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On Dissimilar Welding of AISI 304 and EN 8 Steels through Metal Active Gas Welding: Part I - Parametric Optimization Using Taguchi's Orthogonal Array

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Abstract

Gas metal arc welding is a flexible technique for joining numerous metallic materials, both similar and dissimilar. AISI 304 stainless steel and EN 8 medium carbon steel plates are welded in this experiment. 100% CO_2 gas is used as a shielding gas in this method. Experiments are planned using the Taguchi technique, which employs a three-column, nine-row orthogonal array. This design is chosen based on three welding parameters, each of which has three levels. Heat input, root gap, and torch angle are being used as welding parameters for this investigation. Grey relational analysis approach is utilized for optimization purposes. S/N ratio is calculated for each level of process parameters. Because this experiment aims at maximizing the Grey relational grade (GRG), the best configuration for input parameters is the one with the most significant S/N ratio. Analysis of variance is employed to analyze the significance of input parameters. It is found that sample 9 has the highest GRG of 0.861431. So, the sound weld joint can be obtained at the optimum level where the values of input parameters have heat input of 0.747 kJ/mm, root gap of 2 mm and torch angle of 45°. It is quite challenging to weld dissimilar materials. In this work, a sound weld joint is achieved in between AISI 304 stainless steel and EN 8 medium carbon steel flats, and optimum results are effectively determined.

Keywords: GMAW, MAG Welding, Dissimilar Welding, GRA, Taguchi Analysis, ANOVA.

1.0 Introduction

Gas metal arc welding process is an automated or semiautomatic arc welding method in which the workpiece is heated by an electric arc produced between a constantly fed electrode and the workpiece, resulting in coalescence. Inert or active gases are used as shielding gas in this method. The constant voltage supply is applied from a DC generator. The wire electrode is pulled from a spool and pushed into the welding gun at the necessary speed by a wire feeder. Shielding gas at appropriate pressure and flow rate are supplied to the welding area with the help of a pressure regulator and a flow meter [1-3]. Dissimilar weld joints are applied in a wide variety of sectors, including pressure vessel applications in power plants to join the tank and the stanchion. Two furnace shells are made from dissimilar metal joints made of carbon steel and stainless steel. In heavy manufacturing, it may be more cost-effective to create huge components entirely out of stainless steel. So along with stainless steel, low carbon steels are used in specific areas (such as low corrosion zone, low heat exposure area) [4]. Because of its superior corrosion resistance, strength, and hardness, stainless steel is utilized in both industrial and everyday applications. However, because of the huge price and scarcity of chromium and nickel resources, an interest has been made in joining dissimilar materials along with Stainless steels [5]. There are several issues or challenges in welding dissimilar materials. For example, if the two metals to be welded have little or no solubility, the weld strength will be poor. If the coefficients of thermal expansion of the two metals are considerably different, there is a change in temperature in the weld zone which leads to the development of internal stresses. [6].

Earlier several experiments were carried out to join similar or dissimilar metals using GMAW process. Sarkar and Das [7] utilized 100% carbon dioxide in the GMAW method of typical steels to determine the best conditions for obtaining a sound weld. They have examined that the weld current should be at its maximum to enhance a best quality of weld joint. To weld 25mm thick micro-alloyed high strength low alloy steel plate, Devakumaran et al. [8] utilized the GMAW and p-GMAW processes. According to reports, altering the groove size did not uniformly change the chemical composition of the metals throughout the operation. The use of the p-GMAW technique improves weld deposition dilution. Augustine et al. [9] used GMAW technique to join Duplex stainless steel & AISI 316L stainless steel. The ANOVA method was used to examine tensile strength, hardness, and impact strength. Ghosh et al. [10] joined ferritic stainless steel of grade AISI409 to austenitic stainless steel of grade AISI316L by using GMAW process. The Taguchi-Desirability analysis was used to optimize the multiple output parameters. It was discovered that within their experimental domain, sound weld was obtained at welding current of 112 A, gas flow rate of 15 l/min and the nozzle to plate distance of 15mm.

Besides, various solid state welding processes were utilized to join dissimilar materials and provided better weld joint properties. Moreira et al. studied the mechanical and metallurgical properties of friction stir welded (FSW) joints made of aluminium alloys 6061-T6 and 6082-T6 [11]. In tensile testing, the dissimilar joints likewise showed intermediate characteristics. The AA6082-T6 alloy plate side has the lowest hardness profile values. Arabi et al. [12] experimented the metallurgical properties of duplex stainless steel resistance spot welding. They employed a constant electrode force of 4.5kN and a welding current ranging from 6 to 18 kA (step size of 1 kA). Duplex stainless steels, unlike advanced high-strength steels, did not undergo considerable overmatching in the melted zone or softening in the HAZ. However, the well-balanced ferrite austenite micro-structure of the parent metal was destroyed in the HAZ and fusion zone, which could affect corrosion behavior of the welded part.

The Taguchi design is used to estimate process parameters for product design and quality improvement. It is a systematic procedure to experiment design and analysis. It is a powerful tool for enhancing productivity in order to offer high-quality items while keeping costs down. Using Grey relational analysis and the Taguchi approach, Jeyaganesh et al. [13] improved the process parameters of the p-GMAW technology. Wire feed rate and weld current were found to be the most important parameters, whereas weld speed was determined to be the least important. In addition, welding of Mild Steel and Stainless Steel of 2 mm thickness was investigated using the L9 Orthogonal Array for optimization [14]. The resistance spot welding parameters were optimized by Thakur et al. [15] and established the impact of input parameters on the strength of welded joints.The validation tests indicated that the Taguchi technique can greatly improve tensile-shear strength.

The present investigation focuses on the joining of AISI 304 and EN 8 steel plates which are dissimilar in chemical composition. Several destructive techniques are done to find the soundness of the weld joint. Grey relational analysis is performed to optimize multiple responses. Then, ANOVA is utilized to calculate the contribution of each input parameter to grey relational grade or GRG.

2.0 Experimental

2.1 Experimental Outline

In Metal active Gas Welding Process AISI 304 stainless steel and EN 8 medium carbon steels are used to join. In this procedure, 100 % CO_2 gas is employed as a shielding gas. The welding speed is maintained at constant by using motor guided vehicle. The experimental setup for Gas Metal Arc Welding Process (Make: ESAB, Model: AutoK 400) as in shown in **Fig. 1**. The schematic representation of the weld bead that forms during the MAG welding of two plates is shown in **Fig. 2**.

The Taguchi approach is used to design experiments using an L-9 orthogonal array with three columns and nine rows. This DOE is chosen based on three welding parameters, each having three levels. Heat input, root gap, and torch angle are being used as welding parameters for this investigation. To improve process parameters, the grey relational analysis technique is applied. The purpose of this experiment is to increase the grey relationship grade as much as possible (GRG). ANOVA statistical analysis is also carried out to assess whether or not process parameters are statistically significant.

2.2 Design of Experiments

To join the dissimilar steels together, after some trial runs the input parameters are selected and leveled. The input parameters are then organized using Taguchi's L9 orthogonal array. Total 9 experimental runs are carried out.

For optimizing process parameters, design of experiments (DOE) and statistical approaches are commonly utilized. The

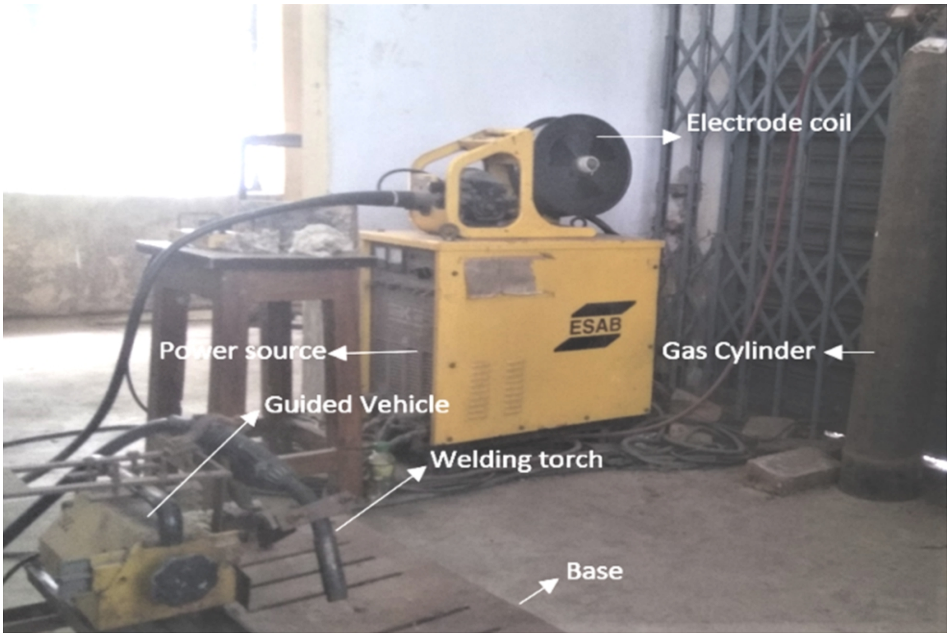

Fig. 1 : Experimental setup of GMAW processy

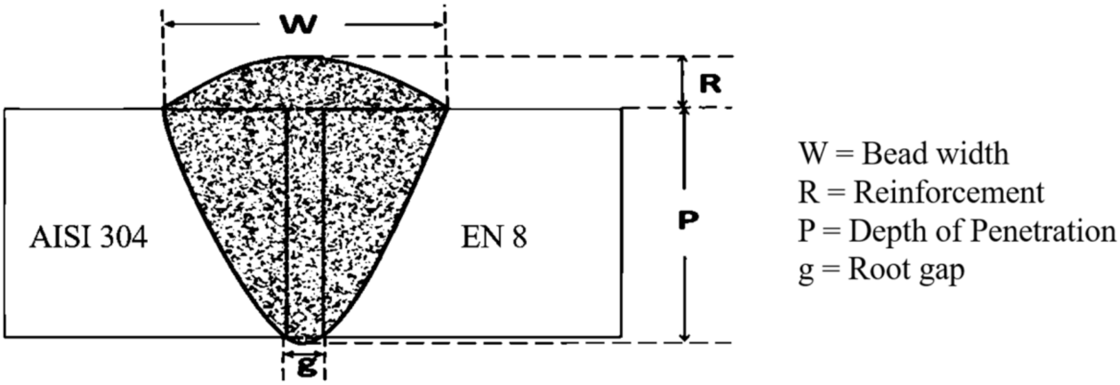

Fig. 2 : Schematic diagram of weld bead geometry

welding process parameters of metal active gas (MAG) welding may very well be adjusted in the current study to get a sound weld of the weld joint while also minimizing the number of trials without harming the outcomes. The optimization of process parameters can increase product quality while lowering the expense of conducting several trials and reducing wastage of resources. This study investigates the effect of welding parameters on weld structure, hardness, and maximum bending load of AISI 304 stainless steel and EN 8 medium carbon steel joints.

Calculation of Heat Input

$$\text{Heat input} = \frac{(V \times I)}{1000 \times S}\,\eta \ \text{(kJ/mm)} \ \ldots\ldots\ldots\ldots\ldots\ \text{(Equation 1)}$$

Where V= Arc voltage (Volt) I = Welding Current (Amp.)
S= weld Speed (mm/s) η = Thermal Efficiency (0.8)

Now from the equation 1, heat input for each condition is calculated as given in **Table 1**.

Weld bead geometrical parameters are described in **Fig. 2**.

Table 1 : Heat input calculated

Current (A)	Voltage (V)	Weld Speed (mm/s)	Heat Input (kJ/mm)
120	24	4.17	0.552
140	24	4.17	0.645
160	24	4.17	0.737

Now as per Taguchi's L9 orthogonal array, three levels are considered for three input parameters as shown in **Table 2**. Then the experiment is processed as per the listed input parameter in **Table 3**.

Table 2 : Levels of input parameter

Parameters	Level 1	Level 2	Level 3
Heat input (kJ/mm)	0.552	0.645	0.737
Root Gap (mm)	0	1	2
Torch Angle (Degree)	30	45	75

Table 3 : Input parameters

Exp. Run	Heat Input (kJ/mm)	Root Gap (mm)	Torch Angle (degree)
1	0.552	0	30
2	0.552	1	45
3	0.552	2	75
4	0.645	0	45
5	0.645	1	75
6	0.645	2	30
7	0.737	0	75
8	0.737	1	30
9	0.737	2	45

3.0 Results and Discussion

AISI304 and EN8 dissimilar steel plates are welded by using GMAW process under varying process conditions. Welded plates are tested to observe soundnessof weld. For evaluating the best welded joints, macro-etch, hardness, and bending tests are performed. Observations made are shown in **Table 4**.

Table 4 : Results obtained from destructive testing

Sl. No.	Levels of Input parameters			Reinforce-ment (mm)	Depth of Penetration (mm)	Bead Width (mm)	Rockwell Hardness (Scale A)	Max. Bending Load (kN)
	Heat Input	Root Gap	Torch Angle					
1	1	1	1	2.928	1.508	9.72	56	2.8
2	1	2	2	2.327	5	12.16	58	5.2
3	1	3	3	1.781	6	11.30	59	8.4
4	2	1	2	4.047	3.628	12.06	63	4.4
5	2	2	3	4.145	6	11.40	56	6.4
6	2	3	1	1.857	6	15.40	55	6
7	3	1	3	2.214	2.750	11.72	67	7.2
8	3	2	1	3.149	6	10.42	60	6.4
9	3	3	1	1.857	6	10.58	63	8.4

From the above results, it can be stated that depth of penetration and hardness increases as heat input and root gap is increased. It is very difficult to mention which sample shows a sound weld joint than others. Furthermore, the impact of each input parameter on the output parameters is challenging to determine. For such reasons, optimization of multiple output parameters is required.

3.1 Optimization of Weld Joint Characteristics using GRA

For finding out the optimum parametric combination of MAG welding for joining dissimilar steel specimens within the experimental domain, depth of penetration, reinforcement, bead width, Rockwell hardness and maximum bending load are selected as the response as detailed in **Table 4**. Response data and the quality criteria show the normalized data for use of Grey relational grade generation, where maximum and minimum reading for each response is assigned the value of 1 and 0 respectively.

So, at first normalized values are calculated depending upon the criteria of each output parameters as stated in **Table 5**.

The normalized data for Lower-the-Better condition is written as:

$$x_i(k) \quad \frac{\max \gamma i(k) - \gamma i(k)}{\max \gamma i(k) - \min \gamma i(k)}$$

For normalized data for Lowr-the-Better condition is written as :

$$x_i(k) \quad \frac{\gamma i(k) - \min \gamma i(k)}{\max \gamma i(k) - \min \gamma i(k)}$$

Using above equations normalized values of each output respponses are calculated as shown in **Table 6**.

After the sequence has been normalized, the deviation sequence is derivedand the results are presented in **Table 7**.

Deviation sequence: $\Delta_{oi} = x_0(k) - x_i(k)$

The sequences of deviation, reference, and comparability are indicated by Δ_{oi}, $x_0(k)$, and $x_i(k)$ respectively.

The grey relation coefficient can be derived as:

$$\varepsilon_i(k) = \frac{\Delta \min + \omega\Delta\max}{\Delta\ oi(k) + \omega\Delta\max}$$

The grey relation coefficient is denoted by $\varepsilon_i(k)$. The largest and smallest value among Δ_{oi} are denoted by and Δ_{max} and Δ_{min} respectively. ω is the distinguishing coefficient ($0 \leq \omega \leq 1$). The values of GRC of each response are shown in **Table 8**.

Finally, grey relational grade is calculated which is listed in **Table 9**.

The GRG (z_i)is obtained as:

$$Z_i = \frac{1}{\eta}\Sigma_k^n = 1^{\varepsilon i(k)}$$

After obtaining the GRG, results are ranked from higher to lower. The highest GRG states that, corresponding values of parameters are optimal.

Now to find Grey Relational Grade, normalized value, deviation sequence and Grey relational coefficient values are sequentially calculated which are shown below :

Table 5 : Evaluation Criteria Description

Criterion	Maximum Reading	Minimum Reading	Quality Criteria
Reinforcement (mm)	4.145	1.781	lower-the-better
Depth of Penetration (mm)	6	1.508	larger-the better
Bead width (mm)	15.4	9.72	lower-the-better
Rockwell Hardness	67	55	larger-the-better
Maximum bending load (kN)	8.4	2.8	larger-the-better

Table 6 : Normalized values of output parameters

Sl. No.	Reinforcement (mm)	Depth of Penetration (mm)	Bead Width (mm)	Rockwell hardness in scale A	Max bending load
1	0.514805	0	1	0.083333	0
2	0.769036	0.777382	0.570423	0.25	0.428571
3	1	1	0.721831	0.333333	1
4	0.041455	0.47195	0.588028	0.666667	0.285714
5	0	1	0.704225	0.083333	0.642857
6	0.967851	1	0	0	0.571429
7	0.816836	0.276492	0.647887	1	0.785714
8	0.42132	1	0.876761	0.416667	0.642857
9	0.967851	1	0.848592	0.666667	1

Table 7 : Deviation Sequence of each response

Sl. No.	Reinforcement (mm)	Depth of Penetration (mm)	Bead Width (mm)	Rockwell hardness in scale A	Max bending load
1	0.485195	1	0	0.916667	1
2	0.230964	0.222618	0.429577	0.75	0.571429
3	0	0	0.278169	0.666667	0
4	0.958545	0.52805	0.411972	0.333333	0.714286
5	1	0	0.295775	0.916667	0.357143
6	0.032149	0	1	1	0.428571
7	0.183164	0.723508	0.352113	0	0.214286
8	0.57868	0	0.123239	0.583333	0.357143
9	0.032149	0	0.151408	0.333333	0

Table 8 : Grey Relational Coefficient of each response

Sl. No.	Reinforcement (mm)	Depth of Penetration (mm)	Bead Width (mm)	Rockwell hardness in scale A	Max bending load
1	0.507514	0.333333	1	0.352941	0.333333
2	0.684028	0.691929	0.537879	0.4	0.466667
3	1	1	0.642534	0.428571	1
4	0.342807	0.486358	0.548263	0.6	0.411765
5	0.333333	1	0.628319	0.352941	0.583333
6	0.939587	1	0.333333	0.333333	0.538462
7	0.731889	0.408661	0.586777	1	0.7
8	0.463529	1	0.80226	0.461538	0.583333
9	0.939587	1	0.767568	0.6	1

Table 9 : Grey Relational Grade of each output parameters

Sample No.	Heat Input	Root Gap	Torch Angle	GRG	Rank
1	1	1	1	0.505424	8
2	1	2	2	0.5561	7
3	1	3	3	0.814221	2
4	2	1	2	0.477838	9
5	2	2	3	0.579585	6
6	2	3	1	0.628943	5
7	3	1	3	0.685465	3
8	3	2	1	0.662132	4
9	3	3	1	0.861431	1

3.2 Application of GRA

After optimizing the multiple output parameters, corresponding input parameters are indicated. The measured data were evaluated using MINITAB 19 software, which is made for experiment design. To evaluate the performance characteristics, the experimental data i.e., GRG is converted into S/N ratio. The impact of Heat Input, Root Gap, and Torch Angle on Grey Relational Grade (GRG) was investigated.

For nine experiments, S/N ratio and mean values are calculated. Then from each level, average of S/N ratio and mean are calculated as listed in **Table 10**. These are ranked as per the Delta value. Also, responses of S/N ratio and mean values of each level are calculated and shown in **Table 11** and **12** respectively.

Table 10 : S/N ratio and mean values

Sl. No.	S/N ratio	Mean
1	-5.92688	0.505424
2	-5.09694	0.556100
3	-1.78515	0.814221
4	-6.41438	0.477838
5	-4.73765	0.579585
6	-4.02777	0.628943
7	-3.28029	0.685465
8	-3.58111	0.662132
9	-1.29559	0.861431

3.2.1 Grey Relational Grade versus Heat Input, Root Gap, Torch Angle

Table 11 : Response for S/N Ratios Larger is better

Level	Heat Input	Root Gap	Torch Angle
1	-4.270	-5.207	-4.512
2	-5.060	-4.472	-4.269
3	-2.719	-2.370	-3.268
Delta	2.341	2.838	1.244
Rank	2	1	3

Table 12 : Response for Means

Level	Heat Input	Root Gap	Torch Angle
1	0.6252	0.5562	0.5988
2	0.5621	0.5993	0.6318
3	0.7363	0.7682	0.6931
Delta	0.1742	0.2120	0.0943
Rank	2	1	3

Fig. 3 depicts the optimum results of S/N ratio. The rank reveals that Root gap (rank=1) has the largest impact on signal-to-noise ratio in the experimental study for Grey Relational Grade. Heat Input is the second most important factor in S/N ratio, followed by Torch Angle. It is required to enhance the S/N ratio in Taguchi investigations.

Fig. 3 : Main effects plot for S/N ratio

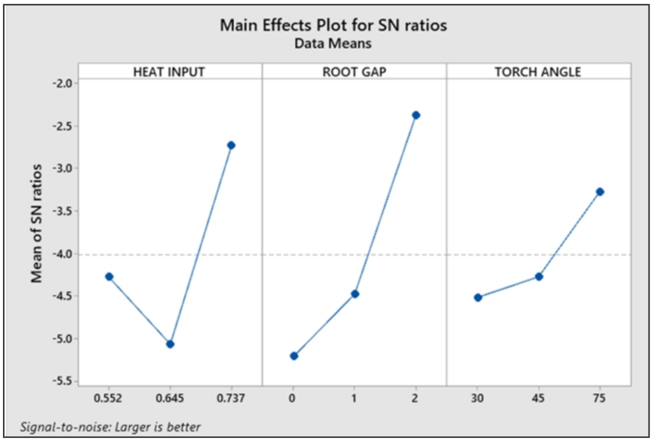

Table 13 : ANOVA for S/N ratio

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Heat Input	2	8.5091	8.5091	4.25454	123.53	0.008	35.16
Root Gap	2	13.0131	13.0131	6.50655	188.91	0.005	53.77
Torch Angle	2	2.6096	2.6096	1.30482	37.88	0.026	10.78
Residual Error	2	0.0689	0.0689	0.03444			0.285
Total	8	24.2007					

Table 13 provides the ANOVA statistics for S/N ratio of GRG at a 95% confidence level.

According to **Fig. 4**, Root gap has 54% of contribution to grey relationship grade, followed by Heat input with a 35% of contribution and Torch angle with a 11% of contribution.

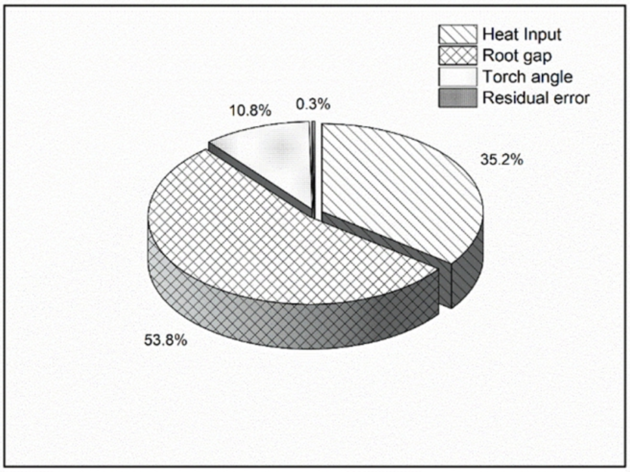

Fig. 4 : Pie chart for percentage of contribution

3.3 Discussion on Results obtained from Contour Plot

From the contour plot of **Fig. 5** (GRG vs Heat input vs Root gap), it is observed that mean grey relational grade is the highest corresponding to maximum heat input (0.74 kJ/mm) and root gap (2 mm), and hence, in this consideration, these are the optimum input parameters.

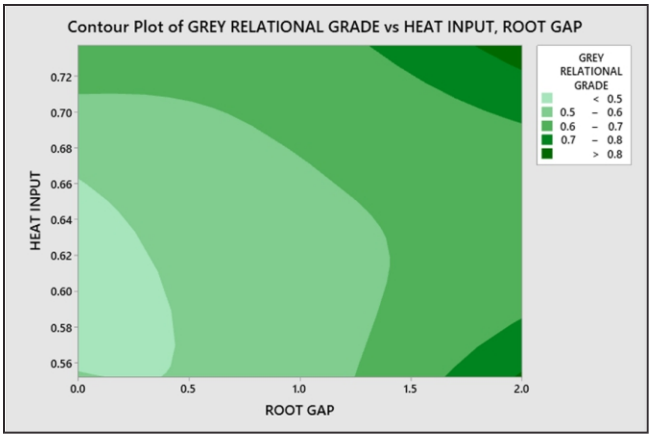

Fig. 5 : Contour Plot of Grey Relational Grade vs Heat Input vs Root Gap

Similar plot of mean grey relational grade in the domain of torch angle and root gap is depicted in **Fig. 6**. In this figure, maximum value of mean GRG is obtained to a root gap of 2 mm and torch angle in the range of 35° to 75°.

In the domain of torch angle and heat input, mean GRG is mapped in **Fig. 7**. It is also discovered that the dark region on the right-hand side of the map correlates to the highest computed mean GRG. This is the optimum region given by a heat input of 0.74kJ/mm and torch angle in the range of 35° to 65°.

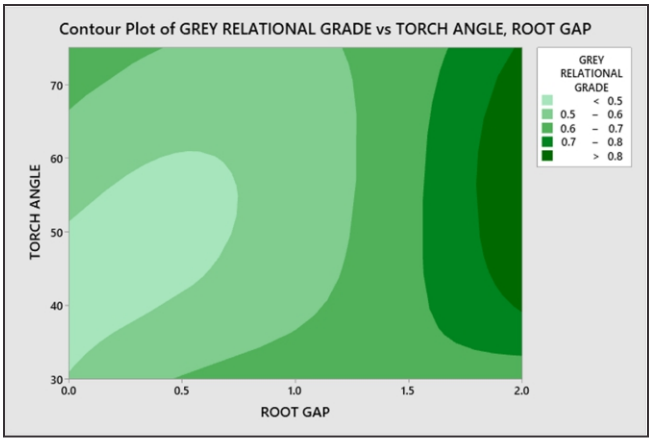

Fig. 6 : Contour Plot of Grey Relational Grade vs Torch Angle vs Root Gap

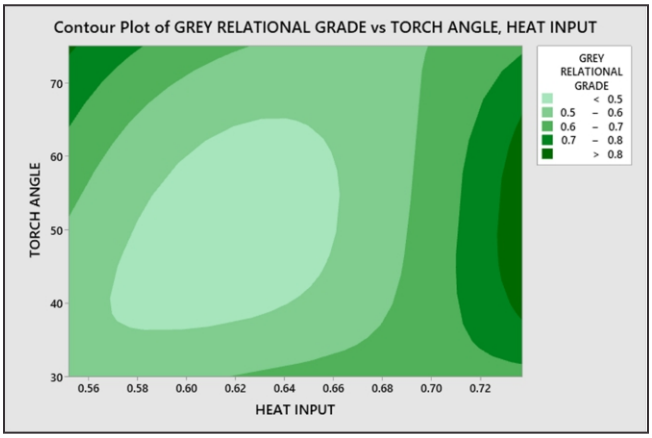

Fig. 7 : Contour Plot of Grey Relational Grade vs Torch Angle vs Heat Input

4.0 Conclusion

Two dissimilar steel plates are joined using a Metal active Gas welding process. There are several problems leading to failure in dissimilar weld joints. To find the effectiveness of the joint, Non-destructive testing are performed and then the results are optimized to find the optimum process parameters. Also, Contour plots are made between GRG and two different combinations of input parameters. From the Grey relational analysis, S/N ratio, ANOVA and Contour plots following conclusions are made, which indicate the best welded joint.

- According to grey relational analysis (GRA), sample no. 9 has the highest grey relational grade (0.861431) within the experimental domain. So, the sound weld joint can be obtained at optimum level where the values input parameters are heat input of 0.747 kJ/mm, root gap of 2 mm and torch angle of 45°.
- At optimum condition, the output parameters obtained, are reinforcement of 1.857 mm, depth of penetration of 6 mm, bead width of 10.58 mm, Rockwell hardness of 63 and maximum bending load at failure of 8.4 kN.
- As per the ANOVA results of GRA, it is mentioned that the root gap (53.77%) has a major impact on multiple responses followed by heat input (35.16%) and torch angle (10.78%).
- From the contour plot of GRA vs Heat Input vs Root Gap, it is observed that mean grey relational grade is the highest corresponding to maximum heat input (0.74 kJ/mm) and root gap (2 mm). When it is plotted against GRG vs Torch Angle vs Root Gap, maximum value of mean GRG is obtained to a root gap of 2 mm and torch angle in the range of 35° to 75°. Also, for the contour plot of GRG vs Torch Angle vs Heat Input, the optimum region is given by a heat input of 0.74kJ/mm and torch angle in the range of 35° to 65°.

Finally, it is stated that AISI 304 stainless steel and EN 8 medium carbon steel can be successfully joined by the MAG welding process. The related optimum process parameters are calculated using Taguchi's GRA method. Several mechanical analyses found that heat input influences the joint strength, followed by root gap and torch angle.

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