RESEARCH PAPER

COMPARATIVE INVESTIGATIONS ON THE WELD DEPTH OF PENETRATION IN ACTIVATED TIG WELDING OF STAINLESS STEEL THROUGH THE USE OF BINARY FLUX MIXTURE

R. Sakthivel[1], M. Sudhahar[2], V. Vinoth Kannan[3]

[1]Student, Department of Mechanical Engineering, PRIST Deemed to be University, Tamil Nadu, India.
Email: vel.rajame1994@gmail.com

[2]Assistant Professor, Department of Mechanical Engineering, PRIST Deemed to be University, Tamil Nadu, India.

[3]Associate Professor, Department of Mechanical Engineering, PRIST Deemed to be University, Tamil Nadu, India.

***Corresponding author: R. Sakthivel, Student, Department of Mechanical Engineering, PRIST Deemed to be University, Tamil Nadu, India.**

Email: vel.rajame1994@gmail.com

Abstract

Conventional Tungsten Inert Gas (TIG) welding is widely employed for joining stainless steel; however, its relatively shallow weld penetration often requires multiple welding passes and additional joint preparation for medium-thickness plates. Activated Tungsten Inert Gas (A-TIG) welding offers an effective alternative by employing activating fluxes to improve heat concentration within the weld zone. The present study investigates the effect of a binary oxide flux consisting of zirconium dioxide (ZrO_2) and aluminium oxide (Al_2O_3) on the weld penetration characteristics of AISI 304 austenitic stainless steel through a comparative evaluation of conventional TIG and A-TIG welding. Bead-on-plate welding experiments were carried out under identical process parameters using an automated welding system to ensure that the influence of the binary flux could be evaluated independently. The welded specimens were prepared using standard metallographic procedures, and the weld bead geometry was assessed by measuring penetration depth, bead width, and the depth-to-width ratio. The experimental observations showed that the application of the ZrO_2–Al_2O_3 binary flux produced a deeper and narrower weld profile than conventional TIG welding, indicating improved utilisation of heat within the fusion zone. The enhancement in weld geometry is attributed to the combined influence of arc constriction and the modification of molten metal flow within the weld pool. The results demonstrate that the proposed binary oxide flux is an effective approach for improving weld penetration and can contribute to more efficient single-pass welding of medium-thickness AISI 304 stainless steel components.

Keywords: Activated TIG welding (A-TIG); AISI 304 stainless steel; binary oxide flux; zirconium dioxide (ZrO_2); aluminium oxide (Al_2O_3); weld penetration; weld bead geometry; arc constriction; Marangoni convection.

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I. Introduction:

AISI 304 austenitic stainless steel is one of the most widely used engineering materials because of its excellent corrosion resistance, good mechanical strength, high ductility, and reliable performance over a broad range of operating temperatures. Owing to these properties, it is extensively employed in chemical processing equipment, power generation facilities, food and pharmaceutical industries, pressure vessels, and cryogenic applications. Since the service performance of these structures depends largely on the quality of their welded joints, selecting an appropriate welding process is essential for achieving sound metallurgical properties and long-term structural reliability.

Among the available fusion welding techniques, Gas Tungsten Arc Welding (GTAW), commonly referred to as Tungsten Inert Gas (TIG) welding, is widely preferred for joining stainless steels because it provides excellent control over heat input, produces high-quality welds, and minimises spatter and contamination. The process uses a non-consumable tungsten electrode together with an inert shielding gas, usually argon, to protect the molten weld pool from atmospheric oxidation. Although conventional TIG welding produces welds of superior quality, its application to medium- and thick-section plates is often limited by relatively shallow penetration and a wide fusion zone. The dispersed arc distributes heat over a larger surface area, reducing the current density at the weld centre. Consequently, thicker plates generally require edge preparation, multiple welding passes, and additional filler material, leading to longer production times, higher fabrication costs, greater heat input, and an increased risk of distortion.

Activated TIG (A-TIG) welding was developed to overcome these limitations without major modifications to conventional welding equipment. In this process, a thin layer of activating flux is applied to the workpiece surface before welding. During welding, the flux interacts with the arc plasma and molten metal, modifying both the electrical characteristics of the arc and the fluid flow within the weld pool. These changes promote greater heat concentration beneath the electrode, allowing significantly deeper penetration to be achieved under the same welding current and shielding conditions.

The improvement in penetration obtained during A-TIG welding is generally attributed to two complementary mechanisms. The first is **arc constriction**, in which the decomposition products of the activating flux capture electrons around the outer region of the plasma column. This reduces electrical conductivity in the peripheral region and forces the arc to contract toward its centre, thereby increasing current density and heat concentration directly below the electrode. The second mechanism involves **Marangoni convection** within the molten weld pool. During conventional TIG welding, molten metal flows from the hotter central region toward the cooler edges because the surface tension decreases with increasing temperature. This outward flow promotes wider and shallower weld beads. When suitable activating fluxes introduce surface-active elements, particularly oxygen, the surface tension behaviour changes, reversing the direction of fluid flow. The molten metal then moves inward toward the weld centre and downward into the joint, enhancing penetration while producing a narrower weld profile.

Numerous oxide-based activating fluxes, including TiO_2, SiO_2, ZrO_2, Al_2O_3, Cr_2O_3, and MnO_2, have been investigated individually for A-TIG welding. Although many of these oxides increase weld penetration compared with conventional TIG welding, each possesses distinct physical and chemical characteristics that influence arc stability, oxygen transfer, and weld pool behaviour. As a result, the performance of single-component fluxes is often inconsistent, with some formulations causing unstable arc characteristics or undesirable slag formation.

To improve overall welding performance, recent studies have focused on binary and multi-component flux systems that combine the beneficial characteristics of different oxides. Properly selected flux combinations can improve arc stability, optimise oxygen transport into the molten pool, and produce more favourable weld bead geometry than individual fluxes. Despite these developments, relatively few studies have examined the behaviour of specific binary oxide mixtures under identical welding conditions while directly comparing them with conventional TIG welding.

The present study investigates the influence of a binary activating flux composed of zirconium dioxide (ZrO_2) and aluminium oxide (Al_2O_3) on the weld bead geometry of AISI 304 stainless steel. To ensure that the observed changes result solely from the activating flux, all welding parameters—including current, travel speed, shielding gas flow rate, arc length, and torch position—were maintained constant throughout the experiments. The effectiveness of the binary flux was evaluated by measuring penetration depth, bead width, and the depth-to-width ratio using macrostructural analysis of the welded specimens.

The results of this investigation contribute to a better understanding of the role of binary oxide activating fluxes in controlling weld pool behaviour during A-TIG welding. Furthermore, the findings provide practical guidance for improving weld penetration, reducing the need for multi-pass welding, minimising thermal distortion, and enhancing productivity in the fabrication of stainless steel components used in demanding industrial applications.

1.1 Problem Statement:

Conventional Tungsten Inert Gas (TIG) welding is widely used for joining AISI 304 stainless steel because it provides clean welds and good metallurgical control. However, its inherent limitation is the wide, divergent arc profile, which typically results in limited penetration depth. As a consequence, thicker sections (above 3 mm) often require groove preparation, multiple passes, and additional filler material to achieve proper joint integrity.

Activated TIG (A-TIG) welding partially overcomes these drawbacks through the use of activating fluxes, but single-component oxide fluxes can introduce process-related issues such as unstable arc behavior, arc wandering, and slag entrapment. To address these limitations, combinations of oxide fluxes in binary form have been proposed as a way to improve weld pool stability while enhancing penetration characteristics.

However, available literature still lacks comprehensive and systematic data on how engineered binary oxide flux systems influence weld pool geometry, flow behavior, and overall weld performance. In particular, the mechanisms governing geometric evolution and fluid flow transitions under such flux combinations are not fully established. Therefore, a detailed experimental and analytical study is required to evaluate the effect of selected binary oxide fluxes on weld bead formation and to assess their capability in producing high aspect ratio weld joints.

1.2 Objectives:

- To develop and apply a binary oxide flux mixture (ZrO_2–Al_2O_3) on AISI 304 stainless steel and evaluate its suitability for automated A-TIG welding applications.
- To measure and analyze key weld bead geometry parameters, including penetration depth (D), bead width (W), and depth-to-width ratio (D/W), under controlled welding conditions.
- To compare weld joints produced using conventional TIG welding (without flux) and those produced using the proposed binary flux system in terms of geometry and macrostructure.
- To examine weld pool behavior by correlating macrostructural observations with underlying mechanisms such as arc constriction at the periphery and changes in Marangoni convection flow.
- To determine whether the selected binary flux composition achieves sufficient arc stability and improved weld geometry to support single-pass industrial welding applications.

II Literature Review:

[1] Modenesi, Apolinário, and Pereira (2000) The authors investigated the mechanisms responsible for increased penetration in A-TIG welding. Their findings showed that activating fluxes alter weld pool behavior through arc constriction and modifications in surface-tension-driven fluid flow. These effects collectively enhance heat concentration at the weld center, resulting in deeper penetration and improved bead geometry compared to conventional TIG welding.

[2] Venkatesan, Muthupandi, and Justine (2016) This study examined mono-component and multi-component activating fluxes during A-TIG welding of AISI 304L stainless steel. The results indicated that optimized flux combinations produced significantly higher penetration than single fluxes. Arc constriction was identified as the primary mechanism behind penetration improvement, emphasizing the importance of flux composition in weld quality.

[3] Kumar, Deheri, and Masanta (2019) The researchers evaluated TiO_2, Al_2O_3, and CaF_2 fluxes for bead-on-plate welding of AISI 304 stainless steel. TiO_2 produced the highest penetration and improved depth-to-width ratio, while Al_2O_3 showed moderate enhancement. The study also reported changes in microstructure and hardness, confirming that flux selection strongly influences weld characteristics.

[4] Babbar, Kumar, and Gupta (2019) This work focused on a hybrid flux system combining TiO_2, SiO_2, and Al_2O_3. The results demonstrated improved penetration, tensile strength, and microhardness compared to individual fluxes, while maintaining acceptable weld quality. The study concluded that multi-component flux systems can provide superior overall performance.

[5] Niagaj (2021)
A comparative analysis of different activating fluxes was carried out for various steels, including AISI 304L stainless steel. TiO_2 and SiO_2 consistently produced higher penetration levels than several other fluxes. The study highlighted that both flux composition and base material significantly influence weld geometry and penetration behavior.

[6] Patil et al. (2022)
The authors studied TiO_2 and Al_2O_3 fluxes in A-TIG welding of AISI 304 stainless steel. TiO_2 produced deeper penetration and improved bead shape compared to Al_2O_3. The study confirmed that activating fluxes enhance heat concentration in the weld zone without degrading weld quality, making them suitable for stainless steel fabrication.

[7] Recent studies on SiO_2–TiO_2 binary flux systems (2026)
Recent investigations on binary oxide fluxes, particularly SiO_2–TiO_2 combinations, have reported improved penetration, better bead geometry, and enhanced mechanical and corrosion properties compared to conventional TIG welding. These findings suggest that binary flux systems are a promising approach for improving productivity while maintaining weld quality in stainless steel applications.

III. Profile Analysis & Selection:

AISI 304 austenitic stainless steel was chosen as the substrate for this study due to its widespread use in high consequence engineering applications, including corrosive chemical processing environments, structural pressure containment, and sanitary fluid transport systems. While conventional TIG welding is typically used for these applications to ensure clean, high quality joints, its low inherent energy density restricts single pass depth capability. A-TIG welding addresses this limitation by using surface active compounds to focus thermal energy without demanding higher electrical inputs.

To systematically evaluate these effects, this investigation isolates an engineered binary oxide flux mixture composed of Zirconium Dioxide (ZrO2) and Aluminium Oxide (Al2O3). While historical profiles frequently leverage standalone TiO2 or SiO2 configurations, this study focuses on the synergistic interactions of a ZrO2-Al2O3 matrix to optimize arc constriction and fluid flow dynamics. Experimental trials were conducted under identical automated welding parameters, contrasting flux assisted runs directly against a fluxless conventional TIG reference baseline (S1). This approach ensures that all measured variations in macrostructural dimensions, fusion boundaries, and aspect ratios are driven entirely by the chemical composition of the applied binary flux layer.

AISI 304 austenitic stainless steel was selected as the base material for this investigation owing to its extensive application in critical engineering sectors such as corrosive chemical processing, pressure-retaining structural systems, and hygienic fluid transport infrastructure. In such applications, conventional TIG welding is commonly preferred because it produces clean and contamination-free joints. However, its relatively low power density limits the achievable penetration in a single pass. Activated TIG (A-TIG) welding overcomes this limitation by introducing surface-active compounds that concentrate thermal energy at the weld zone without increasing electrical input.

To examine this behavior in a controlled manner, the present study employs a binary oxide flux system consisting of zirconium dioxide (ZrO_2) and aluminium oxide (Al_2O_3). While earlier studies have predominantly focused on single oxides such as TiO_2 or SiO_2, this work investigates the combined effect of ZrO_2–Al_2O_3 to enhance arc constriction and modify weld pool flow behavior. All experiments were carried out using identical automated welding parameters, with direct comparison between flux-assisted welds and a flux-free conventional TIG baseline (S1). This ensures that any observed differences in bead geometry, fusion characteristics, and aspect ratio are solely attributable to the applied binary flux composition.

IV. Materials and Methods:

The experimental procedure was structured to systematically identify and quantify the geometric changes produced by the application of a binary activating flux during automated GTAW (gas tungsten arc welding). The workflow includes base material preparation, flux formulation, slurry application, controlled bead-on-plate welding, specimen sectioning, and quantitative geometric evaluation.

- **Step 1:** Plates of AISI 304 stainless steel with dimensions 150 × 75 × 6 mm were used as the base material.
- **Step 2:** Surface preparation was performed using SiC abrasive papers followed by acetone cleaning to eliminate contaminants.
- **Step 3:** A flux slurry was prepared by mixing ZrO_2 and Al_2O_3 powders with acetone as the carrier medium.
- **Step 4:** The slurry was applied uniformly over the weld track using a fine brush to ensure consistent coating thickness.
- **Step 5:** Welding was carried out using an automated A-TIG setup at 150 A, DCEN polarity, and a torch angle of 70°–80°.
- **Step 6:** After welding, the specimens were sectioned transversely for metallographic examination.
- **Step 7:** The cross-sections were etched using hydrochloric acid (HCl) to reveal weld bead morphology.
- **Step 8:** Weld geometry parameters, including penetration depth (D), bead width (W), and D/W ratio, were measured and analyzed.

All process parameters such as current, travel speed, and arc length were kept constant throughout all trials to ensure that any variation in weld profile was exclusively due to the presence of the activating flux.

4.1 Base Material:

Bead-on-plate samples measuring 150 mm × 75 mm × 6 mm were machined from commercially available AISI 304 stainless steel. This material possesses a fully austenitic microstructure and is widely used in applications requiring reliable mechanical and corrosion resistance performance. The chemical composition of the base metal is presented in Table 4.1.

Table 4.1 Chemical Composition of AISI 304 Stainless Steel

Element	Composition (wt.%)
Carbon (C)	≤0.08
Silicon (Si)	≤1.00

Manganese (Mn)	≤2.00
Phosphorus (P)	≤0.045
Sulphur (S)	≤0.030
Chromium (Cr)	18.0–20.0
Nickel (Ni)	8.0–10.5
Iron (Fe)	Balance

4.2 Selection of Activating Fluxes:

The study utilizes a binary flux system composed of zirconium dioxide (ZrO_2) and aluminium oxide (Al_2O_3). These oxides were selected based on their thermal stability, high melting points, and favorable behavior under high-temperature arc conditions.

Zirconium Dioxide (ZrO_2): ZrO_2 was chosen due to its very high melting temperature and low thermal conductivity, which contribute to arc constriction and concentration of heat at the weld center. It also influences surface tension gradients in the molten pool, promoting deeper penetration.

Aluminium Oxide (Al_2O_3): Al_2O_3 offers strong thermal resistance and assists in stabilizing molten metal flow. It helps maintain arc stability, reduces arc wandering, and supports the formation of a uniform bead profile with improved depth-to-width characteristics.

When combined, these two oxides form a synergistic binary flux system that enhances penetration depth while maintaining arc stability and overall weld quality.

Table 4.2 Selected Binary Flux Conditions

Specimen	Flux Condition
S1	Conventional TIG (No Flux)
S2	ZrO_2 + Al_2O_3 Binary Flux

4.4 Welding Equipment and Experimental Setup:

All welding experiments were conducted using an automated GTAW system operating in DCEN polarity. A 2.4 mm diameter, 2% thoriated tungsten electrode was used, prepared with a consistent tip geometry to ensure repeatability of arc characteristics. High-purity argon (99.99%) was employed as the shielding gas to prevent atmospheric contamination.

To eliminate external variability, the torch was fixed at a constant travel angle of 70°–80° relative to the plate surface. The controlled welding parameters used in the study are summarized in Table 4.3.

Table 4.3 Welding Parameters

Parameter	Value
Welding Process	Activated TIG (A-TIG)
Base Material	AISI 304 Stainless Steel
Electrode	2.4 mm, 2% Thoriated Tungsten
Polarity	DCEN
Shielding Gas	Argon (99.99%)
Welding Current	150 A
Arc Voltage	12–14 V
Travel Speed	100 mm/min
Gas Flow Rate	12–14 L/min
Arc Length	2 mm

4.5 Specimen Preparation:

Before welding, the surface of each AISI 304 plate was mechanically cleaned using silicon carbide (SiC) abrasive papers to remove oxide layers, surface irregularities, and contamination. This was followed by thorough degreasing using acetone to eliminate residual oils and organic impurities.

The binary flux was prepared by mixing equal proportions (1:1 by weight) of ZrO_2 and Al_2O_3 powders. The powders were dispersed in acetone to form a uniform slurry. This mixture was applied along the weld path using a fine brush to achieve a thin and consistent coating. The acetone was then allowed to evaporate naturally at room temperature, leaving behind a dry, adherent flux layr prior to welding.

4.6 Experimental Procedure:

The study began with conventional TIG welding (S1) to establish a baseline weld profile without flux influence. Subsequently, A-TIG welding was performed on specimen S2 using the prepared ZrO_2–Al_2O_3 flux coating. Both tests were conducted using identical welding parameters as specified in Table 4.3.

After welding, the samples were allowed to cool naturally to room temperature in a controlled, draft-free environment to minimize thermal distortion. Cross-sectional specimens were then extracted perpendicular to the weld direction using a precision cutting system. The sections were mounted, polished progressively to a mirror finish, and etched using hydrochloric acid (HCl) to clearly reveal fusion boundaries and weld morphology.

4.7 Evaluation of Weld Characteristics:

The etched cross-sections were examined using optical image analysis techniques to evaluate flux-induced changes in weld geometry. Measurements included penetration depth (D), defined from the original surface to the deepest point of fusion, and bead width (W), measured at the weld face. The depth-to-width ratio (D/W) was subsequently calculated to assess weld efficiency.

Finally, the results from the flux-free sample (S1) and the flux-assisted sample (S2) were compared to determine the effectiveness of the ZrO_2–Al_2O_3 binary flux in enhancing arc constriction, heat concentration, and overall weld pool behavior.

V. Experimentation:

To systematically study the geometric changes induced by the oxide coating, bead-on-plate welding trials were performed using the automated setup described in Section IV. The primary aim was to maintain identical process conditions across all experiments so that the chemical influence of the ZrO_2–Al_2O_3 binary flux could be treated as the only variable affecting weld behavior. After completing the flux-free baseline run (S1), the prepared binary flux formulation was applied and tested on specimen S2. Both welds were produced using a constant current of 150 A to ensure that observed differences were purely due to flux activity rather than changes in electrical input.

Once welding was completed and the arc extinguished, the samples were allowed to cool naturally inside a draft-free enclosure until room temperature was reached. This controlled cooling procedure helped avoid thermal disturbances such as rapid cooling stresses or convection-induced distortion of the weld profile.

For metallographic analysis, transverse sections were extracted perpendicular to the welding direction using a precision, water-cooled diamond wafering saw. This approach minimized frictional heating and prevented any alteration of the heat-affected zone (HAZ) or fusion boundary characteristics.

The extracted specimens were then subjected to standard metallographic preparation. Grinding was carried out using silicon carbide (SiC) abrasive papers in progressively finer grades from 240 to 1200 grit to eliminate surface damage and deformation layers. This was followed by fine polishing using a 1 µm diamond suspension to obtain a mirror-like surface finish.

To reveal weld fusion boundaries and penetration profiles, the polished samples were etched for 15–20 seconds using a modified aqua regia solution composed of three parts hydrochloric acid (HCl) and one part nitric acid (HNO_3). Finally, weld geometry parameters—including penetration depth (D), bead width (W), and depth-to-width ratio (D/W)—were measured using an optical stereomicroscope combined with calibrated digital image analysis software.

This section presents the comparison between conventional TIG welding and activated TIG welding using the engineered ZrO_2–Al_2O_3 binary flux. The baseline condition (S1) was used as a reference and compared with specimen S2, which was welded under identical parameters with a 1:1 weight ratio of zirconium dioxide and aluminium oxide as the activating layer.

6.1 Weld Bead Macrostructural Dimensions:

Visual inspection confirmed that both welding conditions produced continuous, defect-free weld tracks with smooth surface profiles. No visible defects such as undercutting, surface porosity, or cracking were observed in either case. However, clear differences were noted in the cross-sectional weld geometry. The measured values are summarized in Table 6.1.

Table 6.1 Comparison of Weld Geometry

Specimen	Welding Condition	Bead Width (mm)	Penetration Depth (mm)	D/W Ratio
S1	Conventional TIG	7.80	3.15	0.40
S2	A-TIG (ZrO_2 + Al_2O_3)	6.05	6.02	1.00

In the baseline sample (S1), the weld exhibited the typical behavior of conventional TIG welding on austenitic stainless steel, where heat distribution is relatively broad. This resulted in a wide bead width of 7.80 mm but limited penetration of 3.15 mm, producing a shallow weld profile with a low aspect ratio of 0.40.

In contrast, the flux-assisted sample (S2) showed a significant improvement in penetration under the same welding parameters. The penetration depth increased to 6.02 mm, representing a 91.1% improvement compared to S1, and effectively achieving near full penetration in the 6 mm thick plate. At the same time, the bead width reduced to 6.05 mm, indicating a 22.4% decrease in surface spread. As a result, the depth-to-width ratio increased to 1.00, reflecting a much more efficient and concentrated weld profile.

The weld morphology also changed noticeably. The S1 fusion zone exhibited a broad, shallow profile characteristic of lateral heat dispersion. In comparison, S2 showed a narrow, deeper, and more column-like fusion profile, indicating stronger energy concentration and improved depth penetration.

6.2 Physical Mechanisms of Enhancement:

The improved weld geometry in S2 can be attributed to two primary interacting mechanisms: arc constriction and modification of Marangoni convection within the molten pool.

In conventional TIG welding (S1), the arc tends to expand as it approaches the workpiece, resulting in a wider distribution of current and reduced heat concentration at the center. In addition, AISI 304 stainless steel typically exhibits a negative surface tension temperature gradient. This means surface tension decreases at the hotter central region of the weld pool and is higher at the cooler edges. As a result, molten metal flows outward from the center toward the periphery, leading to lateral heat loss and a shallow weld profile.

When the ZrO_2–Al_2O_3 flux is introduced (S2), the behavior of the arc and weld pool changes significantly. At high temperatures, the flux decomposes and interacts with the arc plasma, causing electron attachment at the outer arc regions. This results in a narrowing of the arc column, forcing current flow into a more concentrated central path. Consequently, current density and arc pressure increase directly beneath the electrode, enhancing localized heat input.

Simultaneously, oxygen-related species generated from flux decomposition dissolve into the molten pool and modify its surface chemistry. This alters the surface tension temperature coefficient from negative to positive. As a result, the direction of Marangoni flow reverses: instead of moving outward, the molten metal is drawn inward from the cooler edges toward the hotter center and directed downward into the weld root. This inward convection significantly improves heat transfer to deeper regions of the weld pool, explaining the marked increase in penetration depth observed in S2.

VII. Conclusion:

This study investigated the influence of a ZrO_2–Al_2O_3 binary activating flux on the weld geometry of 6 mm thick AISI 304 stainless steel during automated TIG welding. The results clearly demonstrate that the application of the binary flux significantly enhances weld penetration under constant process conditions (150 A current and 100 mm/min travel speed).

The penetration depth increased from 3.15 mm in the conventional TIG process to 6.02 mm in the activated TIG condition, representing a 91.1% improvement. At the same time, the bead width decreased from 7.80 mm to 6.05 mm, corresponding to a 22.4% reduction in lateral spread. These combined effects increased the depth-to-width ratio from 0.40 to 1.00, indicating a substantial improvement in weld efficiency and energy concentration within the fusion zone.

Macrostructural analysis confirmed that the binary flux promotes stable arc behavior and uniform weld formation without introducing surface defects. The observed improvements are primarily driven by arc constriction and reversal of Marangoni convection, which together enhance heat localization and promote deeper penetration.

Overall, the ZrO_2–Al_2O_3 binary flux system demonstrates strong potential for achieving near full penetration in a single pass on medium-thickness stainless steel sections. This capability reduces the need for multi-pass welding and joint preparation, offering clear advantages in productivity, cost reduction, and industrial fabrication efficiency.

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