



Joining dissimilar metals using cold metal transfer process: a review

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Abstract

In modern engineering applications, there is a growing demand for reducing the overall component weight without compromising strength and integrity. This has led to the combined use of multiple materials. Conventionally, various methodologies such as mechanical fastening, friction stir welding, and transition joints have been proposed to join dissimilar metals. It is worth noting that components made of dissimilar metals present several challenges when it comes to metallurgical joining. These challenges arise from the chemical and thermal properties of the metals, which result in the formation of intermetallic compounds at the interfaces and the occurrence of thermal stresses in the joints. Cold metal transfer method employs controlled short circuiting to minimize heat input, making it ideal for dissimilar metal welding. This reduced heat input effectively prevents excessive thermal stress, distortion, and the formation of brittle intermetallic compounds at the joint interfaces. The current work is presented with a view of providing the various process parameters adopted across combinations of dissimilar metals using CMT method, the complications in the fabrication of joints, and the respective counter actions carried out to attain a solid metallurgical bonding between the metals.

Keywords Cold metal transfer · Dissimilar metals · Intermetallic · Material combinations · Metallurgical joining

1 Introduction

New-age manufacturing has turned its focus towards utilizing the favorable attributes of different metals and combining them as a single entity to achieve superior and contrasting properties such as strength, weight reduction, and corrosion resistance [1, 4, 5]. In high-end industries like aircraft construction, nuclear structures, and shipbuilding, the demand for superior mechanical properties takes precedence. These applications require materials that not only enhance performance across various aspects but also preserve the fundamental structural integrity and essential

features of the final product [2, 3, 16, 17, 20, 43, 47]. Similar demands exist in stream of automobiles where the reduction of the encompassed weight of the product is prioritized, thereby impacting various aspects such as performance, cost-efficiency, and logistics [7, 9, 13, 15, 18, 23, 30, 34, 35, 42, 46] which can be addressed by using dissimilar material combinations. Dissimilar metals are two or more metals that have different chemical compositions, physical properties, and/or melting points. Considering the applications of the cold metal transfer (CMT) technique, the most benefited industries include the aerospace industry, automotive industry, shipbuilding industry, oil and gas industry, and the heavy machinery industry. Specifically, in aerospace and shipbuilding industries, the combination of a lighter material, such as aluminum, with a mechanically superior and corrosion resistant material, like Inconel, is prioritized due to their combined favorable physical responses [5, 14, 30, 44]. However, combining dissimilar metals tends to exhibit several challenges, especially in attaining a considerable joint strength and sub-surface integrity [6]. Processes such as mechanical roll bonding reportedly produce only physical interlocking between the materials which would not suffice the strength achieved through metallurgical bonding such as

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welding and brazing [13]. Although conventional metal joining methods like diffusion bonding and friction stir welding (FSW) have reportedly produced robust joints of dissimilar metals, their lack of flexibility and resistance to the formation of intermetallic compounds (IMCs) due to vast differences in melting temperatures further diminishes their reliability [17, 26, 27, 41]. To overcome the above-mentioned drawbacks in conventional metal joining techniques, CMT, a variant of gas metal arc welding, is employed wherein controlled short circuiting through timely retraction of filler wire is employed, leading to welding at low heat input [42, 56]. Various research articles have examined a significant number of material combinations, such as aluminum alongside other metals like steel, magnesium, and nickel alloys, while also discussing issues with weldments, particularly the development of brittle intermetallic compounds at the weld interface, a key factor determining joint strength [3, 7, 8, 10, 13, 19]. For instance, combinations of aluminum (Al)- and magnesium (Mg)-based alloys have attracted a significant spike in interest due to their potential to reduce the overall weight of automobiles while maintaining the structural strength. The primary advantage of employing CMT is the achievement of virtually spatter-free joints at low-energy input between a variety of materials with high precision while also facilitating the joining of thin cross-sections [5]. In the following sections, the parametric overview of the CMT method and the inferences from the experimental results of the published works are presented.

2 Cold metal transfer: an overview

As discussed in the previous section, CMT is a technique that can be utilized to join dissimilar metals with major merits such as reduction in thermal heat input, low distortion, and higher precision [43, 48, 53]. This section aims to provide a summary of the different definitions and interpretations of the CMT method as presented by various researchers. Selvi et al. (2017) [2] cited the CMT method as “mechanically assisted droplet deposition” due to its primary functional principle where the retraction of the filler wire is achieved by a push-pull MIG torch system. Similarly, Venkumar et al. (2019) [4] depicted CMT as a modified form of MIG welding in which the filler metal is purposefully inserted into the weld zone and then removed after the short circuiting, resulting in a metal droplet covering the joint. In essence, CMT is recognized as a variant of gas metal arc welding (GMAW), employing controlled heat input for welding materials [44]. Pickin et al. (2011) [24] described the cold metal transfer as a method for joining disparate metals and cladding with low dilution. Likewise, due to the precise control of weld bead dilution, the technology can also be used distinctively as a

cladding process. The sequence of occurrences in CMT is shown in Fig. 1.

The entire cold metal transfer process is divided into two states, namely, hot and cold, based on the temperature at the weld zone. The phase responsible for arc generation is called the hot state, while the retraction of the electrode, leading to heat reduction, is termed the cold state [1, 54]. CMT is typically conducted using low welding currents, resulting in welded joints with minimal spatter [4, 8, 43, 48]. As the electrode wire tip meets the molten pool during the process, a digital process control system initiates the reversal of the servomotor integrated into the robotic welding torch. This reversal action subsequently initiates the retraction of the electrode wire, thereby facilitating the transfer of the droplet [9, 50]. The process is divided into three phases: the arcing phase, background phase, and short-circuit phase. In the arcing phase, a constant arc voltage, associated with a high pulse of current, ignites the welding arc, heating the wire electrode to form the metal droplet. The subsequent background current phase corresponds to the instant where the current is decreased to prevent the globular transfer of the liquid droplet formed on the wire tip, continuing until short circuiting occurs. Here, the current is very low due to which the droplet does not grow noticeably and is maintained until the droplet contact the weld pool, and short-circuit phase starts [55]. In the short circuiting phase, the arc voltage is reduced to zero while simultaneously sending a return signal to the wire feeder. This phase facilitates the fracture of the liquid droplet and the transfer of material into the welding pool [2].

Essentially, during metal transfer, the current drops to near-zero (as seen in Fig. 2), thereby reducing the spatter generation. After the completion of the metal transfer, the arc is re-ignited, and the wire is fed again towards the melt pool with a set value of welding current. To investigate and comprehend the allocation of energy across various stages within the droplet transfer process, it becomes essential to study the waveforms of both current and voltage. Chen et al. (2017) [54] discussed about the effect of current waveforms on the welded joints. In the aspect of droplet deposition, the deposition rate reportedly increases with boost current or boost duration even at constant preset wire feed rate. During the process, the melted and deposited wire is balanced by the wire pushed out of the contact tip. Hence, due to the lack of spatter, the deposition rate shall be equal to the actual wire feed speed in CMT. Also, it is seen that the CMT metal transfer frequencies (the rate at which a small amount of molten metal is transferred from the welding wire to the workpiece during the welding operation) fluctuated very little with the boost duration, boost current, and preset wire feed speed which indicated that the boost duration, boost current, and the wire feed rate had no direct effect on the transfer frequency during welding of mild steel using

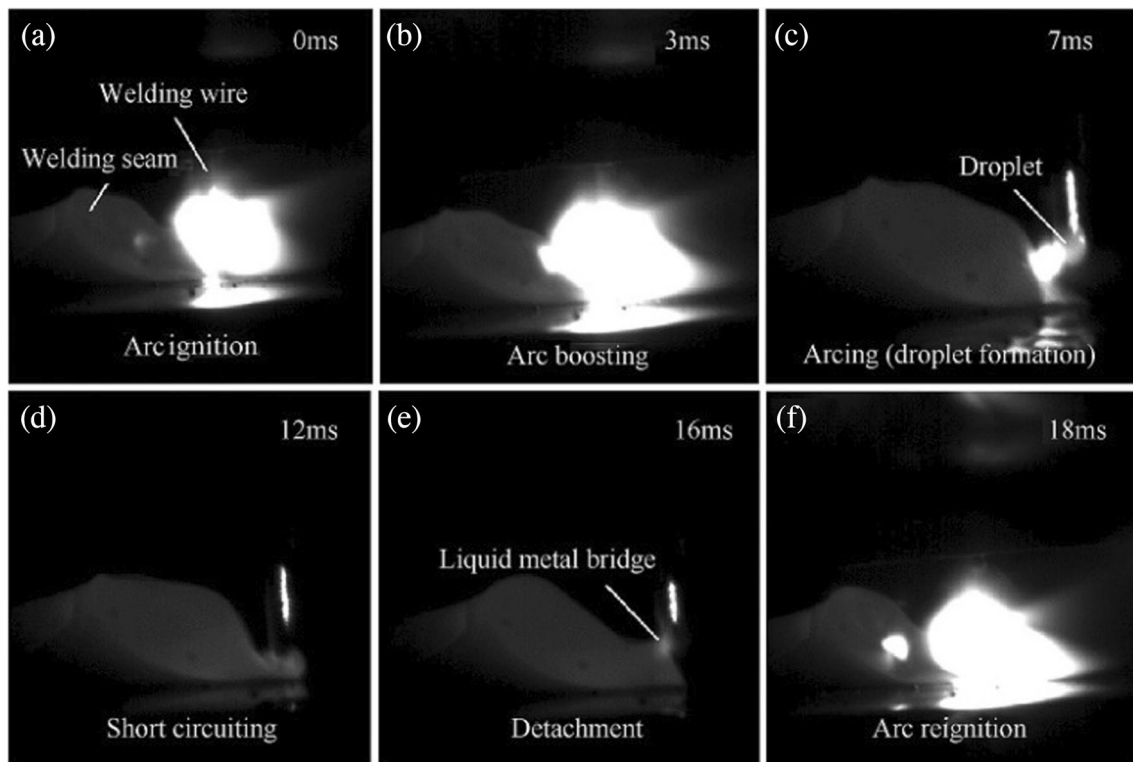


Fig. 1 Cold metal transfer process [2]. **a** Arc ignition. **b** Arc boosting. **c** Arcing. **d** Short circuiting. **e** Detachment. **f** Arc reignition

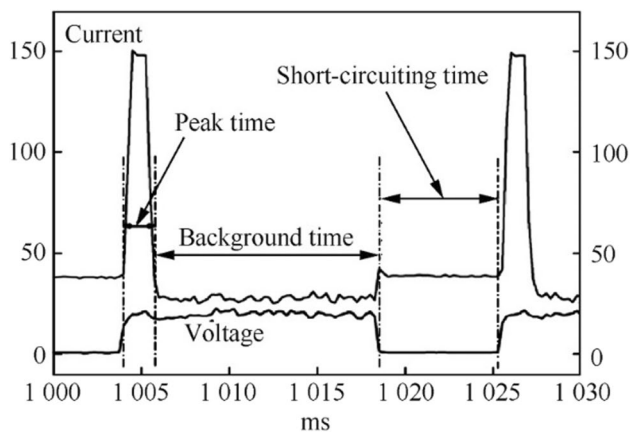


Fig. 2 General current and voltage waveforms in CMT [2]

CMT method. Additionally, the experimental results demonstrated significant influence of boost current and duration on the weld profile and size due to their effect on the arcing power. It was reported that the increase in boost current or boost duration increased the penetration and weld width with negligible variation in reinforcement. Liu et al. (2018) [37] summarized the advantages of CMT for joining dissimilar metals. The major highlights included the presence of a digital coordination to control the movement of the wire feeding

and transfer of droplets at a low welding heat input. Also, there is no splash transition or large spatters produced during the process which is achieved through the precise introduction and retrieval of the filler metal. The notable heat input reduction produces good weld quality at high precision and even facilitates the joining of thin sheets such as in automobile bodies [8, 43, 47]. Additionally, less spatter and fumes are produced which lowers post-weld cleanup costs and the need for personal protective equipment and ventilation systems while using this technique.

3 Material combinations

In the light of the literature survey, it is observed that cold metal transfer has been highly utilized to produce metallurgical joints of both similar and dissimilar alloys few of which are discussed in the article. Selvi et al. (2017) [2] had presented several material combinations joined using CMT and their post-fabrication analysis to validate the suitability of the method. Reportedly, satisfactory joining between the similar substrates was achieved in Inconel 718, aluminum 7075, galvanized steel, and AA2219-T851 due to the stability of the weld alongside the reduction of porosity. In the same article, a list of the possible combination of dissimilar metals was provided which comprised the combination of Al-based

alloys with zinc-coated steels, Mg–Al alloys, Mg-based alloys with zinc-coated steels, Al–Ti combinations, magnesium- and copper-based alloys, titanium- and magnesium-based alloys, aluminum and nickel alloys, titanium–stainless steel, etc. Similarly, Cao et al. (2013) [3] and Xu et al. (2022) [22] reported the mechanisms for joining titanium Ti–6Al–4V alloys and aluminum A6061-T6 alloys using cold metal transfer technology. The experimental outcomes of joining of aluminum alloys with different combinations using CMT were depicted in [5, 9, 23]. Aluminum–zinc-coated steel [6–8, 13, 15, 20] and aluminum–magnesium [10, 11, 17–19, 44] are one of the other commonly reviewed and validated combinations of dissimilar metals fabricated using CMT apart from stainless steel-based and Al/Ti/Ni compounds as reported in [1, 3, 22]. From the literature, it was observed that the procedures adapted to analyze the welded joints included several common features in fabrication such as the type of joint (mostly lap joints), angle of weld torch (45°), thickness of samples (around 1–3 mm), testing procedures (tensile testing, SEM, EDS), shielding gas flow rate (15 L/min), and weld overlap (10 mm). Likewise, the methodology adopted to the effectiveness of the joints comprised the microscopic inspection of the fabricated samples for the presence, composition, and the scale of intermetallic compounds alongside the inspection for tensile strength and occasional exposure to quasi-static testing and impact tests. These inspection methods provide an insight about the weld formed between the substrates which can be attributed to the characteristics of the welded metals and the consumables. The reported outcomes for various combinations of materials are briefed in the forthcoming sections.

3.1 Dissimilar joining of aluminum-based alloys with steels

The metallurgical joining of aluminum alloys with galvanized steels entitles the production of components with attributes such as low weight and good corrosion resistance. The feasibility of attaining the combination was observed

through the analysis of the published literature. In this regard, several aspects of the process could be segregated such as the filler metals used, composition of the substrates, and the intermetallic compounds formed. Cao et al. (2013) [6] reported the study involving the lap joining of Al-based alloys (AA6061, AA7075, and AA5183) with galvanized mild steel of identical thickness (1 mm) using different filler materials (aluminum 4043, 4047, 5356).

The inspection of the weld–brazing interface revealed three distinctive zones: weld metal, zinc-rich zone, and aluminum fusion zone (Fig. 3) and the presence of FeAl, FeAl₂, Fe₂Al₅, FeAl₃, and FeAl₆ intermetallic compounds. Earlier, Feng et al. (2007) [33] had adopted an almost identical approach in analyzing the zinc distribution and microstructure of CMT joints of Al and galvanized steel where the microstructural study exhibited Al–Fe–Zn as the interface component with the presence of FeAl₃ IMC close to the interface between the substrates. Regarding the mechanism of joint formation, it is seen that the Al-based filler metal fuses with the aluminum substrate to create a welded joint, while the filler metal combines with the steel to establish an Al–steel brazed joints. However, the integrity of the joints needs to be ensured which are often impacted by the quantity/thickness of the brittle IMCs formed during the joining process as reported by Singh et al. (2019) [20] and Ünél et al. (2017) [23]. It is seen that the formation of intermetallic compounds is a particular issue that impacts the integrity of the joints produced in the CMT apart from the inception of the Zn-rich zone at the weld interface. The study on the impact of heat input on joint strength revealed that the intermetallic thickness increased with the heat input, potentially leading to joint fracture.

As mentioned earlier, various compositions of IMCs are observed in the weld–brazing interface which include Fe₂Al₅, FeAl₃, and FeAl [20, 23, 26, 32, 40]. Considering the formation and growth of IMCs, various factors such as solid solubility between Al and steel, crystal structure of the compound, inter-diffusion coefficient, and interatomic interaction potentials are reported as the critical contributing factors.

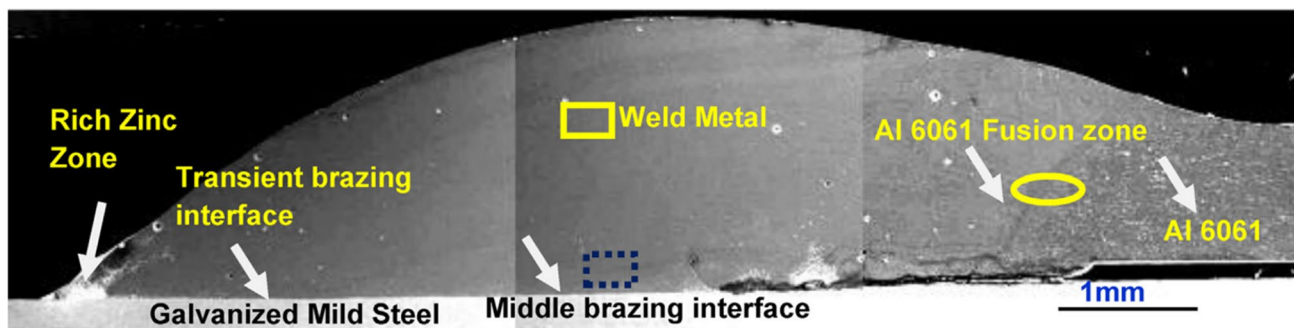


Fig. 3 Zones at the weld–brazing interface [6]

Apparently, the origination of these binary compounds (FeAl_3 , Fe_2Al_5) is essential to form a functional attachment between the base metals. However, this two-stage outcome (chemical reaction between Al and steel, inter-diffusion between iron and aluminum) affects the overall strength of the metallurgical bonding since they inevitably contribute to the augmentation in brittleness and deterioration of mechanical properties. As reported by Lin et al. (2013) [8] and Singh et al. (2019) [20], the effective IMC thickness for joining of dissimilar should ideally be less than $10\ \mu\text{m}$ to attain a solid bonding between the substrates. As discussed in the aspect of the brittle IMCs, the impact of thickness, surface composition of the substrates, and the filler metal on the weld–brazed joints also were evident as per the reported literature. Babu et al. (2019) [34] had attempted to establish a metallurgical joint between AA 2219 (Al–Cu alloy) and AISI 321 (SS alloy). The microscopic analysis of the FSW joint between the stainless steel (SS) substrate and aluminum coating demonstrated an IMC-free attachment with similar surface roughness and mean grain size across different thickness of Al coatings. Reportedly, the joint with the lowest coating thickness provided high bond area and fillet length which drew a conclusion that the joint would be stronger than the joints with coatings of other thickness. The rise of contact angle in the weld bead with the increase in thickness of the surface coating was attributed with the faster rate of heat dissipation during the process. Similarly, the investigation of the lap shear strength of the welded joints also revealed that the highest fillet area contributed to the highest lap shear performance, while the unmelted Al coating of several microns at the interface would apparently improve the joint strength between the metals.

In this regard, Lin et al. (2013) [8] reported two modes of failures in shear strength testing, i.e., fusion line failure and interface failure where the former was identified as the most common form of failure while producing a CMT-brazed lap joint of Al 6061 with zinc-coated mild steel of different thickness using ER4043 filler material. As seen in Figure 4, the joint revealed the presence of pores and incomplete fusion at the interface. It was observed that the microhardness at weld metal and the fusion line was almost identical and lower than the parent metal, respectively, on the Al side, revealing a decreased tensile strength and yield limit. Also, low shear strength joints were attained while joining Al with thin or low-strength steels, drawing an inference that the thickness and grade of the steel joined with the steel base metal play a significant role in the weld strength [21].

The effect of coatings on the weldability of CMT joining of AA6061T6 alloy to boron steels with Al4043 filler was studied by Cao et al. (2014) [26]. The observation of the weld quality between aluminum and uncoated boron steel revealed that the affinity of the filler was higher with the boron base metal, barely covering the aluminum substrate

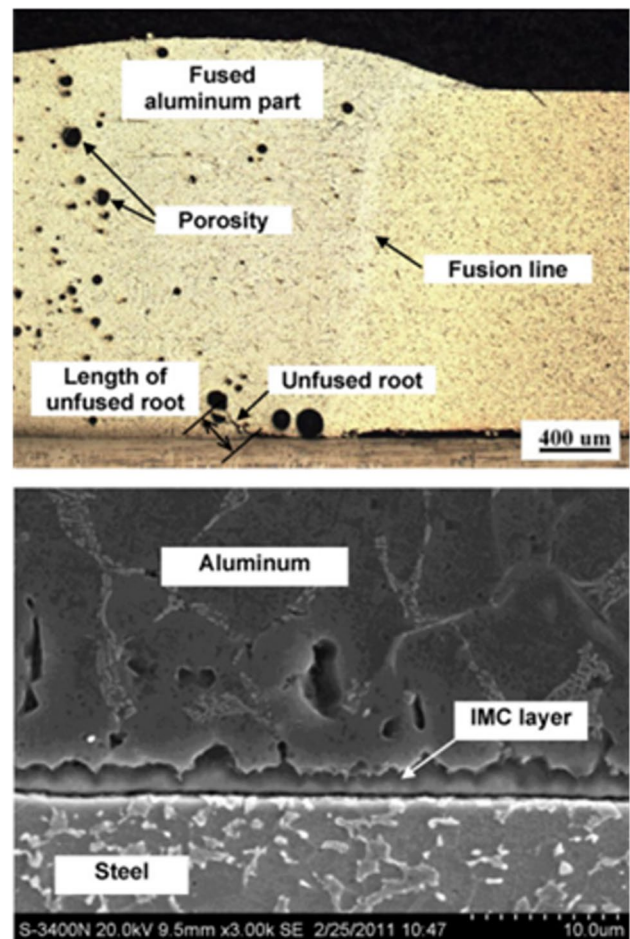


Fig. 4 Porosity formed due to gas entrapment (top). Intermetallic layer at the fusion zone (bottom) [8]

due to the lower enthalpy involved in the mixing of aluminum in iron than aluminum in aluminum. Also, the presence of highly brittle Fe-based intermetallic compounds (Fig. 5) formed due to the fusion of boron steel with the aluminum base metal under the intense heat of the electric arc was confirmed at the brazing interface between aluminum and bare boron steel, suggesting that a solid metallurgical bond cannot be established between uncoated boron steels and aluminum using the CMT method which also was presented by Truppel et al. (2019) [40]. The formation of cracks at the interface between the metals suggests the same as shown in Fig. 6. Likewise, Singh et al. (2019) [20] outlined the impact of composition of filler metals and reported the reduction of intermetallic during the welding of Al and steels through the manipulation of composition of filler metal composed of elements such as silicon alongside Mg, Mn, Cu, Zn, and Zr.

Zhang et al. (2009) [32] had emphasized that control of the brittle intermetallic layer thickness can be achieved through control of heat input and addition of elements such

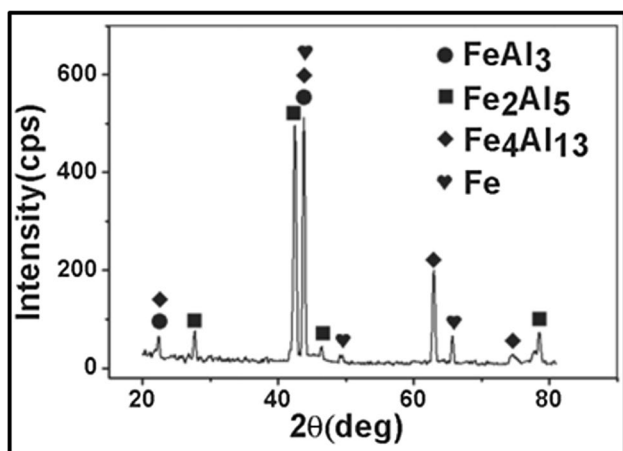


Fig. 5 XRD analysis showing the presence of intermetallic at the weld interface [26]

as silicon to the filler material (AlSi) which apparently produced an IMC thickness of around 4 μm and bond tensile strength of about 83 MPa. Similarly, Agudo et al. (2008) [41] reported that $\text{Al}_{99.5}$ and AlSi_3Mn_1 filler materials under the use of optimal parameters produced a brittle intermetallic layer (θ -phase Al_3Fe and the η -phase Al_5Fe_2 ; Al (Fe, Mn) Si phase) between the molten filler and steel with thickness less than the critical value involved in the joining of DX54D+Z200 steel sheets AW5182-H111 sheets. As reported by Song (2009) [47], a satisfactory joint between 5A06 aluminum alloy and AISI 321 stainless steel was attained in butt joint weld configuration through the inclusion of silicon which prevents the formation of the IMC layer and reduces its thickness. With a Si inclusion of 5 wt.%, the IMC layer reportedly demonstrates optimum mechanical properties in terms of hardness and tensile strength which accentuates the impact of filler metal compositions even in lower proportions.

Further, Ünel et al. (2017) [23] presented the influence of the filler composition and zinc coating on the stability of arc and quality of welded joints of DX54D+Z galvanized steel and 1.0-mm EN-AW-5754-H111 alloy using AlSi_3Mg (ER4020) filler wire. It was reported that the Zn coating over the surface of the substrate had an ambiguous effect on the joints. But Truppel et al. (2019) [40] and Cao et al. (2013) stated that galvanization of the substrates increased

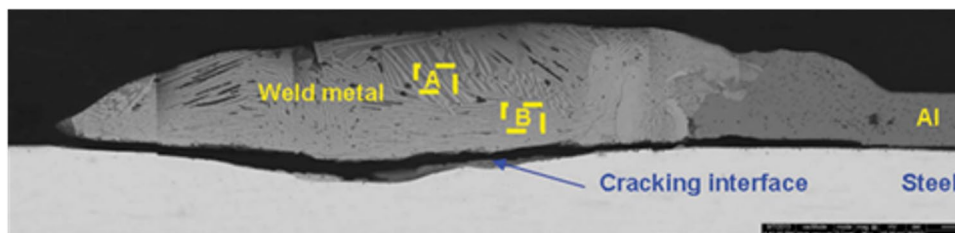
the wetting of filler metal over the base metal, attributed to higher affinity of Al to Zn and stabilized the arc, thereby resulting in satisfactory weldment between the metals. This impact of the presence of zinc in the weld zone is attributed to the sacrificial tendency of zinc, i.e., combustion under the heat of electric arc, resulting in a zinc-rich zone at the interface. Further, the formation of the Zn-rich zone interrupts the growth of IMCs, making them discontinuous and thin which contributes to the intactness of the produced virtually spatter-free joints and increase in mechanical properties such as tensile strength [6, 40]. Besides this, the stability of the arc and the formation of intermetallic compounds are found to be closely related since heat input, the factor contributing to the IMC growth and spatters during the process, is identified as a function of I Boost; i.e., higher value of I Boost results in higher heat input which tends to increase the thickness of IMCs. This phenomenon was experimentally verified by Truppel et al. (2019) [40] and Hao et al. (2015) [43]. It was seen that consistent bead dimensions and with an increase in I Boost resulted in increased width and decreased contact angle. However, I Boost beyond the optimal value resulted in the formation of Fe–Al and Fe–Al–Si IMCs and thermal stresses that affect the strength of the welded joints.

3.2 Dissimilar joining of aluminum-based and magnesium-based alloys

In industrial streams such as automobiles, the reduction of the curb weight is prioritized, thereby optimizing the production in various aspects such as performance, cost-efficiency, and logistics [7, 9, 13, 15, 18, 23, 30, 34, 35]. Beyond that, the reduced density, excellent strength-to-weight ratio, and simplicity of recycling of the elements add to their credibility of their use in automobile industries [19, 36, 39, 48, 49]. Just as Al–steel alloy combinations, comprehensive study of dissimilar joining of Mg and Al-based alloys using CMT has been carried out in the aspect of the formation and impact of the composition of intermetallics and filler metals. Shang et al. (2012) [17] presented the microstructural and mechanical property analysis of CMT-based metal joining of magnesium (Extruded AZ31B) and aluminum alloys (Al 6061) with pure copper (HS201) as the filler material.

The presence of a large quantity of Cu_2Mg at the points of interface (1, 2, 3) shown in Fig. 7a and b reportedly

Fig. 6 Cracks formed due to the presence of intermetallic compounds [26] (A coarse columnar grains, B equiaxed crystalgrains)



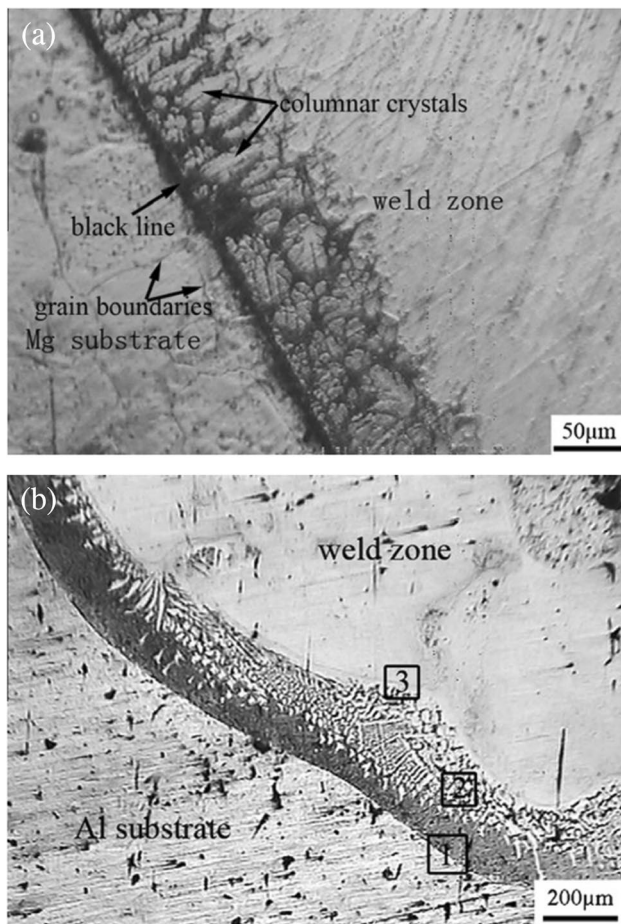


Fig. 7 **a** Optical micrograph of fusion zone on Mg side [17]. **b** Optical micrograph of fusion zone on Al side [17]

increased the microhardness, thereby inducing brittle fracture during tensile testing, albeit exhibiting successful bonding between the dissimilar base metals. Using a similar approach, Cao et al. (2013) [19] had attempted to join magnesium AZ31B-to-aluminum A6061-T6 with aluminum 4047 filler metal. Reportedly, a notable amount of Al and Mg-based IMC's was identified at the weld interface which could potentially reduce the joint strength of the base metals. Similarly, Wang et al. (2020) [10] had used Inconel-625 as the filler material to join Mg-AZ31B and Al 6061. Observation of the topography of the weld revealed some spatters and porosity, attributed to the vapor pressure of Mg droplets during the material transfer process.

A brief review given on the dissimilar joining of various material combinations by Burhanuddin et al. (2020) [48] had stated that CMT can be used to satisfactorily join Al- and Mg-based alloys with a minimum substrate thickness of 0.7 mm. In a similar fashion, Jadav et al. (2022) [49] had comprehensively reviewed various techniques used for the welding of magnesium and aluminum alloys. It was highlighted the differences in melting temperatures, thermal

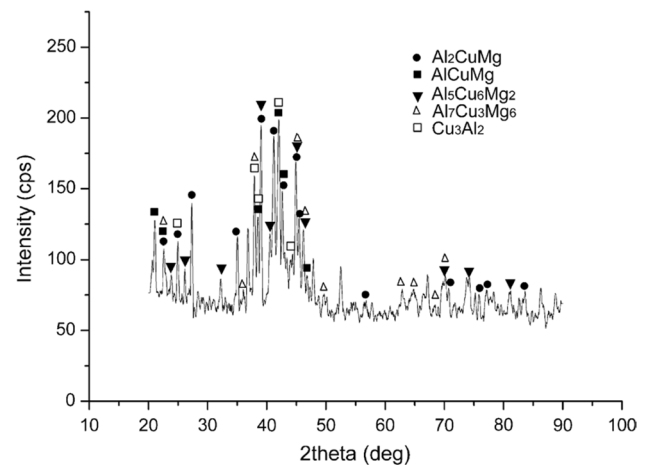


Fig. 8 X-ray diffraction pattern showing the presence of intermetallic at the weld interface [17]

conductivity, and chemical properties between the alloys as the major set of challenges faced in the joining of the alloy materials. Notably, it was proposed that the filler material should have similar mechanical and chemical properties as the base metals to ensure a high-quality weld.

In the light of the above-mentioned studies, the influence of filler metals has had a significant role to play in the quality of joints and other aspects such as the formation of IMCs between the Al and Mg substrates. For instance, the use of HS201 (pure Cu) as the filler has reportedly produced a successful metallurgical Al–Mg (Al 6061-Extruded AZ31B) bonding albeit in the presence of IMCs such as AlCu, CuAl₂, Cu₂Mg, and Cu₉Al₄ (Fig. 8) [17]. Likewise, aluminum 4047 was found to significantly reduce the thickness of IMCs at the weld–braze interface due to the presence of Si (12%) during the joining of AZ31B(Mg) to A6061-T6 (Al) [19]. It is also seen that the use of In625 filler forms Mg-based vapors while reacting with Mg substrate which influences the bonding strength between the substrates. However, the formation of intermetallics such as Al₃Ni, Al₇Cr, and Mg₂Al₃ formed during the process are found to be inefficiently restricted albeit exhibiting good tensile strength than while using Al-based filler metals.

3.3 Miscellaneous combinations with nickel-based alloys

Nickel-based alloys have gained interest from researchers owing to their superior mechanical properties which entitles them to be used in applications involving extreme ambient conditions. Several researchers have discussed the consequences of change in parameters in terms of the composition of intermetallics and quality of weld as reported below. Liu et al. (2015) [12] evaluated the use of AlSi₅ filler wire for joining of 5A06 Al alloy plates and N6 pure Ni plates using

CMT method. The joint's microstructure was divided into nickel base metal, Ni_3Al , $\text{Ni}_{0.9}\text{Al}_{1.1}$, and Ni_2Al_3 intermetallic layers alongside columnar NiAl_3 layers, and an Al–Si solid solution fractures where the cracks were mostly located proximal to the NiAl_3 and NiAl intermetallic layers. It was stated that the thickness of the intermetallic layer decreases and then increases as the welding velocity increases, while the joint strength increases as intermetallic thickness decreases. Notably, at a speed of 15 mm/s, the base thickness layer of IMC under $10\ \mu\text{m}$ and high shear strength of 42 MPa was achieved. Similar discussions regarding the influence of parameters on the microstructure of the joints were briefed by Evangeline et al. (2019) [28]. Reportedly, during the joining of In625 with 316L stainless steel material using the CMT method, the base metal dilution exhibits an initial increase followed by a subsequent decrease, and this trend is observed to be proportional to the welding current. This phenomenon is attributed to the rise in heat input to the base metal as the welding current increases, leading to an initial surge in dilution. Microstructurally, the clad bead has cellular dendrites with secondary dendrite arm spacing and columnar dendrites and exhibits extreme hardness alongside the point of interaction. This behavior was attributed to the enrichment of Mo and Cr at the interface. Also, it was stated that the proportion of chromium and molybdenum in the Fe–Ni-based alloys increases the corrosion resistance, which is influenced by the dendritic arm space. The impact of the

composition of filler metals was discussed by Naffakh et al. (2009) [25] using an experimental research involving four filler materials: Inconel 82 (68.9% Ni, 20 wt.% Cr approx.), Inconel A (64 wt. % Ni, 15% Cr), Inconel 617 (63.3% Ni, 25 wt. % of Cr approximately), and 310 stainless steels for the joining of AISI 310 austenitic stainless steel and Inconel 657 substrates. As reported, Inconel A demonstrated the highest hardness, attributed to its high strength while 310 stainless steels, the lowest as seen in Fig. 9. Also, it was reported that Inconel A is prone to hot cracking, whereas Inconel 82 and 310 stainless steel weld metals have a greater propensity to crack.

3.4 Miscellaneous combinations with aluminum-based alloys

The literature survey on various material combinations revealed that aluminum alloys of different grades have also been considered for study regarding the feasibility and effectiveness of joints using CMT. An experimental study by Gungor et al. (2014) [5] observed the weldability and the performance of CMT-based welds by joining 5083–H111 and 6082–T651 aluminum alloys as dissimilar (5083–H111 and 6082–T651) and similar joints (5083–H111 with 5083–H111 and 6082–T651 with 6082–T651). It was seen that joining 5083 as similar alloys did not produce intermetallic in the HAZ but static recrystallization, whereas joining 6082

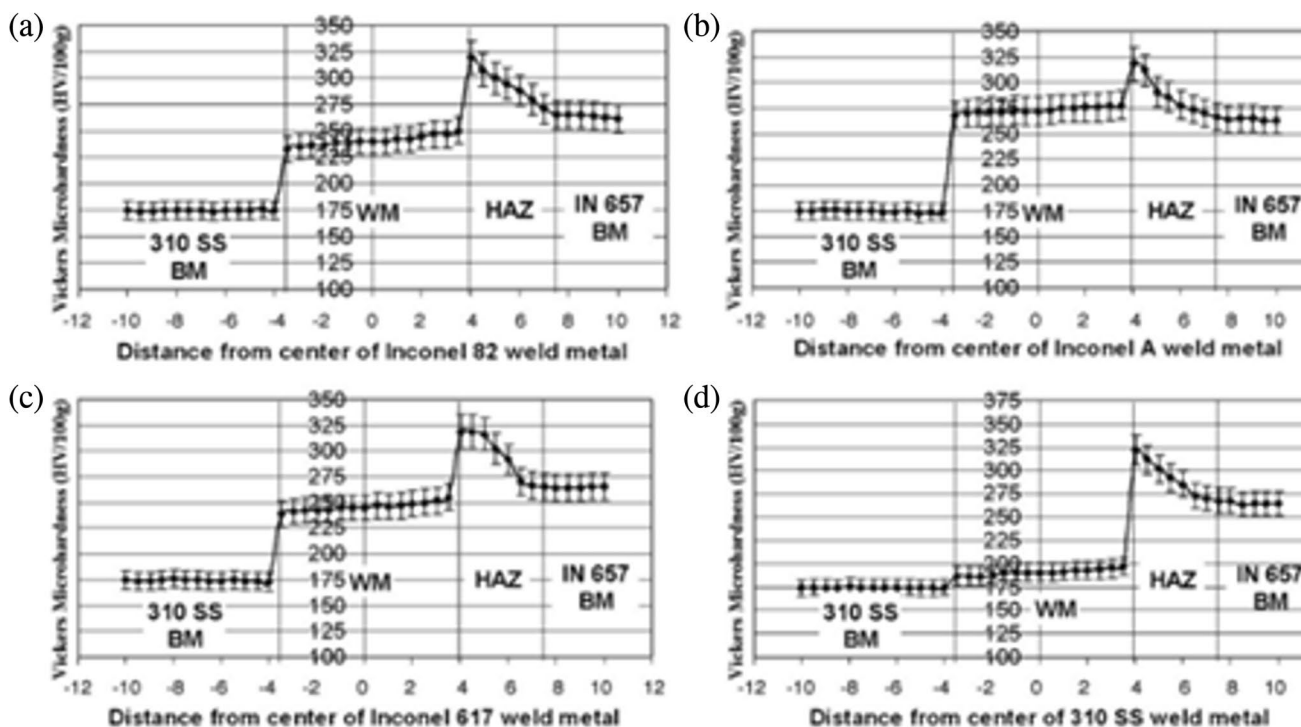


Fig. 9 Microhardness profiles for different filler metals [25]. (a) Inconel 82 joint. (b) Inconel A joint. (c) Inconel 617 joint. (d) Three hundred ten stainless steel joint

as similar alloys resulted in coarsening and coalescence with weld metal in the fusion line. In that aspect, Selvamani et al. (2021) [38] reported that welding of AA7071 T-6 aluminum alloys using ER 4043 filler using CMT could produce a finer and homogeneous microstructure which leads to improved stress corrosion behavior in the joints. Koli et al. (2021) [9] stated that the presence of silicon and manganese in the substrates could facilitate the generation of Mg_2Si intermetallic compounds, resulting in high hardness while provoking cracking of the joints. The use of Al–Si filler helps in joining dissimilar alloys of aluminum with considerably low formation of intermetallic compounds. Likewise, Wang et al. (2015) [39] studied the formation of dissimilar joints between Al5052 alloy and aluminized steel substrates using four types of filler metals: Al 4043, 4047, 5356, and 5183. For different combinations of steel and filler, wettability was not affected by the composition of filler metal, while the presence of silicon in the filler largely influenced the thickness of the IMC layer as seen in Fig. 10.

It is also seen that process parameters have a key role to play in the quality of joints produced using CMT method. As stated by Peng (2022) [45], the formation of intermetallic and the difference in thermal properties alongside the process parameters such as welding speed, current, and voltage weld quality largely influences the quality of the weld joint. Xu et al. (2021) [15] highlighted that an increased wire feed speed and low welding speed may not produce the optimal joint between the substrates since it may increase the heat input of the process, despite improving the wetting characteristics of the filler metal while reporting the presence

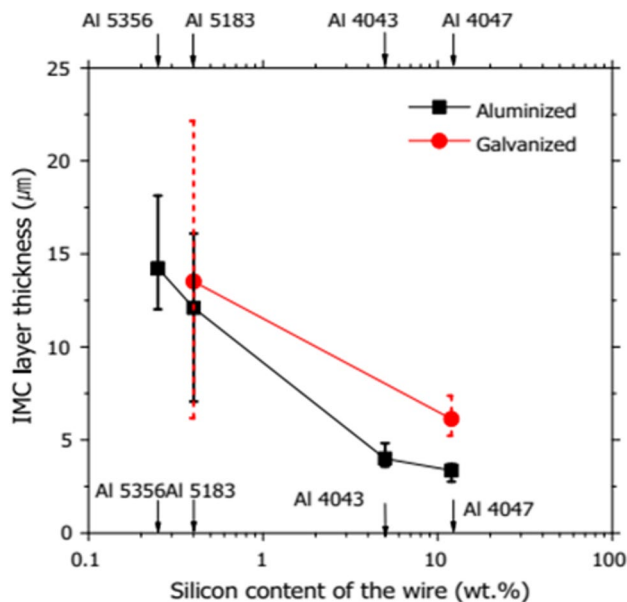


Fig. 10 Relationship between the silicon content and the average thickness of the IMC layer [39]

of Fe_2Al_5 and $Fe_3Al_2Si_4$ IMCs while joining stainless steel 304 and aluminum 5083. Similarly, Li et al. (2020) [31] mentioned that the wettability of the filler metal is low at low wire feed speeds which is ascribed to the proportionality between heat input and wire feed speeds while joining pure copper and Al 6061 alloy using a $AlSi_{12}$ (4047) filler metal. Concerning the mechanical properties of the joints, the tensile strength of the joint increased with the wire feed rate (Fig. 11), while microhardness increased with the formation of brittle intermetallic compounds.

3.5 Miscellaneous combinations with titanium-based alloys

Much like Ni-based alloys, Ti-based alloys, owing to their unique properties, such as high strength, low weight, and excellent corrosion resistance, make it a popular choice in various industries; the ability to seamlessly fuse it with other alloys opens new avenues for engineering applications. In this aspect, researchers have discussed the consequences of change in parameters, formation of intermetallics, and quality of weld [29]. Cao et al. (2013) [3] presented the influence of process parameters on the quality of joints between Ti–6Al–4V with $AlSi_5$ under CMT method. As reported, at higher wire feeder speeds ($4.3\text{--}4.8\text{ m min}^{-1}$), the deviation distance (the deviation from the wire to the edge of the lapped weld seam) does not contribute much to the tensile strength, while at medium wire feeder speeds (around $3.5\text{--}4.3\text{ m min}^{-1}$), the tensile strength of the welded joints improves with the deviation distance. Apart from the process variables such as wire feed speed and deviation distance, the chemical affinity of filler and the base metals was found to influence the factors such as wettability and spread ability. This attribute may lead to a discontinuity in weld interface on the substrate with low affinity (Fig. 12). In the

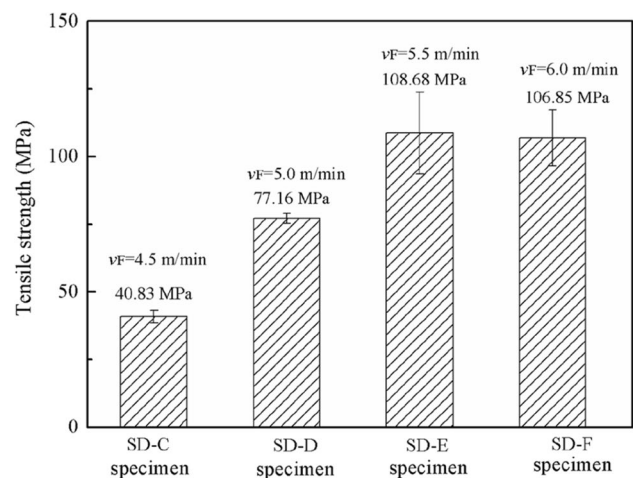
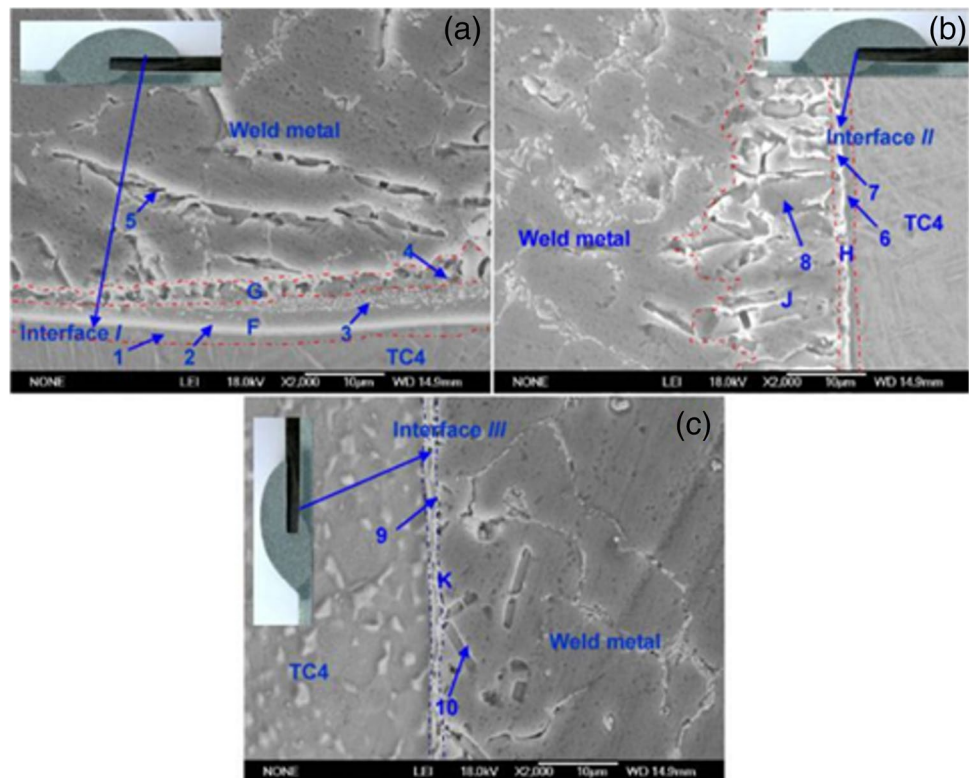


Fig. 11 Tensile strength of the specimens [31]

Fig. 12 Microstructures of brazing interface between fusion welding joint and Ti alloy matrix [3]



view of process parameters, it is seen that inefficient bonding between the substrates may occur despite a good weld appearance at lower wire feeder speeds, while a better weld appearance alongside a good wettability of the filler metal was observed at higher wire feeder speeds. Similarly, Cao et al. (2014) [30] mentioned that the quality of the welded joints between Ti and Mg-based alloys based is largely influenced by the variables such the supplied voltage and wire feed speed while denoting the formation of intermetallics such as Ti_3Al , $Mg_{17}Al_{12}$, and $Mg_{0.97}Zn_{0.03}$ at the brazing interface between the base metals as shown in Fig. 13.

In this aspect, Pardal et al. (2016) [16] reported a preferable wetting of the substrate with high hardness at higher heat input with moderate changes in the weld geometry, while the samples with decreased heat input exhibited lower hardness and do not wet the stainless steel plate correctly. Observing the substrates with various thickness of the transition material (Cu), it is seen that the increase in the thickness of the coating largely reduces the thickness of the intermetallic layer formed which comprised Fe, Cr, Si, Ti, and Cu. A similar approach by Cao et al. (2014) [35] in studying the properties of lap welded CMT joints of titanium and copper showed that the difference in deviation distance of the process impacts the wettability and continuity of the welded joints alongside other specifications such as weld speed and wire feed speed. Regarding the presence of intermetallics, brittle phases such as Ti_2Cu , $TiCu$, and $AlCu_2Ti$ were identified at the titanium weld interface. These compositions of

IMCs were identical to those reported by Cao et al. (2014) [52] while joining commercially pure TA2 Titanium and T2 copper of similar thickness through CMT method with $ERCuNiAl$ as the filler metal.

4 Conclusions

The current work has provided an overview of the cold metal transfer process used to effectively join two dissimilar metals and has discussed the reported results from various literature regarding the process parameters, identified complications, and the counter processes. It is seen that the need for the combination of contrasting properties in a single entity has aggravated has found application in almost any stream irrespective of the scale. CMT has established the capability of inducing a metallurgical joining between two completely contrasting materials with all the desirable properties at the required scale. Further exploration of the application of material combinations needs to be carried out which can result in improved outcomes in complex applications such as aircrafts and nuclear power generation.

The following conclusions can be drawn from this review paper:

1. The major merit of using CMT method over conventional welding methods for the purpose of joining dissimilar metals lies in its ability to timely retraction of filler wire. This action leads to a reduced heat input,

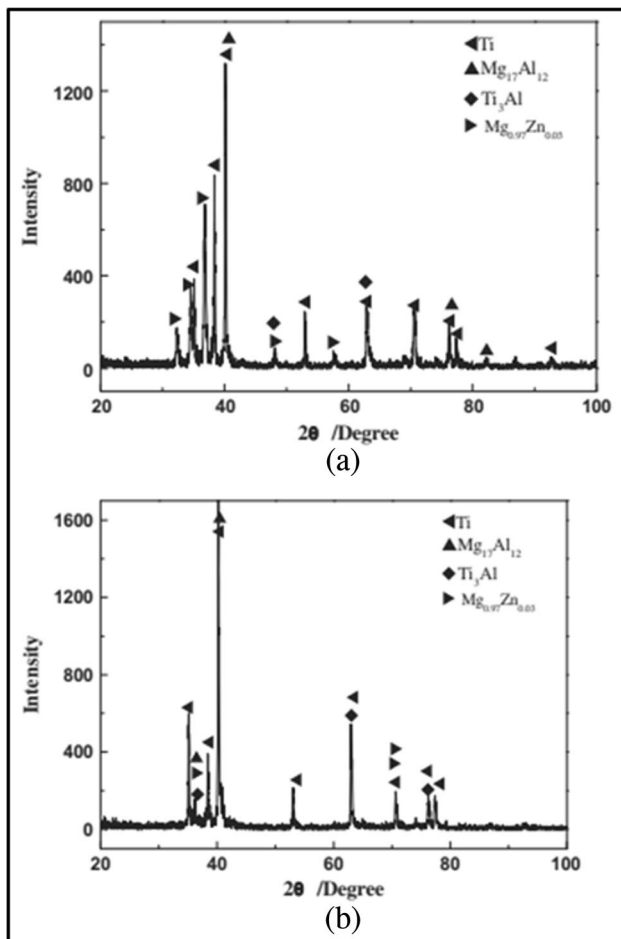


Fig. 13 XRD analysis of brazing interface: **a** Mg–Ti joint (top Mg sheet, bottom Ti sheet), **b** Ti–Mg joint (top Ti sheet, bottom Mg sheet) [30]

which limits the growth of brittle intermetallics which inevitably weaken the joints between the substrates.

- For joining Al-based alloys and Fe-based alloys, the incorporation of elements such as silicon alongside Mg, Mn, Cu, Zn, and Zr have reportedly restricted the growth of intermetallic phases and provided feasible mechanical properties.
- The presence of intermetallic was reported for most combinations of materials. However, if the thickness of the brittle intermetallic layer was found beyond the critical value of 10 μm , modification of parameters and application of surface coatings with elements such as zinc have proved to reduce their thickness. The IMC thickness more than 10 μm leads to inefficient joints.
- The capability of CMT method to weld thick as well as thin materials while maintaining high welding quality is often attributed to the control in heat input and a

wire feeding system that allows for precise control of the amount of material added to the weld.

- The study of impact of heat input on joint strength revealed that the intermetallic thickness increased with the heat input, potentially leading to joint fracture.
- It is noteworthy that the formation of intermetallics has only been reduced to a large extent rather than eradication in both conventional welding methods and CMT approach where the choice of filler metal is also critical.

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Data Availability The data that supports the findings of this study are available within the article [and its supplementary material].

Declarations

Conflict of interest The authors declare no competing interests.

References

- Furukawa K (2006) New CMT arc welding process—welding of steel to aluminium dissimilar metals and welding of super-thin aluminium sheets. *Weld Int* 20(6):440–445
- Selvi S, Vishvakshenan A, Rajasekar E (2018) Cold metal transfer (CMT) technology—an overview. *Def Technol* 14:28–44
- Cao R, Sun JH, Chen JH (2013) Mechanisms of joining aluminium A6061–T6 and titanium Ti–6Al–4V alloys by cold metal transfer technology. *Sci Technol Weld Join* 18(5):425–433
- Venukumar S, Cheepu M, VijayaBabu T et al (2019) Cold metal transfer (CMT) welding of dissimilar materials: an overview. *Mater Sci* 969:685–690
- Gungor B, Kaluc E, Taban E et al (2014) Mechanical and microstructural properties of robotic cold metal transfer (CMT) welded 5083–H111 and 6082–T651 aluminum alloys. *Mater. Des.* 54:207–211
- Cao R, Yu G, Chen JH et al (2013) Cold metal transfer joining aluminum alloys-to-galvanized mild steel. *J Mater Process Technol* 213(10):1753–1763
- Zhang HT, Feng JC, He P (2008) Interfacial phenomena of cold metal transfer (CMT) welding of zinc coated steel and wrought aluminium. *J Mater Sci Technol* 24(11):1346–1349
- Lin J, Ma N, Lei Y et al (2013) Shear strength of CMT brazed lap joints between aluminum and zinc-coated steel. *J Mater Processing Technol* 213(8):1303–1310
- Koli Y, Yuvaraj N, Aravindhan S (2021) CMT joining of AA6061–T6 and AA6082–T6 and examining mechanical properties and microstructural characterization. *Trans India Inst Met* 74(2):313–329
- Wang P, Zhang H, Hu S et al (2020) Microstructure and mechanical behaviour of CMT-welded Mg/Al dissimilar joint using Inconel 625 as filler metal. *Sci Technol Weld* 25(1):10–19

11. Pakieła W, Tański T, Bryant Z et al (2016) The influence of laser alloying on the structure and mechanical properties of AlMg-5Si2Mn surface layers. *Appl Phys A* 122(4):1–9
12. Liu YB, Sun QJ, Sang HB et al (2015) Microstructure and mechanical properties of cold metal transfer welded aluminium/nickel lap joints. *Sci Technol Weld* 20(4):307–312
13. Arbo SM, Bergh T, Holmedal B et al (2019) Relationship between Al-Ni intermetallic phases and bond strength in roll bonded steel-aluminum composites with nickel interlayers. *Met Mater Int* 9(8):827
14. Corigliano Crupi V (2021) Fatigue analysis of Ti6Al4V/INCONEL 625 dissimilar welded joints. *Ocean Eng* 221:108582
15. Xu W, He H, Yi Y et al (2021) Dissimilar joining of stainless steel and aluminum using twin-wire CMT. *World Weld* 65(8):1541–1551
16. Pardal G, Ganguly S, Williams S et al (2016) Dissimilar metal joining of stainless steel and titanium using copper as transition metal. *Int J Adv Manuf Technol* 86(5):1139–1150
17. Shang J, Wang K, Zhou Q et al (2012) Microstructure characteristics and mechanical properties of cold metal transfer welding Mg/Al dissimilar metals. *Mater Des* 34:559–565
18. Wang P, Hu S, Shen J et al (2016) Effects of electrode positive/negative ratio on microstructure and mechanical properties of Mg/Al dissimilar variable polarity cold metal transfer welded joints. *Mater Sci Eng A* 652:127–135
19. Cao R, Wen BF, Chen JH et al (2013) Cold metal transfer joining of magnesium AZ31B-to-aluminum A6061-T6. *Mater Sci Eng A* 560:256–266
20. Singh J, Arora KS, Shukla DK (2019) Dissimilar MIG-CMT weld-brazing of aluminium to steel: a review. *J Alloys Compd* 783:753–764
21. Talalaev R, Veinthal R, Lansoo A et al (2012) Cold metal transfer (CMT) welding of thin sheet metal products. *Estonian J Eng* 18(3):243
22. Xu W, Wang W, Yang Q et al (2022) CMT Twin welding-brazing of aluminum to titanium. *World Weld* 66(6):1121–1130
23. Ünel E, Taban E (2017) Properties and optimization of dissimilar aluminum steel CMT welds. *World Weld* 61(1):1–9
24. Pickin CG, Young K (2006) Evaluation of cold metal transfer (CMT) process for welding aluminium alloy. *Sci Technol Weld Join* 11(5):583–585
25. Naffakh H, Shamanian M, Ashrafizadeh F et al (2009) Dissimilar welding of AISI 310 austenitic stainless steel to nickel-based alloy Inconel 657. *J Mater Process Technol* 209(7):3628–3639
26. Cao R, Sun JH, Chen JH et al (2014) Weldability of CMT joining of AA6061-T6 to boron steels with various coatings. *Weld J* 93(6):193s–204s
27. Kwon YJ, Shigematsu I, Saito N (2008) Dissimilar friction stir welding between magnesium and aluminum alloys. *Mater* 62(23):3827–3829
28. Evangeline A, Sathiyaraj P (2019) Cold metal arc transfer (CMT) metal deposition of Inconel 625 superalloy on 316L austenitic stainless steel: microstructural evaluation, corrosion and wear resistance properties. *Mater Res Express* 6(6):066516
29. Li J, Sun Q, Liu Y et al (2017) Cold metal transfer welding-brazing of pure titanium TA2 to aluminum alloy 6061-T6. *Adv Eng Mat* 19(2):1600494
30. Cao R, Wang T, Wang C et al (2014) Cold metal transfer welding-brazing of pure titanium TA2 to magnesium alloy AZ31B. *J Alloys Compd* 605:12–20
31. Li G, Song J, Lu X et al (2020) Investigation on microstructure and mechanical properties of Al/Cu butt joints by CMT method in asymmetrical V-groove configuration. *Metall Res Technol* 117(3):303
32. Zhang HT, Feng JC, He P et al (2009) The arc characteristics and metal transfer behaviour of cold metal transfer and its use in joining aluminium to zinc-coated steel. *Mater Sci Eng A* 499(1–2):111–113
33. Feng JC, He P, Hackl H (2007) Distribution of Zn and interfacial microstructure of braze-welding CMT joints between aluminium and galvanized steel sheets. *Solid State Phenom* 127:43–48
34. Babu S, Panigrahi SK, Ram GJ et al (2019) Cold metal transfer welding of aluminium alloy AA 2219 to austenitic stainless steel AISI 321. *J Mater Process Technol* 266:155–164
35. Cao R, Feng Z, Chen JH (2014) Microstructures and properties of titanium-copper lap welded joints by cold metal transfer technology. *Mater Des* 53:192–201
36. Rajeshkumar R, Niranjani VL, Devakumaran K et al (2021) Fusion boundary microstructure evolution and mechanical properties of cold metal transfer welded dissimilar A5754 and A5083 joint. *Mater* 284:128877
37. Liu Y, Yao Y, Ye H et al (2018) Study on microstructure and properties of dissimilar welded joints of steel and aluminum by CMT welding process. *IOP Conf Ser: Mater Sci Eng* 382(4):042025
38. Selvamani ST (2021) Microstructure and stress corrosion behaviour of CMT welded AA6061 T-6 aluminium alloy joints. *J Mater Res Technol* 15:315–326
39. Kang M, Kim C (2015) Joining Al 5052 alloy to aluminized steel sheet using cold metal transfer process. *Mater Des* 81:95–103
40. Truppel GH, Angerhausen M, Pipinikas A et al (2019) Stability analysis of the cold metal transfer (CMT) brazing process for galvanized steel plates with ZnAl 4 filler metal. *Int J Adv Manuf Technol* 103:2485–2494
41. Agudo L, Weber S, Pinto H et al (2008) Study of microstructure and residual stresses in dissimilar Al/steels welds produced by cold metal transfer. *Mater Sci Forum* 571:347–353
42. Feng J, Zhang H, He P (2009) The CMT short-circuiting metal transfer process and its use in thin aluminium sheets welding. *Mater Des* 30(5):1850–1852
43. Hao LU (2015) CMT welding technology of thick aluminum alloy plates for high speed train. *Trans Chin Weld* 36(4):75–78
44. Srinivasan D, Sevel P, Solomon IJ et al (2022) A review on cold metal transfer (CMT) technology of welding. *Mater Today: Proc* 64(1):108–115
45. Peng M, Liu H, Liang Y et al (2022) CMT welding-brazing of Al/steel dissimilar materials using cycle-step mode. *J Mater Res Technol* 18:1267–1280
46. Schubert E, Klassen M, Zerner I et al (2001) Light-weight structures produced by laser beam joining for future applications in automobile and aerospace industry. *J Mater Process Technol* 115(1):2–8
47. Song JL, Lin SB, Yang CL et al (2009) Effects of Si additions on intermetallic compound layer of aluminum-steel TIG welding-brazing joint. *J Alloys Compd* 488(1):217–222
48. Burhanuddin NM, Redzuan N, Ahmad N et al (2020) Brief review on dissimilar welding using cold metal transfer. *IOP Conf Ser: Mater Sci Eng* 884:012115
49. Jadav H, Badheka V, Upadhyay G et al (2022) Dissimilar welding of magnesium alloy to aluminium alloy: a review. *Adv Mater Process Technol* 8(4):3794–3821
50. Cao R, Huang Q, Chen JH et al (2014) Cold metal transfer spot plug welding of AA6061-T6-to-galvanized steel for automotive applications. *J. Alloys Compd* 585:622–632
51. Kimapong K, Watanabe T (2005) Lap joint of A5083 aluminum alloy and SS400 steel by friction stir welding. *Mater Trans* 46(4):835–841
52. Cao R, Feng Z, Lin Q et al (2014) Study on cold metal transfer welding-brazing of titanium to copper. *Mater Des* 56:165–173
53. Norrish J, Polden J, Richardson I (2021) A review of wire arc additive manufacturing: development, principles, process physics, implementation and current status. *J Phys D: App Phys* 54(47):473001
54. Chen M, Zhang D, Wu C (2017) Current waveform effects on CMT welding of mild steel. *J Mater Process Technol* 243:395–404
55. Hu YY, Mu S, Wang J (2014) Arc behavior and droplet transfer process of VP CMT. *App Mech Mater* 467:81–85

56. Das A, Shome M, Das CR, Goecke SF, De A (2015) Joining of galvanized steel and aluminium alloy using controlled short circuiting gas metal arc welding process. *Sci Technol Weld Join* 20(5):402–408

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