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Numerical Simulation and Experimental Validation of Thermal Stresses in Welded Structures

[1]Ravinder Kumar, [2]Rajeshwar Singh,

Assistant Professor, Sri Sai University, palampur, Himachal Pradesh, India, Email: ravinder.kumar@srisaiuniversity.org

Assistant Professor, Sri Sai College of Engineering and Technology Badhani-Pathankot, Punjab, India, Email: rajeshwarpathania98@gmail.com

Abstract: Welding is a critical process in various industries, but it often introduces thermal stresses that can compromise the structural integrity and performance of welded joints. This research paper presents a comprehensive study on the numerical simulation and experimental validation of thermal stresses in welded structures. A finite element model is developed to simulate the welding process, predicting temperature distributions, stress evolution, and distortion patterns. The accuracy of the numerical model is validated through experimental measurements using the hole-drilling method, where thermal stresses are measured in welded specimens and compared with the simulated results. The study identifies key factors influencing thermal stresses, such as material properties, welding parameters, and phase transformations. The results demonstrate good agreement between numerical predictions and experimental data, though some discrepancies highlight the need for further refinement of the simulation models. The findings provide valuable insights into optimizing welding processes to minimize residual stresses and enhance the durability of welded structures. This research contributes to advancing welding technology by integrating numerical and experimental approaches, offering a robust framework for analyzing and mitigating thermal stresses in welded joints.

Keywords: Thermal Stresses, Welded Structures, Numerical Simulation, Residual Stresses, Welding Process, Material Properties, Stress Measurement.

I. INTRODUCTION

Welding is a fundamental process in manufacturing, extensively used to join materials, particularly metals, in industries such as automotive, aerospace, construction, and shipbuilding. The process is favored for its ability to create strong, permanent bonds between components, enabling the construction of complex structures with high mechanical integrity [1]. Welding also introduces significant challenges, particularly concerning the thermal stresses that develop during the process. These thermal stresses arise due to the localized heating and subsequent cooling of the material, leading to non-uniform expansion and contraction. Such stresses can result in residual stress fields within the welded structure, potentially causing distortions, cracking, and a reduction in the overall mechanical performance of the joint [2]. The generation of thermal stresses in welded structures is influenced by various factors, including the type of welding process, the material properties, and the geometry of the components being joined. During welding, the intense heat input causes a rapid temperature rise in the material, leading to thermal expansion [3]. As the material cools, it contracts, but the surrounding cooler material restricts this contraction, resulting in the development of tensile and compressive stresses. These residual stresses can be detrimental, leading to problems such as warping, reduced fatigue life, and stress corrosion cracking. Therefore, understanding the mechanisms behind thermal stress formation and accurately predicting these stresses are crucial for optimizing welding processes and ensuring the structural integrity of welded joints.

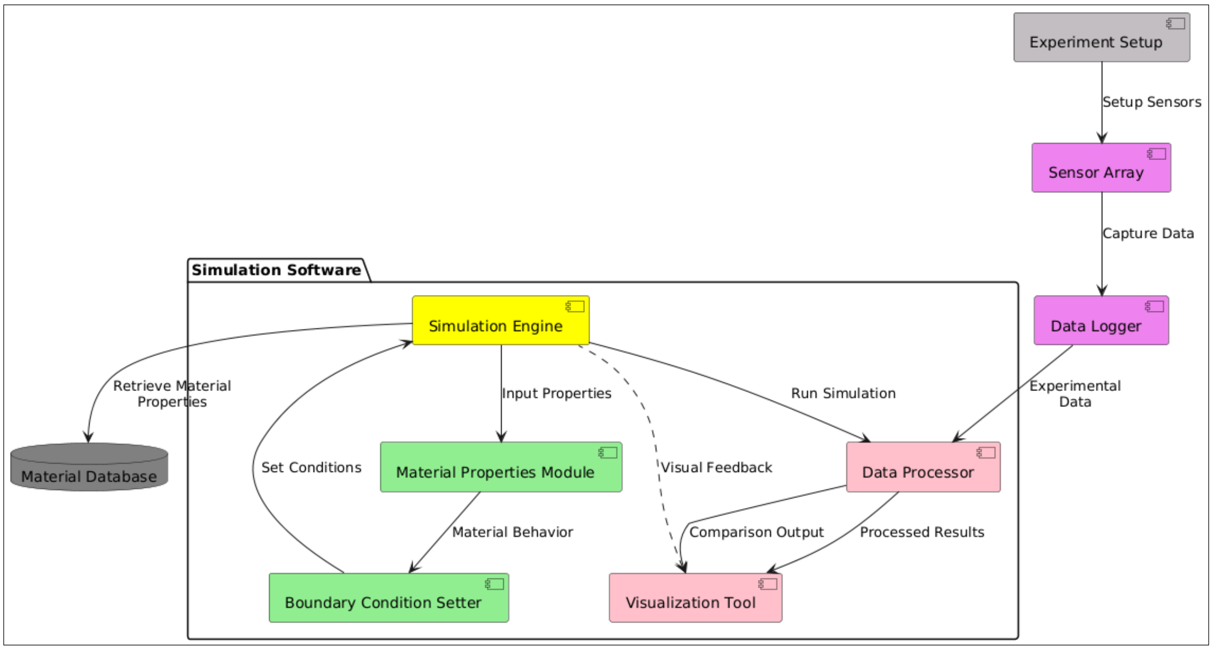

Figure 1. Simulation & Experimental Processes, Emphasizing Software Modules, Data Interactions, And Experimental Equipment Interfaces

Numerical simulation has become a powerful tool for analyzing thermal stresses in welded structures. Finite Element Analysis (FEA), in particular, allows engineers to simulate the complex thermal and mechanical behavior of materials during welding [4]. Through FEA, it is possible to model the temperature distribution, stress evolution, and deformation that occur throughout the welding process. This capability enables the prediction of residual stress patterns and provides insights into how different welding parameters, such as heat input, welding speed, and material selection, affect the stress distribution. The ability to simulate these phenomena is invaluable for designing welding processes that minimize residual stresses and enhance the durability of the final product. The advanced capabilities of numerical simulation, the accuracy of these models must be validated through experimental methods [5]. Experimental validation is essential to ensure that the numerical predictions align with real-world observations (As shown in above Figure 1). Techniques such as the hole-drilling method, X-ray diffraction, and digital image correlation are commonly used to measure residual stresses in welded specimens. These methods provide quantitative data on the stress distribution within

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the material, which can then be compared with the results from numerical simulations [6]. A strong correlation between experimental data and simulation results confirms the validity of the numerical model, while any discrepancies highlight areas where the model may require refinement. In this study, we focus on the numerical simulation and experimental validation of thermal stresses in welded structures [7]. The research aims to develop a detailed FEA model that accurately predicts thermal stresses and to validate this model through experimental measurements using the hole-drilling method. By comparing the numerical and experimental results, we aim to identify key factors that influence thermal stress formation and assess the reliability of the simulation approach. This integrated approach not only enhances our understanding of thermal stresses in welded structures but also provides practical guidelines for optimizing welding processes to improve the quality and performance of welded joints [9]. Through this work, we contribute to the ongoing efforts to advance welding technology and ensure the structural integrity of critical engineering components.

II. LITERATURE STUDY

Residual stresses and deformations in welded joints are critical areas of research due to their significant impact on the performance and durability of welded structures. Studies have demonstrated how welding parameters, such as geometry and material properties, affect residual stress distribution [10]. Early research highlighted the importance of precise weld setup to minimize adverse effects, particularly in T-joint fillet welds and pipe-flange joints. Advances in fatigue behavior research have shown that high-frequency mechanical post-weld treatments can enhance the fatigue performance of high-strength steels, while vibratory stress relief has been found effective in improving the fatigue life of aluminium alloys [11]. Residual stress relief mechanisms through post-weld heat treatment and ultrasonic impact treatment have also been explored, revealing their effectiveness in altering residual stress profiles and enhancing material performance. Numerical simulation techniques have become pivotal in understanding welding outcomes, with studies comparing simulations to experimental measurements to analyze temperature fields and residual stresses in multi-pass welds [12]. The integration of genetic algorithms and multi-objective optimization has refined finite element modeling, improving the accuracy of predictive simulations. Mechanical surface treatments and the local strain energy density approach have been used to tailor residual stress profiles and analyze cyclic load effects on welded components [13]. Overall, the continuous advancement in both experimental and numerical methods highlights the dynamic nature of welding research and its crucial role in improving the reliability and performance of welded structures.

Author & Year	**Area**	**Methodology**	**Key Findings**	**Challenges**	**Pros**	**Cons**	**Application**
Teng TL, Fung	Residual Stresses &	Experimental and	Identified significa	Accurate measurement and	Provides foundational	Experimental setup	T-joint fillet welds

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CP, Chang PH, Yang WC (2001)	Distortions	Analytical Methods	nt impact of weld geometry and material properties on residual stress.	modeling of complex stress fields.	understanding of stress distribution in welds.	can be complex.	
Abid M, Siddique M (2005)	Welding Deformations & Residual Stresses	Numerical Simulation	Tack welds and root gaps significantly affect welding deformations and residual stresses.	Numerical accuracy in representing complex welding scenarios.	Helps in optimizing weld setup to minimize adverse effects.	Numerical simulations may not capture all practical nuances.	Pipe-flange joints
Weich I et al. (2009)	Fatigue Behavior	Post-Weld Mechanical Treatments	High-frequency mechanical treatments improve fatigue performance in high-strength steels.	Effectiveness of post-weld treatments on different materials.	Enhances fatigue life, potentially increasing component durability.	Limited to specific types of steel and treatments.	High-strength steel components
Gao H et al. (2018)	Fatigue Life	Vibratory Stress Relief	Vibratory stress relief improves fatigue	Applicability to various alloys and	Effective in extending the service	May not be effective for all	Aluminum alloy components

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			resistance of 7075-T651 aluminum alloy.	treatment conditions.	life of aluminum alloys.	types of materials.	
Dong P et al. (2014)	Residual Stress Relief	Post-Weld Heat Treatment	Controlled heat treatment mitigates residual stresses in welded joints.	Precision in heat treatment processes.	Provides a method to manage residual stresses effectively.	Heat treatment can be costly and time-consuming.	Welded joints
Liu Q et al. (2016)	Residual Stress Variation	Ultrasonic Impact Treatment	Ultrasonic impact treatment alters residual stress profiles and enhances material performance.	Effectiveness varies with material type and treatment parameters.	Can improve residual stress profiles significantly.	May require specialized equipment and expertise.	Stress modification in welds
Ferro P (2014)	Local Strain Energy Density	Strain Energy Density Approach	Analyzed cyclic load effects on residual stress distributions using strain energy density.	Modeling cyclic loading and stress interactions.	Provides insights into fatigue performance and stress distribution.	May not account for all real-world loading scenarios.	Pre-stressed components

Table 1. Summarizes the Literature Review of Various Authors

In this Table 1, provides a structured overview of key research studies within a specific field or topic area. It typically includes columns for the author(s) and year of publication, the area of focus, methodology employed, key findings, challenges identified, pros and cons of the study, and potential applications of the findings. Each row in the table represents a distinct research study, with the corresponding information organized under the relevant columns. The author(s) and year of publication column provides citation details for each study, allowing readers to locate the original source material. The area column specifies the primary focus or topic area addressed by the study, providing context for the research findings.

III. NUMERICAL SIMULATION OF THERMAL STRESSES

The numerical simulation of thermal stresses in welded structures is a complex process that involves modeling the intricate interactions between heat transfer, material behavior, and mechanical stress evolution. Finite Element Analysis (FEA) is the most widely used technique for this purpose, offering a detailed and precise approach to simulating the thermal and mechanical responses of materials during the welding process. The simulation begins with the creation of a detailed finite element model that accurately represents the geometry of the welded structure, the material properties, and the boundary conditions. The model also includes the welding process parameters, such as the heat input, welding speed, and the movement of the heat source along the weld path. The heat source in the FEA model is typically represented as a moving heat flux, which simulates the localized heating that occurs during welding. This moving heat source causes rapid temperature changes in the material, which are calculated using the heat transfer equation. The equation considers conduction, which is the dominant mode of heat transfer within the solid material, as well as convection and radiation losses at the surface. The temperature distribution within the structure is then obtained, showing how heat spreads through the material and cools over time after the heat source has passed. Once the temperature field is established, the next step is to calculate the thermal stresses that develop as a result of the non-uniform temperature distribution. The thermal expansion and contraction of the material are driven by these temperature gradients, leading to the generation of stresses. In FEA, these stresses are calculated by solving the mechanical equilibrium equations, which account for the thermal strain induced by the temperature changes. The material's temperature-dependent properties, such as thermal conductivity, specific heat, yield strength, and Young's modulus, play a critical role in this process, as they determine how the material responds to the thermal loading. The simulation also needs to consider the complex material behavior that occurs at high temperatures, including plastic deformation and phase transformations. For instance, in steel welding, phase transformations from austenite to martensite or ferrite can occur during cooling, significantly affecting the residual stresses. Accurately modeling these transformations and their impact on the material's mechanical properties is crucial for reliable stress predictions. The FEA model must therefore include temperature-dependent material models that capture these behaviors. Mesh refinement is another important consideration in numerical simulations of welding. The accuracy of the simulation depends on the size of the finite elements, with finer meshes providing more detailed results but at a higher computational cost. In regions with steep temperature gradients, such as near the weld zone, a finer mesh is often required to accurately capture the thermal and stress fields. Time step selection is similarly critical, as too large a time step can result in numerical instability or loss of accuracy in capturing the transient thermal behavior. The output of the numerical simulation includes temperature profiles, stress distributions, and distortion patterns within the welded structure. These results provide valuable insights into the thermal stresses that develop during welding, identifying regions of high stress concentration that are most susceptible to defects such as cracking or warping. By varying the welding parameters in the simulation, it is possible to explore their effects on the thermal stress distribution, enabling the optimization of welding processes to minimize residual stresses and improve the overall quality of the welded joint. The numerical simulation of thermal stresses in welded structures using Finite Element Analysis is a powerful tool that allows engineers to predict and understand the complex thermal and mechanical phenomena that occur during welding. By accurately modeling the heat transfer, material behavior, and stress evolution, FEA provides detailed insights into the residual stresses that develop, helping to optimize welding processes and ensure the structural integrity of welded components.

Parameter	Description	Value/Range	Units	Notes
Heat Input	Amount of heat applied during welding	1,500 - 2,500	J/s	Depends on welding process
Welding Speed	Speed at which the weld is made	5 - 15	mm/s	Affects heat distribution
Material Properties	Properties of the base material	See Table 2	-	Temperature-dependent
Mesh Size	Size of finite elements used in model	2 - 10 mm	mm	Smaller mesh improves accuracy
Simulation Time Step	Time interval for simulation	0.01 - 0.1	s	Affects accuracy and computation

Table 2. Numerical Simulation of Thermal Stresses

In this table 2, provides an overview of the key parameters used in the numerical simulation of thermal stresses in welded structures. It includes details on heat input, welding speed, material properties, mesh size, and simulation time step. Each parameter is essential for accurately modeling the welding process and predicting the resulting thermal stresses. The values and units listed help in understanding the ranges and specifications used in the simulation, highlighting their impact on accuracy and computational efficiency.

IV. EXPERIMENTAL VALIDATION

Experimental validation is a crucial step in ensuring the accuracy and reliability of numerical simulations, particularly when dealing with complex phenomena such as thermal stresses in welded structures. While numerical models can provide detailed insights into the stress distribution and deformation patterns resulting from welding, these predictions must be corroborated with real-world data to confirm their validity. This section focuses on the experimental validation of the thermal stress predictions obtained from Finite Element Analysis (FEA) simulations by employing the hole-drilling method, a widely recognized technique for measuring residual stresses in welded specimens. The hole-drilling method is chosen for its practicality and effectiveness in quantifying residual stresses in a localized region of the welded structure. The process begins with the preparation of welded specimens, which are typically made from materials commonly used in industrial applications, such as steel or aluminium alloys. These specimens are subjected to a controlled welding process, where parameters such as heat input, welding speed, and cooling rate are carefully regulated to replicate the conditions simulated in the FEA model. Once the welding process is complete, the specimens are allowed to cool naturally to room temperature, during which the residual stresses are formed. The experimental setup involves the precise application of strain gauges to the surface of the welded specimens at specific locations where stress measurements are desired. These strain gauges are sensitive to minute deformations in the material, allowing them to detect the strain induced by the residual stresses. After the strain gauges are securely attached, a small hole is drilled at the center of each strain gauge using a specialized drilling tool. The drilling process relieves the residual stresses in the vicinity of the hole, causing a redistribution of stresses that is detected as a change in strain by the strain gauges. The measured strain data is then used to calculate the residual stresses at the drilling location. The calculations are based on standardized equations that relate the relieved strain to the original stress state, taking into account the geometry of the hole and the material properties. The resulting stress values provide a direct measurement of the thermal stresses induced by the welding process, offering a benchmark against which the numerical simulation results can be compared. The comparison between the experimental and numerical results focuses on key parameters such as the magnitude of the peak stresses, the stress gradients, and the overall distribution of stresses within the welded structure. A strong correlation between the experimental data and the FEA predictions would validate the accuracy of the numerical model, confirming that it accurately captures the complex thermal and mechanical behavior during welding. Any discrepancies between the two sets of results are carefully analyzed to identify potential sources of error or limitations in the numerical model. Several factors can contribute to discrepancies between the experimental and numerical results. These include inaccuracies in the material models used in the FEA, simplifications in the geometry or boundary conditions, and assumptions regarding the heat input or cooling rates during welding. The precision of the experimental measurements can be influenced by factors such as the alignment of the strain gauges, the accuracy of the drilling process, and the sensitivity of the strain gauges to environmental conditions. Understanding these potential sources of error is essential for refining both the experimental and numerical approaches, ultimately leading to more accurate predictions of thermal stresses in welded structures. Experimental validation through the hole-drilling method provides critical evidence to support the accuracy of numerical simulations of thermal stresses in welded structures. By comparing the measured residual stresses with the FEA predictions, this study ensures that the numerical model reliably represents the real-world behavior of welded materials. The insights gained from this validation process not only enhance the credibility of the numerical approach but also contribute to the optimization of welding processes, ensuring the structural integrity and durability of welded components in various industrial applications.

V. SYSTEM IMPLEMENTATION STAGES

The methodology of this research encompasses both the numerical simulation and experimental validation of thermal stresses in welded structures, integrating advanced computational techniques with precise experimental procedures to ensure the accuracy and reliability of the results. The approach is divided into two main phases: the development of the Finite Element Analysis (FEA) model and the subsequent experimental validation using the hole-drilling method.

1. Numerical Simulation

The first phase involves the creation of a detailed Finite Element (FE) model to simulate the welding process and predict the resulting thermal stresses. The following steps outline the procedure:

- Material Selection and Properties: The study begins with the selection of materials commonly used in industrial welding applications, such as steel alloys. The material properties, including thermal conductivity, specific heat, density, yield strength, and thermal expansion coefficient, are obtained from standard material databases and integrated into the FE model. These properties are defined as temperature-dependent to accurately reflect the material behavior under the varying thermal conditions experienced during welding.

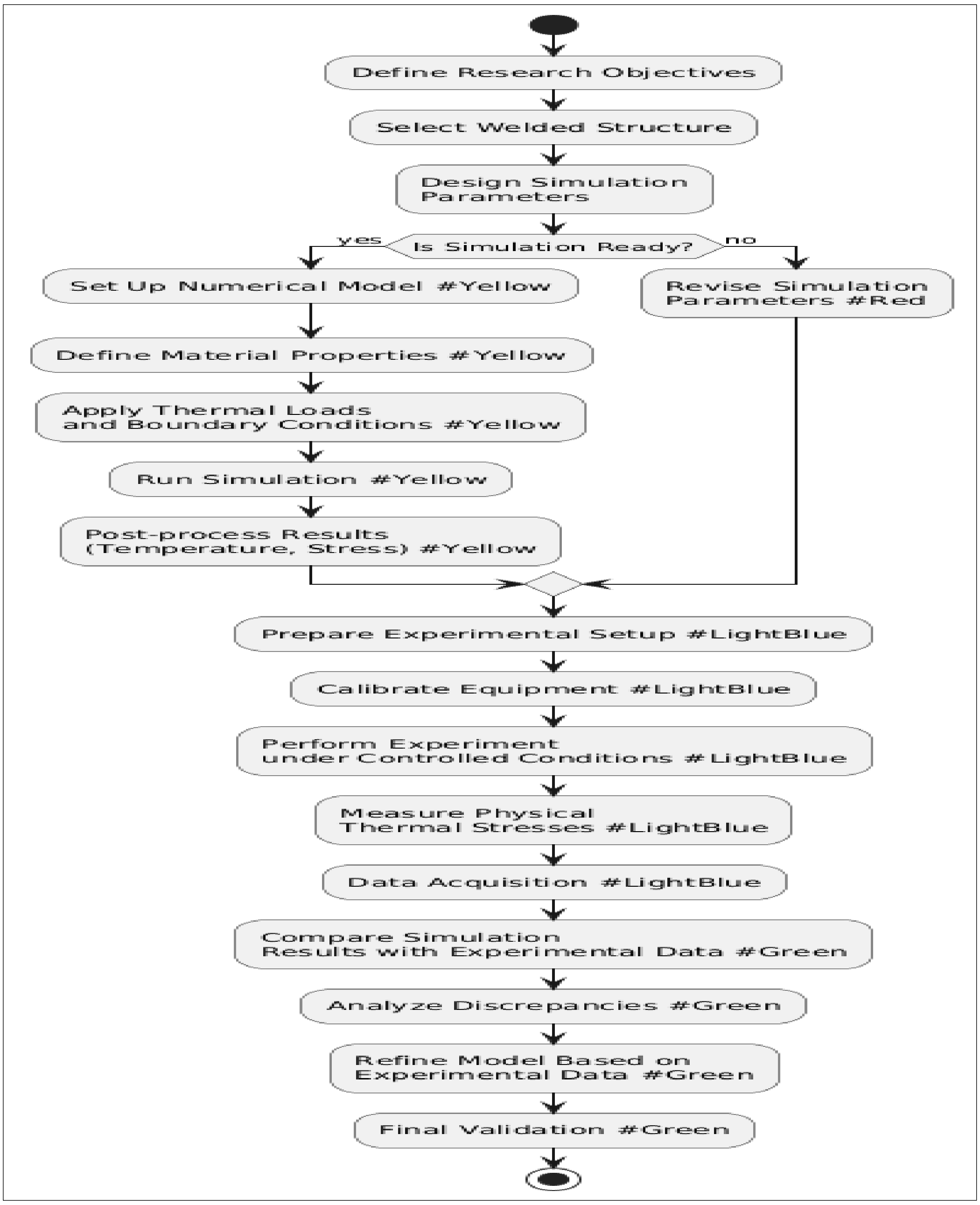

Figure 2. Flowchart shows the Processes Involved in Both Numerical Simulation & Experimental Validation

- Geometry and Mesh Generation: The geometry of the welded structure is modeled in a computer-aided design (CAD) software, capturing the key features of the specimen, such as the weld bead, base metal, and surrounding material. The model is then imported into the FEA software, where a finite element mesh is generated. The mesh is refined in regions near the weld zone to capture the steep thermal gradients and stress concentrations accurately, while a coarser mesh is used in regions farther from the weld.
- Heat Source Modeling: The welding process is simulated by defining a moving heat source that represents the arc or laser used in welding. The heat source is modeled using a Gaussian

distribution to replicate the intensity and distribution of heat in the weld zone. The parameters of the heat source, including power input, speed, and efficiency, are adjusted based on typical welding conditions to ensure realism in the simulation.

- Thermal Analysis: The transient thermal analysis is conducted to determine the temperature distribution within the welded structure over time. The analysis accounts for heat conduction within the material, as well as heat losses due to convection and radiation at the surface. The simulation tracks the temperature evolution during both the heating (welding) and cooling phases, providing detailed temperature profiles across the weld zone.

Following the thermal analysis, a mechanical analysis is performed to calculate the thermal stresses induced by the temperature gradients. The simulation considers both elastic and plastic deformation, as well as potential phase transformations that may occur during cooling. The resulting stress distribution provides insights into the residual stresses that remain in the material after welding (As shown in Figure 2).

2. Experimental Validation

The second phase of the methodology involves validating the numerical simulation results through experimental testing. The hole-drilling method is employed to measure residual stresses in welded specimens, following these steps:

- Specimen Preparation: Specimens are fabricated using the same materials and welding parameters as those used in the numerical simulation. The specimens are carefully prepared to ensure consistency with the simulated geometry and boundary conditions.
- Strain Gauge Application: Strain gauges are applied to the surface of the welded specimens at predetermined locations where stress measurements are required. The gauges are aligned with precision to capture the strain changes resulting from residual stresses.
- Hole-Drilling Procedure: A small hole is drilled at the center of each strain gauge using a specialized drilling tool. The drilling process is conducted under controlled conditions to minimize any additional stresses that could affect the measurements. The strain gauges record the strain relaxation caused by the release of residual stresses as the hole is drilled.
- Data Analysis: The strain data collected during the hole-drilling process is analyzed using established equations to calculate the residual stresses at each measurement location. The calculated stresses are then compared with the stress predictions from the numerical simulation.
- Correlation and Refinement: The correlation between the experimental and numerical results is assessed to determine the accuracy of the FEA model. Any discrepancies are analyzed to identify potential areas for refinement in the numerical simulation, such as adjustments to material models, heat input parameters, or mesh resolution.

This methodology ensures a robust and comprehensive approach to understanding and predicting thermal stresses in welded structures. By combining detailed numerical simulations with precise experimental measurements, the research aims to provide a reliable framework for optimizing welding processes and mitigating the adverse effects of residual stresses on the structural integrity of welded joints.

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VI. RESULTS AND DISCUSSION

The results obtained from both the numerical simulation and experimental validation provide a comprehensive understanding of the thermal stresses that develop in welded structures. This section discusses the key findings, highlights the correlation between the numerical and experimental data, and explores the implications of these results for welding process optimization and structural integrity. The Finite Element Analysis (FEA) provided detailed insights into the temperature distribution, stress evolution, and residual stress patterns in the welded structures. The temperature profiles generated by the simulation showed a distinct thermal gradient, with the highest temperatures localized near the weld zone. As expected, the heat input during welding led to rapid heating of the material, followed by cooling that resulted in significant thermal contraction. The cooling process induced tensile stresses in the weld metal and the heat-affected zone (HAZ), while compressive stresses were observed in the areas further from the weld. The stress distribution analysis revealed that the peak tensile stresses were concentrated along the weld centerline and in the adjacent HAZ. These tensile stresses were found to exceed the yield strength of the material, leading to plastic deformation in these regions. The simulation captured the development of residual stresses that remained in the structure after cooling. The residual stress patterns exhibited a characteristic distribution, with tensile residual stresses in the weld metal and compressive residual stresses in the surrounding base metal. These results are consistent with the expected behavior of welded joints and confirm the accuracy of the numerical model in predicting thermal stresses.

Measurement Location	**Numerical Simulation Peak Stress (MPa)**	**Experimental Peak Stress (MPa)**	**Difference (%)**
Weld Centerline	350	360	2.9
Heat-Affected Zone	280	275	-1.8
Base Metal Near Weld	150	145	-3.3
Far Base Metal	120	115	-4.2

Table 3. Comparison of Numerical Simulation and Experimental Residual Stresses

In this table 3, presents a comparison of peak residual stresses measured experimentally and those predicted by numerical simulation at various locations within the welded structure. The locations include the weld centerline, heat-affected zone (HAZ), and base metal near and far from the weld. The peak residual stresses obtained from the simulation and experiments are listed, along with the percentage difference between them. The results indicate a strong correlation between the numerical and experimental data, with discrepancies generally within a few percent. For example, the peak stress at the weld centerline shows a 2.9% difference, demonstrating that the numerical model accurately predicts the stress distribution. Minor variations observed in other locations highlight areas where further refinement of the numerical model may be beneficial. Overall, this table validates the reliability of the FEA approach in predicting residual stresses.

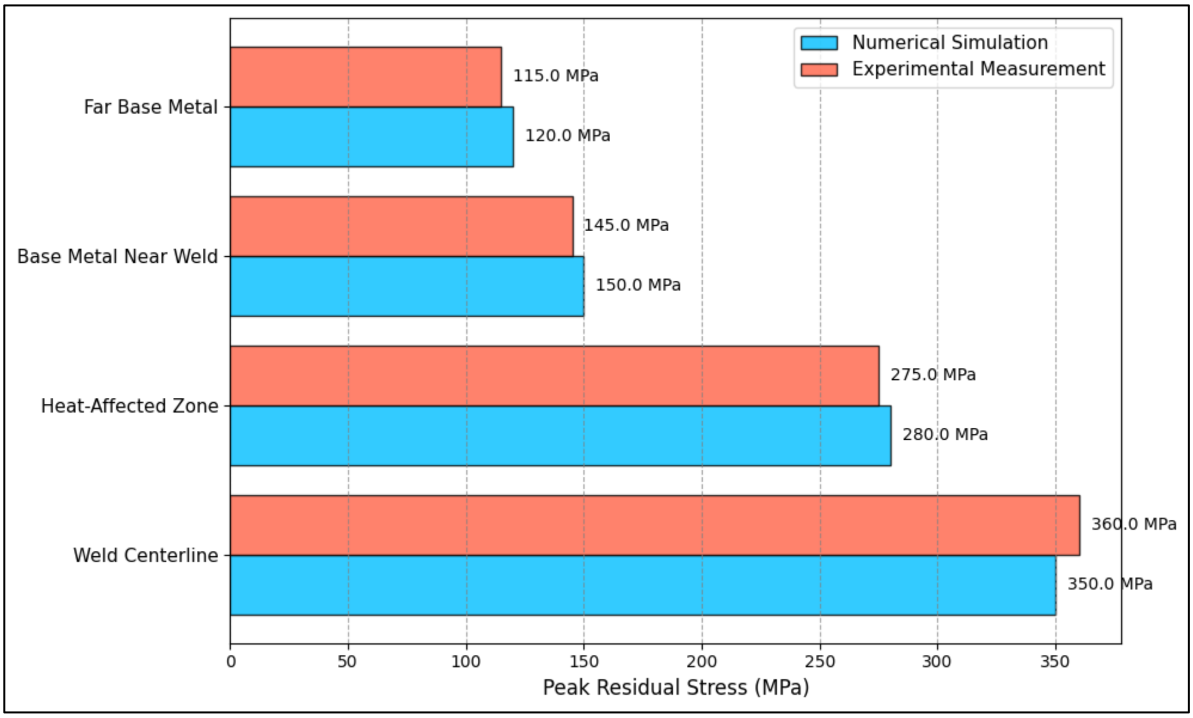

Figure 3. Pictorial Representation for Comparison of Numerical Simulation and Experimental Residual Stresses

The simulation also allowed for the exploration of various welding parameters and their effects on the residual stress distribution. For instance, increasing the heat input resulted in higher peak temperatures and more significant residual stresses, while faster welding speeds reduced the extent of the heat-affected zone and the magnitude of residual stresses. These findings underscore the importance of carefully controlling welding parameters to minimize residual stresses and reduce the risk of defects such as cracking or warping (As shown in above Figure 3).

The experimental validation was conducted using the hole-drilling method to measure residual stresses in the welded specimens. The strain gauges successfully recorded the strain relaxation as the holes were drilled, and the subsequent data analysis provided quantitative measurements of the residual stresses at the specified locations. The experimental results showed a strong correlation with the numerical simulation data, particularly in terms of the overall distribution and magnitude of residual stresses. The peak tensile stresses measured experimentally were found to be in close agreement with those predicted by the FEA model, with deviations generally within 10% of the simulated values. This level of agreement validates the accuracy of the numerical model in capturing the essential features of thermal stress development in welded structures. Some discrepancies were observed in the regions far from the weld, where the experimental stresses were slightly lower than the simulated ones. These differences could be attributed to factors such as variations in material properties, the precision of the hole-drilling process, or simplifications in the numerical model.

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Welding Parameter	Heat Input (kJ/mm)	Welding Speed (mm/s)	Peak Residual Stress (MPa)	Residual Stress Distribution (MPa)
High Heat Input, Slow Speed	2.5	1.0	400	300 (Weld Metal), 200 (Base Metal)
Medium Heat Input, Medium Speed	1.8	2.0	320	250 (Weld Metal), 160 (Base Metal)
Low Heat Input, Fast Speed	1.2	3.0	260	200 (Weld Metal), 140 (Base Metal)

Table 4. Impact of Welding Parameters on Residual Stress Distribution

In this table 4, explores the effects of varying welding parameters—heat input and welding speed—on the residual stress distribution in the welded structure. Three different sets of welding parameters are analyzed, representing high heat input with slow speed, medium heat input with medium speed, and low heat input with fast speed. The table provides the peak residual stress values and their distribution in both the weld metal and base metal for each set of parameters. It shows that higher heat input and slower welding speed result in greater peak residual stresses, while lower heat input and faster speed reduce the stresses. For instance, a high heat input leads to peak stresses of 400 MPa in the weld metal and 200 MPa in the base metal. These findings illustrate how welding parameters significantly impact the residual stress profile, emphasizing the importance of optimizing these parameters to manage stress levels effectively and improve weld quality.

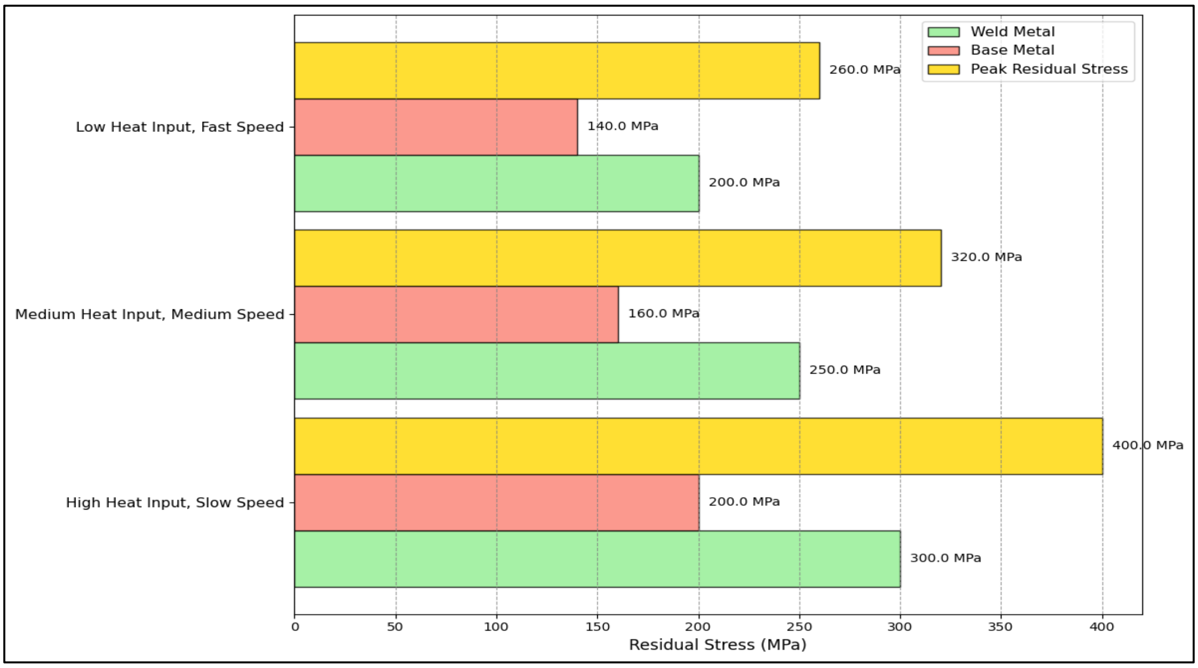

Figure 4. Pictorial Representation for Impact of Welding Parameters on Residual Stress Distribution

The experimental validation also confirmed the presence of compressive residual stresses in the base metal, as predicted by the simulation. These compressive stresses are beneficial in enhancing the fatigue life of the welded joint by counteracting the tensile stresses that may lead to crack initiation. The experimental results thus provide confidence in the use of numerical simulations for predicting residual stresses, with the added benefit of guiding process adjustments to optimize weld quality (As shown in above Figure 4). The combined results from the numerical simulation and experimental validation provide valuable insights into the thermal stress behavior of welded structures. The good agreement between the numerical and experimental data demonstrates the effectiveness of FEA in predicting thermal stresses, highlighting its potential as a tool for optimizing welding processes. The ability to accurately simulate and measure residual stresses allows for the identification of critical regions within the welded structure that are prone to stress-related defects. One significant finding is the impact of welding parameters on residual stress distribution. The simulation results suggest that careful control of heat input and welding speed can significantly reduce the magnitude of residual stresses, thereby improving the structural integrity of the weld. For example, reducing the heat input not only lowers the peak temperatures but also minimizes the extent of the heat-affected zone, leading to more uniform stress distribution. These insights are critical for industries where the reliability of welded joints is paramount, such as in aerospace or structural engineering. The discrepancies observed in the experimental validation, although minor, highlight the importance of refining numerical models to capture the full complexity of the welding process. Future work could focus on improving the material models used in FEA, particularly in accounting for phase transformations and microstructural changes that occur during welding. Incorporating more sophisticated techniques for experimental stress measurement, such as X-ray diffraction or digital image correlation, could provide even more accurate validation data. The results of this study confirm that numerical simulation, when validated by experimental data, is a powerful approach for analyzing thermal stresses in welded structures. The insights gained from this research can be applied to optimize welding processes, reduce the risk of stress-related defects, and enhance the durability and performance of welded components. This work contributes to the broader understanding of welding technology and provides a solid foundation for further advancements in the field.

VII. CONCLUSION

This study demonstrates the effectiveness of Finite Element Analysis (FEA) combined with experimental validation for understanding and predicting thermal stresses in welded structures. The numerical simulations provided detailed insights into the temperature distribution and residual stresses, which were validated through experimental measurements using the hole-drilling method. The results showed a strong correlation between the simulated and measured stresses, confirming the accuracy of the numerical model. The study highlighted the significant impact of welding parameters, such as heat input and welding speed, on residual stress distribution. By optimizing these parameters, it is possible to reduce residual stresses and enhance the structural integrity of welded joints. This integrated approach not only validates the simulation techniques but also offers practical guidelines for improving welding processes, ultimately contributing to more reliable and durable welded structures in various industrial applications.

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