

Study on Wire Arc Additive Manufacturing Geometric Properties Using Simulation

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Abstract

In Wire Arc Additive Manufacturing, controlling residual stress and keeping constant bead geometry during fabrication is one of the major challenges; it poses limitations to the quality and mechanical properties of its final components. Due to insufficiently optimized heat source parameters, unpredictable thermal distributions and stress formations are produced in WAAM. In this study, A numerical simulation model is developed using finite element analysis. WAAM parameters are optimized based on the Taguchi method to enhance the bead geometry and mechanical properties of WAAM products. WAAM parameters were optimized, voltage and travel speed keeping current and wire feed speed constant. Optimal parameters of 13V and 5 m/min were identified, and the model was developed using a numerical simulation model built with Simufact Welding and optimized through the Taguchi method using an L9 orthogonal array. Single-bead validation produced a 6.0 mm bead width and 4mm bead height with uniform hardness distribution. In comparison, a 10-layer WAAM process gave a final bead width of 9 mm through experimental, 2.27 mm maximum displacement, and equivalent stress of 1.44 Mpa to 274.45 Mpa Through simulation The results from this work show that the optimized parameters are satisfactory, and WAAM is a feasible method to produce high-quality components with enhanced accuracy and improved structural integrity.

1. Introduction

Engineers and researchers have extensively used Additive Manufacturing (AM) over the last twenty years to revolutionize the manufacturing industry by creating medium-to-large numbers of near-net shape components. Additive manufacturing (AM) is a rapid, cost-effective method with minimal waste [1]. The introduction should describe general information on the subject matter area of study. It is usually arranged in such a manner to gradually bring to focus the specific motivations of the current study, the research questions, the problem statements, the hypotheses, the objectives, as well as the expected outcome.

With the help of an electric arc to melt a continuous wire feedstock material, Wire Arc Additive Manufacturing (WAAM) is a potential additive manufacturing process that enables the layer-by-layer deposition of metal components straight from a digital design. Although WAAM has several benefits, including high deposition rates, cost-effectiveness, and appropriateness for large-scale part production, residual stress is a problem. Due to its efficiency and low cost, WAAM produces large quantities more effectively. Gas metal arc welding (GMAW), cold metal transfer (CMT), gas tungsten arc welding (GTAW), and plasma arc welding (PAW) are the four primary heat sources used in the WAAM process to melt wire metal [2].

In this research, we want to design a numerical simulation model specifically for WAAM components to predict bead geometry and formation of residual stress accurately. To achieve this objective, leverage advanced simulation, Simufact Welding, known for its capability to model complex welding processes precisely. Common and severe defects typically occurring in WAAM are residual stresses and distortion caused by the high heat input.

This research explores the relationship between using Stainless steel 316L in the WAAM process. Research has shown that stainless steel 316L can suffer from severe grain coarsening and high residual tensile stress due to the complex thermal history involved, leading to limitations in its yield strength and potential applications [3].

In this analysis, through validated numerical simulation, we aim to systematically investigate how process parameters like travel speed, wire speed, heat input, and voltage influence the bead geometry and distribution of residual stresses in WAAM components. The simulation model will optimize WAAM process parameters to mitigate residual stress development before physical part fabrication.

This research is to find an analytical design numerical simulation method using Finite Element Method (FEM) to find how the heat source parameter effects on bead geometry by simulation and experimental validation. This will be accomplished through three main objectives: Investigation of the optimum parameters configured for Wire Arc Additive Manufacturing (WAAM) via the Taguchi methodology, modeling of a comprehensive numerical simulation model for the WAAM components, and simulation study of these determined optimum parameters to improve geometry and mechanical properties. The research aims to develop a strong methodology for predicting and optimizing of WAAM process parameters for part quality and performance through simulation.

This study focuses on a comprehensive investigation of WAAM process parameters, specifically examining the effects of current, voltage, travel speed, and wire feed speed through both Taguchi method optimization and Finite Element Method (FEM) simulation by using Simufact Welding 6.0. The research scope encompasses analyzing these parameters' impact on bead geometry and residual stress patterns to identify optimal heat source WAAM parameters that can effectively predict the geometry and stress in the simulated environment. Furthermore, the study will evaluate how these optimized parameters influence the geometric accuracy and mechanical properties of the fabricated components. To ensure the practical applicability of the findings, the research includes validation of simulation results through comparison with physical experimental outputs, thereby establishing the reliability and accuracy of the optimized parameters for future WAAM applications.

2. Methodology

The materials and methods section, otherwise known as methodology, describes all the information required to obtain the study's results.

2.1 Material

The material involved in this study is Stainless Steel (Table 1), which is SS316L. SS316L is one of the most preferred materials in the Wire Arc Additive Manufacturing method because of its properties. The simulations will be performed using SS316L for the wire arc additive manufacturing process to investigate the process parameter's influence on bead geometry and residual stress.

Table 1 Mechanical properties of grade 316L Stainless Steel as filler wire [4]

Property	Value
Yield Strength	280 MN/m
Tensile Strength	650MN/m
Modulus of Elasticity	211 GN/m
Vickers Hardness	140-200Hv

2.2 Design of Experiment

In this study, the optimizing Wire Arc Additive Manufacturing (WAAM) parameters in a systematic approach combining simulation and experimental validation is shown in Table 2. The initial simulations begin using Simufact Welding software to analyze critical parameters such as current, voltage, travel feed speed and wire feed speed, with some parameters based on previous research, and others kept constant (Table 3). Finally, the simulation results are then verified using the L9 orthogonal array by Taguchi method's 'nominal is the best' approach to determine optimal voltage and travel feed speed (Table 4). Finally, physical single bead WAAM experiments at these optimized parameters are verified and Vickers hardness testing is performed for structural characterization of the material. Further analysis of experimental results is conducted using Minitab software to

more finely tune the parameters; the parameter optimization is then fed to Simufact Welding for final simulation validation. Finally, the study is concluded through a multi-layer of 10 layers WAAM experiment using optimized parameters to investigate the bead geometry and residual stress distribution on the multi-layer process.

Table 2 *The constant parameters*

Constant Parameter of the Simulation Process	
Current (A)	160
Wire Feed Speed (m/min)	5.9
Gas Composition	100% Argon
Mean length/height/width/thickness (mm)	105/ 37.5/ 25/ 3.75

Table 3 *Three level of response and variable of experimental design*

Parameters	Low	Medium	High
Voltage (v)	9	11	13
Travel Speed (mm/s)	3	5	10

Table 4 *Taguchi design matrix of L9 orthogonal array*

Experiment	Voltage (v)	Travel Speed (mm/s)	Geometry/ Thickness (mm)
1	9	3	(Result 1)
2	9	5	(Result 2)
3	9	10	(Result 3)
4	11	3	(Result 4)
5	11	5	(Result 5)
6	11	10	(Result 6)
7	13	3	(Result 7)
8	13	5	(Result 8)
9	13	10	(Result 9)

2.3 Simulation Setup

SS316L material property of the base plate is implemented in Simufact Welding 6.0 software by constant wire feed speed, current and input power followed by different travel speed and voltage.

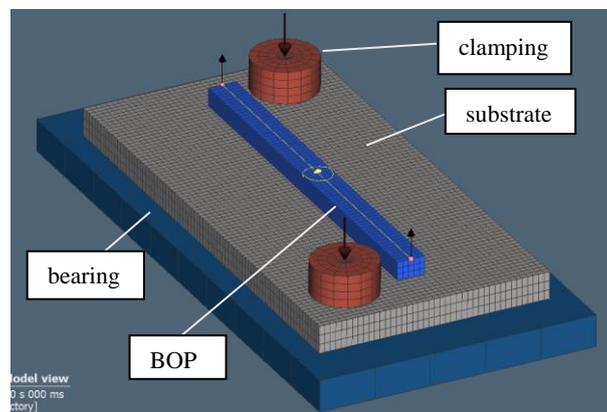


Fig 1 *Simulation setup for a single bead process*

The simulation is set to obtain optimum voltage and travel speed parameters using the Taguchi Method by Minitab Statistical Software after specifying the plate dimensions. To simulate weld bead geometry (bead width) and the evolution of residual stress distribution in the welded piece at different stages of the welding process, this comprehensive simulation analyzes how these optimized parameters affect the final mechanical properties of the WAAM-produced components.

A 1 kN clamping force was applied to a bearing acting as the base metal dimensions 50mm in width, 100mm in length, and 6mm in height to avoid distortion and displacement during the welding simulation procedure, which is similar to conditions of practical welding.

3. Results and Discussion

Table 5 shows maximum and minimum displacement results for a single bead in the nine trials where voltage and travel speed were changed while keeping the current and wire feed speed constant. The displacement values represent investigated bead geometry and material deformation in the welding process, simulated with Simufact Welding 6.0.

Table 5 Displacement simulation result for single bead

Trial	Voltage (V)	Travel Speed (mm/min)	Displacement (Min)	Displacement (Max)
1	9	3	0	0.21
2	9	5	0	0.19
3	9	10	0	0.13
4	11	3	0	0.31
5	11	5	0	0.22
6	11	10	0	0.17
7	13	3	0	0.27
8	13	5	0	0.19
9	13	10	0	0.16

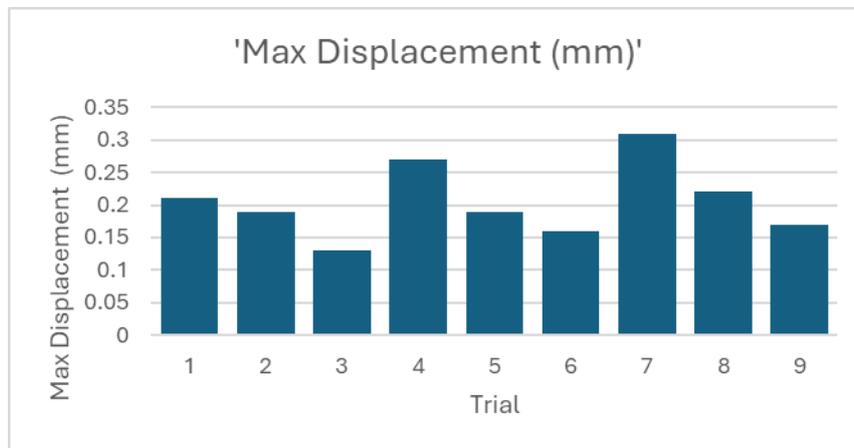


Fig 2 Graph of displacement single bead result

Values for displacement show an approximately symmetric displacement field from 0.13 mm to 0.31 mm, without negative deformation. In trial 4, it has the highest displacement (0.31 mm) when the voltage is 11V and travel speed is 5mm/min; the smallest displacement (0.13 mm) appears in trial 3 with voltage 9 V and travel speed 10 m/min. This result illustrated that combinations of slow travel speeds and high voltages lead to greater material deformation because of increased in heat input. Trial 8 shows balance in terms of parameters. The trial is carried out at a voltage of 13 V, travel speed of 5 mm/min, and maximum displacement of 0.19 mm, which is moderate compared to the extremes found in the other trials and need to validate by Taguchi method.

3.1 Optimized Parameter by Taguchi Method

The Taguchi method was implemented using the Minitab statistical software to identify the optimal combination of process parameters which is voltage and travel speed by which the displacement value can be varied to achieve a balanced set of parameters to predict the bead geometry. The trial of experimental trials to get the output responses, analysis of output response values to find the best parameters is then confirmed using the best setting for the optimal setting [5].

Table 6 Displacement mean analysis

Response Table for Means

Level	Voltage	Travel Speed
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1	0.1767	0.2000
2	0.2067	0.2633
3	0.2333	0.1533
Delta	0.0567	0.1100
Rank	2	1

From the Taguchi analysis using the "nominal is better" approach the optimal parameters were determined to be of 5 mm/min travel speed and 13 V voltage, corresponding with mean values of 0.2633 and 0.2333 respectively. According to [6], the optimized set of process factors defines travel speed (TS) 3 mm/s and voltage range 10–20V. The results accord with prior studies indicating that lower travel speeds and higher voltages yield better results. The analysis found that displacement has more dependence on travel speed than voltage.

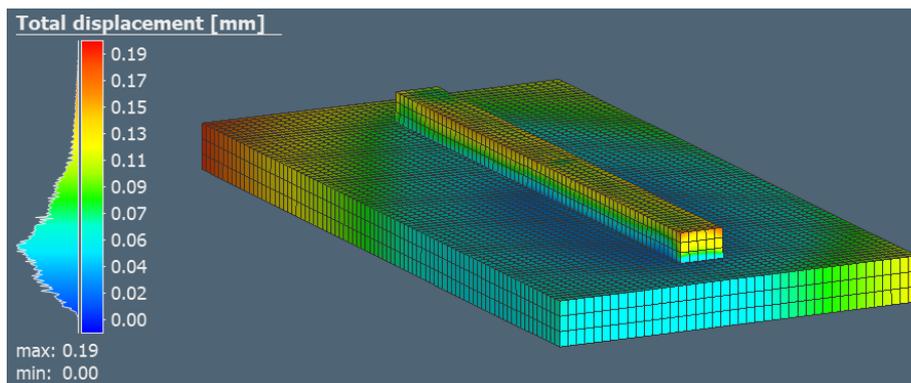


Fig 3 Displacement of optimized parameter

3.2 Experimental of single bead result

In this section, the simulated versus experimental bead geometry is examined with respect to the consistency of the single bead WAAM process. The experimental validation was carried out using the optimized set of parameters identified through the Taguchi method: This was under 13 V and moved at a 5 mm/min travel speed.

Table 7 Bead geometry results for single bead process

Trial	Voltage	Travel Speed	Bead Height	Bead Width
1	13V	3mm/s	4.5mm	7.8mm
2	13V	5mm/s	4.0mm	6.0mm
3	13V	10mm/s	3.5mm	3.0mm



Fig 4 Single bead result

As illustrated in Figure 4, the best and most optimal beads of 6 mm width and 4 mm height were achieved at 13 V and 5 mm/min, with the lowest deviation between the widths, among other parameter combinations. Additional trials were conducted for validation using 13 V at travel speeds of 3 mm/min and 10 mm/min to produce 7.8 mm and 3 mm width beads followed by 4.5 mm and 3.5mm height, respectively. With the optimized parameters, the bead width of 6 mm matches the desired geometry and verifies the effectiveness of the determined process settings. Low porosity wall walls range between 6 to 7 mm in width, among which low porosity with wall width of 6 to 7 mm was shown to be more efficient than the walls with higher widths such as 45mm studied in this study [7].

3.3 Hardness Testing

The hardness distribution across the fabricated part was evaluated by measuring four WAAM load specimens at five distinct points on each specimen. The results were analyzed after four test runs.

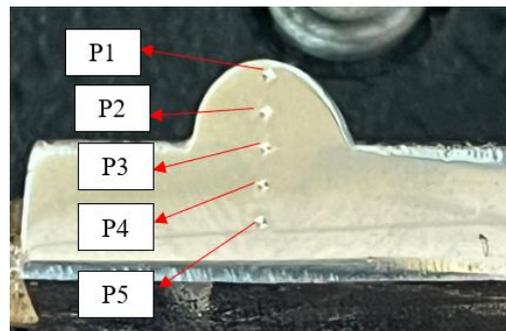


Fig 5 Five distinct points across each WAAM specimen

The testing machine was pre-calibrated with a 30 kg load to standardize the indentation process and ensure measurement consistency.

Table 8 Vickers hardness result

VICKERS HARDNESS (Hv)							
SPECIMEN	P1	P2	P3	P4	P5	AVERAGE	RANGE
1	143.3	144.1	149.0	193.1	150.3	155.96	140-200
2	148.9	159.9	181.8	169.4	147.1	161.42	140-190
3	149.3	146.7	186.2	212.5	192.8	177.5	140-220
4	180	188.3	214.0	210.0	186.5	195.76	170-220

Table 8 showed the results of the Vickers hardness testing of WAAM specimens. It is found that Specimen 1 had an average hardness of 155.96 Hv (range: Specimen 2 had a slightly higher average of 161.42 Hv (range: 140-190 Hv) as compared to Specimen 1 which had 148.58 Hv (range: 140-200 Hv). These values are typical for SS316L stainless steel (140 200 Hv) [4] and some differences in hardness distribution across the specimens were noted. Importantly, the hardness increases at P3 and P4 may be attributed to the presence of the heat-affected zone (HAZ) during the process. HAZ is formed by welding SS316L over mild steel and localized thermal effects thus imparted results in elevated hardness in the region.

3.4 Validation on WAAM Multi-Layer Process

This work focuses on Wire Arc Additive Manufacturing (WAAM) multi-layer wall process validation by comparing results from simulation and experimental studies to provide accuracy and consistency in predicting wall geometry and mechanical properties.

Simufact Welding 6.0 was used to simulate the WAAM walls process with the optimized parameters, obtained from the Taguchi method, for the single bead process. In particular, the voltage was at 13V, the travel speed was 5mm/min and the constant parameters were 160A for a current and 5.9m/min for a wire feed speed. However, using the same base metal dimension as for the single bead process, an extra layer-wise deposition was performed to create a 10-layer WAAM wall structure on which the simulation was performed.

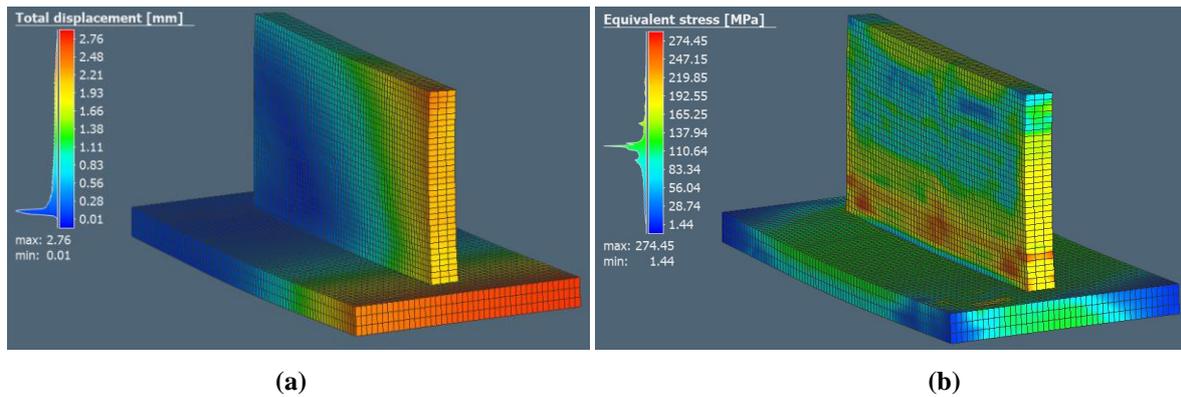


Fig 6 Displacement result (a) Residual stress result (b) for multi-layer WAAM process

Based from Fig 6, it is observed a maximum value of 2.76 mm and a minimum of 0.01 mm, mostly varied from the bead displacement determined by the single bead process. It's different for various reasons. The WAAM wall process causes multi-layer deposition, introducing cumulative thermal effects other than those occurring in the single-layer bead process.

Whereby the analysis of equivalent stress for the 10-layer WAAM wall process provides a wide range of stress values between 274.45 and 1.44 MPa. The combined effects of thermal and mechanical factors on this layer-by-layer deposition process are demonstrated with these results. According to these studies, the WAAM structure is on a structure of tensile longitudinal residual stress with a peak value of 300MPa located at a position of several layers below the top surface [8].



Fig 7 Top view of bead geometry results for multi-layer WAAM process

The experimental WAAM wall process was conducted using the optimal parameters for 13V and a travel speed of 5 m/min, with the welding parameters setup on a robotic welding system. For the WAAM walls, a bead width of 9mm resulted, much larger than the 6 mm bead width measured in the single bead experiment. Based on these studies, when the TS was used as the control variable to minimize the overlap, these studies demonstrated that the optimum given layer width varies between 6 and 9 mm [9].

In the WAAM wall process during layer-by-layer deposition the heat from subsequent layer overlaps heat from previous layers. The existence of this overlap means that peak localized temperature occurs at a higher value and lower cooling rate than that expected from the single bead experiment, producing greater material flow and bead expansion.

4. Conclusion

The research successfully optimized WAAM parameters, identifying optimal values of 13V voltage and 5 m/min travel speed through Taguchi method and Simufact Welding simulation. Single-bead validation achieved a 6.0 mm bead width with uniform hardness distribution, while multi-layer (10-layer) WAAM process revealed maximum displacement of 2.27 mm and equivalent stress ranging from 1.44 to 274.45 MPa, with a final bead width of 9 mm. To further advance WAAM technology, recommendations include improving thermal management strategies, expanding parameter studies, implementing real-time monitoring systems, further studies on breaking time, and collaborating with industry partners for practical applications. These findings and recommendations contribute to establishing WAAM as a reliable manufacturing technique for producing high-quality components with improved dimensional accuracy and structural integrity.

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Conflict of Interest

The authors declare no conflict of interest regarding the paper's publication.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Aniq Harith Khairol Afandi, Mohd Halim Irwan Ibrahim, Sarah Nadiah Mohd Ghazali; **data collection:** Aniq Harith Khairol Afandi; **analysis and interpretation of results:** Aniq Harith Khairol Afandi, Sarah Nadiah Mohd Ghazali; **draft manuscript preparation:** Aniq Harith Khairol Afandi, Mohd Halim Irwan Ibrahim, Sarah Nadiah Mohd Ghazali. All authors reviewed the results and approved the final version of the manuscript.*

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