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Residual Stress and Distortion Analysis Of Saph540 U-Channel in MIG Welding Using a Finite Element Approach

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ABSTRACT: MIG welding and butt joints are commonly used in fabrication processes across various industries. Challenges in the seat air spring component localization project necessitated the switch to SAPH 540 U-channel material to mitigate financial risks associated with minimum order policies. This research focuses on examining the temperature distribution, residual stress, and distortion induced during the MIG welding process of SAPH 540 U-channel butt joints using a numerical method approach through FEA simulation software. The study aims to determine the optimal welding parameters by varying three welding currents: 130 A, 150 A, and 200 A. The results show that the highest temperature (3221.3 °C) and the highest residual stress (von Mises, 441.97 MPa) occur at 200 A, while the lowest values (2103.2 °C and 373.292 MPa) occur at 130 A. All three variations exhibit bending distortion and longitudinal shrinkage. The lowest distortion value at 130 A is 0.0090196 mm, and the highest at 200 A is 0.018751 mm. The simulation modeling indicates that a welding current of 130 A is recommended to achieve minimum residual stress and distortion, serving as a reference for future welding processes.

KEYWORDS: MIG welding, Butt joints, Residual stresses, Distortions, Thermal load

1.0 INTRODUCTION:

The commercial vehicle industry (trucks) plays a crucial role in global transportation and distribution, driving economic activity by delivering goods from production points to factories, industries, or final sale points [Teter 2017]. Due to their importance in sustaining the economy and development, truck manufacturers are motivated to enhance performance to meet current and future needs. A critical truck component is the air spring, which dampens vibrations during operation. The air spring seat is a vital support component, and the industry faces challenges in localizing this part because the minimum order quantity for STKR 400 hollow pipe material is too high, prompting a proposed material change to SAPH 540 U-channel to mitigate financial risk.

Metal Inert Gas (MIG) is widely used in aerospace, shipbuilding, automotive, and machinery industries. It uses a filler wire that is an electrode, continuously fed to create an electric arc with the base metal [2]. Fusion welding results in non-uniform thermal distribution, causing residual stress and distortion in the welded structures [3]. Rapid heating and uncontrolled cooling cause local plastic deformation, which leads to residual stress and distortion during welding [4]. Residual stress can negatively impact metal structures by causing crack growth, creep, distortion, fatigue, and loss of geometric tolerance, necessitating

understanding its magnitude and distribution for effective design and fabrication [5][6]. Heat transfer during the welding process significantly impacts weld quality, affecting residual stress, distortion, microstructure, and reduction/oxidation reactions [7]. Heat flow occurs through conduction and convection, while radiation is negligible. Conduction happens when heat is directly transferred between the heat source and the electrode without any intermediary [8], [9]. Convection involves an intermediary substance, as the weldment surface is exposed to air. The heat flux magnitude influences temperature distribution, affecting the overall heat transfer [10], [11].

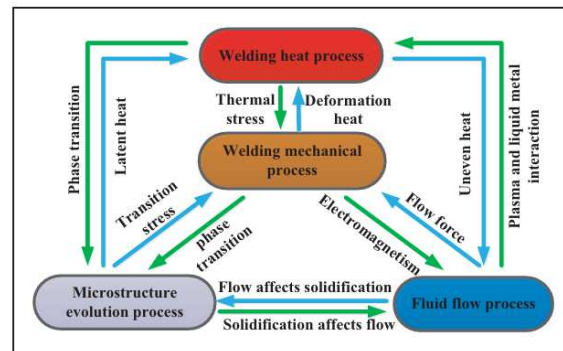


Figure 1: Schematic interaction during the welding process [2]

This study focuses on the residual stress and distortion in MIG welding of butt joints in SAPH 540 U-channels using finite element analysis (FEA). It examines three current levels: 130 A, 150 A, and 200 A to optimize welding parameters. The first objective is to identify the temperature distribution during welding by simulating heat source movement and thermal strain in a numerical model. The second objective is to analyze residual stress and distortion derived from the simulation results, predicting the residual stress field and deformation post-welding. The third objective is to determine the optimal current level that minimizes residual stress and distortion by comparing the results from the three current variations. This involves a detailed evaluation of the thermal and mechanical responses of the welded structure. The analysis helps in understanding the stability and integrity of the welded joints. The findings offer crucial insights for improving welding processes. These results can guide future research and practical applications in welding engineering. This study ultimately contributes to more efficient and reliable welding practices in industrial applications.

2.0 EXPERIMENTAL PROCEDURE

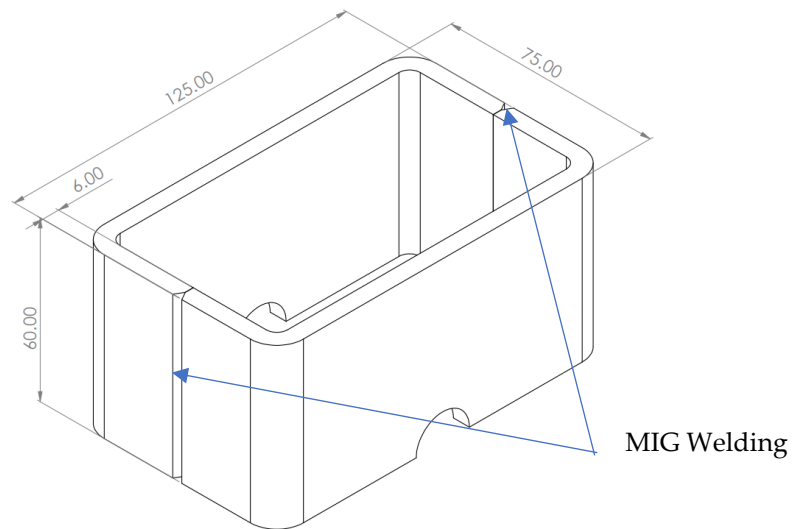


Figure 2: Material percobaan dengan bentuk kanal U SAPH 540

Table 1. Chemical Composition Kanal U SAPH 540 % Wt

C	Si	Mn	P	S
0.0768	0.076	1.393	0.0107	0.0016

Table 2. Material *properties* of SAPH 540

Density	Young Modulus	Poison Ratio	Yield Strength	Tensile Strength	Elongation	Coefficient of Thermal Expansion	Thermal Conductivity
7.8 gr/cm ³	211,56 GPa	0.29	485 MPa	566 MPa	31%	1.32E-05 1/K ^o	45 W/mC ^o

The study utilizes the material properties of SAPH540, encompassing its chemical composition, mechanical properties, and thermal properties, as essential inputs for finite element analysis (FEA) simulation using computer-aided engineering (CAE) software. The chemical composition, comprising elements such as carbon (C), silicon (Si), manganese (Mn), phosphorus (P), and sulfur (S), influences the material's weldability and mechanical strength. Mechanical properties, including yield strength, tensile strength, and elongation, govern how the material responds to mechanical loads and deformations. These properties are crucial in predicting the structural integrity and performance of welded joints under various loading conditions. Additionally, thermal properties, such as thermal conductivity and specific heat capacity, dictate the material's response to thermal gradients and heat flux during welding processes. Understanding these thermal properties aids in simulating heat distribution and predicting temperature gradients within the welded structure, ensuring optimal welding parameters and minimizing distortion and residual stresses.

Using computer-aided design (CAD) software, the U-channel component, with dimensions of 125 x 75 x 60 mm and a thickness of 6 mm, is designed by visualizing its function, necessity, and the study's objectives to facilitate accurate simulation analysis. The geometric shape of the two U-channels can be seen in Figure 3, whereas the meshing process was conducted using FEA software, as shown in Figure 3.

Conducted using FEA software as shown in figure

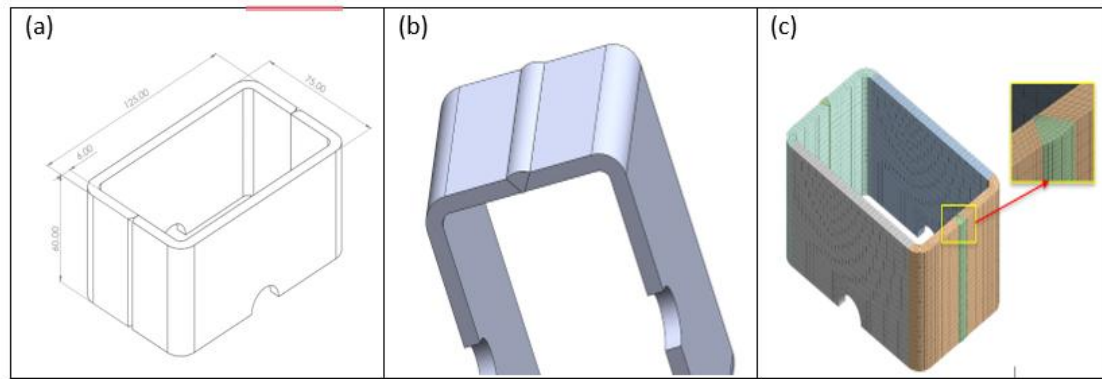


Figure 3: Results of 3D design U-channels and meshing. (a) Dimensions and geometric shape of the U-channel, (b) Butt weld geometry modeling, and (c) Mesh model

The Table summarizes the welding parameters utilized in this study, which include the welding type, filler metal specifications, current and voltage ranges, and gas shielding type.

Table 3. Welding Parameters

Welding Type	Filler Metal	Diameter of Filler Metal	Current	Voltage	Gas Shielding Type
MIG	Wire HTW-50	1 mm	130-220 A	20 – 30 Volt	CO ₂ 100%

The thermal loading modeled in this study refers to the element birth and death technique to accurately represent the welding process. This technique involves deactivating all weld seam elements initially, and then reactivating the corresponding elements sequentially [12]. The loading area in the simulation modeling can be seen in Figure 4.

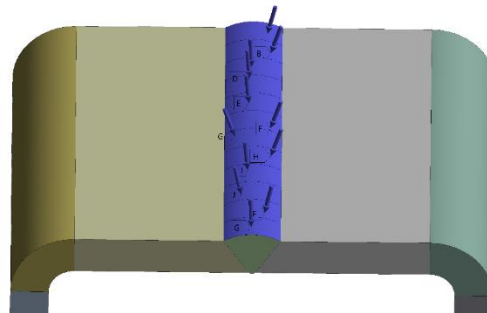


Figure 4: Thermal load area of welding simulation

The boundary conditions or constraints implemented in the transient structural welding simulation are assumed to act as supports during the welding process. The assumed locations on the object's geometry are on the outer right and left surfaces, marked in blue as shown in Figure 4.

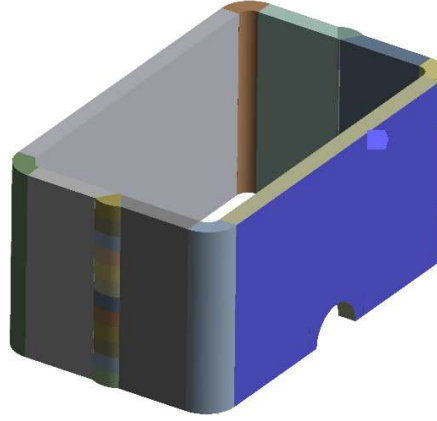


Figure 5: Boundary conditions of the U-channels

To simulate the MIG welding process, a double ellipsoidal heat source was used, as shown in Figure 3. This model consisted of two ellipsoidal heat sources with similar geometries. The parameters f_1 and f_2 determine the energy distribution of the heat source, and $f_1 + f_2 = 2$ [13]. The heat flux distribution function of the double ellipsoid heat source model is shown in equations(1)and (2).

The heat flux distribution function of the front heat source is

$$q_1(x, y, z) = \frac{6\sqrt{3}f_1\eta UI}{a_1bc\pi\sqrt{\pi}} \exp\left(-\frac{3x^2}{a_1^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2}\right) \quad (1)$$

The heat flux distribution function of the rear heat source is

$$q_2(x, y, z) = \frac{6\sqrt{3}f_2\eta UI}{a_2bc\pi\sqrt{\pi}} \exp\left(-\frac{3x^2}{a_2^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2}\right) \quad (2)$$

The energy distribution parameters f_1 and f_2 are

$$f_1 = \frac{2a_1}{a_1 + a_2} \quad (3)$$

$$f_2 = \frac{2a_2}{a_1 + a_2} \quad (4)$$

The total heat flux function of the heat source is

$$q(x, y, z) = q_1 + q_2 \quad (5)$$

Where η is the thermal efficiency, I is the welding current, U is the arc voltage, and a_1 , a_2 , b , and c are the distribution parameters of the double ellipsoid heat source.

Based on the above equation, the heat flux for each element is obtained, supported by the welding parameters as shown in Table 5

Table 4. Heat Flux Of Each Variation

	Variation I (130 A)	Variation II (150 A)	Variation III (200 A)
Heat Flux	30.532 W/mm2	35.229 W/mm2	46.973 W/mm2

3.0 RESULTS AND DISCUSSION

In this section, we present and analyze the outcomes of the MIG welding simulations conducted on the SAPH540 U-channel components. The results, derived from the finite element analysis (FEA) simulations using the specified welding parameters, are evaluated in terms of residual stresses, distortions, and thermal effects. The discussion will focus on how the three variations in welding current, as outlined in the methods section, influence the mechanical and thermal responses of the material. Additionally, we will compare the simulation results with theoretical predictions to validate the effectiveness and accuracy of the adopted numerical approach.

The thermal analysis results include visual representations, such as images and animations of heat and temperature distribution within the model, and time-function graphs at specific nodes. Meanwhile, the structural analysis results encompass visual representations of stress profiles and deformation within the material. The residual stress and deformation are visualized through time- and position-based analysis. Additionally, images or animations that show the residual stress within the model, along with time function graphs at specific nodes, are provided which shown in Figure 6

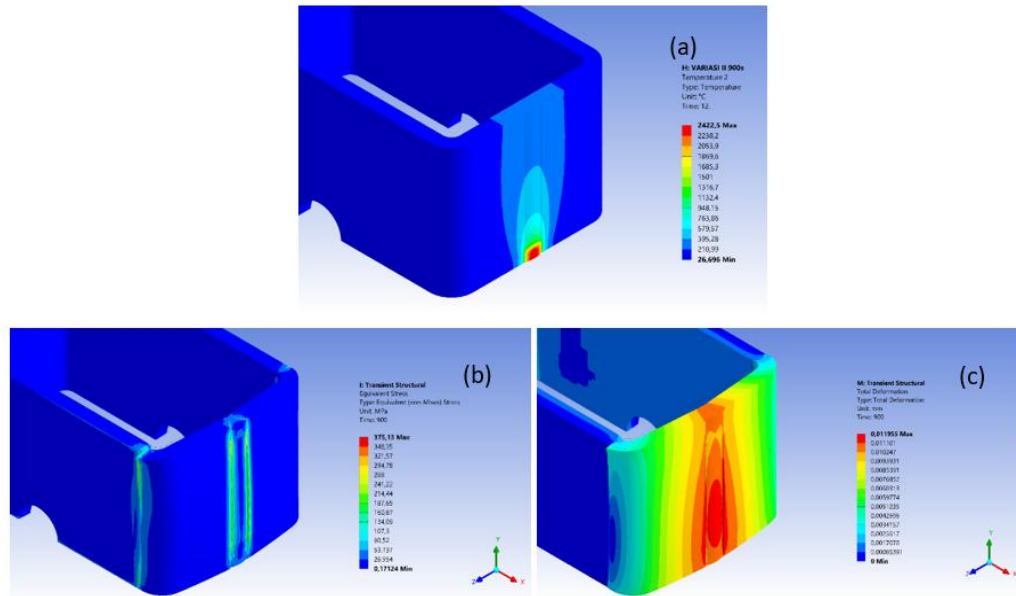


Figure 6: Numerical Analysis Results. (a) Temperature Distribution, (b) von Mises Residual Stress, (c) Distortion

The heat distribution during the welding process is not uniform throughout the material. The heat distribution contour shown in Figure 6 (a) indicates that the welded area and regions adjacent to the weld path experience higher heat distribution than the unwelded areas. During the welding process, heat does not spread throughout the entire material. Heat will spread through conduction in the material after the welding process is completed and enters the cooling phase. The heat distribution for the three variations is shown in Figure 6, so it is very clear that heat is formed along the weld path; this also shows the center of stress caused by the temperature difference that occurs in the weld path, HAZ (Heat Affected Zone), and parent metal.

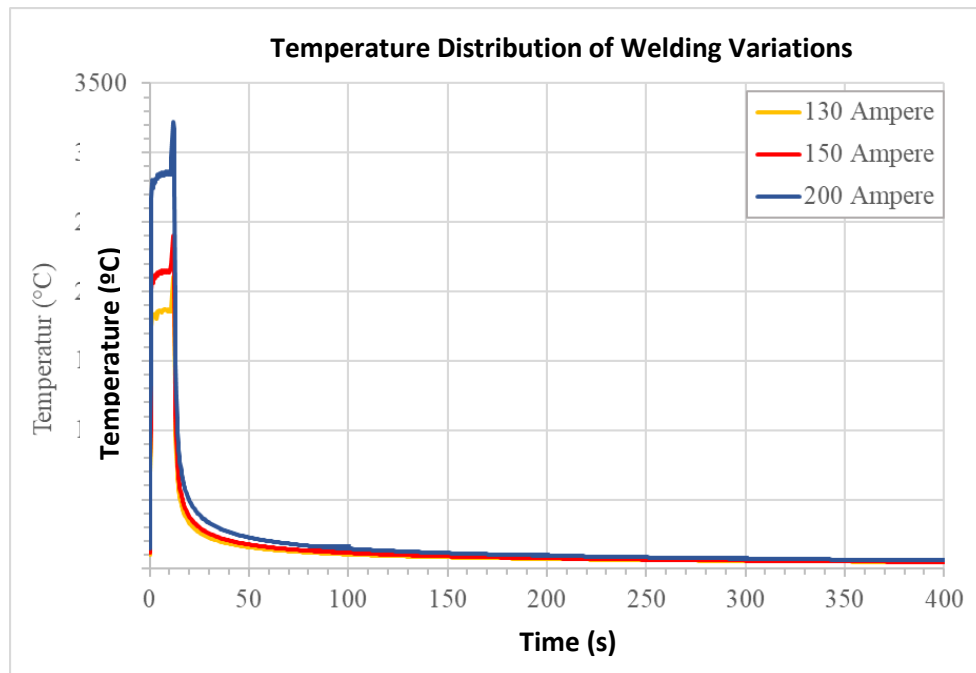


Figure 7: Graph of temperature distribution result in numerical method

The results of the study for the three current variations indicate that in welding variation I with 130 A current, the maximum temperature reached was 2103.2 °C. In variation II with 150 A current, the maximum temperature increased to 2400 °C. Meanwhile, in variation III with 200 A current, the maximum temperature reached 3221.3 °C. The results from the graphs also show that the highest temperatures are achieved at the welding endpoint. Based on these findings, it can be indicated that higher current results in higher heat flux. As heat flux increases, so does the resulting temperature. The results also indicate that the weld fusion zone has exceeded the melting point of the SAPH540 material, which is 1523 °C. This will result in temperature differences in each zone (weld metal, heat-affected area, and parent metal) and will also result in differences in the size of the microstructure grains causing residual stress.

The temperature distribution obtained from the simulation results shows that the highest temperatures are found at the fusion weld line (WCL), where the welding arc directly impacts the area. The heat energy from the welding arc is concentrated, causing temperatures to reach their maximum value in that area. Temperature distribution is not uniform, as temperatures decrease in the Heat Affected Zone (HAZ) and base metal, causing stress

differences in welding using MIG welding. This is due to uneven heat absorption in these areas, where heat conduction and convection occur more slowly than in the WCL area. The thermal cycles simulated can also predict the distribution of the fusion zone and HAZ that will form. Will be the Residual stress is formed.

The residual stress distribution in this research modeling indicates non-uniformity, similar to the temperature distribution resulting from the welding process. These stresses arise due to uneven thermal expansion and non-uniform cooling during welding. During welding, the material around the weld area experiences rapid heating and reaches high temperatures, causing thermal expansion. However, parts of the material further from the weld area remain at lower temperatures, restraining this expansion and generating internal stresses. As the heated material cools and contracts, the cooler parts resist this contraction, creating tensile stresses in the weld area and compressive stresses in the surrounding material.

The simulation results shown in Figure 8 indicate differences in residual stress among the 130, 150, and 200 Ampere current variations. Higher welding currents result in greater residual stresses. The residual stress (von Mises) in the transverse direction of the weld surface on the object, based on path L1 for variation I, reaches 184.22 MPa. In variation II, this value increases to 188.7 MPa, and in the 200 Ampere current variation, it reaches 197.09 MPa.

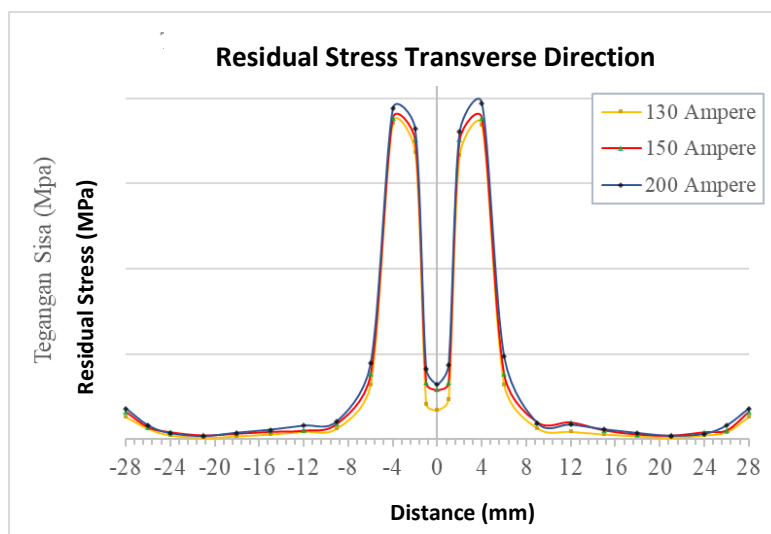


Figure 8: Graph of residual stress in the transverse direction for the three current variations

Based on the simulation results shown in Figure 8, it is observed that the largest residual stress (von Mises) distribution is located at the weld toe area and at the specified boundary or constraint conditions. In welding variation I, the maximum residual stress obtained is 373.292 MPa as shown in Figure 4.8. Variation II shows a value of 375.13 MPa. Meanwhile, welding variation III exhibits the highest residual stress among variations I and II at 441.97 MPa as shown in Figure 4.20. The modeling results indicate that the residual stress values for all three variations remain below the yield strength of SAPH540 material, which is 485 MPa, and well below the tensile strength of 566 MPa. Therefore, it can be inferred that the structures from all three variations are capable of withstanding additional loading, as they have not exceeded the elastic and plastic limits of the base material.

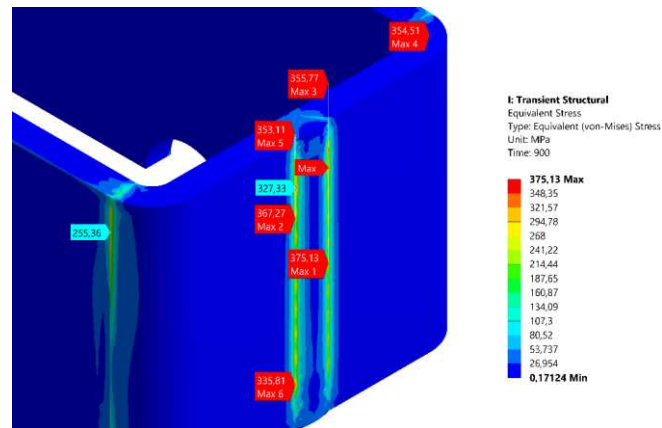


Figure 9: Maximum residual stress (von Mises)

Distortions in welding are associated with residual stresses induced by factors such as thermal loading, rapid thermal cycles within the material, and constraints during the welding process. These factors play a role in the observed deformations during welding operations. Specifically, distortions identified in various welding scenarios in this study typically manifest as bending distortion and longitudinal shrinkage, as illustrated in Figures 9 and 10.

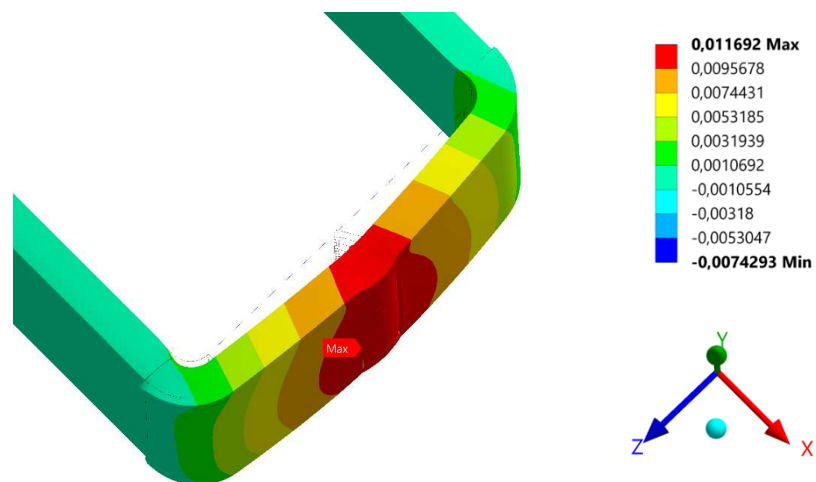


Figure 10: Bending distortion on welding variation II

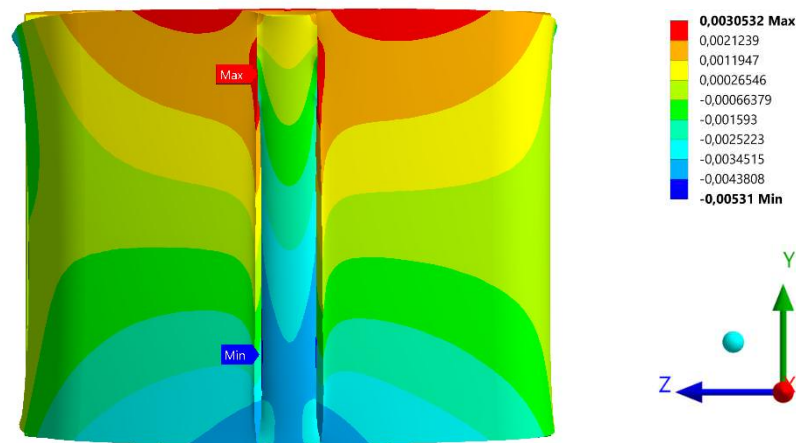


Figure 11: Longitudinal shrinkage on welding variation II

The minimum distortion based on the simulation modeling results occurs in welding variation I, with a value of 0.0090196 mm along the X-axis, corresponding to bending distortion. Meanwhile, the highest distortion is observed in variation III, with a value of 0.018751 mm along the X-axis. Based on the modeling results, it can be identified that welding variation I can be chosen for actual welding operations due to its minimal distortion outcomes.

4.0 CONCLUSION

Heat distribution during the U-channel welding simulation process occurs unevenly on the object. Heat cycles and cooling happen through conduction and convection, with the lowest temperature observed in welding variation I using a current of 130 Amperes, at 2103.2 °C. Meanwhile, the highest temperature is observed in welding variation III using a current of 200 Amperes, at 3221.3 °C.

Residual stress and distortion correlate with the heat cycles, where higher welding current values result in increased residual stress and distortion. The lowest residual stress (von Mises) and bending distortion along the X-axis are observed in welding variation I using a current of 130 Amperes, with values of 373.292 MPa and 0.0090196 mm, respectively. Meanwhile, the highest residual stress (von Mises) and bending distortion are observed in welding variation III using a current of 200 Amperes, with values of 441.97 MPa and 0.018751 mm along the X-axis.

Based on the results of heat distribution, residual stress, and distortion from the simulation modeling conducted on the three variations, the welding current that produces the minimum residual stress and distortion is variation I with a current of 130 Amperes. Therefore, the 130 Amperes current can be used as a reference for actual welding operations.

CONFLICT OF INTEREST

By best practices, this chapter requires disclosure of any financial or non-financial interests, including political, personal, or professional relationships that could potentially influence the manuscript. Authors should include the statement 'The authors declare no conflicts of interest' if no such conflicts exist.

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