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Optimization of Heat Input and Mechanical Performance in Cold Metal Transfer Welding of Thin Aluminum Joints

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Abstract

Cold Metal Transfer (CMT) welding has emerged as a highly effective low-heat-input joining technique for thin-gauge and heat-sensitive metallic substrates, particularly aluminum alloys and dissimilar metal combinations. The digitally controlled wire retraction mechanism inherent to CMT enables stable, spatter-free metal transfer while substantially mitigating thermal distortion relative to conventional arc welding processes. This study critically evaluates the influence of key process parameters voltage, current, wire feed rate, welding speed, and joint gap on heat input and resultant joint quality. Results demonstrate that reduced heat input correlates with diminished porosity, narrower heat-affected zones (HAZ), more favorable hardness distribution, and enhanced tensile strength. However, excessively suppressed heat input was found to compromise fusion adequacy and bead integrity, underscoring a critical process trade-off. Further analysis reveals that welding speed and current constitute the dominant variables governing thermal input, whereas wire feed rate exerts an indirect influence through synergic control mechanisms. Collectively, these findings establish CMT welding as a robust and metallurgically advantageous route for producing high-integrity joints, contingent upon judicious parameter optimization to circumvent

incomplete fusion and insufficient reinforcement. The outcomes offer meaningful implications for process optimization in industrial applications demanding precision, minimal distortion, and superior mechanical performance.

Keywords: Cold Metal Transfer, heat input, thin aluminum welding, weld quality, tensile strength, thermal distortion

1 Introduction

The evolution of arc welding technology, transitioning from traditional foundational processes to high-precision digital systems, represents a defining trajectory in modern joining research. Metal Inert Gas (MIG) and Tungsten Inert Gas (TIG) welding, established as industrial standards since the 1940s, have long constituted the backbone of fusion welding practice. TIG welding is recognized for producing high-quality, stable arcs and superior bead aesthetics; however, it is constrained by low productivity, limited welding speeds, and poor amenability to automation. MIG/MAG welding, conversely, offers high efficiency and deposition rates but is frequently associated with excessive heat input, resulting in undesirable deep penetration, significant spatter generation, and pronounced thermal distortion in thin-sheet applications. Laser Beam Welding (LBW), while advantageous for its low heat input and high processing speeds, remains constrained by high reflectivity in materials such as aluminum and prohibitive costs for large-scale component fabrication. Similarly, Friction Stir Welding (FSW), despite yielding defect-free joints via solid-state processing, is limited by low welding speeds and the operational burden of heavy clamping systems. The persistent challenge of joining thin-gauge materials (0.3–2.0 mm) and dissimilar metal systems catalyzed a critical inflection point in welding research. Pickin and Young at 2006 demonstrated that although pulsed transfer modes were conventionally employed for thin-section welding, spray transfer modes remained excessively thermal, precipitating burn-through defects. Concurrently, Houldcroft and John (1988) identified that conventional short-circuit/dip transfer mechanisms were susceptible to poor material transfer and fusion-related defects, attributable to the inherently low electrical resistance of aluminum filler wires. A further, more formidable obstacle in dissimilar metal joining particularly aluminum-to-steel and aluminum-to-magnesium systems was the formation of brittle intermetallic compound (IMC) layers, notably Fe_2Al_5 and $\text{Mg}_{17}\text{Al}_{12}$. As established by Zhang et al. and Cao et al., IMC layer thicknesses exceeding 10 μm significantly deteriorate joint mechanical performance, thereby underscoring the imperative for a viable low-heat-input joining solution within contemporary manufacturing paradigms [1, 2]. The introduction of Cold Metal Transfer (CMT) welding by Fronius in 2004 constituted a paradigm shift, fundamentally departing from conventional arc welding methodologies. CMT is mechanistically distinguished from other arc processes through its integration of high-frequency (up to 70 Hz) mechanical wire retraction directly within the digital process control architecture. Whereas conventional MIG/MAG processes rely on elevated short-circuit current to induce wire melting—generating substantial spatter and thermal input—the CMT

process detects short-circuit events and instantaneously reduces current to near-zero levels. As demonstrated by Furukawa and Irizalp et al., the filler wire undergoes not only forward feeding toward the weld pool but also controlled mechanical retraction to facilitate droplet detachment [3, 4]. This mechanism enables metal transfer independent of electromagnetic force, substantially reducing thermal input to the workpiece while ensuring a spatter-free process outcome. Subsequent research has extended CMT technology to address increasingly sophisticated industrial requirements. Feng et al. established that the characteristic low heat input of CMT was particularly well-suited to joining thin aluminum sheets, yielding minimal deflection and superior gap-bridging capability [5]. To overcome the limitations of standard CMT for aluminum structures exceeding 3 mm in thickness, Pang et al. investigated the CMT+P (Pulse) variant, wherein high-energy pulses are incorporated into the transfer cycle to enhance penetration depth while preserving process stability [6]. Further advancing the technology, Cong et al. introduced the CMT-PADV mode, which achieves near-complete porosity elimination in aluminum-copper alloy joints through effective oxide layer removal [7]. Additionally, hybrid process configurations have emerged, exemplified by the TIG-CMT process examined by Liang et al., in which a TIG arc functions as a preheating source to enhance wettability during multi-pass cladding operations [8]. This cumulative trajectory of innovation has established CMT as a cornerstone technology within Wire Arc Additive Manufacturing (WAAM), enabling efficient, layer-by-layer fabrication of large-scale, near-net-shape components for aerospace and defense applications.

1.1 Cold Metal Transfer (CMT) process

The Cold Metal Transfer (CMT) process, introduced by Fronius in 2004, has undergone substantial evolution from a revolutionary concept to a cornerstone technology in modern manufacturing. This transformation is rooted in a fundamental departure from conventional dip-transfer MIG/MAG welding methodologies. As documented by Furukawa and Feng et al., the principal innovation underlying CMT lies in its digital control system, which integrates high-frequency (up to 70 Hz) mechanical wire retraction motion directly into the welding cycle. During the arcing phase, a molten droplet forms at the wire tip; upon detection of a short circuit, welding current is reduced to near-zero levels while the wire is simultaneously retracted to facilitate droplet detachment [3, 5]. This "cold" transfer mechanism, as characterized through double-ellipsoidal heat source simulations by Azar, ensures metal transfer occurs with minimal arc pressure and substantially reduced heat input, fundamentally redefining thermal cycle management in fusion welding applications. The demonstrated merits of CMT welding rapidly became the focus of intensive investigation, particularly regarding its capacity to resolve longstanding challenges associated with thin-gauge material joining [9]. Feng et al. and Pickin and Young were among the earliest researchers to establish that reduced heat input yields spatter-free welding, exceptional gap-bridging capability, and minimal thermal distortion in pure aluminum sheet applications [5]. Furthermore, Irizalp et al. demonstrated that systematic optimization of voltage and current parameters to minimize heat input significantly reduces porosity size in weld metal while enhancing tensile strength in 2 mm thick AA1050 sheet joints [4]. These

findings were corroborated by Gungor et al., who established that robotic CMT-MIG welding achieves joint efficiencies and yield strengths comparable to friction stir welding, while offering the additional advantages of enhanced welding speed and reduced operator skill requirements [10]. Critical examination of the literature also reveals significant technical limitations that continue to drive ongoing research efforts. Talalaev et al. identified that the pursuit of high productivity can precipitate increased porosity and unacceptable bead geometries when welding speed is not precisely calibrated, with optimal ranges of 10–12 mm/s reported for stainless steel applications [11]. In magnesium alloy welding, Hu et al. demonstrated that pronounced evaporation from the molten droplet can induce repelled metal transfer and arc instability, necessitating stringent control of wire feed rate parameters [12]. Additionally, Pang et al. noted that standard CMT processing is frequently unsuitable for aluminum structures exceeding 3 mm in thickness due to inherently limited energy input, motivating the development of the CMT+P (Pulse) variant, which incorporates supplementary arcing phases to enhance penetration depth while maintaining short-circuit stability [6]. Selvi et al. further cautioned regarding the risk of incomplete fusion in lap joint configurations, emphasizing the necessity of precise arc length correction to mitigate this defect [13]. Notwithstanding these limitations, CMT applications have expanded substantially into complex, high-value industrial domains. Cao et al. and Singh et al. pioneered dissimilar metal joining of aluminum to galvanized steel, establishing that the characteristically low heat input of CMT effectively retards brittle intermetallic layer growth—a finding of considerable significance for weight reduction initiatives in the automotive sector [2, 14]. The process has additionally demonstrated efficacy in cladding and repair applications; Rajeev et al. and Varghese et al. successfully deposited thick, low-dilution coatings of Al-Si-Mn and Inconel 617M, achieving metallurgical bond quality superior to conventional thermal spray techniques [15, 16]. Most recently, Burhanuddin et al. and Raut et al. have identified CMT as a premier enabling technology for Wire Arc Additive Manufacturing (WAAM), wherein its high precision and controlled solidification behavior facilitate layer-by-layer fabrication of large-scale, near-net-shape structures for aerospace and defense applications [17, 18]. This sustained trajectory of research progress underscores continued efforts toward comprehensive parameter optimization, aimed at fully realizing the potential of this environmentally sustainable and highly efficient welding technology.

1.2 Computational experimental integration

The evolution of Cold Metal Transfer (CMT) welding research reflects a broader transformation within the field of arc welding: the transition from a purely experimental innovation introduced by Fronius to a sophisticated domain characterized by integrated computational-experimental methodologies. In the formative stages of CMT research, process optimization relied predominantly on tedious and resource-intensive experimental trial-and-error approaches, constrained by the absence of suitable predictive modeling frameworks. As industrial demand shifted toward high-precision applications, including ultra-thin sheet joining and dissimilar metal welding, Pickin et al. established that cycle-averaged process values were insufficient for capturing the distinctive electrical transients inherent to CMT. Their work demonstrated that because

the CMT cycle oscillates between arcing and short-circuit phases characterized by substantial disparities in process parameters, accurate heat input calculation necessitates analysis of instantaneous voltage and current data rather than averaged values [19]. A significant inflection point in CMT research emerged with the integration of MATLAB as a computational tool for simulating complex thermal cycles. Azar pioneered a transient heat source model employing a time-dependent double-ellipsoidal distribution to replicate the periodic, recurrent arcing characteristic of CMT processing. Implementation of this model within MATLAB enabled researchers to visualize instantaneous heat source dimensions and heat input sequences across a single metal transfer period. This computational framework facilitated a critical advancement beyond static data analysis, establishing that delivered thermal energy is inextricably coupled to arcing frequency and wire feed rate—parameters that can now be simulated with high fidelity to elucidate weld pool behavior and resultant mechanical property development [9]. As computational capabilities advanced, research emphasis expanded from single-droplet analysis to comprehensive manufacturing strategy, particularly within the domain of Wire Arc Additive Manufacturing (WAAM). Raut et al. emphasized that precise path planning is essential for defect-free component production, referencing foundational work by Jayaprakash et al., who developed proprietary MATLAB algorithms to generate precise toolpaths directly from CAD models [18]. This computational integration proves critical given that WAAM constitutes a dynamic thermal system in which heat accumulation can substantially alter component microstructure and geometry. The concurrent application of MATLAB for thermal history prediction and toolpath optimization has enabled the design of environmentally sustainable manufacturing processes, facilitating the production of lightweight automotive body components with unprecedented dimensional precision. The contemporary landscape of CMT research is characterized by robust correlation between numerical modeling and physical experimentation. Building upon MATLAB-based foundational work, Zapico et al. proposed an enhanced computational model within COMSOL Multiphysics, revealing substantial disparities between peak and average calculated temperatures—findings that elucidate the particular suitability of CMT for thin aluminum alloy applications [20]. Similarly, Selvamani et al. employed ANSYS-based volumetric heat source models, informed by the time-dependent parameter framework originally developed by Azar, to predict heat distribution in galvanized steel welding with experimental agreement within $\pm 5\%$ error [9, 21]. This progressive integration of computational and experimental methodologies now enables pre-emptive optimization of welding speed and joint gap parameters prior to arc initiation, ensuring that each weld achieves optimal strength and structural performance.

1.3 Significance of Heat input in CMT Welding process

The developmental trajectory of Cold Metal Transfer (CMT) welding originated with its introduction by Fronius in 2004 as a modified Gas Metal Arc Welding (GMAW) variant, wherein digital control systems integrate mechanical wire motion directly into the welding cycle to achieve controlled "cold" metal transfer. This innovation, as elucidated by Furukawa and Feng et al., enables droplet detachment through high-frequency wire retraction at near-zero current levels, fundamentally reducing heat

input relative to conventional dip-transfer processes [3, 5]. Early evaluations by Pickin and Young at 2006 established that this controlled, low-energy deposition mechanism affords superior control over penetration and dilution, rendering CMT particularly well-suited to thin-section aluminum alloy applications, where burn-through and thermal distortion constitute primary failure modes. As research in this domain matured, Irizalp et al. demonstrated that systematic optimization of heat input—calculated as the product of voltage and current divided by welding speed—significantly minimizes porosity dimensions while maximizing tensile strength in AA1050 sheet joints [4]. Research emphasis subsequently shifted toward the complex challenges inherent to dissimilar metal joining, where Zhang et al. and Cao et al. established that the characteristically low thermal input of CMT is essential for retarding the growth of brittle intermetallic compound (IMC) layers, which must generally be constrained below 10 μm to prevent joint embrittlement [1, 2]. Building upon this foundation, Mezrag et al. determined that reducing the boost-phase duration within the current waveform increases short-circuit frequency, thereby effectively lowering energy transfer to the base metal while maintaining equivalent deposition rates [22]. This optimization framework was further refined by Sravanthi et al., who regulated welding speed to constrain Al-Fe IMC layer width below 3 μm , yielding simultaneous enhancement of joint strength and corrosion resistance [23]. The inherent complexity of CMT thermal cycles motivated Azar to propose a time-dependent double-ellipsoidal heat source model for simulating periodic arcing behavior, providing deeper mechanistic insight into Marangoni convection dynamics within the weld pool [9]. This computational trajectory was subsequently advanced by Selvamani et al., who correlated volumetric heat distribution with joint integrity in galvanized steel applications, confirming that optimized heat input parameters yield a narrower heat-affected zone alongside a 30% increase in hardness relative to alternative fusion welding processes [21]. Ultimately, the work of Koli et al. synthesized these decades of cumulative research progress, demonstrating that CMT consistently achieves superior joint efficiency and more favorable residual stress distributions compared to conventional MIG welding at equivalent heat input levels—thereby establishing CMT as a premier environmentally sustainable technology for contemporary industrial manufacturing applications [24].

1.4 Literature context and open challenges

The evolution of the Cold Metal Transfer (CMT) process begins with its revolutionary introduction by Fronius in the mid-2000s, an advancement documented by Furukawa at 2006 as a fundamental departure from conventional dip-transfer welding through a novel mechanical droplet-cutting mechanism. This "cold" process operates on the short-circuiting principle, wherein digital process control integrates wire motion directly into the welding cycle, ensuring that the filler wire is not only advanced toward but also mechanically retracted from the workpiece at frequencies of up to 70 Hz.

The thermal characteristics governing this process have been extensively characterized through computational modeling. Azar effectively simulated the underlying thermal cycles using a double-ellipsoidal heat source model, elucidating the influence of periodic arcing and metal deposition on weld pool behavior [9]. The distinctive nature of CMT resides in the extinguishing of the arc and reduction of welding current to

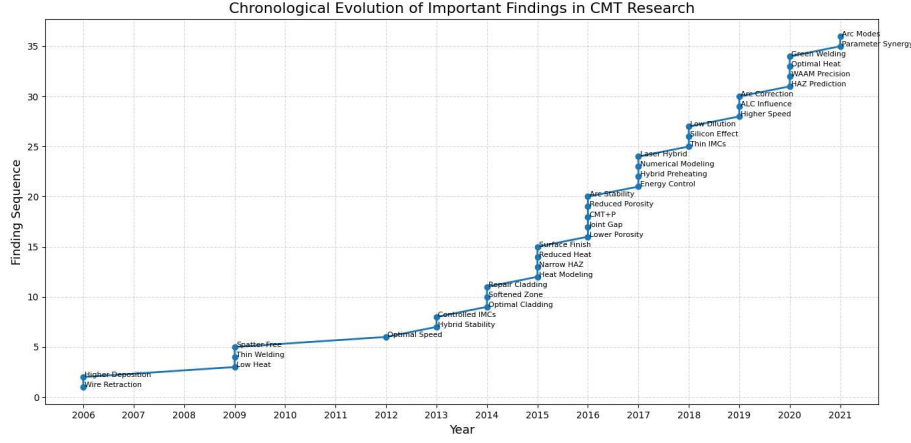


Fig. 1: Milestones of important findings in CMT Research

near-zero levels during the short-circuit phase, a mechanism identified by Lorenzin and Rutili as pivotal to the substantial reduction in heat input delivered to the workpiece [25]. Early investigations by Feng et al. established that this characteristically low heat input was ideally suited to joining thin aluminum sheets, effectively mitigating distortion and burn-through—persistent challenges in conventional arc welding processes [5]. Building upon this foundation, Pickin and Young was conducted a comparative evaluation of CMT and pulsed MIG welding, concluding that CMT affords superior deposition efficiency and enhanced control over penetration and dilution, particularly in aluminum alloy applications. Extending into the mechanical characterization domain, Irizalp et al. investigated 2 mm thick AA1050 aluminum sheets, establishing that reduced heat input significantly decreases weld metal porosity. Employing an efficiency factor of 0.90 to calculate heat input as the product of voltage and current divided by welding speed, their findings confirmed that maximum tensile strength is achieved under minimum heat input conditions. Furthermore, Irizalp examined the influence of joint gap on mechanical performance, observing that gap reduction positively affects bending strength through enhanced fusion performance and increased bonding line length—findings that underscore the critical importance of fit-up precision in thin-sheet aluminum applications where structural integrity is paramount [4]. In the domain of dissimilar metal joining, Zhang et al. (2009) examined arc characteristics and metal transfer behavior during aluminum-to-zinc-coated steel welding, reporting that CMT provides a spatter-free process that mitigates brittle intermetallic compound formation [1]. This finding was subsequently refined by Mezrag et al., who determined that short-circuit frequency increases as boost-phase duration within the current waveform decreases, effectively reducing base-metal heat transfer for a given deposition rate [22]. The challenge of aluminum-to-steel joining was further addressed by Babu et al., who combined CMT with friction surfacing to produce lap joints between AA2219 and AISI 321 stainless steel, finding that the resultant thin intermetallic layer requires careful control to preserve joint strength [26]. Correspondingly, Sravanthi et al. optimized welding speed within a 0.5–1 m/min range, demonstrating

that elevated speeds produce narrower intermetallic compound (IMC) layers, thereby enhancing corrosion resistance [23]. The interdependency among process parameters is further elucidated in the work of Koli et al., who joined dissimilar-thickness AA6061-T6 and AA6082-T6 sheets, establishing that voltage, current, and wire feed rate are inextricably linked within synergic CMT control lines, such that adjustment of any single parameter necessitates corresponding modifications to maintain arc stability. Their optimized parameter set for 2 mm and 3.18 mm sheet combinations—comprising 72 A current and 5.5 mm/s welding speed—yielded joint efficiency exceeding 64% [24]. This process complexity was further examined by Wang et al., who characterized the contribution and limitations of parameters including boost current and wait current, determining that increased wire feed speed initially elevates total energy input before inducing a subsequent decline, with pronounced effects on weld width and contact angle [27]. For high-strength structural applications, Elrefaey demonstrated the efficacy of CMT in welding 7075 aluminum alloys, establishing that the process produces a narrower softening region within the heat-affected zone relative to conventional TIG or MIG welding [28]. This investigation of heat distribution characteristics was advanced by Selvamani et al., who employed an ANSYS volumetric heat source model on galvanized steel to predict that excessive heat distribution generates broader, softer heat-affected zones that substantially compromise joint strength [21]. Extending to magnesium alloy systems, Cao et al. investigated the joining of Mg AZ31B to Al A6061-T6, utilizing wire retraction to facilitate droplet detachment independent of electromagnetic force—a mechanism identified as critical for minimizing Mg-rich and Al-rich intermetallic formation [2]. Hu et al. further analyzed arc characteristics in these magnesium-based CMT welds, establishing that process stability for AZ31 wire requires wire feed speeds constrained to a maximum of 5 m/min for DC-CMT and 4 m/min for pulsed-CMT to prevent repelled droplet transfer induced by magnesium evaporation [12]. Advanced process variants, including CMT+P (Pulse) and CMT-ADV (Advanced), have received considerable research attention. Pang et al. demonstrated that CMT+P, which combines projected droplet transfer with CMT short-circuit dynamics, enables elevated heat input suitable for welding aluminum structures exceeding 3 mm in thickness [6]. Cong et al. further established that while conventional CMT produces finger-shaped weld geometry, the CMT-PADV (Pulse Advanced) variant achieves spherical bead morphology with significantly reduced porosity [7]. Within cladding and hardfacing applications, Rajeev et al. investigated Al-Si-Mn coating deposition on aluminum substrates, finding that dilution ratio and deposition rate exhibit non-linear dependence on welding speed, with 20 in/min identified as optimal for avoiding lack of fusion defects in overlapping bead configurations [15]. Subsequently, Rajeev et al. extended this investigation to Stellite 6 deposition on AISI H13 steel, establishing that Arc Length Correction (ALC) exerts a more pronounced influence on dilution than Dynamic Correction (DC) [29]. Building upon this cladding research, Ola and Doern examined Inconel 718 superalloy deposition, demonstrating a linear relationship between wire feed speed and heat input under synergic CMT control, and identifying a contact angle exceeding 115° as necessary for successful multi-pass material build-up in repair applications [30]. The additive manufacturing potential of CMT, specifically within Wire Arc Additive Manufacturing (WAAM),

was evaluated by Burhanuddin et al., who noted that the process’s high precision and low heat input are essential for fabricating thin-walled automotive body components to reduce fuel consumption [17]. Raut et al. further emphasized that distinct CMT arc modes significantly influence porosity and solidification structure in additively manufactured deposits [18]. To address thick-section applications, Liang et al. proposed a TIG-CMT hybrid welding process wherein a TIG arc preheats the base metal, improving molten metal wettability and enabling reduced contact angle and increased dilution without compromising CMT arc stability [8]. Advancing the computational modeling frontier, Zapico et al. developed an equation-based COMSOL Multiphysics framework for predicting weld pool geometry and distortion effects, providing theoretical accuracy essential for case-specific application investigations, including the Inconel 617M weld overlay coating on stainless steel examined by Varghese et al. wherein CMT was shown to produce low-dilution overlays comparable to laser coating techniques [16, 20]. In dissimilar aluminum-steel welding, Singh et al. reviewed the significant role of silicon and zinc, emphasizing that CMT’s precise wire motion control prevents electromagnetic force intrusion into the weld pool—a mechanism essential for retarding intermetallic growth [14]. Comez and Durmus further established that heat input values between 95 and 110 J/mm are recommended for optimizing both strength and corrosion resistance in dissimilar joint configurations [31]. The significance of contact tip-to-work distance (CTWD) was highlighted by Yacob et al., whose experiments on AA6351 revealed that increased welding speed and material thickness reduce surface roughness, yielding improved weld finish quality [32]. These findings are complemented by Talalaev et al., who determined that a welding speed of 10–12 mm/s is optimal for stainless steel applications, minimizing distortion while avoiding excessive porosity [11]. In thick-plate welding applications, Shu et al. modeled narrow-gap aluminum alloy joints using the CMT+P MIX procedure, identifying a softened zone within the base plate and confirming that elevated thermal diffusion rates contribute to reduced cooling rates [33]. This necessitates precise arc length management, as Kannan et al. observed that Arc Length Correction factor significantly influences joint strength and weld bead geometry in AISI 316L weldments [34]. Further research into hybrid processing by Zhang et al. compared Laser-Cold Metal Transfer Hybrid Welding (LCHW) with Laser-MIG hybrid welding, establishing that the CMT-based hybrid configuration exhibited superior stability and spatter-free performance due to reduced arc pressure on the weld pool [35]. This finding is supported by the comprehensive review of Selvi et al. which concluded that CMT-Laser hybrid welding is generally preferable to alternative laser-based hybrid configurations for automotive and defense sector applications [13]. Synthesizing these cumulative research findings, Balasubramanian et al. established that CMT’s near-complete material efficiency and capacity for joining titanium, magnesium, and aluminum alloys position it as a cornerstone technology in modern manufacturing. The relationship between energy input and resultant microstructure remains a critical research frontier, warranting continued parameter optimization to achieve optimal balance among penetration depth, joint strength, and structural integrity [36]. Collectively, the systematic optimization of voltage, heat input, current, wire feed rate, welding speed, and joint gap enables

precise control over metal transfer dynamics and energy distribution. Through integrated parameter management, weld properties can be tailored to specific application requirements, ensuring that CMT remains a leading environmentally sustainable technology for cleaner, more efficient industrial manufacturing. The novelty of the present study lies in the systematic correlation of CMT process parameters with heat input and joint performance, with particular emphasis on balancing thermal input reduction against fusion quality. Additionally, this work identifies the practical trade-off between minimizing heat input and maintaining acceptable bead geometry—a consideration essential for reliable application in thin-sheet and dissimilar-metal welding contexts.

2 Objective

Table 1: Process parameter optimization directions and rationales.

Parameter	Optimization Direction	Why
Heat input	Lower, but not so low that fusion is lost	Lower heat input reduced pore size and improved tensile strength/hardness in the paper.
Voltage	Use the lowest stable voltage that maintains a stable arc	Higher voltage increases heat input and can enlarge the HAZ if current and speed are unchanged.
Current	Use the minimum current needed for sound fusion	Current directly raises heat input and can increase thermal damage if too high.
Wire feeding rate	Match wire feed to current and travel speed for stable deposition	Too high a feed can force higher current or excess buildup; too low can cause lack of fusion.
Welding speed	Use a higher travel speed within fusion limits	Higher speed reduces heat input; too high can cause incomplete fusion.
Joint gap	Use a small controlled gap	The paper found smaller gap improved fusion and increased bonding line length, which improved bending strength.

3 Methodology

3.1 Estimation of Heat input equation

$$H = \frac{\eta \cdot V \cdot I \cdot 60}{1000 \cdot S} \quad (1)$$

Where:

H is the heat input (kJ/mm),
 V is the voltage (V),
 I is the current (A),
 S is the welding speed (mm/min), and
 η is the arc efficiency.

3.2 Estimation of Thermal forecast equation

$$\rho C_p \left(\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial x} \right) = \nabla \cdot (k \nabla T) + Q(x, y, z, t) \quad (2)$$

Where:

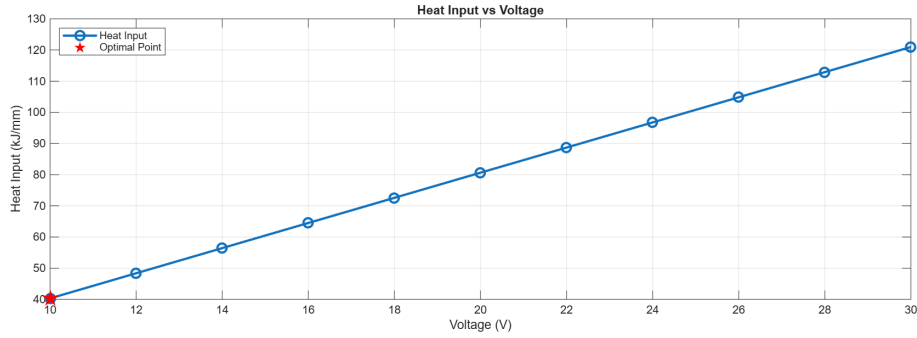
ρ is the material density (kg/m³),
 C_p is the specific heat capacity (J/kg · K),
 k is the thermal conductivity (W/m · K),
 T is the temperature (K or °C),
 t is the time (s), and
 Q_v is the volumetric heat source term (W/m³), which depends on the net heat input rate $q = \eta \cdot V \cdot I$, travel speed v , and heat distribution parameters.

3.3 Data collected for the study Ref: [\[4\]](#)

Table 2: Primary Optimization Parameter

Parameter	Unit	Values
Voltage	V	Sample A: 17.5, B: 17.7, C: 18.2
Current	A	Sample A: 107, B: 112, C: 121
Wire feeding rate	mm/min	Sample A: 4.8, B: 5.0, C: 5.8
Welding speed	mm/min	Sample A: 1.5, B: 1.5, C: 2.0
Heat input	J/mm	Sample A: 74.9, B: 79.3, C: 66.1
Efficiency / heat transfer rate	—	Assumed 0.90 for CMT, based on MIG/MAG literature
Sheet thickness	mm	2
Sheet size	mm ²	250 × 100
Filler material	—	Aluminum-based filler wire
Shielding gas	—	Argon
Hardness test load	kg	1
Hardness dwell time	s	10
Tensile test crosshead rate	mm/min	1
Bending test rate	mm/min	2
Heat input formula constant	—	60, 1000 (used in $H = \frac{\eta \cdot V \cdot I \cdot 60}{1000 \cdot S}$)

4 Result and Discussion

**Fig. 2:** Heat Input Vs Varriable voltage

The observed relationship between voltage and heat input in the Figure: is essentially linear, indicating a stable operating regime free from saturation or threshold effects. This near-proportional trend reflects a well-controlled heat delivery mechanism: as voltage increases, electrical power scales accordingly, resulting in a steady rise in energy deposited per unit length of travel. Such a relationship carries significant implications for thermal processing. Elevated heat input is typically associated with a larger melt pool, reduced cooling rates, and a broader heat-affected zone (HAZ) factors that can promote microstructural coarsening and increased distortion. Conversely, at lower heat input levels, exemplified by the red-star data point in the figure, the process

becomes more thermally localized, favoring finer microstructures and minimal distortion. The red star, marking the operating point at 10 V and 40 kJ/mm, represents the selected optimum condition. This point reflects a deliberate trade-off between minimizing heat input to suppress grain growth and thermal distortion and preserving sufficient energy density to ensure adequate melting, penetration, and bonding. As such, this operating condition exemplifies the balance between energy efficiency and metallurgical performance that is central to optimized thermal processing.

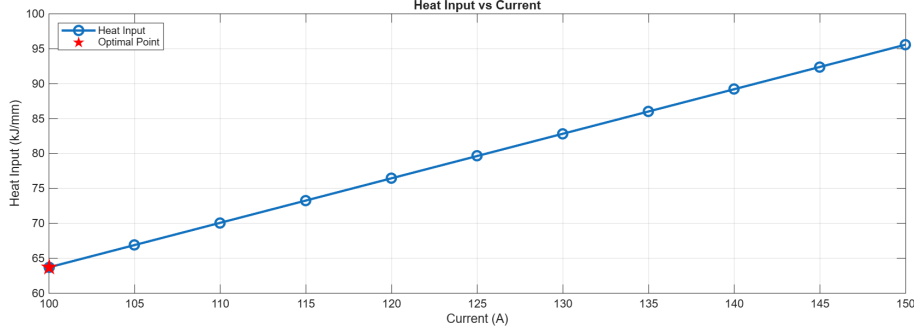


Fig. 3: Heat Input Vs Varriable current

The relationship between welding current and heat input exhibits a strongly linear trend across the tested range of 100–150 A, with heat input increasing from approximately 63–64 kJ/mm to 95–96 kJ/mm. The data points, recorded at 5 A intervals, align closely along a single trend line with negligible scatter or curvature. This high degree of linearity suggests that the dataset was either derived from a theoretical/-analytical model or obtained under tightly controlled experimental conditions, since practical welding processes typically exhibit measurable variability arising from arc instability, spatter, or voltage fluctuations. The optimal operating point, marked at 100 A (heat input 63–64 kJ/mm), corresponds to the lower boundary of the tested current range. This selection reflects a deliberate strategy to minimize heat input while presumably satisfying the required weld quality criteria. Lower heat input at this current level is expected to reduce thermal degradation of the base metal, limiting excessive grain coarsening and softening of the heat-affected zone (HAZ). Assuming that penetration depth and bead geometry remain within acceptable limits at this current parameters not directly captured in the present figure, the selection of 100 A represents an optimal trade-off between achieving adequate fusion and minimizing heat-induced microstructural degradation. This balance is critical in welding process optimization, where excessive heat input can compromise mechanical properties despite improving weld penetration.

The relationship between welding (travel) speed and heat input follows a distinct inverse, hyperbolic trend across the tested range of 1–4 mm/min. Heat input decreases sharply from approximately 107 kJ/mm at 1 mm/min to roughly 26–27 kJ/mm at 4 mm/min, consistent with the fundamental inverse dependence of heat input on travel speed for a fixed power input. Data points, recorded at 0.5 mm/min intervals, reveal a

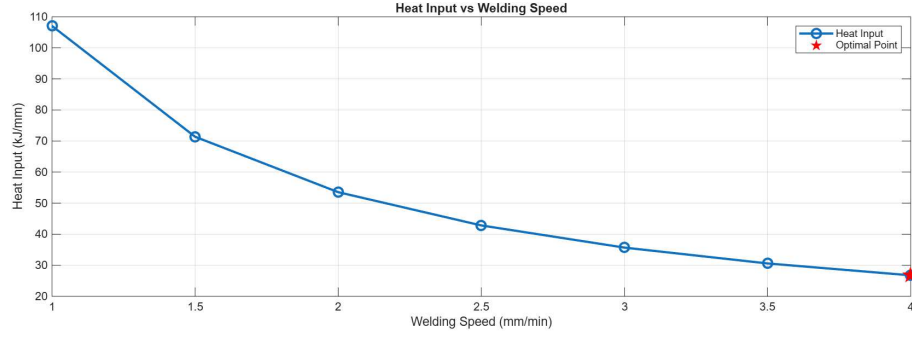


Fig. 4: Heat Input Vs Varriable welding speed

classic diminishing-returns profile. The steepest reduction in heat input occurs between 1 and 2 mm/min (from 107 to 53 kJ/mm), whereas the curve flattens considerably between 3 and 4 mm/min (from 36 to 26 kJ/mm). This behavior indicates a regime of diminishing marginal benefit, wherein further increases in travel speed yield progressively smaller reductions in heat input. The optimal point, identified at the highest tested speed (4 mm/min), corresponds to the minimum heat input (26–27 kJ/mm) within the studied range. This selection aligns with the general objective of minimizing thermal exposure to suppress heat-affected zone (HAZ) widening, grain coarsening, and thermal distortion. However, this outcome warrants a critical caveat. Excessively high welding speeds can compromise weld integrity through defects such as incomplete fusion, undercutting, humping, or insufficient penetration, particularly when the travel speed exceeds the arc’s capacity to adequately melt and fuse the joint. Therefore, while 4 mm/min minimizes heat input in the present analysis, its designation as the true optimal condition should be contingent upon independent verification of weld quality metrics including penetration depth, bead geometry, and defect-free fusion at that speed. A holistic optimization framework should thus balance thermal input minimization against process-window constraints to ensure both metallurgical and geometric weld quality are satisfied.

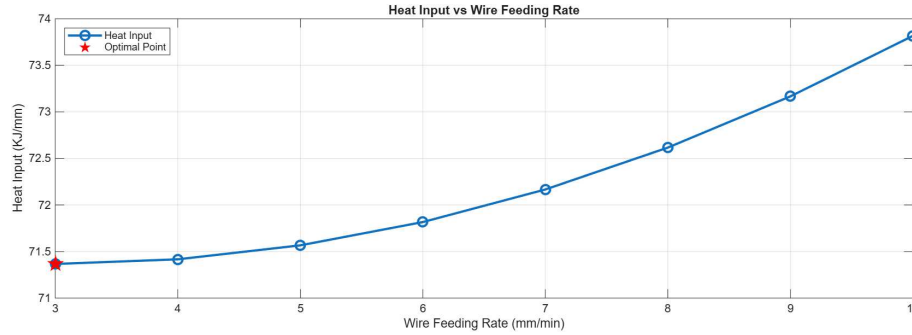


Fig. 5: Heat Input Vs Varriable wire feeding rate

The relationship between wire feed rate (WFR) and heat input, examined over the range of 3–10 mm/min, reveals a subtler yet mechanistically significant trend. Heat input increases modestly from approximately 71.3 kJ/mm at 3 mm/min to 73.8 kJ/mm at 10 mm/min, following a gently convex, nonlinear trajectory rather than the proportional behavior observed for voltage. Data points, recorded at 1 mm/min intervals, reveal a distinct two-stage response. Between 3 and 5 mm/min, heat input remains nearly constant (71.35–71.55 kJ/mm), whereas from 6 mm/min onward, the curve steepens progressively toward the upper end of the range. This convex profile is indicative of a nonlinear, potentially quadratic or higher-order, dependence of heat input on wire feed rate consistent with the physics of arc self-regulation, in which incremental increases in feed rate at lower values exert only marginal influence on welding current, while the effect compounds at higher feed rates. Notably, the narrow y-axis range spanned by this dataset (71–74 kJ/mm, a window of only 2.5–3 kJ/mm) contrasts sharply with the substantially wider heat input variations observed for current (63–96 kJ/mm) and travel speed (26–107 kJ/mm). This comparatively muted sensitivity indicates that wire feed rate exerts a secondary, fine-tuning influence on heat input, rather than acting as a dominant process parameter. The optimal point, identified at the lowest tested wire feed rate (3 mm/min, heat input 71.3–71.4 kJ/mm), aligns with the overarching objective observed across all three parameters: minimizing heat input to mitigate grain coarsening, HAZ widening, and thermal distortion. Nonetheless, an important practical caveat must be considered. Since wire feed rate governs filler metal deposition rate, an unduly low WFR selected solely to minimize heat input may compromise weld reinforcement, bead fill, or fusion adequacy if not appropriately balanced with corresponding current and travel speed settings. Consequently, the true optimality of 3 mm/min cannot be confirmed from heat input data alone and would require validation through complementary assessment of bead geometry, deposition volume, and fusion quality parameters beyond the scope of the present figure.

5 Comparison study

Comparative Analysis of Experimental and Computational Findings on Heat Input in CMT Welding Lower heat input is widely recognized as advantageous in Cold Metal Transfer (CMT) welding, and the present comparison of experimental and computational (MATLAB-based) findings largely reaffirms this principle while revealing important points of divergence. The experimental study demonstrated that Sample C, characterized by the lowest heat input (66.1 J/mm), exhibited the smallest and most uniformly distributed porosity, the highest hardness, and the greatest tensile strength outcomes consistent with established welding metallurgy, wherein faster cooling rates suppress pore coarsening while limiting recrystallization and grain growth. The MATLAB-based analysis arrives at a qualitatively similar conclusion, emphasizing that reduced heat input correlates with a smaller melt pool, a narrower heat-affected zone (HAZ), restricted grain growth, minimized distortion, and generally improved microstructural integrity. Although these findings do not constitute a novel scientific insight, their convergence across independent experimental and computational

Table 3: Experimental Results of CMT Welds (AA1050)

Parameter	Sample A	Sample B	Sample C
Voltage (V)	17.5	17.7	18.2
Current (A)	107	112	121
Wire feed rate (m/min)	4.8	5.0	5.8
Welding (travel) speed (m/min)	1.5	1.5	2.0
Calculated heat input (J/mm)	74.9	79.3	66.1 (lowest)
Porosity behavior	Large pores near weld bead surface (intermediate cooling rate)	Large pores near weld bead surface (intermediate cooling rate)	Small pores, distributed through weld metal (fast cooling)
Joint gap	Larger gap	Larger gap	Minimum gap
Fusion / bonding line	Lack of fusion observed	Lack of fusion observed	Longest bonded line, no lack of fusion
Hardness (weld metal)	Lower	Lower	Highest
Tensile strength	High (failure in HAZ)	Lower	Highest (failure in HAZ)
Three-point bending strength	Lower (despite good tensile)	Middle	Highest (tracks bonding-line length, not heat input)
Failure location (tensile)	HAZ	HAZ	HAZ

Table 4: Comparison between Experimental and MATLAB Analysis

Basis of Comparison	Experimental	MATLAB Analysis
Data type	Measured, physically tested welds	Calculated sweep of Weman's equation, one variable at a time
Heat input scale	66–79 J/mm	26–121 kJ/mm ($\sim 1000\times$ larger)
Voltage range	17.5–18.2 V	10–30 V
Current range	107–121 A	100–150 A (partial overlap at low end)
Speed range	1.5–2 m/min	1–4 mm/min (likely unit mismatch)
WFR range	4.8–5.8 m/min	3–10 mm/min (likely unit mismatch)

approaches reinforces heat input as a critical determinant of weld quality. Despite this overall agreement, both studies caution that heat input minimization alone does not guarantee optimal weld performance. Notably, while Sample C achieved the highest tensile strength, Sample A, produced under comparatively higher heat input exhibited superior bending strength, an improvement attributed to enhanced fusion quality and increased bonding line length rather than heat input per se. Correspondingly, the MATLAB study warns that parameter combinations optimized purely to minimize

heat input (e.g., maximizing travel speed while reducing wire feed rate) may introduce welding defects such as incomplete fusion, undercutting, humping, or insufficient metal deposition. Taken together, these findings underscore that heat input optimization must be evaluated in conjunction with weld geometry and metallurgical soundness, rather than as a standalone criterion. Both studies further identify welding current and travel speed as the dominant parameters governing heat input, with wire feed rate exerting only an indirect influence. This is consistent with Weman’s heat input equation, in which voltage and current enter multiplicatively in the numerator while travel speed appears in the denominator; wire feed rate is notably absent from this formulation. The MATLAB study’s inclusion of wire feed rate is therefore inferred to stem from its indirect coupling with welding current via the synergic control system inherent to CMT power sources a relationship that, while physically plausible, is not explicitly substantiated within the study and represents a methodological gap warranting further clarification. Several substantive discrepancies between the two datasets merit attention. Most notably, the reported heat input magnitudes differ by nearly three orders of magnitude: the experimental study reports realistic CMT heat input values of approximately 66–79 J/mm, whereas the MATLAB study reports values spanning 26–107 kJ/mm. This discrepancy suggests either a unit conversion error or that the MATLAB model reflects a fundamentally different welding process rather than conventional CMT welding, and it should be reconciled before the computational results are used to validate or interpret the experimental findings. A parallel inconsistency emerges in the welding parameter ranges employed by each study. The experimental work utilized voltages of 17.5–18.2 V, currents of 107–121 A, travel speeds of 1500–2000 mm/min, and wire feed rates of 4.8–5.8 m/min, whereas the MATLAB study evaluated an apparent optimal voltage of 10 V, currents of 100–150 A, travel speeds of only 1–4 mm/min, and wire feed rates of 3–10 mm/min. While the current ranges show partial overlap, the travel speed and wire feed rate values in the MATLAB study deviate substantially by orders of magnitude from practically representative CMT welding conditions, again pointing to probable unit inconsistencies or parameter misdefinition. The two studies also differ fundamentally in their basis for identifying optimal welding conditions. The experimental study grounds its conclusions in direct empirical evidence, including tensile and three-point bending tests, hardness measurements, optical microscopy, and porosity characterization. In contrast, the MATLAB study derives optimal parameters primarily from theoretical heat input calculations and graphical trend analysis, while explicitly acknowledging the absence of experimental validation. Accordingly, the parameter values proposed by the MATLAB study should be regarded as theoretical predictions requiring empirical confirmation, rather than as validated conclusions. Finally, the scope of the two investigations differs considerably. The experimental study offers a comprehensive characterization encompassing porosity evolution, joint gap effects, grain structure development, HAZ behavior, hardness distribution, tensile performance, and bending strength. The MATLAB study, by comparison, is confined to a sensitivity analysis of Weman’s heat input equation with respect to voltage, current, travel speed, and wire feed rate, and therefore does not address the broader metallurgical and mechanical phenomena central to the experimental investigation including porosity morphology, bonding-line characteristics, HAZ

softening, and the interplay between joint geometry and mechanical performance. In summary, while both studies converge on the general principle that reduced heat input improves microstructural and porosity-related weld characteristics, the substantial unit and parameter-range discrepancies between the experimental and computational datasets indicate that the MATLAB model requires careful recalibration and experimental validation before its predictions can be meaningfully integrated with, or used to corroborate, the empirical CMT welding results.

6 Conclusion

Cold Metal Transfer (CMT) welding represents a superior low-heat-input process for joining thin metallic sheets, particularly aluminum alloys, owing to its inherently stable metal transfer, reduced spatter generation, and limited thermal damage to the base material. The present analysis confirms that reduced heat input generally enhances porosity control, hardness, and tensile strength; however, excessively aggressive heat input reduction can compromise joint integrity by promoting incomplete fusion and inadequate weld formation. These findings indicate that the optimal CMT welding condition should not be defined solely by minimum heat input, but rather by the best achievable compromise among metallurgical quality, mechanical performance, and process stability. Future work should prioritize experimental validation of the predicted parameter window identified in this study, alongside extension of the analysis to dissimilar material combinations and thick-section applications, in order to establish broader applicability and industrial relevance of the proposed optimization framework.

Declarations

I hereby declare and affirm that all statement entries provided in the Declarations section above—including those regarding funding, competing interests, ethics approval, consent to participate, consent for publication, data availability, materials availability, code availability, and authors' contributions are accurate, true, and complete. I understand that supplying false, misleading, or fraudulent information constitutes academic misconduct under Springer Nature editorial policies and international publishing ethics standards (including COPE guidelines). Should any statement be found inaccurate or untrue, I acknowledge that the journal editor and publisher reserve full authority to take appropriate institutional and editorial actions, which may include manuscript rejection, formal retraction of the published article, notification of author institutions, or restriction from future submissions.

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- Data availability The datasets generated or analyzed during the current study are available from the corresponding author upon reasonable request.
- Materials availability No materials and key reagents used during the study are available from the corresponding author upon reasonable request.
- Code availability Custom code and software scripts used during the current study are available from the corresponding author upon reasonable request.
- Author contribution All authors contributed to the study conception and design. Matlab script writing and analysis were performed by Anish K Raj. The first draft of the manuscript was written by Anish K Raj, and Bikash Ranjan Moharana and Kalinga Simant Bal. All authors read and approved the final manuscript.

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