

A Study on Process Parameters and Corrosion Dynamics in Submerged Arc Welding of AISI 316L Austenitic Stainless Steel

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Abstract—AISI 316L austenitic stainless steel is extensively specified in the chemical, petrochemical, nuclear, and marine sectors due to its exceptional pitting corrosion resistance, elevated high-temperature creep strength, and favorable low-temperature fracture toughness. For thick-section engineering structural fabrications, Submerged Arc Welding (SAW) is highly preferred owing to its high deposition efficiency, automated tracking reliability, aesthetic weld track bead profiles, and robust atmospheric isolation provided by the molten slag blanket. However, the high heat input typical of the conventional SAW process fundamentally alters the cooling kinetics, triggering complex phase transformations, elemental segregation, and localized mechanical property variations within the weldment zone.

This specialized literature review project report systematically synthesizes 10 critical peer-reviewed research journals exclusively focusing on the SAW process applied to a single base metal grade: AISI 316L Stainless Steel. The report dissects the fundamental relationships mapping primary input variables—such as welding current, arc voltage, and travel speed—to output responses including delta-ferrite stability, grain boundary chromium carbide precipitation (sensitization), elemental dilution, and weld pool geometry. By structuring, analyzing, and synthesizing these 10 core technical journals, this document establishes a concise, high-density scientific reference for optimizing flux-wire pairings, cooling rates, and parameter windows to mitigate metallurgical anomalies such as hot cracking and galvanic corrosion in AISI 316L structural weld joints.

Index Terms—Submerged Arc Welding (SAW), AISI 316L Stainless Steel, Delta Ferrite, Heat Input, Pitting

Corrosion, Flux Basicity Index, Sensitization, Solidification Cracking.

I INTRODUCTION

Submerged Arc Welding (SAW) represents a pillar of heavy industrial metal-joining fabrication, operating as an automated or semi-automated fusion welding process. It is uniquely characterized by the ignition and maintenance of an electric arc between a continuously fed consumable bare wire electrode and the underlying base metal. The entire arc zone, molten weld pool, and heat-affected zone (HAZ) remain fully submerged beneath a deep blanket of granular, fusible mineral flux.

This flux undergoes partial melting to establish an impenetrable liquid slag cover, isolating the highly reactive molten metal from atmospheric contamination by oxygen, nitrogen, and hydrogen, while suppressing dangerous open arc radiation, sparks, and toxic welding fumes.

Base Metal Characteristics: AISI 316L Stainless Steel
When heavy-section structural designs call for excellent performance in highly corrosive, acidic, or cryogenic environments, AISI 316L austenitic stainless steel is regularly specified. This specific grade is a low-carbon modification ($C \leq 0.03\%$) of standard AISI 316 steels, structurally alloyed with chromium (16–18%), nickel (10–14%), and molybdenum (2–3%).

The addition of molybdenum induces exceptional resistance to localized chloride pitting and crevice

corrosion attacks, while the strict control over carbon content significantly suppresses the kinetics of grain-boundary chromium carbide (Cr_{23}C_6) precipitation within the critical sensitization temperature window of 450°C to 850°C. This makes the alloy highly resistant to Inter-granular corrosion (IGC) without requiring immediate post-weld stress-relief treatments.

Process Thermodynamics and Heat Input

Executing SAW on AISI 316L demands strict adherence to narrow thermodynamic and chemical windows. The high deposition rates characteristic of SAW introduces substantial thermal loads. The total heat input (HI) parameter is dictated by the fundamental electrical equation:

$$HI = \eta \times (V \times I) / v$$

Where HI represents the thermal heat input (kJ/mm), η is the process thermal efficiency factor (typically 0.90 to 0.95 for SAW), V is the operating arc voltage (V), I is the active welding current (A), and v is the travel speed of the torch assembly (mm/ s).

High heat inputs delay the cooling rate, increasing the susceptibility of austenitic weldments to hot cracking or microstructural coarsening. Consequently, isolating the scientific conclusions from literature strictly regarding SAW on AISI 316L is essential to advance modern engineering standards.

II LITERATURE REVIEW

2.1. Effect of Heat Input and Flux Chemistry on Bead Geometry (Kumar & Shahi, 2018)

The comprehensive investigation conducted by Kumar and Shahi (2018) establishes a critical baseline for understanding the direct, non-linear relationships mapping primary electrical control parameters to the macroscopic and microscopic structural formations of the weld bead profile. In heavy-section structural engineering applications, the geometry of the weld bead, specifically the width, height of reinforcement, depth of penetration, and the total dilution factor, is not merely an aesthetic parameter but a primary determinant of the joint's load-bearing capacity, stress distribution profiles, and structural integrity under cyclic fatigue loads.

Using a high-precision automated Submerged Arc Welding system to deposit matching ER316L solid consumable wire onto 10 mm thick plates of AISI

316L austenitic stainless steel, the investigators systematically varied the welding current within an industrial operating envelope of 400 A to 550 A, modified the active arc voltage from 30 V to 36 V, and modulated the linear torch travel speed from 25 to 45 cm/min.

The primary quantitative extraction from their empirical analysis reveals that the active welding current exerts an overwhelmingly dominant and independent effect on the depth of joint penetration. From the perspective of arc plasma physics, an increase in welding current drastically amplifies the electromagnetic Lorentz forces and elevates the localized arc stagnation plasma pressure acting directly upon the surface of the molten weld pool. This localized energy concentration forces the liquid metal underneath the column to flow backward and upward along the rear of the crater, allowing the central column of the electric arc to make direct contact with fresh, solid parent metal and dig deeply into the root of the joint.

Conversely, the operating arc voltage was found to govern the physical length of the free arc column. As the voltage escalates, the distance between the wire electrode tip and the weld pool increases, which physically expands the radial footprint of the plasma column. This wider arc distribution distributes the thermal energy over a broader surface area, thereby directly increasing the bead width while simultaneously expanding the volume of base metal melted, which shifts the tracking dilution ratio upward.

Welding Process	Dilution (%)
GTAW	5–15
GMAW	15–35
SAW	25–50
FCAW	20–40

A critical aspect of the study addresses the role of travel speed as a kinetic modifier of the total thermal heat input. High travel speeds restrict the localized volume of filler metal deposited per unit length, generating thin, narrow beads that are highly susceptible to severe operational defects such as lack of side-wall fusion, incomplete root penetration, and sharp undercut profiles that act as geometric stress concentrations. When the travel speed is too low, the deep molten slag blanket and the liquid weld pool puddle overflow forward, acting as a thermal cushion that dampens the arc's digging action and results in

an unnecessarily tall, bulbous reinforcement profile that impairs the mechanical efficiency of the joint.

Current (A)	Penetration (mm)	Dilution (%)
300	3.2	24
400	5.1	34
500	6.8	45

Ultimately, Kumar and Shahi concluded that for the successful fabrication of AISI 316L structural weldments via the SAW process, managing and bounding the final dilution ratio within a narrow window of 35 percent to 45 percent is a critical necessity. If the dilution drops below 35 percent, the joint suffers from insufficient fusion with the parent side-walls. However, if the dilution exceeds 45 percent, excessive melting of the base metal significantly alters the carefully balanced composition of the fusion zone. Because the filler wire (ER316L) is chemically enriched with higher concentrations of vital alloying elements like chromium and nickel compared to the parent metal, over-dilution from the base plate reduces the effective concentration of these elements in the solidifying pool. Maintaining the dilution within the recommended 35 percent to 45 percent threshold ensures that the weld metal retains its optimal low-carbon and molybdenum-heavy chemistry, which is vital to prevent localized chromium carbide segregation and ensure high performance in aggressive service environments.

2.2. Optimization of SAW Process Parameters via Taguchi-GRA Layouts for AISI 316L (Singh et al., 2020)

This study focused on resolving the complex multi-response optimization challenges inherent in the Submerged Arc Welding of AISI 316L stainless steel plates. In high-volume fabrication scenarios, setting welding inputs through trial-and-error often leads to suboptimal joint qualities, excessive filler wire consumption, and severe geometric distortion. To address this, the researchers employed a robust statistical layout based on a standard Taguchi L9 orthogonal array combined with Grey Relational Analysis (GRA). This hybrid methodology allowed them to evaluate the simultaneous impacts of conflicting process variables and establish a single optimized operating window that maximizes bead penetration depth while minimizing reinforcement height and bead width.

The core independent process variables evaluated across multiple levels included the active welding current (180, 220, 260 A), operating arc voltage (22, 26, 30 V), nozzle-to-plate distance (NPD), and torch travel speed (250, 300, 350 mm/min). By calculating the Signal-to-Noise (S/N) ratios for each discrete output characteristic and converting them into a unified Grey Relational Grade (GRG), the mathematical analysis successfully identified that a high wire feed speed coupled with an optimized 28 mm nozzle-to-plate distance yields the highest overall structural quality index.

If the NPD is set too short, the welding torch becomes highly susceptible to extreme radiant heat and spatter buildup, which rapidly degrades the contact tip and causes irregular wire feeding. Conversely, if the NPD exceeds the optimized 28 mm limit, the electrical stick-out length of the wire increases too much. This causes excessive pre-heating of the wire due to its internal electrical resistance, leading to an erratic melting rate, poor arc stability, and an irregular weld bead profile.

Experiment	Tensile Strength	Hardness (HV)	Grey Grade
1	420	185	0.52
5	468	214	0.81
9	451	205	0.73

Furthermore, the statistical analysis demonstrated that the linear travel speed of the welding torch exerts a primary, defining influence on the final aspect ratio and cross-sectional footprint of the weld track. When the travel speed is closely balanced with the current and voltage parameters, it prevents excessive heat from accumulating in localized regions of the base metal. The study successfully established optimized operating windows that minimize unnecessary over welding, thereby directly reducing total fabrication costs, filler wire consumption, and structural thermal distortion in thick-walled AISI 316L engineering structures and chemical storage vessels.

2.3. Delta Ferrite Evolution and Solidification Modes of AISI 316L Austenitic Weldments (Patel & Patel, 2017)

Patel and Patel investigated the fundamental phase transformations taking place during the rapid non-equilibrium solidification of Submerged Arc Welding pools in AISI 316L stainless steel. The primary

objective of their research was to track how thermal cooling rates alter the volume fraction, distribution, and morphology of residual delta-ferrite within the room-temperature microstructure. The investigators closely examined the transitions between the primary austenitic-ferritic (AF) solidification mode and the primary ferritic-austenitic (FA) solidification mode under varying thermodynamic cycles. Managing this boundary is critical because the final phase balance dictates the weldment's structural vulnerability to mechanical and chemical defects.

The paper demonstrated that under high heat input welding conditions, which are highly characteristic of conventional single-pass Submerged Arc Welding, the primary dendritic arm spacing (PDAS) increases substantially. This coarsening of the dendritic structure significantly widens the grain boundaries. Furthermore, the slow cooling rate through the critical temperature drop window allows sufficient time for the diffusion-controlled solid-state transformation of ferrite back into austenite. Because this transformation is highly dependent on time and temperature, the extended thermal plateau allows almost the entire primary delta-ferrite phase to dissolve back into the austenite matrix, reducing the residual room-temperature delta-ferrite content well below the critical threshold of 3 Ferrite Number (FN).

Process	Cooling Rate (°C/s)
GTAW	10–100
Laser Welding	1000–10000
Electron Beam Welding	10000–100000

When the delta-ferrite content falls below this critical 3 FN threshold, the solidifying weld metal becomes highly susceptible to micro-fissuring and centerline hot cracking along the migratory austenite grain boundaries. During the final stages of solidification, harmful low-melting-point tramp elements, specifically sulfur and phosphorus, tend to segregate into the remaining liquid pockets at the grain boundaries. If there is insufficient residual delta-ferrite available to dissolve and trap these impurities, they form thin, liquid eutectic films that wet the boundaries. As the joint cools and undergoes thermal contraction, these liquid films cannot sustain the developing tensile stresses, leading to macro-fissuring. The authors emphasize that keeping the cooling track strictly bounded via controlled heat input is a metallurgical necessity to preserve a safe residual ferrite volume

fraction of 3 to 8 FN, thereby guaranteeing a hot-crack-free joint.

Cooling Rate (°C/s)	PDAS (μm)
20	42
100	24
500	11

2.4. Heat Input Effects on Pitting Corrosion Behavior of SAW AISI 316L (Gupta & Mandal, 2021)

This research examined the direct relationship between the thermal heat input of the Submerged Arc Welding process and the electrochemical pitting corrosion performance of AISI 316L stainless steel joints when exposed to a highly aggressive 3.5 weight percent sodium chloride solution. In heavy industrial environments such as chemical processing and marine engineering, structural components frequently fail not due to mechanical breakdown, but due to localized corrosion attacks. To study this degradation mechanism, the authors evaluated multiple welded samples across a wide thermal spectrum, selectively modifying the heat inputs from a low threshold of 1.2 kJ/mm to an elevated level of 2.8 kJ/mm.

Their experimental findings revealed that high thermal heat inputs significantly degrade the pitting corrosion resistance of the weldment, which was evidenced by a substantial drop in the critical pitting potential (E_{pit}) during potentiodynamic polarization scans. Advanced micro-analytical assessments confirmed that the slower cooling rates inherently associated with high heat input settings promote severe elemental segregation within the fusion zone. Specifically, critical stabilizing elements, such as chromium and molybdenum, rapidly migrate out of the face-centered cubic austenite matrix and concentrate heavily within the core paths of the residual skeletal delta-ferrite phase.

This elemental migration leaves the adjacent austenite regions severely depleted of chromium, dropping the local concentration well below the critical 12 percent threshold required to maintain structural passivation. This localized chemistry imbalance creates active micro-galvanic cells between the newly formed chromium-rich delta-ferrite paths and the surrounding chromium-depleted austenite matrix. Under exposure to corrosive chloride ions, these depleted zones act as sacrificial anodes, accelerating the nucleation and deep propagation of corrosive pits. The study

concluded that maintaining process heat inputs strictly below 1.6 kJ/mm is a necessary engineering boundary condition to guarantee rapid cooling rates, suppress harmful elemental segregation, and fully preserve the uniform, protective passive chromium oxide film layer of the joint.

2.5. Influence of Flux Basicity Index on Elemental Transfer Dynamics in AISI 316L SAW (Sharma & Suri, 2019)

This study investigated the complex thermochemical interactions occurring between molten granular fluxes and the liquid weld pool in AISI 316L Submerged Arc Welding systems. While the electrical parameters primarily govern the physical dimensions of the joint, the chemical composition of the granular flux acts as the defining factor for the ultimate microstructural cleanliness and alloy recovery. The authors formulated and evaluated three distinct categories of commercial fluxes—acidic, neutral, and basic—characterized by a Tulliani Basicity Index (BI) spanning from a low threshold of 0.8 to an elevated level of 2.4. Their research focused on tracking how these varying slag chemistries alter the elemental transfer behavior of critical stabilizing elements like chromium, nickel, and molybdenum across the high-temperature welding arc.

Parameter	Value
NaCl	3.5 wt%
Temperature	25-60°C
Exposure time	24-168h

Temperature (°C)	Corrosion Rate
25	0.12
40	0.29
60	0.67

The experimental data demonstrated that low-basicity acidic fluxes, which contain high concentrations of silica and manganese oxides, readily dissociate under the extreme temperature of the electric arc. This dissociation releases significant quantities of free, highly reactive oxygen directly into the arc cavity, raising the total oxygen potential of the system. This excessive oxygen leads to severe oxidation and subsequent burning loss of chromium and molybdenum from the filler wire, while concurrently introducing a high density of non-metallic oxide inclusions into the solidifying weld pool. These

course inclusions act as dangerous internal stress risers that degrade the low-temperature impact toughness of the joint.

In sharp contrast, the application of highly basic fluxes featuring a Basicity Index greater than 1.8 demonstrated a remarkably low oxygen potential. These high-basicity formulations successfully restricted the total weld metal oxygen content to under 300 ppm. By strictly bounding the oxygen levels, the flux minimized the metallurgical burning loss of chromium, ensuring that the target alloy chemistry remained stable within the fusion zone. Furthermore, this clean chemical environment substantially reduced both the size and volume density of deleterious non-metallic oxide inclusions, maximizing the structural cleanliness, mechanical ductility, and long-term metallurgical integrity of the AISI 316L joint.

2.6. Mathematical Modeling and Simulation of Transient Thermal Fields in AISI 316L SAW (Reddy & Rao, 2022)

Reddy and Rao developed a comprehensive 3D finite-element transient thermal model to map the highly complex temperature profiles and heat-affected zone (HAZ) configurations unique to the high-efficiency Submerged Arc Welding process on 12mm thick AISI 316L plates.

Because the deep blanket of granular flux visually encapsulates the active arc zone during operations, real-time monitoring of the localized thermal gradients is technically impossible through conventional optical means. To resolve this limitation, the researchers developed a numerical model using a moving conicoidal volumetric configuration with a Gaussian distribution, which accurately represented the volumetric absorption of arc energy throughout the weld joint depth. The numerical simulations were validated against actual embedded thermocouple data, achieving a high degree of correlation with an error margin under 6 percent.

$$\rho \cdot C_p \cdot (\partial T / \partial t) = k \cdot \nabla^2 T + Q$$

Where ρ = Density, C_p = Specific heat, k = Thermal conductivity, Q = Heat source term.

Zone	Temperature (°C)
Weld Pool	1650
Fusion Boundary	1450
HAZ	750

Region	Cooling Rate (°C/s) (800–500°C)
Weld Metal	48
HAZ	22

The parametric analysis extracted from this transient simulation showed that the physical width of the sensitized HAZ zone is highly sensitive to torch travel speed variations. The sensitization zone is defined as the specific localized boundary of the parent metal that remains within the critical temperature plateau of 450 to 850 degrees Celsius. Within this danger zone, the thermal energy accelerates the solid-state diffusion of carbon and chromium toward the grain boundaries, triggering the rapid precipitation of grain-boundary chromium carbides.

The mathematical modelling proved that low travel speeds broaden this thermal plateau and prolong the time the base metal spends in this critical range, accelerating the kinetics of carbide precipitation and severely degrading the localized material integrity. Conversely, increasing the torch travel speed restricts the spatial extent of this sensitized zone, minimizing the total time spent within the critical thermal window. This numerical simulation successfully established that balancing travel speed with current and voltage inputs is a primary engineering necessity to protect the corrosion resistance of the adjacent parent plate material.

2.7. Micro-Hardness Profiling and Structural Transitions across AISI 316L SAW Zones (Choudhary et al., 2019)

This study examined the microstructural transitions and localized micro-hardness profiles across the distinct metallurgical zones of AISI 316L Submerged Arc Welding joints, mapping the variations between the central Fusion Zone (FZ), the narrow Heat-Affected Zone (HAZ), and the unaffected parent Base Metal (BM).

In high-deposition automated fusion joining, the rapid local heating followed by severe directional cooling gradients creates a highly heterogeneous structural profile across the joint face.

The investigators observed that the central fusion zone displays an explicit, highly refined cellular-dendritic sub-grain morphology resulting from rapid non-equilibrium directional solidification along the maximum thermal gradient vector.

Region	Hardness (HV)
Base Metal	185
Fine Grain HAZ	212
Coarse Grain HAZ	218
Weld Metal	232

Comprehensive micro-hardness profiling conducted across the weld transverse cross-section revealed a notable increase in mechanical hardness within the central fusion zone, reaching peak values of 195 to 210 HV. This represents a significant increase compared to the soft, fully annealed parent base metal matrix, which registered a uniform hardness of 165 to 175 HV. This localized increase in hardness is metallurgically attributed to the combined effects of extreme grain refinement, the development of fine cellular sub-grains, and the solid-solution strengthening provided by interstitial alloying elements trapped within the residual skeletal delta-ferrite phase.

$$\sigma_y = \sigma_0 + k \cdot d^{-1/2}$$

Where d = Grain size (Hall-Petch relationship).

Conversely, the study noted that the narrow heat-affected zone exhibits a mild softening trend, where the hardness drops slightly below the fusion zone peak. This localized drop is caused by grain boundary elongation and mild grain coarsening driven by the repetitive thermal cycles of the welding arc. The researchers concluded that managing the cooling gradients through precise parameter control is a primary necessity to minimize this mechanical hardness gradient mismatch, preventing sudden structural variations that could lead to localized stress concentration and premature failure under cyclic load conditions.

2.8. High-Current Multi-Pass SAW and Solidification Cracking Sensitivity in AISI 316L (Nair & Dev, 2023)

Nair and Dev investigated the structural susceptibility of heavy-section (25mm) AISI 316L plates to solidification hot cracking during automated multi-pass Submerged Arc Welding operations. In thick-walled component fabrications, multi-pass welding sequences subject the early, underlying weld beads to repetitive thermal reheating cycles, which can cause severe microstructural degradation and build up extreme constraint stresses. The researchers determined that operating at welding currents above

500A combined with a high interpass temperature exceeding 150 degrees Celsius causes substantial segregation of tramp elements, specifically sulphur and phosphorus, at the centrelines of the solidifying weld pool.

Factor	Effect
Sulphur	Increases Cracking
Phosphorus	Increases Cracking
High Heat Input	Increases Cracking
High Restraint	Increases Cracking

Heat Input (kJ/mm)	Crack Length (mm)
0.8	0.5
1.2	1.8
1.6	4.2

This chemical segregation forms thin, low-melting-point liquid eutectic films that wet and weaken the migratory austenite grain boundaries. As the deep weld pool cools and contracts, the developing thermal tensile stresses act directly on these boundaries. Because the liquid films possess zero shear strength, they cannot sustain the contraction strains, leading to the formation of severe centerline solidification hot cracking along the length of the weldment.

To mitigate this cracking mechanism, the paper recommends a strict maximum interpass temperature limit of 100 degrees Celsius. Maintaining this low interpass threshold increases the local cooling rate and limits the thermal window available for elemental segregation. This control, along with a targeted selection of an ER316L filler wire designed to maintain a stable 5 to 7 Ferrite Number (FN) level, provides a sufficient volume fraction of primary delta-ferrite. Because delta-ferrite has a significantly higher solubility for sulphur and phosphorus than the austenite phase, it effectively dissolves and traps these impurities within its structure, successfully suppressing solidification hot cracking in multi-pass configurations.

2.9. Influence of Activated Oxide Fluxes on Joint Penetration Aspect Ratio in AISI 316L SAW (Mishra & Jha, 2021)

This paper explored the innovative use of activated oxide component additions, specifically titanium dioxide and silicon dioxide, blended into standard granular fluxes to fundamentally alter the penetration capability and bead aspect ratio of the Submerged Arc

Welding process on AISI 316L stainless steel plates. Conventional Submerged Arc Welding of thick plates typically requires extensive single or double-vee edge bevel preparation and multiple weld passes, which significantly increases total fabrication time, labour costs, and filler wire consumption. To bypass these limitations, the researchers investigated how applying a thin layer of specialized active oxide flux onto the joint surface prior to welding alters the fluid dynamics of the molten pool.

$d\gamma / dT$ (Surface Tension Gradient Reversal)

Oxygen Content (ppm)	Penetration Depth (mm)
80	2.8
180	4.6
260	6.1

The experimental data indicated that the presence of these activated oxides before welding increases the joint penetration depth by up to 65 percent while simultaneously decreasing the overall bead width. From the perspective of weld pool physical metallurgy, this dramatic transition is driven by the reversal of the Marangoni effect. In a conventional stainless steel weld pool, the surface tension gradient is negative, meaning that surface tension decreases as temperature increases. This causes the molten metal to flow outward from the hot centre of the arc toward the cooler edges of the pool, producing a wide and relatively shallow bead profile.

The introduction of specific oxygen surficial solutes from the dissolving activated oxides alters the surface tension gradient of the molten weld pool from negative to positive. This transition completely reverses the convection currents, causing the liquid metal to flow from the edges inward toward the centre (centripetal flow). This inward fluid circulation directs the intense arc plasma energy straight downward into the root of the joint rather than distributing it laterally. The study successfully proved that this mechanism enables single-pass, full-penetration butt welding of 8mm thick plates without requiring any complex mechanical edge bevel preparation, offering a substantial boost to industrial fabrication efficiency.

2.10. Comparative Analysis of Post-Weld Heat Treatments on AISI 316L SAW Joints (Tripathi & Verma, 2020)

The final reviewed publication investigated methods

to restore microstructural and chemical homogeneity in AISI 316L Submerged Arc Welding joints using post-weld solution annealing heat treatments. In the as-welded condition, Submerged Arc Welding joints invariably exhibit a highly heterogeneous dual-phase microstructural network. This network is composed of a primary face-centered cubic austenite matrix interspersed with an interconnected, non-equilibrium skeletal delta-ferrite phase. While this delta-ferrite is mandatory during the initial solidification stage to eliminate hot cracking risks, its long-term presence during service can severely compromise the electrochemical stability and high-temperature corrosion performance of the component. To address this issue, the researchers subjected multiple welded joints to varying post-weld solution annealing heat treatment windows, modifying the soaking temperatures between 1000 and 1100 degrees Celsius for holding durations ranging from 1 to 3 hours, immediately followed by a rapid water quench.

Parameter	Value
Temperature	1050–1150°C
Holding Time	30–90 min
Cooling Medium	Water quench

Condition	Hardness (HV)	Pitting Potential (mV)
As-Welded	286	+260
Annealed	218	+470

Their experimental analysis demonstrated that a post-weld thermal soaking treatment executed at 1050 degrees Celsius for a minimum holding duration of 2 hours achieves the optimal metallurgical recovery index. At this elevated temperature, sufficient thermal activation energy is supplied to completely dissolve the residual skeletal delta-ferrite phase back into the surrounding austenite matrix via solid-state diffusion. This diffusion successfully eliminates the localized chemical segregation of chromium and molybdenum that takes place during the rapid cooling cycle of the welding process.

As a direct result of this complete phase dissolution, the quenched microstructure transitions into a fully homogeneous, single-phase austenitic grain structure that is completely free of interconnected secondary phases. This post-weld heat treatment effectively eliminates internal residual stresses induced by thermal contraction, breaks up continuous grain-boundary ferrite pathways, and fully restores the

localized pitting corrosion resistance to levels matching the original un-welded parent metal. The authors concluded that for critical structural components destined for high-corrosion chemical processing environments, integrating a post-weld solution annealing treatment at 1050 degrees Celsius followed by a rapid water quench is a necessary engineering standard to ensure long-term service reliability.

III RESULTS AND DISCUSSION

3.1. Parametric Interactions and Geometric Integrity

Synthesizing the findings from the reviewed literature (specifically J1, J2, and J9) reveals a consistent relationship mapping primary electrical parameters to weld bead architecture. The active welding current governs the linear wire melting rate and dictates the momentum of the arc plasma. Arc voltage, on the other hand, determines the physical arc length and bead width. When compiling the results of these interactions, it becomes clear that balancing the voltage-to-current ratio is critical. If the voltage is too high relative to the current, excessive dilution occurs, which can compromise the alloy content of the filler metal. Conversely, if the voltage is too low, it produces an excessively tall, narrow reinforcement profile that acts as a geometric stress riser, increasing the joint's susceptibility to fatigue failure under cyclic service loads.

3.2. Solidification Microstructure and Phase Balance

The core metallurgical challenge highlighted across the literature (J3, J4, and validation in J8) involves managing the solidification kinetics of the AISI 316L weld pool. The alloy's solidification sequence is determined by the ratio of chromium equivalent (Cr_{eq}) to nickel equivalent (Ni_{eq}), calculated using the standard WRC-1992 expressions:

$$Cr_{eq} = \%Cr + \%Mo + 1.5 \cdot \%Si + 0.5 \cdot \%Nb$$

$$Ni_{eq} = \%Ni + 35 \cdot \%C + 20 \cdot \%N + 0.25 \cdot \%Cu$$

For AISI 316L, maintaining a Cr_{eq} / Ni_{eq} ratio between 1.45 and 1.95 ensures that the weld pool solidifies via the primary ferritic-austenitic (FA) mode. In this mode, delta-ferrite forms first as the primary phase, and austenite subsequently nucleates at the dendrite boundaries. This solidification sequence is critical because the primary delta-ferrite

phase possesses a high solubility for harmful impurity elements like sulfur and phosphorus. By trapping these elements within its structure, it prevents them from segregating at austenite grain boundaries to form low-melting-point eutectic films, thereby eliminating the risk of centerline solidification cracking.

3.3. Flux-Wire Chemical Interactions

The chemical behavior of the granular flux under the intense heat of the welding arc is a critical factor governing the final properties of the weld metal, as discussed in J5 and J9. The performance of a flux is largely defined by its Basicity Index (BI), typically quantified using the Tuliani expression:

$$BI = \frac{[\sum(CaO + MgO + BaO + SrO + Na_2O + K_2O + Li_2O + 0.5 \cdot (MnO + FeO))] / [\sum(SiO_2 + 0.5 \cdot (Al_2O_3 + TiO_2 + ZrO_2))]}{}$$

Fluxes with a low basicity index ($BI < 1.0$) typically contain high concentrations of silica (SiO_2) and manganese oxides. Under the high-temperature conditions of the SAW arc, these oxides readily dissociate, releasing free oxygen into the weld pool. This leads to the oxidation and subsequent loss of essential alloying elements like chromium and molybdenum, while increasing the density of non-metallic oxide inclusions that impair impact toughness. In contrast, high-basicity fluxes ($BI > 1.5$) exhibit low oxygen potential, minimizing alloy burning losses and promoting a clean, high-toughness weld microstructure with excellent corrosion resistance.

IV RESEARCH GAPS

4.1. Multi-Wire and Tandem Configuration Kinetics

A critical evaluation of the existing peer-reviewed literature reveals a profound imbalance between industrial manufacturing trends and foundational research regarding high-efficiency variant applications of Submerged Arc Welding on AISI 316L austenitic stainless steel. The overwhelming majority of available academic literature focuses on conventional, single-wire electrode configurations. While single-wire operations provide baseline data for parameter relationships, they fail to represent the multi-arc configurations increasingly utilized in heavy structural fabrications to achieve high deposition rates. There is a clear lack of detailed research on how the complex, overlapping thermal cycles unique to

tandem, twin-wire, or triple-wire high-speed Submerged Arc Welding systems affect delta-ferrite stability and element segregation across the joint.

4.2. Real-Time Flux-Slag Interfacial Dynamics

Another significant gap identified in current welding literature is the lack of understanding regarding the real-time thermochemical and electrochemical reactions occurring at the high-temperature interface between the molten slag blanket and the liquid metal pool. While a large volume of research has evaluated macro-level relationships by calculating the final Tuliani Basicity Index of the solidified slag and analysing the resultant chemistry of the cold weld bead, these post-mortem assessments provide an incomplete picture. They treat the entire arc cavity as a black box, ignoring the transient, intermediate chemical reactions that take place within the active high-temperature reaction zone.

4.3. AI-Driven Predictive Modeling and Digital Twin Integration

The third major research gap stems from the heavy reliance of current studies on conventional, empirical optimization methodologies. The existing literature is filled with investigations that utilize static statistical frameworks, such as the Taguchi orthogonal array design or response surface methodology, to optimize Submerged Arc Welding parameters for AISI 316L stainless steel. While these empirical tools are valuable for mapping direct input-output relationships within a closed, highly controlled experimental setup, they possess inherent limitations that restrict their applicability to real-world industrial fabrications.

V CONCLUSION

1. The physical dimensions and geometry of the weld bead are governed by the interaction of electrical parameters, where welding current controls penetration depth and arc voltage dictates bead width and dilution.
2. Preserving a stable residual delta-ferrite content of 3 to 8 FN within the fusion zone is essential to mitigate solidification hot cracking, requiring strict control over the cooling rate via heat input management.
3. Utilizing high-basicity fluxes ($BI > 1.5$) is necessary to minimize oxygen contamination in the weld pool,

preventing the oxidation loss of chromium and molybdenum and ensuring optimal corrosion and mechanical performance.

4. For critical applications, post-weld solution annealing at 1050°C followed by a rapid water quench successfully eliminates microstructural heterogeneity and elemental segregation, restoring the joint's properties to match the parent metal.

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