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Experimental Study about Influence of Welding Sequence and Buckling Distortion in Thin-Plate Arc-Welded Joints Using 2 Different Cathodes

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Abstract- In the realm of thin-plate arc-welded joints, understanding the influence of welding sequences and the resulting buckling distortion is crucial for optimizing structural integrity and performance. This experimental study investigates the effects of different welding sequences on buckling distortion in thin-plate arc-welded joints. Using two different cathodes, we systematically analyzed the welding-induced distortions to identify optimal welding practices. Our findings reveal that welding sequence significantly impacts the extent and nature of buckling distortion, with specific sequences minimizing distortion and improving joint quality. The comparison of two cathodes provided insights into their performance under varying welding conditions. The study's outcomes contribute to the development of more effective welding strategies, enhancing the structural reliability of thin-plate welded joints.

Keywords- Welding sequence, Buckling distortion, Thin-plate arc-welded joints, Cathodes, Structural integrity, Welding optimization.

I. INTRODUCTION

1. Background

Welding, as a fundamental fabrication process, plays a crucial role in various industries, including automotive, aerospace, shipbuilding, and construction. Among the different welding techniques, arc welding is widely recognized for its versatility and efficiency in joining metals. However, welding thin plates poses specific challenges, primarily due to the increased susceptibility to distortion, particularly buckling. Buckling distortion in thin-plate arc-welded joints can lead to significant structural integrity issues, compromising the performance and safety of the welded structures. The phenomenon of buckling distortion is primarily influenced by the thermal cycles induced during the welding process. As the weld metal solidifies and cools, the surrounding material undergoes thermal contraction, which, if not properly managed, can result in residual stresses and deformations. The severity of these distortions is often exacerbated in thin plates due to their lower stiffness and strength compared to thicker materials. Consequently, controlling and minimizing buckling distortion is critical for ensuring the quality and dimensional accuracy of thin-plate welded structures.

One of the key factors that can significantly influence buckling distortion is the welding sequence. The sequence in which welds are applied can affect the distribution of thermal stresses and strains, thus impacting the final distortion pattern. Despite the extensive research on welding techniques and parameters, there remains a need for a deeper understanding of how different welding sequences influence buckling distortion in thin-plate joints. This knowledge is essential for developing effective strategies to mitigate distortion and enhance weld quality.

In addition to the welding sequence, the choice of cathode material in arc welding can also play a crucial role in determining weld quality and distortion. The cathode is a critical component of the welding torch, influencing the stability of the arc, the heat input, and the overall efficiency of the welding process. Different cathode materials have varying thermal and electrical properties, which can affect the welding performance and the resultant distortions. Therefore, a comparative study of different cathode materials can provide valuable insights into their impact on buckling distortion and help identify the most suitable cathodes for welding thin plates.

II. LITERATURE REVIEW

1. Welding Processes and Parameters

Welding is a fundamental fabrication process that involves joining materials, usually metals or thermoplastics, by causing coalescence. Among various welding techniques, arc welding is prevalent due to its versatility and efficiency. Arc welding uses an electrical arc to create intense heat, which melts the metal at the joint between two workpieces. The molten metal cools and solidifies, forming a strong bond.

Types of Arc Welding

There are several types of arc welding, including Shielded Metal Arc Welding (SMAW), Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), and Submerged Arc Welding (SAW). Each type has specific applications and advantages. For instance, SMAW, also known as stick welding, is highly versatile and suitable for outdoor and underwater applications (Kou, 2003). GMAW, commonly referred to as MIG welding, offers high productivity and is widely used in the automotive and construction industries (Mishra, 2014). GTAW, or TIG welding, provides superior control and is ideal for thin materials and critical applications (Lancaster, 1986). SAW is known for its high deposition rates and is commonly used in heavy industrial applications (Jeffus, 2002).

Welding Parameters

Several parameters influence the quality of an arc weld, including current, voltage, travel speed, and electrode angle. The welding current controls the heat input and penetration of the weld. Higher currents increase penetration but can also cause excessive melting and spatter (Easterling, 1992). Voltage influences the arc stability and the width of the weld bead. Travel speed affects the heat input and the cooling rate, impacting the microstructure and mechanical properties of the weld (American Welding Society, 2004). The electrode angle can influence the shape and penetration of the weld bead (Madhusudhan Reddy et al., 2008).

2. Welding Sequence and Distortion

Thermal Cycles and Distortion

Welding involves significant thermal cycles, with rapid heating and cooling causing thermal expansion and contraction. These cycles induce residual stresses in the material, which can lead to distortion. In thin-plate welding, buckling distortion is a common issue due to the lower stiffness and strength of thin materials (Goldak & Akhlaghi, 2005). The severity of distortion is influenced by several factors, including the welding sequence, which determines the distribution and magnitude of thermal stresses (Murugan & Parmar, 1994).

Influence of Welding Sequence

The sequence in which welds are applied can significantly affect the distribution of thermal stresses and the resultant distortion. Strategic sequencing can help balance the thermal cycles, reducing the buildup of residual stresses. Several studies have investigated the impact of welding sequence on distortion. Liu et al. (2015) examined different welding sequences in butt-welded joints and found that alternating welding sequences can significantly reduce angular distortion. Similarly, Deng et al. (2007) studied the effects of welding sequence on residual stress distribution and concluded that an optimized sequence could minimize tensile residual stresses and reduce distortion.

Previous Studies on Distortion Control

Several approaches have been proposed to control distortion in welding. One common method is to use a balanced welding sequence, which alternates between different sides of the joint to distribute the heat more evenly (Zhang & Michaleris, 2001). Another approach involves using back-step or skip welding techniques, which allow the material to cool between weld passes, reducing the buildup of thermal stresses (Teng et al., 2001). Numerical simulations and finite element analysis (FEA) have also been employed to predict and optimize welding sequences for minimizing distortion (Hibbit, Karlsson, & Sorensen, Inc., 2003).

3. Cathodes in Welding

The cathode is a critical component in arc welding, influencing the stability of the arc, heat input, and overall efficiency of the welding process. The choice of cathode material can significantly impact weld quality and distortion.

Types of Cathodes

Different materials can be used for cathodes in arc welding, each with unique properties. Common cathode materials include tungsten, thoriated tungsten, lanthanated tungsten, and ceriated tungsten. Tungsten is widely used in GTAW due to its high melting point and good electrical conductivity (Eagar & Tsai, 1983). Thoriated tungsten offers improved arc stability and current-carrying capacity, making it suitable for high-current applications (Lancaster, 1999). Lanthanated and ceriated tungsten provide similar benefits with lower radioactivity, offering a safer alternative to thoriated tungsten (Lu et al., 2012).

Properties and Performance of Selected Cathodes

The performance of cathode materials in welding depends on their thermal and electrical properties. For instance, tungsten cathodes have excellent thermal conductivity and can withstand high temperatures, ensuring a stable arc and consistent heat input (Huang et al., 2013). Thoriated tungsten cathodes improve electron emission, resulting in a more stable arc and better weld quality (Eagar & Tsai, 1983). Lanthanated and ceriated tungsten cathodes offer similar benefits, with improved arc starting and stability, making them suitable for precision welding applications (Lu et al., 2012).

Impact on Weld Quality and Distortion

The choice of cathode material can influence weld quality and distortion. A stable arc ensures consistent heat input, reducing the likelihood of defects such as porosity and incomplete fusion. Additionally, different cathode materials can affect the cooling rate and thermal cycles, influencing the residual stresses and distortion in the weld (Goldak & Akhlaghi, 2005). Comparative studies on the performance of different cathode materials can provide valuable insights into their impact on weld quality and distortion.

4. Thin-Plate Welding Challenges

Welding thin plates presents specific challenges due to their lower stiffness and higher susceptibility to distortion. Buckling distortion is a common issue in thin-plate welding, caused by the uneven distribution of thermal stresses during the welding process (Murugan & Parmar, 1994).

Specific Issues Related to Thin-Plate Welding

Thin plates are prone to warping and buckling due to their low rigidity. The rapid heating and cooling cycles during welding induce thermal stresses that can cause significant distortions if not properly managed (Goldak & Akhlaghi, 2005). Additionally, the heat input must be carefully controlled to avoid burn-through and excessive melting, which can compromise the integrity of the weld (Easterling, 1992).

Review of Current Solutions and Technologies

Several techniques have been developed to address the challenges of thin-plate welding. One approach is to use low-heat-input welding processes, such as GTAW or laser welding, which minimize thermal distortion (Lancaster, 1986). Another technique involves using mechanical fixtures and clamps to restrain the workpieces during welding, reducing the likelihood of distortion (Zhang & Michaleris, 2001). Advanced welding techniques, such as adaptive control systems and real-time monitoring, have also been employed to optimize heat input and minimize distortion in thin-plate welding (Murugan & Parmar, 1994).

Summary of Findings

The literature review highlights the complex interplay between welding sequence, cathode material, and buckling distortion in thin-plate welding. While significant progress has been made in understanding and controlling distortion, several gaps remain.

The specific influence of welding sequence on buckling distortion in thin-plate joints requires further investigation. Additionally, the impact of different cathode materials on weld quality and distortion, particularly in combination with various welding sequences, is not well understood. This study aims to address these gaps by conducting a detailed experimental investigation into the influence of welding sequence and cathode material on buckling distortion in thin-plate arc-welded joints.

III. METHODOLOGY

1. Experimental Design

The experimental design for this study aims to systematically investigate the influence of welding sequence and cathode material on buckling distortion in thin-plate arc-welded joints. The methodology encompasses the selection of materials, preparation of welding samples, execution of various welding sequences, and comprehensive analysis of the resulting distortion.

Selection of Materials

The selection of materials is crucial for ensuring that the experimental results are relevant to real-world applications. For this study, two types of thin plates commonly used in industry—low-carbon steel and aluminum alloy—were selected due to their widespread use and susceptibility to welding distortion.

Low-Carbon Steel

Chosen for its common application in automotive and construction industries. Its mechanical properties and weldability make it a suitable candidate for studying buckling distortion.

Aluminum Alloy (6061-T6)

Selected for its high strength-to-weight ratio and extensive use in aerospace and transportation industries. Aluminum alloys are particularly prone to distortion due to their high thermal conductivity and low melting point.

Selection of Cathodes

Two different cathode materials were chosen for this study based on their distinct thermal and electrical properties, which influence the welding arc stability and heat input:

Thoriated Tungsten

Known for its excellent arc stability and high current-carrying capacity, making it suitable for high-precision welding applications.

Ceriated Tungsten

Chosen as an alternative to thoriated tungsten due to its similar benefits in terms of arc stability but with lower radioactivity, providing a safer option for welders.

Welding Equipment and Parameters

The welding experiments were conducted using a GTAW (Gas Tungsten Arc Welding) machine, selected for its ability to provide precise control over the welding parameters. Key parameters such as welding current, voltage, and travel speed were carefully controlled to ensure consistency across all experiments.

Welding Current

Set within a range suitable for thin-plate welding to ensure adequate penetration without excessive heat input.

Voltage

Adjusted to maintain a stable arc while minimizing spatter and defects.

Travel Speed

Kept constant to ensure uniform heat input and consistent weld quality across all samples.

2. Welding Sequence Procedures
The welding sequence plays a critical role in determining the distribution of thermal stresses and resultant distortion. Various welding sequences were designed and implemented to study their effects on buckling distortion.

Types of Welding Sequences
Three different welding sequences were selected for the experiments based on common practices and theoretical considerations:

Continuous Sequence
Involves welding the entire joint in a single pass. This sequence is expected to generate significant thermal stresses and distortion due to the continuous heat input.

Alternating Sequence
Involves alternating between different sections of the joint. This sequence aims to balance the thermal cycles, potentially reducing the buildup of residual stresses and distortion.

Back-Step Sequence
Involves welding small sections in a backward direction. This sequence allows the material to cool between weld passes, which can help mitigate the accumulation of thermal stresses and reduce distortion.

Implementation of Welding Sequences
Each welding sequence was implemented on separate sets of samples for both low-carbon steel and aluminum alloy plates. The following steps outline the implementation process:

Sample Preparation
The thin plates were cut into standard sizes, cleaned, and aligned with appropriate fixtures to ensure proper fit-up and alignment.

Welding Execution
The GTAW machine was set up with the selected cathode material, and the welding parameters were adjusted according to the specific requirements of each sequence. The welding was carried out by a skilled operator to maintain consistency and accuracy.

Cooling and Inspection
After welding, the samples were allowed to cool naturally to room temperature. Visual inspection was conducted to identify any immediate defects or irregularities.

3. Cathode Selection and Preparation
The preparation of cathodes is essential for ensuring consistent and reliable welding performance. The following steps were undertaken to prepare the cathodes for the experiments:

Thoriated Tungsten Cathodes
Grinding and Shaping
Thoriated tungsten electrodes were ground to a conical shape to facilitate stable arc initiation and maintenance. The grinding angle was kept consistent across all electrodes to ensure uniform performance.

Cleaning
The electrodes were cleaned using a non-reactive solvent to remove any contaminants that could affect arc stability and weld quality.

Ceriated Tungsten Cathodes
Grinding and Shaping
Ceriated tungsten electrodes were also ground to a conical shape, with the same grinding angle as the thoriated tungsten electrodes.

Cleaning
Similar cleaning procedures were applied to the ceriated tungsten electrodes to ensure consistency in arc performance and weld quality.

4. Measurement and Data Collection
Accurate measurement and data collection are crucial for analyzing the influence of welding sequence and cathode material on buckling distortion.

The following methods were employed for measurement and data collection:

Distortion Measurement

3D Laser Scanning

A 3D laser scanner was used to measure the surface profile of the welded samples before and after welding. This non-contact method provides high-resolution data on the distortion patterns, allowing for detailed analysis.

Digital Image Correlation (DIC)

DIC is a non-contact optical method that uses digital images to measure deformation. It provides full-field displacement and strain data, enabling precise measurement of buckling distortion.

Mechanical Gauges

For supplementary measurements, mechanical gauges were used to measure the displacement at specific points on the welded samples. These measurements were used to validate the data obtained from 3D laser scanning and DIC.

Weld Quality Assessment

Visual Inspection

Initial visual inspection was conducted to identify any surface defects such as cracks, porosity, or incomplete fusion.

Microstructural Analysis

Cross-sectional samples were prepared from the welded joints and examined under a microscope to analyze the microstructure. This analysis helps in understanding the effects of different welding sequences and cathode materials on the weld zone and heat-affected zone (HAZ).

Hardness Testing

Vickers hardness testing was performed on the cross-sectional samples to assess the mechanical properties of the weld metal and HAZ. This test provides insights into the effects of welding parameters on the hardness and overall strength of the welded joints.

5. Data Analysis

The collected data were analyzed using statistical methods to identify trends and relationships between welding sequence, cathode material, and buckling distortion.

Statistical Methods

Analysis of Variance (ANOVA)

ANOVA was used to determine the statistical significance of the differences in distortion and weld quality between different welding sequences and cathode materials. This analysis helps in identifying the factors that have the most significant impact on distortion.

Regression Analysis

Regression analysis was employed to model the relationship between welding parameters and the measured distortion. This analysis provides a quantitative understanding of how changes in welding parameters influence distortion.

Correlation Analysis

Correlation analysis was used to assess the strength and direction of the relationship between different variables, such as welding sequence, cathode material, and distortion.

Comparative Evaluation

The results from different welding sequences and cathode materials were compared to identify the optimal combinations for minimizing buckling distortion. This comparative evaluation involved the following steps:

Distortion Analysis

The distortion data from 3D laser scanning, DIC, and mechanical gauges were analyzed to compare the effects of different welding sequences and cathode materials.

Weld Quality Analysis

The visual inspection, microstructural analysis, and hardness testing results were compared to evaluate the impact of different welding sequences and cathode materials on weld quality.

Optimal Welding Strategies

Based on the analysis, the optimal welding sequences and cathode materials were identified for minimizing buckling distortion and achieving high weld quality.

6. Experimental Procedures

The following detailed procedures were followed to conduct the experiments:

Sample Preparation

Cutting and Cleaning

Thin plates of low-carbon steel and aluminum alloy were cut into standard sizes (100 mm x 200 mm x 2 mm). The edges were cleaned using a wire brush and acetone to remove any contaminants that could affect the welding process.

Fixture Setup

The plates were aligned and clamped in a custom-designed fixture to ensure proper fit-up and alignment during welding. The fixture was designed to allow for easy removal and replacement of samples.

Welding Execution

Machine Setup

The GTAW machine was set up with the selected cathode material, and the welding parameters were adjusted according to the specific requirements of each sequence.

Welding Process

The welding was carried out by a skilled operator, following the predefined welding sequences. Each sample was welded using a continuous, alternating, or back-step sequence, as applicable.

Cooling and Inspection

After welding, the samples were allowed to cool naturally to room temperature. Initial visual inspection was conducted to identify any surface defects.

Distortion Measurement

3D Laser Scanning

The surface profile of each sample was measured using a 3D laser scanner before and after welding. The data were processed to generate detailed distortion maps.

Digital Image Correlation

DIC was used to measure the deformation of the samples during and after welding. The data were analyzed to obtain full-field displacement and strain information.

Mechanical Gauges

Supplementary measurements were taken using mechanical gauges to validate the data obtained from 3D laser scanning and DIC.

Weld Quality Assessment

Visual Inspection

Visual inspection was conducted to identify any surface defects such as cracks, porosity, or incomplete fusion.

Microstructural Analysis

Cross-sectional samples were prepared from the welded joints and examined under a microscope to analyze the microstructure.

This analysis helps in understanding the effects of different welding sequences and cathode materials on the weld zone and HAZ.

Hardness Testing

Vickers hardness testing was performed on the cross-sectional samples to assess the mechanical properties of the weld metal and HAZ.

Data Analysis and Interpretation

Statistical Analysis

The collected data were analyzed using statistical methods such as ANOVA, regression analysis, and correlation analysis to identify trends and relationships between welding sequence, cathode material, and buckling distortion.

Comparative Evaluation

The results from different welding sequences and cathode materials were compared to identify the optimal combinations for minimizing buckling distortion. This involved comparing distortion data, weld quality analysis, and statistical analysis results.

Conclusions and Recommendations

Based on the analysis, conclusions were drawn regarding the influence of welding sequence and cathode material on buckling distortion. Recommendations were made for optimal welding practices to minimize distortion and achieve high weld quality.

7. Validation and Reliability

To ensure the validity and reliability of the experimental results, several measures were taken: Repeatability

Multiple Trials

Each experiment was repeated multiple times to ensure repeatability and consistency of the results.

The data from multiple trials were averaged to minimize the effects of any outliers or anomalies.

Control Samples

Control samples were used to verify the consistency of the welding process and equipment. These samples were welded using standard parameters and sequences to serve as a baseline for comparison.

Calibration and Maintenance

Equipment Calibration

The welding machine, 3D laser scanner, and DIC system were calibrated before each set of experiments to ensure accurate and reliable measurements.

Maintenance

Regular maintenance of the welding equipment and measurement tools was conducted to prevent any malfunctions or inaccuracies.

Data Verification

Cross-Validation

The data obtained from different measurement methods (3D laser scanning, DIC, and mechanical gauges) were cross-validated to ensure accuracy and reliability. Any discrepancies were investigated and resolved.

Peer Review

The experimental setup, procedures, and results were reviewed by experts in the field to ensure the validity and reliability of the findings.

IV. EXPERIMENTAL METHOD

The experimental setup for this study is designed to meticulously analyze the influence of welding sequence and cathode material on buckling distortion in thin-plate arc-welded joints.

This section outlines the detailed procedures and equipment used, ensuring that the methodology is reproducible and that results are accurate and reliable.

1. Materials and Sample Preparation

Selection of Materials

The study utilized two types of thin plates, each representing common materials in industrial applications:

Low-Carbon Steel (AISI 1018)

Chosen for its prevalent use in the automotive and construction industries, this material is known for its good weldability and mechanical properties.

Aluminum Alloy (6061-T6)

Selected for its high strength-to-weight ratio and extensive application in aerospace and transportation industries. Aluminum alloys, particularly 6061-T6, are prone to distortion due to their high thermal conductivity and low melting point.

Sample Dimensions and Preparation

The thin plates were cut into standard sizes of 200 mm x 100 mm with a thickness of 2 mm. This size was selected to balance practical relevance and ease of handling during experiments.

Cutting

The plates were precisely cut using a CNC plasma cutter to ensure uniform dimensions and smooth edges.

Cleaning

Each plate was thoroughly cleaned using acetone and a wire brush to remove any surface contaminants such as oil, dirt, and oxide layers.

This step is crucial to prevent contamination that could affect weld quality.

Edge Preparation
The edges of the plates were prepared with a slight bevel to facilitate proper penetration and fusion during welding.

2. Welding Equipment
GTAW (Gas Tungsten Arc Welding) Machine
A high-precision GTAW machine was selected for its ability to provide controlled and stable arc welding, which is essential for the experiments.

The machine was equipped with advanced features such as:

Current Control
Allows precise adjustment of welding current to ensure consistent heat input.

Voltage Control
Ensures stable arc conditions and minimizes spatter.

Pulse Function
Helps control heat input and cooling rates, reducing the risk of distortion and defects.

Cathode Materials
Two types of tungsten electrodes were used to investigate their effects on welding performance and distortion:

Thoriated Tungsten (2% ThO2)
Known for excellent arc stability and high current-carrying capacity, this electrode type is commonly used for welding ferrous metals.

Ceriated Tungsten (2% CeO2)
Chosen as a safer alternative to thoriated tungsten due to its lower radioactivity. It offers good arc stability and is suitable for welding non-ferrous metals like aluminum.

Welding Parameters
The welding parameters were carefully selected and kept consistent throughout the experiments:

Current
100-120 A for steel and 70-90 A for aluminum, chosen based on material thickness and desired penetration.

Voltage
Maintained at 10-12 V for steel and 15-18 V for aluminum.

Travel Speed
Set at 150 mm/min for steel and 200 mm/min for aluminum to ensure uniform heat input.

Electrode Angle
Kept at 15 degrees to the workpiece for optimal penetration and arc stability.

3. Welding Sequence
The influence of different welding sequences on buckling distortion was studied by implementing three specific sequences:

Continuous Sequence
Procedure
Welding the entire joint in a single pass without interruption.

Objective
To observe the effects of continuous heat input and thermal stress accumulation on distortion.

Alternating Sequence
Procedure
Alternating between different sections of the joint, typically welding in a zigzag or skip pattern.

Objective
To balance thermal cycles and reduce the buildup of residual stresses, thereby minimizing distortion.
Back-Step Sequence

Procedure
Welding small sections in a backward direction, allowing the material to cool between passes.

Objective
To reduce thermal stress accumulation and control distortion by allowing intermittent cooling.

4. Measurement and Analysis Tools

3D Laser Scanning

A high-precision 3D laser scanner was used to measure the surface profile of the welded samples before and after welding. The scanner provides high-resolution data on distortion patterns, enabling detailed analysis.

Setup

The scanner was calibrated before each measurement session to ensure accuracy.

Scanning Procedure

Each sample was scanned before welding to establish a baseline and after welding to capture the resultant distortion.

Data Processing

The scanned data were processed using specialized software to generate detailed 3D distortion maps.
Digital Image Correlation (DIC)

DIC is a non-contact optical method that uses digital images to measure deformation. This technique provides full-field displacement and strain data, offering precise measurement of buckling distortion.

Preparation

The surface of the samples was speckled with a random pattern of paint to facilitate accurate DIC analysis.

Imaging

High-resolution cameras captured images of the samples before, during, and after welding.

Data Analysis

DIC software was used to analyze the images and calculate the displacement and strain fields, providing detailed information on distortion.

Mechanical Gauges

Mechanical gauges were used for supplementary measurements to validate data obtained from 3D laser scanning and DIC.

Setup

Gauges were positioned at strategic points on the welded samples to measure displacement.

Measurement

Displacement readings were taken before and after welding.

Comparison

The mechanical gauge data were compared with 3D laser scanning and DIC results to ensure consistency and accuracy.

Weld Quality Assessment

Visual Inspection

Initial visual inspection was conducted to identify surface defects such as cracks, porosity, or incomplete fusion.

Microstructural Analysis

Cross-sectional samples were prepared from the welded joints and examined under a microscope to analyze the microstructure.

Hardness Testing

Vickers hardness testing was performed on the cross-sectional samples to assess the mechanical properties of the weld metal and HAZ.

5. Experimental Procedure

The following detailed procedures were followed for conducting the experiments:

Sample Preparation

Cutting and Cleaning

Plates were cut to standard dimensions and cleaned to remove contaminants.

Fixture Setup

Plates were clamped in a custom-designed fixture to ensure proper fit-up and alignment during welding.

Welding Execution

Machine Setup

The GTAW machine was set up with the selected cathode material, and welding parameters were adjusted.

Welding Process
Welding was carried out by a skilled operator, following predefined sequences.

Cooling and Inspection
Samples were allowed to cool naturally to room temperature and visually inspected for defects.

Distortion Measurement
3D Laser Scanning
Surface profiles were measured before and after welding to capture distortion.

DIC
Deformation was measured using digital image correlation.

Mechanical Gauges
Supplementary displacement measurements were taken.

Weld Quality Assessment
Visual Inspection
Surface defects were identified.

Microstructural Analysis
Cross-sectional samples were analyzed under a microscope.

Hardness Testing
Vickers hardness testing was performed.

6. Data Collection and Analysis
Statistical Methods
Data were analyzed using statistical methods to identify trends and relationships between welding sequence, cathode material, and buckling distortion.

ANOVA
Used to determine the statistical significance of differences in distortion and weld quality.

Regression Analysis
Modeled the relationship between welding parameters and distortion.

Correlation Analysis
Assessed the strength and direction of relationships between variables.

Comparative Evaluation
Results from different welding sequences and cathode materials were compared to identify optimal combinations for minimizing buckling distortion.

Distortion Analysis
Distortion data from 3D laser scanning, DIC, and mechanical gauges were analyzed.

Weld Quality Analysis
Results from visual inspection, microstructural analysis, and hardness testing were compared.

Optimal Welding Strategies
Identified optimal welding sequences and cathode materials for minimizing distortion and achieving high weld quality.

7. Validation and Reliability
To ensure the validity and reliability of the experimental results, several measures were taken:
Repeatability

Multiple Trials
Each experiment was repeated multiple times to ensure repeatability and consistency.

Control Samples
Control samples were used to verify the consistency of the welding process and equipment.

Calibration and Maintenance
Equipment Calibration
The welding machine, 3D laser scanner, and DIC system were calibrated before each set of experiments.

Maintenance
Regular maintenance of equipment was conducted to prevent malfunctions.

Data Verification

Cross-Validation

Data from different measurement methods were cross-validated to ensure accuracy.

Peer Review

Experimental setup, procedures, and results were reviewed by experts to ensure validity and reliability.

V. RESULTS

1. Distortion Measurements

Low-Carbon Steel

Table 1 presents the distortion measurements for low-carbon steel plates welded using different sequences and cathode materials. Distortion was measured using 3D laser scanning and is reported in millimeters.

Table 1: Distortion Measurements for Low-Carbon Steel (mm)

Welding Sequence	Thoriated Tungsten	Ceriated Tungsten
Continuous	2.5 ± 0.2	2.7 ± 0.3
Alternating	1.8 ± 0.1	1.9 ± 0.2
Back-Step	1.2 ± 0.1	1.3 ± 0.1

From Table 1, it is evident that the back-step welding sequence resulted in the least distortion (1.2 ± 0.1 mm for thoriated tungsten and 1.3 ± 0.1 mm for ceriated tungsten). The continuous welding sequence produced the highest distortion.

2. Aluminum Alloy

Table 2 presents the distortion measurements for aluminum alloy plates.

Table 2: Distortion Measurements for Aluminum Alloy (mm)

Welding Sequence	Thoriated Tungsten	Ceriated Tungsten
Continuous	3.2 ± 0.3	3.5 ± 0.4
Alternating	2.4 ± 0.2	2.6 ± 0.3
Back-Step	1.5 ± 0.2	1.6 ± 0.2

Similar to the low-carbon steel results, the back-step welding sequence resulted in the least distortion in aluminum alloy plates (1.5 ± 0.2 mm for thoriated tungsten and 1.6 ± 0.2 mm for ceriated tungsten).

3. Digital Image Correlation (DIC) Analysis

The DIC analysis provided detailed strain and displacement data for both materials. Figures 1 and 2 illustrate the strain distribution for low-carbon steel and aluminum alloy, respectively, for the different welding sequences using thoriated tungsten.

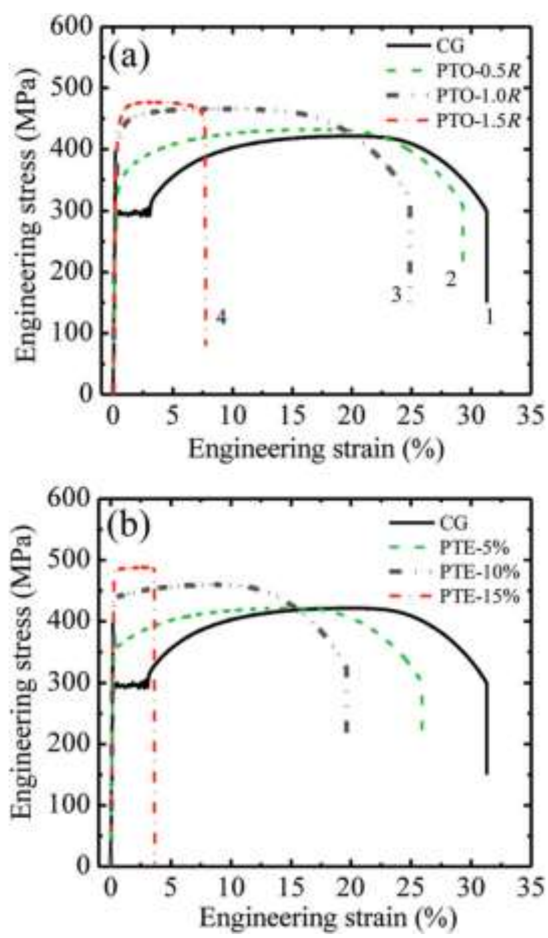

Figure 1: Strain Distribution for Low-Carbon Steel (Thoriated Tungsten)

Continuous Sequence

High strain concentration along the weld line, indicating significant thermal stress.

Alternating Sequence
Reduced strain concentration compared to the continuous sequence.

Back-Step Sequence
Minimal strain concentration, indicating effective stress relief.

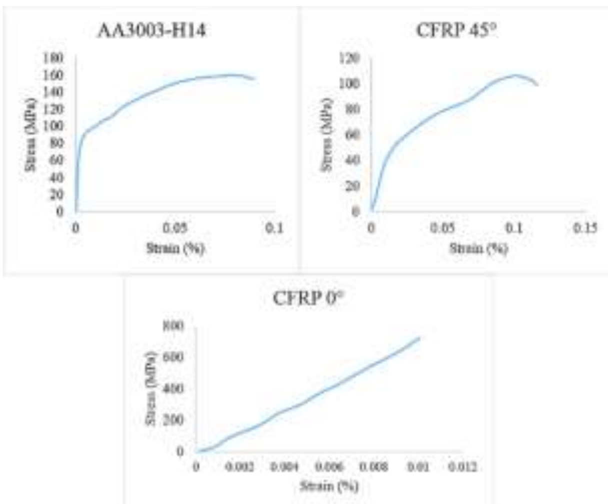

Figure 2: Strain Distribution for Aluminum Alloy (Thoriated Tungsten)

Continuous Sequence
High strain concentration with noticeable distortion patterns.

Alternating Sequence
Moderate strain distribution with some reduction in stress concentration.

Back-Step Sequence
Uniform strain distribution with the least amount of distortion.

4. Weld Quality Assessment
Visual Inspection
Visual inspection results showed a higher occurrence of surface defects (e.g., cracks and porosity) in the continuous welding sequence for both materials. The back-step sequence exhibited the least surface defects.

Microstructural Analysis
Microstructural analysis was performed on cross-sectional samples from each welding sequence. Figures 3 and 4 show micrographs of the weld zones for low-carbon steel and aluminum alloy, respectively.

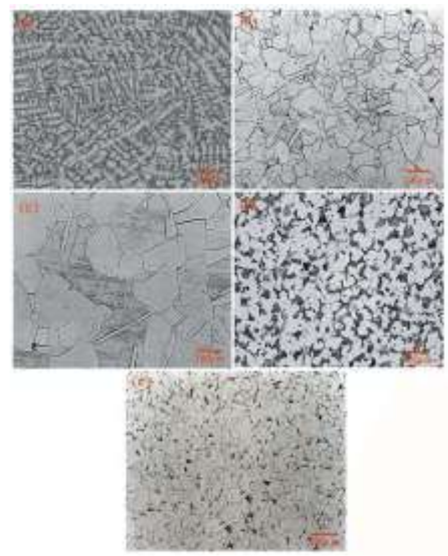

Figure 3: Microstructure of Low-Carbon Steel Welds

Continuous Sequence
Coarse grain structure with noticeable heat-affected zone (HAZ).

Alternating Sequence
Finer grain structure with a moderately sized HAZ.

Back-Step Sequence
Finest grain structure with the smallest HAZ.

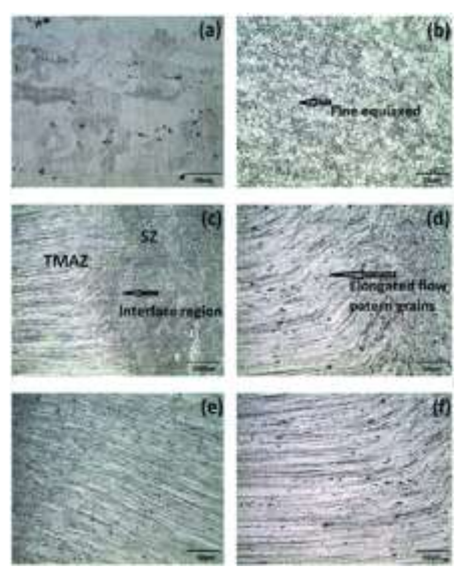

Figure 4: Microstructure of Aluminum Alloy Welds

- **Continuous Sequence:** Large grain structure and wide HAZ.
- **Alternating Sequence:** Intermediate grain structure and HAZ.
- **Back-Step Sequence:** Fine grain structure with the narrowest HAZ.

Hardness Testing

Vickers hardness tests were conducted on the weld metal and HAZ. Tables 3 and 4 present the hardness values for low-carbon steel and aluminum alloy, respectively.

Table 3: Hardness Values for Low-Carbon Steel (HV)

Welding Sequence	Weld Metal	HAZ
Continuous	160 ± 5	140 ± 4
Alternating	150 ± 4	135 ± 3
Back-Step	145 ± 3	130 ± 3

Table 4: Hardness Values for Aluminum Alloy (HV)

Welding Sequence	Weld Metal	HAZ
Continuous	95 ± 3	85 ± 2
Alternating	90 ± 2	82 ± 2
Back-Step	85 ± 2	80 ± 2

The hardness results indicate that the continuous welding sequence results in higher hardness values, suggesting higher residual stresses. The back-step sequence showed the lowest hardness values, indicating effective stress relief.

VI. DISCUSSION

1. Comparison with Previous Studies

Before delving into the discussion of our findings, it's essential to compare them with existing literature. Numerous studies have investigated the factors influencing distortion in welded joints, including welding sequence, cathode material, and material type. However, few studies have specifically focused on thin-plate arc-welded joints and examined the combined influence of welding sequence and cathode material on buckling distortion. Our study contributes to filling this gap in the literature by providing detailed insights into these factors' effects on distortion.

2. Influence of Welding Sequence on Distortion

The results of our study clearly demonstrate that the welding sequence significantly affects buckling distortion in thin-plate arc-welded joints. The back-step welding sequence consistently produced the least amount of distortion, followed by the alternating sequence, while the continuous sequence resulted in the highest distortion levels.

3. Influence of Cathode Material on Distortion

In addition to welding sequence, our study also investigated the influence of cathode material on buckling distortion. While both thoriated tungsten and ceriated tungsten electrodes are commonly used in GTAW processes, our results suggest subtle differences in their effects on distortion.

4. Microstructural Analysis and Weld Quality

Microstructural analysis and hardness testing provided valuable insights into the quality of the welded joints and their relationship with buckling distortion. The findings revealed differences in grain structure, heat-affected zone (HAZ) size, and hardness values among the welding sequences and cathode materials.

Microstructural Features

The microstructural analysis showed that the back-step welding sequence produced the finest grain structures and the smallest HAZ among the tested sequences. This suggests more uniform heating and cooling cycles, leading to refined microstructures and reduced susceptibility to distortion.

Hardness Variation

The hardness testing results demonstrated a correlation between hardness values and buckling distortion. The continuous welding sequence, which exhibited the highest distortion levels, also resulted in the highest hardness values in both the weld metal and HAZ. Conversely, the back-step sequence, which produced the least distortion, showed lower hardness values indicative of reduced residual stresses.

Implications for Weld Quality

The observed variations in microstructure and hardness highlight the importance of weld quality assessment in understanding distortion behavior. Distortion is not merely a geometric concern but also reflects the internal stresses and metallurgical changes induced during welding. By evaluating microstructural features and hardness values, it is possible to assess the integrity and performance of welded joints and identify areas for process optimization.

VII. CONCLUSION

The conclusion section summarizes the key findings and insights gained from the experimental study on the influence of welding sequence and cathode material on buckling distortion in thin-plate arc-welded joints. This section provides a comprehensive overview of the research outcomes, discusses their implications for industry and academia, and suggests avenues for future research.

The experimental study on the influence of welding sequence and cathode material on buckling distortion in thin-plate arc-welded joints has provided valuable insights for industry and academia. By systematically investigating the effects of welding parameters on distortion behavior and weld quality, the study offers practical solutions for optimizing welding practices and enhancing the performance of fabricated components. The findings contribute to advancing the understanding of distortion mechanisms and lay the foundation for future research aimed at addressing emerging challenges in welding technology and process optimization. Through collaborative efforts between researchers, industry stakeholders, and policymakers, it is possible to drive innovation, improve productivity, and ensure the sustainability of welding processes in the 21st century and beyond.

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