

Root-gap-dependent process window and weldability transition map for DCEN-GTAW butt joining of 0.08 mm AA3003 aluminum foil

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Root-gap-dependent process window and weldability transition map for DCEN-GTAW butt joining of 0.08 mm AA3003 aluminum foil

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Abstract.

Establishing a suitable operating region for joining ultra-thin aluminum foil is challenging because small changes in thermal input can cause a transition from insufficient fusion to burn-through. This study experimentally investigates the weldability transition of 0.08 mm AA3003 aluminum foil during butt joining using direct-current electrode-negative gas tungsten arc welding (DCEN-GTAW) with dual argon shielding. Welding current was varied while travel speed, arc length, electrode geometry, and shielding conditions were kept constant. Three root-gap conditions of 0.5, 1.0, and 2.0 mm were investigated. Weld formation was classified as no stable weld, stable weld, or burn-through, with stable welds further evaluated through bead-width measurements and transverse metallography. Nominal heat input was calculated from the measured arc voltage, welding current, and travel speed. No stable weld was obtained at the 0.5 mm gap. At 1.0 mm, stable welding occurred at 5–10 A, while burn-through occurred at 15 A. At 2.0 mm, stable welding was maintained at 5–9 A before burn-through at 10 A. Bead width and HAZ generally increased with heat input. The results

demonstrate that weldability is strongly influenced by both welding current and root gap, providing an initial weldability-transition map for parameter selection in ultra-thin aluminum foil joining.

Keywords: AA3003 aluminum foil; ultra-thin-sheet welding; DCEN-GTAW; root gap; nominal heat input; weldability-transition map; burn-through.

1. Introduction

1.1. Background and industrial relevance

In GTAW of ultra-thin metal sheets, process control becomes exceptionally difficult because the available thermal window is extremely narrow; even a slight increase in welding current may cause burn-through, edge collapse, or severe distortion, whereas a slight decrease may result in lack of fusion or weld discontinuity [1], [2], [3], [4]. This difficulty has been clearly demonstrated in recent studies of ultra-thin sheets. Manh *et al.* reported that a novel GTAW process was required to achieve reliable butt joining of ultra-thin metal sheets down to 0.03 mm [4]. For aluminum foil, successful butt joining of 0.2 mm AA3003 was shown to depend strongly on heat-input control and arc stability [3]. Similarly, Ngo *et al.* demonstrated that butt joining of 0.2 mm ultra-thin silicon steel sheets required a specially adapted GTAW process to maintain weld quality and arc stability under highly constrained conditions [2]. In the low-current regime, Pang and Cao further showed that arc ignition and stability become increasingly difficult in micro-TIG welding, while later numerical analysis by Pang *et al.* confirmed that arcs below about 5 A are more prone to cathode spot movement, arc interruption, and unstable attachment behavior [1], [5]. Therefore, for ultra-thin-sheet GTAW, the central issue is not simply whether the arc can melt the material, but whether the applied current can be maintained within a sufficiently narrow range to produce stable fusion without thermal damage.

Ultra-thin metal sheets are increasingly used in high-value manufacturing sectors where lightweight structures, compact geometry, and high material efficiency are required. Representative examples include butt joining of ultra-thin raw-material coils in production lines [4], stainless-steel bipolar plates for proton exchange membrane fuel cells, where metallic sheets as thin as about 0.1 mm or even thinner are used [6], AA3003-based thin sheets for automotive heat exchangers [7], and laminated electrical steels for stator and rotor cores in electric machines [8]. In such applications, joint quality is highly consequential. Lack of fusion in ultra-thin-sheet welding can severely degrade joint integrity and even lead to seal failure [9].

At the same time, welding-induced thermal damage, residual stress, and distortion are particularly critical in thin-sheet butt joints because of their low structural stiffness [10]. For laminated electrical steels, joining-related damage may also deteriorate magnetic performance through coating disruption, microstructural modification, and residual-stress effects [8], [11]. Accordingly, reliable GTAW of ultra-thin sheets requires not only arc initiation capability but also precise selection of current conditions that can balance fusion and thermal protection.

From this perspective, welding current becomes one of the most decisive process variables in ultra-thin-sheet GTAW because it directly governs arc energy, heat input, and the transition between insufficient fusion and burn-through [1], [2], [3], [5]. Although the influence of welding current has been widely discussed for conventional sheet thicknesses, the applicable current window for butt joining of ultra-thin foil remains insufficiently clarified. This is especially true for open-gap butt-joint configurations, where the tolerance to thermal input is even smaller and successful weld formation depends simultaneously on the current level and gap condition [2], [3], [9]. Therefore, a systematic experimental identification of the feasible current window is needed to clarify the range in which stable joint formation can be achieved in ultra-thin AA3003 foil by GTAW. To illustrate the central role of welding-current control in ultra-thin sheet GTAW, **Figure 1** schematically summarizes the transition from insufficient fusion and weld discontinuity at low current to stable fusion within a narrow optimal range, and ultimately to edge collapse, severe distortion, and burn-through when the current becomes.

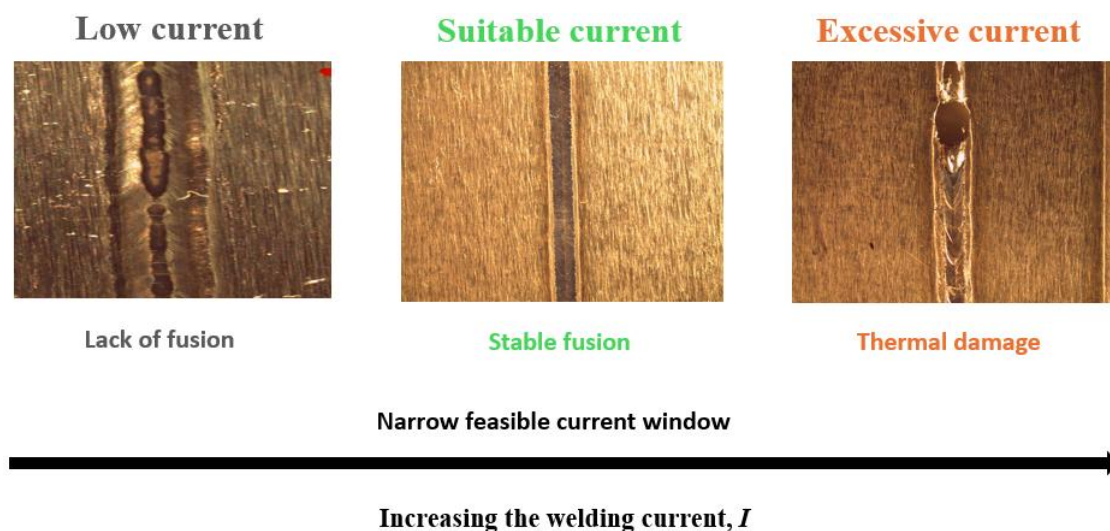


Figure 1. Schematic illustration of welding-current effects on joint formation in GTAW of ultra-thin metal sheets: insufficient fusion at low current, stable joint formation within a narrow feasible current window, and thermal damage at excessive current.

1.2 Research gap

Previous studies have demonstrated that GTAW-based joining of ultra-thin metallic sheets is feasible when the welding process is properly adapted [2], [3], [4]. In particular, successful joining has been reported for ultra-thin metal sheets in general [4], for 0.08 mm AA3003 aluminum sheets [3], and for ultra-thin silicon steel sheets [2]. In parallel, low-current micro-TIG studies have shown that arc ignition and stability become increasingly difficult as the current decreases toward the ultra-low regime [2]. These findings collectively indicate that ultra-thin-sheet welding is governed by a very narrow thermal and electrical operating window [1], [2], [3], [4].

However, the feasible current window for constant-current GTAW of ultra-thin AA3003 foil has not yet been systematically clarified. Although previous work has demonstrated the possibility of joining ultra-thin AA3003 sheets [3], limited information is available regarding how fixed current levels affect the transition among no-weld, successful fusion, and burn-through under butt-joint conditions with different root gaps. This limitation is important because, in ultra-thin-sheet GTAW, the allowable thermal margin is extremely small, and even a slight variation in current may significantly alter weld formation, bead continuity, and joint integrity [1], [2], [3].

Moreover, existing studies mainly emphasize process feasibility and joining outcomes rather than explicitly defining the practical operating boundaries for stable weld formation. In particular, the transition limits between insufficient fusion, acceptable gap bridging, and burn-through under different root-gap conditions have not yet been clearly established for 0.08 mm AA3003 foil [2], [3]. As a result, the current selection basis for butt joining of ultra-thin AA3003 foil by GTAW remains insufficiently defined. **Figure 2** summarizes the main technical challenges and unresolved questions motivating the present investigation. These include the narrow operating window of ultra-thin-sheet GTAW, the difficulty of low-current arc ignition, the unclear feasible current range, the limited understanding of current-dependent weld behavior, and the lack of experimentally defined transition boundaries.

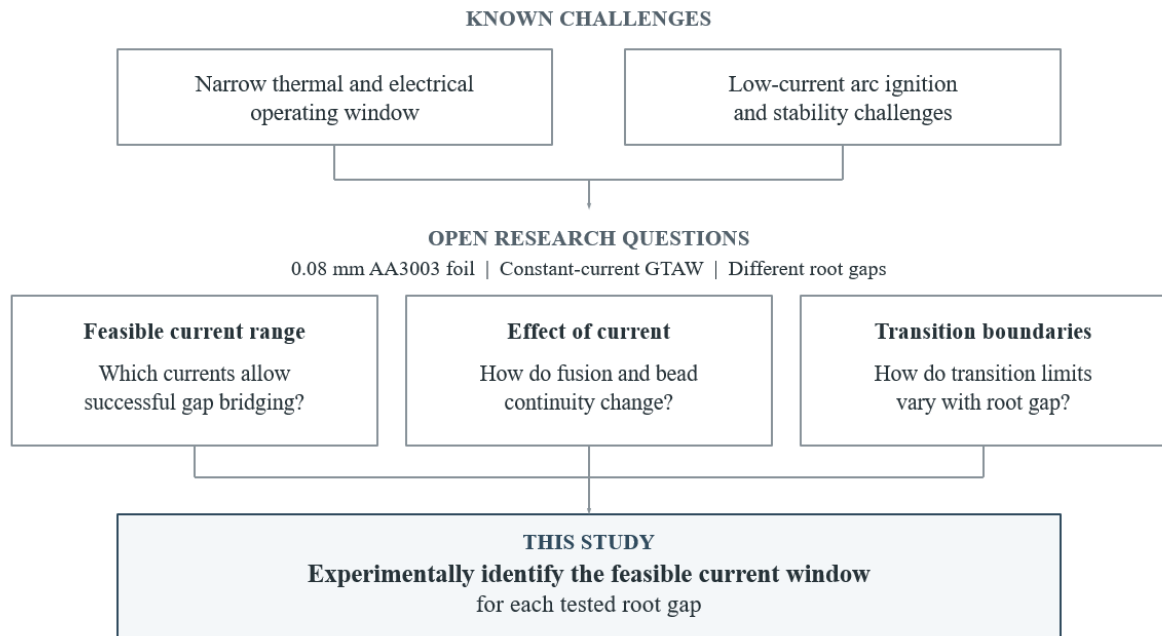


Figure 2. Schematic overview of the technical challenges and research questions motivating the identification of the feasible current window for constant-current GTAW butt joining of 0.08 mm AA3003 foil at different root gaps.

Therefore, a systematic experimental identification of the feasible current window is still needed for butt joining of 0.08 mm AA3003 foil by GTAW. Such clarification would provide not only a better understanding of weldability limits in ultra-thin-sheet joining but also a practical basis for selecting suitable current levels to achieve stable fusion while minimizing thermal damage, distortion, and burn-through [1], [2], [3].

1.3 Objective and contributions

This study experimentally characterizes the root-gap-dependent weldability transition behavior of 0.08 mm AA3003 aluminum foil during butt joining by DCEN-GTAW. Building on previous work that demonstrated the feasibility of joining ultra-thin AA3003 foil under selected welding conditions, the present investigation examines how the weld outcome changes with welding current under different nominal root-gap conditions. The study specifically distinguishes among three observed response states: no stable weld, stable weld formation, and burn-through [1], [2], [3], [4].

Welding current was selected as the principal process variable because it directly controls the arc energy delivered per unit length of the joint, whereas root gap was treated as

the geometric variable affecting molten-pool bridging and thermal stability. All remaining welding conditions were maintained constant so that the observed weldability response could be interpreted primarily in terms of current and root-gap interaction. In addition to outcome classification, face and root bead widths were evaluated for stable-weld conditions, and transverse metallographic observations were used to assess HAZ development as the process approached burn-through [12].

The contributions of the present study are threefold. First, it provides an experimental characterization of weldability-transition behavior in ultra-thin AA3003 foil under controlled DCEN-GTAW conditions. Second, it constructs an initial root-gap-dependent transition map from the tested matrix by distinguishing no-stable-weld, stable-weld, and burn-through outcomes. Third, it identifies candidate operating conditions within the observed stable-weld region by considering bead development and thermal influence on the surrounding foil. Because the present matrix is intended as an initial experimental mapping study, further repeated tests and boundary-refinement experiments are required before a statistically robust process window and recommended operating range can be established [1], [2], [3], [12].

2. Materials and Methodology

2.1 Materials and joint configuration

In this study, AA3003 aluminum foil with a thickness of 0.08 mm was used as the base material for butt-joint GTAW experiments. AA3003 is an Al–Mn alloy consisting primarily of aluminum, with manganese as the main alloying element. The alloy is widely used in thin-sheet applications because it offers a favorable combination of moderate strength, good ductility, excellent formability, and satisfactory corrosion resistance [3], [7]. These characteristics make AA3003 suitable for lightweight heat-transfer and thin-plate components, while also making it a representative material for investigating weldability under ultra-thin-sheet conditions. Owing to its extremely small thickness, however, the material possesses a very limited thermal tolerance during arc welding, so that even slight changes in energy input may cause insufficient fusion, local edge collapse, or burn-through [3].

A butt-joint configuration was selected in order to evaluate the weldability of ultra-thin AA3003 foil under highly restricted thermal conditions. This joint type was adopted because it represents a demanding joining condition in which both heat-input control and gap-bridging

capability are critical to successful weld formation. Unlike overlap-type joints, the butt-joint configuration provides little geometric tolerance to excessive or insufficient melting, making it suitable for identifying the practical welding limits of the process. In the present work, three fixture-gap conditions were considered, namely 0.5 mm, 1.0 mm, and 2.0 mm, to investigate how joint opening influences the feasible current window for weld formation. These gap values were selected to represent different levels of bridging difficulty and to clarify the transition behavior among no-weld, successful fusion, and burn-through under constant-current GTAW conditions.

To ensure repeatable alignment and consistent joint geometry, the foil specimens were mounted in a dedicated fixture during welding. The fixture was designed to hold the two foil edges in position, maintain the prescribed gap, and minimize unintended movement or misalignment during arc exposure. Such mechanical support is particularly important for 0.08 mm foil, since the extremely low thickness of the material makes it highly susceptible to thermal deformation and instability during welding. Therefore, the selected material and joint configuration provide an appropriate experimental basis for examining the weldability limits and feasible current window of ultra-thin AA3003 foil in GTAW butt joining. The material, joint geometry, and fixture arrangement used in this study are illustrated in **Figure 3**.

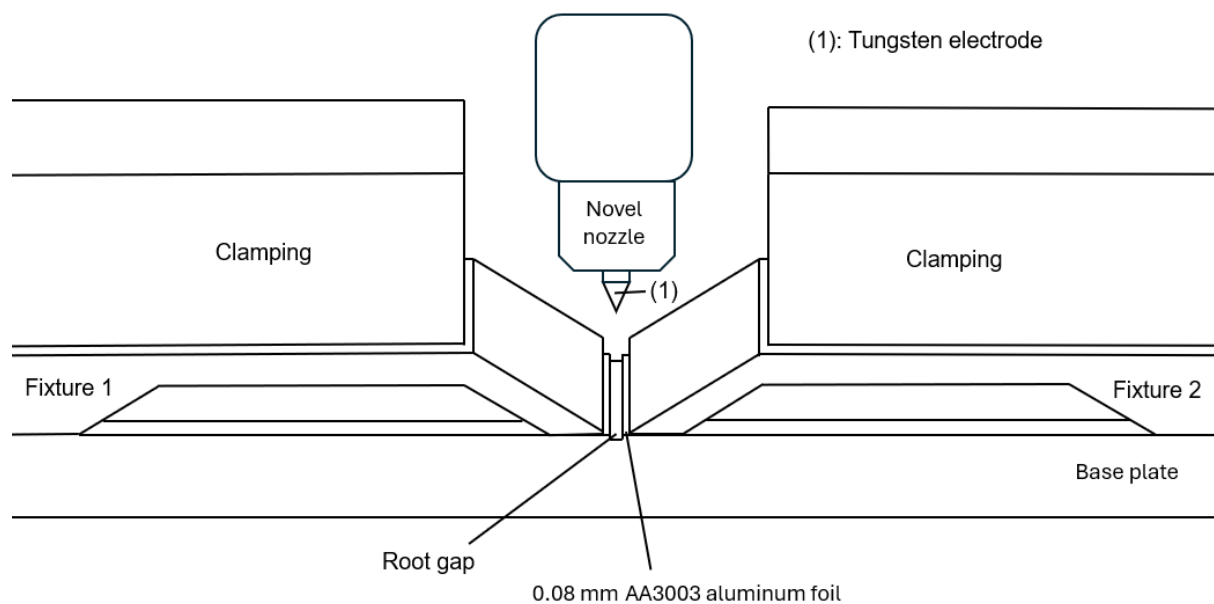


Figure 3. Schematic illustration of the experimental setup for GTAW of ultra-thin AA3003 aluminum foil.

2.2 Experimental setup

The welding experiments were carried out using a gas tungsten arc welding (GTAW) system operated in direct-current electrode-negative (DCEN) mode. This polarity was selected because previous studies on ultra-thin AA3003 aluminum foil have demonstrated the feasibility of butt joining under DCEN-based novel GTAW conditions [3]. In the present study, the DCEN-GTAW configuration comprised a non-consumable tungsten electrode, dual argon shielding through outer and inner gas flows, and a dedicated fixture for maintaining the prescribed butt-joint gap during welding. A non-consumable tungsten electrode with a diameter of 1.6 mm was used. The electrode tip angle reported in this study refers to the full tip angle, which was fixed at 45°. This value was selected on the basis of preliminary screening tests performed at 30°, 45°, 60°, and 90°. The choice of a sharp electrode geometry is also consistent with previous ultra-thin-sheet GTAW studies, in which a 45° tip angle and a 1.6 mm tungsten electrode were adopted to maintain stable welding behavior under highly restricted conditions [2]. The arc length was set to 0.3 mm in the present work to provide a highly localized arc suitable for butt joining of ultra-thin AA3003 foil. The use of a very short arc length is consistent with the general requirement of ultra-thin-sheet GTAW, where short arc operation is necessary to confine heat input and maintain weldability within a narrow thermal margin [4].

Pure argon was used for both the outer and inner shielding gases. The outer shielding gas flow rate was maintained at 6.0 L/min, while the inner shielding gas flow rate was fixed at 2.5 L/min. This shielding arrangement was adopted to protect the arc zone and molten region from atmospheric contamination while improving arc concentration and stability during welding. Previous studies on novel GTAW have also shown that multi-layer argon shielding and constricted gas flow play an important role in arc concentration, heat-input reduction, and stabilization of the molten region, particularly for ultra-thin sheets [2], [4]. The fixed welding conditions used in this study are summarized in **Table 1**.

Table 1. Fixed welding conditions used in this study

Parameter	Value
Base material	AA3003 aluminum foil
Thickness	0.08 mm
Welding process	DCEN GTAW

Travel speed	15 mm/s
Arc length	0.3 mm
Tungsten electrode diameter	1.6 mm
Electrode tip angle	45° (full tip angle)
Outer shielding gas	Pure Ar, 6.0 L/min
Inner shielding gas	Pure Ar, 2.5 L/min

During welding, the torch was aligned with the butt-joint line, and the foil specimens were mounted in a dedicated fixture to maintain the prescribed nominal root gap and minimize misalignment. Three nominal root-gap conditions, namely 0.5 mm, 1.0 mm, and 2.0 mm, were established using the fixture and subsequently examined in the experimental matrix described in Section 2.3. The fixture also helped suppress unintended movement of the foil during arc exposure, which was essential because of the very low stiffness and high thermal sensitivity of the 0.08 mm material. Except for the applied welding current and the prescribed nominal root-gap condition, all setup parameters, including polarity, travel speed, electrode geometry, arc length, shielding condition, torch alignment, and fixture arrangement, were kept constant throughout the experiments. This experimental arrangement allowed the observed weldability response to be examined under controlled conditions as a function of welding current and nominal root gap. The overall experimental setup used in the present study is illustrated in **Figure 4**.

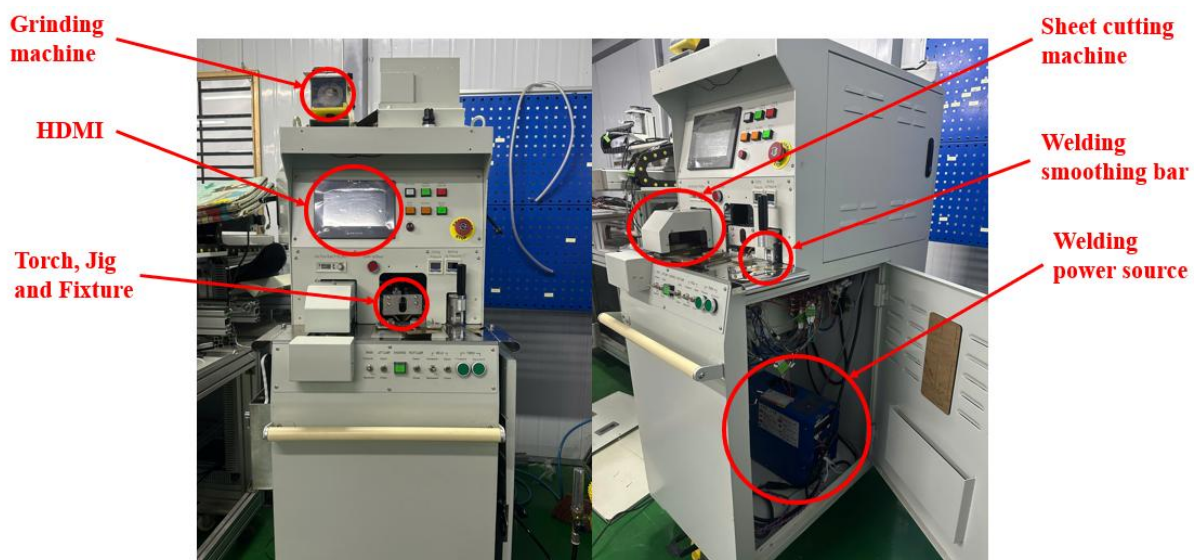


Figure 4. Experimental setup for butt welding of 0.08 mm-thick AA3003 aluminum foil using the DCEN-GTAW process with dual argon shielding and a dedicated fixture.

Figure 5 shows the key components of the welding system and specimen preparation equipment. The experimental setup comprised a sheet-cutting machine, electrode grinding machine, welding torch, jig and fixture, human-machine interface (HMI), welding power source, and welding smoothing bar. Prior to welding, the aluminum foil was cut to obtain straight and mutually perpendicular edges, ensuring consistent edge alignment along the joint line. The tungsten electrode was prepared using a dedicated grinding machine to obtain a consistent electrode geometry and reproducible arc characteristics.

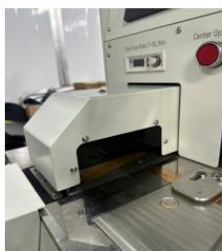
The welding torch was equipped with the proposed novel nozzle, which provided dual argon shielding and maintained the tungsten electrode in a controlled position relative to the joint. The jig and fixture secured the foil specimens and maintained the prescribed root gap throughout the welding process. The fixture also facilitated heat dissipation from the welding region, thereby limiting excessive thermal deformation of the ultra-thin foil. Welding parameters, including welding current, travel speed, and welding start and end positions, were configured through the touch-screen HMI. A welding power source supplied a stable direct-current electrode-negative (DCEN) output over the low-current range required for ultra-thin foil joining. After welding, a manually operated smoothing bar was applied along the weld line to reduce local surface irregularities and correct minor out-of-plane deformation.



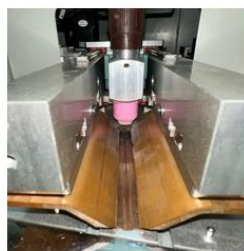
Grinding machine



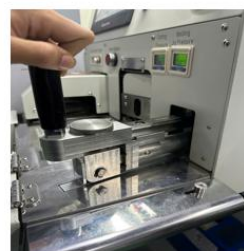
HMI



**Sheet cutting
machine**



**Torch, Jig,
and Fixture**



**Welding
smoothing bar**



**Welding
power source**

Figure 5. Detailed views of the key components of the experimental setup, including the HMI, welding torch and fixture, sheet-cutting machine, welding smoothing bar, welding power source, and grinding machine.

2.3 Experimental design and arc-energy calculation

A constant-current experimental strategy was adopted in this study to examine the weldability response of ultra-thin AA3003 foil under different nominal root-gap conditions. Welding current was treated as the principal process variable because it directly governs the electrical energy delivered to the joint and strongly affects the transition from insufficient fusion to stable weld formation and, eventually, to burn-through [1], [3]. In addition to welding current, the nominal fixture gap was considered as a secondary geometric variable, since the joint opening affects molten-pool bridging and is therefore expected to influence the practical current range for stable joining [2], [3].

All welding-system parameters described in Section 2.2 were kept constant throughout the experiments, except for the applied welding current and the prescribed nominal root-gap condition. These fixed parameters included DCEN polarity, travel speed, arc length, electrode geometry, shielding-gas conditions, torch alignment, and fixture arrangement. Under this controlled configuration, the observed weldability response was evaluated primarily in relation to the combined effects of welding current and nominal root gap.

Three nominal fixture-gap conditions, namely 0.5 mm, 1.0 mm, and 2.0 mm, were investigated. For the 0.5 mm gap condition, welding currents of 10, 20, 40, and 80 A were examined. For the 1.0 mm gap condition, currents of 5, 10, and 15 A were examined. For the 2.0 mm gap condition, currents from 5 to 10 A at 1 A intervals were examined. The selected matrix was used to provide an initial experimental mapping of the observed transition among no stable weld, stable weld, and burn-through under the investigated DCEN-GTAW conditions. Because the tested current intervals were not equally refined for all nominal gap conditions, the present matrix is interpreted as an initial weldability-transition assessment rather than as a statistically established definition of final process boundaries.

For comparison of the relative thermal severity among the tested conditions, the arc energy delivered per unit weld length was calculated from the measured average arc voltage, applied welding current, and travel speed according to:

$$E_l = \frac{VI}{v}$$

where (E_l) is the arc energy per unit length in J/mm, (V) is the measured average arc voltage in V, (I) is the welding current in A, and (v) is the travel speed in mm/s. Because no thermal-efficiency factor was introduced into this calculation, the reported quantity is referred to as arc energy per unit length rather than net heat input. The detailed experimental matrix, calculated arc-energy values, and observed weld outcomes are summarized in **Table 2**.

Table 2. Experimental matrix and weld outcomes for butt joining of ultra-thin AA3003 foil

Fixed welding conditions: DCEN polarity; travel speed = 15 mm/s; arc length = 0.3 mm; tungsten electrode diameter = 1.6 mm; full tip angle = 45°; outer Ar flow = 6.0 L/min; inner Ar flow = 2.5 L/min.						
Root gap (mm)	Current (A)	Average voltage (V)	Heat input (kJ/mm)	Weld condition	Face bead width (mm)	Root bead width (mm)
0.5	10	10.4	0.0069	No weld	—	—
	20	10.8	0.0144		—	—
	40	11.6	0.0309		—	—
	80	13.2	0.0704		—	—
1.0	5	10.2	0.0034	Successful weld	0.956	0.917
	10	10.4	0.0069	Successful weld	1.552	1.540
	15	10.6	0.0106	Burn-through	—	—
	5	10.2	0.0034	Successful weld	1.044	1.017
	6	10.2	0.0041	Successful weld	1.326	1.258

2.0	7	10.3	0.0048	Successful weld	1.407	1.338
	8	10.3	0.0055	Successful weld	1.462	1.672
	9	10.4	0.0062	Successful weld	1.705	1.727
	10	10.4	0.0069	Burn-through	–	–

In Table 2, the reported heat-input values were calculated from the measured average arc voltage, welding current, and travel speed using ($H = VI/v$). Because the thermal-efficiency factor was not explicitly introduced, these values should be interpreted as nominal heat input, equivalent to arc energy per unit length, rather than as the net heat absorbed by the foil. The term “successful weld” used in Table 2 corresponds to the stable-weld condition defined in Section 2.4.

2.4 Weld-outcome classification and bead-width measurement

The weldability of ultra-thin AA3003 foil under each experimental condition was evaluated on the basis of weld appearance, joint continuity, and bead geometry. For the purpose of this study, the observed welding outcome was classified into three categories, namely no stable weld, stable weld, and burn-through. This classification was adopted to distinguish the observed transition in weld formation as the applied current changed under each nominal root-gap condition, which is consistent with the narrow weldability range reported for ultra-thin-sheet GTAW [1], [2], [3].

A condition was classified as no stable weld when stable and continuous fusion across the butt joint was not obtained. Under this condition, the molten region did not effectively bridge the prescribed gap, and the joint remained discontinuous or incompletely fused along the examined welding path. A condition was classified as a stable weld when a continuous weld bead was formed along the joint line without visible perforation, severe collapse of the foil, or loss of joint continuity. In this case, effective fusion and gap bridging were observed while the joint geometry remained intact. A condition was classified as burn-through when excessive melting resulted in visible perforation, severe local edge collapse, or complete loss of joint continuity [2], [3].

In addition to qualitative classification, bead geometry was evaluated from the welded specimens. The face bead width and root bead width were measured from post-weld images to assess the influence of current level on weld formation. The face bead width was defined as the characteristic width of the fused region on the torch-facing surface of the joint, whereas the root bead width was defined as the corresponding fused width on the opposite surface. These geometric values were reported only for the stable-weld conditions, because no-stable-weld and burn-through cases did not provide continuous and measurable bead geometries suitable for comparison. Such geometric evaluation has also been commonly used in previous ultra-thin-sheet GTAW studies to characterize weld formation under highly restricted thermal conditions [2], [3], [4].

The arc energy per unit length calculated from the measured average arc voltage, applied current, and travel speed, as described in Section 2.3, was used as an indicator of the relative thermal severity of each tested condition. By combining weld-outcome classification with bead-width evaluation, the experimental results could be interpreted in terms of the current-dependent transition from insufficient joint formation to stable weld formation and, ultimately, to burn-through. This evaluation procedure provided the basis for constructing the initial root-gap-dependent weldability-transition map for DCEN-GTAW butt joining of 0.08 mm AA3003 foil under the investigated conditions [1], [2], [3].

2.5 Metallographic observation and HAZ measurement

Transverse metallographic observations were performed on selected specimens classified as stable welds in order to examine the development of the weld zone (WZ) and heat-affected zone (HAZ) under different welding-current conditions. Based on the experimental matrix summarized in **Table 2**, the examined cross-sections included the stable-weld conditions obtained at a nominal root gap of 1.0 mm under currents of 5 and 10 A, and at a nominal root gap of 2.0 mm under currents of 5, 6, 7, 8, and 9 A. The no-stable-weld conditions obtained at the 0.5 mm gap and the burn-through conditions observed at 15 A for the 1.0 mm gap and 10 A for the 2.0 mm gap were excluded because they did not provide continuous cross-sectional geometries suitable for comparative metallographic analysis. This approach is consistent with previous ultra-thin-sheet GTAW studies in which weld formation and thermally affected regions were examined under tightly controlled process conditions [2], [3], [4].

The selected specimens were sectioned perpendicular to the welding direction within a representative stable portion of the weld bead. The cross-sectional samples were mounted in epoxy resin, ground sequentially using SiC abrasive papers from 400 to 2000 grit, polished with diamond suspension to obtain a mirror-like finish, and etched using Keller's reagent (95 mL H₂O, 2.5 mL HNO₃, 1.5 mL HCl, and 1.0 mL HF) to reveal the weld microstructure. The prepared samples were subsequently examined using an optical microscope.

From the transverse metallographic images, three regions were distinguished: the weld zone (WZ), the heat-affected zone (HAZ), and the unaffected base-metal zone (BMZ). In the present study, the HAZ was defined exclusively as the thermally affected region located within the AA3003 foil adjacent to the WZ. The fixture and surrounding components were not included in the HAZ definition. This distinction is important because the present analysis focuses on the metallurgical influence of welding within the 0.08 mm foil rather than on heat dissipation into the supporting fixture. Previous studies have similarly reported that welding-current conditions affect weld-bead geometry, penetration behavior, and the extent of the thermally affected region [2], [3], [13].

The HAZ width was measured from calibrated transverse metallographic images using ImageJ software [14]. For each investigated condition, the reported HAZ width was determined as:

$$W_{\text{HAZ}} = x_{\text{BMZ}} - x_{\text{FB}}$$

where x_{FB} is the position of the fusion boundary and x_{BMZ} is the position at which the unaffected base-metal zone begins. Thus, W_{HAZ} represents the lateral extent of the thermally affected region between the fusion boundary and the unaffected base metal. For each welding condition, measurements were taken at three locations along the cross-section, and the average value was reported. HAZ-width measurements were reported only for the stable-weld conditions because the no-stable-weld and burn-through cases did not provide continuous cross-sectional geometries suitable for meaningful comparison.

A qualitative schematic is presented in **Figure 6** to illustrate the progressive widening of the WZ and adjacent HAZ as the welding current increases. The schematic is intended only as a conceptual representation and does not constitute a numerical thermal simulation. As shown in the figure, the WZ and HAZ remain entirely within the foil thickness, while the lateral extent of the affected regions increases as the process approaches the burn-through condition.

This qualitative trend is consistent with the increase in nominal heat input, equivalent to the arc energy delivered per unit weld length as defined in Section 2.3. Previous studies have likewise demonstrated that changes in welding-current conditions can modify bead geometry, penetration behavior, and HAZ development [3], [13].

To provide supplementary evidence of local microstructural variation across the weld-cross-section. Microhardness measurements were conducted under a test load of 0.05 kgf (HV0.05) with a dwell time of 10 s. Because the hardness profile was obtained from only one representative specimen, it was used as supplementary evidence and was not employed to define the weldability-transition boundaries or the candidate operating region.

The metallographic observations and supplementary microhardness measurements were interpreted together with the bead-geometry results to assess the progressive thermal influence associated with increasing welding current under the tested stable-weld conditions [3], [13].

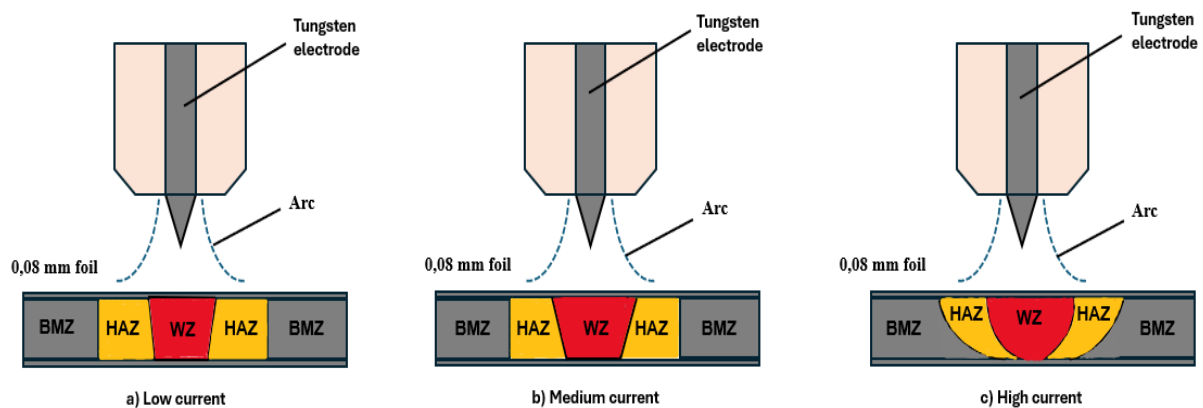


Figure 6. Schematic of weld-zone (WZ) and heat-affected-zone (HAZ) development in 0.08 mm AA3003 foil at different welding currents: (a) low, (b) medium, and (c) high (near burn-through). BMZ denotes the unaffected base-metal zone. Not to scale.

3. Results and Discussion

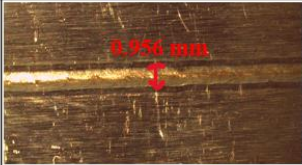
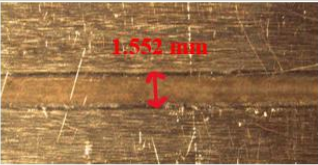
3.1. Classification of weldability transition states

Weld formation in ultra-thin AA3003 foil depended strongly on the applied welding current, and the response varied clearly with the fixture-gap condition. Under the present GTAW conditions, three distinct weldability states were identified, namely no weld, successful

weld formation, and burn-through. This behavior confirms that the joining of 0.08 mm AA3003 foil is governed by a narrow current window, within which the supplied energy is sufficient to produce continuous fusion but not excessive enough to cause thermal collapse of the foil.

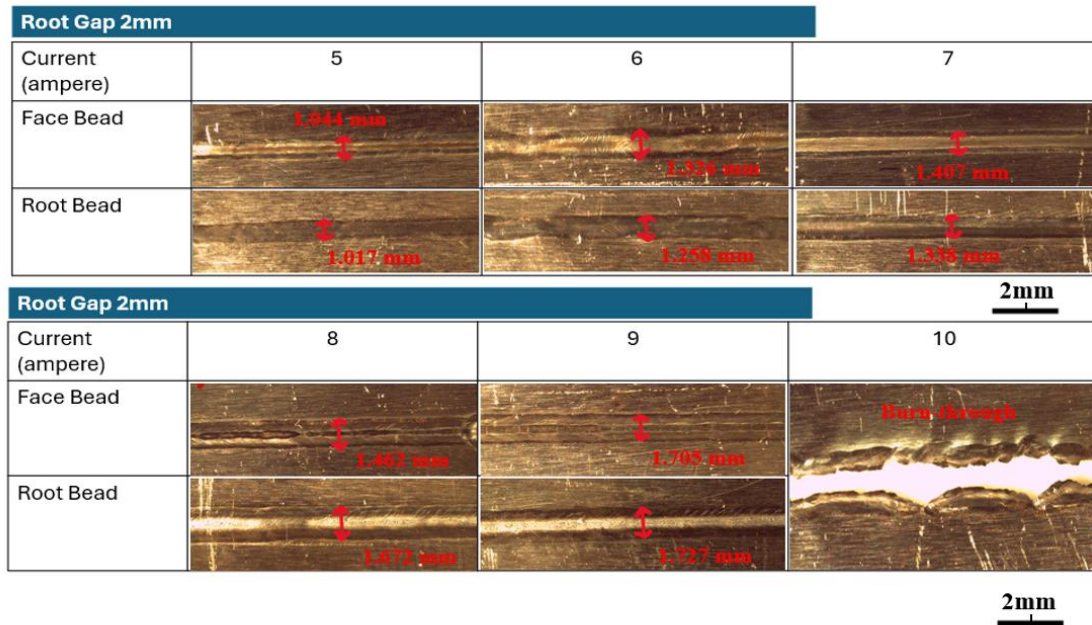
For the 0.5 mm fixture-gap condition, none of the tested current levels produced a stable weld, indicating that effective and continuous fusion was not achieved within the investigated range. By contrast, for the 1.0 mm gap condition, successful weld formation was obtained at 5 and 10 A, corresponding to heat inputs of 0.0034 and 0.0069 kJ/mm, whereas burn-through occurred at 15 A with a heat input of 0.0106 kJ/mm. For the 2.0 mm gap condition, the successful-weld region extended from 5 to 9 A, corresponding to a heat-input range of 0.0034–0.0062 kJ/mm, and burn-through occurred at 10 A with a heat input of 0.0069 kJ/mm. These results indicate that weldability was controlled not only by the current level, but also by the interaction between current magnitude and the root-gap condition.

Representative weld appearances are shown in **Figure 7**. The successful-weld condition in **Figure 7(a)** is characterized by continuous bead formation and effective gap bridging without visible perforation, whereas the burn-through condition in **Figure 7(b)** exhibits local collapse and clear perforation of the ultra-thin foil. Although the no-weld condition is not shown in the representative photographs, it was identified experimentally by the absence of stable and continuous fusion across the butt joint.

Root Gap 1mm			
Current (ampere)	5	10	15
Face Bead			
Root Bead			

2mm

a)



b)

Figure 7. Representative weld appearances under different welding-current levels for different fixture-gap conditions: (a) 1.0 mm gap and (b) 2.0 mm gap.

Overall, the results demonstrate that weld formation in ultra-thin AA3003 foil is highly sensitive to welding current and associated heat input. A current level that is too low cannot establish effective joint formation, whereas excessive current rapidly leads to burn-through. Between these two extremes, only a narrow operating region allows stable weld formation. This weldability transition provides the basis for the subsequent analyses of bead geometry, HAZ development, and practical current-window definition.

3.2. Bead-geometry evolution within the stable-weld region

The influence of welding current on bead geometry is shown in **Figure 8(a)** and **Figure 8(b)**. In general, both the face bead width and root bead width increased with heat input under the successful-weld conditions, indicating that higher current promoted a larger fused region. However, the increase was not uniform over the whole range, and the geometric response depended on the root-gap condition.

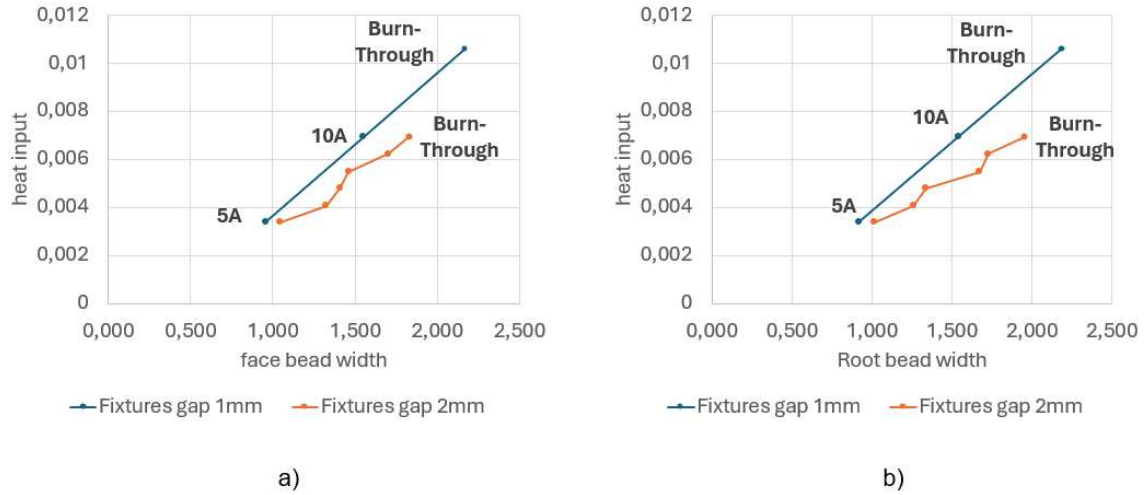


Figure 8. Relationship between heat input and measurable bead width under successful-weld conditions for different fixture-gap conditions: (a) face bead width and (b) root bead width.

For the 1.0 mm gap condition, only two successful-weld points were obtained before burn-through occurred. As the heat input increased from 0.0034 to 0.0069 kJ/mm, the face bead width increased from 0.956 to 1.552 mm, while the root bead width increased from 0.917 to 1.540 mm. The close agreement between face-side and root-side widths suggests that fusion developed in a relatively balanced manner through the foil thickness. When the heat input increased further to 0.0106 kJ/mm at 15 A, the joint failed by burn-through, indicating that the upper thermal limit had been exceeded.

A more detailed trend was observed for the 2.0 mm gap condition because a wider sequence of successful-weld data was available. As the current increased from 5 to 9 A, the face bead width increased from 1.044 to 1.705 mm, whereas the root bead width increased from 1.017 to 1.727 mm. Although both increased overall, the face bead did not expand at a constant rate. The largest face-side increase occurred between 5 and 6 A, where the width increased from 1.044 to 1.326 mm. By contrast, the increases from 6 to 7 A and from 7 to 8 A were much smaller, with the face bead width increasing only to 1.407 and 1.462 mm, respectively.

This non-uniform response suggests that the interval from 5 to 6 A corresponded to a threshold region for stable molten-pool formation and effective gap bridging. Beyond this threshold, further increases in current did not produce a similarly large lateral expansion on the face side. Instead, the additional thermal input appears to have contributed more strongly to through-thickness fusion and root-side development. This interpretation is consistent with the root bead data in **Figure 7(b)**, which shows a more pronounced increase at higher current

levels, particularly from 7 to 8 A, where the root bead width increased from 1.338 to 1.672 mm.

Another notable feature is that, for the 2.0 mm gap condition, the root bead width became slightly larger than the face bead width at higher successful-weld currents. At 8 A, the face bead width was 1.462 mm, whereas the root bead width reached 1.672 mm; at 9 A, the corresponding values were 1.705 and 1.727 mm. This indicates that, as the process approached the burn-through threshold, through-thickness penetration became increasingly dominant. Once the current reached 10 A, corresponding to a heat input of 0.0069 kJ/mm, burn-through occurred, and no stable measurable bead could be obtained.

Overall, the bead-geometry results show that increasing welding current enlarged both the face-side and root-side fused regions, but the response was not purely linear. At low current, a moderate current increase strongly improved bead formation, whereas at higher current, the additional heat was increasingly associated with deeper penetration and root-side widening. At excessive current, the thermal load exceeded the capacity of the ultra-thin foil and resulted in burn-through. These geometric trends provide important evidence for defining the practical limits of the feasible current window in ultra-thin AA3003 foil GTAW.

3.3. Thermal influence and HAZ evolution approaching the burn-through boundary

The influence of welding current on HAZ development was evaluated through transverse metallographic observations, in which the weld zone (WZ), heat-affected zone (HAZ), and base metal zone (BMZ) could be clearly distinguished. In general, the metallographic results showed that increasing welding current enlarged not only the weld zone but also the adjacent HAZ, indicating that a greater amount of thermal energy was transferred from the fusion region into the surrounding ultra-thin foil. This trend is consistent with the increase in heat input associated with higher current levels and confirms that HAZ development is a sensitive indicator of thermal loading in GTAW of 0.08 mm AA3003 foil.

For the 1.0 mm root-gap condition, representative transverse sections are shown in **Figure 9**. At 5 A in **Figure 9(a)**, the HAZ remained relatively narrow and was confined close to the fusion boundary, indicating that the thermal influence on the surrounding foil was limited under the lower-current condition. At 10 A in **Figure 9(b)**, both the WZ and the HAZ became visibly wider, showing that the increase in current promoted stronger fusion and greater thermal

diffusion into the adjacent base material. This comparison indicates that, even within the successful-weld region, the thermal margin of the ultra-thin foil decreased noticeably as the current increased. At 15 A, burn-through occurred; therefore, no stable HAZ morphology suitable for comparative metallographic measurement was considered for that condition.

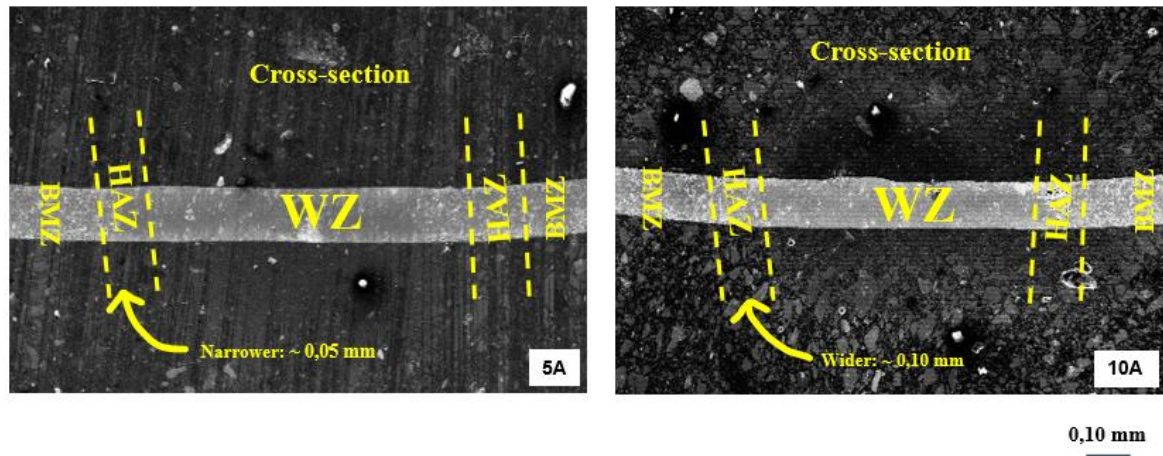


Figure 9. Representative transverse metallographic images of welds produced at a root gap of 1.0 mm: (a) 5 A and (b) 10 A, showing the weld zone (WZ), heat-affected zone (HAZ), and base metal zone (BMZ).

A more detailed HAZ evolution was observed for the 2.0 mm root-gap condition, as shown in **Figure 10**. At 5 A, the HAZ was relatively limited, and the thermally affected region remained close to the weld center. As the current increased to 6 A and 7 A, the HAZ expanded gradually, indicating progressive growth of thermal influence in the surrounding foil. At 8 A and 9 A, the HAZ became more pronounced, and the thermally affected region extended farther from the fusion boundary. This progressive widening suggests that the additional energy introduced at higher current levels was increasingly transferred beyond the weld zone and into the neighboring material. In other words, once stable joint formation had been established, further increases in current not only improved fusion but also increased the thermal burden imposed on the foil. At 10 A, burn-through occurred, and this condition was therefore excluded from the comparative HAZ image series.

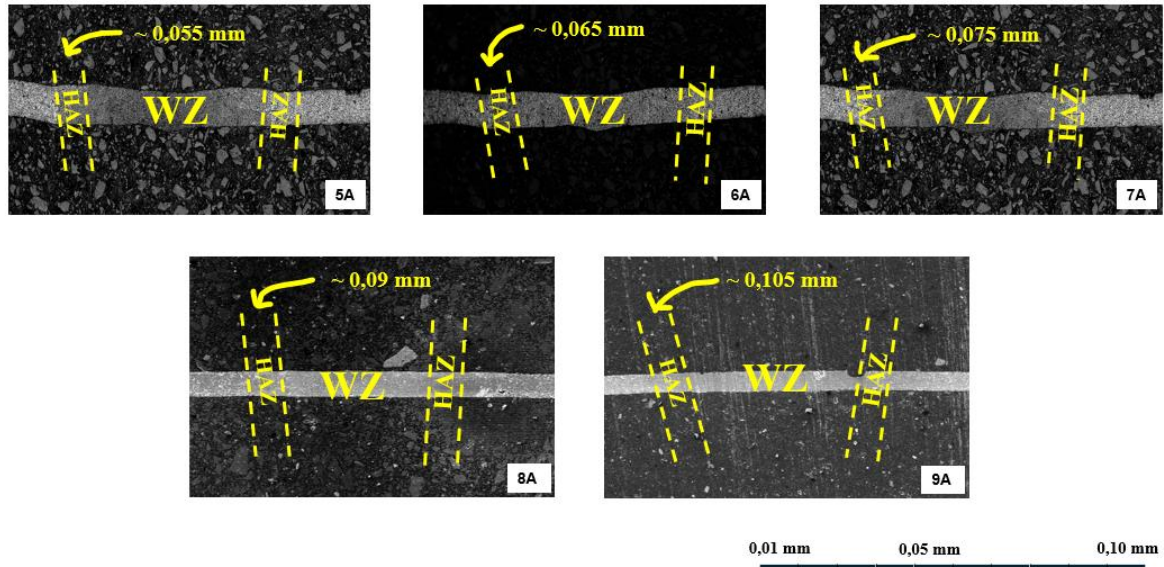


Figure 10. Representative transverse metallographic images of welds produced at a root gap of 2.0 mm under different welding currents: 5 A, 6 A, 7 A, 8 A, and 9 A, showing the evolution of the weld zone (WZ), heat-affected zone (HAZ), and base metal zone (BMZ).

The metallographic observations also support the bead-geometry results discussed in Section 3.2. In the intermediate-current range, where the increase in face bead width became less pronounced while the root bead width continued to increase, the HAZ images indicate that the added heat was increasingly associated with through-thickness penetration and outward thermal diffusion rather than simple face-side spreading. This explains why some increments in current produced only limited lateral widening on the face side while still leading to a clearly larger thermally affected region. Thus, HAZ development provides complementary evidence that the process was progressively approaching thermal overload as the current increased.

Overall, the HAZ observations confirm that welding current is a dominant factor controlling thermal influence in ultra-thin AA3003 foil GTAW. Although higher current can improve fusion and gap bridging, it simultaneously enlarges the thermally affected region and reduces the available safety margin before burn-through. Therefore, the HAZ results indicate that the practical welding condition should be selected not only based on successful joint formation, but also based on limited thermal damage to the surrounding foil.

To further support the metallographic interpretation, a supplementary Vickers microhardness traverse was performed across one representative weld cross-section, as shown in **Figure 11**. The measured profile showed a non-uniform hardness distribution across the

weld-affected region, with values ranging from 33.91 to 57.01 HV0.05 and a mean value of 44.23 HV0.05. This behavior is consistent with local microstructural modification induced by the welding thermal cycle. Although this result was obtained from a single specimen and is therefore not sufficient to establish generalized hardness trends for all welding conditions, it provides supportive evidence for the existence of a thermally and microstructurally differentiated weld region.

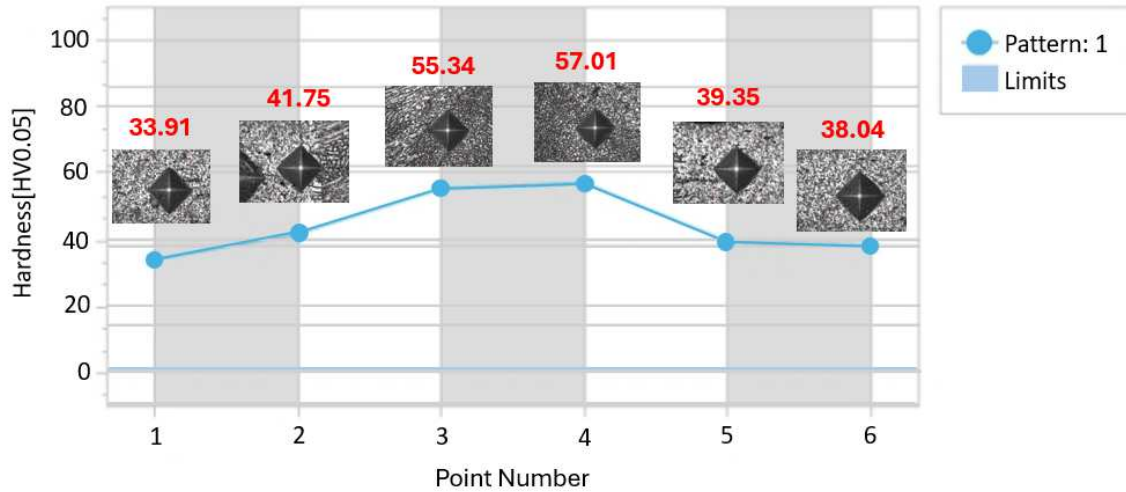


Figure 11. Microhardness profile across one representative weld cross-section

3.4. Root-gap-dependent process window

The experimental results demonstrate that the feasible current window for GTAW butt joining of ultra-thin AA3003 foil was strongly dependent on the root-gap condition. Although welding current was the principal process variable in the present study, the practical weldability of the joint could not be interpreted independently of the joint opening. This is because the root gap directly modifies the gap-bridging requirement of the molten region and, at the same time, affects the remaining thermal margin before burn-through [2], [3].

A clear difference in weldability response was observed among the investigated gap conditions. For the 0.5 mm gap, none of the tested current levels produced a stable weld, indicating that no feasible current window was identified within the investigated range. For the 1.0 mm gap, successful weld formation was obtained at 5 and 10 A, whereas 15 A resulted in burn-through. For the 2.0 mm gap, successful weld formation was maintained over a broader tested range from 5 to 9 A, while burn-through occurred at 10 A. These results show that the

feasible current window did not change monotonically in a simple manner with gap size, but instead depended on how the joint opening interacted with molten-pool development and thermal stability [1], [2], [3].

From the present data, the lower and upper bounds of the feasible window can be interpreted separately. The lower bound is associated with the onset of effective fusion and stable gap bridging, whereas the upper bound is associated with excessive thermal input leading to local collapse and burn-through. In this sense, the 1.0 mm gap retained a larger upper thermal margin than the 2.0 mm gap, since successful welding was still achieved at 10 A for the former but not for the latter. By contrast, the 2.0 mm gap showed a longer sequence of successful-weld conditions within the tested range, but the process approached burn-through more rapidly at the upper end. This interpretation is also consistent with previous studies emphasizing the narrow thermal tolerance of ultra-thin-sheet joining, the difficulty of low-current arc control, and the high sensitivity of thin butt joints to thermal damage and distortion [1], [9], [10].

Overall, the effect of root gap on the feasible current window should therefore be understood as a combined geometric and thermal constraint. A gap-dependent current selection is required because a condition that is acceptable for one joint opening may become insufficient or thermally excessive for another. Accordingly, the feasible current window for ultra-thin AA3003 foil GTAW should be regarded not as a single current range, but as a root-gap-dependent operating region defined by the balance among fusion capability, bead stability, HAZ development, and resistance to burn-through [3], [9], [10].

The contribution of the present study should be distinguished from the feasibility demonstration reported in previous work on ultra-thin AA3003 foil joining. Whereas the earlier study established that a sound butt joint could be produced under selected novel-GTAW conditions, the present work examines how the weldability response changes across combinations of nominal root gap and welding current. The principal outcome is therefore not another demonstration of successful joining, but an initial experimental mapping of the transition from no stable weld to stable weld formation and finally to burn-through. This distinction is important for practical parameter selection because a successfully demonstrated condition does not by itself reveal the thermal margin available before loss of joint continuity or foil collapse occurs.

3.5. Weldability transition map and candidate operating region

The experimental results indicate that the weldability response of ultra-thin AA3003 foil progressed through three distinct states as the welding current increased: no weld, successful fusion, and burn-through. This transition reflects the balance between two competing requirements in ultra-thin-sheet GTAW: the current must be high enough to generate stable fusion and effective gap bridging, but still low enough to avoid excessive thermal loading and collapse of the foil [1], [3], [5]. Because the thickness of the material was only 0.08 mm, the interval between these two limits was extremely narrow under the present butt-joint conditions [1], [3].

In the no-weld region, the applied current was insufficient to sustain stable and continuous fusion across the joint opening. Under these conditions, the molten region could not effectively bridge the prescribed gap, and the joint remained discontinuous or unfused. This state corresponds to the lower bound of the operating window, where the supplied arc energy is below the threshold required for practical weld formation. In ultra-thin-sheet welding, such conditions are also associated with a lack of fusion and unstable joint continuity [1], [9]. **Figure 12** presents the initial experimental weldability transition map constructed from the tested combinations of welding current and nominal root gap. The map distinguishes among no-weld, successful-weld, and burn-through conditions. Only the experimentally tested conditions are plotted; blank regions represent untested conditions, and no continuous process boundaries are inferred from the present dataset.

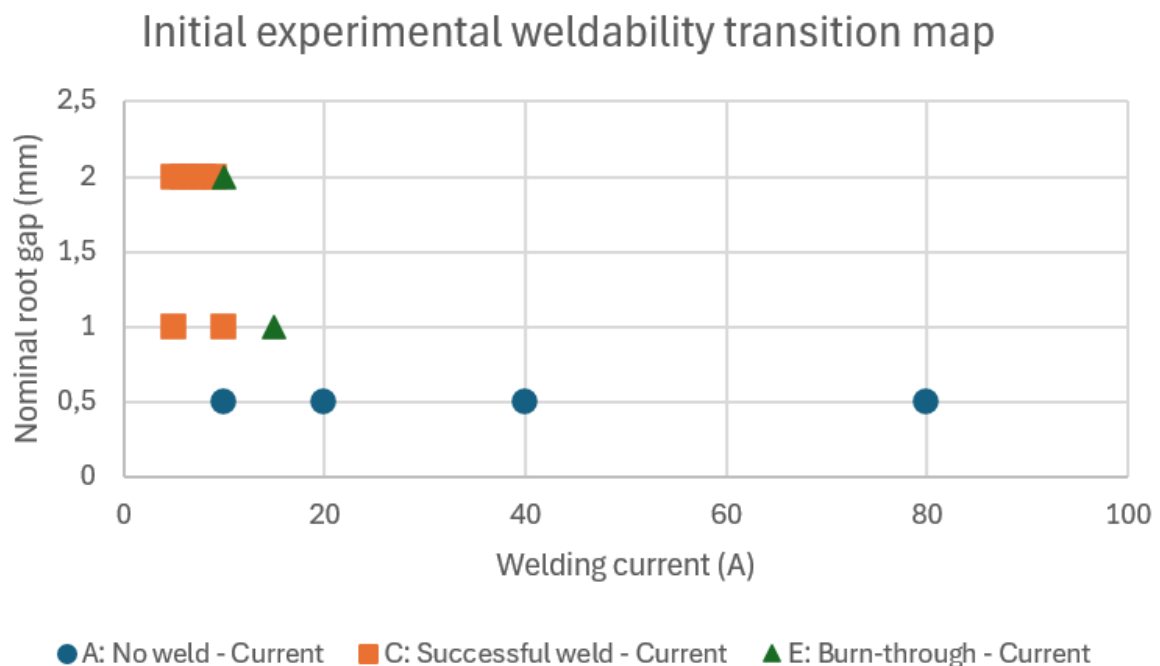


Figure 12. Experimental weldability transition map for DCEN-GTAW butt joining of 0.08 mm AA3003 aluminum foil at different nominal root gaps. Symbols indicate tested conditions only; blank regions represent untested conditions.

As the current increased into the successful-weld region, the thermal input became sufficient to establish a stable molten pool and continuous joint formation. In this range, effective gap bridging was achieved without visible perforation or collapse, and measurable bead widths could be obtained on both the face and root sides. This region, therefore, represents the practically useful operating range of the process, in which both fusion capability and thermal stability are maintained simultaneously [3], [5].

When the current increased further, the process entered the burn-through region. In this state, the added heat no longer contributed only to stable fusion but increasingly promoted deeper penetration, stronger root-side development, and wider thermal influence in the surrounding foil. Once the upper thermal limit was exceeded, the ultra-thin material could no longer support the molten region, and local collapse or perforation occurred. In this sense, burn-through should be understood not as an isolated event, but as the final stage of a progressive transition from stable joining to thermal overload [3], [10].

This transition from no weld to successful fusion and ultimately to burn-through can therefore be interpreted as a current-driven evolution of fusion capability and thermal damage. At insufficient current, the process fails because fusion is incomplete; at intermediate current, stable joining becomes possible; and at excessive current, the foil's thermal capacity is exceeded. Such behavior explains why the feasible current window in ultra-thin AA3003 foil GTAW is inherently narrow and highly sensitive to both current magnitude and root-gap condition [1], [3], [9], [10].

3.6. Practical current-window map for ultra-thin AA3003 foil GTAW

Based on the combined results of weld formation, bead geometry, and HAZ development, the practical current-window map for GTAW butt joining of ultra-thin AA3003 foil can be interpreted as a root-gap-dependent operating region rather than a single current range. In practical terms, a welding condition should not be regarded as acceptable solely because fusion is achieved. Instead, the condition should simultaneously satisfy three requirements: stable joint continuity, acceptable bead geometry, and limited thermal damage to the surrounding foil [3], [10], [15].

For the 0.5 mm root-gap condition, no stable weld was obtained within the investigated current range. Accordingly, no practical current window could be identified under the present conditions. For the 1.0 mm root-gap condition, successful weld formation was achieved at 5 and 10 A, while burn-through occurred at 15 A. This result indicates that a practical operating range exists, but the present matrix remains too sparse near the upper boundary to define the recommended sub-range with high precision. For the 2.0 mm root-gap condition, successful weld formation was maintained from 5 to 9 A, whereas burn-through occurred at 10 A. This condition, therefore, exhibited the clearest successful-weld region within the tested range, although the thermal margin near the upper limit became progressively smaller as the current approached 10 A [1], [3], [9].

A practical interpretation of the current-window map should therefore distinguish between merely feasible and practically recommended conditions. The lower part of the successful-weld region is limited by insufficient fusion and unstable gap bridging, whereas the upper part is limited by excessive penetration, HAZ expansion, and imminent burn-through [1], [9], [10]. The most suitable practical condition is thus expected to lie within the intermediate part of the successful-weld region, where continuous fusion is achieved while both bead enlargement and thermal damage remain controlled. Under the present conditions, this balance appears more favorable in the mid-range of the successful-weld region than at the upper boundary, where root-side development and HAZ growth become increasingly pronounced [3], [10], [15].

The practical current-window map proposed in this study therefore provides more than a simple pass-fail classification. It establishes an application-oriented basis for current selection in ultra-thin AA3003 foil GTAW by distinguishing unsuitable conditions, feasible conditions, and more practically reliable operating conditions. Such a framework may be useful for subsequent fixture design, parameter refinement, and future development of current-control strategies for ultra-thin-sheet joining [3], [15].

4. Conclusions

This study investigated the root-gap-dependent weldability transition behavior of 0.08 mm AA3003 aluminum foil during butt joining using DCEN-GTAW with dual argon shielding. Under the investigated conditions, no stable weld was obtained for the 0.5 mm nominal gap. For the 1.0 mm gap, stable welds were observed at 5 and 10 A, whereas burn-through occurred

at 15 A. For the 2.0 mm gap, stable weld formation was maintained from 5 to 9 A, followed by burn-through at 10 A, indicating the clearest observed stable-weld region within the tested matrix.

Within the stable-weld conditions, both face and root bead widths generally increased with increasing arc energy per unit length. In particular, the 2.0 mm gap condition showed stronger root-side development as the current approached the burn-through boundary. Metallographic observations further revealed progressive HAZ enlargement with increasing current, confirming that improved fusion capability was accompanied by a reduced thermal margin.

These results demonstrate that the weldability of ultra-thin AA3003 foil is governed jointly by welding current and nominal root gap. The present study therefore provides an initial experimental weldability-transition map for identifying candidate operating conditions, while further repeated tests and boundary-refinement experiments are required to establish a statistically robust process window.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CRediT authorship contribution statement

Quang Nam Nguyen: Conceptualization, Formal analysis, Investigation, Visualization, Writing – original draft. **Trong Duc Nguyen:** Experiment, Validation, Writing – review & editing. **Van Anh Nguyen:** Resources, Conceptualization, Supervision, Project administration, Writing – review & editing. **Manh Ngo Huu:** Writing – review & editing. **Thu Quy Le:** Writing – review & editing. **Thanh Hai Le:** Writing – review & editing.

Data availability

The raw materials and data are available from the corresponding authors on reasonable request.

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