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OPTIMIZATION OF RESIDUAL STRESS IN MILD STEEL GAS TUNGSTEN ARC WELDED JOINT USING RESPONSE SURFACE METHODOLOGY.

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ABSTRACT

Residual stress also referred to as locked-in stress present in welded structures, greatly compromises the quality, reliability and service life of the weldment. This study was carried out with the aim of relieving the residual stress distributed in mild steel weldment during welding processes. Thirty (30) sets of experiments were done, adopting the central composite experimental design. The parameters considered in this study are current, voltage, gas flow rate and welding speed. The material used was 80mm x 60mm x 6mm mild steel plates. Gas tungsten arc welding (GTAW) machine was employed to weld the plates. Prediction and optimization of residual stresses in the sample were also achieved. The numerical optimal solution produced a welded material having a Residual Stress of 296MPa at a current of 180 Amp, voltage of 16 volt, welding speed of 351mm/min and gas flow rate of 16lit/min.

Key Words: Central composite design, RSM, Residual Stress, optimization and Gas tungsten arc welding (GTAW)

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1.0 INTRODUCTION

Residual stresses are locked-in stresses present in engineering components even when there is no external load and these develop primarily due to non-uniform volumetric change in metallic component irrespective of manufacturing processes such as welding, heat treatment, machining, mechanical deformation, casting, coating etc (Pranbhat, 2020; Bhanu et al, 2017). In welded joints, residual stresses primarily develop due to differential weld thermal cycle (heating, peak temperature and cooling at any moment during welding) experienced by the weld metal and region close to the fusion boundary i.e. heat affected zone (Nadkarni, 2010). Olabi et al (1995) stated that residual stresses are stresses that remain in a solid material after the original cause of the stresses has been removed. Residual stress may be desirable or undesirable, it can occur through a variety of mechanisms including inelastic (plastic) deformations, temperature gradients (during thermal cycle) or phase transformation (Cheong and Marcus, 1987; Vasantharaja et al.,2012). James (2010) carried out research on Residual Stress Influences in Mechanical Engineering. He briefly introduced several of the more interesting or unusual problems associated with residual stresses and also considered powerful modern ways of measuring residual stress data in real components.

Residual stress measurement techniques can be classified as destructive or non-destructive (Benyounis, 2007). The former is based on disturbance of the state of equilibrium of the residual stress after sectioning of the specimen, machining, layer removal or drilling. The redistribution of the internal forces leads to local strains, which are measured to evaluate the residual stress field. The most usual methods are hole drilling, ring core and sectioning (Berezhnyts'ka, 2001). The non-destructive methods are based on the relationship between the physical and crystallographic parameters and the prevailing stress state. Sindhu et al. (2010) studied the effects of residual stress by hole drilling method in a lap joint. They predicted that the residual stresses were harmful and they decreased with the welding speed. According to Cullity in 2001, the two most often employed methods of measuring Residual stress are X-ray and neutron diffraction. Ultrasonic techniques are also available and are based on variations in the velocity of ultrasonic wave propagation in the materials under the action of mechanical stresses (Qozam, 2006).

Dharmendra and Shri (2010) used Ultrasonic Technique and Device to measure Residual Stress. The present version of the Ultrasonic Computerized Complex allows measuring the averaged through thickness residual stresses in plates 2 - 150 mm thick.

Bray et al (2001) in their experiment used a linear relationship between the velocity of ultrasonic wave and the stress of material to determine the residual stress. The result showed that a change in stress can be calculated by applying a stress-strain relationship in one dimension to an elastic solid.

Palanichamy et al (2009) used in their experiment the contact measurement device, which includes an ultrasonic box, computer and time of flight (TOF) measuring element. The result showed that the ultrasonic box which is a 100 MHz ultrasonic testing device can be effectively used to determine residual stress.

The aim of this study is to relieve the residual stress distributed in mild steel weldment during welding processes using Response Surface Methodology (RSM) to address this problem.

2. Materials and Methods

2.1. Material Properties

Mild steel plate of 6 mm thickness was selected as material used for the experiment. The mild steel plate was cut to a dimension of 80 mm x 60 mm using a power hacksaw and grinded at the edge to smoothen the surfaces to be joined. The surfaces of the coupon were polished with emery paper. Thereafter the mild steel plates were fixed on the work table with flexible clamp to weld the joints of the specimen. A TIG welding process was used with alternate current to perform the experiments as it concentrates the heat in the welding area, using 100% argon shielding gas. Residual strain was measured for each sample using ultrasonic technique. For each experimental runs, 5 specimens were used, and the average of the 5 experimental readings were recorded for the 30 run, generated by the design expert 7.01 software adopting the central composite design. The key parameters considered in this work are gas flow rate (F), welding current (I), welding voltage (V), and welding speed (S) ; and the output parameter is the residual stress. Plate 1, 2, 3 and 4, shows the experimental samples, tungsten inert gas welding machine, argon shielding gas cylinder and finally the ultrasonic computerized complex for measurement of Residual Stresses.



Plate 1: Experimental Samples



Plate 2: Gas tungsten arc welding machine



Plate 3: Shielding Gas Cylinder and Regulator



Plate 4: Ultrasonic computerised complex for measuring Residual Stress

2.2 METHODOLOGY

The range of value of the process parameters was obtained from literature, and each parameter has two levels which comprise of the high and low. This is expressed in Table 1.

Table 1: Welding parameters and their levels

Parameters	Unit	Symbol	Coded value	Coded value
			Low(-1)	High(+1)
Current	Amp	I	180	220
Gas flow rate	Lit/min	F	16	22
Voltage	Volt	V	18	24
Welding speed	mm/min	S	350	450

This design is for input parameters considered within the range of 3- 5 levels. In this study the central composite design was developed using the design 7.01 software, it generated 30 runs for the experiment, and it is shown in Table 2.

Table 2: Central Composite Design Matrix (CCD)

Type	Run	Current (A)	Voltage (V)	Gas Flow Rate (lit/min)	Welding Speed (mm/min)
Center	1	200	21	19	400
Center	2	200	21	19	350
Center	3	180	18	16	350
Center	4	200	21	19	400
Center	5	180	18	22	450
Center	6	200	21	19	400
Axial	7	180	24	16	350
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Fact	21	220	18	22	350
Fact	22	220	24	22	450
Fact	23	200	24	19	400
Fact	24	200	15	19	400
Fact	25	200	21	19	400
Fact	26	240	21	19	400
Fact	27	220	24	16	450
Fact	28	200	21	19	400
Fact	29	180	18	22	350
Fact	30	200	21	19	450

2.3. Second-Order polynomial model

When there is a curvature in the response surface, the first-order model is insufficient. A second-order model is useful in approximating a portion of the true response surface with parabolic curvature. The second-order model includes all the terms in the first-order model, plus all quadratic terms like $\beta_{ii} x_i^2$ and all cross product terms like $\beta_{ij} x_i x_j$. It is usually expressed as

$$y = \beta_0 + \sum_{j=1}^q \beta_{jj} x_j^2 + \sum \sum_{kj} \beta_{kj} x_k x_j + \varepsilon$$

$$= \beta_0 + x_i' \beta - x_i' \beta x_i + \varepsilon_{ij} \tag{1}$$

Where y is the predicted response, β_0 is the constant coefficient, β_i is the *i*th linear coefficient of the input factor *x_i*.

The second-order model is flexible, because it can take a variety of functional forms and approximates the response surface locally. Therefore, this model is usually a good estimation of the true response surface.

3. RESULTS AND DISCUSSION

3.1 Response Surface Methodology

The experimental design, numerical and graphical optimization was done with the aid of the design expert 7.01 software, which generated the experimental runs, obeying the principles of experimental design. Table 3 shows the experimental results for the residual stress.

Table 3 Experimental results for Residual stress

Run	Current (Amp)	Voltage (volt)	Gas Flow Rate (Lit/min)	Welding Speed (mm/min)	Residual Stress (MPa)
1	200	21	19	400	361
2	200	21	19	350	363
3	180	18	16	350	301
4	200	21	19	400	364
5	180	18	22	450	323
6	200	21	19	400	365
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27	220	24	16	450	328
28	200	21	19	400	359
29	180	18	16	350	301
30	200	21	19	450	324

3.2. MODELLING RESIDUAL STRESS

To check for model suitability, the analysis of variance and goodness of fit statistics were employed. This are shown in Tables 4 and 5.

Table 4 Analysis of variance for residual stress

	Sum of		Mean	F	p-value	
Source	Squares	Df	Square	Value	Prob> F	
Model	16578.9	14	1184.207	24.28672	< 0.0001	Significant
I-current	793.5	1	793.5	16.27377	0.0011	
V-voltage	192.6667	1	192.6667	3.951371	0.0654	
F-gas flow rate	1014	1	1014	20.79597	0.0004	
S-welding speed	1066.667	1	1066.667	21.8761	0.0003	
IV	870.25	1	870.25	17.84782	0.0007	
IF	156.25	1	156.25	3.204507	0.0936	
IS	3080.25	1	3080.25	63.17238	< 0.0001	
VF	2352.25	1	2352.25	48.24194	< 0.0001	
VS	380.25	1	380.25	7.798489	0.0137	
FS	1560.25	1	1560.25	31.99893	< 0.0001	
I ₂	1589.49	1	1589.49	32.59861	< 0.0001	
V ₂	3162.347	1	3162.347	64.85609	< 0.0001	
F ₂	1642.119	1	1642.119	33.67796	< 0.0001	
S ₂	552.3471	1	552.3471	11.328	0.0042	
Residual	731.3917	15	48.75944			
Lack of Fit	659.9167	10	65.99167	4.616416	0.0526	not significant
Pure Error	71.475	5	14.295			
Cor Total	17310.29	29				

The Model F-value of 24.29 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case I, F, S, IV, IS, VF, VS, FS, I₂, V₂, F₂, S₂ are significant model terms.

Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

To validate the significance and adequacy of the model based on its ability to optimize the residual stress, the goodness of fit statistics presented as shown in table 5 was used.

Table 5: Goodness of fit statistics for validating model significance and adequacy towards minimizing residual stress

Std. Dev.	6.982796	R-Squared	0.957748
Mean	339.49	Adj R-Squared	0.918313
C.V. %	2.056849	Pred R-Squared	0.774467
PRESS	3904.044	Adeq Precision	22.48064

The "Pred R-Squared" of 0.7745 is in reasonable agreement with the "Adj R-Squared" of 0.9183.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. A ratio of 22.481 indicates an adequate signal. This model can be used to navigate the design space to develop the optimal equation.

3.2.1 Final Equation in Terms of Actual Factors:

$$\begin{aligned} \text{residual stress} = & -3739.70556 + 15.04167I + 86.34444V + 79.04444F + 4.64600S \\ & -0.12292IV + 0.052083IF - 0.013875IF - 1.34722VF + 0.032500VS \\ & -0.065833FS - 0.019031I^2 - 1.19306V^2 - 0.85972F^2 - 0.001795S^2 \end{aligned} \quad (2)$$

From the response surface model, I= Current, V = Voltage, F = Gas flow rate and S = welding Speed. When I is increased by unity, holding all other variables constant, the residual stress is expected to increase by 15.02MPa. If V is increased by unity, holding all other variables constant, the residual stress is expected to increase by 85.15MPa. If F is increased by unity, holding all other variables constant, the residual stress is expected to increase by 78.18 MPa. Also if S is increased by unity, holding all other variables constant, the residual stress is expected to increase by 4.6MPa.

From the contour plot in figure 1, the residual stress is 343.906 MPa at current 180 amps and 360mm/min welding speed.

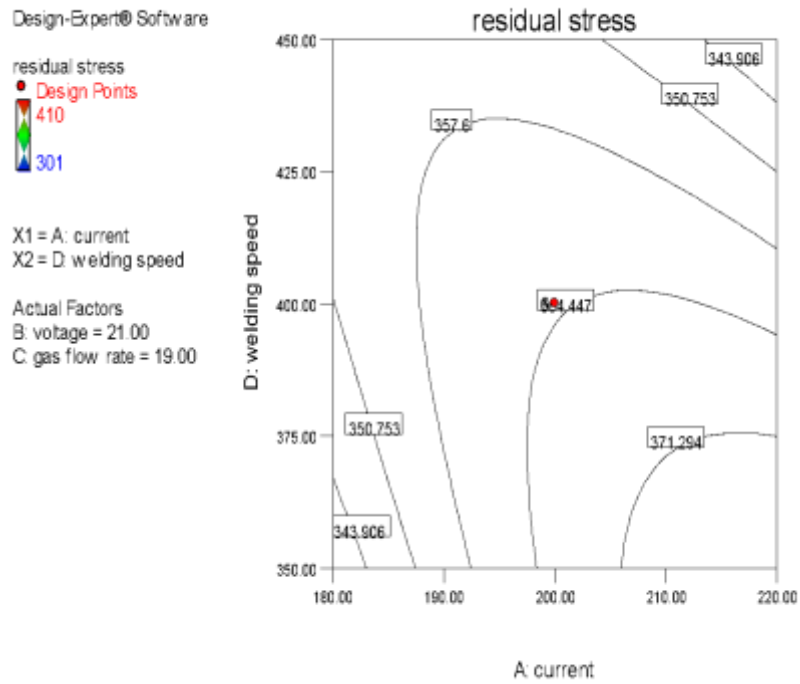


Figure 1: Contour plot of welding speed and current for residual stress

From the contour plot in Figure 2, the residual stress is 336.058 MPa at voltage 18volts and 16.7Lit/min gas flow rate.

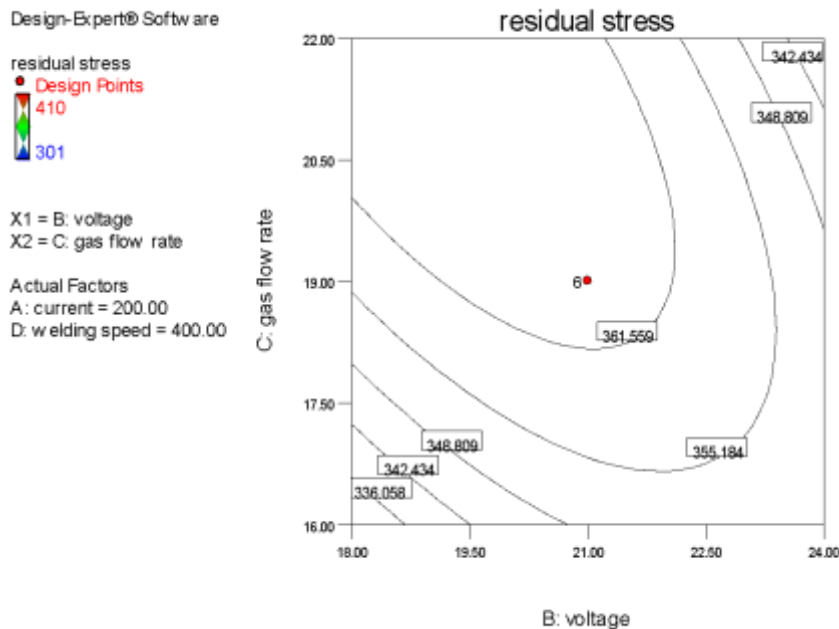


Figure 2: Contour plot of voltage and gas flow rate for residual stress

To study the combined interaction between voltage, current and residual stress, surface plots are produced as shown in Figures 3 and 4.

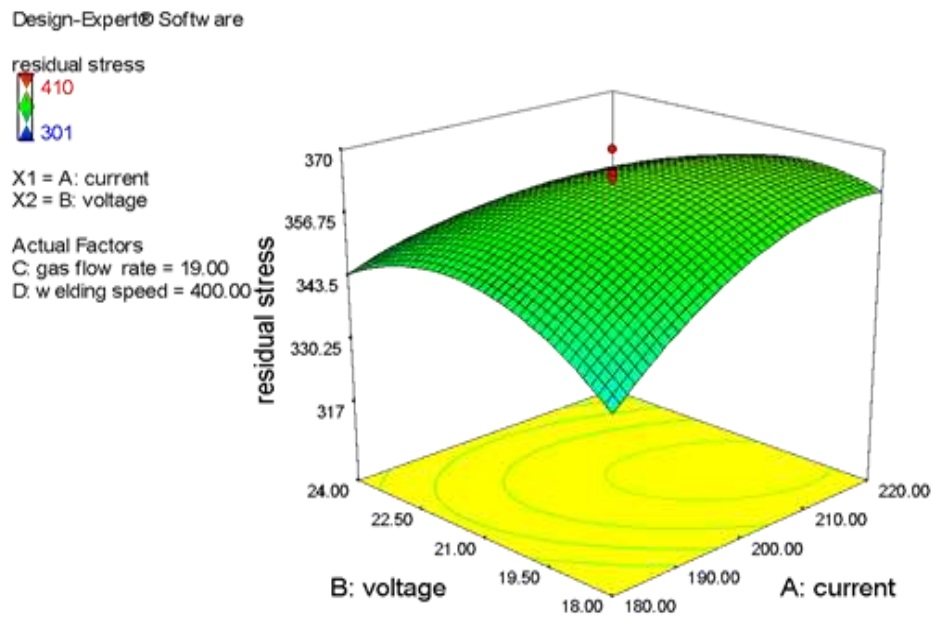


Figure 3: Effect of current and voltage on residual stress

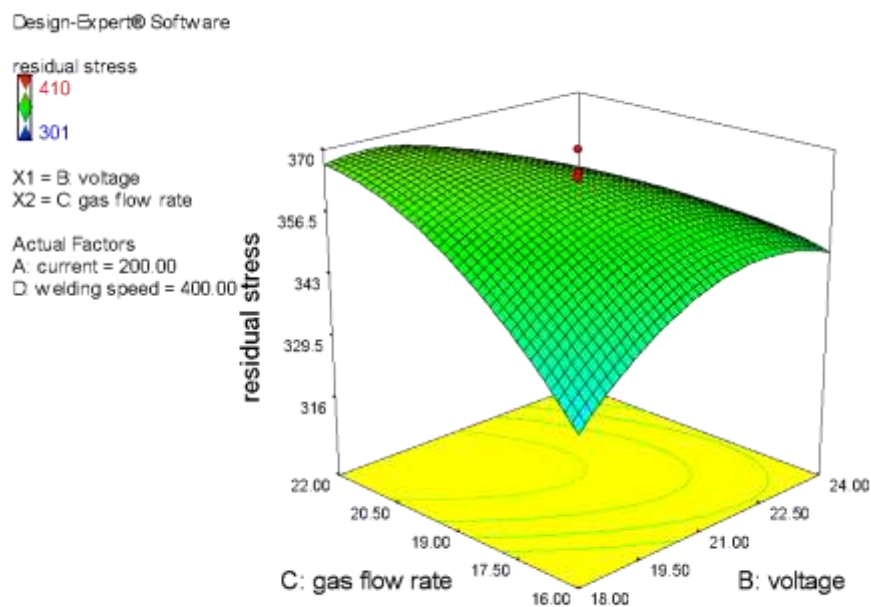


Figure 4: Effect of voltage and gas flow rate on Residual stress

Figure 3 shows that as increase in current and voltage, results to higher residual stress. Figure 4 shows that increase in the gas flow rate and voltage also increases the residual stress.

3.2.2 Solutions of numerical optimization model

The numerical optimization produces 30 optimal results, 29 of them are presented as shown in Table 6 below.

Table 6: Solutions of numerical optimization model

S/N	Current (Amp)	Voltage (volts)	gas flow rate (Lit/min)	welding speed (mm/min)	Residual Stress(MPa)	Desirability	
1	180	18	16	352.16	296.2847	0.999992	Selected
2	180	18	16	351.84	296.6245	0.999017	
3	180	18	16	354.81	297.8313	0.998857	
4	180	18	16	350.14	300.0535	0.981659	
5	182.26	18	16	358.89	303.0358	0.968426	
6	180	18	16	381.22	306.8722	0.964711	
7	180	18	16	392.07	310.0345	0.952625	
8	180	18.01	16	398.01	311.7333	0.946258	
9	180	18	16	449.59	319.7747	0.944905	
10	180	18	16	449.87	318.0357	0.942759	
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26	210	19	22	449.9	339.2587	0.783259	
27	220	24	22	350	320.9435	0.74545	
28	220	24	22	349.99	340.4686	0.566897	
29	220	24	22.21	450	340.8609	0.521977	

From the results of table 6, it was seen that current (180amp), voltage (18.00volt), welding speed (352.16mm/min) and gas flow rate (16litre/min) will produce a minimum residual stress of 296.2847MPa. This solution was selected by design expert as the optimal solution having a desirability value of 0.999992.

4. Conclusion

The quality of a weld is determined by the geometry, joint type and optimal combination of process parameters. For optimization of the welding parameters, different combinations of the current, voltage, gas flow rate and welding speed were used. If the values of the current, gas flow rate, welding speed and voltage are increased, the residual stresses also increases. The optimum welding parameters for the weldability of mild steel weld specimen of dimension 80mm× 60mm × 6 mm for minimum residual stress of 296MPa are current of 180amp, voltage of 16volt, gas flow rate of 18.04lit/min and welding speed of 351mm/min. In this study, the response surface methodology was used to predict and optimise residual stress present in welded mild steel plates which gave R² of 99.96%.The optimum results obtained can help to produce weld pool with fewer spatters, less defects and a favourable kinematic viscosity which translates into a high quality weldment. It has been shown that the optimization and prediction of residual stress can improve the reliability, service life and integrity of welded joints. It is

therefore recommended that welding and fabrication industries should endeavour to use the optimum welding process parameters achieved in this study to produce high quality welds in Tungsten inert gas welding process.

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