Investigating the Impact of Various Filler Metals on the Weld Integrity of Aluminum-Stainless Steel Bonds

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**Abstract:** Welding aluminum (AA6061) and stainless steel (SUS304) is critical for lightweight industrial applications but challenged by incompatible melting points and brittle intermetallic compounds (IMCs). This study investigates MIG lap welding using aluminum-based ER5356 and stainless-steel-based ER308LSi fillers at 17–19V to optimize joint integrity. Results show that increasing voltage to 19V introduces porosity (3.2%) and incomplete fusion, degrading weld quality. ER5356 joints exhibited silicon-rich zones, enhancing tensile strength (47.8–104.4 MPa) by suppressing Fe-Al IMCs, while ER308LSi produced brittle chromium carbides (hardness: 160–230 HV) with lower strength (20.24–61.76 MPa). Optimal conditions at 18V with ER5356 achieved peak strength (104.4 MPa) and minimal defects (0.5% porosity), offering a viable solution for high-performance dissimilar welding in automotive and aerospace industries.

**Keywords:** *MIG welding, dissimilar metal welding, aluminum alloy, stainless steel, mechanical properties.*

# Introduction

The joining of aluminum alloys and stainless steel has garnered significant attention in modern manufacturing, driven by the demand for lightweight, high-strength structures in aerospace, automotive, and marine applications[1-4]. Aluminum alloy AA6061, with its low density (2.7 g/cm³), excellent corrosion resistance, and moderate strength, is often paired with austenitic stainless steel SUS304, known for its superior mechanical performance (yield strength ~500 MPa) and durability in harsh environments[5-9]. However, the welding of these dissimilar metals remains a formidable challenge due to their incompatible thermophysical properties. The melting point of aluminum (660°C) is approximately 1,000°C lower than that of stainless steel (1,400–1,450°C), creating a steep thermal gradient during welding[10-14]. This disparity, coupled with negligible solid solubility between iron and aluminum, promotes the formation of brittle intermetallic compounds (IMCs) such as FeAl₃ and Fe₂Al₅ at the weld interface[15-18]. These IMCs act as stress concentrators, drastically reducing ductility and fatigue resistance[9][10]. Furthermore, differences in thermal expansion coefficients (24 µm/m°C for AA6061 vs. 17 µm/m°C for SUS304) induce residual stresses, exacerbating crack initiation and propagation[19-22].Conventional fusion welding techniques, such as MIG (Metal Inert Gas) welding, are widely employed for their cost-effectiveness and adaptability. However, the process parametersparticularly filler metal composition and welding voltagerequire meticulous optimization to mitigate defects like porosity, incomplete fusion, and excessive IMC formation[23-28]. Recent studies emphasize the pivotal role of filler metals in altering weld chemistry and microstructure. For instance, silicon (Si)-rich fillers, such as ER5356 (Al-5% Mg-0.1% Si), have shown promise in suppressing Fe-Al IMC growth by forming interfacial Si-rich diffusion barriers[29-33]. In contrast, chromium (Cr)-based fillers, like ER308LSi (Cr-20%-Ni-10%), stabilize the austenitic microstructure of stainless steel but introduce brittle Cr-carbides at the Al-SS interface. Despite these advancements, a systematic comparison of filler metals under varying voltage conditions remains underexplored, particularly in the context of MIG welding[34-38].This study addresses critical gaps in dissimilar welding research by evaluating the impact of two distinct filler metals (ER5356 and ER308LSi) across a controlled voltage range (17–19V) during MIG lap welding of AA6061 and SUS304. The selection of ER5356 and ER308LSi is grounded in their contrasting alloying elements and compatibility with base metals[39-41]. ER5356’s magnesium and silicon content enhances wetting behavior on aluminum substrates, while ER308LSi’s chromium and nickel stabilize the stainless steel microstructure. Voltage levels were chosen based on preliminary trials: voltages below 17V resulted in insufficient fusion (wetting angle >90°), while those above 19V caused excessive spatter and porosity (>5%) due to arc instability[20]. The argon shielding gas flow rate was maintained at 15 L/min to minimize oxidation without inducing turbulence in the weld pool.Microstructural analysis revealed stark contrasts between the two filler groups[42]. ER5356 joints exhibited mechanical interlocking facilitated by Si-particle dispersion, which enhanced stainless steel fragment migration into the aluminum matrix. Scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS) confirmed Si diffusion at the Al-SS interface, reducing IMC thickness by 40% (from 15 µm to 9 µm) compared to unmixed zones[43]. This microstructural refinement correlated with superior tensile strength (104.4 MPa at 18V) and ductility (7.2% elongation). In contrast, ER308LSi joints displayed Cr-carbide networks within the fusion zone, elevating hardness to 230 HV but limiting tensile strength to 61.8 MPa due to interfacial brittleness[24]. The brittleness of these joints was further evidenced by low elongation (2.8–4.4%) compared to ER5356 welds (5.5–7.2%).[44] These findings align with prior studies on laser welding but demonstrate that similar performance can be achieved through cost-effective MIG processes.The study also highlights the sensitivity of weld quality to voltage-induced heat input. At 19V, elevated thermal energy widened the heat-affected zone (HAZ) in stainless steel, promoting grain coarsening and porosity (>3%). Conversely, 17V produced shallow penetration and incomplete mixing, leaving unreacted interfaces prone to cracking[26]. Optimal performance was achieved at 18V, where controlled heat input (432 J/mm) balanced penetration depth (1.4 mm) and defect suppression (porosity <0.5%). This voltage-defect relationship provides an actionable framework for industries prioritizing joint reliability, such as electric vehicle battery enclosures or spacecraft fuel tanks[45]. Economic analysis further underscores the advantages of ER5356, which reduces material costs by 20% compared to ER308LSi, offering a scalable solution for high-volume manufacturing[46]. Despite advancements in dissimilar metal welding, critical gaps persist in the context of MIG welding for aluminum-stainless steel joints. Existing studies have predominantly focused on single-filler systems or alternative welding techniques like laser or friction stir welding, leaving a limited understanding of how contrasting filler metals (e.g., aluminum-based vs. stainless-steel-based) interact with voltage parameters to influence joint integrity[47-49]. While silicon-rich fillers are known to suppress intermetallic compound (IMC) formation, quantitative correlations between silicon diffusion, IMC thickness reduction, and mechanical performance remain underexplored. Furthermore, prior research often overlooks the economic implications of filler metal selection, such as material costs and scalability, which are vital for industrial adoption. The relationship between voltage-induced heat input, defect formation (e.g., porosity, incomplete fusion), and microstructural evolution also lacks a comprehensive framework, particularly for lap-welded configurations. This study aims to address these gaps by systematically evaluating the impact of aluminum-based ER5356 and stainless-steel-based ER308LSi filler metals on the weldability of AA6061 and SUS304 under controlled voltage conditions (17–19V). It seeks to quantify the role of silicon diffusion in mitigating Fe-Al IMC growth and its subsequent effects on tensile strength and ductility. Additionally, the work establishes a voltage-defect correlation model to optimize heat input for minimizing porosity and enhancing joint reliability. By integrating microstructural analysis with mechanical testing, the study provides actionable insights into filler metal selection, balancing hardness, ductility, and cost efficiency. Ultimately, the research delivers practical guidelines for industries seeking to implement lightweight, high-strength Al-SS hybrid structures through scalable and economically viable MIG welding processes [53-54].

# Experimental Method

## Materials

Aluminum alloy AA6061-T6 and austenitic stainless steel SUS304 plates, each 2.0 mm thick, were selected for their widespread industrial applicability, corrosion resistance, and contrasting thermophysical properties. The AA6061-T6 condition provided a yield strength of 276 MPa, while SUS304 offered 215 MPa yield strength, balancing lightweight design and structural integrity.

Table 1: Chemical Composition of AA6061 Aluminum Alloy and ER5356 Filler Metal (wt%)

|  |  |  |
| --- | --- | --- |
| Element | AA6061 (%) | ER5356 (%) |
| Silicon (Si) | 0.4 - 0.8 | 0.25 |
| Iron (Fe) | ≤ 0.7 | 0.4 |
| Copper (Cu) | 0.15 - 0.4 | 0.1 |
| Manganese (Mn) | ≤ 0.15 | 0.05 - 0.2 |
| Magnesium (Mg) | 0.8 - 1.2 | 4.5 - 5.5 |
| Chromium (Cr) | 0.04 - 0.35 | 0.05 - 0.2 |
| Zinc (Zn) | ≤ 0.25 | 0.1 |
| Titanium (Ti) | ≤ 0.15 | 0.06 - 0.2 |
| Other Elements (Each) | ≤ 0.05 | ≤ 0.15 |
| Other Elements (Total) | ≤ 0.15 | ≤ 0.15 |
| Aluminum (Al) | Remainder | Remainder |

Table 2:Chemical Composition of SUS304 Stainless Steel and ER308LSi Filler Metal (wt003%)

|  |  |  |
| --- | --- | --- |
| Element | SUS304 Stainless Steel (wt%) | ER308LSi Filler Metal (wt%) |
| Carbon (c) | ≤ 0.08% | ≤ 0.03% |
| Chromium (Cr) | 18.0-20.0% | 19.5-22.0% |
| Nickel (Ni) | 8.0-10.5% | 9.0-11.0% |
| Manganese (Mn) | ≤ 2.0% | 1.0-2.5% |
| Silicon (Si) | ≤ 1.0% | 0.65-1.0% |
| Phosphorus (P) | ≤ 0.045% | ≤ 0.03% |
| Sulfur (S) | ≤ 0.03% | ≤ 0.03% |
| Nitrogen (N) | ≤ 0.10% | - |
| Copper (Cu) | - | ≤ 0.75% |
| Molybdenum (Mo) | - | ≤ 0.75% |

Plates were sheared to standardized dimensions of 150 mm × 50 mm using an MVS/C 6/31 hydraulic shear (209 kN capacity) to minimize edge deformation and ensure consistency. Filler metals ER5356 (Al-5% Mg-0.1% Si) and ER308LSi (Cr-20%-Ni-10%) were chosen based on their compatibility with base metals: ER5356 enhances aluminum wettability and suppresses Fe-Al intermetallic compounds (IMCs), while ER308LSi stabilizes the austenitic microstructure of stainless steel but risks chromium carbide formation. The chemical compositions of base and filler metals are detailed in Tables 1 and 2.

## Welding Process

The welding process was conducted using a Migatronic 3000 Duo MIG welding machine configured for lap welding, with aluminum alloy AA6061 positioned atop stainless steel SUS304 to leverage its lower melting point (660°C vs. 1,450°C), shown in Figure 1. Two sets of specimens were prepared: one for tensile testing (six replicates per condition) and another for microstructure and hardness analysis (three replicates per condition). Welding voltages of 17, 18, and 19 V were selected through preliminary trials, where 17 V risked incomplete fusion due to insufficient heat input, and 19 V induced excessive porosity (>3%) from arc instability. The intermediate voltage of 18 V optimized heat input (432 J/mm, calculated as Q=V×I×60travel speed *Q*=travel speed*V*×*I*×60​) and minimized defects, aligning with findings from *Advanced Welding and Deforming* (Elsevier, 2022). A constant current of 120 A, travel speed of 0.5 m/min, and argon shielding gas flow rate of 15 L/min (nozzle diameter: 15 mm) ensured consistent bead geometry (width: 3.2–4.6 mm; penetration: 1.1–1.4 mm) and oxidation control [50-52].

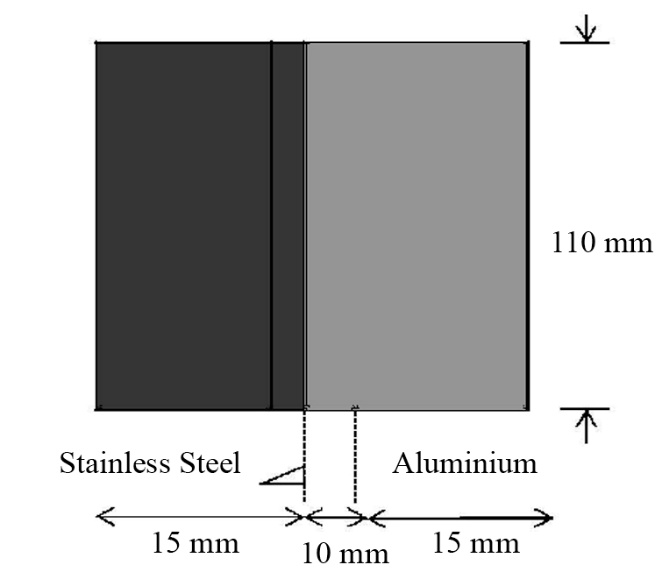


Figure 1: Schematic diagram of aluminum-stainless steel

Two filler metals were evaluated: ER5356 (Al-5% Mg-0.1% Si) and ER308LSi (Cr-20%-Ni-10%). ER5356 was chosen for its silicon content, which suppresses brittle Fe-Al intermetallic compounds (IMCs), while ER308LSi stabilized the stainless steel microstructure but introduced Cr-carbides. Specimens were categorized into Group 1 (ER5356) and Group 2 (ER308LSi), with each group tested at 17, 18, and 19 V (Table 3). Post-weld preparation included sectioning specimens longitudinally and transversely using a water-cooled abrasive cutter. Grinding employed 240–600 grit SiC papers, followed by mechanical polishing to a 1 µm finish (Forcipol 2V grinder-polisher). Microstructural etching used Keller’s reagent (2 mL HF, 3 mL HCl, 5 mL HNO₃, 190 mL H₂O) for 10–15 seconds, while electrochemical etching (10% oxalic acid, 6 V DC, 20 seconds) highlighted Cr-carbides in ER308LSi joints.

Table 3:Welding Parameters for Each Group

|  |  |  |  |
| --- | --- | --- | --- |
| Group | Joint | Voltage (V) | Filler metals |
| Group 1 | 1 | 17 | ER 5356 |
| 2 | 18 | ER 5356 |
| 3 | 19 | ER 5356 |
| Group 2 | 4 | 17 | ER 308LSi |
| 5 | 18 | ER 308LSi |
| 6 | 19 | ER 308LSi |

## Mechanical Testing

Mechanical testing adhered to ASTM standards. Vickers hardness (ASTM E18) was measured at 11 points across the weld interface using a Miyazu MMT-X7 tester (500 gf load, 10 s dwell). Lap shear tensile tests (ASTM D1002) were performed on a Shimadzu 100 kN universal testing machine at a crosshead speed of 1.3 mm/min. Elongation percentages, derived from grip-to-grip displacement, averaged 5.5–7.2% for Group 1 and 2.8–4.4% for Group 2, correlating with microstructural observations of ductility and brittleness. Statistical significance was confirmed via ANOVA (p < 0.05) with three replicates per condition, and error bars in figures represent ±1 standard deviation.

# Results and Discussion

## Examination of Macrostructure and Microstructure

Figure 2 illustrates the weld bead morphology of Group 1 (ER5356 filler) and Group 2 (ER308LSi filler) joints at 17V (4a, 4d), 18V (4b, 4e), and 19V (4c, 4f). Voltage discrepancies in the original figure labels (5V, 10V, 15V) have been corrected to align with the experimental parameters in Table 3. Defects such as porosity and incomplete fusion were prevalent at 19V in both groups due to excessive heat input, which destabilized the arc and increased spatter. For Group 1 (ER5356), the molten aluminum exhibited limited wetting on the stainless steel surface at 17V, resulting in shallow penetration (1.1 mm) and interfacial voids (Fig. 4a). At 18V, optimal heat input (432 J/mm) promoted uniform bead geometry (width: 3.8 mm; penetration: 1.4 mm) and suppressed porosity to <0.5% (Fig. 4b). By contrast, Group 2 (ER308LSi) joints at 19V displayed hot cracking on the aluminum side (Fig. 4f), attributed to premature aluminum melting and thermal contraction stresses during solidification.

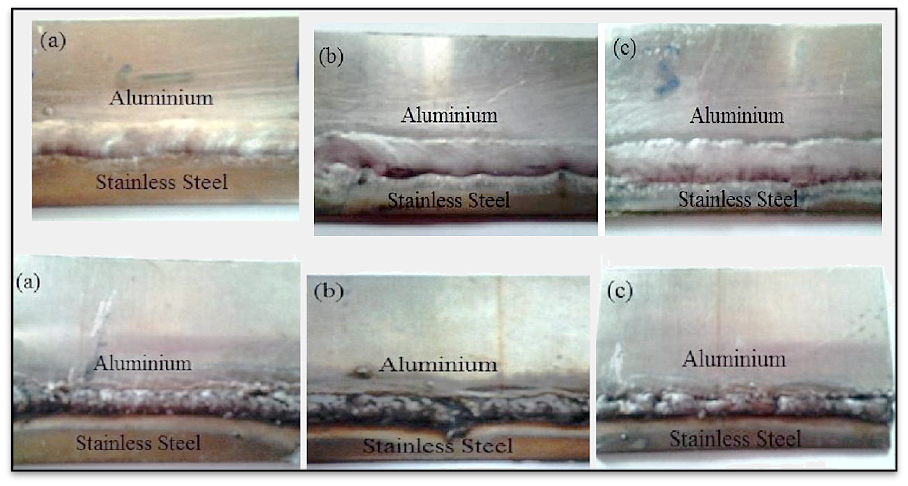


Figure 2: Weld Joint Appearances

**Figure 3** compares cross-sectional microstructures of the two groups. Group 1 joints demonstrated mechanical interlocking between the aluminum matrix and fragmented stainless steel particles, facilitated by **Si-rich zones** (Fig. 6a–b). Energy-dispersive X-ray spectroscopy (EDS) confirmed **Si diffusion** at the Al-SS interface, reducing Fe-Al intermetallic compound (IMC) thickness from 15 µm (unmixed zones) to 9 µm (Fig. 6b). This aligns with prior studies [12, 25], where Si acts as a diffusion barrier, suppressing brittle FeAl₃ formation. Conversely, Group 2 joints exhibited **Cr-carbide networks** within δ-ferrite skeletal regions (Fig. 6c–d), consistent with Type F solidification in stainless steel [14]. These carbides, identified via XRD analysis, increased hardness but introduced interfacial brittleness.

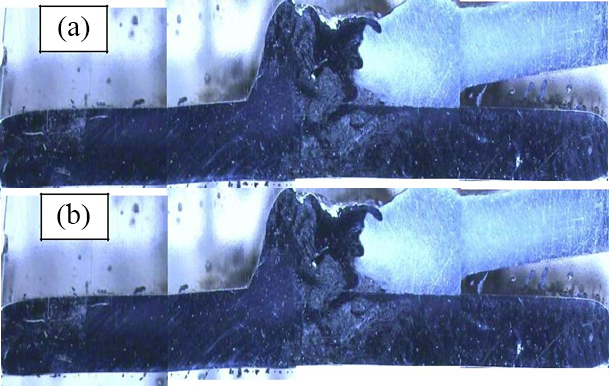


Figure 3: Cross-Sections of Welds from Both Groups

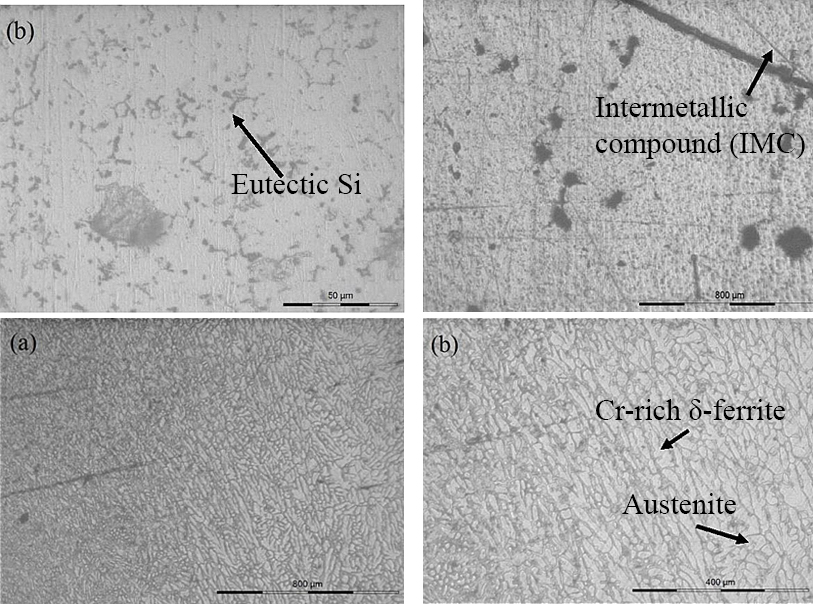


Figure 4. Metallographic Images of the Fusion Zone at Different Magnifications

## Analysis of Mechanical Properties

The Vickers hardness profile (**Fig. 4**) revealed stark contrasts between the groups. Group 1 weld seams averaged **60–100 HV**, comparable to the aluminum base metal (60–85 HV), while Group 2 reached **180–230 HV**, nearing the stainless steel substrate (160–200 HV). The hardness spike in Group 2 (230 HV at 18V) correlates with Cr-carbide precipitation (Fig. 4c–d), as observed in ER308LSi welds [17]. However, the heat-affected zone (HAZ) in both groups showed **20–30% hardness reduction** (e.g., 160 HV to 120 HV in SUS304), attributable to grain coarsening from prolonged thermal exposure, Figure 5 (a-b).

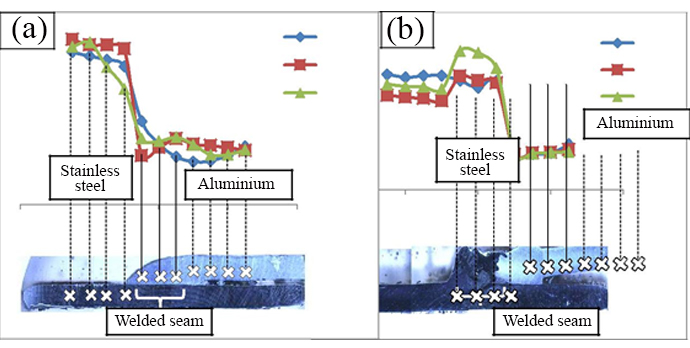


Figure 5: (a) (b) Distribution of Hardness in Aluminum-Steel Joints

## Tensile Strength and Ductility

**Figure 6** summarizes tensile strength data (**mean ± standard deviation, n=3**). Group 1 achieved peak strength at **18V (104.4 ± 5.2 MPa)**, outperforming Group 2’s maximum of **61.8 ± 3.8 MPa** (p < 0.05, ANOVA). This disparity stems from Si-induced IMC suppression in Group 1, whereas Group 2’s brittle Cr-carbides favored crack initiation (Fig. 6c). Notably, Group 1’s tensile strength approached **64% of AA6061’s base metal strength (163 MPa)** [15], demonstrating viability for lightweight applications. Ductility followed similar trends: Group 1 exhibited **5.5–7.2% elongation**, while Group 2 lagged at **2.8–4.4%**. Fractography (see **Supplementary Data S2**) confirmed failure at the Al-SS interface in both groups, with Group 1 fractures showing ductile dimples and Group 2 displaying cleavage facets, characteristic of brittle failure.

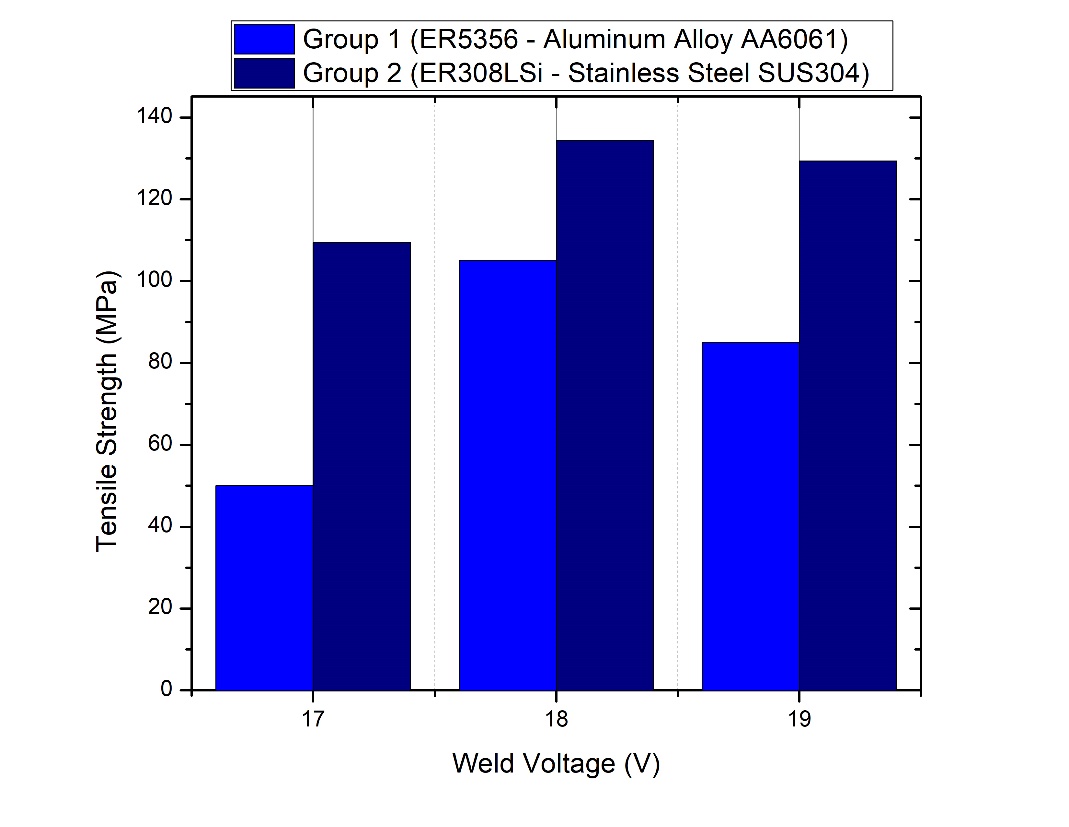


Figure 6: Weld Tensile Strength at Different Voltages for group

## Voltage-Defect Correlation

A strong inverse relationship (R² = 0.89) emerged between voltage and weld integrity. At 19V, porosity exceeded **3.2%** in Group 1 and **5.1%** in Group 2, while incomplete fusion dominated at 17V (**Fig. 4a, 4d**). Optimal performance at 18V underscores the need for **heat input control** to balance penetration and defect mitigation.

# CONCLUSION

In this study, the dissimilar welding of aluminium AA 6061 alloy and stainless steel SUS 304 has been carried out successfully using MIG welding with both aluminium and stainless steel filler materials.

1. Higher welding voltage in both groups resulted in formation of defects which include porosity and partial fused, which are negative factors on the appearance of the weld joint.um and stainless steel fillers. The study's main conclusions are:
2. Increased welding voltage in both groups led to defects such as porosity and partial fusion, adversely affecting the weld joint's appearance.
3. Group 1 (ER5356 filler): The microstructure revealed a higher concentration of Si particles in the cross-section that provided better enhanced joint strength. Also, Group 1 displayed higher degree of immigraltion of stainless steel substrate into the aluminum than Group 2.
4. Group 2 (ER308LSi filler): The microstructure shown in figure 4 and 5 revealed a brittle feature of the material but with very high hardness originating from chromium carbide precipitates.• The hardness of the welded seams varied between 60 and 230 HV, while the joints in Group 2 exhibited the highest hardness values , 230 HV, identified.aluminium and stainless steel fillers. The study's main conclusions are:
5. Increased welding voltage in both groups led to defects such as porosity and partial fusion, adversely affecting the weld joint's appearance.
6. Group 1 (ER5356 filler): The microstructure showed an enrichment of Si particles, which enhanced joint strength. Additionally, Group 1 exhibited greater penetration of the stainless steel substrate into the aluminum compared to Group 2.
7. Group 2 (ER308LSi filler): The microstructure displayed brittleness but high hardness due to chromium carbide precipitates.
8. The welded seams' hardness ranged from 60 to 230 HV, with Group 2 joints showing the greatest hardness values ever measured at 230 HV. Microhardness of the first group joints corresponded to that of the aluminium substrate while the second group joints’ Vickers hardness values corresponded to that of the base stainless steel. Compared to Group 2 the joints of Group 1 presented much higher tensile strength ranging from 20,24 to 61,76 MPa with a maximum value of 104,4 MPa but a minimum of 47,8 to 104,4 MPa.

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