



Journal of Engineering for Development, Vol. 13(1), October (2021) pp.85-97

OPTIMIZATION OF Ar-CO₂ SHIELDING GAS COMPOSITION TO MINIMIZE RESIDUAL STRESS ON MIG WELDED JOINT.

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ABSTRACT

The existence of residual stresses causing fatigue and distortion in welded structures has been responsible for failure of machine in service. Various trial and error welding runs have to be carried out while hoping for the best performance during operation. This is wasteful of time, material and finance. This research was carried out with the aim of optimizing Ar-CO₂ shielding gas mixtures to minimize residual stress formation in mild steel MIG welded joint using response surface methodology (RSM). An experimental matrix of twenty (20) runs was generated using central composite design (CCD) and a total of one hundred samples of five shielding gas composition were considered. The process parameters were current, voltage and gas flow rate. Mild steel plate's coupons of 60mm x 40mm x 10mm were joined using MIG welding process. The residual stress was measured using X-ray diffraction and RSM was used to optimize the residual stress. An optimum weld residual stress of the shielding gas were obtained as 242.237MPa for 100%Ar – 0%CO₂, 158.819MPa for 75%Ar – 25%CO₂, 158.691MPa for 50%Ar – 50%CO₂, 166.646MPa for 25%Ar – 75%CO₂, and 196.785MPa for 0%Ar – 100%CO₂ at an optimal current of 110amp, 24V and 45mm/s wire feed rate. The overall desirability value was 91.20%.

Keywords: Residual Stress, Argon, Carbon dioxide, Shielding gas, Optimization, Response Surface Methodology.

Article Information:

Received 20 September, 2021

Revised 04 October, 2021

Accepted 10 October, 2021

Available online 08 March, 2022

1.0 Introduction

During welding process, a great amount of heat is generated. Much of the heat escapes to the atmosphere, but a large percentage of it is transferred to the metal being welded. Much of the heat that is transferred to the base metal is localized in the fusion zone of the weld and diminishes through the heat-affected zone and into the surrounding metal.

The primary function of shielding gas is to protect the molten metal from atmospheric gases as the weld pool is being formed. During welding, shielding gas interact with the welding wire thereby determining the strength, toughness, corrosion resistance of weld deposits and also promote a stable arc and uniform metal transfer. Therefore, the quality, efficiency, penetration pattern and overall operating acceptance of the welding operation are strongly dependent on the shielding gas, (Gertsovich and Svanberg, 2008). According to Luoma (2019), argon is the most commonly used inert gas for MIG welding either on its own or mixed with one or more other gases. Ar-CO₂ blend are versatile mixtures mainly used as shielding gas at present for MIG welding carbon steel, all kinds of structural steel, farm implements and machinery, low alloy and some stainless steel.

Residual stresses are locked-in stresses present in the engineering components even when there is no external load. These develop primarily due to non-uniform volumetric change in metallic component irrespective of manufacturing processes such as heat treatment, machining, mechanical deformation, casting, welding, coating etc. Residual stresses in welded joints develop mainly due to localized heating and cooling leading to differential volumetric expansion and contraction of metal around the weld zone. According to Ebert (1974), residual stresses can be, and very often are, very significant factors in producing catastrophic failures, and/or shortening the useful life of many materials and structures; however, their major input into the failure very often goes unrecognized. These stresses if not properly controlled can lead to loss of lives and property. The highlight is that various trial and error welding runs have to be carried out while hoping for the best performance during operation. This is wasteful of time, material and finance. Many efforts are made to predict and relax residual stresses in welded structures. A well-known method of stress relieving is by heat treatment. Other equally effective methods of stress relief are typically mechanical. These include localized peening, shot blasting, hydrostatic testing and vibratory stress relieving (Hornsey 2006). Relevant advances in numerical and experimental stress relieving techniques should be explored to provide protection against the risk of initiation and propagation of brittle fracture (Coules 2012)

Mild steel (low-carbon steel) consists of 0.15% to 0.3% carbon. It is a common welding material and therefore was chosen for this study. During welding processes, the low-carbon steel undergoes a solid-state phase transformation of heating and cooling thereby inducing residual stress on the weldment. Mohamed (2009), stated that the selection of shielding gas for carbon steel welds depends on the influence of the shielding gas on the weldability, weld bead geometry, appearance, generation of porosity and also their related effects on the mechanical properties.

Previous studies were directed to examine the effect of shielding gases on weldment properties, optimization of Ar-CO₂ mixture to avoid/reduce weld spatter, but little is known about residual

stresses created from the combinations of these gases. This study therefore focuses on the optimization of gas mixtures to minimize residual stress formation in mild steel MIG welded joint using response surface methodology (RSM). RSM is a collection of mathematical and statistical techniques that is useful for the approximation and optimization of stochastic models. Myers et al. (2009) stated that, RSM is an efficient statistical tool for design, development, improvement, and optimization of product designs and processes. According to Eboigbe and Achebo (2019), the optimization and prediction of residual stress can improve the reliability, service life and integrity of welded joints.

2.0 Materials and Method

Mild steels plate of 10mm thickness was sectioned to the size of 60mm × 40mm and grinded at the edge to smoothen the surfaces to be joined. Using various mixtures of Ar-CO₂ as the shielding gas, Metal Inert Gas welding (MIG) process was used to join the mild steel coupons. The welding parameters include a welding voltage, a welding current, wire feed rate as shown in Table 1. Five (5) types of Ar-CO₂ mix ratio of shielding gases were considered as: 100%Ar-0%CO₂, 75%Ar-25%CO₂, 50%Ar-50%CO₂, 25%Ar-75%CO₂ and 0%Ar-100%CO₂ for the experiment. Central composite design (CCD) was used to create 20 experimental runs for the five (5) shielding gas variations. The input parameters and output parameters make up the experimental matrix while the responses recorded from the weld samples were used as the data. Table 2 shows the CCD matrix. These samples residual stress were examined using the X-ray diffraction technique. The results obtained from the residual stress test were optimized using RSM.

Table 1: Process parameters and their levels

Factors	Unit	Symbol	Low (-1)	High (+1)
Welding Current	Ampere	I	110	200
Welding Voltage	Volts	V	20	24
Wire Feed Rate	mm/s	WFR	45	65

Table 2 Central Composite Design (CCD) matrix.

	Factor 1	Factor 2	Factor 3
Run	A:Welding Current	B:Welding Voltage	C:Wire Feed Rate
	Ampere	Volts	mm/s
1	200	20	45
2	110	20	45
3	200	24	45

4	230	22	55
5	110	24	65
6	200	20	65
7	155	22	55
8	200	24	65
9	79	22	55
10	155	22	55
11	155	22	55
12	155	22	55
13	155	22	55
14	110	20	65
15	110	24	45
16	155	22	71
17	155	22	55
18	155	18	55
19	155	25	55
20	155	22	38

3.0 Experimental results

Two coupons each of the mild steel were welded together using the established CCD process parameters and the five shielding gas composition. The samples residual stress (R.S) was examined

using the X-ray diffraction technique. The results obtained are shown in Table 3.

Table 3: Results of residual stress responses from the process parameters obtained using CCD

	Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3	Response 4	Response 5
Run	A:Welding Current	B:Welding Voltage	C:Wire Feed Rate	100%Ar	75%Ar-25%CO ₂	50%Ar-50%CO ₂	25%Ar-75%CO ₂	100%CO ₂
	Ampere	Volts	mm/s	MPa	MPa	MPa	MPa	MPa
1	200	20	45	290.851	157.891	193.932	250.838	210.604
2	110	20	45	255.840	156.448	161.303	270.985	164.228
3	200	24	45	269.399	158.699	208.442	186.276	170.083

4	230	22	55	284.585	160.691	164.905	183.050	204.887
5	110	24	65	260.731	218.907	262.517	223.023	231.212
6	200	20	65	278.537	228.989	171.351	151.861	248.412
7	155	22	55	317.903	208.246	214.272	230.742	248.750
8	200	24	65	265.247	162.489	173.102	183.096	160.178
9	110	22	55	263.161	186.985	198.469	270.801	244.878
10	155	22	55	317.903	208.246	214.272	230.742	248.750
11	155	22	55	317.903	208.246	214.272	230.742	248.750
12	155	22	55	317.903	208.246	214.272	230.742	248.750
13	155	22	55	317.903	208.246	214.272	230.742	248.750
14	110	20	65	306.146	258.996	261.140	270.997	275.018
15	110	24	45	249.483	156.000	167.730	163.059	201.514
16	155	22	71	275.764	229.000	260.426	163.041	264.571
17	155	22	55	317.903	208.246	214.272	230.742	248.750
18	155	18	55	286.405	218.991	163.086	290.191	197.304
19	155	25	55	267.673	164.362	171.706	217.407	170.791
20	155	22	38	258.417	156.001	184.926	191.529	182.286

4.0 Optimization of results using RSM

Applying RSM to analyze the response, Table 4 to 8, shows the Predicted R^2 of 0.7499, 0.8160, 0.7949, 0.8610, and 0.9310 respectively, being in reasonable agreement with the respective Adjusted R^2 of 0.9471; 0.9536; 0.9442; 0.9669; and 0.9854; i.e. the difference was less than 0.2. The Adequate Precision is used to measure the signal to noise ratio of the system; the adequate precision of 18.543, 22.739, 19.586, 27.836, and 37.507 is more than the minimum requirement of 4. A ratio greater than 4 is desirable. Therefore, these models can be used to navigate the design space.

Table 4: Fit Statistics of R.S using 100% Argon shielding gas

Std. Dev.	5.75	R^2	0.9722
Mean	285.98	Adjusted R^2	0.9471
C.V. %	2.01	Predicted R^2	0.7499
		Adeq Precision	18.5429

Table 5: Fit Statistics of R.S using 75%Ar - 25%CO₂ shielding gas

Std. Dev.	6.81	R^2	0.9756
Mean	193.2	Adjusted R^2	0.9536
C.V. %	3.53	Predicted R^2	0.8160
		Adeq Precision	22.7389

Table 6: Fit Statistics of R.S using 50%Ar - 50%CO₂ shielding gas

Std. Dev.	7.72	R²	0.9706
Mean	201.43	Adjusted R²	0.9442
C.V. %	3.83	Predicted R²	0.7949
		Adeq Precision	19.5861

Table 7: Fit Statistics of R.S using 25%Ar - 75%CO₂ shielding gas

Std. Dev.	7.25	R²	0.9826
Mean	220.03	Adjusted R²	0.9669
C.V. %	3.29	Predicted R²	0.861
		Adeq Precision	27.8356

Table 8: Fit Statistics of R.S using 100% CO₂ shielding gas

Std. Dev.	4.44	R²	0.9923
Mean	220.92	Adjusted R²	0.9854
C.V. %	2.01	Predicted R²	0.931
		Adeq Precision	37.5065

4.1 Residual Stress Model developed

Model developed for residual stress with the different mixing ratio of 100%Ar-0%CO₂, 75%Ar25%CO₂, 50%Ar-50%CO₂, 25%Ar-75%CO₂ and 0%Ar-100%CO₂ shielding gas are shown respectively:

$$y_1 = +317.70 + 4.84A - 11.31B + 4.77C + 2.13AB - 9.75AC - 3.86BC - 15.12A^2 - 13.44B^2 - 17.97C^2 \quad (1)$$

$$y_2 = +207.55 - 9.38A - 15.37B + 26.67C - 3.14AB - 11.32AC - 13.37BC - 11.51A^2 - 5.43B^2 - 4.31C^2 \quad (2)$$

$$y^3 = +213.54 - 11.98A + 0.2399B + 19.697C + 1.06AB - 31.57AC - 2.23BC - 9.67A^2 - 12.71B^2 + 5.40C^2 \quad (3)$$

$$y^4 = +231.16 - 22.27A - 21.50B - 7.46C + 15.32AB - 20.27AC + 19.47BC - 2.04A^2 + 4.66B^2 - 20.30C^2 \quad (4)$$

$$y^5 = +248.68 - 11.07A - 17.69B + 22.24C - 15.28AB - 14.07AC - 16.10BC - 8.83A^2 - 22.22B^2 - 9.29C^2 \quad (5)$$

The equation in terms of coded factors obtained from the input parameter of current (A), voltage (B) and gas flow rate (C) that describe the residual stress resulting from the use of shielding gasses with the five mix ratio is given in Eq. 1 to 5 and can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

In other to optimize the responses, design expert 11 was employed using the lower and upper limits of input process parameters obtained from the central composite design (CCD) as presented in Table 9.

Table 9: Boundary conditions for factors and responses

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Welding Current	is in range	110	200	1	1	3
B:Welding Voltage	is in range	20	24	1	1	3
C:Wire Feed Rate	is in range	45	65	1	1	3
100%Ar - 0%CO₂	Minimize	249.483	317.903	1	1	5
75%Ar - 25%CO₂	Minimize	156	258.996	1	1	3
50%Ar - 50%CO₂	Minimize	161.303	262.517	1	1	3
25%Ar - 75%CO₂	Minimize	151.861	290.191	1	1	3
0%Ar - 100%CO₂	Minimize	160.178	275.018	1	1	3

As shown in Figure 1, our goal was to optimize the residual stresses obtained from the five (5) shielding gases, by minimizing all responses obtained from the experiment. This is to help us get a universal process parameter, ideal for MIG welding, irrespective of the shielding gases used.

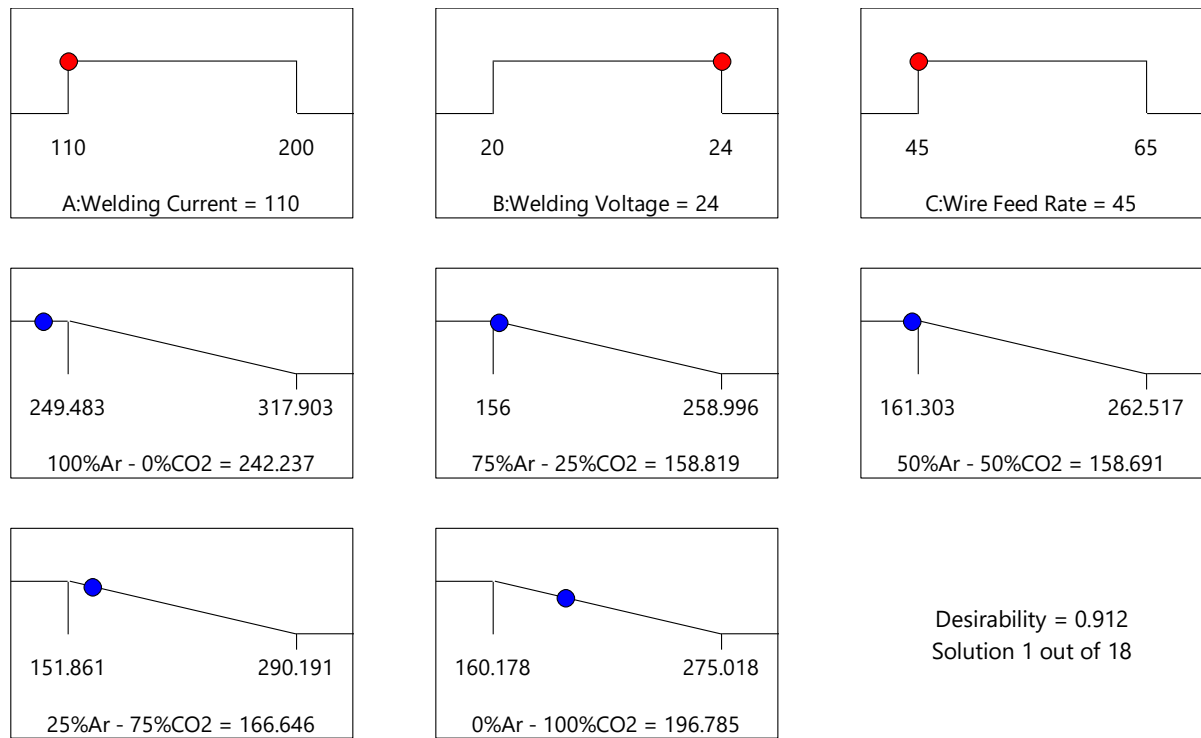


Figure 1: Target diagram for the experiment.

Presented in Table 10, is eighteen (18) optimum solutions that would generate good MIG weld quality with the best gotten from the combination of 110 Amp of current, 24 volts of weld voltage and 45 mm/s of wire feed, which produced a weld residual stress of 242.237MPa using a shielding gas of 100%Ar-0%CO₂, 158.819MPa using a shielding gas of 75%Ar-25%CO₂, 158.691MPa using a shielding gas of 50%Ar-50%CO₂, 166.646MPa using a shielding gas of 25%Ar-75%CO₂, and 196.785MPa using a shielding gas of 0%Ar-100%CO₂

Table 10: Optimum solutions of 18 responses

S/N	Welding Current	Welding Voltage	Wire Feed Rate	100%Ar - 0%CO ₂	75%Ar - 25%CO ₂	50%Ar - 50%CO ₂	25%Ar - 75%CO ₂	0%Ar - 100%CO ₂	Desirability	
1	110.00	24.00	45.00	242.24	158.69	158.82	166.65	196.79	0.91	Selected
2	110.69	24.00	45.00	242.95	159.15	159.30	166.91	196.87	0.91	
3	110.00	23.98	45.00	242.59	158.91	158.93	167.11	197.09	0.91	
4	111.23	24.00	45.00	243.51	159.41	159.78	167.12	196.93	0.91	
5	111.62	24.00	45.00	243.92	159.59	160.12	167.27	196.97	0.91	
6	110.00	23.95	45.00	243.09	159.04	159.25	167.75	197.49	0.91	

7	112.92	24.00	45.00	245.23	160.19	161.25	167.77	197.09	0.91	
8	110.00	24.00	45.19	243.14	159.47	159.44	168.06	197.54	0.91	
9	113.32	24.00	45.00	245.62	160.37	161.59	167.92	197.13	0.91	
10	200.00	24.00	65.00	257.97	160.39	171.77	176.76	156.36	0.90	
11	199.99	23.98	65.00	258.27	160.71	171.96	176.59	157.05	0.90	
12	200.00	24.00	64.89	258.44	160.46	171.80	177.28	156.63	0.90	
13	199.59	24.00	65.00	258.27	160.81	172.32	177.04	156.88	0.90	
14	115.39	24.00	45.00	247.65	161.27	163.35	168.70	197.30	0.90	
15	200.00	23.90	65.00	258.59	161.06	172.18	176.41	157.82	0.90	
16	116.34	24.00	45.00	248.56	161.67	164.14	169.06	197.37	0.89	
17	110	23.79	45.00	245.84	159.76	161.03	171.52	199.71	0.89	
18	200.00	24.00	64.75	259.10	160.56	171.85	177.99	157.03	0.89	

The desirability bar graph which shows the accuracy with which the model is able to predict the values of the selected input variables and the corresponding responses is presented in Figure 2

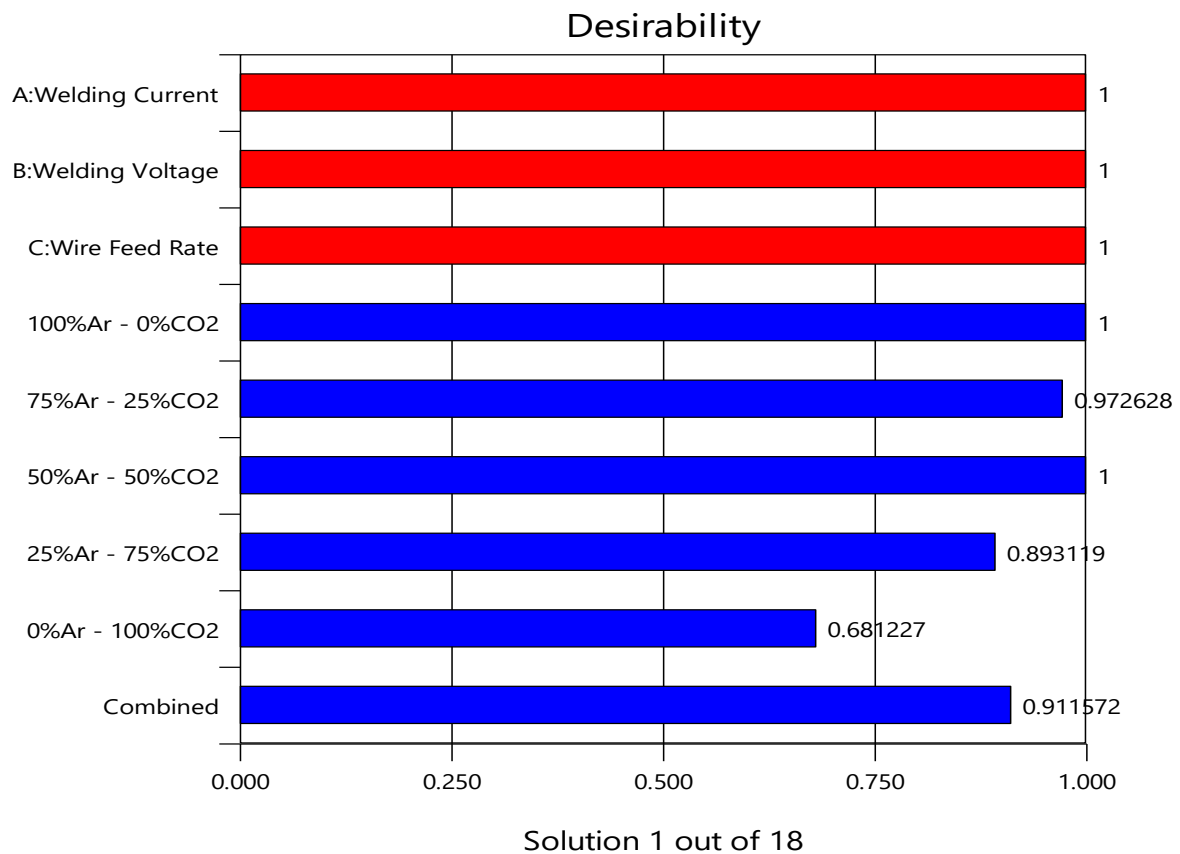


Figure 2: Prediction accuracy of numerical optimization

It can be deduce from the result of Figure 2 to 7 that the model developed based on response surface methodology and numerical optimization method, was able to optimize the residual stresses from the shielding gases with an accuracy level of 100%, for 100%Ar-0%CO₂, 97% for 75%Ar-25%CO₂, 100% for 50%Ar-50%CO₂, 89% for 25%Ar-75%CO₂, 68% for 0%Ar-100%CO₂ with overall combination (also known as desirability) of 91.2%.

The contour plot is interpreted using lines and colour, the lines are used to describe the calibrated scale for the response, while red, green and blue indicates the high, normal and low level of targeted research. As for the five shielding gas, the blue region was aimed to minimize the residual stresses from the welding process as shown below.

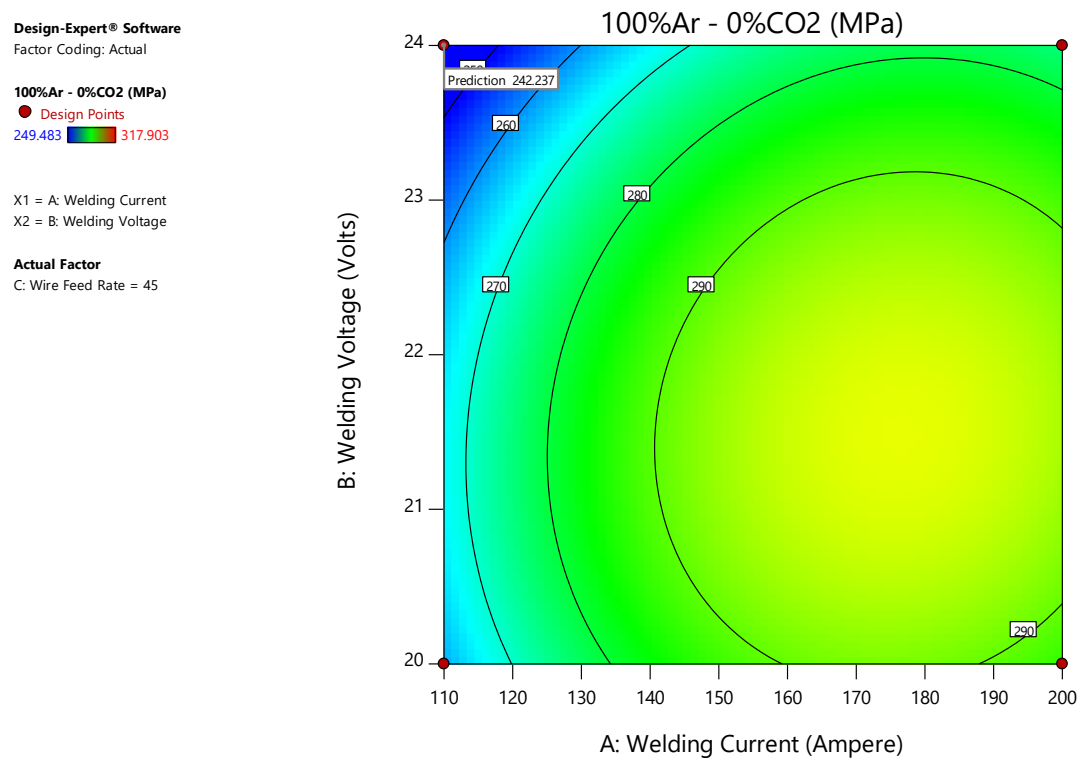


Figure 3: Contour plot for the optimized shielding gas of 100%Ar-0%CO₂

Design-Expert® Software
Factor Coding: Actual

75%Ar - 25%CO₂ (MPa)
● Design Points
156 258.996

X1 = A: Welding Current
X2 = B: Welding Voltage

Actual Factor
C: Wire Feed Rate = 45

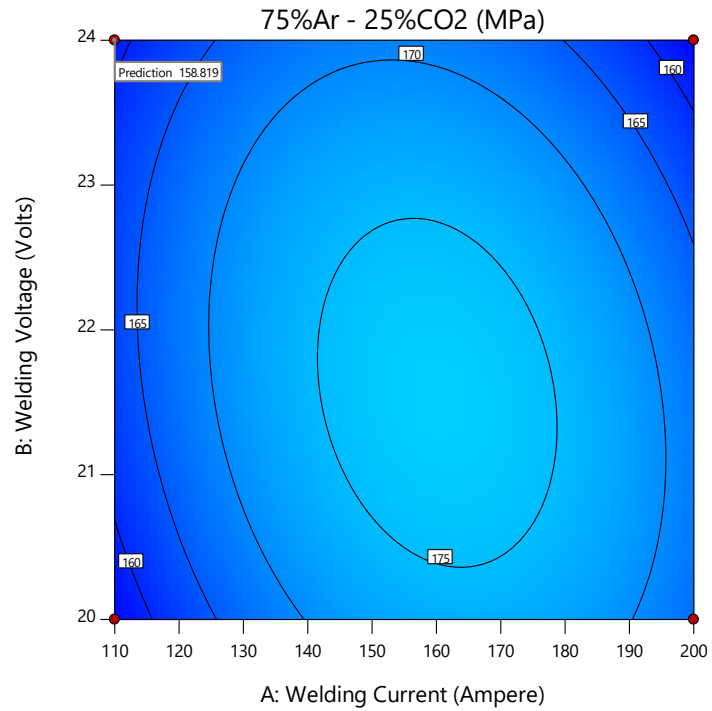


Figure 4: Contour plot for the optimized shielding gas of 75%Ar-25%CO₂

Design-Expert® Software
Factor Coding: Actual

50%Ar - 50%CO₂ (MPa)
● Design Points
161.303 262.517

X1 = A: Welding Current
X2 = B: Welding Voltage

Actual Factor
C: Wire Feed Rate = 45

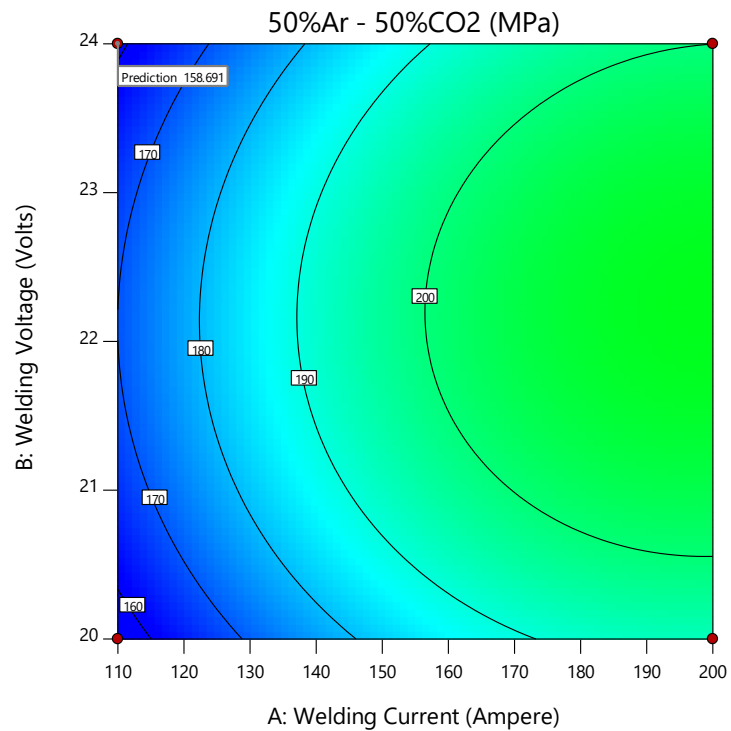


Figure 5: Contour plot for the optimized shielding gas of 50%Ar-50%CO₂

Design-Expert® Software
Factor Coding: Actual

25%Ar - 75%CO₂ (MPa)
● Design Points
151.861 290.191

X1 = A: Welding Current
X2 = B: Welding Voltage

Actual Factor
C: Wire Feed Rate = 45

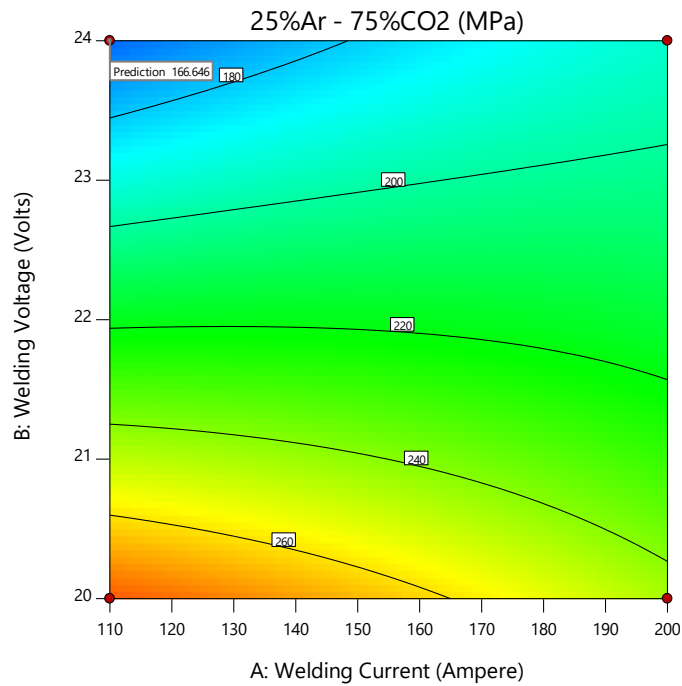


Figure 6: Contour plot for the optimized shielding gas of 25%Ar-75%CO₂

Design-Expert® Software
Factor Coding: Actual

0%Ar - 100%CO₂ (MPa)
● Design Points
160.178 275.018

X1 = A: Welding Current
X2 = B: Welding Voltage

Actual Factor
C: Wire Feed Rate = 45

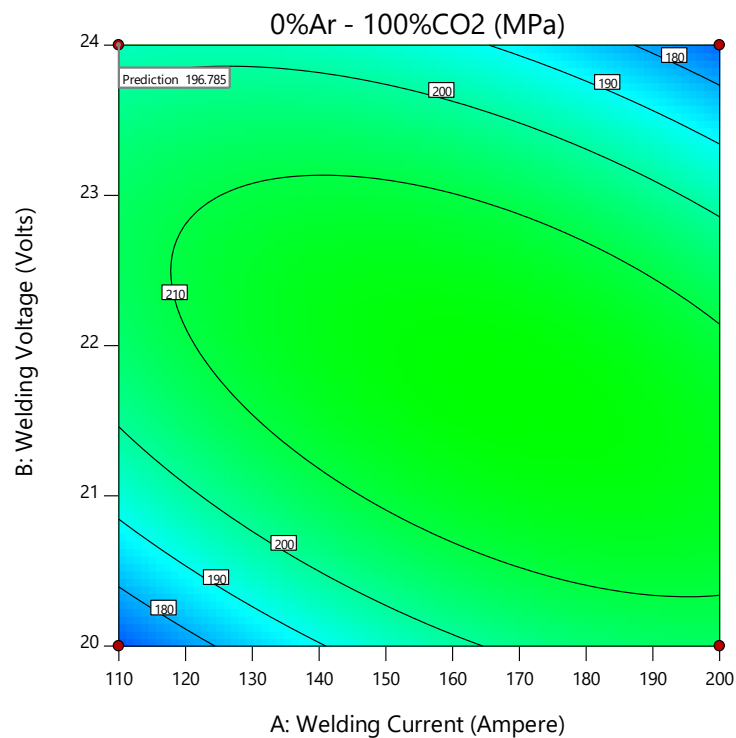


Figure 7: Contour plot for the optimized shielding gas of 0%Ar-100%CO₂

5.0 Conclusion

The integrity of weldment from MIG welding process is determined by the input parameter selected and the choices of weld shielding gases employed as demonstrated in this work. Keeping the material's residual stress as low as possible is a very important factor to consider

in assessing the quality of welds. This study employed RSM to optimize the residual stresses arising from shielding gas composition of 100%Ar-0%CO₂, 75%Ar-25%CO₂, 50%Ar-50%CO₂, 25%Ar-75%CO₂ and 0%Ar-100%CO₂ for welding mild steel using MIG welding process. The research has shown that the choice of shielding gases mixtures, current; voltage and gas flow rate has strong influences on residual stress. The models developed possesses a high goodness of fit with Coefficient of determination (R^2) values of 91.9%, 93.2%, 92.8% and 86.9% for 100%Ar-0%CO₂, 75%Ar-25%CO₂, 50%Ar-50%CO₂, 25%Ar-75%CO₂ and 0%Ar-100%CO₂ shielding gases respectively. Adequacy precision values of 18.5, 22.7, 19.6, 27.8 and 37.5 were obtained. The model produced numerical optimal solution of 110amp of current, 24V of weld voltage and 45mm/s of wire feed rate, which produces a welded joint having minimal residual stress of 242.237MPa using a shielding gas of 100%Ar-0%CO₂, 158.819MPa using a shielding gas of 75%Ar-25%CO₂, 158.691MPa using a shielding gas of 50%Ar-50%CO₂, 166.646MPa using a shielding gas of 25%Ar-75%CO₂, and 196.785MPa using a shielding gas of 0%Ar-100%CO₂ with an overall desirability value of 91.20%.

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