Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 3 (2024)

Investigation of Sustainable Prospects of Fabricating Galvanized Steel with Gas Metal Arc Welding

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Abstract:- Welding operations, in general, have been and continue to be critical for daily comfort and pleasure, as well as important in a variety of industries and infrastructure development. Welding technology is constantly evolving, enabling research and innovation in a variety of disciplines and contributing to the creation of more efficient and advanced materials, as well as sustainable solutions. Aside from other aspects, the quality of welding that contributes directly to sound, strong, and safe welded joints without lowering the design yield properties of materials is heavily influenced by the optimisation of welding parameters chosen for the welding project. This research investigates the optimisation parameter values for welding galvanised steel with gas metal arc welding (GMAW) or metal inert gas (MIG). The most optimum of the parameter combinations is chosen using the multi-criteria decision making (MCDM) technique employing Technique for Order Preference by Similarity to Ideal Solution(TOPSIS) analysis, whereas the most influencing parameter is determined by the Signal-to-Noise Ratio and Analytical Variance analysis methods. This investigation, which used TOPSIS, and ANOVA analyses, found that the combination of parameters used to weld 'Specimen 18' was the best combination of parameter optimisation, and that the welding speed ranked highest among the variable parameters chosen, making it the most influential. Following weld speed came root gap, welding current, and shielding gas flow rate.

Keywords: Gas Metal Arc Welding (GMAW), Metal Inert Gas (MIG) welding, galvanized steel, Multi-criteria decision making (MCDM), TOPSIS.

1. Introduction

Welding related fabrications encounter almost related challenges of improper settings or control of various optimization parameters [1]. Hence, researches that examine the entire sets of dynamic complexities and interactions among the welding parameters, the welding processes and their combinations that affect welding integrity, and purpose assumes its importance. A great number of studies trying to examine various welding process and how they are influenced by different sets of process parameters exists. These studies used a range of materials also. However, due to the complexity in deciding which combination of optimization of parameters work best for a particular material of interest employing a particular welding process is still essential. This is because different types of materials find their application in different scenarios. Further, use of different materials, economics of fabrication process and few other factors compel to employ different welding process in varied situations. It is also essential to investigate which optimization parameter is the most influential so that more focus could be laid on controlling that parameter. The multi-criteria decision making using TOPSIS is being used here not only for its popularity but proven accuracy together with S/N ratio and ANOVA.

The objective of this research is to investigation the optimization parameters that promote sustainable prospects of fabricating galvanized steel using Metal Inert Gas(MIG) welding process. Most optimization parameters to be studied can be limited by type and model of MIG equipment available. In this study 4 number of MIG welding parameters, welding speed electrode/filler wire feed rate, the shielding gas flow rate, and varying root gap in the welding joints were chosen for joining Galvanized steel. This study further investigated the sustainable prospects of fabricating galvanized steel with MIG welding process.

2. Literature Review

Gas Metal Arc Welding (GMAW) or commonly known as MIG (Metal Inert Gas) welding has been used extensively since its development around 1940's, and its commercialization in 1950's. It was developed during World War II to weld materials like aluminium, magnesium and other non-ferrous metals that were difficult to weld by other welding processes. By 1970s, GMAW gained widespread adaptation, and becoming one of the most commonly used welding processes. The versatility and speed of GMAW created wide ranges of applications including automotive, aerospace, construction, and manufacturing. The spool of electrode wire automatically fed during MIG welding played a significant role in increased productivity not found in other processes.

Into the 21st century, GMAW has evolved with improvement in electrode feed wire system, welding power sources, and digital controls. The process became crucial in the welding industry, with applications from thin sheet material to heavy industrial structures.

Chavda et al. (2014) [3], explored MIG welding parametrs on out pu parameters while weding medium carbon steel. The parameters selected for this investigation were welding current, welding voltage, shielding gas flow rate, wire feed rate, etc. Patil and Waghmare (2013) [4] analyzed the ultimate tensile strength of AISI 1030 mild steel using MIG welding based on optimization parameters like welding current, welding voltage, and weld speed. The study concluded that the welding current and welding speed were the major parameters which influenced the tensile strength of the welded joint. Irfan and Achwal (2014) [1] studied and analyzed the effects of welding galvanized steel using MIG. The voltage and current remained constant throughout at 23 volts and 100 amps. The parameters studied were the welding speed, depth of penetration and welding bead size. Another study by Jeet, et al., (2018) [6] on optimization of welding parameters using GMAW employed technique for Order of preferences by similarity to ideal solution(TOPSIS) method in search for an optimal metal deposition rate (MDR), ultimate tensile strength and hardness of the MIG weld in consideration.

3. Math

If Galvanized steel material is shaped(figure 1), cut from middle and welded as shown in figure 2. The specimen is 600 mm in overall length by 45mm at both ends with a thickness of 6mm. The welding parameters and their different settings are presented in table 1.

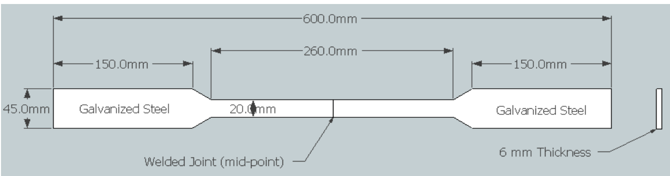

Fig. 1. Specimen dimensions

Fig. 2. Galvanized steel Specimen

Table 1: Welding parameters

	Parameter		Levels		
		Units	1	2	3
1	Welding Current (Ip)	Amps	70	85	100
2	Welding Speed (s)	mm/min	100	125	150
3	Shielding Gas Flow Rate (f)	l/min	16	18	20
4	Root Gap (t)	mm	1.0 /1.2	1.0/1.2	1.0/1.2

Then a multi-criteria decision method (MCDM) using TOPSIS is used to determine the ranking of the best combination of optimization parameter, and the analysis of variance is used to rank the best parameter.

The equipment used throughout the study are;

- The MIG welding machine (MIGWELD 200) (see figure 3)
- The Universal Testing Machine (UTM) (see figure 4)
- Hand-grinder (125mm)
- 125 mm metal-cutting discs, and 125 mm metal grinding wheels.

The MIG CIGWELD 200 equipment used for this study. The shielding gas is 100 % argon, with a multi-purpose steel coil of filler wire.

Fig. 3. MIG Welding Machine

Fig. 4. Tensile Test Set-up selected.

3.1 The Study Layout Using the L_9 Orthogonal Array

With reference to, the L9 orthogonal array layout is given for two sets of optimization of parameters to be investigated; giving a total of 18 specimens assigned to specific variable parameters. All awhile the basis of the study of optimization of parameters is well accomplished with the L9 Orthogonal Array layout introduced by Dr. Genichi Taguchi of Nippon TTC [4]; thus the Taguchi technique method.

It has to be noted that the design of L9 orthogonal array (OA) by Dr. Taguchi provides the minimum experiments needed to study by 'optimizing the variance to a reduced minimum' to attain the desired output. The selection of OA pave way for Dr. Taguchi's signal-to-noise (S/N) ratios, which are log functions of desire output, serve as objective functions in optimization, help in data analysis and estimation of optimum results [4].

The Taguchi technique fall into two groups; static and dynamics. When dealing with static problems, three signal-to-noise ratios are determined; small-the-higher, larger-the-better, and nominal-the-fine. Slope and linearity are the two signal-to-noise ratios that are used to finish the optimization process in dynamics problems.

3.2 Signal to Noise Ratio

The S/N ratio for each level of input is based on the S/N

ratio analysis. Given the tensile strength of a weld joint, a higher S/N means a better quality (larger-the-better scenario) [13].

The standard (S/N) ratio for such response is:

S/N = -10 log (M.S.D), where M.S.D is the mean square deviation for the output characteristic.

For 'n' number of total experiments, 'Y_{ij}' is the quality of the i^{th} trial and j^{th} experiment

$n_i = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} \frac{1}{Y_{ij}^2} \right]$

The S/N ratio is given by: $n = 10\ Log\left(\frac{\beta^2}{\sigma^2}\right)$ where β is the proportionality constant usually = 1, and σ^2 is the variance, which is the mean of the sum of squares of deviations of measured data points from the best line of fit.

The three criteria of S/N ratio analysis are;

(1) Larger-the-better

$$S/_N\ Ratio = -10 \log \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2}$$

(2) Smaller-the-better

$$S/_N\ Ratio = -10 \log \frac{1}{n} \sum_{i=1}^{n} y_i^2$$

(3) Nominal-the-better

When a specified value is MOST desired (neither a smaller nor larger value is desirable)

$$S/_N\ Ratio = -10 \log \left(\frac{\bar{y}^2}{\sigma^2}\right)$$

Where: n = number of trials carried out

y_i = output value (signal mean) obtained in each trial

$\bar{y}$ = mean value of the obtained output responses for different trials

$\sigma =$ Standard Deviation

3.3 Optimization of MIG Welding Parameters using TOPSIS

Given the results of the tests, method of selecting the most optimum parameter is necessary and to determine the optimum parameter. TOPSIS has been chosen to better this approach in multi-criteria decision making.

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) has been widely used over the last 4 decades for such decision making and so is highly preferred. TOPSIS is utilized in various field s such as engineering, management, economics, and environmental studies to assist in decision-making processes when multiple criteria need to be considered simultaneously, as in this case. It offers a structural approach for selecting the most favorable option based on the established criteria and their relative importance.

TOPSIS is one of the numerical methods of the multi-criteria decision making [9]. "The fundamental principle is that the chosen alternative should have the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution".

3.4 Technique for Order Preference by Similarity to Ideal Solution(TOPSIS)

The multi-criteria decision making (MCDM) using TOPSIS was first introduced by Hwang and Yoon in 1981. The essence of this method is a compromise concept of alternative solution chosen to have the closest distance to a positive ideal solution (optimal solution) and having the furthest distance from the ideal solution (non-optimal solution) [10].

TOPSIS can be a compensatory method too where the method allows the compromise between varying criteria for a bad result in one criteria can be compensated by a good result in another criteria. An assumption of TOPSIS method rests with each criteria being a monotonically increasing or decreasing preference [9].

The TOPSIS method describes the optimum parameters as value of best solution from the results being compared, and which can also be inferred as the best value from the greatest distance from the worst possible.

The advantage of using TOPSIS is that it is simple and easy to understand and computing is efficient, and measure relative performance of decision alternatives in simple mathematical form.

The TOPSIS method may be better understood with the following steps;

1. Define and establish the criteria and alternatives used for evaluation

There are set of alternatives (options or choices) and a set of criteria (factors or attributes) that can be used to evaluate the alternatives. The criteria can be quantitative or qualitative and should be relevant to the decision at hand.

- Create a decision (D) in the form of a matrix for each criterion (d_{ij})

2. Normalize Data often to a common scale usually between 0 and 1. This step is essential because the criteria may have different units and magnitudes.

- Normalized the decision matrix ($\bar{y}$)

The normalized values $\bar{y}_{ij}$is calculated as; $\bar{y}_{ij} = \frac{Y_{ij}}{\sqrt{\sum_{j=1}^{n}(l_{ij})^2}}$

3. Weighting or determine the Ideal and Anti-Ideal Solution. Assigning weights to each criteria based on their importance in the decision making process. The weights reflect the relative significance of each criterion; the sum of which should be equal to 1. Weighted normalised matrix can be obtained using analytical hierarchy process (AHP) method or similar if not given. In this study AHP is used.

$$\sum_{i=1}^{n} wi = 1$$

4. Calculate the Similarity (Proximity) to Ideal Solution

   a. The positive ideal solution is the best possible value for each criteria, where the values are maximized for benefit and minimised for cost criteria

Let S^+ be the ideal solution, and the negative solution S^-

$S^* = \{s_1^*, s_2^* \ldots s_n^*\} = \{(\max s_{ij}|d\in C), (\min s_{ij}|d\in D)\}$

The negative ideal solution is the opposite of the positive ideal solution, where the values are minimized for benefit criteria and maximized for cost criteria.

$S^- = \{s_1^-, s_2^- \ldots s_n^-\} = \{(\max s_{ij}|d\in C), (\min s_{ij}|d\in D)\}$

5. Calculate the Relative Closeness to Ideal Solution

- Euclidean distance calculation

The distance of each alternative from the ideal solution (positive and negative) is calculated. Typically, the distance is determined using a distance metrics.

$S_i^+ = \sqrt{\sum_{c=1}^{n}\left(V_{ij} - V^*\right)^2}$ 1≤ i ≥m, 1 ≤ j ≥ n; $S_i^- = \sqrt{\sum_{c=1}^{n}\left(V_{ij} - V^*\right)^2}$

- Similarity to Ideal Solution

A similarity measure is calculated for each alternative based on its distance from the positive and negative idea solution. The similarity is often represented as a relative closeness or proximity to the ideal solution.

$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$; 1 ≤ i ≥ m

6. Rank and Select the Alternatives

Alternatives are ranked based on their similarity to the ideal solution. The alternative with the highest similarity score,P_i is considered the best choice.

4. Results

Tensile tests were carried out using UTM (universal testing machine) at the Civil Engineering laboratory. The final tensile test results for each specific specimen are given in Table . .

Table 2: Tensile Tests Results

Specimen No.	Root Gap (mm)	Current (A) (amp)	Welding Speed (s) (mm/s)	Gas Flow Rate (f) (l/min)	Energy Density (J/mm)	UTS (MPA)	Elongation (%)
1	1	120	300	12	6.912	361	11.57
2	1	120	400	15	5.184	322	12.46
3	1	120	500	18	4.147	313	13.34
4	1	140	300	12	8.661	390	15.55
5	1	140	400	15	6.496	327	11.28
6	1	140	500	18	5.197	317	14.19
7	1	160	300	12	10.624	396	12.04
8	1	160	400	15	7.968	372	12.85
9	1	160	500	18	6.374	339	13.26
10	1.2	120	300	12	6.912	392	12.92
11	1.2	120	400	15	5.184	355	13.18
12	1.2	120	500	18	4.147	348	15.69
13	1.2	140	300	12	8.661	426	17.34
14	1.2	140	400	15	6.496	342	13.63
15	1.2	140	500	18	5.197	335	11.38
16	1.2	160	300	12	10.624	432	16.54
17	1.2	160	400	15	7.968	389	14.32
18	1.2	160	500	18	6.374	364	15.61

5. Analysis of Results

If The effects of optimization on ultimate tensile stress is plotted see figure 6. Amongst the 4 main effects, 'Speed' indicated a larger signal-to-noise response, indicating that speed had the major influence over other optimization parameters selected herein. The level of signal-to-noise with the criteria of larger-is-better has been seen with speed with gas flow the least response.

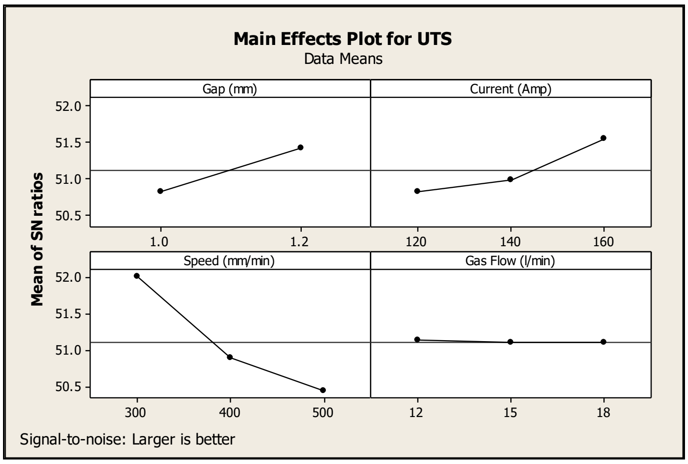

Fig. 6. Main Effect Plot for UTS

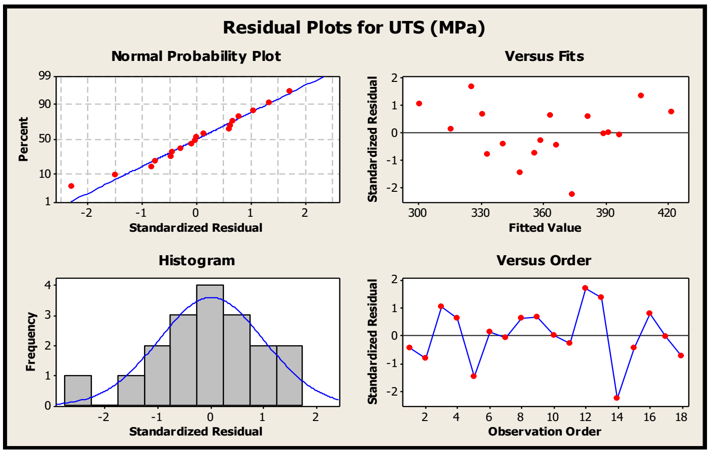

Fig. 7. Residual Plot for UTS

The residual plots indicates the optimization input variables deviations from the regression analysis, in a more acceptable manner. The histogram gives the standardized residual and lacked no disproportionate influence by any parameter, and violation of underlying assumptions. The study was acceptable in all modes supported by Figure 7.

6. Discussion

The results of the study show the welding speed has more influence in the optimizing levels ranking highest Table 1, followed by root gap, the welding current setting and gas flow rate in that order of 'preference' by analysis using analysis of variation.

TOPSIS was a great tool also that unveils the complexity of 'multi-criteria decision making', and the accuracy is highly favorable not only in this study but in many related studies found in the literature review. In this study, TOPSIS analysis shows that Specimen 18 ranked highest from Table 3, in the optimization combination of variable parameters selected.

Table 3: TOPSIS Ranking

Specimen	Root Gap	Current	Weld Speed	Gas Flow	Energy Density	UTS	Elongation	S^+	S^-	P	Ranking
Type											
Weighted	**0.34646**	**0.093**	**0.0756645**	**0.11206**	**0.145213673**	**0.2266**	**0.143828**				
1	0.073933	0.06952	0.173809965	0.006952	0.004004582	0.209151	0.00670327	0.1229	0.0394	0.242929784	**18**
2	0.073933	0.06952	0.231746619	0.00869	0.003003436	0.186556	0.00721891	0.0861	0.0645	0.428148139	**11**
3	0.073933	0.06952	0.289683274	0.010429	0.002402633	0.181342	0.00772875	0.0690	0.1191	0.633169646	**6**
4	0.073933	0.08111	0.173809965	0.006952	0.005017894	0.225953	0.00900915	0.1190	0.0485	0.289746483	**17**
5	0.073933	0.08111	0.231746619	0.00869	0.003763565	0.189453	0.00653525	0.0848	0.0616	0.420732161	**12**
6	0.073933	0.08111	0.289683274	0.010429	0.003010968	0.183659	0.00822121	0.0677	0.1174	0.634243089	**5**
7	0.073933	0.0927	0.173809965	0.006952	0.00615519	0.229429	0.00697557	0.1200	0.0505	0.296187859	**16**
8	0.073933	0.0927	0.231746619	0.00869	0.004616393	0.215524	0.00744486	0.0714	0.0689	0.491003236	**8**
9	0.073933	0.0927	0.289683274	0.010429	0.003692882	0.196405	0.0076824	0.0587	0.1178	0.667168755	**3**
10	0.088719	0.06952	0.173809965	0.006952	0.004004582	0.227112	0.00748542	0.1191	0.0515	0.301986357	**15**
11	0.088719	0.06952	0.231746619	0.00869	0.003003436	0.205675	0.00763605	0.0746	0.0671	0.473486684	**9**
12	0.088719	0.06952	0.289683274	0.010429	0.002402633	0.20162	0.00909026	0.0510	0.1199	0.701491396	2
13	0.088719	0.08111	0.173809965	0.006952	0.005017894	0.24681	0.01004622	0.1175	0.0665	0.361675111	**14**
14	0.088719	0.08111	0.231746619	0.00869	0.003763565	0.198143	0.00789677	0.0802	0.0615	0.434096016	**10**
15	0.088719	0.08111	0.289683274	0.010429	0.003010968	0.194088	0.00659319	0.0593	0.1172	0.663871667	**4**
16	0.088719	0.0927	0.173809965	0.006952	0.00615519	0.250286	0.00958272	0.1191	0.0690	0.366768862	**13**
17	0.088719	0.0927	0.231746619	0.00869	0.004616393	0.225374	0.00829653	0.0688	0.0728	0.513941023	**7**
18	0.088719	0.0927	0.289683274	0.010429	0.003692882	0.210889	0.00904391	0.0482	0.1196	0.712568202	**1**
Step 4								*Step 5*	*Step 6*	*Step 7*	*Step 8*
V_+	0.073933	0.06952	0.289683274	0.006952	0.002402633	0.250286	0.00653525				
V^*	0.088719	0.0927	0.173809965	0.010429	0.00615519	0.181342	0.01004622				

7. Implications

The result of the study may determine improvements in fabricating galvanized steel using MIG welding where the optimizing parameters that influence the weld strength and quality can be employed. The welding speed had much influence in this study indicates that it can be employed in automation with greater ease in welding galvanized steel using MIG and that the other optimization parameters that contribute to influence its performance like current setting and gas flow are good indicators of the combinations that work well.

Throughout this study, a further realization of the state of MIG welding has prompted an issue of not investing in it and it is worth mentioning the need to promote the use of MIG welding, strongly recommending the use of the optimization parameters, and realization of its importance as an investment to the development of manufacturing especially in Papua New Guinea. The study determined that welding speed had more influence over other parameters, then utilizing this ‘speed’ is increasing productivity overall by MIG welding; a characteristic of automation of welding process found in MIG welding where may be lacking in other processes.

It can be seen that investing in MIG welding process is a greater benefit not only in achieving much needed infrastructure, improved manufacturing, and being cost-effective, but it will also increase skills level, provide training and fulfilling the workforce needs of welding capacity building.

Even the cost of initial capital in investing in MIG welding is higher compared to metal arc welding, the value of productivity in mass producing, and related benefits are worth the investment. The increase in use of galvanized steel in particular makes the value of fabricating galvanized steel using MIG welding even beyond break-even otherwise better.

This also can contribute to sustainable development by reducing energy consumption, minimizing waste, lowering emissions, and improving the durability of products, and improve productivity.

Such study is vital for Papua New Guinea where emphasis is placed elsewhere and much is lacking in promoting MIG welding optimization on different materials to sustain the prospects of vital processes, and livelihood in general.

8. Conclusion

Welding in general plays a very critical role in the development of infrastructure and to our daily lives. With more emphasis on sustainable practices, it is practical to adopt best practices in order to increase productivity with reliable outcomes. Various studies in fabricating galvanized steel using MIG welding optimum parameters have otherwise promoted the process, and this study had added an optimization analysis shown by TOPSIS technique, analysis of variance (ANOVA) and S/N ratio analysis that the welding speed stands out to influence more the weld (UTS) strength, and in fact productivity by nature of the parameter.

By use of TOPSIS multi-criteria decision making method, all of the 18 specimens were ranked accordingly to see which specimen or the combination of optimization of MIG welding parameters represented by a said specimen had the most influence over the other 17 specimens. According to Table ‘Specimen 18’ ranked 1 (with the highest performance score of 0.712568202) indicating that Specimen 18 was the best combination of optimization parameters. This however, does not show which variable parameter is really influencing the weld characteristics. In order to figure this out, the Signal-to-noise ratio and analytical variance (ANOVA) were utilized also to further ‘separate’ the contribution of each parameter in the combination of parameters (in a specimen), and show its ranking amongst the combinations.

In the final analysis using Analytical Variance Table 1 and Signal-to-Noise ratio Figure , the specimens were analysed and it was seen that ‘Speed’ or welding speed dominated the ranking of ANOVA and was consistent with S/N ration ‘larger-the-better’.

This conclude that the welding speed influenced more the ultimate strength of welding galvanized steel using MIG welding.

References

[1] M. Kesse, Artificial Intellegence - A Modern Approach to Improving Weld Quality in TIG Welding, 2021.

[2] S. P. Chavda, J. V. Desai and T. M. Patel, "A review on optimization of MIG Welding parameters using Taguchi's DOE Method.," International Journal of Engineering and Management Research (IJEMR), vol. 4, no. 1, pp. 16-21, 2014.

[3] S. R. Patil and C. A. Waghmare, "Optimization of MIG Welding Parameters for improving strength of welded joints.," Int. J. Adv. Eng. Res. Stud, 14, p. 16, 2013.

[4] S. Irfan and V. Achwal, "An experimental study on the effect of MIG welding parameters on the weldability of galvenize steel.," International Journal on Emerging Technologies, vol. 5, no. 1, p. 146, 2014.

[5] G. Livelli and T. Langill, "Guidelines for welding galvanized steel.," *PCI journa*, vol. 43, no. 3, pp. 40-48, 1998.

[6] S. Jeet, B. Parida, A. Barua, B. B. Sanoo and D. K. Bagal, "Multi-Objective Optimization of Welding Parameters in GMAW in Stainless Steel and Low Carbon Steel Using Hybrid RSM-TOPSIS-GA-SA Approach," *International Journal of Technical Innovation in Modern Engineering and Science (IJTIMES)*, vol. 4, no. 8, p. 11, August 2018.

[7] A. D. S. S. Ajit Hooda, "Optmization of MIG Welding Process Parameters to Predict Maximum Weld Strength in AISI1040," *International Journal of Mechanical Engineering and Robotic Researchs*, 2012.

[8] V. A. Sindiri Mahesh, "Optimization of MIG Welding Parameters for Improving Strengths of Welded Joints," International Journal of Innovative Technology and Research, 2017.

[9] R. Zulqarnain, M. Saeed, N. Ahmad, F. Dayan and B. Ahmad, "Application of TOPSIS Method for Decision Making," *Internationsl Journal of Scientific Research in Mathematics and Statistical Sciences*, vol. 7, no. 2, pp. 78-81, 2020.

[10] Z. Pavic and V. Novoselac, "Notes on TOPSIS Method," *International Journal of Research in Engineering and Scienece* , vol. 1, no. 2, pp. 05-12, 2013.

[11] G. Ginting, Fadina, S. A. P. U. S. Mesran and R. Rahim, "Technical Approach of TOPSIS in Decision Making," International Trends in Engineering and Research , vol. 3, no. 8, 2017.

[12] A. Nasir and B. L. Jarvis, New Developments in Advance Welding, England: Woodhead Publishing Limited, 2005.

[13] J. Pasupathy and V. Ravisankar, "Parametric optimization of TIG welding parameters using taguchi method for dissimilar joint (Low carbon steel with AA1050).," Journal of Scientific & Engineering Research,, vol. 4, pp. 25-28, 2013.

[14] C. A. W. S.R. Patil, " Optimization of MIG Welding Parameters for Improving Strength of Welded Joints," *"Advanced Engineering Journal of Research and Studies,* 2013.

[15] S. E. W. A. Singh, V. I. K. A. S. Chawla and G. S. Brar, "The performance of TIG welded similar and dissimilar weldments under tensile loading: An experimental investigation.," *Int. J. Mech. Prod. Eng. Res. Dev*, , vol. 9, no. 4, pp. 1015-1026, 2019.

[16] S. Weis, R. Grunert, S. Brumm and U. Prank, "Study on MIG-TIG hybrid brazing of galvanised thin sheet.," Welding in the World,, vol. 67, no. 5, pp. 1215-1221., 2023.