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Progressive Developments in Cold Metal Transfer Welding Technique: A Review and Trends

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Abstract

This comprehensive review paper examines the Cold Metal Transfer (CMT) welding process and its wide-ranging applications across various industries. With a focus on elucidating the fundamental principles, process characteristics, and recent advancements, the paper offers a comprehensive overview of CMT welding's versatility and effectiveness. The review delves into the intricate mechanics of the CMT welding process, highlighting its unique metal transfer modes like CMT-P, CMT advanced, CMT pulse rose, and CMT dynamic, along with its controlled heat input mechanisms. Moreover, the review addresses the diverse applications where CMT welding has found relevance, like in aerospace, automobile, sheet metal joining industries, and composite joint fabrication. In conclusion, this review consolidates the collective knowledge surrounding the CMT welding process and its applications, serving as a comprehensive resource for individuals and organizations interested in harnessing the full potential of this technique. As industries continue to seek innovative and efficient welding solutions, the insights provided in this review paper pave the way for the continued advancement and widespread adoption of CMT welding across diverse sectors.

Keywords: Cold metal transfer (CMT) welding, CMT-modes, Porosity, Microstructure, Applications

INTRODUCTION

At present, the CMT welding technique has gained much attention due to the advantages of low heat input processing and complete computer control, which is lacking in traditional MIG (metal inert gas) or TIG (tungsten inert gas) welding procedures [1, 2]. Due to this, CMT has advantages over GMAW (gas metal arc welding), such as cheap cost and high efficiency, as well as lower processing heat input and faster cooling [3, 4]. The automotive industry uses the CMT technique to lighten vehicles to join dissimilar aluminum, magnesium along with plastic-composite assemblies and repair aluminum alloy components using a low-heat input process [5]. No melt-back and no bending of the parent metal are the results of low heat input [6]. This technology does not require highly skilled labor because it is automatic.

Amin S. Azar et al. [7] developed a heat source model which helped to understand the weld pool behavior in a more suitable way and design in CMT welding. Furthermore, the execution of this model on the weld pool provided extended information about the Marangoni convection inside the weld pool as a function of varying arc parameters. The same thing was done by Eriel Pe'rez Zapico et al. [8], in which equations were evaluated numerically within COMSOL Multiphysics for CMT aluminum alloy welding. A new type of CMT Arc Additive Die Manufacturing Process was developed by An Zhang et al. [9] because of its high efficiency; it has considerable application in aluminum alloy

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additive manufacturing industries. In the experiment, it was observed that by using copper plates, the hydrogen pores were minimized, and the mean grain size was reduced from 16.2 ± 1.4 to 13.6 ± 1.3 μm. The CMT+P technique was evaluated by O. T. Ola et al. [10] to repair ZE41A-T5 magnesium alloy-based aerospace components. A high-quality weld was achieved with the desired penetration, fewer defects, and sound reinforcement. In comparing CMT to laser hot wire cladding (LHWC) for the structural steel repair of AISI 4340, they showed different properties despite having the same filler material, mainly because of varying process efficiency. The distortion formed by CMT was comparatively lesser than LHWC. The strength was higher in the case of CMT, while elongation was reduced [11].

This paper starts by explaining the CMT technique's fundamental principle and its merits and demerits, making it better than conventional welding techniques. Further, numerous applications of CMT have also been discussed, followed by its various arc modes.

WORKING PRINCIPLE OF CMT TECHNOLOGY

CMT is a process in which wire flow and metal deposition rates are controlled simultaneously. This way, heat input supplied to the workpiece is maintained to a minimum. At the time of a short circuit, the power is cut for a short period, and at that point, wire retraction takes place, allowing the use of a spatter-free joint with meager heat input [12–17]. In one cycle, there are a total three steps as follows:

i. Heat input is given to the filler wire by which it can melt. After that, it starts moving toward the weld pool, refer to Figure 1 (a) [18, 19].
ii. The arc gets extinguished When the filler wire gets dipped into the weld pool; refer to Figure 1 (b).
iii. To detach the wire from the weld pool, a process called wire retraction takes place; refer to Figure 1 (c).

After this, the whole cycle repeats, as shown in Figure 1 (d).

In brief, the control unit retracts the filler wire when it detects a short circuit occurrence, allowing the arc to generate for only a very short period, thereby reducing the volume of heat input used in the process. After this process, the circuit is controlled with a minimal current value, making a spatter-free joint. The arc length can be maintained with the help of mechanical means [20, 21]. For these reasons, the CMT technique's application field is vast.

Merits

a. The welding technique is automatic and the accuracy and precision are very high thus, highly skilled workers are not necessarily required to perform the welding process [22].
b. The volume of heat input consumption is very low as the arc produced at the time of welding is not continuous.
c. Its range of applications is not limited to a few industries as it can be used in any position and environment.

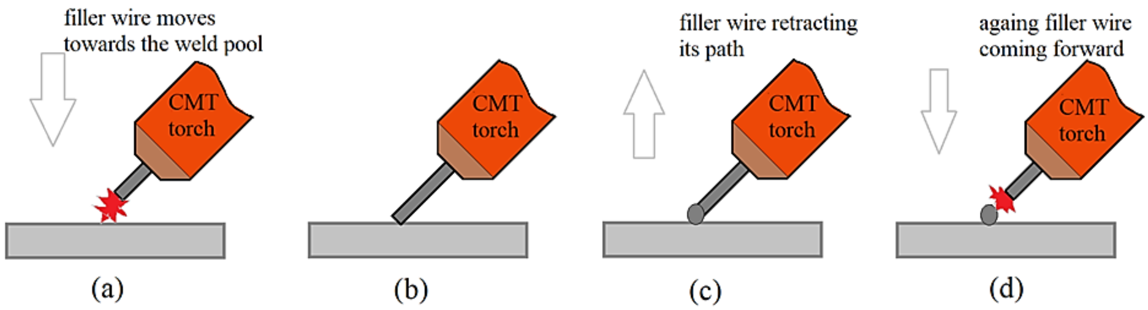

Figure 1. Steps involved in the CMT welding process (adapted from [13]).

Demerits

a. A short circuit process does not exist for higher currents.
b. When the transition zone starts, the upper limits of application are near the conventional short arc process [23].

APPLICATION OF CMT WELDING

This type of welding is used to join similar and dissimilar metals like Aluminum, Steel, Brass, Copper, Magnesium, etc., with varying thicknesses; it can be thick plates or thin sheets [24]. MIG and TIG have less precision in welding thin sheets as their heat input is very high. Furthermore, heat input is also the main factor in changing a metal's structure. For this reason, nowadays, CMT is used as an alternative heat source in additive manufacturing [25–29]. Moreover, conventional welding technology requires a heat-safeguarding environment to prevent the warping of metal workpieces.

On the other hand, CMT welding does not require a need for such an environment. Due to these main factors, this technology is involved in many industries, like joining thick metal sheets in ships, aerospace, automobiles, sheet metal industries, and many more [30, 31]. In addition, it has a high degree of accuracy; compared to other MIG welding modes, CMT is the most suitable technique for welding electronic enclosures, automotive panels, etc. [32–34]. In some studies, CMT technique was also employed in reinforcing composite and hybrid joints with metals like steel and titanium welded pins [35]. However, in one study the effectiveness of CMT welded steel pins was higher compared to titanium pins [36]. Recent research has found that the CMT technique has applications in power generation industries, as the method is feasible in depositing pure copper cladding [37].

In the following section, the classifications of CMT welding have been discussed, along with their characteristics.

CMT MODES

CMT technology is an updated/evolved version of the MIG method [38]. It uses low heat input, stable arc, droplet transfer with no spatter, and other characteristics. The technique can join both thick and thin plates (<9mm) and is economically sound compared to other conventional welding techniques. Some modes of CMT technique are present, which include conventional CMT, CMT plus pulse (CMT+P), CMT advance (CMT-Adv), CMT pulse advanced (CMT-PADV), and CMT dynamic (depicted in Figure 2) [39, 40]. Different modes have their specifications, advantages, and limitations. Also, CMT+P is used to obtain more metal deposition with a wide range of heat input [40]. Some of these techniques are discussed below.

CMT+P

CMT plus pulse combines the conventional CMT technique with pulses in which the droplet transfer is carried out with an alternate transition between short circuit and beating at the welding time [41–43]. Moreover, in this mode, droplets can be refined with a pulse, reducing the number and size of porosity [42, 44]. Zhi-Qiang Liu et al. investigated different CMT+P technique parameters by applying them in the additive manufacturing of 4043 aluminum alloy. A thin wall fabricated by the CMT+P had fewer pores than that of the normal CMT mode (shown in Figure 3 a,b). a difference in tensile strength was formed between the two modes [45]. There were more pulse currents in CMT+P than in normal CMT refer to Figure 4 a,b. The pulsed arc increases the heat input.

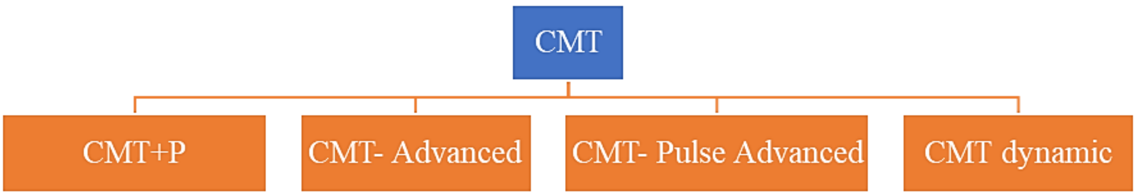

Figure 2. Classification of CMT welding.

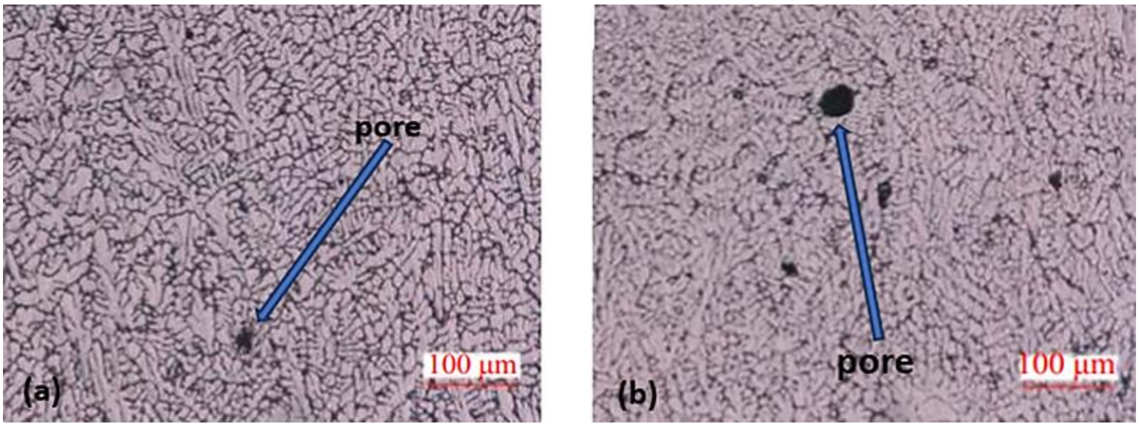

Figure 3. Microstructure of (a) CMT-P, and (b) conventional CMT [45].

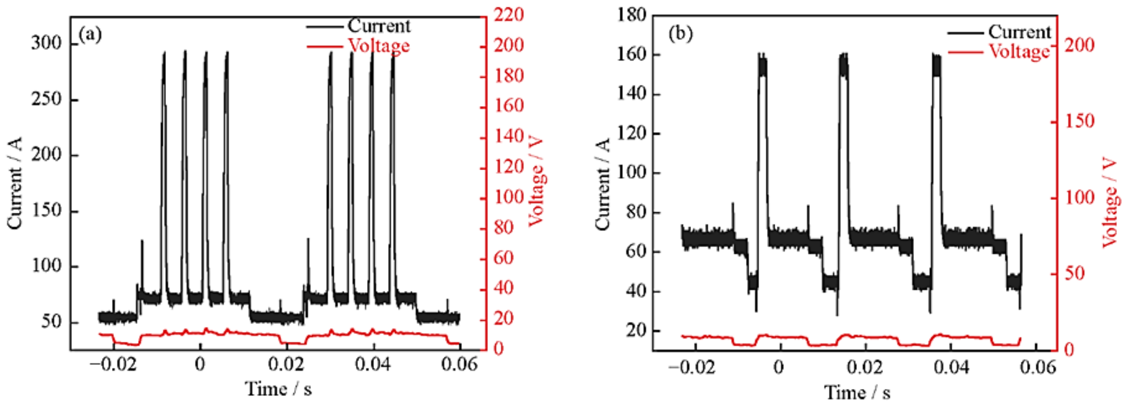

Figure 4. Voltage and current variation against time of (a) CMT+P and (b) conventional CMT [45].

Critical characteristics of CMT+P are as follows:
- The speed of joining, flexibility, and performance are enhanced.
- Good additive seams can be formed with proper height and width ratios and wetting angles [46].
- Moreover, the pulse period in CMT+P welding can be adjusted by pulse correction, leading to a change in current.
- A pulse period with a high current allows a wide range of heat input [47].

CMT-Advanced

The CMT-Advance mode was developed for additive manufacturing. It can have extremely high gap-bridging because of its high deposition rate [48]. In this arc mode, the deposition rates can be accurately adjusted with the help of negative and positive process cycles. CMT-Advance allows more significant deposition rates with no escalation of heat input, and the fumes are completely reduced without any distortion [49]. Yunpeng Nie et al. performed an experiment in which variable polarity CMT welding was employed to manufacture 4043 aluminum parts. The microstructure of the single-walled sample showed distinct transitions at the top, middle, and bottom portion (depicted in Figure 5 a,b,c). The advantage of CMT-Advance was that the effect of cathode cleaning was achieved at the time of negative and positive alternating processes of the wire, thereby the thermal input was further reduced. It also has an advantage in cooling time with every layer due to lower thermal inputs. The mechanical properties of 4043 Al parts obtained with CMT-Advance mode were relatively good, as no anisotropy was discovered in the horizontal and vertical axes. It was found that decreasing the arc ending current and increasing the angle starting current can reduce the hump and collapse problem shown in Figure 6 in the fast manufacturing of 4043 Al parts [50]. Critical Characteristics of CMT-advanced are as follows:

- A high deposition rate enables it to form extremely high-gap bridging.
- The deposition rate can also be adjusted.
- An increment in deposition rate is done without any escalation in heat input.
- Fumes are also reduced with zero distortion.

CMT-Pulse Advanced

During CMT-advanced welding, the positive cycles were interchanged with the negative ones. The CMT-advanced technique combines the CMT cycles with a positive polarity phase of the pulse and a negative polarity electrode. Welding of steel having superior strength is possible by using the CMT-pulse advanced technique with a higher rate of deposition coupled with lower heat input [49]. Baoqiang Cong et al. investigated the porosity defect caused by different arc modes on additively manufactured AA2219 alloy. It was experimentally found that the porosity was efficiently controlled in the case of CMT-pulse advanced, as shown in Figure 7 a,b,c,d. because of the low heat input, equiaxed grain structure formation, and effective oxide layer cleaning. It was concluded that CMT-pulse advanced was the most suitable technique for depositing Al alloy because of its excellent porosity control characteristic [51]. K.F. Ayarkwa et al. also studied the impact of process parameters on wall dimensions using CMT pulse advanced for aluminum WAAM. The study found that the critical factor for wall dimensions is the ratio of the wire feed speed to weld speed. It was observed in the experiment that with the increasing wire feed speed to fuse speed ratio, the porosity also increased (shown in Figure 8 a,b,c) [52].

Critical characteristics of CMT-pulse advanced are as follows:

- The most preferable technique for depositing Al alloy is its excellent porosity control characteristic [53].
- The welding technique attains a high deposition rate during the negatively poled phase with lower heat input [54].
- It is most effective in the WAAM processes**.**

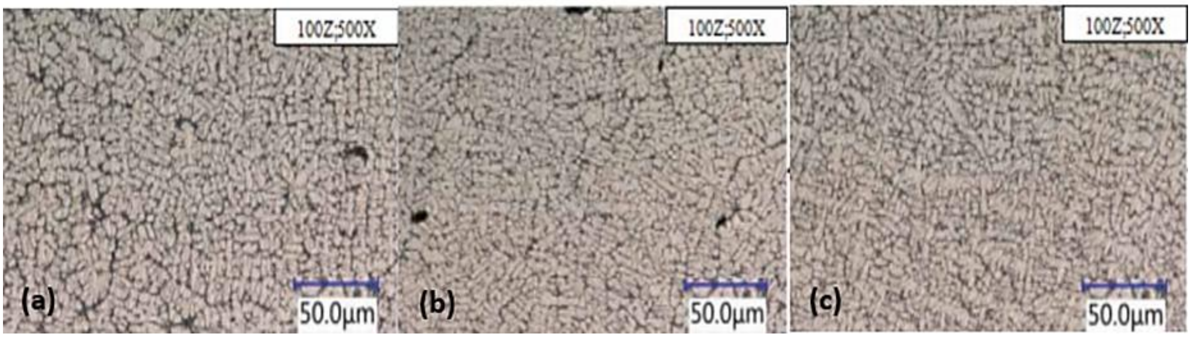

Figure 5. Microstructural image of (a) top, (b) middle, and (c) bottom region [50].

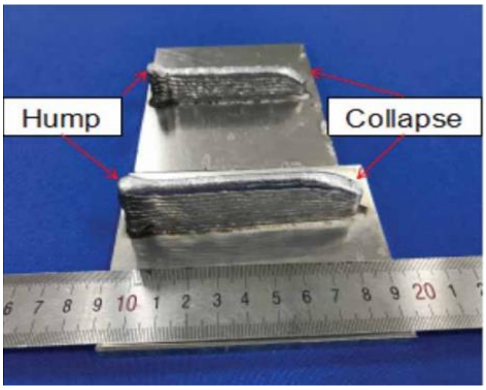

Figure 6. Formation of the hump and collapse in single-way stacking method [50].

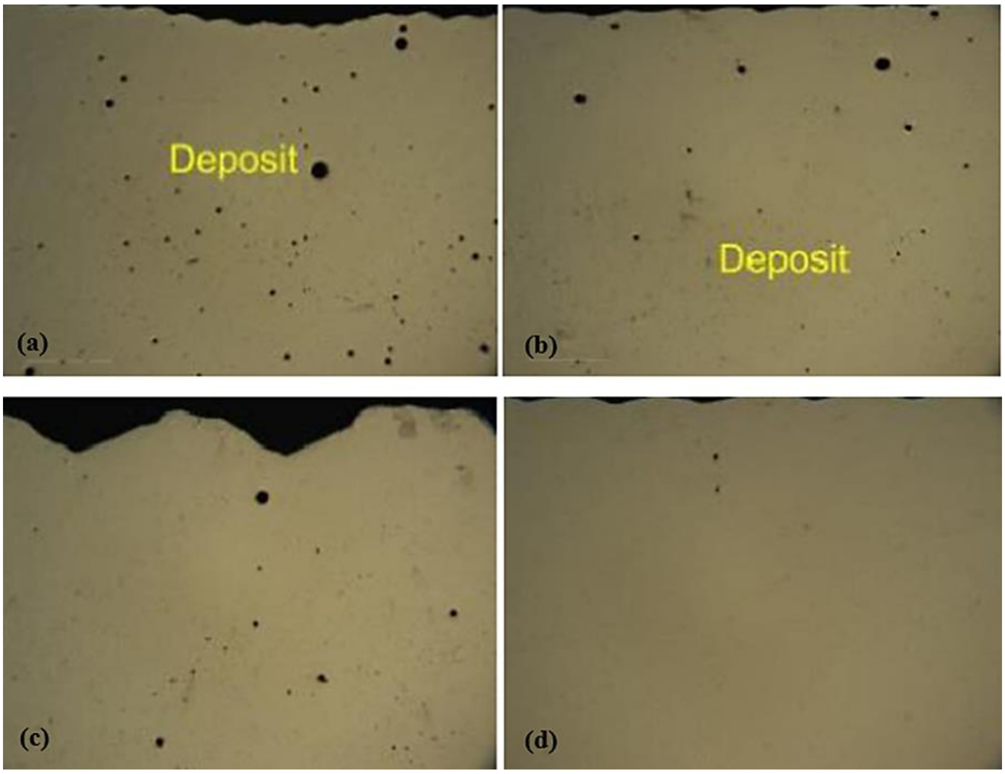

Figure 7. Optical micrographs porosity images of (a) conventional CMT, (b) CMT-P, (c) CMT-ADV, and (d) CMT-PADV [51].

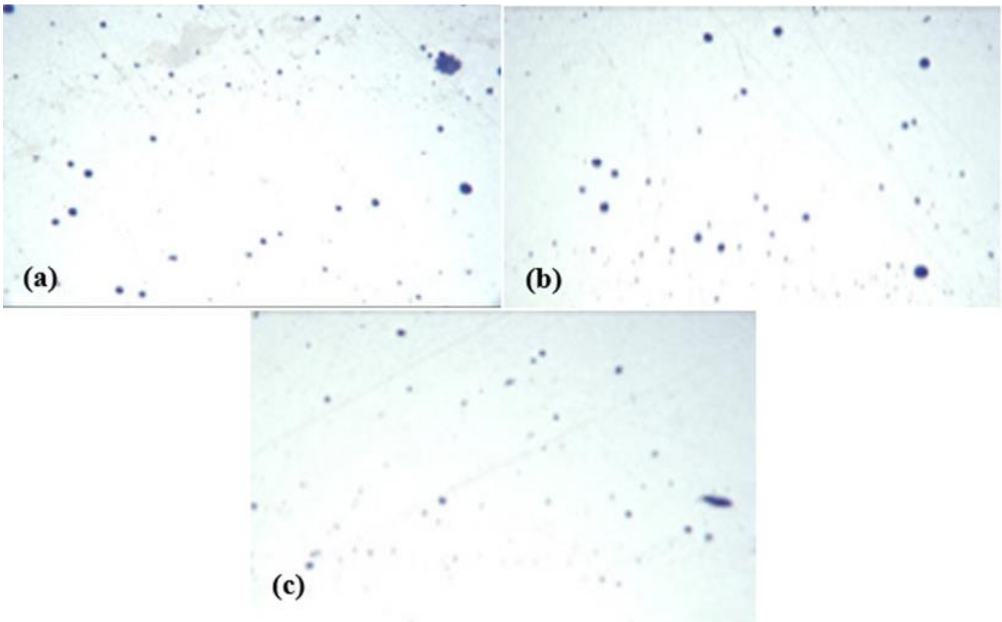

Figure 8. Optical micrographs showing increasing order of porosity while increasing the wire feed speed to weld speed ratio from bottom to top [52].

CMT-Dynamic

The CMT-dynamic technique is the latest invention in CMT welding technology. Joining thicker sections of dissimilar and similar metals was the central role of this technique. With the increase in the movement speed of the wire, the penetration depth also increased, as shown in Figure.9, thereby allowing faster joining momentum with increased wire feed rate; the deposition rate also increased.

Figure 9. CMT dynamic working on steel with ER70S-6 filler wire.

Key characteristics of the CMT dynamic are as follows:

- The CMT-dynamic technique involves high heat input with an escalated pressurized arc [49].
- The forward-backward movements of the wire are increased up to a frequency of 130 Hz, thus escalating the range of the conventional type CMT technique.

CONCLUSIONS

1. The CMT-pulse advanced welded joints in the WAAM process had the fewest pores because of the low heat input method, development of an equiaxed grain structure, and efficient cleaning of the oxide layer. Moreover, the horizontal tensile strength was also enhanced.
2. CMT welding is a highly efficient technique for joining thin and thick sheets of similar and dissimilar metals, offering advantages such as reduced heat input, increased deposition rates, stable arc, and no spattering.
3. CMT application was also found helpful in composite joint pin fabrication, cladding, hardfacing of metal, and wire arc additive manufacturing.
4. As the CMT technology is fully automated, the online monitoring of the workpiece can also be done. With some more evolution, an engineer could also give commands from a place far from the workshop.

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