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Research Article

Optimization Of The Ductile Properties Of A Arc Welded Plate Based On The Yield Strength, Elongation And Modulus Of Elasticity

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Abstract

As a means of controlling the setback associated with the ductile properties of the welded joint, the optimal ductile properties of a mild steel weld were studied based on empirical data generated using the metal inert gas (MIG) welding process with specific references to the yield strength, percentage elongation, poisson ratio and modulus of elasticity using the Response Surface Methodology (RSM) and Genetic Algorithm (GA). The results judging from the remarkable quality of the ductility of the weld reveals the adequacy of the yield strength, poisson ratio, and percentage elongation as key determinant in ascertaining the ductility of a weld as against the tensile strength which have been widely used in previous studies. Further analysis to determine the optimal ductile properties using the optimization techniques generated two different results which were further compared by means of a confirmatory test. The GA results recorded a more accurate optimal responses compared to the RSM having a yield strength of 270.28N/mm^2, 31.01% percentage elongation, 0.359 poisson ratio, and modulus of elasticity of 1660.3N/mm^2. The results not withstanding their differences reveals that manufacturers can obtain the optimal ductile weld properties using the GA and RSM techniques if the right combination of process parameters is made.

Keywords: Welding; Yield strength; Modulus of elasticity; Elongation; Optimization.

1. Introduction

The production of strong and durable connections between metal materials has been made possible by means of the different welding processes. With these welding processes, the manufacture of strong and durable mechanical components and engineering structures devoid of the regular setbacks associated with joining processes such as riveting and bolts has been overcome (Stenberg et al., 2017). Besides the advantage of having permanent joints provided by applying welding, critical structures and mechanical components requiring the assembled of multiple components with differing properties have been made possible. However, the efficiency of the welding process which comprises the strength of the weld and its performance capacity in withstanding any given load is dependent on the metallic continuity across the metal or members being joined. According to Sada (2018a), in considering the design of a weld, the purpose for which the welded joint is been designed for and a number of factors such as, the loading of the joints, the welding process and the geometry of the structure and the type of steel must be considered. These key factors when not properly considered, ultimately results in the short lifespan of the structure, leading to the formation of a fracture and subsequent structural failure (Griffith 1993). Zuheir et al. (2017), identified ductile failure as a very common failure mode associated with welded metals owing to excessive plastic deformation. According to Somer and Pense (1994), these failures can be attributable to five categories of causes: weld geometrical design, weld process parameters, material-process incompatibilities, weld process execution, and anticipated service requirements. Based on the report of Becker and Shipley (2002), a wide range of failed welded joints, which have mostly been attributed to the aforementioned factors, with many cases recording catastrophic loses can be overcome if proper diligence is observed by applying improved weld techniques. Nathan et al., (2015) reported in their study that among numerous techniques, determining the right combination of process parameters can enable manufacturers control these factors and produce superior joint strength. Different researchers (Haragopal, et. al., 2011; Sittichai, et al., 2012; Palani, et. al., 2013; Mahadevi and Manikandan 2014; Rohit and Jha 2014; Kadaganchi et al., 2015; Amit 2015; Satnam, et al., 2015; Choudhary and Duhan 2015; Abhyankar, et al., 2016; Monika and Jagdip 2017; Nabendu, et al., 2017) in a bid to solving these challenges considered the adequacy of employing optimal combination of process parameters in controlling the ductile properties of the welded joints through the application of statistical means. As presented in

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Table 1, with references to the type of weld specimens, welding process, process parameters, and optimization techniques studied, tensile strength and percentage elongation have been the most featured parameters used in analysing the ductility of the welded joints.

Table 1
Taxonomy of Related Studies Based on Input and Output parameters.

Ref.	Weld Specimen	Welding Process Types	Optimization Technique Applied	Process Parameters Studied	Response Evaluated
Amit 2015	Mild Steel	GTAW	Taguchi	welding voltage, filler wire rate and v-butt angle	tensile strength and elongation
Monika and Jagdip 2017	Mild Steel	GMAW	Taguchi	welding current, voltage, gas flow rate, welding speed and gas pressure	tensile strength and percentage elongation
Nabendu, et al., 2017	Austenitic Steel	GMAW	Taguchi	current, gas flow rate and nozzle to plate distance	tensile strength and percentage elongation
Sittichai, et al., 2012	Steel	GMAW	Factorial	shielding gas mixture, welding current and welding speed	ultimate tensile strength and percentage elongation
Mahadevi and Manikandan 2014	Magnesium	GTAW	RSM	welding current, welding speed, arc voltage, electrode stick out	tensile strength and percentage elongation
Palani, et. al., 2013	Aluminium	GTAW	RSM	travel speed of welding, current and flow rate of gas	tensile strength and percentage elongation
Kadaganchi et al., 2015	Aluminium	FSW	RSM	spindle speed, welding speed, tilt angle and tool pin profile	yield strength, tensile strength and elongation
Haragopal, et. al., 2011	Aluminium	GMAW	Taguchi	gas pressure, current, groove angle and pre-heat	tensile strength, percentage elongation and impact energy
Satnam, et al., 2015	Mild Steel	SAW	RSM	gas pressure, current, groove angle	tensile strength and percentage elongation
Rohit and Jha 2014	Mild Steel	SMAW	NIL	welding current, welding speed, arc voltage, and Joint design	tensile strength, yield strength, and percentage elongation
Choudhary and Duhan 2015	Stainless Steel	GTAW		welding current, welding speed, arc voltage, and Joint design	tensile strength, percentage elongation, Penetration depth, width and depth to width ratio
Abhyankar, et al., 2016	Stainless Steel	GTAW	Taguchi	current, electrode angle and welding speed	Hardness (H) & Ultimate Strength
Kumar S. 2010.	Aluminium	GTAW	Experimental study	welding current, welding speed and frequency	ultimate tensile strength (UTS), yield strength, hardness and percent elongation

However, based on the findings of sada (2018a), tensile strength is inadequate in determining or evaluating the ductility of a welded joint, as it is mostly associated to failure arising from fracture under static loading. A prominent feature of ductility which they failed to consider is the yield strength of the weld metal, a very key parameter in the analysis of failures arising from plastic deformation. Besides this notable lapses, most of the studies reviewed have been on the use of statistical optimization techniques, thereby basing their findings without any comparism to other known techniques such as the genetic algorithm (GA) (Correia, et al., 2004) and Artificial Neural Networks (ANN) (Sette et al., 1996). Fatehi-Kivi et al., (2021) reports that genetic algorithm (GA) techniques is very powerful and useful in handling combinatorial optimization problems. Javadian et al., 2021 states also that machine learning algorithms such as genetic algorithm are often applied on the bases of classification accuracy, performance speed, and solution accuracy and quality. According to Kim and Rhee (2001), Genetic algorithm, when compared to techniques such as full-factorial experiments, Taguchi, and Response Surface Methodology (Sada and Achebo 2020) etc, can overcome problems often encountered in obtaining the near optimal condition.

This study focuses on improving the ductile properties of a mild steel gas metal arc weld, by evaluation the responses; yield strength, modulus of elasticity, poisson ratio and percentage elongation through the application the response surface methodology and genetic algorithm optimization techniques:, with the aim of determining the best optimal parameters.

2. Methodology

The Gas metal arc welding (GMAW) process has been selected for the experiment, and a mild steel plate of 10mm thickness, designed with a 30º single V edge butt joint, was selected as specimen for the experiment. Based on the findings from selected literature, the following input process parameters with very significant effect on the weld have been identified; **w**elding current, arc voltage, flow rate, and filler rod.

To perform the experiment, 30 experimental run was generate with the aid of the central composite design using the design expert software. The test for the responses: yield strength, percentage elongation, poisson ratio and modulus of elasticity, were performed at the completion of the welding process, using specimens cut at cross section of each welded plate.

2.1 Optimization Technique

2.1.1 Response Surface Methodology

Developing the response surface models basically involves three phases; the generation of the factors or variables, the factor levels or setting, and the use of an optimization technique also known as the method of steepest ascent (descent) (Myers and Montgomery, 2002). In performing the optimization, the first-order model is applied, which is given in terms of coded variable as shown in equation 1:

However, due to curvature introduced by the interaction of factors into the response function, the first-order model becomes inadequate (Sada 2018b). Hence the need for a second order model is required to describe the system (Montgomery, 2005). Basically, the second-order model is represented as shown in equation 2;

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum\sum_{ij} \beta_{ij} x_i x_j \qquad (1)$$

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

The "β" parameters of the polynomials are estimated by the method of least squares. With the response data obtained, the least square method was used to determine the relationship between the response y and the independent variables x_1, x_2, x_3 and x_4.

The second-order model is widely used in RSM because it is very flexible and can take on a wide variety of functional forms. Kathleen et al (2004), states that the steps involved in the development of an effective response surface model include approximation of the response functions in the current region of interest by a second-order model, analysis of the model for adequacy, and optimization of the responses if the model looks good.

2.1.1 Test for Significance for Individual Model Coefficient

The test of significance is performed using the analysis of variance (ANOVA) test to form the basis with which the model optimization can be performed. This is achieved with the aid of parameters such as the P-value or probability value, F-value etc. with the "Prob. > F" value for example, the level of significance of each of the model terms can be established, by comparing it with the desired probability (or α-level).

2.2 Genetic algorithm (GA)

Genetic Algorithm (GA) is an example of non-traditional optimization techniques applied mostly in solving optimization problems involving large number of process variables and cost function classified generally as constrained and unconstrained (Cemel 2006). Its operation is based on Darwin's "survival of the fittest theory" wherein the randomized population is generated from the fittest species based on the fitness value (Sada 2020). With the genes of this fittest species passed to future generation by means of reproduction, they become dominant. Thereby creating new solutions after the fitness value of both the new and old species have been compared (Rao 2016). According to Rao (2016), to perform optimization using GA, the following five steps listed below are required:

i. Initialization of the random population.
ii. Determination of the fitness function of each input based on the generated population.
iii. Generation of new population with the aid of the following genetic parameters: selection, crossover and mutation.
iv. Calculation of the fitness function using newly generated population.
v. Repeat process from ii-iv, until satisfactory condition is obtained.

In the case of multi-objective optimization as is the case of this study, different set of input parameters can be optimize simultaneously. With the 'gamultiobj' optimization tool in MATLAB R2015B the optimization was performed.

3. Results and discussion

Table 2

Experimental Results

Exp No	*Yield Strength (N/mm²)*	*Percentage Elongation (%)*	**Poisson Ratio (v)**	*Modulus of Elasticity (N/mm²)*
1	243.0	29.8	0.3575	1615.8
2	250.3	28.3	0.3438	1753.7
3	202.3	25.6	0.2905	1900.0
4	202.3	28.7	0.3476	1727.9
5	241.1	35.0	0.3455	1418.0
6	230.7	30.0	0.3574	1587.3
7	244.9	28.5	0.2965	1743.2
8	240.1	29.5	0.3545	1698.3
9	251.2	33.5	0.4315	1450.5
10	220.5	24.0	0.3132	1972.5
11	280.1	33.6	0.3555	1405.7
12	250.3	33.2	0.2955	1475.9
13	240.5	33.0	0.3564	1364.6
14	244.3	34.2	0.3575	1418.1
15	275.3	32.9	0.3453	1485.4
16	210.3	29.9	0.3912	1570.6
17	244.3	35.7	0.3975	1345.4
18	242.5	31.3	0.3711	1425.9
19	240.7	30.1	0.3975	1674.4
20	200.9	29.3	0.3755	1624.9
21	200.1	29.7	0.3935	1657.6
22	261.2	30.4	0.3521	1605.6
23	241.2	29.2	0.2875	1636.3
24	241.5	32.8	0.3175	1490.9
25	262.1	29.3	0.3275	1655.3
26	205.3	31.5	0.3965	1453.0
27	260.5	29.8	0.3534	1584.9
28	273.3	33.0	0.3544	1460.9
29	250.4	30.7	0.3543	1584.0
30	213.1	32.1	0.3341	1511.5

In order to develop the mathematical model of the input and output parameters, multiple regression analysis was applied based on the experimental data obtained. For each of the responses, the optimal équations in terms of actual factors as shown in Equations 3, 4, 5 and 6 have been developed for maximizing the résponses. The input process parameters; weld current, arc voltage, gas flow rate and filler rod diameter are represented by the variables With x_1, x_2, x_3 and x_4 respectively.

$$\text{YIELD STRENGTH} = -2360.207 + 4.462x_1 + 41.573x_2 + 122.938x_3 + 308.161x_4 - 0.007x_1x_2 - 0.034x_1x_3 - 0.903x_1x_4 - 1.754x_2x_3 + 1.071x_2x_4 + 3.882x_3x_4 - 0.004x_1^2 - 0.119x_2^2 - 2.068x_3^2 - 42.402x_4^2 \quad (3)$$

$$\text{PERCENTAGE ELONGATION} = -136.962 - 0.163x_1 + 0.637x_2 + 12.255x_3 + 28.640x_4 + 0.012x_1x_2 - 0.002x_1x_3 - 0.032x_1x_4 - 0.163x_2x_3 - 0.009x_2x_4 - 0.773x_3x_4 + 0.001x_1^2 + 0.029x_2^2 - 0.144x_3^2 - 1.165x_4^2 \quad (4)$$

$$\text{POSSION RATIO} = +9104.804 + 15.985x_1 + 69.110x_2 - 633.613x_3 - 1807.790x_4 - 0.762x_1x_2 - 0.264x_1x_3 + 3.846x_1x_4 + 6.043x_2x_3 + 1.098x_2x_4 + 46.702x_3x_4 - 0.012x_1^2 - 2.071x_2^2 + 9.439x_3^2 + 18.543x_4^2 \quad (5)$$

$$\text{MODULUS OF ELASTICITY} = +9104.804 + 15.985x_1 + 69.110x_2 - 633.613x_3 - 1807.790x_4 - 0.762x_1x_2 - 0.264x_1x_3 + 3.846x_1x_4 + 6.043x_2x_3 + 1.098x_2x_4 + 46.702x_3x_4 - 0.012x_1^2 - 2.071x_2^2 + 9.439x_3^2 + 18.543x_4^2 \quad (6)$$

3.1 Results of Analysis of Variance Test

As stated in section 2.1.1 of this article, the ANOVA test was performed to determine significance of each of the model terms. Table 3, 4, 5, and 6 shows the result of the test on each of the responses.

Table 3
Analysis of Variance Test (ANOVA) for the Yield Strength

Source	*Sum of*	*df*	*Mean*	*F-value*	*p-value*	
Model	13501.46	14	964.39	9.36	<0.0001	*Significant*
A-Weld Current	986.55	1	966.66	9.56	0.0074	
B-Weld Voltage	5.70	1	5.70	0.00554	0.8171	
C-Gas Flow Rate	346.64	1	345.84	3.39	0.0856	
D-Filler Rod Dia	2202.25	1	2202.25	21.38	0.0003	
AB	15.60	1	15.60	0.1534	0.7008	
AC	67.65	1	67.65	0.6569	0.4303	
AD	1861.39	1	1881.39	18.27	0.0007	
BC	4924.53	1	4924.53	47.82	<0.0001	
BD	73.53	1	73.53	0.7140	0.4114	
CD	154.36	1	154.38	1.50	0.2397	
Residual	1544.73	15	102.98			

Table 4
Analysis of Variance Test (ANOVA) for the Percentage Elongation

Source	*Sum of squares*	*df*	*Mean Squ*	*F-value*	*P-value*	
MODEL	169.71	14	12.12	6.45	0.0005	*Significant*
A-Weld Current	20.72	1	20.72	11.02	0.0047	
B-Weld Voltage	16.50	1	16.50	8.78	0.0097	
C-Gas Flow Rate	3.01	1	3.01	1.60	0.2250	
D-Filler Rod Dia	0.9204	1	0.9204	0.4896	0.4948	
AB	47.96	1	47.96	25.51	0.0001	
AC	0.2256	1	0.2256	0.1200	0.7338	
AD	2.33	1	2.33	1.24	0.2835	
BC	42.58	1	42.58	22.65	0.0003	
BD	0.0056	1	0.0056	0.0030	0.9571	
CD	6.13	1	6.13	3.26	0.0912	
Residual	26.20	15	1.60			

Table 5
Analysis of Variance Test (ANOVA) for the Poisson ratio

Source	*Sum of Squares*	*df*	*Mean Sq*	*F-value*	*P-value*	
Model	0.0308	14	0.0022	8.34	0.0001	*Significant*
A-Weld Current	0.0051	1	0.0051	19.23	0.0005	
B-Weld Voltage	0.0030	1	0.0030	11.44	0.0041	
C-Gas Flow Rate	0.0016	1	0.0016	6.04	0.0267	
D-Filler Rod Dia	0.0031	1	0.0031	11.90	0.0036	
AB	0.0004	1	0.0004	1.69	0.2130	
AC	0.0050	1	0.0050	18.96	0.0006	
AD	0.0000	1	0.0000	0.1614	0.6935	
BC	0.0004	1	0.0004	1.43	0.2503	
BD	0.0009	1	0.0009	3.39	0.0853	
CD	0.0004	1	0.0004	1.64	0.2203	
Residual	0.0040	15	0.0003			

Table 6
Analysis of Variance Test (ANOVA) for the Modulus of Elasticity

Source	*Sum of Squares*	*df*	*Mean Sq*	*F-value*	*P-value*	
Model	5.632E+05	14	40227.80	5.97	0.0007	*Significant*
A-Weld Current	58117.99	1	58117.99	8.63	0.0102	
B-Weld Voltage	30770.10	1	30770.10	4.57	0.0495	
C-Gas Flow Rate	12724.08	1	12734.08	1.89	0.1895	
D-Filler Rod Dia	2.19	1	2.19	0.0003	0.9859	
AB	2088E+05	1	2.088E+05	30.99	<0.0001	
AC	4014.81	1	4014.81	0.5960	0.4521	
AD	34076.24	1	34076.24	5.06	0.0400	
BC	58429.77	1	58429.77	8.67	0.0100	
BD	77.13	1	77.13	0.0115	0.9162	
CD	22334.56	1	22334.56	3.32	0.0886	
Residual	1010E+05	15	6736.08			

From the results obtained for all the responses as shown Tables3, 4, 5, and 6, model F-values of 9.36, 6.45 and 5.97 at P< 0.001 indicates that the models obtained are significant. From the results, the parameters; weld current and filler rod diameters recorded the most significant effect on the model.

3.2.1 Weld Current and Gas Flow Rate

3.2 Surface Plot

To visualize graphically the response surface, a 3D surface plot showing the model interaction of atwo variable on the measured responses is made. Figure 1-5shows a plot of different variables combined for each of the responses.

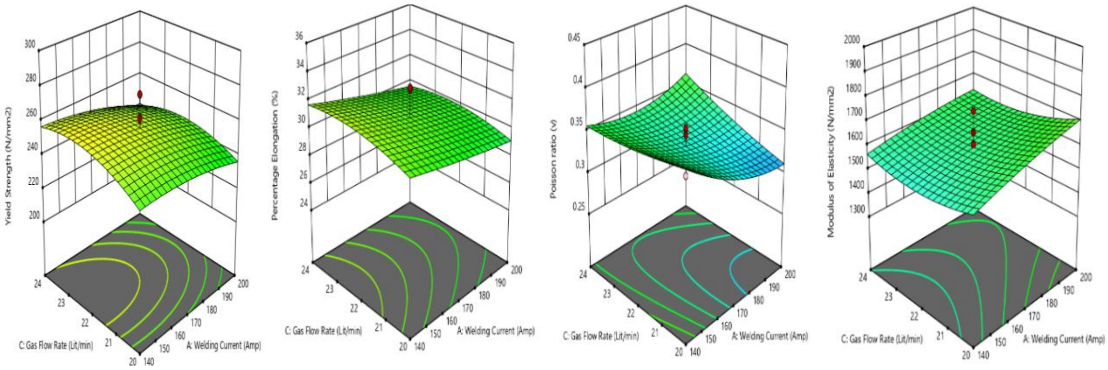

Fig.1. Effect of Weld Current and Gas Flow Rate on the Responses.

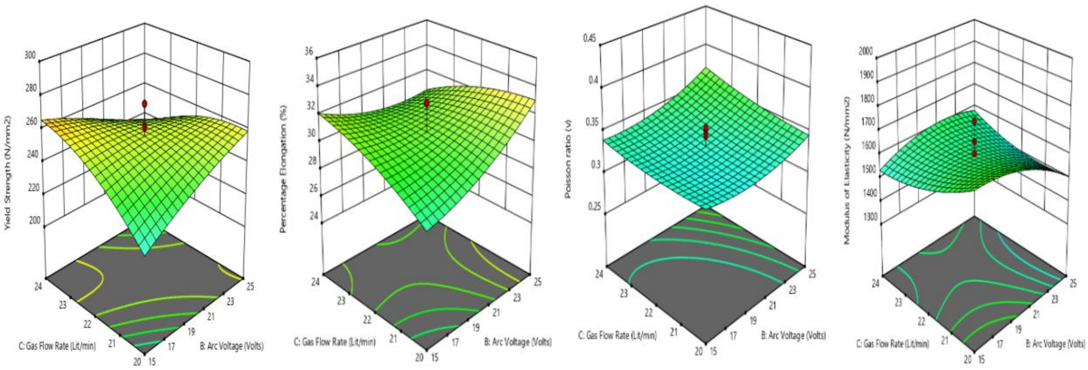

Fig. 2. Effect of Arc Voltage and Gas Flow Rate on the Responses.

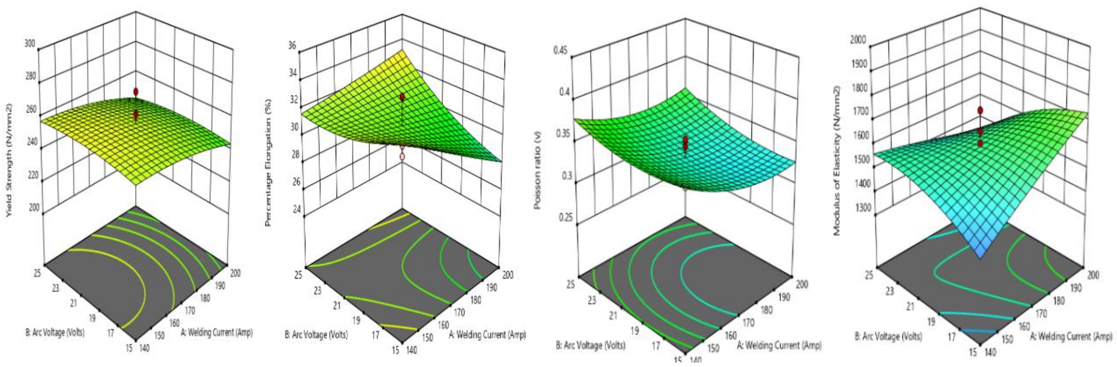

Fig. 3. Effect of Weld current and Arc Voltage on the Responses.

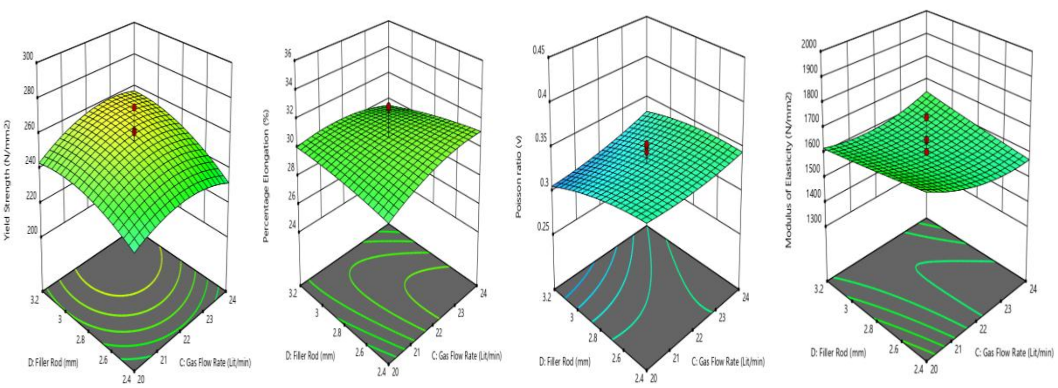

Fig.4. Effect of Gas Flow Rate and Filler Rod on the Responses.

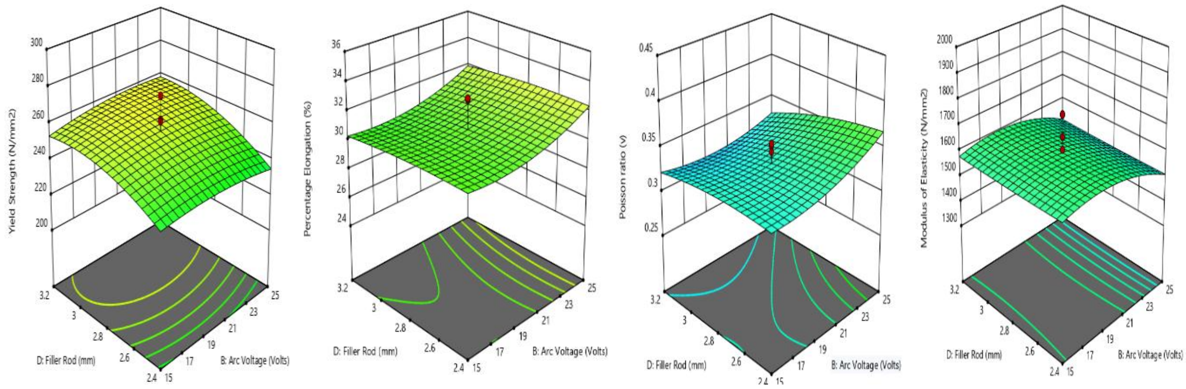

Fig. 5. Effect of Arc Voltage and Filler Rod on the Responses.

The effect of the interaction and variation the combined variables is clearly display in the surface plots shown in Figure 1-5. The effects of the combined parameters on the responses as they are increased and decreased is reveal from the plots. From Figure 1, where the weld current and gas flow rate is combined, the responses shows little or no changes, signifying an insignificant effect. However the combined effect of arc voltage and gas flow rate shown in Figure 2, and weld current and arc voltage shown in Figure 3, shows a clear variation in the responses as the combined variables are adjusted. This clearly depicts the significance of the combine input variables. From Figure 3, where the arc voltage and filler rod is combined, only the yield strength is affected by the changes made to the variables. The other responses recorded like or no changes. A similar observation is recorded in Figure 4, where the combine effect of arc voltage and filler rod diameter has been evaluated.

3.3 Numerical Optimization

Haven developed the mathematical model of the responses, numerical optimization was performed by applying desirabilty function using the design expert software. The responses: yield strength, percentage elongation, possion ratio and modulus of elasticity were optimised along with the process parameters.

From the results obtained, a maximized yield strength, percentage elongation, possion ratio and modulus of elasticity of 279.04N/mm^2, 34.68%, 0.351577 and 1696.41N/mm^2 respectively at combined process parameters of140.00amp for weld current,15.00volt for arc voltage, 24.00l/min for gas flow rate and 3.01mmfor filler rod diameter was recorded at a desirability value of 0.894.

3.4 Optimization using genetic algorithm

To perform the optimization of the responses, a major requirement is the fitness or objective function. The mathematical models developed in equations 3-6 was used as the objective functions and with the aid of the "gamultiobj" tool in MATLAB R2012, multi-objective genetic algorithm was performed with the mathematical models written in coded form as M-files. The result of the solver was obtained with the GA parameters set at Population size: 50, Creation function: Feasible population creation function, 0.8 Crossover probability, single point type of crossover, 0.01 Mutation probability and 1e-4 function tolerance: 1e-4 along with the process variables set as constraints.

A successful outcome was observed at 196 iterations with the following results recorded; yield strength 270.28N/mm^2, percentage elongation 31.01%, poisson ratio 0.359and modulus of elasticity 1660.3N/mm^{2}at combined process variable 140.83amp weld current, 24.49volt arc voltage, 22.61l/min gas rate and 3.19mm filler rod diameter.

3.5 Confirmatory Test

A test to confirm the adequacy of the results was performed using results from both optimization outcome. A more accurate result was obtained from the experiment conducted using the GA results. An accuracy of 95% was recorded compared to the RSM which gave a percentage difference of 16% less than the GA.

4. Conclusion

The optimization of the ductile properties of a metal inert gas weld have been successfully carried based on the study of the yield strength, percentage elongation, possion ratio and modulus of elasticity response parameters. From the results of the study, a mathethical model of the responses were developed and analysed using the analysis of variance (ANOVA) test and found to be adequate.

With the surface response plot, the variation of the combined effect of the process parameters was revealed. A major observation recorded shows that performing a combined optimization of weld responses without considering the yield strength of the weld renders the process inadequate. As can be seen from the analysis of the response surface plot. The parameters clearly shows that with other responses, the parameters can be adjusted with little effect on the weld. But the yield strength reveals that after a certain level of increment the weld begins to fail. According to Björk*et al* (2012) and Collin*et al*., (2005) whose work collaborates the findings of this study, the ductility of welded joint is increased by the addition of filler metal.

In determining the optimal parameters of the weld, the two selected optimization techniques RSM and GA was applied. Results obtained from both techniques and confirmed by means of an experiment reveals that the accuracy of the GA technique is much higher compared to the RSM. The results not withstanding their differences reveals that manufacturers can obtain the optimal ductile properties of the weld using the GA and RSM techniques if the right combination of process parameters is applied.

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