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Studies on Stress Relief Heat Treatment of 316L Stainless Steel in Wire Arc Additive Manufacturing using Simufact Welding Simulation

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Abstract

Wire Arc Additive Manufacturing (WAAM) is gaining recognition in various industries for producing large scale metal components, but the high heat input during the process causes significant residual stress, compromising the mechanical properties and reliability of the final product. This study focuses on mitigating these stresses by developing a numerical simulation model to optimize stress relief heat treatment (SRHT) for 316L steel WAAM components. It begins with an introduction to WAAM's industrial significance and challenges, followed by a literature review on residual stress causes, existing SRHT techniques, and numerical modelling. The methodology includes designing a simulation model, optimizing SRHT parameters using Simufact Welding software, and validating the results through experimental comparisons. The findings highlight the model's effectiveness in reducing residual stress and improving mechanical properties, showcasing how advanced simulation techniques enhance WAAM technology and offer practical solutions for industrial applications and future research involving diverse materials and geometries.

1. Introduction

Wire Arc Additive Manufacturing (WAAM) is an innovative technique for quickly producing large, complex metal components. However, the high heat input from this process can lead to significant residual stress, which may compromise the final product's mechanical properties, reliability, or cause defects like cracks. Mitigating these stresses is crucial, and Stress Relief Heat Treatment (SRHT) is a promising method to address this challenge. A review of existing literature on WAAM and SRHT reveals that research on simulating SRHT for WAAM components, especially for high-strength steel, is limited. This study aims to fill that gap by developing a numerical simulation model to optimize SRHT parameters for 316L stainless steel components made with WAAM. WAAM machine parameters can include travel speed, voltage, and the gas mixture ratio. Different heat inputs and paths can affect grain size, with a vertical path tending to produce a more uniform grain orientation that helps with plastic deformation. Optimal results can be achieved by controlling factors like heat, bead size, layer height, and deposition speed. Modeling and simulation, particularly using software like Simufact Welding, are valuable tools for understanding the physical phenomena and identifying the best conditions for creating defect-free parts. These simulations can help analyze the influence of operating parameters on geometry, thermal cycles, microstructure, distortions, and residual stresses. The ultimate tensile strength, yield strength, and elongation of WAAM-produced materials are often superior to those made by casting due to better control over heat input. Furthermore, the microstructure of the filler material during cooling can influence residual stress. A three-phase microstructure (austenite, ferrite, and martensite), for instance, can reduce strains and residual stresses.

2 Methodology

The methodology of this study is shown in Figure 1 below, involves a four-step process. First, a numerical model of the WAAM welding process is created using FEM analysis. Second, a stress relief heat treatment simulation is performed using Simufact Welding software to analyze how it affects residual stress and displacement. Third, a virtual experiment is run to verify the parameters created in the simulation. Finally, the simulation results are used to determine the mechanical characteristics of the WAAM components, such as tensile strength and hardness.

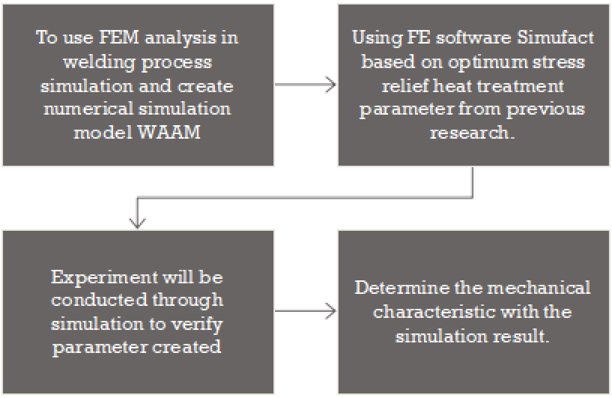

Figure 1 Flow Chart

The study starts with a simulation of the welding process to create a numerical model for WAAM technology. This model is used to understand how heat, temperature, and stress affect 316L stainless steel. Table 1 below shows the WAAM process parameter

Table 1 WAAM Process Parameter

Parameter	Value
Current	160 A
Voltage	13 V
Travel speed	5 mm/s
Wire feed speed	5.9 m/min
Shielding gas composition	80% argon, 20% CO_2
Mean length/height/width/thickness	105 mm x 40 mm x 6.5 mm x 4 mm

Stress relief heat treatment is simulated using Simufact Welding software. Parameters, including temperature and holding time, are taken from previous studies and listed in Table 2. The purpose is to evaluate how the treatment reduces residual stress and displacement while improving mechanical properties like tensile strength and hardness.

Table 2: Heat Treatment Parameter

Parameter	Value
Temperature	600°C, 700°C, 800°C
Holding time	1 hour, 4 hour, 6 hours

To confirm the efficacy of the parameter combinations, studies are carried out in a virtual environment once the stress relief heat treatment parameters have been simulated. This involves checking that the simulation results match the anticipated decreases in residual stress and improvements in material performance.

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In the final stage of the study, the mechanical properties of the WAAM components are determined following the simulation. The simulation results are utilized to assess important characteristics such as tensile strength, residual stress distribution, hardness, and deformation. The findings from this stage are considered critical for the identification of ideal conditions for improved material performance and for the evaluation of the effectiveness of the stress relief heat treatment.

2.1 Taguchi Orthogonal Array

Heat treatment settings were optimized using a Taguchi Design of Experiments (DOE). The temperature and holding time parameters were systematically changed using an L9 orthogonal array.

2.2 Signal to Noise Ratio

S/N ratio was determined using the Taguchi method with Minitab software. This calculation enabled a detailed evaluation of parameters like temperature and holding time to see how they affect residual stress or displacement. The purpose was to identify the most optimal setup for the wire arc additive manufacturing process.

3 Results and Discussion

The final results of the study were divided into several parts. which are the results of the Numerical Model, Residual Stress Distribution, Effect of SRHT on Stress and Displacement, and also the Taguchi Method with Optimal Parameters.

3.1 Result of Numerical Model by Simufact Welding

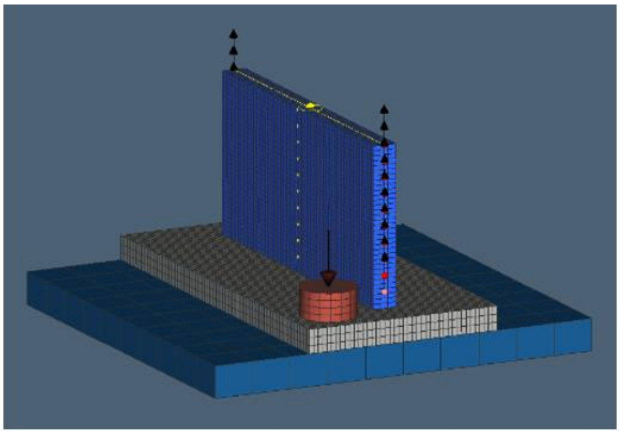

Figure 2 WAAM Simulation Model

WAAM numerical simulations in Figure 2 provide a detailed examination of the 316L stainless steel components. The model is used to analyze key factors like temperature profiles, stress distribution, and deformation.

3.2 Result of Residual Stress Distribution

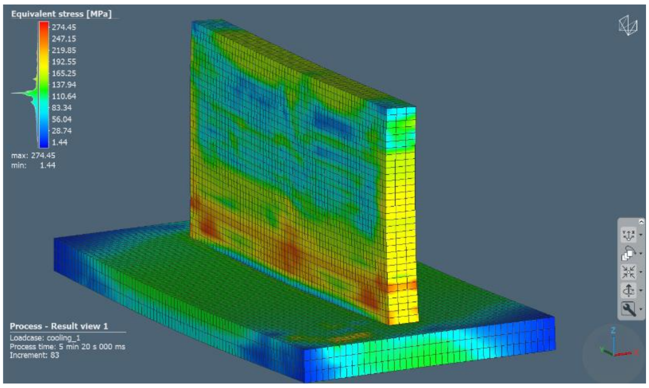

Figure 3 Equivalent Stress Distribution

The simulation results from Simufact Welding as in Figure 3 above illustrate the equivalent stress distribution within the structure. Stress values, ranging from 1.44 MPa to a maximum of 274.45 MPa, are shown on a colour scale where blue indicates low stress and red indicates high stress. Low stress is observed in areas near the baseplate and the bottom of the wall due to effective heat dissipation and material support. Conversely, moderate to high stresses are found in the central and top regions, likely caused by thermal gradients and solidification shrinkage. These residual stresses, generated by the heat input from the arc and cooling cycles, can lead to distortion or cracking if they exceed the material's yield strength. The simulation's high-resolution settings allow for a detailed capture of these thermal and mechanical phenomena.

3.3 Result of Stress Relief Heat Treatment on Stress Distribution

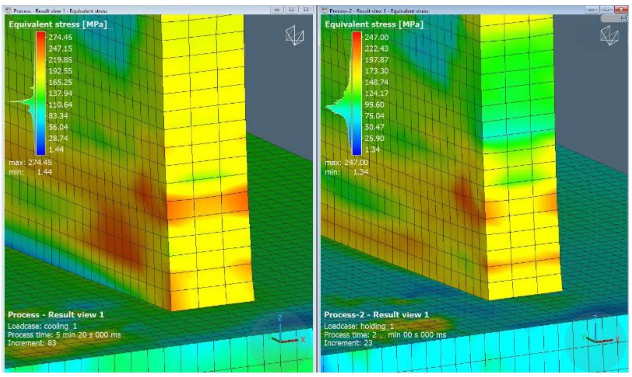

Figure 4 Stress Distribution Before and After

As shown in Figure 4, heat treatment effectively reduced residual stress. The maximum stress before treatment was 274.45 MPa, which was concentrated in certain areas and could cause issues like cracks or reduced fatigue life. After treatment, the maximum stress dropped to 247.00 MPa, a reduction of about 10%, and was more evenly distributed. This indicates that heat treatment improved the material's reliability and enhanced its mechanical properties.

3.4 Result of Stress Relief Heat Treatment on Displacement

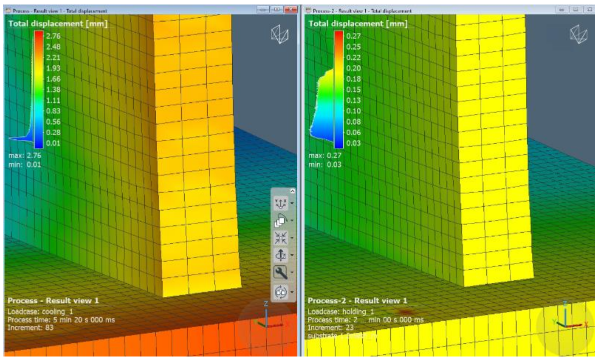

Figure 5 Total Displacement Before and After

According to Figure 5, the total displacement of the specimen was significantly reduced after heat treatment. The maximum displacement was initially 2.76 mm, but it dropped by approximately 90% to just 0.27 mm after the treatment. This indicates that the heat treatment increased the material's stiffness and improved its structural integrity, making it more stable and resistant to deformation.

3.5 Taguchi Method Result

According to the result in Table 4 below, simulation 9, with a temperature of 800°C and a holding time of 6 hours, achieved the lowest residual stress at 215.88 MPa. These settings were also found to produce the lowest displacement value of 0.41 mm. These findings suggest that using a higher temperature and a longer holding time is the most effective approach for minimizing residual stress while maintaining acceptable displacement levels in this particular process.

Table 3 Result L9 Orthogonal Array by Taguchi Method

Experiment	Temperature °C	Holding time (hour)	Residual stress (MPa)	Displacement (mm)
1	600	1	247.00	0.27
2	600	4	247.39	0.55
3	600	6	244.76	0.54
4	700	1	230.67	0.55
5	700	4	231.90	0.41
6	700	6	231.35	1.89
7	800	1	216.83	0.42
8	800	4	213.74	2.87
9	800	6	215.88	0.41

3.6 Main Effects Plot for Means

The main effects plot in Figure 6 below further corroborates these findings, displaying a drastic decline in the response variable with increasing temperature, underscoring its significant effect. In contrast, the nearly flat line for holding time illustrates its negligible impact. Together, the data and visualization suggest that temperature is the primary factor affecting the response variable, making it the critical focus for process optimization.

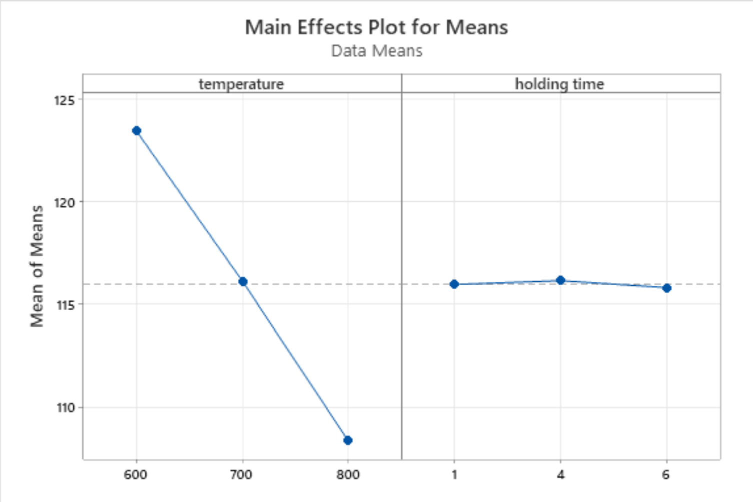

Figure 6 Plot for Mean

3.7 S/N Ratio

The main effects plot in Figure 7 below visually confirms the findings. The temperature line has a sharp slope, indicating a significant effect on the signal-to-noise ratio, while the holding time line is relatively flat, showing it has a minimal effect. The "smaller is better" criterion suggests that optimizing the process should focus on controlling temperature.

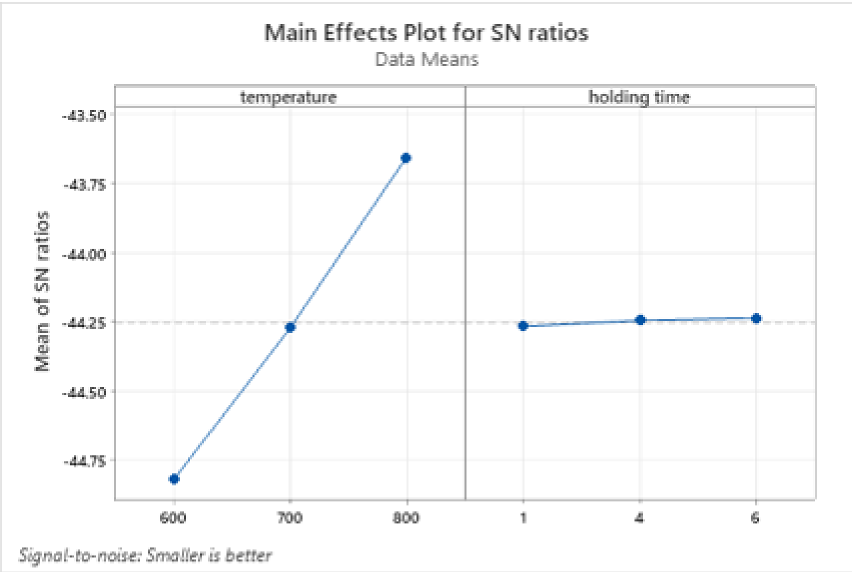

Figure 7 S/N ratios

3.8 Residual Stress & Displacement

The equivalent residual stress diagrams, as shown in Figures 8 and 9, demonstrate the stress reduction patterns caused by heat treatment. A comparison of the figures shows that the high-stress areas (450 MPa) are significantly reduced, although the maximum stress near the weld remains unchanged. Stress is also reduced in the green zone (202–252 MPa), far from the weld. The high-stress areas on both sides of the weld are reduced, along with stress reductions in the green zone far from the weld. The study concludes that heat treatment can effectively reduce residual stress, with optimal parameters being a higher temperature and longer duration time. Post-weld heat treatment has a limited effect on welding deformation, as the overall deformation of the weld plate is minimal. Similarly, the simulation in this study showed a very small displacement value of only 0.41 mm at the optimal parameters.

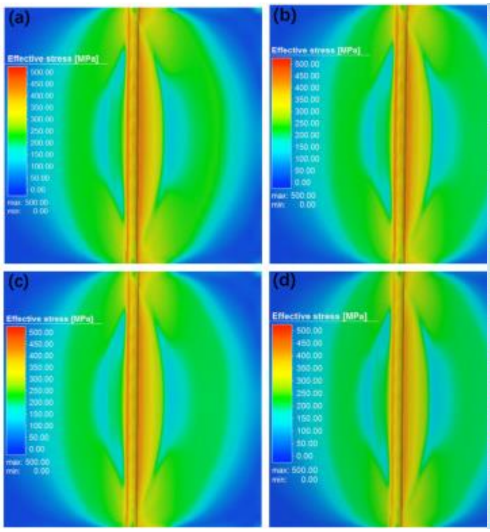

Figure 8 Equivalent stress: (a) before heat treatment, (b) Case1, (c) Case2, (d) Case3 (B. Huang et al., 2020)

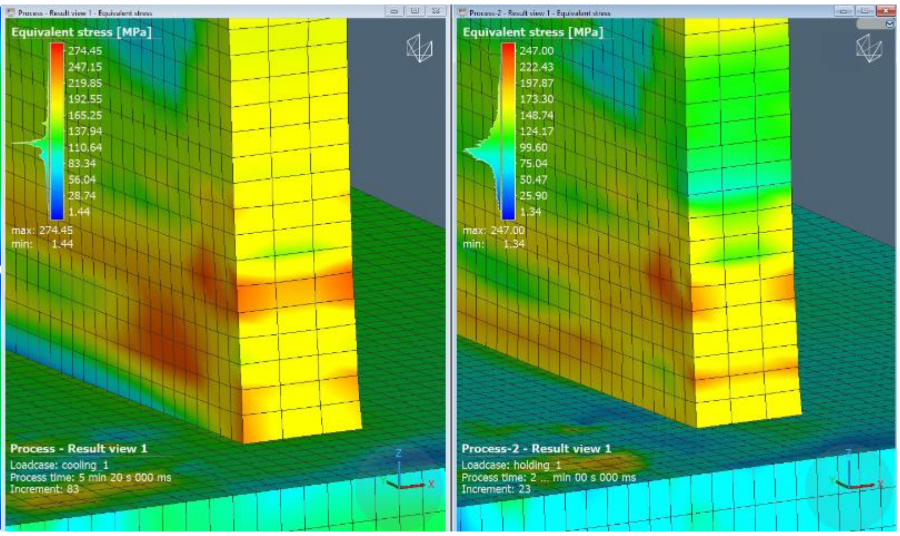

Figure 9 Residual Stress of the specimen before and after heat treatment

4 Conclusion

The study successfully demonstrated the effectiveness of stress relief heat treatment (SRHT) in improving the mechanical properties and reducing residual stress and displacement in WAAM-produced 316L stainless steel components. The final discussion involved validating the data by comparing it to previous literature on reducing residual stress and displacement.
The Taguchi method was used to fine-tune the process by creating S/N ratio and mean charts, which helped identify which factors were most important in the heat treatment parameters. The optimal heat treatment was determined to be a temperature of 800°C with a holding time of 6 hours. This resulted in a minimal residual stress of 215.88 MPa and a total displacement of just 0.41 mm, which improved the material's structural integrity and resistance to deformation.

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