

Droplet Temperature Measurements of GMAW and MCAW Steel Wires

Droplet formation affects temperature leading to possible health and environmental benefits

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Abstract

Droplet temperatures in metal-cored arc welding (MCAW) were measured for the first time using a solid-state calorimeter and a water-cooled cathode, with a commercial metal-cored wire and pure argon shielding gas, and a current range of 210 to 290 A. In MCAW, droplet temperatures ranged from 1900°C to 2145°C with an average uncertainty of $\pm 35.5^\circ\text{C}$. Compared to gas metal arc welding (GMAW) at the same current range, droplet temperatures in MCAW were consistently lower than those in GMAW, with an average difference of approximately 260°C. High-speed video revealed that the metal core, consisting mostly of iron powder in the MCAW, remained in a near-solid state until immediately before detachment, contributing to lower droplet temperatures. A mass and energy balance analysis indicated that the sheath was hotter than droplet temperature by approximately 150°C and 90°C at the assumed core temperatures of 1200°C and 1500°C, respectively. The molten sheath temperature was predicted to be comparable to that of solid wire in GMAW under similar conditions. In MCAW, the metal transfer mode remained globular, while the transfer morphology shifted from symmetrical to biased droplet formations with rising current. MCAW also exhibited higher overall anode fall voltages (7.9–10.0 V) compared to GMAW (6.8 V), which was attributed to either the Thomson effect near the electrode or changes in metal transfer morphology. The presence of a colder powder core suggests a reduction in manganese evaporation, which could significantly lower manganese

fume emissions, an important consideration for occupational health and environmental safety.

Keywords

- Metal-Cored Arc Welding
- Calorimetry
- Droplet Temperature
- Metal Transfer
- Fall Voltage

Introduction

In arc welding, the droplet surface can be superheated by the arc, causing the formation of metallic vapors (Ref. 1). As the vapors cool down, fine particles are formed (1–100 nm), which grow into visible welding fumes ($>1\ \mu\text{m}$) (Ref. 2). Inhaling welding fumes pose serious respiratory health risks (Refs. 3–6). Solutions like optimizing ventilation, wire design, and welding conditions have been proposed (Ref. 7). With stricter occupational health standards, reducing fume emissions is becoming increasingly essential.

Fume formation in welding has been explored both experimentally (Refs. 4, 5, 8, 9) and theoretically (Refs. 1, 2, 3, 10). In gas metal arc welding (GMAW), fumes mainly originate from the superheated molten droplet, unlike the mechanism in gas tungsten arc welding (GTAW), whose fumes form only at the molten pool (Refs. 2, 11). Tashiro et al. found that in GMAW, more metal vapor is emitted from the high-temperature droplet than the colder weld pool, generating fumes near the droplet and downstream in the arc plasma (Ref. 2). This highlights the droplet temperature as a key factor in fume formation.

Understanding the factors that govern droplet temperature in GMAW is crucial for reducing fume formation. Through modeling of GMAW, considering heat transfer mechanisms, droplet size, and transfer mode are known to influence the

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droplet temperature (Ref. 12). Previous measurements of droplet temperature found that the temperature ranged from 1700°C to 2700°C depending on current, electrode composition, and type of shielding gas (Refs. 13, 14–19). The droplet temperature can be determined from mass and energy balances (Refs. 13, 20–22), with higher melting (deposition) rates resulting in lower droplet temperatures at the same current. Metal-cored arc welding (MCAW) is used when higher deposition rates are required. It shares most characteristics with GMAW except for the wire structure, in which the steel sheath covers the iron-based powder. With a higher deposition rate, the droplet temperature of MCAW is expected to be lower than that of GMAW, thus reducing fume generation.

Droplet temperature measurements have been conducted using pyrometry, calorimetry, and thermocouples (Refs. 13, 17, 22). Calorimetry has been shown to overcome the inherent limitations of the pyrometer, since the surface temperature of the droplet is not a representative measure of the droplet temperature (Ref. 13). Through calorimetry, the droplet temperature is calculated from the heat content of the molten metal collected. Soderstrom et al. investigated droplet temperature in pure argon GMAW for carbon steel, stainless steel, and aluminum, using a water-based calorimeter (Ref. 13). For all experimental wires, the results revealed a local minimum in droplet temperature at the transition zone, where the metal transfer mode changes from globular to spray, with carbon steel reaching 1800°C at around 205 A. A water-based calorimeter experienced water evaporation from the hot incoming droplets, leading to inaccuracies in droplet temperature measurements. To address this issue, Scott et al. used a solid-state calorimeter (Ref. 16). This method allows for a more accurate measurement of the heat content by relying on the temperature change of the calorimeter itself, without the effects of water evaporation. The reliability of the solid-state calorimeter was validated by a minimum droplet temperature of approximately 2200°C for carbon steel at a transition current of 205 A under pure argon shielding. Based on the works by Soderstrom (Ref. 13) and Scott (Ref. 16), McIntosh et al. found that the effect of CO₂ content in Ar-CO₂ shielding gas mixtures (0%, 5%, and 10%) had minimal effect on droplet temperature (Ref. 20).

There is potential for volatile elements in welding consumables to affect droplet temperature. To clarify this effect, Yan et al. investigated droplet temperatures in GMAW using aluminum alloy wires, ER5183 (high magnesium content) compared to ER1100 (low magnesium content) (Ref. 21). Their results showed that the ER5183 wire exhibited lower droplet temperature, by about 300K in the spray and transition modes, and 400K in the globular transfer mode, compared to ER1100. Similar findings were reported by Ramgopal (Ref. 22), suggesting that elements with low boiling points can contribute to droplet temperature reduction. For improving the mechanical properties of weld metal, manganese is added to the consumable, which also has a low boiling point (2062°C) and produces particularly harmful fumes that can lead to Parkinson's disease. As mentioned above, it is expected that the droplet temperature in MCAW can be decreased compared to GMAW through adequate process controls and consumable designs to achieve lower fume generation. However, the droplet temperature of MCAW,

as well as the energy balance governing it, remains poorly understood.

This study is the first to investigate the relationship between droplet temperature and welding current in MCAW using pure argon shielding, with a comparative analysis to GMAW. The welding current ranged from 210 A to 290 A, featuring a mixed globular and projected transfer at low currents and reaching streaming spray transfer at high currents. A custom water-cooled copper cathode and a solid-state calorimeter were used to measure temperature. At the same time, high-speed camera observations were carried out to better understand the mechanism governing droplet temperature.

Experimental Procedure

Experimental Method

Droplet Temperature Measurement

Figure 1 illustrates the experimental setup, including the welding torch for GMAW, water-cooled cathode, and solid-state calorimeter. The system features a specially designed water-cooled copper cathode with a step hole (small diameter of 7 mm and bigger diameter of 12 mm) that allows droplets to pass into a solid-state calorimeter (Ref. 13). The calorimeter was a high-purity copper cylinder with a diameter of 50.8 mm and a height of 34.4 mm. Three Omega GKQSS-18G-12 K-type thermocouples were attached to the bottom of the calorimeter to measure its temperature, and thermal equilibrium was achieved within ~10 seconds. Data acquisition was performed using an OMEGA TC-08 board with an accuracy of the sum of $\pm 0.2\%$ of the reading and $\pm 0.5^\circ\text{C}$ at a sampling rate of 100 ms.

The calibration process for these thermocouples is detailed in Ref. 22. Each thermocouple was calibrated using a Fluke 9173 Metrology Well at six points between 50°C and 300°C. The temperature difference between the thermocouples and the metrology well was used to fit a fourth-degree polynomial. The polynomial provided the required calibration for the thermocouples. Using this function, the accurate temperature could be determined by adding the recorded thermocouple temperature to the calculated deviation. The average corrected temperature was determined by averaging the corrected readings from all three thermocouples over the recorded time.

Each experiment lasted 500 seconds from arc ignition to mass measurement, involving four main steps. First, the arc was ignited over a flux tray installed in a drawer between the cathode and the calorimeter for ~5 seconds, until a stable arc formed. The drawer was then opened, allowing molten metal droplets to fall onto the calorimeter for ~10 seconds before the arc was shut off and the drawer was closed. The temperature data of the droplet and calorimeter system were collected for at least 300 seconds. Finally, once cooled, the mass of the droplets was collected from the calorimeter and weighed.

Welding Conditions

The welding power source used in this study was a Lincoln Electric Power Wave S500, operating in Direct Current Electrode Positive (DCEP) mode. Two programs were used for the

Table 1 — Chemical Composition of Welding Consumables Used (% mass)

Wire	Type	C	Si	Mn	P	S
ER70S-6	Solid	0.08	0.95	1.70	0.019	0.015
MX-Z100	Metal core	0.06	0.50	1.40	0.013	0.009

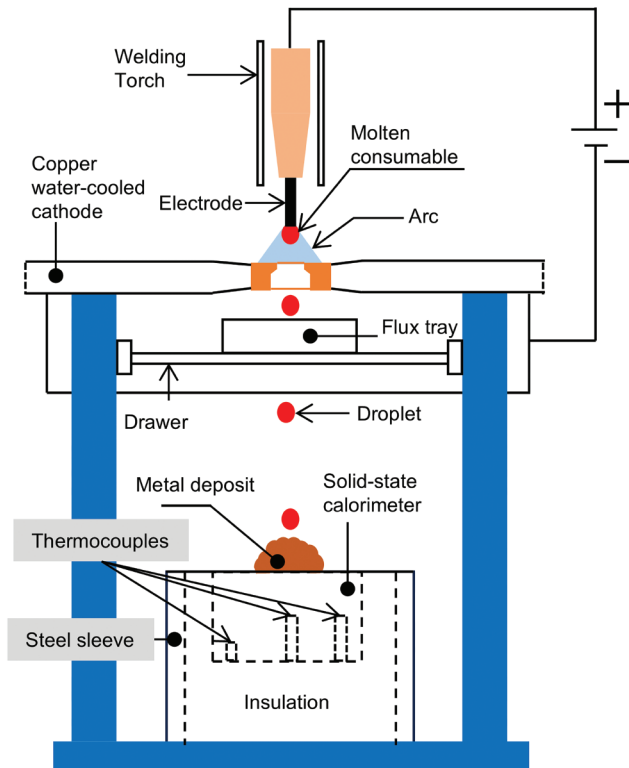


Fig. 1 — Experimental setup including welding torch for GMAW, water-cooled cathode, and solid-state calorimeter.

experiments: Program 5 for welding with solid wire and Program 7 for welding with metal-cored wire. A welding torch was set with a Contact Tip to Workpiece Distance (CTWD) of 20 mm. To analyze the droplet temperature trend in MCAW, a series of experiments was conducted with welding currents ranging from 210 A to 290 A. The welding current was calculated as the average of the recorded signal data for each primary WFS and voltage setting during the experiment. The arc length was kept approximately constant at $6 \text{ mm} \pm 1 \text{ mm}$ by adjusting the welding voltage between 27.0 V and 30.50 V. Pure argon was used as the shielding gas at a flow rate of 20 L min^{-1} .

Arc and Metal Transfer Morphologies Observation

Figure 2 shows the schematic of the system used to observe the arc and metal transfer morphologies. The observations were carried out using a high-speed camera (Phantom VEO 1310) synchronized with a data-acquisition system (National Instruments USB-6351) to record real-time welding current and voltage. An objective Macro Sigma lens with a 105 mm

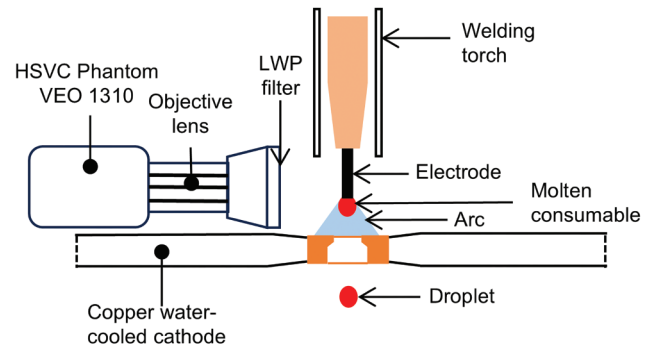


Fig. 2 — Schematic of the system used to observe the arc and metal transfer morphologies.

focal length and a 1:2.8 focus ratio, equipped with a large extension tube, was used for imaging. The observation was conducted at 648×600 pixels at 10,000 fps, with an aperture of $f/19$, an exposure time of $6 \mu\text{s}$, and an exposure index of 25,000. To reduce the arc radiation, a 950 nm long-wave pass filter was applied.

Materials

In this study, the commercial metal-cored wire (MX-Z100, Kobelco, Japan) was used to measure droplet temperature, and the results were compared with those obtained with the commercial mild steel solid wire (ER70S-6, Kobelco, Japan). Table 1 displays the chemical composition of these wires. The wire diameter was 1.2 mm for both consumables used.

Analysis

Droplet Temperature

The droplet temperature, $T_{d,i}$, is calculated using Equation 1, which is derived from an energy balance between the initial state (hot incoming droplets and cold calorimeter) and the final stage once the droplets and calorimeter are in thermal equilibrium (Ref. 22):

$$T_{d,i} = T_{\text{ref,liq}} + \frac{1}{c_{\text{ref,liq}}} \quad (1)$$

$$\left\{ \frac{m_c}{m_d} [A_{\text{Cu}} (T_f^2 - T_{c,i}^2) + B_{\text{Cu}} (T_f - T_{c,i})] \right\} - \Delta i_{\text{ref}} - c_{\text{ref,sol}} (T_{\text{ref,sol}} - T_f)$$

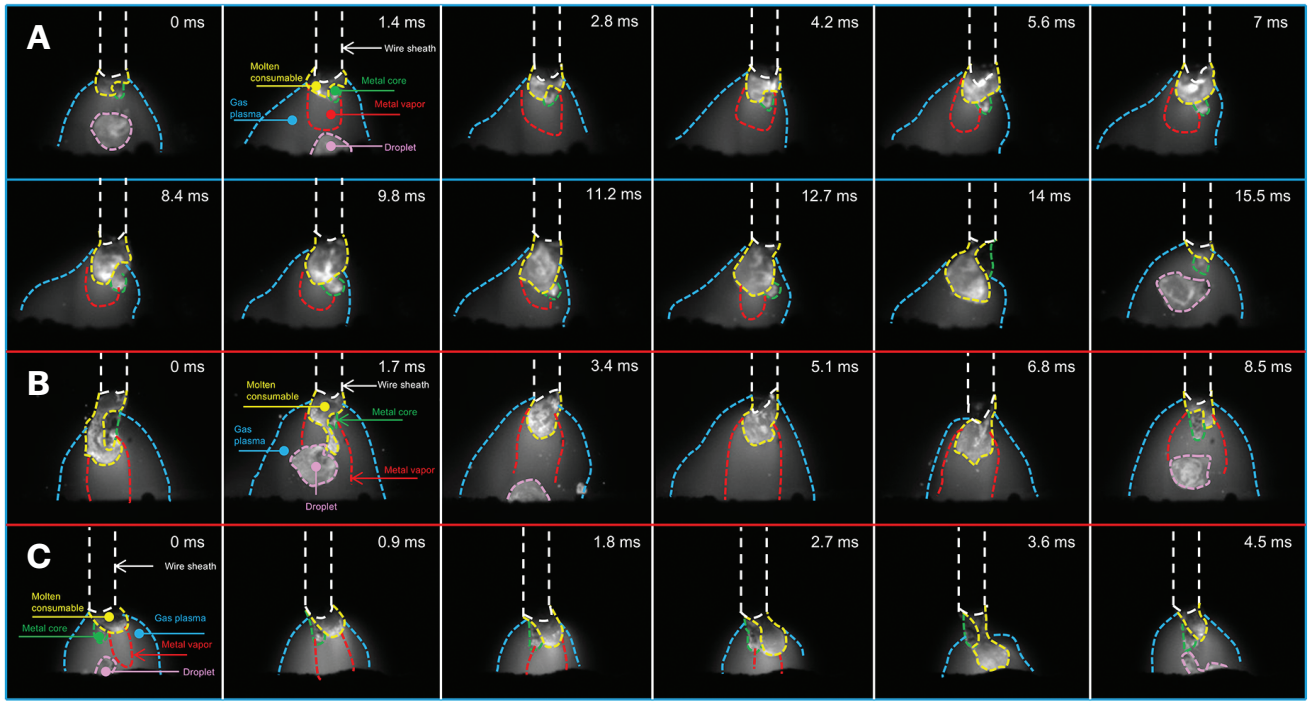


Fig. 3 – Time-sequential images of arc and metal transfer morphologies at: A – 210 A; B – 250 A; C – 290 A for MCAW.

Table 2 – Reference Values Used for Calculation of Droplet Temperature

Wire	$T_{\text{ref,sol}}$ [K]	$T_{\text{ref,liq}}$ [K]	$c_{\text{ref,sol}}$ [J/kg ⁻¹]	$c_{\text{ref,liq}}$ [J/kg ⁻¹]	Δi_{ref} [J/kg ⁻¹]
ER70S-6	293.15	2773.15	450.47	825.64	209.0510 ⁴
MX-Z100	293.15	2773.15	448.10	825.65	209.2510 ⁴

Where $T_{\text{ref,sol}}$ and $T_{\text{ref,liq}}$ denote the reference temperatures of consumables in solid and molten states with corresponding specific heats $c_{\text{ref,sol}}$, $c_{\text{ref,liq}}$, respectively. The enthalpy difference between these reference temperatures is denoted as Δi_{ref} . The calorimeter mass m_c was 623.40 g. The specific heat of the copper calorimeter was modeled as a second-order polynomial over the range 20°C to 400°C, which covers the operational temperature range of the calorimeter. This method helped ensure the deviations in specific heat with temperature were accounted for. The coefficients of this second-order polynomial for specific heat are $A_{\text{Cu}} = 6.90 \cdot 10^{-2} \text{ J kg}^{-1} \text{ K}^{-2}$ and $B_{\text{Cu}} = 3.45 \cdot 10^2 \text{ J kg}^{-1} \text{ K}^{-1}$ (Ref. 22). The mass of droplets that reach the calorimeter is m_d . $T_{\text{c,i}}$ represents the initial temperature of the calorimeter, and T_f represents the final temperature obtained by the calorimeter and the metal droplets after a thermal equilibrium has been attained. The reference thermal properties provided in Table 2 were calculated using ThermoCalc with the method discussed in Ref. 22.

The total uncertainty in droplet temperature measurements ($\delta T_{\text{d,i}}$), as derived from Equation 1, was calculated using partial differentiation as shown in Equation 2. This approach

considered the contributions of all parameters related to the droplet temperature calculation, as shown in Ref. 22.

$$\begin{aligned} \delta T_{\text{d,i}}^2 = & \left(\frac{\partial T_{\text{d,i}}}{\partial T_{\text{ref,liq}}} \delta T_{\text{ref,liq}} \right)^2 + \left(\frac{\partial T_{\text{d,i}}}{\partial c_{\text{ref,liq}}} \delta c_{\text{ref,liq}} \right)^2 \\ & + \left(\frac{\partial T_{\text{d,i}}}{\partial m_c} \delta m_c \right)^2 + \left(\frac{\partial T_{\text{d,i}}}{\partial m_d} \delta m_d \right)^2 + \left(\frac{\partial T_{\text{d,i}}}{\partial A_{\text{Cu}}} \delta A_{\text{Cu}} \right)^2 \\ & + \left(\frac{\partial T_{\text{d,i}}}{\partial T_f} \delta T_f \right)^2 + \left(\frac{\partial T_{\text{d,i}}}{\partial T_{\text{c,i}}} \delta T_{\text{c,i}} \right)^2 + \left(\frac{\partial T_{\text{d,i}}}{\partial B_{\text{Cu}}} \delta B_{\text{Cu}} \right)^2 \\ & + \left(\frac{\partial T_{\text{d,i}}}{\partial \Delta i_{\text{ref}}} \delta \Delta i_{\text{ref}} \right)^2 + \left(\frac{\partial T_{\text{d,i}}}{\partial c_{\text{ref,sol}}} \delta c_{\text{ref,sol}} \right)^2 + \left(\frac{\partial T_{\text{d,i}}}{\partial T_{\text{ref,sol}}} \delta T_{\text{ref,sol}} \right)^2 \end{aligned} \quad (2)$$

Where the uncertainties of these coefficients in the specific heat of the calorimeter are $\delta A_{\text{Cu}} = 8.73 \cdot 10^{-4} \text{ J kg}^{-1} \text{ K}^{-2}$ and $\delta B_{\text{Cu}} = 6.15 \cdot 10^{-1} \text{ J kg}^{-1} \text{ K}^{-1}$, as discussed in detail in Ref. 22.

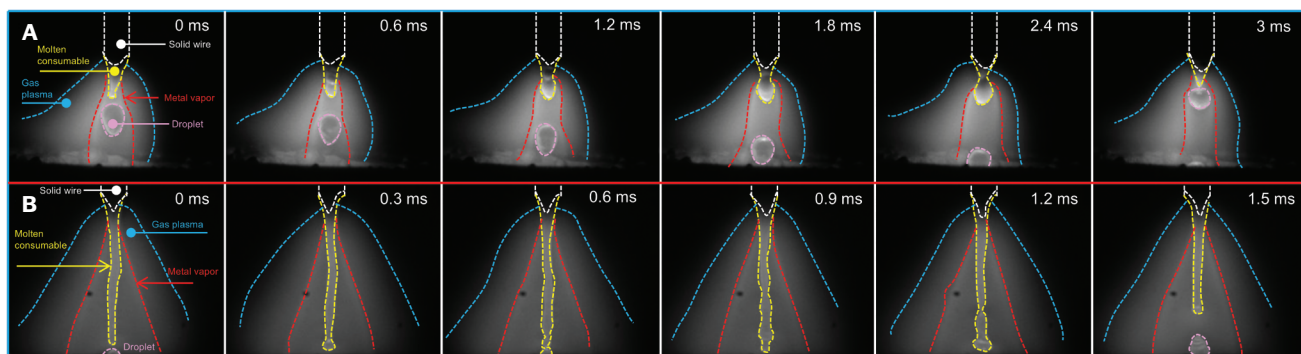


Fig. 4 — Time-sequential images of arc and metal transfer morphologies at: A — 210 A; B — 290 A for GMAW.

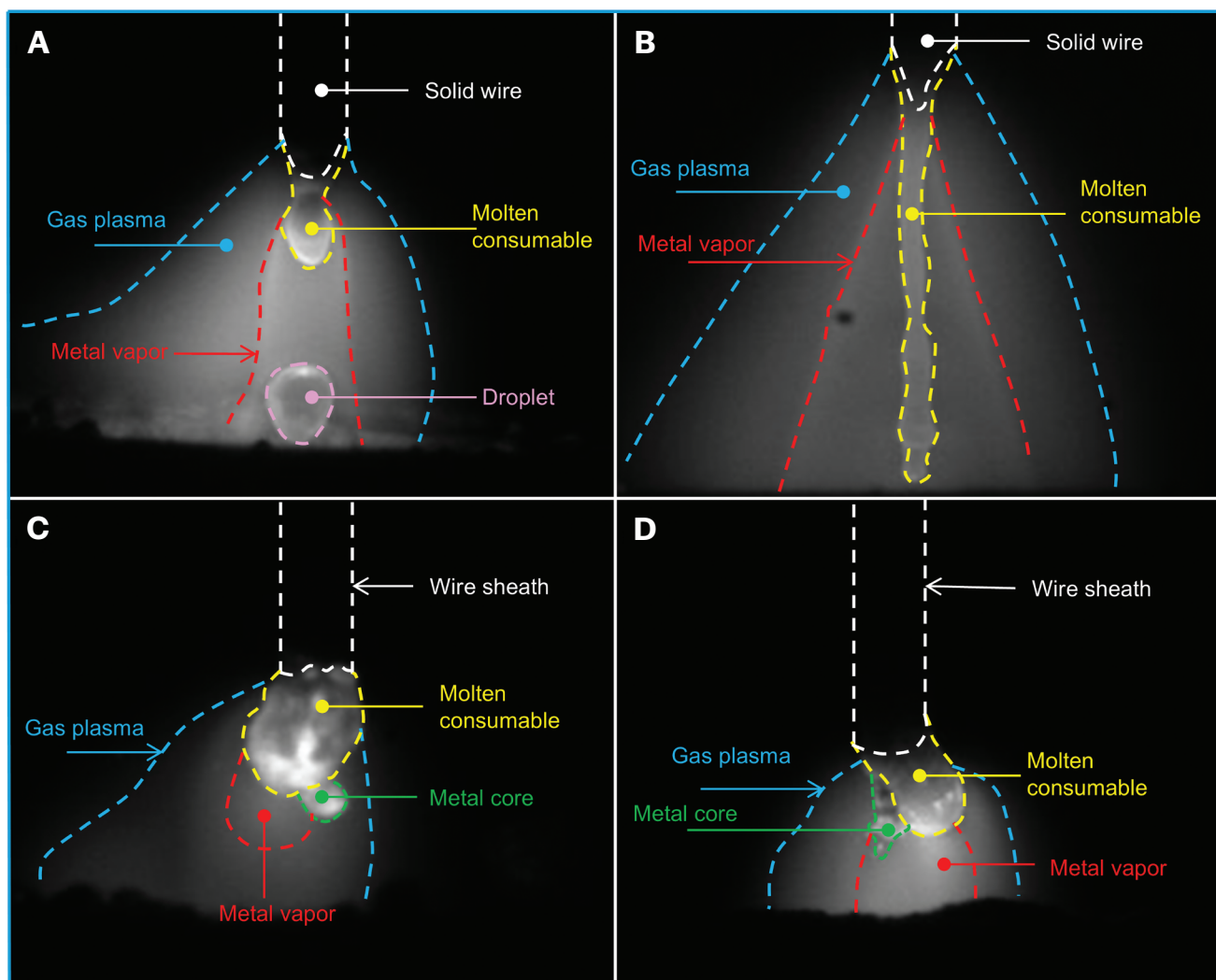


Fig. 5 — Typical metal transfer morphology observed for: A — GMAW at 210 A; B — GMAW at 290 A; C — MCAW at 210 A; D — MCAW at 290 A.

Arc and Metal Transfer Morphologies

A high-speed videography analysis was performed to compare the arc and droplet formation morphologies between MCAW and GMAW. Figure 3 shows the time-sequential images of arc and metal transfer morphologies observed at A — 210 A, B — 250 A, and C — 290 A for MCAW. This figure

shows that the arc attachment, indicated by the blue dashed lines, shifted from the upper-middle part of the molten metal to its lower part as the current varied from low (210 A) to high (approximately 290 A), due to elongation of the molten consumable. Furthermore, the arc center became brighter as the welding current increased.

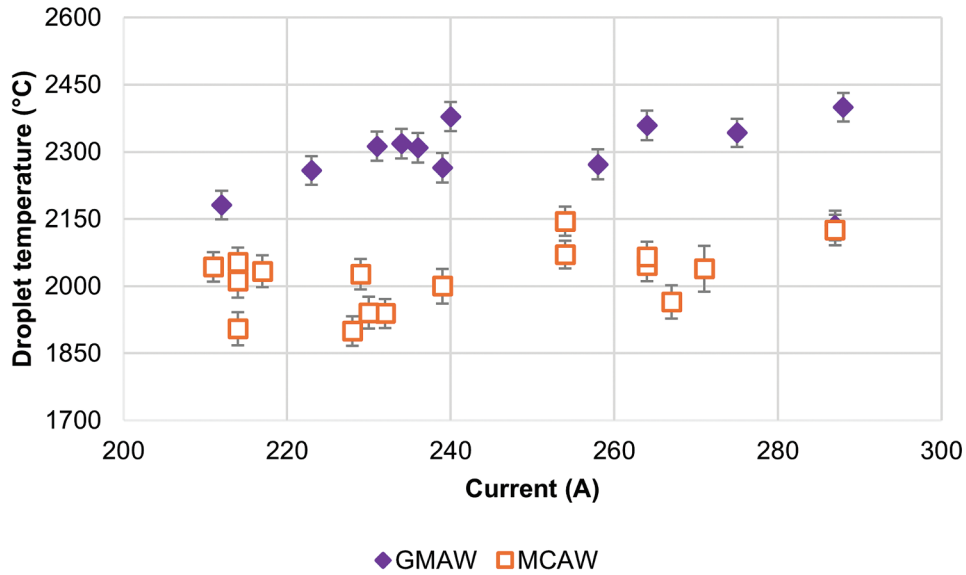


Fig. 6 – Droplet temperature as a function of current for MCAW and GMAW.

The metal transfer mode in MCAW could be divided into two sub-modes according to the gradual variation in the position of the molten metal (pendant droplet) as the current increases from low to high, symmetrically to the wire axis around the cylindrical metal core of mostly solid powders at low currents referred to as Fig. 3A while biased to the side as shown in Fig. 3C at high currents. A mixture of these two modes at both low and high currents (Fig. 3B) showed a transition of metal transfer modes at intermediate currents of 250 A.

Figure 4 illustrates time-sequential images of arc and metal transfer morphologies at A – 210 A and B – 290 A for GMAW. Unlike in MCAW, the arc attachment in GMAW was located higher, near the wire tip, at both low and high currents.

In GMAW, as the welding current increased, a transition was observed from a projected transfer mode to a streaming transfer mode. In both modes, a taper near the wire tip was captured by high-speed videography. At low current (210 A), droplets (approximately equal to the electrode diameter) formed at the wire tip prior to detachment. At high current (290 A), the metal transfer appeared as a long molten metal column, as shown in Fig. 4B.

Figure 5 presents typical metal transfer morphology observed for A – GMAW at 210 A, B – GMAW at 290 A, C – MCAW at 210 A, and D – MCAW at 290 A. As a result, the metal transfer morphology differed significantly between GMAW and MCAW. The mechanism that led to this difference is explained in the discussion section.

Anode Fall Voltage

When an electric discharge occurs between the anode and cathode, a voltage reduction happens near both, which is called the fall voltage or potential drop (Refs. 14, 23, 24). This is attributed to the temperature drop of the plasma at the boundary layer over the electrode surface, reducing thermal ionization to lower the electrical conductivity (Ref.

25). The thickness of this region is of the order of 100 μm (Refs. 14, 26, 27).

The overall anode fall voltage is determined by an energy balance at the electrode (Ref. 28), as shown in Equation 3. This balance accounts for heat input and output at the electrode tip, helping estimate the voltage drop in the anode region. Radiative energy exchange during welding was considered negligible in this study. McIntosh and Mendez (Ref. 24) reported that 13–33% of the total arc energy is lost as radiation, depending on the welding parameters and arc length; however, the distribution of this radiative heat among the anode, cathode, and torch remains unclear. In addition, Cobine and Burger (Ref. 29) and Quigley et al. (Ref. 25) demonstrated that the majority of energy delivered to the anode originates from the welding current, with convection and radiation from the plasma contributing only marginally. Heat losses from the molten droplets to the surrounding environment via convection and radiation have also been shown to be negligible under typical steel welding conditions (Ref. 28). Therefore, radiative effects were not included in the present study.

$$(V_{an}I + R_{ct}I^2) + \frac{I^2 L_{EE} \rho_{eff}}{A_c} = U_c m'_c [\Delta i_{ref} + c_{ref,liq}(T_{d,i} - T_{ref,liq})] \quad (3)$$

The overall anode fall voltage, V_{an} , is a key parameter in the energy balance. R_{ct} represents the contact electrical resistivity between the contact tip and the wire ($\sim 1 \text{ m}\Omega$ [Ref. 30]), while the welding current is denoted by I . The energy lost through evaporation is considered negligible and is therefore disregarded. While L_{EE} is the electrode extension of $14 \text{ mm} \pm 1 \text{ mm}$, ρ_{eff} represents the electrode extension's resistivity of $7.20 \cdot 10^{-7} \Omega\text{m}$ (Ref. 28) for steel, and A_c as the cross-sectional area of the wire consumable. The wire feeding speed is represented by U_c , while m'_c denotes the mass density of the consumable.

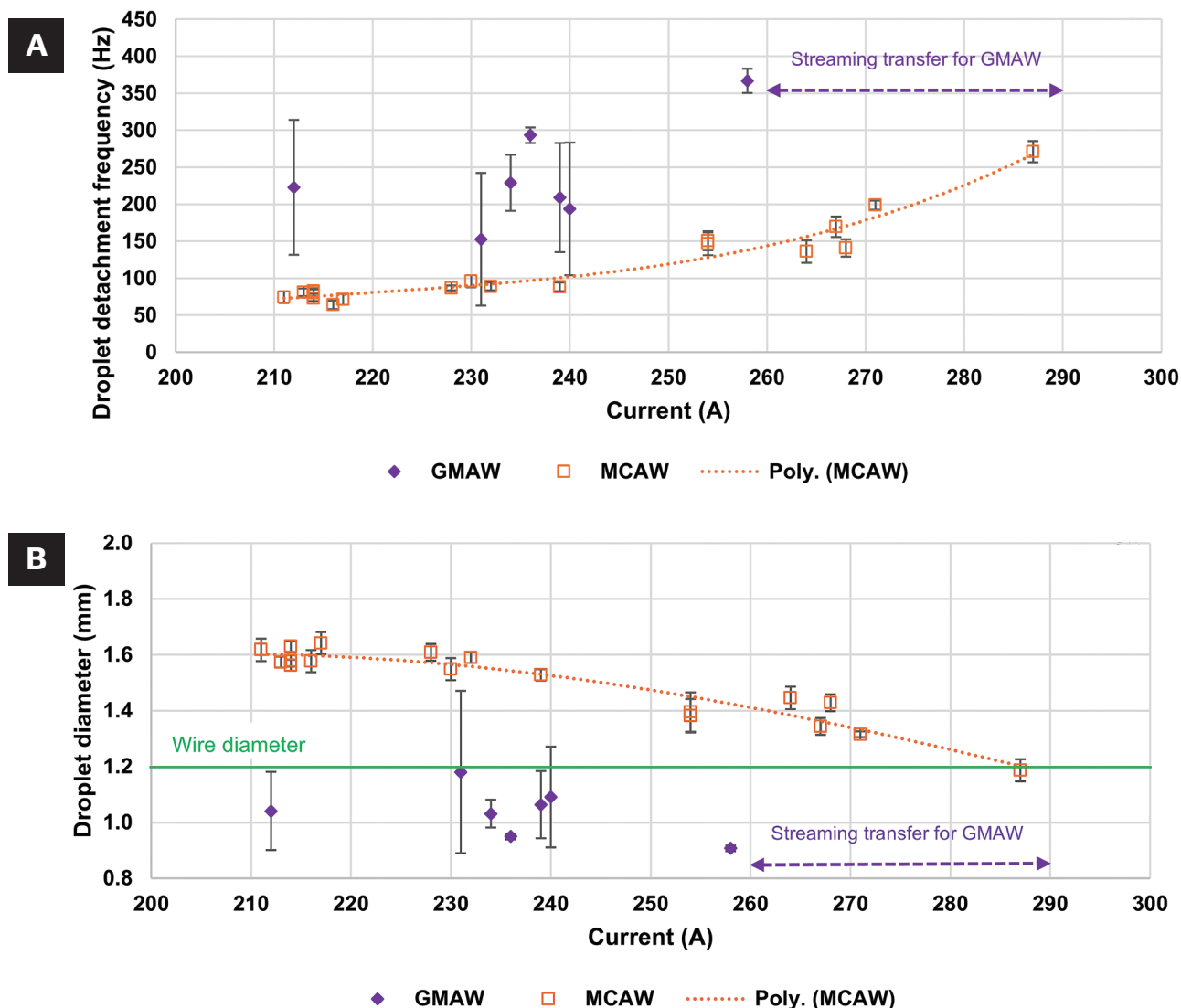


Fig. 7 – A – Droplet detachment frequency; B – equivalent droplet diameter as a function of current for MCAW and GMAW.

Apart from Equation (3), the overall anode fall voltage was given by the following equation (Ref. 24):

$$V_{an} = \frac{q_{an}}{I} - V_{EE} - V_{CT} = \phi_{an} + \frac{3kT}{2e} + V_A \quad (4)$$

Here, q_{an} represents the total heat input to the anode. The voltage loss at the electrode extension is denoted by V_{EE} , while V_{CT} corresponds to the contact tip voltage loss. ϕ_{an} denotes the work function of anode material, k is the Boltzmann constant, T represents the electron temperature, and e denotes the electrical charge. Lastly, the anode sheath voltage is given by V_A .

Results

Droplet Temperature

Figure 6 illustrates droplet temperatures as a function of current for MCAW and GMAW, calculated using the method in Ref. 22. The results showed that the average temperature of the droplet in MCAW did not vary significantly with current, ranging from 1900°C to 2145°C with an average uncertainty of $\pm 35.5^\circ\text{C}$. The measured droplet temperatures in GMAW were consistently higher than those in MCAW under similar currents, with an average difference of approximately 260°C.

Arc and Metal Transfer Morphologies

Figure 7 compares A – droplet detachment frequency and B – equivalent droplet diameter versus current for MCAW and GMAW. The overall frequency was averaged from five

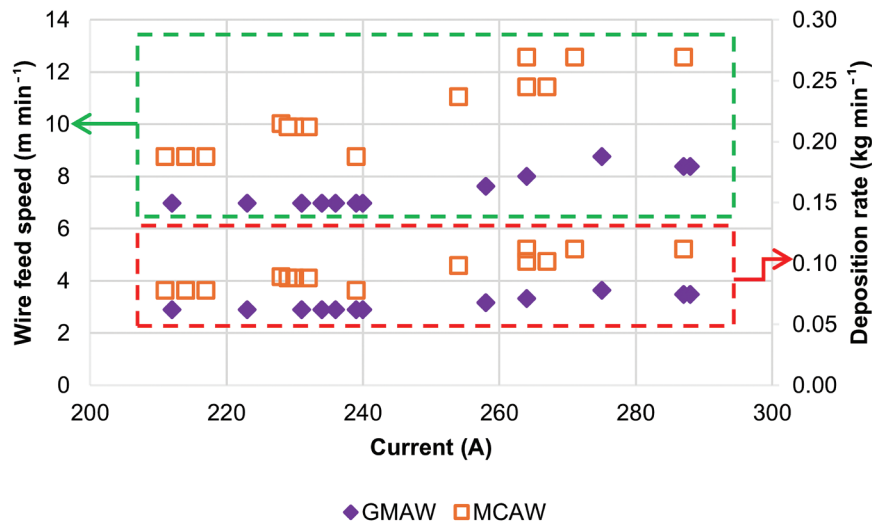


Fig. 8 – Wire feed speed and deposition rate as a function of current for MCAW and GMAW.

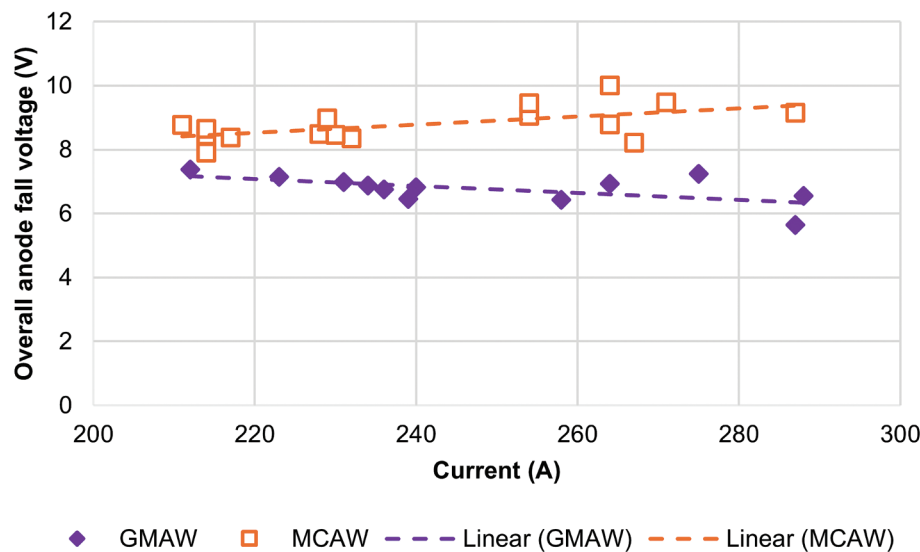


Fig. 9 – Overall anode fall voltage for GMAW and MCAW as a function of current.

calculations, each based on droplet counts during randomly selected 100 ms intervals within a 1-second video. Error bars represented the standard deviation. The equivalent droplet diameter was then estimated using this frequency, assuming spherical droplets, following the method described in Ref. 31.

The results indicate that the metal transfer in MCAW primarily maintained a globular transfer mode. In contrast, under similar conditions in GMAW, the transfer mode shifted from the mixed globular and projected transfer at low currents to the streaming transfer at high currents.

Figure 7A shows that GMAW had a higher and more variable metal transfer frequency than MCAW. In MCAW, a frequency of ~80 Hz was observed between 210 and 240 A due to symmetrical droplet formation, then gradually increased to 271 Hz at 290 A as droplets became biased. Despite changes in morphology, MCAW consistently showed globular transfer with minimal frequency errors. In contrast, GMAW showed

large frequency deviations from 210–240 A due to mixed globular and projected transfers, while streaming transfer above 260 A made frequency measurement impossible.

Figure 7B shows that for MCAW, the droplet diameter remained relatively constant at ~1.6 mm for currents between 210–240 A. As the current increased beyond this range, the droplet diameter gradually decreased, though it remained larger than the wire diameter. At approximately 290 A, during projected spray transfer, the droplet diameter became smaller than the wire diameter (~1.19 mm). In contrast, GMAW consistently produced droplet diameters smaller than the wire diameter throughout all of the current range examined.

Wire feed speed and deposition rate as a function of current for MCAW and GMAW are shown in Fig. 8. Results indicate that the wire feed speed and deposition rate in MCAW were greater than in GMAW for a given current, ranging from 8.76

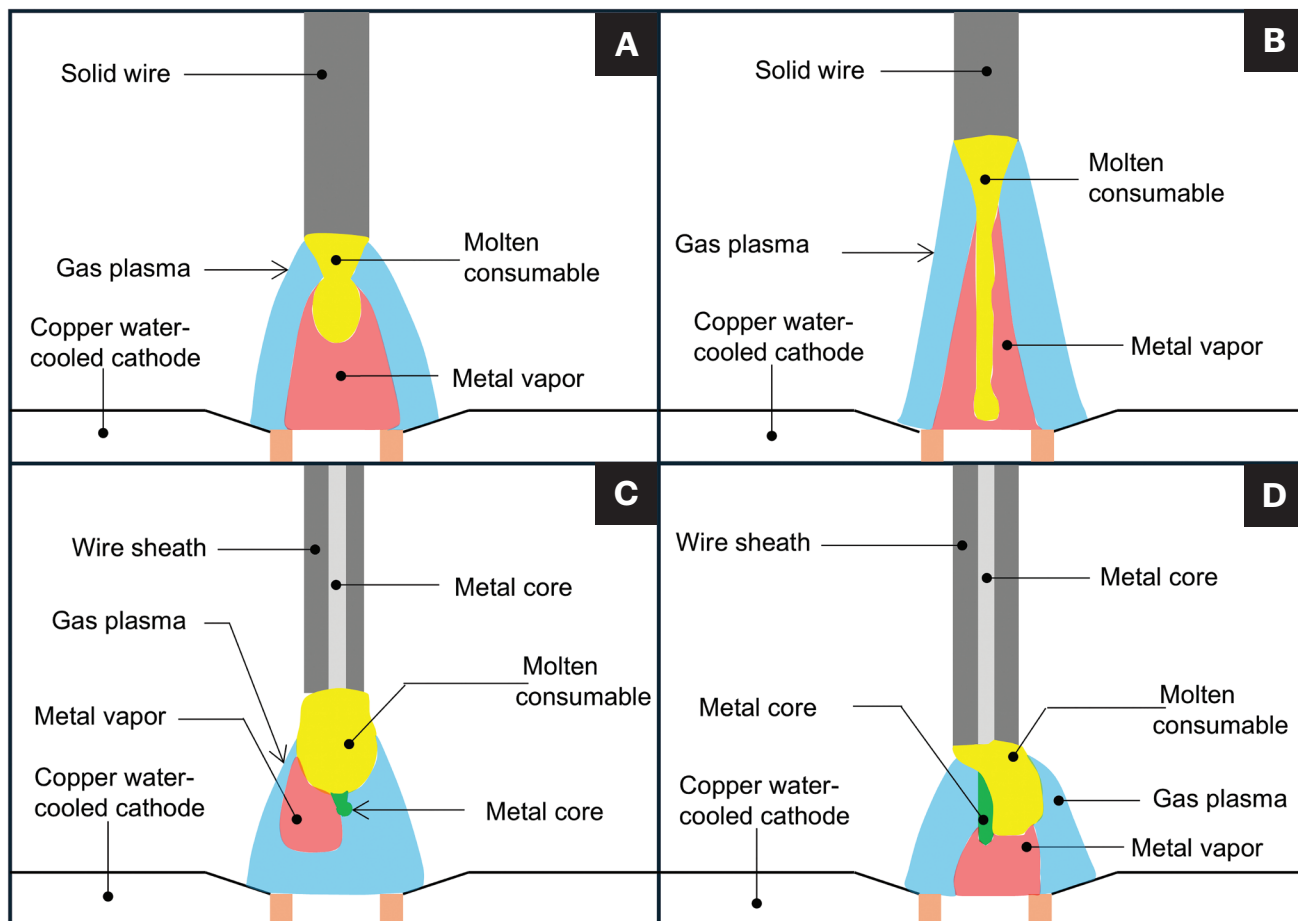


Fig. 10 — Schematic comparison of metal transfer morphology in GMAW: A — at 210 A; B — at 290 A; in MCAW: C — at 210 A; D — at 290 A.

to 12.57 m min^{-1} (from $0.078 \text{ kg min}^{-1}$ to $0.110 \text{ kg min}^{-1}$) in MCAW compared to consistently around $7.50 \text{ m min}^{-1} \pm 0.70 \text{ m min}^{-1}$ ($\sim 0.067 \text{ kg min}^{-1} \pm 0.006 \text{ kg min}^{-1}$) in GMAW.

Anode Fall Voltage

Figure 9 shows the overall anode fall voltage for GMAW and MCAW as a function of current. According to the mass and energy balance, it was found that the V_{an} in MCAW (metal core wire) was greater than in GMAW (solid wire). While solid wire showed a V_{an} of around $6.8 \text{ V} \pm 0.5 \text{ V}$ between 210 A and 290 A, MCAW showed a V_{an} increasing gradually with current from 7.9 V to 10.0 V in a similar range of currents.

Discussion

The droplet temperature ranged from 2180°C to 2400°C as the current varied from 210 A to 290 A in GMAW using pure argon shielding gas, as presented in Fig. 6. The results align with those in previously published studies (Refs. 15, 17, 18, 20). The minimum temperature of 2181°C at 212 A closely matches the well-known transition temperature of 2254°C at 206 A reported in Refs. 13, 16, 20.

The factors governing the difference in metal transfer morphology in GMAW and MCAW are considered. Figure

10 schematically compares factors influencing metal transfer morphology in GMAW A — at 210 A, B — at 290 A, and in MCAW C — at 210 A, D — at 290 A. In GMAW, arc attachment expands upward with current, increasing downward Lorentz force and forming a long-tapered molten column (Ref. 31). In contrast, MCAW maintains the globular transfer mode across all currents. This is because the solid powder core hinders neck formation needed for droplet detachment (Ref. 31). The change in sub-modes of globular transfer with current in MCAW is thought to be caused by the variation in force balance among the Lorentz force, surface tension, and gravity. At lower currents, the weaker Lorentz force allowed gravity to dominate droplet detachment, resulting in larger droplets and the formation of a more symmetrical molten metal surrounding the wire core. At higher currents, the stronger Lorentz force increased the droplet detachment frequency and caused a notable droplet formation preferential to one side of the solid powder core. The metal transfer morphology in MCAW was noted to alter the arc appearance at the current range studied in comparison to GMAW.

The mechanism attributed to the lower temperature in MCAW remains unclear. However, based on the results of the experiments in this work, an explanation can be proposed based on the existence of a metal core observed with high-speed video and a higher V_{an} in MCAW compared to in GMAW.

Firstly, a cylindrical metal core composed mostly of unmelted powders was consistently observed during the MCAW process. To elucidate its effect on the droplet temperature, the temperature of the wire sheath (T_{sheath}), which was primarily made of iron, was calculated and compared to the droplet temperature in GMAW. For this analysis, the metal core temperature (T_{core}) was assumed to be below the melting point of iron, using two specific values: 1200°C, which approximates the low melting temperature of a eutectic alloy, and 1500°C, which represents the melting temperature of unalloyed steel. It was also assumed that the specific heat of the molten droplet, the wire sheath, and the metal core was constant, an approximation within the margins of other uncertainties in these experiments. Normally, in commercial metal-cored wire, the metal core accounts for 15% of the total mass. By applying mass and energy balance principles among the droplet temperature and the temperatures of the wire sheath and the metal core, the following equation was derived:

$$T_{d,i} = 0.85T_{\text{sheath}} + 0.15T_{\text{core}} \quad (5)$$

Using Equation 5, Fig. 11 compares the droplet temperature in GMAW and MCAW, along with the estimated wire sheath temperature in MCAW for metal core temperatures of 1200°C and 1500°C. The latter is slightly lower than the melting point of iron (1538°C). The results show that the sheath's temperature was approximately 150°C and 90°C higher than the droplet temperature for metal core temperatures of 1200°C and 1500°C, respectively. The temperature of the molten sheath is consistent with that of a molten metal droplet with a solid wire at similar currents, with an average temperature of 2164°C or 2110°C for a metal core temperature of 1200°C or 1500°C, respectively, compared to 2294°C in GMAW. The results suggest that the mixture of the molten sheath droplet and the mostly solid metal core results in a lower deposited metal temperature in MCAW than in GMAW.

Secondly, the effect of higher V_{an} on lowering droplet temperatures in MCAW is discussed. The average value of V_{an} in GMAW in this study was $6.8 \text{ V} \pm 0.5 \text{ V}$, which agreed well with values reported by McIntosh et al. (Ref. 20), which was lower than the V_{an} obtained for MCAW.

Equation 4 indicates three factors influencing the V_{an} , but the dominant one remains unclear. The work function seems to not be dominant, as MCAW and GMAW wires consist primarily of iron, so both have almost similar work functions. The second factor is the electron thermal energy transported to the anode, which is a function of electron temperature. The plasma in MCAW consists of two regions: metal plasma (~6000 K) beneath the molten metal and gas plasma (~12,000 K) surrounding the metal plasma (Ref. 32). In the above temperature range, the voltage corresponding to this energy changes from 0.8 to 1.6 V, suggesting this effect alone cannot explain the V_{an} variation. The third factor is the anode sheath voltage, which is considered negligible (Ref. 25). Therefore, while the factors in Equation 4 provide some insight, they cannot fully explain the higher fall voltage observed in MCAW, necessitating further investigations.

One possible explanation is that the Thomson effect near the electrode is affected by the different metal transfer con-

figurations between the streaming spray in GMAW and the varying transfer mode in MCAW, which changes with current. Another possibility is that metal transfer morphology in MCAW affects the inferred overall anode fall voltage. In MCAW, despite maintaining globular transfer mode, the metal transfer is disrupted by the existence of the metal core of mostly solid powder reported by Trinh et al. in (Ref. 13). As explained above, one factor to cause this different metal transfer morphology might be associated with an increase in the Lorentz forces with rising current, along with a shift in current conduction from a uniform distribution around the sheath's perimeter to a single point of contact. The change of metal transfer morphology also altered the arc appearance of different currents. More detailed analysis is necessary to clarify the mechanism in future studies.

The colder core enables a reduction of manganese evaporation compared to solid wires, through a decrease in the droplet temperature. This could significantly lower the amount of manganese in welding fumes, which is an important consideration for environmental and occupational health.

Conclusion

A solid-state calorimeter and water-cooled copper cathode were used to measure droplet temperatures for the first time in MCAW with a commercial metal-cored wire and pure argon shielding gas in the 210-290 A range. These measurements were compared with GMAW using a solid carbon steel wire. The droplet temperatures in GMAW agreed with values reported in recent studies.

In MCAW, the average droplet temperature remained relatively stable across different currents ranging from 1900°C to 2145°C with an average uncertainty of $\pm 35.50^\circ\text{C}$, but being consistently lower than that in GMAW by approximately 260°C.

The estimated sheath's temperatures were approximately 150°C and 90°C higher than the droplet temperature for the assumed metal core temperatures of 1200°C and 1500°C, respectively. The mixture of cold core and hot sheath is thought to result in an overall lower droplet temperature in MCAW.

The overall anode fall voltage for MCAW ranged from 7.9 to 10.0 V, which was higher than the $6.8 \text{ V} \pm 0.5 \text{ V}$ obtained for GMAW in the same current range. The higher overall anode fall voltage observed in this analysis requires further study, but it is likely associated with either the Thomson effect near the electrode or variations in metal transfer morphology.

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