by employing the regression model obtained in equations 2, 3, and 4 as the objective function in the algorithm. The result obtained at 119 iterations shows that an optimal impact strength, tensile strength, and fatigue life values of 489.81N/mm^2, 587.25N/mm^2, and 299635.0 respectively was obtained at a combined input variables of weld current 197.30amp, arc voltage 15.65volts, gas flow rate 23.99l/mm and filler rod 2.80mm. A plot showing the Pareto front of the three objective functions is presented in figure 11, with the plot function, the performance of the solver for the responses at run time is visualized.

From the graphics shown (Figure 11), each of the solution obtained is revealed from the points, an indication that a reasonable Pareto front representation has been obtained. From the plot, it can be further deduced that the solutions are non-dominated (Vijayan and Abhishek, 2018) since there are no other solution resulting in lower objective function values.

3.4 Confirmatory Test

Confirmatory test was conducted using the optimized input process parameter obtained from both optimization techniques and tabulated as shown in Table 6.



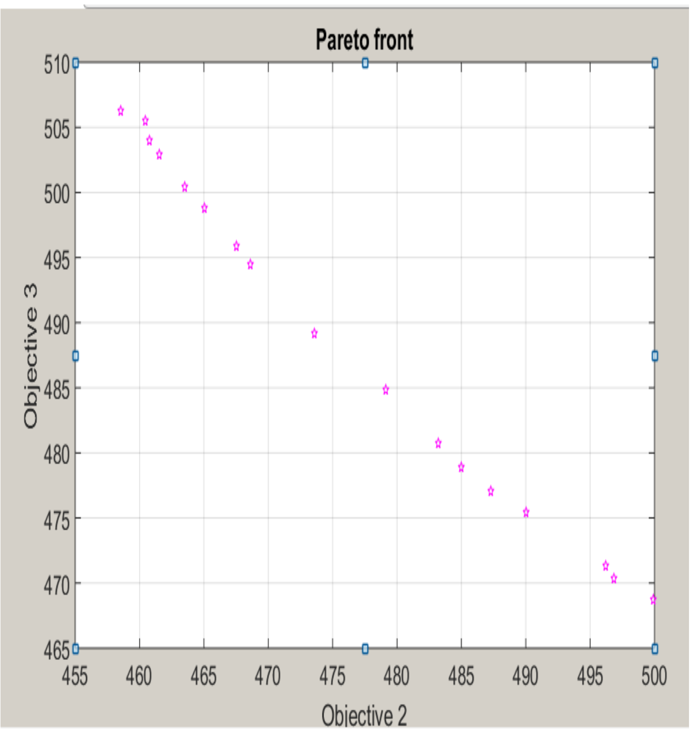


Figure 11: Pareto Optimal Set of the Objectives function

Table 7: Results of Comfirmatory Test

Parameter	Responses Tested								
	IMPACT Strength N/mm^2			**TENSILE Strength (J)**			**Fatigue Life (No of cycles)**		
	Optimization	Exp.	Diff.	Optimization	Exp.	Diff	Optimization	Exp.	Diff
RSM Parameters	576.61	531.50	45.11	491.46	443.63	47.83	288306.00	288213.00	93.00
GA Parameters	489.81	473.54	16.27	587.25	568.25	19.00	299635.00	299621.00	14.00

The results obtained were compared to check the accuracy of the optimum weld parameter generated by comparing the optimal parameters to experimentally obtained values. A higher accuracy value was recorded for the results obtained from the GA technique.

4. Conclusions

The determination of the optimal fatigue life as well as tensile & impact strength of a GTAW welded joint was successful carried out using the response surface methodology (RSM) and genetic algorithm (GA) techniques. With the aid of Analysis of variance (ANOVA), mathematical models of the responses developed using regression analysis were validated, the result revealed that the model terms; weld current, arc voltage and filler rod diameter had the most significant effect on the model based on their p values ($p<0.001$). The test also revealed that the models is a good predictor of the responses haven obtained R2 values of 93.06%, 93.01%, and 83.6% for the tensile strength, impact strength and fatigue life respectively.

The GA result obtained at 119 iterations shows that an optimal tensile strength, impact strength, and fatigue life values of 489.81N/mm2, 587.25N/mm2, and 299635.0 respectively was obtained at a combined input variables of weld current 197.30amp, arc voltage 15.65volts, gas flow rate 23.99l/mm and filler rod 2.80 mm. While the RSM result recorded optimal tensile strength, impact strength, and fatigue life values of 491.462N/mm2, 576.609N/mm2, and 288306cycles at a combined process parameters of 200.00amp for weld current, 15.00 volt for arc voltage, 24.00l/min for gas flow rate and filler rod 2.93mm. Confirmatory test performed using the optimal values revealed that the GA technique had the most accurate performance with a percentage error of 3% compared to the RSM results which recorded an error of 11%.

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