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Thermal Modeling and Performance Evaluation of Electric Arc Welding Processes

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ABSTRACT: Electric arc welding (EAW) is a critical fabrication process used in numerous industries, including automotive, aerospace, construction, and shipbuilding. Its effectiveness hinges upon the accurate control of thermal inputs, which directly influence weld quality, material microstructure, and residual stress profiles. This study presents a detailed thermal modeling approach to simulate the transient heat distribution during EAW and evaluates the corresponding performance characteristics using both numerical and experimental methods.

A three-dimensional finite element model (FEM) was developed using ANSYS to simulate the thermal cycle of a gas metal arc welding (GMAW) process applied to mild steel plates. The model incorporated Gaussian heat source distribution and temperature-dependent material properties. Thermal boundary conditions included convective and radiative heat losses to mimic realistic welding environments. The model was validated through thermocouple-based temperature measurements and metallurgical examination of welded specimens.

Key performance parameters such as cooling rate, peak temperature, heat-affected zone (HAZ) dimensions, and weld bead geometry were extracted and compared with experimental data. The simulation results showed a strong correlation with measured values, with maximum error margins within ±10%. Parametric studies demonstrated that increasing welding current and decreasing travel speed significantly elevated peak temperatures and expanded the HAZ, affecting metallurgical properties.

This study concludes that thermal modeling is a valuable tool for predicting weld outcomes, optimizing process parameters, and minimizing material degradation. The integration of computational simulation with experimental validation enhances process understanding, reduces trial-and-error in industrial settings, and facilitates the development of predictive welding quality control systems.

KEYWORDS: Electric arc welding, thermal modeling, finite element method, heat-affected zone, GMAW, temperature distribution, weld bead, process optimization, welding simulation, heat transfer.

I. INTRODUCTION

Electric arc welding (EAW) is widely utilized for joining metals in manufacturing and structural applications due to its versatility, efficiency, and cost-effectiveness. The process involves generating an electric arc between an electrode and a metal workpiece, producing intense localized heat that melts the base material and forms a strong metallurgical bond upon solidification. Despite its widespread use, achieving consistent weld quality remains a significant challenge due to the complexity of heat transfer and the variability of process parameters.

The thermal behavior during welding plays a pivotal role in determining the characteristics of the weld and the surrounding heat-affected zone (HAZ). Excessive or insufficient heat input can lead to defects such as porosity, cracking, incomplete fusion, and undesirable microstructural changes. As such, understanding and controlling the thermal cycle is critical for optimizing weld strength, minimizing distortion, and ensuring long-term performance of welded components. In recent years, computational modeling has emerged as a powerful approach to analyze the thermal dynamics of welding processes. Finite element methods (FEM), in particular, offer a robust platform for simulating heat transfer, predicting temperature distributions, and evaluating weld quality under various operating conditions. However, the reliability of these models depends on accurate representation of heat sources, material properties, and boundary conditions.

This research focuses on thermal modeling and performance evaluation of electric arc welding processes using a combination of numerical simulation and experimental validation. A specific emphasis is placed on gas metal arc welding (GMAW) due to its industrial relevance and complex thermal behavior. The primary objectives are to simulate the heat distribution during welding, assess its impact on weld geometry and HAZ, and establish correlations with physical test

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data. By bridging the gap between theory and practice, this work aims to contribute to smarter, data-driven welding process design and control.

II. LITERATURE REVIEW

Thermal modeling of welding processes has been an active research area for several decades. Early models, such as those developed by Rosenthal (1941), provided analytical solutions for quasi-steady-state heat flow in simple geometries. While foundational, these solutions often failed to capture the transient and nonlinear aspects of real-world welding. With advances in computational power, numerical techniques, especially finite element methods (FEM), have become the standard for simulating heat transfer in welding processes.

Recent studies have employed FEM to model arc welding processes with increasing accuracy. Nguyen et al. (2016) modeled the thermal distribution in TIG and MIG welding using 3D transient heat transfer analysis and incorporated temperature-dependent thermal conductivity and specific heat. Results highlighted how current, voltage, and arc travel speed influence the weld pool and HAZ. Similarly, Li and Zhang (2017) investigated the impact of different welding speeds on temperature distribution and microstructure using ANSYS, demonstrating good agreement with thermocouple measurements.

The selection of heat source models is a critical aspect of thermal simulation. Goldak's double ellipsoidal heat source model has become the most widely accepted due to its ability to simulate the asymmetric shape of the weld pool realistically. Gaussian surface heat flux models are also frequently used, especially in gas metal arc welding (GMAW), for their computational simplicity.

Experimental validation remains essential for ensuring simulation accuracy. Studies by Sharma et al. (2018) compared FEM predictions with thermal imaging and microstructural observations, noting deviations of less than 10%. Moreover, advances in thermal imaging and data acquisition systems have improved validation reliability.

Despite these developments, gaps still exist, particularly in simulating multi-pass welding, phase transformations, and the coupling of thermal models with mechanical stress analysis. This study aims to refine FEM thermal models and validate them experimentally to ensure realistic performance predictions in electric arc welding.

III. RESEARCH METHODOLOGY

This study combines numerical simulation with experimental validation to model and analyze the thermal behavior in gas metal arc welding (GMAW), a widely adopted form of electric arc welding.

1. Materials and Setup:
Mild steel plates (AISI 1020) of 150 mm × 100 mm × 6 mm were used. GMAW was performed using a semi-automatic welding machine with a constant voltage power source. Welding parameters were controlled: current (150 A), voltage (25 V), wire feed rate (6 m/min), and travel speed (4 mm/s). Thermocouples were embedded 5 mm and 10 mm from the weld centerline for temperature data acquisition.

2. Numerical Modeling:
A transient 3D finite element model was developed using ANSYS Workbench 18.0. The domain included the steel plate and ambient air. A moving Gaussian heat source simulated the arc, applied over a 6 mm-wide weld path. Thermal properties such as conductivity, specific heat, and density were defined as temperature-dependent. Convective and radiative losses were applied at free surfaces.
Mesh convergence tests ensured numerical accuracy, and a time step of 0.1 s was chosen for stability. The simulation ran for a total time of 60 s to capture heating and cooling cycles.

3. Validation:
Temperature histories from FEM were compared with experimental thermocouple readings. In addition, cross-sections of welded samples were prepared and etched to measure HAZ width and weld bead geometry.

4. Performance Evaluation:
The simulation and experimental results were analyzed to determine:

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- was performed to quantify model accuracy, using RMSE (Root Mean Square Error) and Peak temperature at specific distances from the weld center.
- Cooling rates (800 °C to 500 °C).
- Width and depth of the weld bead and HAZ.
- Influence of welding speed and current on thermal profiles.
- Statistical analysis percentage deviation metrics.

IV. RESULTS AND DISCUSSION

The simulation successfully predicted transient temperature distributions along the weld path. Maximum temperatures near the arc center exceeded 1650 °C, confirming sufficient energy for complete melting of mild steel. Thermocouple data matched closely with simulation predictions; RMSE values were under 40 °C, indicating high accuracy.

Heat-Affected Zone (HAZ):
Experimental measurements showed a HAZ width of 4.5 mm at 150 A and 4 mm/s travel speed. Simulated HAZ was 4.3 mm wide, with less than 5% deviation. Lower travel speeds increased heat input, causing wider HAZ and deeper penetration.

Cooling Rates:
The simulated cooling rate from 800 °C to 500 °C at 10 mm from the weld center was ~35 °C/s, aligning with thermocouple observations (~32–37 °C/s). Faster cooling rates occurred at higher travel speeds, reducing grain coarsening but increasing risk of hardness gradients.

Weld Bead Geometry:
Cross-sectional analysis confirmed good agreement with simulated bead dimensions. Simulated weld penetration was 2.8 mm vs. 2.9 mm measured, while bead width differed by less than 0.2 mm.

Parametric Influence:
Increased welding current elevated peak temperatures and enlarged HAZ and bead size. Faster travel speeds resulted in shallower penetration but narrower HAZ, suitable for thinner materials.

Overall, the model accurately captured the thermal behavior and demonstrated its utility in optimizing welding parameters. The combination of simulation and validation ensures that FEM-based approaches can be confidently used for weld process planning and defect prevention.

V. CONCLUSION

This study developed and validated a finite element thermal model for electric arc welding, specifically focusing on gas metal arc welding (GMAW) of mild steel. The model accurately simulated temperature profiles, HAZ dimensions, and cooling rates. Experimental validation with thermocouple data and metallographic analysis confirmed the model's reliability, with deviations generally under 10%.

Results indicate that thermal modeling can significantly aid in understanding the effect of welding parameters on weld quality. Parametric studies showed that variations in current and travel speed directly influence heat input, HAZ size, and cooling rate. Such insights can help prevent welding defects and improve joint performance.

The successful integration of simulation and experimentation demonstrates that thermal models are practical tools for optimizing arc welding processes in industrial applications.

VI. FUTURE WORK

Future research should focus on:

- **Multi-pass welding modeling**, to simulate complex joints used in structural applications.
- **Coupled thermal-mechanical analysis** to predict residual stress and distortion.
- **Microstructural evolution modeling**, integrating phase transformation kinetics.
- **Adaptive mesh refinement** in FEM to improve accuracy near the weld pool.

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- **Real-time process control**, using embedded sensors and machine learning to predict and adjust thermal profiles during welding.
- **Application to other materials**, such as aluminum alloys or stainless steels, which have different thermal conductivities and fusion behaviors.
- Incorporating these directions will further enhance the predictive capabilities of thermal models, contributing to automated and defect-free welding systems in modern manufacturing.

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