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Review Article

Cold metal transfer welding: A systematic review of process parameters and performance

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The increasing demand for stainless steel across various industries has prompted researchers to develop efficient and viable methods for welding steel and its alloys. This study has been aimed to conduct a thorough and critical assessment of the current state of welding techniques for joining different stainless steel materials. In this systematic review, we have seriously assessed the process parameters and performance of CMT. CMT is an advanced form of the MIG welding. Additionally, the application of CMT welding in different material combinations has been thoroughly examined and compared to alternative joining methods. In this study, the latest developments in the field of stainless-steel welding has been explored, focusing on the improvement of mechanical properties and advancements in high-performance welding techniques. This organized review has been followed an accurate methodology involving an extensive search and selection criteria of relevant available literature and industrial reports. The evaluation of mechanical and microstructural properties has provided valuable insights into the performance and weld excellence. The CMT welding, being an advanced approach, has garnered considerable attention from researchers, particularly in exploring its application in joining stainless steels.

Keywords: Cold metal transfer, Different materials, Mechanical properties, Stainless steel, Welding joints

1 Introduction

Stainless steel (SS), renowned for its corrosion resistance and heat-resisting properties, plays a pivotal role in various industrial applications. To optimize its usage, researchers and manufacturers continually seek improvements in cost-effectiveness, strength, and quality. The term ‘steel’ indicates that Fe represents the largest part of the material, whereas the word ‘stainless’ means lack of rusting in an environment in which normal steel is very prone [1]. It is an alloy based on iron comprising 10.5% to 30% Chromium (Cr) and Carbon (Fe) varying from 0.03% to 0.12%. Fe-Cr is the basis, stainless steel consists of other alloying elements which enrich mechanical, machining properties and weld ability. Molybdenum (Mo) is included to improve the material's ability to resist corrosion, and Nickel (Ni) is added in some categories [2]. Stainless steel may contain a variety of alloying elements, to ensure that the resultant alloy remains steel, their percentage is usually lower than iron content. An extensive variety of engineering approaches can be used to fabricate the stainless steel and it is entirely recyclable once it reaches the end of its usable life. Stainless steel is commonly designated for industrial shapes like stages, fences, food, and beverage equipment supports and pharmaceutical industries. Manufacturers are continually aiming the development of stainless steel with reduced costs, minimum lead times, low weight- high strength and improved quality. These enhancements support to reduce the cost of stainless steel [3].

Different types of steels have different properties. Due to good corrosion resistance, forming and fabrication properties austenitic and duplex categories are widely used in structural purposes. Whereas ferritic stainless steel offers a very competitive and economical alternate due to the presence of many attractive characteristics such as good corrosion resistance and low cost [4].

2 Materials & Methods

2.1 Austenitic stainless steel (ASS)

SS is the extensively utilized material of all. The most used austenitic (fcc) stainless steel is AISI 300 series (UNS S3xxxx series). It is an iron-chromium-nickel alloy system. Due to the existence of 18-20% Cr and 8-12% Ni, it is more resistant to corrosion. It is

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a very appealing engineering material due to its exceptional characteristics [5]. AISI 200 series (UNS S2xxxx) contains 4-15% manganese and up to 0.60% nitrogen, for some replacement of nickel [6].

Austenitic stainless steels find extensive application in chemical, mechanical, nuclear, and corrosive chemical environments. Austenitic stainless steels exhibit non-magnetic properties and can undergo hardening through cold working techniques[7].

2.2 Ferritic stainless steel (FSS)

The FSS are the grade of utility which offers excellent corrosion resistance than carbon steel. They are having excellent ductility, impact resistance and good formability. Ferritic is very economical and price stable as compared to austenitic grade because it contains very less or no nickel whereas austenitic contains a high percentage of nickel. Due to fluctuating and the high price of Ni, industries are focusing on increasing the scope of possible applications of ferritic stainless steels [89]. It is a Fe-Cr base alloy, a bcc structure with a good amount of chromium (10.5% to 30%).

Ferritic are more than two dozen grades and can be categorised into three groups.

The first generation, AISI types include 430 (Cr 16% to 18%), 442 (Cr 18% to 23%) and 446 (Cr 23% to 27%) consist of chromium as ferrite stabilizer but they have maximum carbon contents of 0.12%, 0.20% and 0.20% respectively.

The second generation includes 405 and 409 consisting of (Cr 10.5% to 14.5%) and 0.08% carbon. 0.10% to 0.30% Al was added to 405 whereas 0.75% titanium was added to 409. Due to titanium addition, 409 is extensively used in automobile catalytic converters, and tanks for agriculture sprays [10].

The third generation of ferritic includes AISI type 444 steel developed due to accessibility of the most effective steel decarburization method, it allows steel production with carbon and nitrogen contents of about 0.02%.

The fourth generation of ferritic stainless steels like UNS S44627 and UNS S44735 is commercially labelled as super ‘ferritic stainless steel’(SFSS). The addition of a considerable Mo component, high Cr content and low carbon permits Ni addition without ‘destabilizing’ the ferritic phase which improves corrosion resistance and toughness. Pressure vessels, food processing applications, petroleum refineries industries, desalination plants and chemical plants are the leading applications of SFSS [11].

2.3 Austenitic-ferritic (Duplex) stainless steel

Duplex stainless steels combine both austenitic and ferritic SS characteristics [12]. The austenitic ferritic duplex SS is highly corrosion-resistant steel in comparison to ferritic and offers higher strength at least twice to the austenite family. Duplex steels have large applications in chemical industries and offshore technological approaches combining high strength and superior corrosion resistance is essential. The duplex steels consist of Cr 18% to 29%, Ni 2% to 8%, Mn 1% to 2.5% and other elements for example Mo and Cu 1% to 5% [13].

2.4 Martensitic stainless steel

The martensitic SS contains almost chromium content ranging from 10.5% to 18% and the incorporation of additional alloying elements like niobium, Mo and tungsten up to 3%. The martensitic stainless-steel family offers the ability to achieve high tensile strength and desirable hardness through the process of quenching and tempering. Though, due to the limited content of Cr, and some addition of N and Ni this grade has poor corrosion resistance [14]. Martensitic SS is extensively used in assemblies, medical tools, ball bearings and structural components [15].

2.5 Precipitation hardening stainless steel

Precipitation hardening SS find several applications because of its remarkable strength and brilliant corrosion resistance. and good toughness [16]. This grade generally contains Cr 12% to 18% and 3% to 10% Ni with the existence of supplementary elements like copper, titanium, niobium and Al [17].

As industrial technology is developing, stainless steel consumption has increased significantly. From a commercial and scientific point of view, stainless steel represents an exciting material family which owns good strength, and ductility along with high corrosion resistance. In industrial sectors, stainless steel is commonly applied in various forms, including thick and thin sections whereas generating a structure of less than 3 mm thickness is cumbersome using standard techniques. For thin sections the main problems during welding are burning through, the need for control of metal penetration and distortion. So, to weld thin sections of stainless steel, low heat input CMT was found suitable. [1618]. It is also a well-established method for the different metal welding of Al and steel employed to enhance the quality and reliability of the process in industrial purposes [19]. The dissimilar welding of Al and steel using laser MIG hybrid welding led to deeper penetration but excessive laser power caused excessive melting of Al, resulting in the formation of voids and cracks [20]. However, friction stir welding (FSW) provides that higher rotational speed and a slower welding speed yield higher residual stresses in the joint [21]. Meanwhile, a hybrid welding approach that combines fusion and solid-state welding techniques for Al/steel showed an interface between dissimilar materials without cracks and voids but intermetallic compounds (IMCs) are generated at the junction between the materials. [22]. For welding Al/steel together FSW, laser welding (LW) and arc welding are the main methods. By utilizing inter layers such as copper and nickel, there is a possibility to minimize the formation of brittle IMCs during welding, enabling them to lead to weld cracking and reduced mechanical properties. The mechanical characteristics, including tensile strength and toughness, can be improved through the use of post-weld heat treatment (PWHT)[23]. The application of the CMT process, when coupled with the welding technique, results in the prevention of intermetallic compound layer formation, which works on low thermal input and produces joints without spatter, with outstanding gap-bridging capabilities [24].

Therefore, CMT is defined as a modified technique of MIG welding that is widely practised frequently to join similar and dissimilar materials [25]. During CMT welding filler wire is heated and a little amount of drop is created at maximum current mode. As the welding current is rapidly lowered to a lower current it stops the globular transfer, and it remains until the short-circuiting occurs. Through the short circuit, the filler wire contacts the base material and brings the voltage to zero. As the droplet at the weld's wire touches the molten pool, a back signal is sent to the weld wire feeding mechanism which retracts the wire. Consequently, the liquid metal contact is broken, and the metal drop is transmitted to the weld area. Again, the arc is reignited, the wire is advanced and the cycle restarts [26].

The novelty of CMT welding is the addition of weld wire's movement into welding as well as incorporated digital process monitoring. During the short circuit, the withdrawal motion permits the liquid to drop into the molten pool without using electromagnetic forces. Therefore, spatter and thermal input can be reduced [27]. In conventional MIG short-circuiting, Lorentz's electromagnetic force is responsible for droplet detachment. Fronius Company of Austria developed CMT in 2004 and researchers are still exploring this low-heat input welding technique. Mechanical and interfacial characteristics of steel change after welding as the base metal melts during heating. But low heat input CMT reduces these changes in the substrate, in contrast to other traditional techniques. CMT is an attractive technique due to several advantages i.e., low heat input (90% less heat input), the dissimilar joining of Al and steel with high welding speeds (five times faster than traditional techniques), exceptional gap-bridging 2.5 mm (0.1 in. gap), very low welding time (fraction of seconds only), environment friendly (without fumes and smokes), allows welding thin to thick sheets, very good precision and 99% less spatter generation.

To understand the process of CMT, the line diagram and welding set-up are shown in Fig. 1. CMT power source is responsible for low heat input, the wire feeder unit regulates the movement of filler wire, and a high-speed image camera captures the droplet images, welding current and arc voltage are controlled by the sensing probe. An oscilloscope, functioning as an imaging system, is employed for capturing images of metal transfer[28].

The CMT power supply source and the voltage-current waveform are shown in Fig. 2, for a complete cycle [24]. It consists of three stages, In the first stage, due to peak current, the filler wire heats, and metal droplet formation takes place. The second, background current stage corresponds to a lower current. And it continues before short-circuiting occurs and this lower current prevents the transfer of globular droplets from the weld wire.

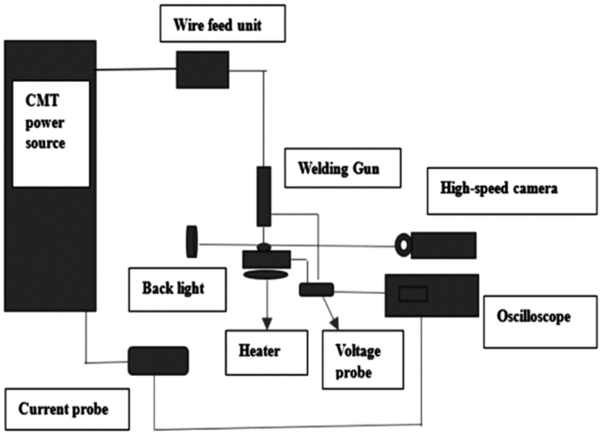

Fig. 1 — The experiment set-up of CMT technique [28].

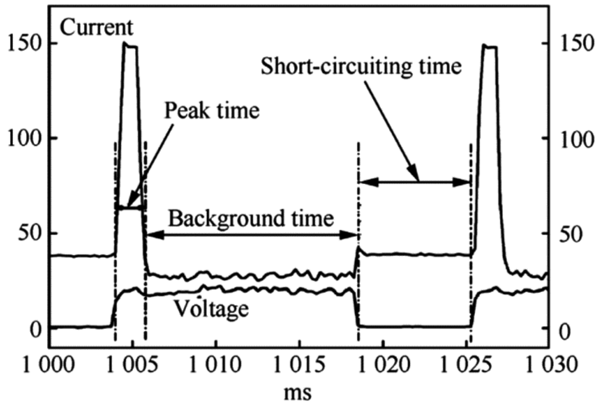

Fig. 2 — Voltage and current waveforms of the CMT technique [24]

In the third short-circuiting stage weld wire meets the molten metal and during this time, arc voltage diminishes to zero. In the meantime, the filler wire feeder will send a feedback signal which provides the filler wire with a retraction force. This retraction force is responsible for liquid fracture and movement of filler wire into the molten pool. After this CMT weld cycle is completed.

CMT welding presents a viable solution that effectively addresses the challenges at hand like increased welding speed, reduced welding duration and more precise control over the wire movement. So CMT welding has good capability to deliver solutions for future perspective.

3 Results and Discussion

3.1 Importance of CMT and its variations

The process of joining steel requires careful consideration and thoughtful planning to ensure that the resulting weld is strong, durable, and able to withstand the demands placed upon it. Joining dissimilar steels can present several challenges including, different metallurgical properties, different thermal expansion coefficients, and material compatibility, corrosion, and weld quality. Various types of failures that can occur in steel welding are cracking most common type of failure, porosity making it more prone to corrosion, incomplete fusion resulting in a weak joint, lack of penetration resulting in a weak joint, distortion causes to deform the base metal resulting in a poor fit between two parts and brittle fracture caused by improper heat treatment or welding techniques. Galvanized steel is commonly referred to as a substrate material due to the protective zinc coating that prevents pre-weld oxidation of the steel plate. Contrarily, an oxide film would form on the steel surface, harming the wetting capacity of the weld wire during the joining method.

The necessity of CMT is experienced when:

a. Undesirable effects arise from the heat-affected zone (HAZ) caused by welding method, which effects in alterations to the microstructure of the workpiece. This leads to a modification in the properties of the metals, which can be detrimental [29].
b. Fusion welding, which is commonly used, produces a fusion area and a thick intermetallic integration layer that can have a severe impact on joint strength and cause cracks in the weld.
c. The dissimilarity in melting point and solubility between different base metals can create difficulties in achieving a solid joint. However, CMT welding offers a superior solution for overcoming these challenges [30].
d. The GMAW CMT process possesses a range of additional advantages, such as the capacity to produce a weld joint free of spatter, exceptional ability to bridge gaps, and low thermal input. These benefits contribute to superior tensile characteristics relative to traditional welding techniques.
e. Adopting the CMT welding technique as a preferred method can yield long-term cost savings regarding the equipment aspect and tooling expenses, power usage, and weld joint quality. Therefore, performing a cost analysis of different joining methods demonstrates the cost-effectiveness of using CMT welding.

When it comes to various welding parts and elements that require high power, the CMT process is the ideal choice, as it offers substantial weld joint efficiencies, remarkable mechanical characteristics, superior wear and wear resistance, and great microstructural durability. This versatile welding technique is used in various applications such as welding cryogenic motors, aeroplane bodies, advanced automobiles, marine components, and spacecraft structures. Steel, extensively utilized in construction, automotive, energy, and appliances, can be used in thin and heavy forms. After findings, that the conventional CMT joining process was inadequate for welding materials with thicknesses greater than 3mm due to its lower heat input, it was believed that the conventional CMT technique was only suitable for applications in thin sheets engineering. To overcome this limitation, the Fronius company has introduced three additional processes that offer an optimal solution for joining varying thickness sheets in various scenarios, ensuring excellent results. The Fronius company has introduced three additional processes to overcome the limitations of traditional CMT welding for thicker structures. These processes include Pulsed Cold metal transfer (CMT+ p), Cold metal transfer advanced (CMT-ADV) and Cold metal transfer advanced pulse (CMT-PADV).

i The CMT + p technique integrates a planned transfer mode throughout the CMT phase along with a drop per pulse short circuit transfer phase, resulting in a unique combination. This method incorporates a pulsating cycle in conjunction with a CMT (Cold Metal Transfer) cycle to increase the thermal inputin a precise and customizable way, resulting in enhanced working and flexibility.

ii The CMT- ADV mechanism offers even lower temperatures than the conventional CMT process and features integrated process control through the polarity of welding current. To maintain welding firmness during the short-circuit the inversion of polarity is employed, resulting in tightly regulated thermal input, high gap-bridging potential, and up to 60% increase in deposition rate.

iii The CMT-PADV this method combines cold metal transfer cycles with negative polarity and pulsing cycles with anodic polarity, resulting in contrasting electrical polarities for each phase of the process, resulting in highly precise and proficient arc performance. To illustrate the differences between the various processes, Fig. 3 shows the voltage and current waveforms for conventional CMT, CMT+ p, CMT-ADV and CMT-PADV.

3.2 Dissimilar metal welding

The CMT welding process can efficiently produce dissimilar metal joints, making it a popular solution for solving the issue of joining different metals. With its high accuracy and low thermal input, CMT welding could be a promising optionfor incorporating steel inautomobiles and construction resulting in high-performance fusion welding [32].

3.3 Aluminium 1060 to zinc-coated steel

Zhang et al. [33] conducted a study on joining an aluminium alloy with zinc-coated steel using the CMT method, to examine the arc characteristics, droplet transfer mechanism, and metal conversion during welding and brazing. Lap joints of hot-dip galvanized steel and plain Al 1060 sheet were used, with Al-Si alloy cables as weld wire, and the joints were evaluated for tensile strength and microstructure. The study found that CMT welding resulted in no-spatter welding with lower energy input, stable material transfer, and modified arc heating behaviour through wave control and back-drawing power. The CMT method was successful in joining dissimilar

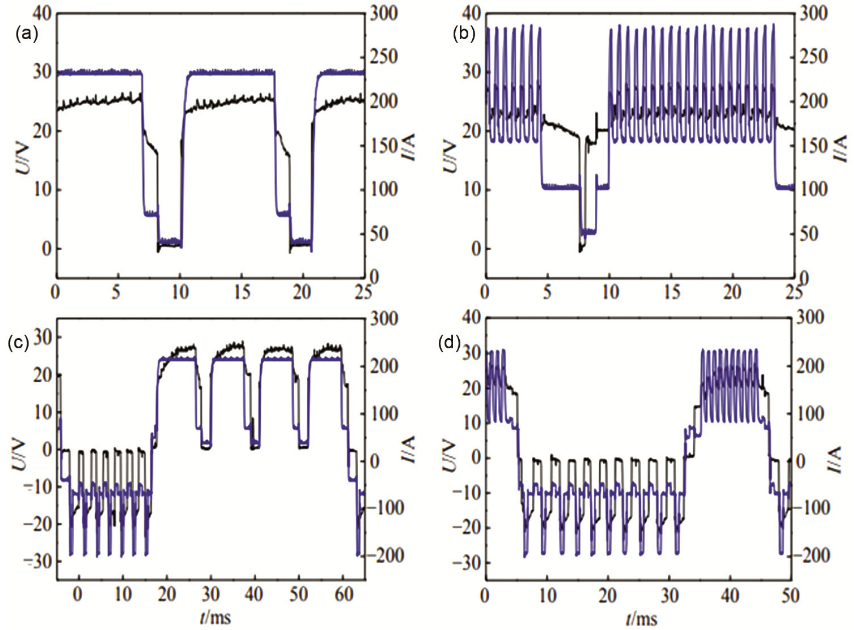

Fig. 3 — Waveform cycle for voltage and current (a) CMT, (b) CMT-AdV, (c) CMT-P and (d) CMT-PADV [31].

materials, like aluminium and galvanized steel, without fracture in a lap joint. The junction of steel and weld metal showed a complex film with Fe_2Al_5 and $FeAl_3$ phases, and a transparent intermetallic layer was formed between the steel and the work material, which is shown in Fig. 4(a) The fractures occurred in the aluminium's HAZ, as seen in Fig. 4(b). The CMT method offers a durable metal transfer system and adjustable arc heating, making it a viable option for joining dissimilar materials without cracks. By controlling the width of the IM layer, weld joint strength can be maintained.

3.4 AA5083-H111 to 6082-T651 Al alloys

Gungor et al.[34] conducted a study through pulsed robotic CMT and CMT-MIG to weld AA5083-H111 and 6082-T651 Al alloys, to review the mechanical characteristics of similar and different materials. The study found that CMT-MIG provided high speed, exhibit high weld joint efficiency, and great tensile and wear tolerance. The joint efficiency of M55 (5083-5083), M66 (6082-6082), and M56 (5083-6082) was 83%, 67%, and 70%, respectively. When compared to M55, the tensile specimens derived from M56 and M66 fractured at the HAZ of the 6082-BM. The optimum wear result was attained by M55, followed by M66 and M56.

3.5 Al 5754 to Al 5083 Al alloys

Rajesh kumar et al. [35] performed an investigation on the microstructure of fusion boundaries and their impact on the tensile characteristics of CMT involving numerous Al 5754 and Al 5083 alloys. Their findings revealed the development of a non-dendritic equiaxed fine zone between the WM region and the partially melted zone. In the case of the Al 5754 interface, the EQZ was broader with coarser grains compared to the Al 5083 interface. The coarser WMZ dendrites at the Al 5754 interface have contributed to lower strength ratings. According to the study, the presence of EQZ instead of WMZ is the primary cause for the decline in strength at the interfaces.

3.6 AA6061 to AA6082 Al alloy

The utilization of ultrasonic-CMT technique, according to Koli et al. [36], leads to a great proportion of Al-Si in globular shape compared to traditional CMT welding. This results in a reduction of porosity in the welded specimen. Additionally, the application of ultrasonic vibrations (UV) during U-CMT promotes grain refinement, which is not observed in non-vibration samples. The improved grain structure is associated with increased tensile strength and microhardness, as well as fine equiaxed dimples and micro-cavities on the worn faces of the tensile samples, indicating maximal strength. Radiography tests also reveal that UV eliminate porosity in the joint. Furthermore, ultrasonic vibrations during CMT welding result in faster solidification of the molten weld area, leading to improved weld width and penetration and decreasing the contact angle.

3.7 AA5754 and AA7075 Al alloys

The study by Çömez et al [37] investigated how the heat used in the welding procedure affects the mechanical qualities and corrosion rate of dissimilar aluminium joints. The researchers used CMT and ER5356 weld wire to weld AA5754 and AA7075 alloys together. They found that pore development occurred in the HAZ of the AA7075 due to the vaporization of zinc, while the AA5754 face of the weld had a pore-free microstructure. Hardness measurement was employed to identify over-ageing in the AA7075 BM, and high thermal input worsened the harmful impacts of over-ageing on mechanical qualities, resulting in a ductile fracture. Interestingly,

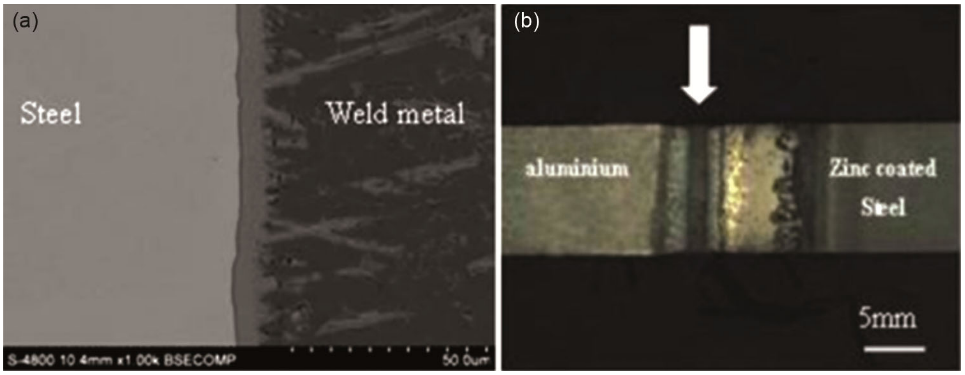

Fig. 4 — (a)Scanning electron microscopy revealed microstructures at the steel-weld metal interface and (b) Fracture located at joint designated by white arrow [33].

the corrosion rate reduced as thermal input improved, which was attributed to the shielding impact of AA7075 BM over-ageing.

3.8 AA5754 to AA 6061 Al alloys

Çömez et al. [38] conducted a study on joining dissimilar metals, AA5754 and AA6061, using the CMT technique, which is considered the most suitable technique for uniting thin sheets and different materials. The research found that high heat input during welding generated grain roughening in the HAZ of AA5754 and BM over-ageing in AA6061 due to an enlarged partially melted zone. This caused in a lowering in tensile strength, with the specimen having the minimum thermal input displaying the least corrosion rate. While the sample with lower thermal input showed only small cavities of dissolution at the AA6061 interface, the weld and BM of the high thermal input specimen suffered severe pitting and intergranular corrosion. The study also revealed that as the heat input increased, the tensile strength of the joint decreased and the corrosion resistance decreased due to pitting and intergranular corrosion.

3.9 Mg to Aluminium alloy

Mg AZ31 to galvanized steel the study conducted by Cao *et al.* [39] focused on investigating the wire type's impact on the effectiveness of CMT-plug technique of MgAZ31 galvanized steel with different wire types (Fig. 5). Mechanical and micro-hardness observations were carried out on the connections, and the fracture mechanism and static strength of junctions were analysed based on the joint quality. Considering the outcomes, a suitable wire was recommended for a 1 mm galvanized steel CMT plug with 3 mm thick MgAZ31.

The A and B edges shown in Images 6 (b) and (c), which were formed between the Mg AZ31 and WM at contacts C and D, were the first to be sheared during the testing process. Figure 6(a) depicts a close-up view of the brazed interface A. Figure 6 (e) shows that the Mg AZ31 welded object is made up of two phases: the Mg + Mg-Zn eutectic and the Mg-Zn IM phase. Region C of Fig. 6 (a) exhibited solely a coarse-grained microstructure. The feasibility of joining MgAZ31 galvanized sheet metal and MgAZ61 threaded parts using a CMT-plug weld was demonstrated in Fig. 7 (b and f). The study findings showed that all tested wires produced excellent connections between Mg AZ31 and galvanized steel, particularly when the MgAZ61 wire was used. The weld metal of MgAZ31 experienced fracturing, which was attributed to the development of a thin fusion region between the base and WM. Although with NRNiCu-7 weld wire resulted in high pseudo-tensile strengths for galvanized steel and Mg AZ31 couplings, it also caused localized flaws in the weld metals, which could potentially affect the joints' fatigue performance. To sum up, caution should be exercised when using NRNiCu-7 wire for constructing joints between galvanized steel and Mg AZ31 due to its tendency to induce flaws in the weld metals. The study recommends the use of a CMT plug with MgAZ61 wire to join galvanized steel and MgAZ31 based on the findings [40]. Magnesium alloys are widely considered the most suitable and lightweight metal for manufacturing parts and components in advanced industries including automobiles, electronics, and aerospace [41,42].

Presently, the scientific community is actively exploring welding techniques applicable to magnesium alloys and other metals characterized by

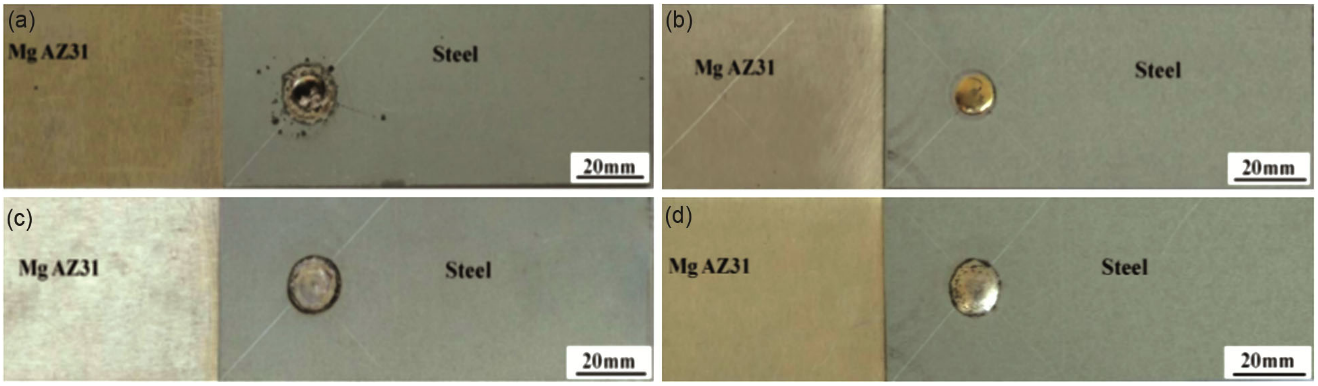

Fig. 5 — Weld quality and appearance of CMT plug joined Mg AZ31 to galvanized steel using different wires (a) H08Mn2SiA weld wire, (b) ER Cu Ni-Al weld wire, (c) NRNiCu-7 weld wire and (d) Mg AZ61 weld wire [39].

low melting points and high strength. As new manufacturing materials emerge, it is necessary to develop welding technologies for alloys such as Al and Mg [43]. Currently, FSW [44,45] and diffusion bonding [46,47] are employed to attain stronger Al/Mg joints. The use of solid-phase links is limited, while traditional welding processes such as TIG [48], MIG [49], and laser welding[50,51] result in a thick IMC in the fusion zone, which can cause cracks that significantly reduce joint strength [52]. CMT welding has been found to produce minimal intermetallic compounds with a lower heat input, and it has been effectively used to create different metal joints between Al and Steel with high efficiency [53,54]. The formation of intermetallic compounds ultimately led to joint embrittlement and the build-up of tension, thereby reducing the strength of the joint [52]. The fusion region was prone to fracture due to the presence of brittle IMC that were dispersed throughout the area [55]. Before conducting destructive tests, non-destructive evaluations such as sensory and radiological analyses were performed [56]. The fracture appeared in the FZ of the Mg side, where the microhardness was maximum and a brittle fracture mode was observed [52-55]. The joining of AZ31B Mg alloy and 6061 Al alloy was accomplished by using CMT with ER4043 filler metal by Jing et al. [57]. The welded joints were studied using various techniques, which showed a sensible interface between the WM and aluminium substrate. In the WM and Mg substrate, an epitaxial solidification area was formed with IMC of Mg_2Al_3, $Mg_{17}Al_{12}$, and Mg_2Si. The microhardness dispersion decreased from the Mg side to the Al side in the weld region. The weld joint was found to be brittle fractured in the fusion area of the Mg side due to the continuous distribution of Mg_2Si, Mg_2Al_3, and $Mg_{17}Al_{12}$. Aluminium alloy A6061-T6 and AZ31B Mg were joined together using Al-5%Si weld metal[58] through cold metal transfer welding to form lap joints. The weld exhibited residual tensile stresses, which were influenced by the heat input used during welding. The higher tensile strength was associated with lower tensile residual stresses and the presence of smaller precipitates. This study found a correlation among thermal input, weld strength, residual stress, and corrosion rate. Increasing heat input led to improved corrosion resistance and stronger joints. This is due to greater heat penetration into the interior of the joint, resulting in more uniform cooling and lower tensile stress. When the tensile strength exhibit lower in a weld metal, the propagation of cracks is slower. The relationship between the strength of a weld and the fracture stress is

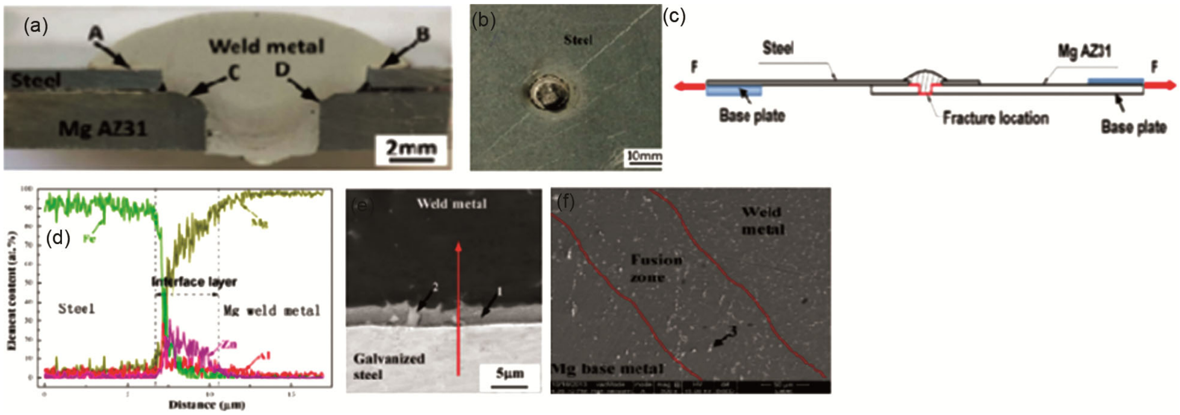

Fig. 6 — (a) Picture showing the inside view of a CMT welded joint between Mg AZ31 and galvanized steel with Mg AZ61 filler wire, (b) Fractured surface where the steel was pulled out, (c) Diagram showing the location of fracture at the FZ between the WM and the BM of Mg AZ31 in a joint made with Mg AZ61 wire and steel, (d) Close-up view of the interface zone A in Figure 6 (a), (e) line scanning examination of the enlarged feature in region B along the red line in Figure 6 (d) and (f) enlarged view of region C in Figure 6 (a) [39]

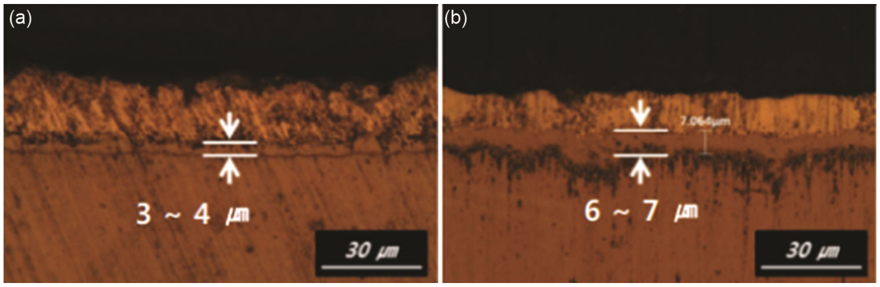

Fig. 7 — Picture of the IMC layer for specimens (a) as received without pre-heating and (b) pre-heated [63].

directly proportional. Therefore, an increase in the corrosion resistance also increases the weld joint strength [59-62].

3.9.1 Hot-dip aluminized steel tubes and Al 5052 alloy

Kang and Kim [63] used CMT arc welding with less energy input to weld hot-dip aluminized steel tubes with Al 5052. They explored the different materials joints using four types of weld wires: Al 4043, 4047, 5356, and 5183.The study revealed that the welding properties of Al 5052 when joined with various weld wires to aluminized steel closely resembled the characteristics observed in joints between galvanized steel and Al 5052. Researchers used Al-Mg filler wires to join dissimilar materials through braze welding, specifically steel sheets. However, welding steel and Al alloys together is difficult due to varying material properties. Corrosion is also a concern due to electrochemical potential differences in dissimilar material joints. The weld metal's great Si content improved the wettability of galvanized steel, but not aluminized steel. A notable increase in the tensile strength was observed across all material arrangements as test speed enhanced due to the strain rate effect. Upon substituting galvanized steel with aluminized steel, notable variations were observed in the experimental outcomes, the IMC layer had reduced thickness. To investigate the effect of thick IMC, an experimental study was conducted involving a preheated aluminized steel plate heated at 600°C for 16 hours as shown in Fig. 7, resulting in an IMC layer exhibited twice as thick as the original thickness. The presence of microcracks and porosities can lead to a thinner IMC layer and subsequently lead to a reduction in tensile shear strength. Galvanized steel had higher wettability compared to aluminized steel. The tensile strength of Al 5052/aluminized steel/Al-Mg with Al 5356 & 5183 weld wires was equivalent to that of the Al 5052 HAZ. However, the weld joint strength decreased with prolonged salt spray exposure in a corrosion check [63].

3.9.2 Hot Dip Galvanized DC03 to 6022-T4 Al alloy

Lei et al.[64] conducted CMT arc spot welding of 1-mm AA6022-T4 to 1.5-mm HDG low-carbon steel, DC03, and studied the corrosion behaviour in their recent research. The weld joints were analysed and compared by examining their micro and macrostructure, mechanical properties, and weld bead geometry after exposure. It was noted that the OCP (open circuit potential) of the galvanized plate was very negative, like the lowest face of the weld joint. The Fe-Al IMC layer in the weld interface incorporates Zn also had a very little OCP. The OCP of the Al weld decreased due to zinc vapour accumulation during welding. The steel substrate displayed the highest corrosion resistance with the most positive OCP. Salt spray tests were performed, to compare the performances of welds with and without e-coating after 20 and 63 cycles. The average shear strength dropped by 12% after 20 cycles and by 41% after 63 cycles a transition in fracture mode occurred, indicating interfacial failure, where the nugget pulls out through the Al.The Zn layer on the steel exhibits the lowest electrochemical potential and is more prone to corrosion [64].

3.10 Titanium alloy to other alloys

The CMT method was used to fabricate joints between TC4 and 304L SS in a 45° V-shaped groove using an ERCuSi-A wire by Mou *et al.* [65]. The joint had maximum strength of 294 MPa. These joints experienced fracture at the interface between copper and titanium when the welding torch was placed at position 1 and the weld wire speed was set at 5.5 m/min as shown in Fig. 8 (a & b). Increasing wire speed resulted in higher back reinforcement, a thicker Cu/Ti interface film, and improved the ultimate strength. Low thermal input can worsen wetting conditions and offsetting the weld torch to the TC4 side can result to worsened ultimate tensile strength. The fracture modes depend on the joining strength between Cu/Ti and Cu/Fe interfaces and the size of Fe-Si-Ti intermetallic also affects the fracture modes[65].

AZ31B magnesium alloy was joined to pure titanium TA2 using the CMT welding-brazing method by Cao *et al*[66]. Two lap-shear weld joints were created: the Mg-Ti weld joint and Ti-Mg joint using AZ61 Mg weld wire. A good Mg-Ti joint has a weld material, a FZ on the Mg AZ31 sheet and a brazing interface. A high-quality Ti-Mg joint typically consists of two brazing and two welding interfaces. To successfully join Mg and Ti BM, the brazing interface mostly consists of IMC such as Ti_3Al, $Mg_{17}Al_{12}$, and $Mg_{0.97}Zn_{0.03}$. The presence of Al and Zn components in the Mg BM and Mg weld wire is critical for the joining process. Cao et al. [67] used pure Ti TA2 and pure Cu T2 with ERCuNiAl Cu weld wire. Joint I, Fig. 9 (a & b) and Joint II Fig. 9 (c & d) consisted of weld material, a Cu-weld, and one Ti-weld interface. Joint I had one Ti-weld metal interface, while Joint II featured three interfaces. The

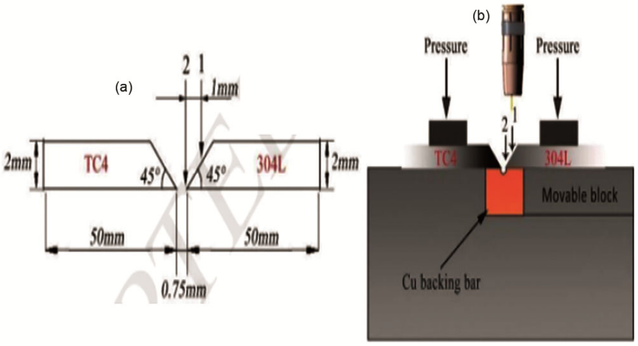

Fig. 8 — Experimental setup schematic diagram (a) plate size and (b) Torch positions [65].

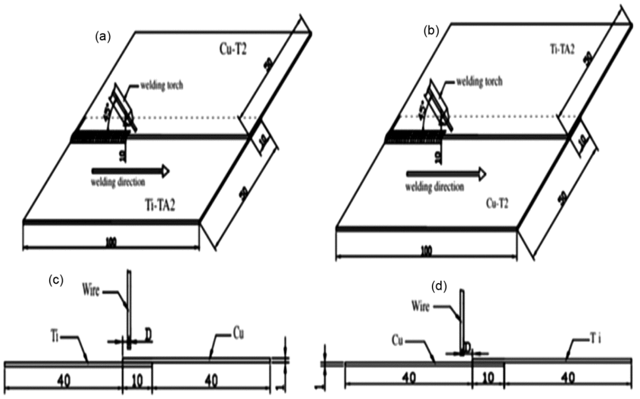

Fig. 9 — Images of CMT for TA2 titanium and T2 copper (a) joint I (top Cu bottom Ti), (b) images of Joint I, (c) joint II (top Ti bottom Cu) and (d) images of Joint II [67].

interface between titanium and copper contained a covering of IMCs such as Ti_2Cu, TiCu, and $AlCu_2Ti$. The thickness and microstructure of the IMCs coating varied in the Ti-weld interface due to differences in temperature gradient and interfacial reaction time [67][68].

Ti6Al4V and Al A6061-T6 sheets were joined by CMT welding-brazing using $AlSi_5$ wire by Cao et al [69] joint on the Al side and a brazing joint on the Ti side. The joints were characterized using SEM, EDS, and tensile-shear tests, and had satisfactory weld geometry and mechanical properties. The joint had three brazing interfaces which improved its strength. At the brazing interface, an IMC layer was formed, consisting of Ti_3Al, TiAl, and $TiAl_3$. Two fracture forms were detected: one at between the welding/brazing interface and WM, and another at the Al HAZ. Weld joints that fractured at the Al HAZ exhibited higher tensile strength as compared to another combination. SS and Ti were successfully joined using CuSi-3 weld wire. The thermal input played a crucial role in the study. Higher thermal input caused in the highest tensile properties for the brazed samples. Conversely, samples subjected to the lowest heat input exhibited inadequate bonding with the BM, resulting in the least mechanical features [70]. The IMC are generally found at the interfaces between the Cu and BM. Additionally, there are dispersed IMC's present in the Cu weld bead.

3.11 Aluminium AA6061-T6 to galvanized mild carbon steel

Cao et al. focused on joining 1 mm thick Al AA6061-T6 to 1 mm thick galvanized steel using the CMT spot plug welding. Controlling the weld wire feeder speed appropriately enabled the attainment of a sound joint [71]CMT variant of the MIG procedure is a favourable resolution due to its stability in terms of arc and molten pool. It is not just because of its low power but also because of the smooth transition between high power and very low power phases, making it highly effective [72]. The CMT method, when compared to traditional MAG welding using a short arc, has the following benefits: low energy consumption, no spattering, high welding speed, and the ability to weld thin sheet metal [73][74][75][76]

4 Conclusion

A contemporary welding technique, such as the CMT process and its variations, offers a promising solution for overcoming challenges in welding low melting points and high-strength materials as stainless steel. The welding of diverse combinations of dissimilar materials using modern and advanced techniques remains an area that requires further exploration and research. A thorough examination and systematic research on the microstructural and mechanical characteristics of these material combinations are crucial to optimize for industrial applications.

Wire retraction during welding plays a significant role as it has led to protect the formation of spatter and better weld aesthetic produces. Welding speed, voltage, current and weld wire feed speed are responsible for welding efficiency.

The utilization of CMT and its variations can significantly enhance the mechanical characteristics of stainless steel and its alloys. Dedicated efforts and attention are necessary to achieve successful bonding and enhance the qualities of welded joints in different material junctions

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