Identification of dominant factors determining droplet temperature in gas metal arc welding

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Abstract
In this study, to identify dominant factors of droplet temperature in a gas metal arc welding, the effects of polarity on droplet temperature were investigated. In particular, the droplet temperature, the wire heat input, and the wire melting rate with electrode positive (EP) polarity and electrode negative (EN) polarity using 100% Ar gas and 100% CO2 gas were measured. As a result, the droplet temperature with EP polarity was higher than EN polarity's one using 100% Ar gas within the range of 130–230 A. This result showed the reverse tendency compared with the case of 100% CO2. Moreover, the wire heat input and the wire melting rate with EN polarity were larger than EP polarity’s ones regardless of the shielding gas type. The simplified calculation suggested that this was because the ion current ratio was about 80% or more. Besides, especially with EP polarity, the wire melting rate using 100% CO2 was larger than 100% Ar’s one. It was suggested that this was because the wire melting rate was made a difference by the wire preheating effect depending on the droplet frequency determined by the specific heat of the shielding gas. These results identified the dominant factors of droplet temperature as the welding current, the ion current ratio, and the specific heat of the shielding gas.

Keywords
Gas metal arc welding; polarity; droplet temperature; calorimeter; heat input; ion current ratio; wire melting rate; droplet frequency

1. Introduction
In gas metal arc welding, the electrode wire is melted by the heat of the arc plasma and in most cases becomes a spherical molten metal (hereinafter called ‘droplet’) that is transferred to the weld pool. The droplet not only plays a role in forming the weld part together with the molten base metal but also transports the heat quantity transported from the arc plasma to the electrode wire and finally to the weld pool. Not only have most of the heat transport mechanisms from arc plasma to base metal been elucidated [1–4] but also attempts have been made to develop a prediction system for penetration shape [5,6] by applying these findings. On the other hand, the amount of heat transported by the droplet, i.e. the droplet temperature, affects the penetration shape, because it changes the temperature field of the weld pool [7–15].

Therefore, it is essential to control the droplet temperature to put the prediction system of penetration shape into practical use. To achieve droplet temperature control, we need to identify the dominant determinants of droplet temperature as a first step. In gas metal arc welding, the droplet temperature is thought to be determined by the complex effects of various welding conditions, such as wire material type, wire feed rate, polarity, welding current, wire extension, and shielding gas type. Previous studies have clarified the relationship between welding conditions and droplet temperatures, such as wire material type, wire extension, welding current, and mixing ratio of carbon dioxide gas to argon gas [16–20]. However, it is difficult to investigate the relationship between all possible welding conditions and droplet temperature because of the large time and economic costs involved, and the dominant determinants of droplet temperature have not yet been identified. Therefore, it is necessary not only to systematically investigate the effect of each welding condition on the droplet temperature as in previous studies but also to investigate the physical mechanism by which each welding condition
determines the droplet temperature. The final goal is to identify the dominant determinants of droplet temperature.

On the other hand, in recent years, gas metal arc welding with AC (Alternating Current) and DCEN (Direct Current Electrode Negative) polarity has been partially put into practical use and is the subject of research [21,22]. In particular, features, such as low heat input and high gap resistance of AC gas metal arc welding are attributed to the lower droplet temperature in the EN (Electrode Negative) polarity than in the EP (Electrode Positive) polarity [23,24]. Therefore, there is a need to elucidate the effect of polarity on droplet temperature. However, there have been few studies on the effect of polarity on droplet temperature, because gas metal arc welding has traditionally been used with EP polarity. The relationship between polarity and droplet temperature has not yet been clarified. It is essential to reexamine the relationship between polarity and droplet temperature and to obtain experimental data to confirm the mechanism by which polarity affects droplet temperature to further improve the functionality of gas metal arc welding methods using AC and DC positive polarity.

In this paper, the effect of polarity on droplet temperature was investigated. Moreover, discussions of the physical mechanism identified the dominant determinants of droplet temperature. The results of the droplet temperature measurement into 'heat input to the wire per unit time' and 'mass of wire melted per unit time (herein-after referred to as “wire melting rate”)', were considered to be determinants of droplet temperature were subdivided. The mechanisms of the effect of polarity on droplet temperature were discussed by investigating and comparing the effects of polarity on each element. To make the findings obtained highly versatile, the subject of research in this paper was gas metal arc welding using mild steel for wire and 100% argon gas and 100% carbon dioxide gas for shielding gas.

2. Experimental method

Figure 1 shows a schematic diagram of the experimental setup used in this study. This experimental setup consists of a digital inverter-controlled automatic welding machine, welding torch, base metal (water-cooled copper, 50 × 50 × 45 mm thick), Bakelite plate, copper cup, insulating container, water filling between the copper cup and the insulating container, K-type thermocouple, data logger, stirrer, and magnetic stirrer.

Figure 1. Schematic illustration of the experimental setup.

In this experiment, the average welding current during welding, which is displayed on the welding machine after welding is completed, was read and recorded as the welding current. Figure 2 shows photographs of some of the experimental setups. Figure 2(a) shows a copper cup, Figure 2(b) shows a heat insulator, and Figure 2(c) shows the copper cup, heat insulator, and Bakelite plate combined for use in the experiment.

The welding torch was set horizontally so that the distance from the bottom of the copper cup was about 200 mm to prevent the droplets from being reheated by the radiated heat of the arc after falling [25]. The base metal was water-cooled copper, and the torch was tilted at a 30° angle to the torch to prevent the droplets from falling through the base metal. Bakelite plates were placed on top of the adiabatic vessel to prevent the water in the adiabatic vessel from being heated by the radiated heat of the arc. The water in the adiabatic vessel was constantly stirred by a stirrer rotating with a stirrer, and its temperature was kept almost uniform. The stirring speed was set at 250 min⁻¹ [26]. The heat loss during the falling droplets was not taken into account in this experiment.

The droplets formed by the arc discharge above the device fall into a copper cup placed in an insulated container, and the heat retained by the droplets was transferred to the copper cup. The heat transferred from the droplets to
the copper cup was then transferred to the water filling the space between the copper cup and the insulated container. The water temperature before and after the experiment was measured by thermocouples connected to a data logger. In this study, the increase in droplet mass due to oxidation during droplet fall was ignored. Since the temperature of the droplet after the experiment is equal to the temperature of the copper cup and the water temperature, the droplet temperature can be obtained by substituting the measured water temperature and measured mass of the droplet into Equation (1) \(^\text{[27]}\).

\[
m_d \left[ C_{pl}(T_1 - T_m) + \Delta H_m + C_{ps}(T_m - T_h) \right] = m_w \left[ C_{pw}(T_h - T_0) \right] + m_c \left[ C_{pc}(T_h - T_0) \right]
\]

Here, \( m_d \) is the mass of the collected droplets, \( m_w \) is the mass of the water used in the experiment, \( m_c \) is the mass of the copper cup, \( C_{pl} \) is the specific heat of iron at constant pressure above the melting point, \( C_{ps} \) is the specific heat of iron at constant pressure below the melting point, \( C_{pw} \) is the specific heat of water at constant pressure, \( C_{pc} \) is the specific heat of copper at constant pressure, \( T_1 \) is the droplet temperature, \( T_m \) is the melting point of iron, \( T_h \) is the water temperature after the experiment, \( T_0 \) is the water temperature before the experiment, \( \Delta H_m \) is the latent heat of fusion of iron, respectively. The specific heat of water at constant pressure is \( 4.22 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1} \), the specific heat of copper at constant pressure is \( 0.386 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1} \), and the specific heat at constant pressure is independent of temperature\(^\text{[27]}\). Table 1 shows the welding conditions, and Table 2 shows the physical properties of the iron used to calculate the droplet temperature.

### 3. Experimental results

**Figure 3(a)** shows the measured results of droplet temperature in gas metal arc welding using argon gas as the shielding gas. The horizontal axis shows the average welding current during welding. Red triangles indicate data measured with DCEP polarity, and blue circles indicate data measured with DCEN polarity. The results for the DCEP polarity show that the droplet temperature increases from about 2200 to 3000 K with the increasing welding current in the current range of about 130–260 A. The results for DCEN polarity also showed that the droplet temperature tended to increase from about 1900 to 2300 K with the increasing welding current in the current range from about 100 to 230 A. In addition, when argon gas was used as the shielding gas, the temperature of the droplets tended to be higher in the DCEP polarity case than in the DCEN polarity case in the current range of about 130–230 A. The temperature of the droplets in the DCEP polarity case was higher than that in the DCEN polarity case. For example, the temperature at about 130 A was about 200 K higher, and at about 210 A about 300 K higher.

**Figure 3(b)** shows the measured results of droplet temperature in gas metal arc welding using carbon dioxide as the shielding gas. The horizontal axis shows the average current during welding. The red triangles indicate data measured with DCEP polarity, and the blue
circles indicate data measured with DCEN polarity. The results for the DCEN polarity show that the droplet temperature increases from about 1900 K to about 2400 K with the increasing current in the current range of about 120–300 A, similar to the DCEP polarity. In addition, when carbon dioxide gas was used as the shielding gas, the dissolution temperature was higher for DCEN polarity than for DCEP polarity in the current range of about 160–300 A, showing the opposite tendency to that observed when argon gas was used as the shielding gas. For example, at about 170 A, the temperature was about 200 K higher, and at about 280 A, the temperature was about 100 K higher.

4. Discussions

4.1. Determinants of droplet temperature

If the heat retained by the droplet per unit mass is \( H \), the temperature \( T_i \) of the droplet can be expressed as follows, based on the left-hand side of Equation (1), which shows the heat retained by the droplet.

\[
T_i = T_m + \frac{H - C_{pw}(T_m - T_h) - \Delta H_m}{C_{pl}}
\]  (2)

In other words, the droplet temperature is determined by the heat retained by the droplet per unit mass, the specific heat of constant pressure, and the latent heat of fusion. On the other hand, it is known that the relationship between the heat retained by the droplet per unit mass and the wire melting rate is given by the following Equation (3) [28].

\[
\nu_m = \frac{1}{\rho H} (\Phi I + R_0 j I^2)
\]  (3)

Where \( \nu_m \) is the wire melting velocity, \( \rho \) is the wire density, \( \Phi \) is the equivalent voltage of heat input from the arc plasma to the wire, \( j \) is the current density, \( R_0 \) is the resistivity of the wire, and \( I \) is the wire extension. The first term in the right-hand parentheses is the heat input from arc plasma to wire. The second term represents the resistive heating of the wire. In this study, the cross-sectional area of the wire is constant. The equation can be rewritten as follows.

\[
H = \frac{1}{M} (\Phi I + R_0 j I^2)
\]  (4)

Where \( M \) is the wire melting rate, \( I \) is the welding current, \( R \) is the resistance of the wire per unit length. From this equation, it was found that the droplet temperature is determined by the ‘heat input to wire per unit time’ and the ‘wire melting rate’.

4.2. Heat input to wire per unit time

4.2.1. Effect of polarity and shielding gas type

In this study, the heat input to the wire per unit time [W] was obtained by multiplying the heat retained by the droplet [J·kg\(^{-1}\)] by the wire melting rate [kg·s\(^{-1}\)]. The heat retained by the droplet, \( H \) is determined by the following Equation (5), which is based on Equation (1).

\[
H = \frac{m_w [C_{pw}(T_h - T_0)] + m_c [C_{pc}(T_h - T_0)]}{m_d}
\]  (5)

On the other hand, the welding power supply used in this study has a constant-voltage characteristic and the ‘self-adjusting effect of the power supply’ is activated, so the average wire melting speed is equal to the wire feed rate. Therefore, the wire melting rate is calculated by multiplying the wire feed rate at the time of the droplet temperature measurement experiment by the wire cross-sectional area and wire density. The density of iron is used here as the density of the wire because the wire used consists almost entirely of iron.
Figure 4(a) shows the calculation results of ‘heat input to wire per unit time’ in gas metal arc welding using argon gas as the shielding gas. The horizontal axis shows the average current during welding. The red triangles indicate the data for the DCEP polarity, and the blue circles indicate the data for the DCEN polarity. The DCEP polarity results show that the heat input of the wire per unit time increases from about 1000 to 3000 W with the increasing current in the current range of about 130–230 A. The DCEN polarity results show that the heat input of the wire per unit time increases from about 1200 to 3300 W with the increasing current in the current range of about 90–230 A. Thus, when argon gas was used as the shielding gas, the ‘heat input to the wire per unit time’ tended to be larger in the DCEN polarity case than in the DCEP polarity case in the current range of about 130–230 A. For example, at about 130 A, the power was about 500 W, and at about 210 A, it was about 700 W higher. As described in Chapter 3, when argon gas was used as the shielding gas, it was confirmed that the droplet temperature tended to be higher for the DCEN polarity than for the DCEP polarity in the current range of about 160–300 A. Therefore, it was confirmed that the effect of polarity on ‘heat input per unit time’ showed the same tendency as that of polarity on the drooping temperature.

In addition, comparing the calculated values for the DCEN polarity in each of the results in Figure 4 according to the shielding gas type, the ‘heat input to wire per unit time’ for both results ranges from about 1500 to 3000 W in the current range of about 130–230 A. Although the difference was small below 200 A, the overall value was about 1500 W. The heat input tended to be higher with carbon dioxide than with argon.

4.2.2. Estimated heat input to wire per unit time

As described in the previous section, it was confirmed that the ‘heat input to wire per unit time’ was higher for DCEN polarity than for the range of about 160–300 A. The DCEN polarity results showed that ‘heat input per unit time’ increased from about 1500 to 4000 W with increasing welding current in the current range of about 120–300 A. Thus, when carbon dioxide gas was used as the shielding gas, the ‘heat input per unit time’ tended to be larger for DCEN polarity than for DCEP polarity in the current range of about 160–300 A. For example, at about 160 A, the power was about 500 W, and at about 300 A, the power was about 1000 W higher. As described in Chapter 3, when carbon dioxide gas was used as the shielding gas, it was confirmed that the droplet temperature tended to be higher for the DCEN polarity than for the DCEP polarity in the current range of about 160–300 A. Therefore, it was confirmed that the effect of polarity on ‘heat input per unit time’ showed the same tendency as that of polarity on the drooping temperature.

Figure 4(b) shows the calculated heat input to the wire in gas metal arc welding using carbon dioxide as the shielding gas. The horizontal axis shows the average welding current during welding. The red triangles indicate the calculated values for the DCEP polarity, and the blue circles indicate the calculated values for the DCEN polarity. The DCEP polarity results showed that ‘heat input per unit time’ increased from about 1500 to 3000 W with increasing welding current in the current range of about 160–270 A. Although the difference was small below 200 A, the overall value was about 1500 W. The heat input tended to be higher with carbon dioxide than with carbon dioxide.
DCEP polarity, regardless of the shielding gas type. To investigate the cause of this tendency, we estimated and compared the ‘heat input to the wire per unit time’ for both polarities. The amount of resistive heating of the wire was not considered, since it was considered to be largely unaffected by polarity. The energy balance per unit area at the anode during gas metal arc welding is shown in Equation (6) [29].

\[
q_A = j_1 \left( \frac{5 k_B T_{arc}}{2e} + V_A + \frac{\phi_A}{e} \right) - j_2 \frac{\phi_K}{e} + |\kappa \nabla T_{arc}| + U_{arc} - U_A
\]  

(6)

Where \( q_A \) is the heat input per unit area at the anode, \( k_B \) is Boltzmann’s constant, \( T_{arc} \) is the temperature of the arc plasma, \( e \) is the elementary charge, \( V_A \) is the anode drop voltage, \( \phi_A \) is the work function of the anode, \( \kappa \) is the thermal conductivity, \( U_{arc} \) is the radiation energy from the arc plasma, \( U_A \) is the radiation energy from the wire, respectively. The first term on the right side of Equation (6) refers to anode heating by electrons. The first term in parentheses represents the equivalent voltage of the electron enthalpy. On the other hand, the energy balance per unit area at the cathode is shown in Equation (7) [29].

\[
q_K = j_1 \left( \frac{3 k_B T_{arc}}{2e} + V_K + \frac{\epsilon_i - \phi_K}{e} \right) - j_2 \frac{\phi_K}{e} + |\kappa \nabla T_{arc}| + U_{arc} - U_K
\]  

(7)

Where \( q_K \) is the heat input per unit area at the cathode, \( j_1 \) is the ion current density, \( V_K \) is the cathode drop voltage, \( \epsilon_i \) is the ionization energy of the gas near the wire tip, \( \phi_K \) is the work function of the cathode, \( j_2 \) is the electron current density, and \( U_K \) is the radiation energy from the cathode. In Equation (7), the first term on the right-hand side refers to cathode heating by cations. The first term in parentheses represents the equivalent voltage of the cation’s kinetic energy. The second term on the right side of Equation (7) refers to the cooling of the cathode by electron emission. In this study, the heat fluxes due to heat conduction and radiation are assumed to be almost the same depending on the polarity, and only the anode heating is considered for the DCEP polarity, while the cathode heating and cooling effects due to electron emission are estimated and compared for the DCEN polarity. Assuming that all energies are transferred only at the cross-section of the wire tip, the relationship is as in Equation (8).

\[
I = j \cdot A
\]  

(8)

Where \( A \) represents the cross-sectional area of the wire. Therefore, the ‘heat input to wire per unit time’ in DCEP polarity is obtained by Equation (9).

\[
Q_A = I \left( \frac{5 k_B T_{arc}}{2e} + V_A + \frac{\phi_A}{e} \right)
\]  

(9)

Where \( Q_A \) is the ‘heat input per unit time’ to the wire in DCEP polarity; the ‘heat input per unit time’ in DCEN polarity is calculated by Equation (10).

\[
Q_K = I \left[ \frac{3 k_B T_{arc}}{2e} + V_K + \frac{\epsilon_i - \phi_K}{e} \right] - I_i \frac{\phi_K}{e}
\]  

(10)

Where \( Q_K \) is the ‘wire per unit time’ in DCEN polarity. \( I_i \) and \( I_e \) are the ion current and electron current, respectively. The following table shows the results of the analysis. In this case, the ion current and electron current are obtained from Equations (11) and (12).

\[
I_i = I \cdot r_i
\]  

(11)

\[
I_e = I - I_i
\]  

(12)

Where \( r_i \) is the ratio of the ion current to the total current, i.e. the ion current fraction. The ion current fraction is expressed as in Equation (13).

\[
r_i = \frac{I_i}{I_i + I_e}
\]  

(13)

Therefore, the ‘heat input to wire per unit time’ in DCEN polarity is obtained as in Equation (14).

\[
Q_K = I \left[ r_i \left( \frac{3 k_B T_{arc}}{2e} + V_K + \frac{\epsilon_i - \phi_K}{e} \right) \right]
\]  

(14)

In this study, the ion current fraction is a computational parameter and is determined arbitrarily. According to Kanamaru et al., the ion current fraction in MIG welding ranges from about 40 to 90%, depending on the surface temperature of the weld pool [30]. Therefore, in this study, the ion current fraction is estimated to be either 50 or 80%. Table 3 shows the approximate conditions.

It was assumed that the heat input per unit time to the wire during gas metal arc welding using argon gas or carbon dioxide gas as the shielding gas. The approximate assumption was that the arc plasma near the wire tip was
composed only of iron atoms \[31,32\]. Furthermore, the arc plasma temperature and drop voltage near the wire tip shall be unaffected by the welding current.

Figure 5(a) shows the estimated ‘heat input to the wire per unit time’ when the ion current rate is 50\% the horizontal axis shows the current. Red results indicate DCEP polarity and blue results DCEN polarity. The solid line shows the results when argon gas is used as the shielding gas, and the dashed line shows the results when carbon dioxide gas is used as the shielding gas. The DCEP polarity results in the current range from 50 to 350 A showed that the wire heat input when argon gas was used tended to be 143–998 W larger than that when carbon dioxide gas was used. The reason for this may be that the anode drop voltage and the potential energy of the anode material are lower when carbon dioxide is used as the shielding gas than when argon gas is used. The DCEN polarity results in the current range from 50 to 350 A showed that the heat input tended to be 53 W to 368 W higher when carbon dioxide was used as the shielding gas than when argon gas was used. These results indicated that the difference in heat input to the wire between argon gas and carbon dioxide gas was smaller than that for DCEP polarity. The reason for this was that the difference in anode drop voltage between shielding gas types used in this study was 2.1 eV, while the difference in cathode drop voltage between shielding gas types was relatively small at 0.6 eV. The results of the experimental calculations confirmed that the DCEP polarity results differed depending on the shielding gas type, but the DCEN polarity results differed a little depending on the shielding gas type.

Therefore, the above argument was valid for actual phenomena. It was also shown that the ‘heat input to wire per unit time’ was greater for the DCEP polarity than for the DCEN polarity, regardless of the shielding gas type. The difference ranged from 325 to 2277 W when argon gas was used as the shielding gas, and from 130 to 912 W when carbon dioxide gas was used. As mentioned in the previous section, the ‘heat input to the wire per unit time’ calculated from the experimental results was larger for the DCEN polarity than for the DCEP polarity. Therefore, when the ion current rate was set to 50\%, the estimated ‘heat input to wire per unit time’ showed a different tendency from the experimental and calculated results.

Figure 5(b) shows the estimated ‘heat input to the wire per unit time’ when the ion current rate is 80\%. The horizontal axis shows the current. The red results are for DCEP polarity and the blue results are for DCEN polarity. The solid line shows the results when argon gas is used as the shielding gas, and the dashed line shows the results when carbon dioxide gas is used. The results showed that the ‘heat input to wire per unit time’ was greater for the DCEN polarity than for the DCEP polarity, regardless of the type of shielding gas, a tendency that was consistent with the experimental and calculated results. The difference ranged from 17 to 120 W when argon gas was used as the shielding gas, and from 221 to 1548 W when carbon dioxide gas was used. The reason for this was that the cathode heat generation increased due to the increased ion current rate, and the ‘heat input to wire per unit time’ increased in the DCEN polarity due to the reduced cooling effect of electron emission resulting from the decreased electron current rate.

An ion current fraction near the wire tip in gas metal arc welding with DCEN polarity of about 80\% or more was consistent with the tendency of experimental measurements. Therefore, the reason why the ‘heat input to wire per unit time’ in the case of DCEN polarity exceeds that in the case of DCEP polarity is thought to be because the ion current rate is about 80\% or more in DCEN polarity.

### 4.3. Effect of polarity and shielding gas type on wire melting rate

Figure 6(a) shows the calculation results of the ‘wire melting rate’ when argon gas is used as the shielding gas. The horizontal axis shows the average current. The red triangles indicate calculated values for DCEP polarity, and the blue
circles indicate calculated values for DCEN polarity. The results for DCEP polarity showed that the ‘wire melting rate’ increased from about $0.5 \times 10^{-3}$ to $1.4 \times 10^{-3}$ kg·s$^{-1}$ with the increasing current in the current range of about 130–270 A. The results for DCEN polarity showed that the ‘wire melting rate’ increased from about $0.7 \times 10^{-3}$ to $1.8 \times 10^{-3}$ kg·s$^{-1}$ with the increasing welding current in the current range of about 90–230 A. Thus, when argon gas was used as the shielding gas, the ‘wire melting rate’ tended to be higher for DCEN polarity than for DCEP polarity in the current range of about 130–230 A. This tendency was consistent with the effect of polarity on the ‘heat input per unit time’ of the wire. The temperatures were about $0.5 \times 10^{-3}$ kg·s$^{-1}$ higher at about 130 A and about $0.7 \times 10^{-3}$ kg·s$^{-1}$ higher at about 210 A, respectively.

Figure 6(b) shows the calculation results of the ‘wire melting rate’ when carbon dioxide gas is used as the shielding gas. The horizontal axis shows the average welding current. Red triangles indicate data calculated with DCEP polarity, and blue circles indicate data calculated with DCEN polarity. The results for DCEP polarity showed that the ‘wire melting rate’ increased from about $1.2 \times 10^{-3}$ to $1.8 \times 10^{-3}$ kg·s$^{-1}$ with the increasing welding current in the current range of about 160–300 A. The results for DCEN polarity showed that the ‘wire melting rate’ increased from about $1.0 \times 10^{-3}$ to $2.5 \times 10^{-3}$ kg·s$^{-1}$ with the increasing welding current in the current range of about 120–300 A. Thus, even when carbon dioxide gas was used as the shielding gas, the ‘wire melting rate’ tended to be higher in the DCEN polarity than in the DCEP polarity in the current range of about 160–300 A. This tendency was consistent with the effect of polarity on the ‘heat input per unit time’ of the wire. The following is a summary of the results of the study. For example, the values were about $0.1 \times 10^{-3}$ kg·s$^{-1}$ higher at about 170 A. The value was about $0.6 \times 10^{-3}$ kg·s$^{-1}$ higher at about 300 A, respectively.

Comparing the calculated values in the DCEN polarity of the respective results in Figure 5, the ‘wire melting rate’ was about $1.0 \times 10^{-3}$ to $1.8 \times 10^{-3}$ kg·s$^{-1}$ in the current range of about 130–230 A, the experimental and calculated values showed almost the same
tendency with increasing average welding current. This tendency was consistent with the tendency of the effect of shielding gas type on ‘heat input to wire per unit time’. On the other hand, a comparison of the calculated values for DCEP polarity showed that the ‘wire melting rate’ using carbon dioxide as the shielding gas tends to be higher than that using argon gas in the current range of about 160–270 A. In this case, for example, the value was about \(0.4 \times 10^{-3}\) kg s\(^{-1}\) higher at about 180 A. This tendency was opposite to the tendency of the effect of the shielding gas type on the ‘heat input to wire per unit time’. Figure 7 shows a schematic diagram of the effect of droplet migration frequency on droplet temperature.

According to a report by Tanaka et al., when argon gas was used as the shielding gas, the frequency of droplet migration was about 200–400 Hz in the current range of about 240–300 A [35]. Therefore, it was thought that the droplets detach the wire end with little heat transfer to the unmelted portion of the wire. On the other hand, when carbon dioxide gas was used as the shielding gas, the frequency was <50 Hz in the same current range, suggesting that the preheating effect of the wire was greater due to heat conduction from the droplet to the unmelted portion of the wire [35]. The specific heat of argon gas was lower than that of carbon dioxide gas. In this case, the thermal pinch effect was smaller with argon gas than with carbon dioxide gas. As a result, the electromagnetic pinch effect with argon gas was larger than that with carbon dioxide gas, and the droplet migration frequency was expected to be higher. Following this mechanism, it can be inferred that the ‘wire melting rate’ was higher when carbon dioxide gas was used as the shielding gas than when argon gas was used.

4.4. Mechanism of influence of polarity on droplet temperature and identification of dominant determinants of droplet temperature

Table 4 summarizes the experimental results of the ‘heat input per unit time’, ‘wire melting rate’, and ‘droplet temperature’ investigated in this study. The aforementioned discussion of these results reveals the following mechanism by which polarity affects droplet temperature. A wire given a ‘heat input per unit time’ determined by the dominant factors of welding current and ion current rate will have a higher weld droplet migration frequency. The ‘wire preheating effect’ was determined by the wire preheating effect, in which the rate of melting was determined by the rate at which the wire was melted. With a higher heat input, the temperature of the droplet was higher when the molten volume of the wire was larger than that of the droplet. The larger the droplet, the droplet temperature was low. It was clarified that the droplet temperature changed with polarity based on this mechanism. Finally, the dominant determinants of droplet temperature were identified by pinpointing the elemental determinants associated with this mechanism. The following are the
dominant determinants of droplet temperature identified in this study.

1. Welding current
2. Ion current rate near wire end
3. Specific heat of shielding gas

5. Conclusions

To obtain a guideline for controlling the droplet temperature in gas metal arc welding, this study aimed to identify the dominant determinants of the droplet temperature, especially the effect of polarity on the droplet temperature and its mechanism. Based on the results of experimental measurements of droplet temperature, the effects of polarity on ‘heat input per unit time’ and ‘wire melting rate’ were calculated, and the results obtained were discussed. The conclusions of this paper are summarized as follows:

1. The effect of polarity on droplet temperature was investigated. When argon gas was used as the shielding gas, the droplet temperature tended to be higher in the DCEP polarity than in the DCEN polarity in the current range of about 130–230 A. The droplet temperature was higher in the DCEP polarity than in the DCEN polarity in the current range of about 130–230 A. When carbon dioxide gas was used as the shielding gas, the temperature of dissolved droplets in the DCEN polarity was higher than that in the DCEP polarity in the current range of about 160–300 A, showing the opposite tendency to that observed when argon gas was used as the shielding gas.

2. As a result of investigating the effect of polarity on ‘heat input per unit time’, it was confirmed that ‘heat input per unit time’ tended to be larger in the DCEN polarity than in the DCEP polarity in the current range of about 130–230 A when argon gas was used as the shielding gas. When carbon dioxide gas was used as the shielding gas, the ‘heat input to the wire per unit time’ tended to be larger for the DCEN polarity than for the DCEP polarity in the current range of about 160–300 A.

3. By estimating the ‘heat input per unit time’, it was thought that the reason why the ‘heat input per unit time’ for the DCEN polarity exceeded that for the DCEP polarity was that the ion current to total current ratio was about 80% or higher for the DCEN polarity.

4. As a result of investigating the effect of polarity on the ‘wire melting rate’, when argon gas was used as the shielding gas, the ‘wire melting rate’ tended to be higher for DCEN polarity than for DCEP polarity in the current range of about 130–230 A. This indicated that the polarity affected the wire melting rate per unit time. The tendency was consistent with the effect on heat input. When carbon dioxide gas was used as the shielding gas, the ‘wire melting rate’ tended to be higher for DCEN polarity than for DCEP polarity in the current range of about 160–300 A. This tendency was consistent with the effect of polarity on the heat input per unit time to the wire. However, a comparison of the calculated values, especially for the DCEP polarity, showed that the ‘wire melting rate’ tended to be higher when carbon dioxide gas was used as the shielding gas than when argon gas was used, in the current range of about 160–270 A. The ‘wire melting rate’ was higher when carbon dioxide gas was used as the shielding gas than when argon gas was used. This tendency was opposite to the tendency of the effect of shielding gas type on ‘heat input to wire per unit time’.

5. The mechanism of the effect of polarity on droplet temperature was clarified to be as follows. A wire is given a ‘heat input per unit time’ determined by the welding current and ion current rate as dominant factors will melt according to the ‘wire melting rate’ determined by the wire preheating effect where the droplet migration frequency was the dominant factor. Given a larger heat value, the temperature of the droplet was higher, while the larger the molten volume of the wire, the lower the droplet temperature. The droplet temperature changed with polarity based on this mechanism. In addition, it was identified that the welding current, the ion current rate near the wire end, and the specific heat of the shielding gas were the dominant determinants of the droplet temperature.

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