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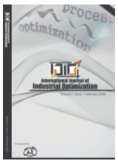

Optimizing welding parameters for high deposition efficiency in waam by using the taguchi method

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ABSTRACT

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Wire arc additive manufacturing (WAAM) is a type of additive manufacturing technology that offers high flexibility in shaping products and is cost-effective due to its low material consumption and rapid time to market. Material consumption can be evaluated by assessing deposition efficiency during welding. The efficiency of a deposited metal depends on various processes and welding parameters, including travel speed, wire feed rate, voltage, distance of the torch from the base, and many others. Therefore, process capability can be efficiently achieved by crucially determining the key parameters that have the most significant effect. In this study, the main objective is to determine the most significant parameters to obtain the optimum deposition efficiency of a gas metal arc welding-based 3D welding machine. The Taguchi experimental design method is used to determine the optimal welding parameters. Results showed that the distance of the torch from the base is the most significant parameter, followed by welding speed and wire feed rate. The observation is validated via a confirmation test.

1. Introduction

Wire arc additive manufacturing (WAAM) is regarded as a cost-effective and efficient technology for producing large-scale and ultra-large-scale metallic components [1]-[4]. This technology has been extensively researched in various fields over the last 2 decades, including the aerospace [5], automotive [6]-[7], and marine industries [8]-[9]. WAAM has received significant attention and adoption from academic researchers and industrial engineers due to its relatively high deposition rate [10]-[13], material efficiency [14]-[18], lower cost [19]-[21], and shorter lead time [20] compared with other powder-based additive manufacturing (AM) techniques. Reference [3] conducted a review on current welding systems, with a specific focus on the software utilized for tool path design, generation, and planning in WAAM to enhance optimal productivity.

Numerous efforts have been exerted to maximize material utilization. [14] proposed a multi node subsection control strategy and observed a 51.4% increase in material utilization and a 128% reduction in production time compared with the conventional method. [15] compared different cooling strategies to accelerate the construction process and aim for maximum material utilization. In this study, the best optimal parameters, namely, travel speed and filler speed, were determined by assessing defect occurrence through dye penetration test and scanning electron microscopy. Similarly, [22] applied active cooling to improve the manufacturing efficiency by 0.97 times. Reference [23] suggested an optimal path planning approach to ensure a faster deposition process and achieve a higher utilization rate. Reference [24] studied the effect of various heat input parameters on energy usage and discovered that at optimal parameters, material utilization can reach up to 94%. Reference [25] achieved a material utilization rate of 98.7%. Reference [26] optimized number of passes in achieving less waste and high accuracy deposition.

Numerous parameters that may influence material utilization have been explored in literature, including welding parameter (e.g., welding speed, current, and feed rate), process parameters (e.g., cooling strategies), and design parameters (e.g., profile complexity and deposition path) [27]-[30]. Although numerous studies have focused on determining material efficiency and utilization, no research has been undertaken to identify the most influential parameters to the outcome. The objective of this study is to determine the most significant parameters that may affect the efficiency of the metal arc AM machine. The primary contributions of this study can be summarized in two aspects: first, the identification of significant parameters in WAAM will aid in ensuring that the process operates at optimal efficiency; and second, it has the potential to improve material utilization.

2. Method

The parameters involved can be categorized into two parts: manipulating variables and constant variables. Travel speed, distance of the torch from the base metal, and wire feed rate are chosen to be manipulated because they are the major factors to be optimized in the WAAM process. Meanwhile, the other parameters, such as the current and deposition path, are placed as constant variables. In this study, Minitab version 19 and GRBL software are used. GRBL software is used for controlling the motion of the machines. Meanwhile, Minitab version 19 software is used for the design of the experiments and data analysis. This study commenced with the setting up of a 3D welding machine and selection of the welding parameters to be explored. The primary goal of this study is to determine the parameters that is significant to the deposition efficiency. Fig. 1 illustrates the flow of the study.

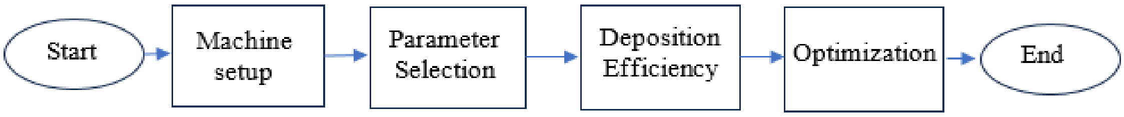


Fig. 1. 3D Flow of the study

2.1. 3D Welding Machine

The machine is developed based on a modular approach, consisting of three modules [31].

i. Welding module that contains a tank, a torch, and a welding unit.
ii. Programming module that contains a laptop and open-source software GBRL for G-code programming
iii. CNC router that comprises a microcontroller, an X–Y table, and a Z-axis movement holder, both equipped with DC motors.

The schematic layout of the machine is shown in Fig. 2. The simple profile can be programed in GBRL software. Meanwhile, the complex profile can be programmed in any CAD software and then exported to the GBRL software. The three manipulating variables are travelling speed (mm/min), distance of the torch to the base metal (mm), and wire feed rate (mm/min). The constant variables are the working angle at 90°, material of the filler wire — Mild Steel Grade ER706-S, base material (i.e., aluminum), and shielding gas (CO_2).

2.2. Material

Table 1 illustrates the chemical composition of the mild steel ER70S-6 based on AWS A5.18 certifications [32]. The major mechanical properties for this material are 480 MPa tensile strength, 400 MPa yield strength, and 22% elongation.

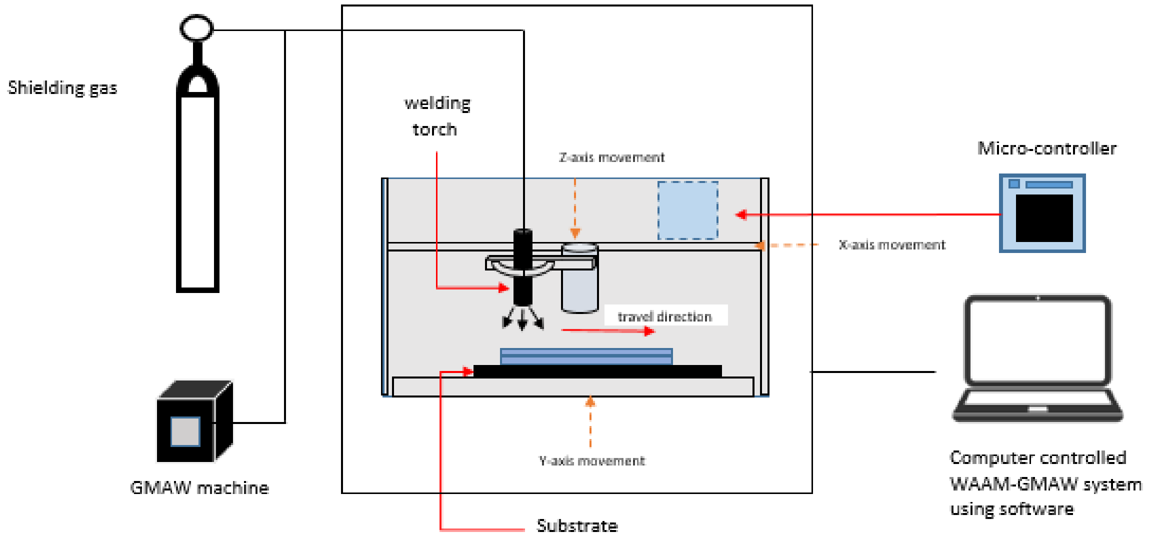


Fig. 2. Schematic layout of the 3D welding machine

Table 1. Material Composition of ER70S-6 [32]

Material Type	**Ni**	**Mn**	**Cr**	**Si**	**Mo**	**Cu**	**S**	**V**	**P**	**C**
AWS chemical composition	0.15 max	1.40 - 1.85	0.15 max	0.80 - 1.15	0.15 max	0.50 max	0.035 max	0.03 max	0.025 max	0.06-0.15

2.3. Experimental Setup

The computer was set up and linked to the wire arc welding machine. The position of the torch must be consistent at 90°, with a certain distance to the base plate (red arrow in Fig. 3). Before initiating the welding process, the weight of the filler wire was measured and returned to the welding unit. The deposition process will commence to produce a single layer on an aluminum base to prevent sticking. Subsequently, the travel speed will be adjusted according to the experimental setting. The weight of the filler wire will be measured again after deposition and recorded. Thereafter, the mass of the consumed material can be obtained. This process will be repeated for all specimens as per the set parameters. Each specimen will be replicated three times to ensure a more reliable result.

2.4. Parameters and Levels

Three parameters have been identified for study in this research, based on the conducted review [33]. Table 2 presents the list of parameters and their corresponding levels.

Table 2. Parameters and level used in the experiment

Travel Speed (mm/ min)	50, 100, 150
Wire Feed Rate (mm/min)	3180, 5220, 7260
Wire Feed Rate Input in GMAW machine	2 for (3180 mm/min), 4 for (5220 mm/min), 6 for (7260 mm/min)
Distance of Torch to Base (mm)	10, 15, 20

2.5. Experimental Design

In this study, the Taguchi Method of Orthogonal Array L9 will be utilized for the design of the experiment to determine the optimal parameters for all factors considered in the experiment. The selection of these parameters will be based on the highest deposition efficiency. This method is chosen because it allows for obtaining a significant amount of data with relatively fewer resources. The estimation of the effect of each variable on the response is more precise. Minitab software version 19 is used to analyze the result, and analysis of variance (ANOVA) was utilized to evaluate the data.

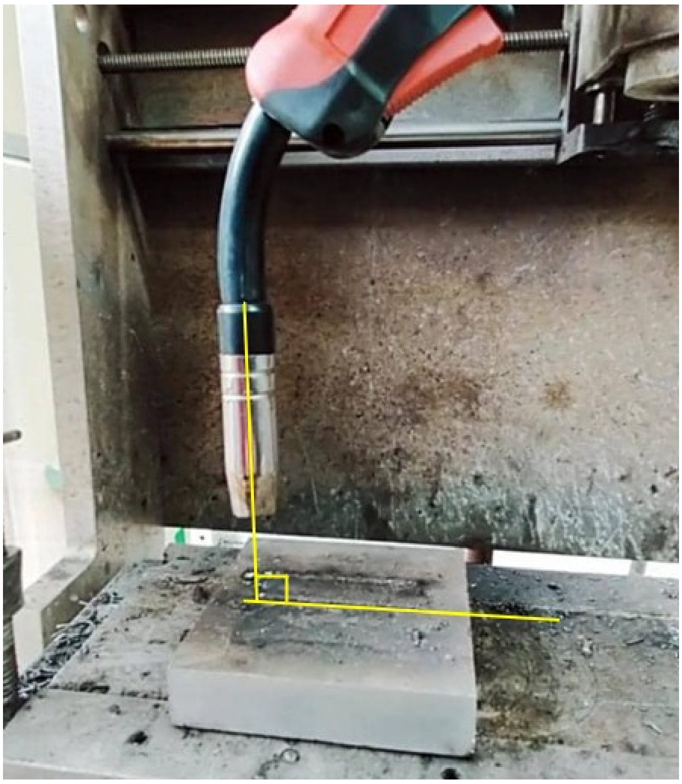


Fig. 3. Position of torch parallel to the base plate

There were 9 experiment data and 3 repetitions. Table 3 shows the details of the experimental design settings using the Taguchi Method Orthogonal Array of L9 to minimize the number of experiments. In this study, a "larger is better" signal-to-noise (S/N) ratio is considered, indicating a preference for higher efficiency values. The larger is better S/N ratio can be expressed by the Eq. (1):

$$SN_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{yi^2}\right) \tag{1}$$

where n is the number of tests, and y^{ij} is the experimental value of the ith performance characteristic in the jth experiment.

Table 3. Design of experiment using taguchi design orthogonal array l9

Experiment	**Experiment parameters**		
	Travel speed (mm/ min)	**Wire feed rate (mm/ min)**	**Distance from torch to base (mm)**
A	50	3180	10
B	50	5220	15
C	50	7260	20
D	100	3180	15
E	100	5220	20
F	100	7260	10
G	150	3180	20
H	150	5220	10
I	150	7260	15

2.6. Deposition Efficiency

Deposition efficiency can be defined in various ways depending on the application. Reference [34] defined deposition efficiency as the ratio of weight of the deposited weld to the weight of the total consumed wire. Reference [35] described deposition efficiency as the percentage of the deposition area and the effective wall area, which is the maximum rectangular area, including the effective wall width, in the cross-sectional image. Reference [36] defined deposition efficiency as the amount of weld metal deposited divided by the amount of filler metal consumed. In this study, a formula was derived based on definition given by weldingtech.net [37]. Where, the deposition efficiency of an arc-based welding is the ratio of the weight of filler metal deposited in the weld to the weight of filler metal used, in percentage and can be calculated from Eq. (2).

$$\begin{aligned} \eta &= (output \div input) \times 100\,\% \\ &= (weight\ deposited\ metal \div weight\ of\ wire\ consumed) \times 100\,\% \end{aligned} \tag{2}$$

The deposited material is weighted using Denver Instrument SI-114, Mettler Toledo weighing platform scale. The wire spool is weighted before and after the welding to determine the weight or amount of wire consumed, as previously mentioned.

3. Results and Discussion

Table 4 shows the average weight of the wire used and average efficiency of the experiment obtained based on an orthogonal array of the Taguchi method. The efficiency was calculated using Eq. (2), while the measurements of deposited metal and weight of wire were taken by using weighing scales (Table 4). Experiments F and G have the highest average efficiency of 98.777% and 98.839%. Meanwhile, Experiment I has the lowest efficiency of 55.756%.

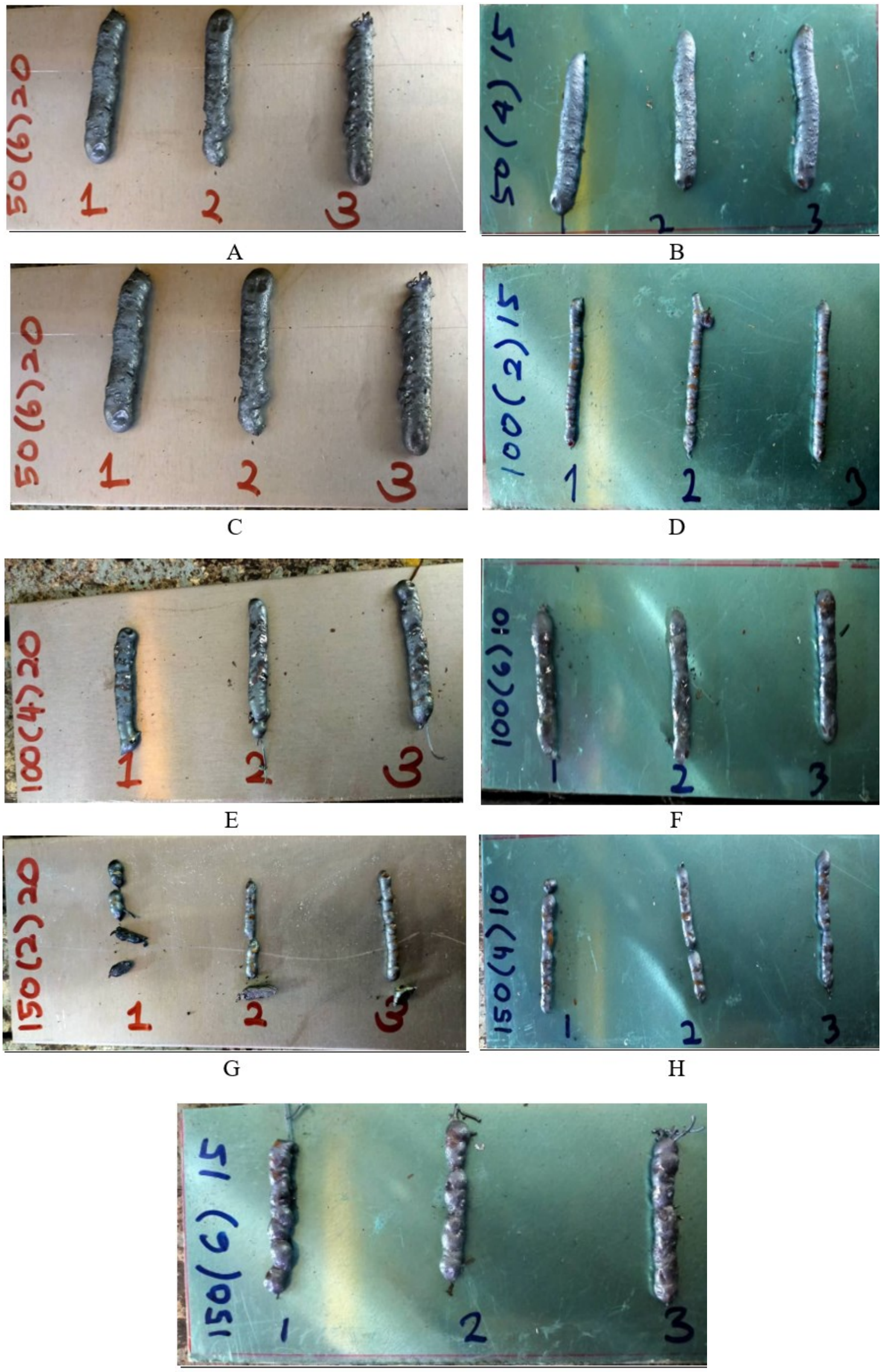
Table 4. Average weight of wire used and average efficiency.

Exp	Travel speed (mm/min)	Wire feed rate (mm/min)	Distance from torch to base (mm)	Average weight of wire used (g)	Average efficiency (%)
A	50	3180	10	13.333	93.219
B	50	5220	15	21.284	96.117
C	50	7260	20	28.358	97.271
D	100	3180	15	6.641	81.751
E	100	5220	20	10.064	94.005
F	100	7260	10	14.000	98.777
G	150	3180	20	3.693	98.839
H	150	5220	10	7.754	87.779
I	150	7260	15	16.000	55.756

Table 5 presents the data of the wire used for every experiment run for before and after the welding process of different parameters. The weight of the specimens for every parameter is presented in Table 6. The experiments are repeated three times for every parameter to obtain the average efficiency. The graph and percentage contribution value explain the outcome analysis of travel speed, wire feed rate, and distance of the torch from the base, based on Fig. 4. Each specified characteristic influenced all the responses based on the S/N ratio. The S/N ratio for travel speed, wire feed rate, and distance of the torch from the base were determined through analysis using Minitab Software. Fig. 4 shows the S/N response graph of travel speed, wire feed rate, and distance of the torch from the base set for the larger the better S/N ratio. The S/N graph was used to determine the optimal parameter for each factor. Regardless of the S/N ratio option, the preference is always given to selecting the highest S/N ratio for the optimized value. The optimal combination of parameters has been determined from the graph in Fig. 4.

Table 5. Experimental data of weight of specimen and efficiency

Exp	**Average Weight of Specimen #1 (g)**				**Efficiency #1**	**Average Weight of Specimen #2 (g)**				**Efficiency #2**	**Average Weight of Specimen #3 (g)**				**Efficiency #3**	**Average efficiency**
	Test 1	Test 2	Test 3	**Ave**		Test 1	Test 2	Test 3	**Ave**		Test 1	Test 2	Test 3	Ave		
A	12.11	12.10	12.00	12.072	90.54	12.466	12.464	12.463	12.464	93.48	12.751	12.752	12.751	12.751	95.64	93.219
B	20.18	20.18	20.18	20.180	94.81	20.476	20.474	20.473	20.474	96.19	20.719	20.72	20.717	20.719	97.34	96.117
C	27.49	27.38	27.38	27.418	96.69	27.527	27.524	27.524	27.525	97.06	27.808	27.81	27.806	27.808	98.06	97.271
D	5.62	5.63	5.63	5.626	84.71	5.377	5.379	5.378	5.378	80.98	5.288	5.306	5.286	5.284	79.56	81.751
E	9.61	9.61	9.61	9.613	95.52	9.235	9.231	9.236	9.234	91.75	9.537	9.535	9.535	9.536	94.75	94.005
F	13.85	13.84	13.84	13.846	98.90	13.744	13.743	13.742	13.743	98.16	13.899	13.898	13.896	13.898	99.27	98.777
G	3.69	3.69	3.69	3.689	99.90	3.613	3.612	3.6	3.608	97.72	3.631	3.653	3.672	3.652	98.90	98.839
H	6.84	6.845	6.844	6.844	88.27	6.908	6.907	6.905	6.907	89.08	6.669	6.665	6.669	6.6677	85.99	87.779
I	8.87	8.875	8.876	8.875	55.47	9.04	9.039	9.038	9.039	56.49	8.848	8.85	8.849	8.849	55.31	55.756



A B

C D

E F

G H

I

Fig. 3. The deposited bead for all experiment set.

Fig 4. Signal to noise for travel speed, wire feed rate and distance from the torch to base

The optimal setting factors for the experiments are travel speed of 50 mm/min, wire feed rate of 5220 mm/min, and distance of the torch of 20 mm. Table 6 shows the response of the factors (travel speed, wire feed rate, and distance of the torch from the base). The aforementioned table explains the significant level of the factor to the response, which is efficiency. Tables 7–9 illustrate that the distance of the torch from the base (rank 1) is more significant than travel speed (rank 2) and wire feed rate (rank 3). The factors that ranked in the first position contribute the highest changes in efficiency in this experiment. One-way ANOVA is carried out to determine the trends between each parameter and the output.

Table 6. Response of signal to noise (s/n) for travel speed, wire feed rate and distance from the torch to base

Level	Travel speed	Wire feed rate	Distance from torch to base
1	39.60	39.18	40.77
2	39.20	39.33	39.7
3	37.90	38.19	40.3
Delta	1.70	1.14	1.08
Rank	2	3	1

Table 7. ONE-WAY ANOVA - analysis of variance for travel speed

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Travel Speed	2	348.5	174.3	0.90	0.456
Error	6	1164.3	194.1		
Total	8	1512.8			

Table 8. ONE-WAY ANOVA - analysis of variance for wire feed rate

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Wire Feed Rate	2	131.3	65.67	0.29	0.762
Error	6	1381.5	230.25		
Total	8	1512.8			

Table 9. ONE-WAY ANOVA - analysis of variance for distance torch to base

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Distance Torch to Base	2	603.1	301.6	1.99	0.217
Error	6	909.7	151.6		
Total	8	1512.8			

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The deposition efficiency also increased by increasing the feed rate. A better deposition can be observed when the speed is reduced. This result is similar to the findings of [24]. However, the effect of distance to base plate is more significantly observed compared with the above-mentioned two parameters. F critical values obtained using the degree of freedom can also be observed from the Taguchi analysis. The value is referenced from the table for two-tailed significance level according to the settings of the ANOVA analysis, which is applicable for two-tailed distributions. The F critical value is 7.26, indicating that all the F values are lower than the F critical values. Accordingly, the null hypothesis is accepted. The ANOVA analysis does not provide information on which specific means are different. Another analysis must be conducted to find out the difference. However, the main highlight in the experiment is the p-value. The p-value of the wire feed rate is 0.762, indicating a 76.2% chance that our null hypothesis is true. Meanwhile, a p-value of more than 5% indicates that our experiments have high chances to accept the null hypothesis. ANOVA analysis is performed to study the percentage significance of the affected parameters. Table 10 presents the summary of the result percentage using R-squared. The tabulated R-squared values illustrate the extent to which the model explains the variation in the response.

Table 10. One-way anova: R squared for every factor on efficiency

Factor	S	R-sq	R-sq(adj)	R-sq(pred)
Travel Speed	13.9302	23.04%	0.00%	0.00%
Wire Feed Rate	15.1738	8.68%	0.00%	0.00%
Distance Torch to Base	12.3132	39.87%	19.82%	0.00%
Total R squared	**71.59 %**			

By considering the percentage that shows significant factors that influenced material efficiency. The optimal combination of process parameters and their levels is determined to be a travel speed of 50 mm/min, a wire feed rate of 5220 mm/min, and a distance of the torch from the base of 20 mm. The final step involves verification through a confirmation test, the % of deviation between predicted and experiment is less than 10% as indicated in Table 11, which prove that the results is acceptable.

Table 11. Results of confirmation test

Optimum Parameter		Predicted	Experimental	% Difference
Travel Speed (mm/min)	50	106.316	99.155	6.736
Wire Feed Rate (mm/min)	5220			
Distance from torch to base (mm)	20			

Comparison made with other studies is as summarized in Table 12. Although different materials are utilized, these studies can still serve as benchmarks for reference. The optimal deposition efficiency obtained from these studies lay between 94-100%. It can be concluded that this value is within the expected deposition efficiency obtained in a typical WAAM capability. The studied parameters are comparable with other methods.

Table 11. Comparison to other studies

Reference	Welding Method	Material	Deposition Efficiency (%)	Parameters Studied
[24]	GMAW	Type S Al 5556	94.0	Feed rate, welding speed and shielding gas composition.
[38]	VP-TIG & FDAM	AA7075	99.5	Deposition strategy

[25]	GMAW	EN S235JR steel	98.7	Welding speed, wire feed rate, current and voltage.
Present study	GMAW	ER706-S	99.16	Torch to base plate distance, travel speed and the wire feed rate

4. Conclusions

The study successfully met its objectives. The primary contribution of the study lies in identifying the most significant parameters and achieving optimal deposition efficiency for the custom-made GMAW-based WAAM machine at the School of Mechanical Engineering, USM. Several conclusions can be drawn from the results of this study. Firstly, numerous factors affect deposition efficiency. All studied parameters are significant to the deposition efficiency. However, the most significant parameters are the distance between the torch and the base plate, followed by travel speed and the wire feed rate. The optimal parameter is obtained from the analysis of the S/N graph based on the Taguchi method. These optimal parameters are at the travel speed of 50 mm/min, wire feed rate of 5220 mm/min, and distance of the torch from the base of 20 mm. The highest efficiency obtained is 99.155%. The confirmation test found that the error between the experimental and the predicted values is less than 10%. For future works, the performance of the deposition efficiency will be further improved by considering the post processing requirement to minimize machining waste as recommended by References [39-41] when dealing with more complex profile and large size via hybridization, multi-material and etc.

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