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Experimental Investigations on the Fabrication of Low Alloy Steels Using Wire Arc Additive Method

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Abstract: Wire arc additive manufacturing (WAAM) has emerged as a transformational technology with the capacity to redefine the landscape of alloy steel component production. This method utilizes an electric arc to selectively fuse a continuous wire feed, progressively constructing intricate metal structures layer by layer. GMAW-based WAAM adaptability enables the creation of complex geometries and customized part designs, making it applicable across diverse industrial sectors. This paper investigates WAAM-specific applications in alloy steel fabrication, focusing on key process variables such as voltage, travel speed, and Gas mixture ratio. The experimental parameters for a single layer are examined with voltage ranging from 20 to 22, travel speed from 23, 25, and 27 mm/min, and Gas mixture ratio 1,5,9 mm/min. It utilizes materials like TM B9, a 1.2-diameter flux-cored wire. Additionally, the study considers the nominal composition (wt-%) of 9 Chromium, and 1 Molybdenum, with small additions of nitrogen and niobium to improve the creep resistance. Furthermore, the final findings of the study suggest that the optimal combination of process variables for achieving high-quality weld beads in WAAM of alloy steel components can be determined through Response Surface Methodology (RSM). RSM is a statistical method for analysing and modeling the relationship between the response of interest and some independent variables. In this case, the response variable would be the quality of the weld bead, which encompasses factors such as bead geometry, integrity, and absence of defects.

Keywords: Alloy steel fabrication, GMAW welding, Wire arc additive manufacturing (WAAM)

Introduction

In modern manufacturing, the pursuit of innovative techniques to enhance efficiency, flexibility, and product quality is ceaseless. One such cutting-edge methodology gaining significant traction is Gas Metal Arc Welding (GMAW)-Based Wire Arc Additive Manufacturing (Shah et al., 2023). This transformative process has become a potent tool for fabricating complex components with unprecedented precision and speed, revolutionizing traditional manufacturing paradigms. Within the realm of GMAW-based WAAM, a particular focus has been directed towards its application in the processing of low alloy steel, such as the renowned alloy TM B9. TM B9, recognized for its exceptional combination of strength, toughness, and corrosion resistance, stands as a prime candidate for a multitude of industrial applications, spanning from automotive to aerospace sectors (Suat et al., 2020). Integrating GMAW-based WAAM into the production of TM B9 components presents an exciting frontier, offering unparalleled opportunities to optimize manufacturing workflows, reduce material waste, and

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expedite production cycles. This introduction sets the stage for a comprehensive exploration into the realm of GMAW-based WAAM for low alloy steel, specifically focusing on the exemplary properties of alloy TM B9. A critical aspect of this exploration involves the meticulous study and optimization of welding parameters, such as voltage, Gas mixture ratio, and travel speed (Vora et al., 2022). These parameters play a pivotal role in determining the quality and characteristics of the fabricated components. In addition to studying and optimizing welding parameters such as voltage, Gas mixture ratio, and travel speed. it is essential to investigate the bead geometry resulting from these parameters for achieving better wall structure in the fabricated components (Dinovitzer et al., 2019). Bead geometry, including bead width, height, and penetration depth, directly influences the structural integrity, mechanical properties, and overall quality of the weld.

Due to the presence of metals like Ni, Mo, and Cr, low alloy steel (TM B9) has excellent mechanical qualities and resistance to corrosion, making it extremely weldable(Rodrigues et al., 2020) . With its higher welding temperature, TM B9 in particular is perfect for WAAM procedures, guaranteeing greater layer fusion. Its primary attributes like high strength, resistance to corrosion, weldability, ductility, makes it ideal for use in a variety of industries, including the oil and gas, biomedical, maritime, and aerospace sectors(Jahns et al., 2023) . The best parameter settings for WAAM variables have been found through the use of optimization techniques, resulting in TM B9 single-layered structures that are clean. Research has shown that in order to build single-layered structures with minimal flaws and desired mechanical qualities, it is crucial to have sufficient control over the design parameters (Chaudhari et al., 2023). In the process of optimizing WAAM parameters for bead shape, research has revealed that voltage and gas mixture ratios are critical variables. Factors including filler type, welding parameters, and bead shapes affect the quality of WAAM components. Since GMAW-based WAAM produces thin-walled structures with ideal process variables, its higher deposition rate makes it superior to other approaches. WAAM technique creates metal additive structures using single-layer deposition.

Due to their unique characteristics and the subtleties of the AM process, different materials are affected by WAAM in different ways. The microstructure and mechanical characteristics of steel are significantly influenced by process factors, and WAAM enables efficient deposition suitable for large-scale manufacturing (Shah et al., 2023). Because of its high heat conductivity and tendency to crack, aluminum presents difficulties and requires exact parameter management to reduce flaws. WAAM is perfect for aerospace and medical applications because it provides titanium with fast deposition rates and meticulous parameter control, both of which are necessary to avoid contamination and guarantee the required mechanical qualities. For high-temperature and corrosion-resistant components, nickel-based alloys benefit from WAAM; nevertheless, careful process optimization is required to overcome cracking and distortion concerns.

Copper and its alloys have great thermal and electrical conductivity, making them valuable in WAAM. Strict parameter selection and shielding gas control are required to reduce oxidation and produce high-quality deposits for electrical components and heat exchangers. All things considered, WAAM offers both potential and challenges for a variety of materials, necessitating customized methods for the best fabrication results(Raut & Taiwade, 2021). Also examine various research papers that concentrate on focuses on bead geometries optimisation of GMAW-based WAAM variables. employs the single-layer deposition method with the Box-Behnken design methodology. uses ANOVA and multivariable regression methods to evaluate feasibility. Chaudhari et al. (2022) emphasises hardness, porosity, and mechanical characteristics. examines the alloy's potential for wire-arc additive fabrication. Thorough rundown of the difficulties, materials, development, and methodology of WAAM. Pay attention to the heat treatment, dimensional precision, microstructural homogeneity, and process parameters. Examines the latest advancements, materials, in-process procedures, difficulties, and WAAM technology (Zhou et al., 2020).

The present work focuses on the experimental analysis of TM B9 bead morphologies using GMAW-based WAAM single-layer deposition. Using WAAM variables (voltage, gas mixture ratio, travel speed) and output responses (BW, BH), experiments were conducted using Taguchi's L9 approach. To determine the significance of WAAM components on output qualities, ANOVA was employed. Main effect plots were made, and the optimal input set of WAAM variables was determined for each unique output variable, to better understand the influence of WAAM parameters on output features(IvánTabernero et al., 2018). To obtain desirable material properties and deposition rates, current research in GMAW-based WAAM concentrates on optimizing process variables such as Gas mixture ratio, voltage, and travel speed. Moreover, research is being done on multi-material deposition, hybrid methods, surface quality enhancement, and the metallurgical behaviour of deposited materials(Shah et al., 2023). Even though problems like surface roughness, porosity, and microstructure control are still present, research is being done to produce new materials, monitor sophisticated processes, and integrate Industry 4.0 technology to overcome these problems.

Materials and Methods

In the current study, bead-on-plate experiments were carried out utilising a 20 mm thick Mild Steel 2062 grade substrate and a 1.2 mm flux core wire (TM B9) employing the GMAW technique. The wire used, TM B9, has the following chemical composition, which is listed in Table 2. Testing was done using the WAAM Machine system. The substrate plate was carefully cleaned and allowed to dry before deposition. A GMAW torch, a wire feeder, shielding gas cylinders containing carbon dioxide and argon, a controller, and a specialised machine were among the apparatus used in the experiment (Chaudhari et al., 2022). The nozzle, which could deposit material on the restricted base metal in any direction, was manipulated by the controller. The torch was maintained in a vertical position, perpendicular to the deposition route. Before the programme began, shielding gas was supplied to prevent the material being deposited from coming into contact with ambient gases. The experimental setup is displayed in Fig. 1. By utilising an experimental matrix created by the Box-Behnken design (BBD) utilising the response surface methodology (RSM), single bead deposition was performed on the substrate plate.

Table 1. Experimental conditions

Variables	**Unit**	**Values**
Voltage	V	20; 21; 22
Travel speed	mm/min.	23; 25; 27
GMR	-	1; 5; 9

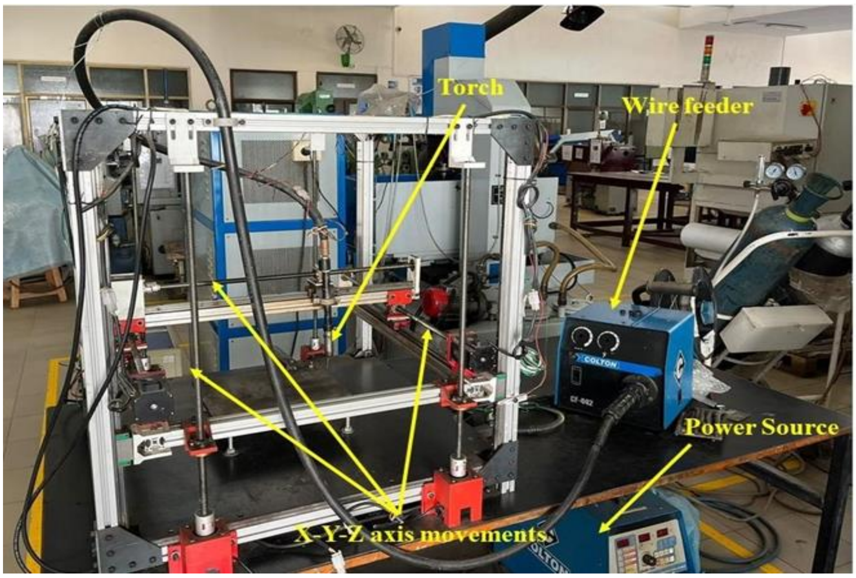

Figure 1. Experimental setup of WAAM

Three input variables were examined in the study: voltage, TS, and wire feed speed. The ratio of CO2 gas to argon is represented by GMR. Over 15 L/h of sustained flow rate were attained. Every bead had the same length, measuring 150 mm (Vora et al., 2022).). Throughout the experiment, a flux core wire with a diameter of 1.2 mm was used in conjunction with a GMAW torch. parameter utilised in the experiment setup is displayed in Table 1.

Table 2. Chemical composition of TM B9

Flux core wire (BM T90)						
Grade	C	Mn	Si	Ni	Cr	Mo
Wt.%	0.25	1.20	0.50	0.80	10.50	1.00
Substrate plate (mild steel 2062)						
Grade	C	Mn	Si	P	S	Fe
Wt.%	0.22	1.50	0.40	0.045	0.045	Balance

By establishing a link between solutions and machining factors, this approach lowers staff expenses and experimentation (Iván Tabernero et al., 2018).After the input variables were altered, nine experiments were produced. To ensure accuracy and reproducibility, each test was done three times. The average outcomes were then chosen for more examination. Once the input variables were altered, fifteen experiments were produced. To guarantee accuracy and repeatability, each test was run three times. The average results were then analysed.

Testing and Characterizations

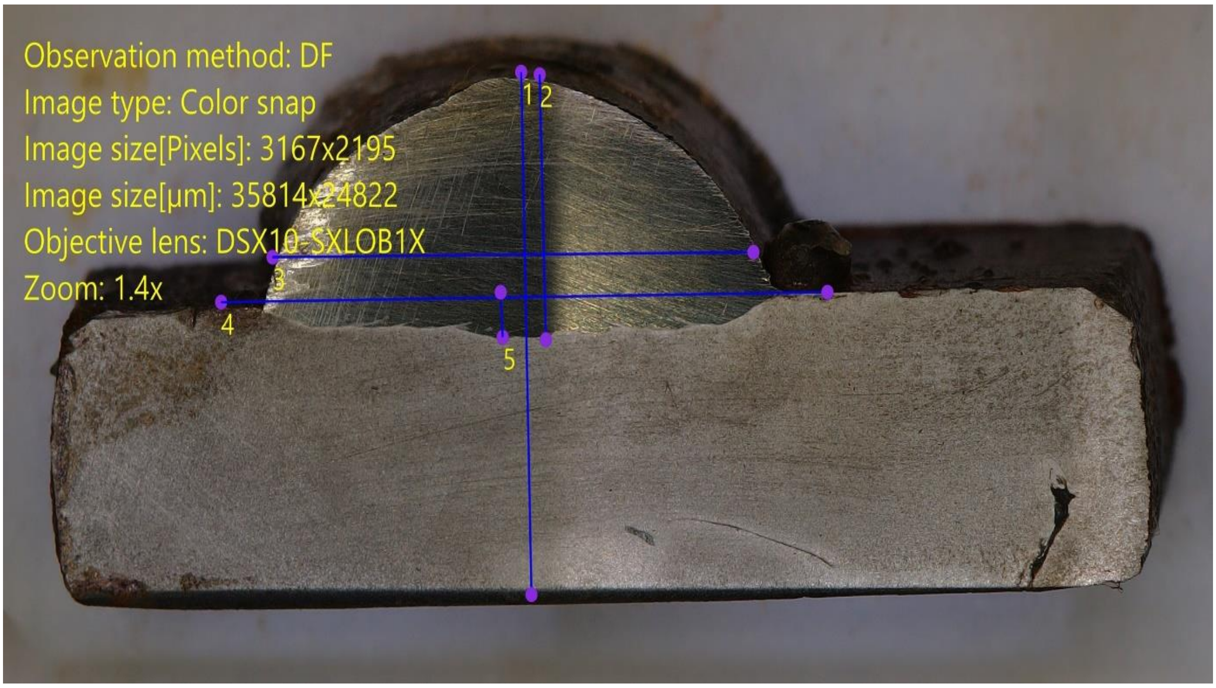

Figure 2. Measurement of output

The current study took into account output metrics such as BH and BW. Small cross-sections of each bead deposition were cut to measure the bead geometries. The band saw machine was used to make the specimens that were used to examine the output variables. All samples were first cleaned and polished with different abrasive sheets before being analyzed. Here, we define various parameters: total height (1), weld bead height (2), weld weight (3), base plate surface (4), and depth of penetration (5). Optical microscopy was utilized to analyse the weld bead height (BH), and weld weight (BW). To ensure precision, three measurements were taken across the cross-section of each deposited bead.

Results and Discussion

Taguchi's L9 array design with WAAM variables and the corresponding results for a subset of replies are shown in Table 3. Utilizing an optical microscope, the response values of BH and BW were examined(Vora et al., 2022). The biggest BH value and the shortest BW value among the nine trials that were performed were 7.41 mm and 8.99 mm, respectively

Table 3. Experiment results

Sr. No	Voltage (V)	GMR	Travel Speed (mm/min)	BH (mm)	BW (mm)
1	20	1	23	7.41	6.92
2	20	5	25	5.89	6.39
3	20	9	27	5.11	5.90
4	21	1	25	5.72	7.93
5	21	5	27	4.97	7.36
6	21	9	23	7.61	7.21
7	22	1	27	4.03	8.99
8	22	5	23	6.34	8.62
9	22	9	25	5.28	8.41

Table 4. ANOVA for BH, and BW

Source	DF	SS	MS	F	P	Significance
For BH						
Regression	3	10.1476	3.3825	28.56	0.001	Significant
TS	1	1.2696	1.2696	10.72	0.022	Significant
Voltage	1	0.1176	0.1176	0.99	0.365	Insignificant
GMR	1	8.7604	8.7604	73.97	0.000	Significant
Error	5	0.5921	0.1184			
Total	8	10.7398				
R-Sq. = 94.49 %; R-Sq. (Adj.) = 91.18 %						
For BW						
Regression	3	8.6596	2.8865	307.96	0.000	Significant
TS	1	7.7230	7.7230	823.96	0.000	Significant
Voltage	1	0.8956	0.8956	95.56	0.000	Significant
GMR	1	0.0409	0.0409	4.37	0.091	Insignificant
Error	5	0.0468	0.0093			
Total	8	8.7065				
R-Sq. = 99.46 %, R-Sq. (Adj.) = 99.14%						

Analysis of Variance for BH, and BW

Analysis of variance (ANOVA), a statistical approach utilized to ascertain the most significant elements for improving product or process quality, was applied to the findings obtained after Taguchi's array. To analyse the data of the response variables BH and BW, Minitab software was used(Chaudhari et al., 2022). In the regression analysis, a 95% confidence interval was taken into account. Accordingly, to show a significant influence on the chosen output response, the input variable's P-value should not be greater than 0.05. The travel speed (TS) and voltage terms had a considerable influence on the BH response, however, the gas mixture ratio (GMR) had no discernible effect on the output response variable. Changes in the level of TS had a significant impact on BH values, as evidenced by the greatest F-value for TS. All three WAAM factors were significant for the BW response; voltage had the greatest effect, followed by GMR and TS (Dinovitzer et al., 2019). It was discovered that the R^2 values of the BH and BW models were 94.49% and 99.46%, respectively, and that their adjusted R^2 values were 91.18% and 99.14%, respectively.

This indicates that the models effectively validated the whole selected design space. For wire arc additive manufacturing (WAAM) to achieve the required weld properties and overall process performance, the relationship between voltage, gas mixture ratio, and travel speed is essential(Jiang et al., 2022). Voltage and Travel Speed have a reciprocal relationship. As voltage increases, it can compensate for higher travel speeds by supplying more heat. Conversely, reducing voltage may be needed to prevent overheating at slower travel speeds to ensure proper fusion. The Gas Mixture Ratio also impacts arc stability and heat transfer, influencing the ideal voltage and travel speed settings. Adjusting the gas composition may be essential to achieve the desired bead shape, depth of penetration, and overall weld quality. In essence, optimizing the relationship between voltage, travel speed, and gas mixture ratio is vital for consistent and high-quality welds in wire arc additive manufacturing(IvánTabernero et al., 2018). Experimentation, analysis, and fine-tuning of these factors are typically necessary to strike the right balance for specific materials, deposition configurations, and process demands.

Main Effect Plots

Main effect plots have been employed to understand how various parameters in Wire Arc Additive Manufacturing (WAAM) affect the output characteristics. When fabricating thin multi-layered structures, Having maximum BH and minimum BW values is desirable. Figure 3 illustrates the impact of input factors on the BH response. Increasing the voltage tends to decrease the BH value as it leads to a longer arc length. Greater Metal Removal (GMR) doesn't significantly affect BH (Jahns et al., 2023). However, Travel Speed (TS) has the most significant impact on BH; increasing TS levels reduces BH because higher travel speeds don't allow sufficient time for molten metal deposition. Thus, to achieve higher BH values, it's advisable to use a lower voltage level of 20V, a higher GMR level of 9, and a lower TS level of 23 mm/s.

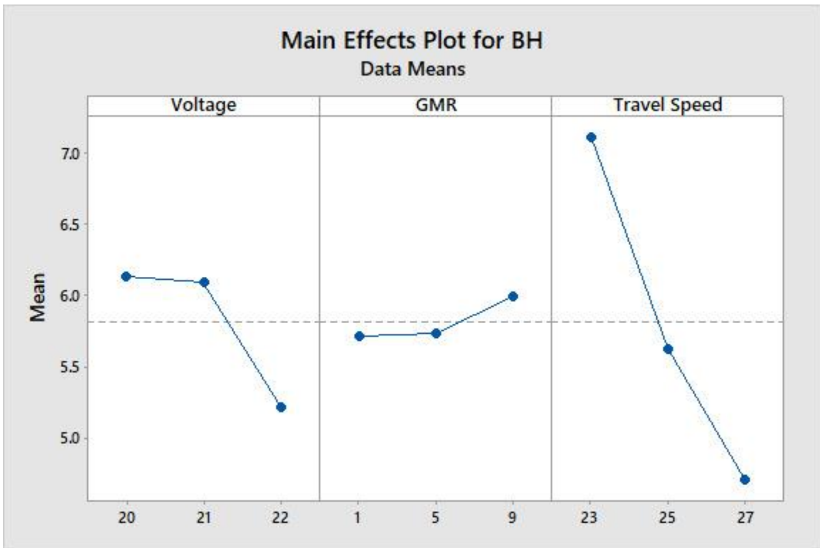

Figure 3. Influence of WAAM factors on BH

Figure 4 shows how different WAAM parameters affect the reaction of the bead width. As the voltage increased from 20 to 22 V, it demonstrated a greater BW response, which was explained by the longer arc length at higher voltages. Increasing Greater Metal Removal (GMR) was found to be beneficial for BW response as it led to a decrease in BW values(Chaudhari et al., 2023). Travel Speed (TS) had minimal impact on BW response; however, slightly decreased BW was observed with higher TS levels due to insufficient time for molten metal deposition at higher travel speeds(IvánTabernero et al., 2018). Thus, to achieve lower BW values, it is recommended to use a lower voltage level of 20V, a higher GMR level of 9, and a lower TS level of 27 mm/s.

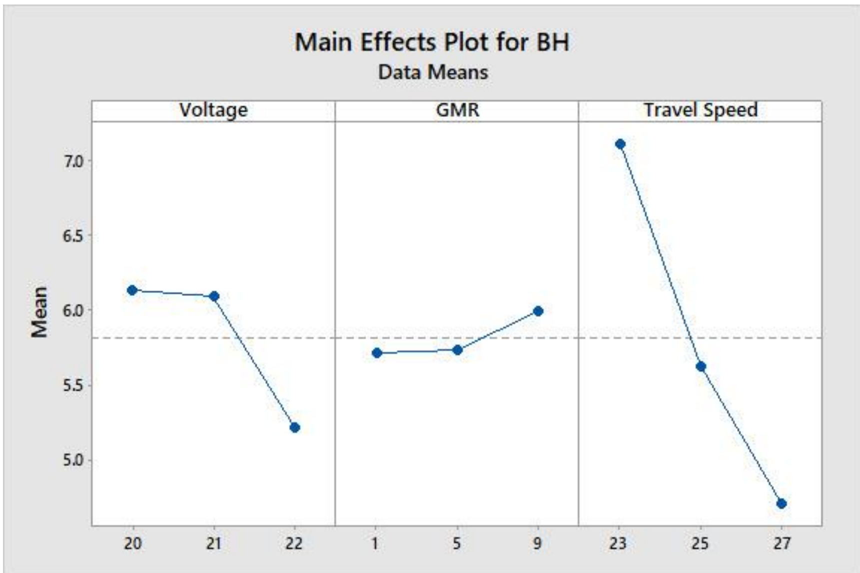

Figure 4. Influence of WAAM factors on BW

Conclusion

The study used TM B9 Flux cored wire with a 1.2 mm diameter to deposit a single bead on a mild steel 2062 substrate plate utilising a GMAW-based (WAAM) process. Bead width and bead height were the output responses of experimental trials that were carried out using Taguchi's L9 technique. The input WAAM variables were voltage, gas mixture ratio (GMR), and travel speed (TS). The biggest BH value and smallest BW value among the nine trials that were performed were 7.61 mm and 5.90 mm, respectively. The ANOVA results indicated that TS was the most important component for BH response, followed by voltage; GMR had no discernible effect on BH response. All three WAAM factors were shown to be significant for the BW response, with voltage having the most impact and GMR and TS following closely behind. To forecast response values within the specified range of WAAM variables. To understand the effect of WAAM factors on output characteristics, main effect plots were created. It is recommended to use a lower voltage level of 20V, a higher GMR level of 9, and a lower TS level of 24 mm/s to get larger BH values. On the other hand, a lower voltage level of 20V, a higher GMR level of 9, and a lower TS level of 27 mm/s are advised to obtain lower BW values.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Author Contribution

Mr. Pruthviraj Chauhan: Methodology, Formal analysis, Data curation, Writing original draft, Mr Vatsal Vaghasia:Visualization, Investigation, Formal analysis, Writing-review &editing, Dr. JayKumar Vora: Writing-review & editing, Supervision, Dr. Rakesh Chaudhari: Methodology, Formal analysis, Writing-review & editing, Supervision

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