Calculation of Solid Wire Melting Rate in CO₂ Welding

**ABSTRACT**

The melting rate of solid wire was studied both theoretically and experimentally during CO₂ arc welding. The effects of welding current, an electrode diameter, and its extension, as well as droplet enthalpy on melting rates, were evaluated. The calculation methods of solid wire melting rate known as the coefficient of melting and having the dimension [g·A⁻¹·h⁻¹] are proposed. The first mathematical model was created using a theoretical equation derived from the thermal equality of the heat runoffs and sources existing in electrode extension. The mathematical relationship between welding variables (the density of welding current and the electrode extension) and droplet enthalpy was derived using the regression analysis of experimental data. The second mathematical model is a regression equation, which connects the coefficient of melting with welding current, electrode diameter, and its extension. Its coefficients were derived from the researchers’ experimental data. Both models allow calculating the coefficient of melting with an acceptable magnitude of error.

**KEYWORDS**

- GMAW
- Carbon Dioxide
- Solid Wire
- Melting Rate
- Coefficient of Melting
- Mathematical Model
- Droplet Enthalpy

**Introduction**

The melting rate of solid wire is one of the major factors that determines the productivity of welding and cladding processes. There are two ways to represent a melting rate. The first manner is an instantaneous melting rate with the dimension [m·s⁻¹], [g·s⁻¹], or [g·h⁻¹]. It is often used during studies concerning the melting of a consumable electrode, and is used in the manner in Ref. 1. It is defined as the mass of the filler metal melted per the unit of time. The second manner melting rate is represented is the specific rate of melting. It has a dimension [g·A⁻¹·h⁻¹], and it is widely used in the Russian welding industry and science literature (Ref. 2). It is known as the coefficient of melting (CM). The coefficient is frequently used during the elaboration of technology, for example, to calculate the deposit area of weld bead (Ref. 3)

\[ F_d = I_w \frac{\alpha_m}{\gamma V_w} (1 - \psi) \]

where \( I_w \) is the welding current, \( \alpha_m \) is the coefficient of melting, \( \psi \) is the arc welding deposition efficiency, \( \gamma \) is the density of electrode material, and \( V_w \) is the welding speed.

In addition, the mathematical model of the CM is the major part of a system of equations applied to calculate welding parameters in computer-aided design (CAD) of technology (Ref. 4).

There are numerous studies concerning the melting rate of welding wire and various investigations have been carried out with the aim to understand the influence of welding current, welding current waveform, polarity, chemical composition, wire diameter and electrode extension, and shielding gas composition on the melting rate. One knows of several experimental studies dedicated to deriving relatively simple mathematical expressions for the calculation of the melting rate.

Lesnevich (Ref. 1) derived the simple expressions to calculate the melting rate as a function of the welding current density and electrode extension during gas metal arc welding (GMAW). To calculate the specific melting rate, Demyantsevich (Ref. 3) proposed the equations for GMAW and submerged arc welding (SAW). Usually, such equations consist of two parts. The parts represent the contribution of heat from the anode region of an arc into the electrode extension is a constant value.

Allum (Ref. 5) studied the influence of welding settings on characteristics of wire melting (wire melting rate and frequency transfer) during welding of mild steel with a mixture of Ar + 5% CO₂, Amin (Ref. 6) and Amin and Nasser-Ahmet (Ref. 7) investigat-
ed welding in mixtures of \(\text{Ar} + 5\% \text{ CO}_2\) and \(\text{Ar} + 20\% \text{ CO}_2\) using low-carbon wire with drop and spray modes. Chandel (Ref. 8) investigated the effect of welding parameters on the characteristics of the melting of the electrode wire of low carbon in welding using a mixture of \(\text{Ar} + 25\% \text{ CO}_2\). Also, Chandel (Ref. 9) elaborated regression models of melting rates, taking into account the effects of SAW variables such as welding current, electrode extension, and electrode diameter.

It should be noted some studies of electrode melting rate conducted by Erohin in argon (Ref. 10), Sannikov et al. in SAW (Ref. 11), and Amin and Nasser-Ahmed in a mixture of \(\text{Ar} + 5\% \text{ CO}_2\) (Ref. 7) have shown the dependence of the melting rate on welding current is significantly nonlinear. Amin and Nasser-Ahmed have examined the relationships between melting rate, current, and electrode extension for \(d_e = 1.2\ mm\).

From the graphs of these relationships based on Amin and Nasser-Ahmed’s data (Fig. 1), one can see the melting rate plots of the graph corresponding to different types of electrode metal transfer have different angles of inclination to the axis of welding current. Rykalin (Ref. 2), Mazel (Ref. 12), Halmøy (Ref. 13), Waszink and Van den Heuvel (Ref. 14), and Lancaster (Ref. 15) performed studies of the melting rate of an electrode. Using the theory of heat transfer in an electrode, Rykalin (Ref. 2) derived an expression to calculate the melting rate of the electrode as a function of the welding current and arc voltage, the enthalpy of a wire, and metal drops. Mazel (Ref. 12) showed a heat source electrode is the arc regions (anode or cathode), and he has stated the energy in these areas is determined by the electron work function (here and following the dimension of electron work function is \(V\) unless otherwise specified), the thermal energy of electrons, and the voltage drop in the corresponding arc region. Halmøy (Ref. 13) studied the relations between wire melting rate, droplet temperature, and effective anode melting potential. Halmøy assumed thermal power at the anode tip is dissipated in an effective anode melting potential made up of the electron work function of wire metal and part of the anode potential in the arc. He derived from an experiment that
effective anode melting potential essentially is equal to or is less than electron work function. Thus, Halmøy considered the effect of an anode voltage drop on the electrode melting is close to zero. The Joule heating in the electrode extension of different welding wires is calculated exactly for real values of resistivity and specific heat using a simple technique of graphical integration, which yields the distribution of enthalpy and voltage along the wire. Adding the effect of anode heating, a simple equation for the melting rate was established.

Waszink and Van den Heuvel (Ref. 14), and Lancaster (Ref. 15) have found that the dominant processes of electrode heating are Joule heating of electrode extension and heat flow from the arc region (anode or cathode) through a liquid drop. Using the energy balance of the process of heating and melting of the electrode wire, these authors derived an expression for the calculation of melting rate as a function of the energy of indicated heat sources and enthalpy of drops. Bish (Ref. 16) proposed a single differential equation linking melting rate, electrode extension, and current density to calculate melting rate. This equation takes into account both the heat transport and heat conduction terms and makes proper allowance for the variations with temperature of the electrical and thermal conductivities of the material of the wire. However, this equation does not take into account heat flow from an anode region.

Experimental works of other authors have confirmed the theoretical

<table>
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<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>S</th>
<th>P</th>
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<tr>
<td>0.05–0.11</td>
<td>0.70–0.95</td>
<td>1.80–2.10</td>
<td>Not more than 0.20</td>
<td>Not more than 0.25</td>
<td>0.025</td>
<td>0.030</td>
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conclusions. The results obtained experimentally by Maruo et al. (Ref. 17) can be summarized as follows: Wire melting rate in GMAW is affected by effective anode melting potential, length and resistance of the electrode wire extension, enthalpy of metal droplets, and applied electric current.

To calculate the rate of melting, the important information about the enthalpy of droplets separated from an electrode tip, anode and cathode potential, was obtained by Rabkin (Ref. 18), Mazel (Ref. 12), Pokhodnya (Ref. 20), Erohin (Ref. 10), and Soderstrom (Ref. 21) et al. To the best of our knowledge, for the first time, Rabkin (Ref. 18) has assessed the magnitude of anode voltage drop $U_a$. He calculated $U_a = 2.43 \pm 0.29$ V, ignoring losses of heat and using the experimental melting rate of a steel electrode. Lenivkin and coworkers (Ref. 19) investigated by the probe method the anode and cathode voltage drop of the arc. They stated the anode voltage drop in CO$_2$ welding is changed from 8.8 to 7.5 V as the welding current increases from 110 to 280 A. The investigations (Refs. 18, 19) showed an anode voltage drop $U_a$ is constant and very slightly depends upon welding current. Pokhodnya (Ref. 20) determined experimentally the effects of welding current, diameter, and chemical composition of the wire and shielding gas on a temperature and an enthalpy of electrode metal droplets in GMAW. Erohin (Ref. 10) showed the effect of a droplet’s enthalpy on the relative rate of melting during welding.

So, average temperature and enthalpy of droplets were determined by Soderstrom et al. (Ref. 21) from calorimetric measurements in free-flight gas metal arc welding in argon for carbon steel, stainless steel, and aluminum electrodes. The results show a local minimum in temperature during the transition from globular to spray transfer modes. In addition, it can be seen that temperature and enthalpy of droplets during globular transfer are smaller than ones during spray transfer modes. Nakamura and Hiraoka (Ref. 22) determined the correlations between equivalent anode melting potential, welding current, electrode diameter, and droplet superheat. In this manuscript, an equivalent anode melting potential is the sum of an anode
voltage drop, work function, and thermal energy of an electron. However, the droplet superheat is very difficult to calculate; thus, derived mathematical equations can be used only as elements of a numerical solution.

Mazel and Pampurs (Ref. 23) investigated various welding wires and determined work function for mild- and low-alloy welding wires as the function of temperature. They stated that rimmed steel has the lowest work function, about 3.9–3.95 eV, low-alloy steel wires containing Mn and Si have a work function of about 4.3 eV, and mild steel has the highest work function, about 4.8 eV.

Information about voltage drop, power, and temperature in a system "contact tube-wire electrode-arc anode region-arc cathode region" has great importance for the calculation of the melting rate. Waszink (Ref. 24) calculated the temperature of the wire and the wire potential, taking into account Joule heating by the wire current, thermal conduction from the liquid drop into the solid metal, thermal radiation from wire surface, and the Thomson effect. Jönsson et al. (Ref. 25) investigated voltage drop due to the contact resistance between the contact tube and the electrode as a function of welding current, as well as total power in the arc, power in the arc column, and the sum of a power in the anode and cathode fall regions as a function of the melting current.

Shimizu and coauthors (Ref. 26) studied the effects of an electric contact between the contact tube and wire on the voltage drop $U_{\text{cont}}$ and a temperature distribution along the electrode extension. In Ref. 26, Joule heating from the sliding of the wire against the contact tube during welding was exactly estimated. The contact resistance of the main sliding point affected the average temperature of the wire, and the current branch affected the deviation temperature of the wire. Also, Shimizu and coauthors have shown using experiment procedure that $U_{\text{cont}}$ didn’t exceed 0.6 V when intended current was 160 A and short-circuit current was changed from 100 to 400 A for Cu-coated wire and for non-Cu-coated wire.

In certain recent work (Ref. 27), researchers offered an expression to calculate the rate of melting of flux-cored wire. Richardson et al. (Ref. 28) took into account the effect of the current pulses at the melting rate. Nevertheless, the newly obtained equations are similar in structure to Lesnevich's equation (Ref. 1). In addition, Pentegov (Ref. 29) derived an equation to calculate the voltage drop in slide contact tube-wire from an experiment.

However, in the result, despite the significant amount of research on the issue of calculating the melting rate of an electrode in GMAW, certain features of the melting of the electrode wire were not considered. In particular, the experimental dependence of droplet enthalpy on welding current was not included in formulas for calculation of melting coefficient. In this paper, the authors discuss a theoretical and experimental study of the melting of the wire.

<table>
<thead>
<tr>
<th>Source of Experimental Data</th>
<th>Welding Wire</th>
<th>$d_s$ (mm)</th>
<th>$L_s$ (mm)</th>
<th>$I_m$ (A)</th>
<th>The Kind of Transfer</th>
<th>$T$, K</th>
<th>$H_{\text{m, J/g}}$, Literature</th>
<th>The CM Calculated Using Eq. 13</th>
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<td>1.2</td>
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<td>220</td>
<td>spray</td>
<td>400</td>
<td>Refs. 34, 40</td>
<td>3400</td>
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<td>15</td>
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<td>1.2</td>
<td>10</td>
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<td>2000</td>
</tr>
<tr>
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<td>Al+6%Mg</td>
<td>1.6</td>
<td>20</td>
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</tbody>
</table>
during CO₂ welding.

The purposes of this article were experimental and theoretical studies of the melting process of the electrode wire during CO₂ welding to explain the nonlinearity dependence relative melting rate upon welding current and to derive mathematical expressions to calculate the relative melting rate of the electrode wire during CO₂ welding when an electrode wire is direct current electrode positive (DCEP).

**Heat Balance on Electrode Extension**

Admittedly, in welding with a consumable electrode, the melting of an electrode depends on two major heat sources in large measure (Ref. 15). The first source is the heat generated into an anode or a cathode arc region. The second source, in accordance with Joule law, is the heat generated into an arc one can write

\[ U_{cont} = \sqrt{\frac{4L(T_{max}^2 - T_{ERT}^2)}{R_e}} \]

where \( L \) is the Lorenz number, \( T_{max} \) is the maximum temperature of the contact portion, and \( T_{ERT} \) is the equivalent anode melting potential (Ref. 22).

\[ U^* = \left( \frac{U_a + \varphi + \frac{3}{2} \frac{k \cdot T_e}{e}}{2} \right) I_w \]

where \( I_w \) is the welding current. The expression in the parentheses is the equivalent anode melting potential (Ref. 22).

\[ U_e = \left( \frac{U_c + \varphi + \frac{3}{2} \frac{k \cdot T_e}{e}}{2} \right) I_w \]

where \( U_c \) is the cathode drop voltage.

Electric current passing through an electrode extension contributes heat, according to Joule law.

\[ q_L = \frac{\rho(T) \cdot L_c \cdot I_w^2}{\pi \cdot R_e^2} \]

where \( \rho(T) \) is the electrical resistivity as the function of temperature, \( L_c \) is the electrode extension, and \( R_e \) is the electrode radius.

The electrical resistivity as the function of temperature may be determined using Ref. 26.

\[ \rho(T) = 6.62 - 4.79 \cdot 10^{-3} T + 9.19 \cdot 10^{-5} T^2 \]

Equation 5 holds for the temperature range from 300 to more than 1033 K.

Other sources of heat exist when operating with electrode extension, such as the electric contact tube-wire (Refs. 24, 26) and the Thomson effect (thermoelectric effect) (Ref. 24). Shimizu and coauthors (Ref. 26) attributed the voltage drop \( U_{cont} \) at the contact tube-wire with a ratio between thermal conductivity to the electrical conductivity of an electrode metal and the temperature using the Wiedemann–Franz law, and they have shown

\[ U_{cont} = \sqrt{\frac{4L(T_{max}^2 - T_{ERT}^2)}{R_e}} \]

where \( L \) is the Lorenz number \( L = 2.44 \times 10^{-8} \text{ W} \cdot \text{Ω} \cdot \text{K}^2 \), \( T_{max} \) is the electrode temperature, and \( T_{ERT} \) is the maximum temperature of contact portion.

Pentegov and coauthors (Ref. 29) showed that \( U_{cont} \) depends on wire diameter and feed speed, and they experimentally derived the next equation

\[ U_{cont} = \left( \frac{V_d}{180 \mu_e} \right)^{0.2} - 1.78 \]

where \( V_d \) is the wire feed speed [m·s⁻¹].

The Thomson effect occurs since welding current is passed through a heated electrode extension. The heat allocated due to the Thomson effect (Ref. 30) one can calculate as

\[ q_{Th} = I_w \cdot \omega(T) \Delta T \]

where \( \Delta T \) is the temperature gradient and \( \omega(T) \) is the Thomson coefficient.

The Thomson effect is the cause of the heating of an electrode extension in the case when the electrode is direct current electrode negative (DCEN) or it is the source of cooling when the electrode is positive (DCEP).

Taking into account the Thomson coefficient for Armco iron is changed from \(-15.3 \pm 0.2\) at 323 K to \(-26.3 \pm 0.2\) at 523 K (Ref. 30), we have calculated that the heat evaluated due to the Thomson effect in electrode extension is changed from 2 to 8 W when welding current is increased from 100 to 300 A. This fact allows us to classify this effect as insignificant.

The comparison of the results of calculation for various heat sources mentioned previously is shown in Fig. 2. To calculate the heat output of the anode region, the following factors were used: the plasma temperature \( T_p = 9000 \text{ K} \), taken in accordance with our data (Ref. 31); anode drop voltage \( U_a = 2.43 \text{ V} \) in accordance with Ref. 18; and an electron work function \( \varphi = 4.5 \text{ V} \) (Refs. 32, 23). The specific electrical resistance of the electrode metal we adopted according to Zinoviev (Ref. 33), \( \rho = 91.4 \cdot 10^6 \Omega \cdot \text{m} \), for a temperature 1000 K of electrode extension. To calculate a feed speed \( V_d \) used in Eq. 7, the equation was elaborated in the present research (see following). One can see the amount of heat power produced on an electric contact tube-wire is comparable with Joule heat.

Our calculated values of the thermal power dissipated in slidding contact tube-wire are in agreement with the data of Shimizu et al. (Ref. 26), which calculated the ones using the measured contact resistance and welding current. As it was shown by Shimizu, the Joule heating power of bulk wire is about 900 W, so Joule heating power of the sliding contacts can change the average and deviation of melting speed during welding. Neglecting the losses of heat caused by the radiation from the surface of an electrode extension and from the surface of a droplet, one can say the sum of the thermal power derived in an electrode extension is used to increase metal electrode enthalpy, which may be calculated as

\[ q_m = \pi \cdot R_e^2 \cdot V_d \cdot \gamma \left( H_m + (T_{dr} - T_m) \cdot C_L \right) \]

where \( H_m \) is the specific heat of melting, \( T_{dr} \) is the temperature of a droplet detached from an electrode tip, and \( T_m \) is
the melting temperature, and $C_l$ is the specific heat of electrode metal. Then, denoting the enthalpy of separating electrode droplets ($H_{dr} + (T_{dr} - O_{dr}) \cdot N_d$) as $H_{av}$, one can write the expression for calculation of the melting rate [m s$^{-1}$] in the case of DCEP.

$$V_d = \left( \frac{U_a + \varphi + \frac{3}{2} k \cdot T_e}{\pi \cdot R_e \cdot \gamma \cdot H_{dr}} \right) + \frac{p(T) \cdot L_e \cdot I_w}{\pi^2 \cdot R_e^2 \cdot \gamma \cdot H_{dr}}$$

From another hand, one may write using the definition of a melting coefficient. Therefore,

$$\alpha_m I_w = V_d = \frac{\alpha_m \cdot I_w}{\pi \cdot R_e \cdot \gamma}$$

Expressing $\alpha_m$ from the last relationship and using Equations 10 and 11, one may write the equation for calculation of the melting coefficient [g·A$^{-1}$·s$^{-1}$].

$$\alpha_m = \frac{\left( \frac{U_a + \varphi + \frac{3}{2} k \cdot T_e}{H_{dr}} \right)}{\frac{p(T) \cdot L_e \cdot I_w}{\pi^2 \cdot R_e^2 \cdot \gamma \cdot H_{dr}}}$$

From the last expression can be rewritten using the density of welding current $J$

$$\alpha_m = \frac{1}{H_{dr}} \left[ U' + p(T) \cdot L_e \cdot J + U_{cont} \right]$$

Analogously, one can write similar equations for the case of DCEN.

However, the use of Equations 10 and 13 in practice is difficult for the following reasons. First, very little is known about the magnitude of anode and cathode voltage drop. There are conflicting experimental data of Refs. 18, 19, and 13 for carbon steel electrode. Second, enthalpy, electrical resistivity, the work function of an electrode material and a droplet temperature, is measured by the functions of arc temperature and the chemical composition of a material, and their values are not known with sufficient accuracy now.

It was the purpose of this research, therefore, to make quantity description of the melting rate of an electrode wire devoid of the above-mentioned drawbacks. The relationships between, on one hand, the CM and, on another hand, welding current, an electrode diameter, its extension, and also the enthalpy of electrode metal were investigated using statistical methods. The regression analysis confirmed the repeatability of the experimental data. A simple regression model was developed based on the known welding parameters to determine the CM.

The following section describes the materials, equipment, and procedures employed in this study.

### Experimental Details

#### Materials

Sheets of 10-mm-thick mild steel were used. A Sv-08G2S (1.2, 1.6, 2.0 mm diameter) welding wire was used as filler metal for the welds on the sheets. The chemical composition of Sv-08G2C welding wire, according to Russian standard GOST 14771, is shown in Table 1. Pure carbon dioxide, according to Russian standard GOST 5226, was used for a shielding arc.

#### Welding Procedures

A transformer-rectifier type VDU-504 and an automatic tractor type ADG-504 were used. During welding, the electronic device was embedded in an electrical welding circuit and connected to an IBM-PC that recorded arc voltage and welding current. The welding procedure consisted of manually setting preselected welding variables, such as welding current density, arc voltage, speed, the diameter of a wire and an electrode extension, starting the carriage and wire feed motors, plus initiating the arc. Direct current electrode positive was used for making all of the welds. Melt runs were made using welding current between 100 and 400 A and at four values of electrode extensions: 13, 18–20, 23, and 25 mm.

In studies of the CM, the important factor is the electrode extension. Many researchers have noted the difficulty of precisely determining an electrode extension. This is due to the difficulty of determining the place of current supply in contact tube-wire and the effect of a droplet’s transition from an electrode tip to a weld pool on the electrode extension. Electrical parameters of a welding process were written by an oscilloscope, and the transfer process of droplets was photographed with the aim of determining the kind of droplet transfer and the electrode extension.

Experimental data obtained by Demyanitshevich (Ref. 3) in the same conditions were included in the mathematical processing and analysis as our own data.

### Results and Discussion

Figure 3 shows the series of graphs describing the influence of the welding current density $J$, the electrode extension $L_e$, and a wire diameter $d$, on the coefficient of melting $\alpha_m$. The influence of the welding current density $J$ on the CM is not linear. Moreover, some curves have the minimum, which is more perceptible with the 1.2-mm-diameter wire and a small electrode extension (up to 20 mm). This trend has the close agreement with the theoretical Equations 10–13. From these equations, one can see that the higher the droplet temperature, the less arc heat conducts to an electrode through a droplet. An anode voltage drop and enthalpy could influence the CM in the same way, but to the best of our knowledge (Refs. 18, 19, 13), an anode voltage drop is slightly changed during a current changing, so it may be considered as a constant value.

From the obtained results using the small wire diameters and the short electrode extensions, it appears the CM is degraded when welding current is increased, but after some current value, the CM is increased again. Pokhodnya (Ref. 20) showed the change of droplet enthalpy might cause this fact. Figure 4 shows the droplet enthalpy is increased from 1600 to 2150 J g$^{-1}$ when the welding current is increased. In addition, one can see from Fig. 4 that the curves of droplet enthalpy have the turning points. Pokhodnya (Ref. 20) attributed the decrease in droplet enthalpy with the heating of electrode extension due to Joule (or resistive) heating. One can see the maximum points of the enthalpy curves correspond to the minimum points of the CM curves, which are shown in Fig. 4.
the 2-mm-diameter electrode is abruptly increased from 1750 Jg⁻¹ at 100 A to 2050 Jg⁻¹ at 150 A. Moreover, this curve grows onward monotonically without any turning point. In this case, the absence of a turning point agrees well with our experimental data presented in Fig. 3.

The effect of the reduced CM when welding current is increased is only noticeable when the small welding current (with suitable arc voltage) and the small electrode extension are used, namely, up to 18-mm extension for 1.2- and 2.0-mm-diameter wires, and up to 15-mm extension for the 1.6-mm-diameter wire. Only in these cases is the amount of Joule heat reduced and its contribution to the heating of the electrode small, so the effect of reducing the amount of heat transferred from the anode region into an electrode extension is manifested.

The nonlinear dependence of the CM on welding current was also mentioned by Pokhodnya (Ref. 20), who investigated carbon dioxide welding, and by Sannikov and colleagues (Ref. 11), who studied submerged arc welding. Figure 5 shows the curves of dependence of the CM upon the density of welding current, which have been obtained by processing Pokhodnya’s experimental data (Ref. 20).

One can see the curve corresponding to the 2-mm-diameter wire has the minimum; however, the curve corresponding to the 1.2-mm-diameter wire has not. There is only the ascending branch for \( d_e = 1.2 \) mm, which corresponds to our data shown in Fig. 3. The observable explicit minimum of the curve for \( d_e = 2 \) mm is due to the use of the small 18-mm electrode extension. One can see the CM is decreased on account of the increase in droplet enthalpy and the negligible amount of Joule heat as the consequence of the small electrode extension, despite the growth of current density in the range 35 A mm⁻² to 80 A mm⁻². The ascending branch of this curve corresponds to our data shown in Fig. 3.

Figure 3 shows that, under the same conditions, the CM of larger diameter wires may be equal to or bigger than that of smaller diameter wires. An example of this can be seen in Fig. 6; at \( J = 120 \) A mm⁻², the CM of \( d_e = 1.6 \) mm is equal to the one of \( d_e = 1.2 \) mm provided the electrode extension is equal to 23 mm in both cases. The sharp increasing of CM for \( d_e = 2 \) mm starts at \( J = 160 \) A mm⁻² that corresponds to the turning point of droplet enthalpy for wire \( d_e = 1.6 \) mm.

Thus, theoretically and experimentally, the enthalpy of drops has a significant impact on the melting of an electrode wire.

### Elaboration of Mathematical Models

Two kinds of mathematical models for calculation of the CM were elaborated. The first model was established by using Equation 13. The equation used multiple regression analysis of experimental data obtained during welding in carbon dioxide (Ref. 20) to elaborate on the relation connecting the droplet enthalpy, \( H \), with the welding current density, \( J \), and \( d_e \). The relation has quadratic form

\[
H = a_0 + a_1 J + a_2 J^2 + a_3 d_e + a_4 d_e^2 + a_5 (14)
\]

where \( a_i \) are the coefficients determined during the experimental study. This equation has the Pearson coefficient \( R = 0.9 \) and explains the 95% variation of experimental data.

Figures 7 and 8 show the comparison of the data calculated by Equations 13 and 14 with the measured data (Ref. 20) to study the dependence of the CM upon the density of welding current. This work function \( \phi \) for steel Sv-08G2C is 4.25–4.3 V at 1100°C–1200°C (Ref. 23), but Lancaster (Ref. 15) has estimated the magnitude of the work function \( \phi \) from 3 to 3.5 V. So the effective cathode potential \( U^* \) calculated from Equation 2 is in the range 6.5–7.9 V. To calculate the electrical resistance of the electrode alloy using Equation 5, we must know the average temperature of electrode extension \( T_{\text{mid}} \). One may estimate \( T_{\text{mid}} = 750°C \) for \( d_e = 1.2 \) mm (Ref. 34) and \( T_{\text{mid}} = 400°C \) for \( d_e = 2 \) mm.

One can see from Figs. 7 and 8, the proposed equations allow for calculation of the CM with acceptable errors. In consideration of enthalphy as the function of welding current density, we have calculated the CM with sufficient accuracy: the absolute error does not exceed 3 A⁻¹ h⁻¹, and the relative error is not bigger than 10% (case \( U^* = 6.5 \) V).

### The Variance of the CM Calculation and Using the Equation in Another Area of GMAW

It is known (Ref. 35) that neglecting correlations or assuming independent variables of the function \( f(x, y, z, \ldots) \) yields a common formula to calculate error propagation, the variance formula

\[
s^2(f) = \left( \frac{\partial f}{\partial x} s_1(x) \right)^2 + \left( \frac{\partial f}{\partial y} s_2(x) \right)^2 + \left( \frac{\partial f}{\partial z} s_3(x) \right)^2 \ldots (15)
\]

where \( s(f) \) represents the standard deviation of the function \( f \), \( s(x) \) represents the standard deviation of \( x \), \( s(y) \) represents the standard deviation of \( y \), and so forth.

In our case, given the accepted variances of welding parameters, the calculated values of the variance \( s^2(\alpha_m) \) were defined using

\[
s^2(\alpha_m) = \left( \frac{\partial \alpha_m}{\partial T} s(T) \right)^2 + \left( \frac{\partial \alpha_m}{\partial \text{cont}} s(\text{cont}) \right)^2 \ldots (16)
\]

Taking into account the welding process settings are subject to random perturbations, random error calculation of the CM has been determined by means of mathematical statistics. We assumed the variance calculation result CM from Equations 12 and 13 is a function of process settings such as welding current, the voltage drop \( U_{\text{cont}} \) at the contact tube-wire, electrode extension, temperature of electrode extension, and their variances (Ref. 35).

The “three sigma rule” (Ref. 38) was used to estimate the standard de-
viation (SD) of each parameter mode. Direct welding current during CO₂ welding is changed periodically due to melted droplet transfer. However, generally one can consider that mean or MSR welding current is changed slightly (Ref. 37) during the stable process. In accordance with Adolfsen’s data (Ref. 37), the welding current maximum deviation from the average is in the range from 10 to 15 A. So we have defined SD = 15/3 = 5 A and then the variance of the welding current s²(I) will be equal to 25 A². If the maximum deviation of welding current is 10 A, then the s²(I) is equal to 11 A². We have assumed the maximum deviation from the average electrode extension is 0.3 cm, then SD = 0.3/3 = 0.1 and variance s²(L) = 10⁻² cm. Assuming that the temperature of electrode extension has the maximum deviation from the average 30 K, we have SD = 30/3 = 10 K. Then the variance s²(T) will be equal to 100 K².

The calculations using Equation 15 show (Fig. 9) the change of welding current from 100 to 300 A for 1.2-mm-diameter welding wire leads to an increased variance of the CM from 0.1 to 0.2 until 0.9 to 1.7 g²/A²h⁻². Moreover, for the welding current in the range from 100 to 270 A, the variance of the CM is almost constant and does not exceed 0.2 g²/A²h⁻². The sharp increase in the variance of the estimated value of the CM occurs at currents over 300 A.

As shown in Fig. 10, the variance of electrode extension has a small effect on the variance of the CM, when the changing of electrode extension is in the range from 10 to 20 mm. It also shows that, when using low currents (150 A), the variance of CM even decreases with increasing electrode extension.

To determine the confidence intervals of calculated value of the CM, the next expression was used (Ref. 38)

\[ \delta \alpha_m = \left( \alpha_m - \tau_p \sqrt{2(\sigma \alpha_m)}\right) \sqrt{t^2 \sigma \alpha_m + t^3 \sqrt{2(\sigma \alpha_m)}} \]

where \(t_p = 3\), \(t_\beta = 1.96\) when probability equals 99.73 and 95%, respectively.

As shown in Fig. 11, when the variance of all above welding parameters is taken into account, the variance of the CM tends to a deviation from the design value of CM from 0.5 g/(A·h) at low currents up to 2 g/(A·h) at 330 A. Thus, in the worst case, the relative error of calculation is not more than 8%. This result can be considered quite acceptable for practical calculations.

In addition, Equations 12 and 13 can be used to calculate the CM in GMAW when other shielding gases and wires of other chemical compositions are used. Following are two examples of the application of Equations 12 and 13.

As the first example of the use, we have calculated values of the CM using experimental data obtained in Ref. 39 when 1.2-mm-aluminum wire containing 99.5% Al was used during welding in argon. Steady direct current electrode-positive (DCEP) welding was performed. Figure 12 shows the results of experimental data processing (Ref. 39) and the results of calculation using Equation 13. Conditions and results of the calculation of the CM are shown in Table 2.

Due to a lack of data for pure aluminum wire, the enthalpy of aluminum drops was accepted according to Ref. 21 despite using in this work the 4043 wire with a diameter of 1.6 mm. In addition, we have accepted the droplet enthalpy of Sv-AMg6 wire as 0.93 and 0.07, respectively, electron thermal energy at arc temperature 10⁴K (Ref. 41) is about 1 V, as well as the lower estimation of anode drop voltage \(U_\text{d}\) = 1.5 V (Ref. 18), we have calculated \(U^\ast = 6.52\) V for the wire Sv-AMg6. Because of the lack of data about the value of voltage drop in contact tube-wire one accepted \(U^\ast_\text{m} = 0\). Figure 12 shows that the calculated values of the CM are in good agreement with the experimental data in a spray area. At the same time, the calculated values described changes of the CM qualitatively well in all areas of transfer.

Some deviations of the calculated values from the experimental data, especially for \(d = 1.2\) mm, have occurred probably due to the mismatch between the areas of droplets’ transfer modes and therefore between the values of droplet enthalpy of the wires studied and adopted for the calculation by reason of their different chemical composition. In addition, the great difference between the work function of silicon (4.6 eV) and magnesium (3.6 eV) can have a significant impact on the work function of the wires applied respectively in Ref. 43 and in our study. Thus, it was shown in two examples that in spite of the lack of accurate data on the enthalpy of droplets and electrode extension temperature of studied welding wires, the equations derived in this study allow us to qualitatively and correctly describe the change in the coefficient of the melting as a function of welding current.

In connection with the previously mentioned difficulties of calculating the CM, following the more simple equations are offered for industrial applications.
Experimental Formulas

The enthalpy of electrode drop is not known for many cases of arc welding; therefore, one needs to develop a regression equation to calculate the CM. The second model was elaborated using simplification of Equation 13 to

\[ q = U I_{\text{w}} + \rho \frac{I_{\text{w}}^2 L_{\text{e}}}{\pi R_{\text{e}}^2} \]

Many researchers proposed using regression theory for deriving an equation to calculate CM due to the uncertainty of \( U^* \) and \( \rho \). Thus, Suban and Tušek (Ref. 27) proposed the equation to calculate a melting rate \( \alpha \) with dimension \([g\cdot s^{-1}]\)

\[ \alpha = a I_{\text{w}} + b \frac{I_{\text{w}}^2 L_{\text{e}}}{\pi R_{\text{e}}^2} \]

where the coefficients \( a, b \) are determined during an experimental study.

As Korinets (Ref. 44) did in the last equation, one can derive the expression for calculation of the CM with dimension \([g\cdot A^{-1}\cdot h^{-1}]\)

\[ \alpha_m = a + b \frac{I_{\text{w}} L_{\text{e}}}{\pi R_{\text{e}}^2} \]

However, the error of this equation reaches 50% in CO\(_2\) welding (Ref. 44). Taking into account the nonlinearity of the relationship \( \alpha_m = J \), the last equation may be written in a nonlinear form as

\[ \alpha_m = a_1 J^{a_2} I_{\text{w}}^{a_3} \]  \hspace{1cm} (17)

where the coefficients \( a_1 = 0.675 \pm 0.214, a_2 = 0.431 \pm 0.052, \) and \( a_3 = 0.349 \pm 0.076 \) were determined by authors using experimental data of CO\(_2\) welding. The dimension of electrode extension is in mm, and the \( J \) is \( A/mm^2\).

In fact, the correlation coefficient was reported by the Pearson coefficient \( R = 0.86 \) and determination coefficient \( R^2 = 0.74 \).

Figure 14 presents examples of the comparison between data calculated by Equation 18 and measured data of the coefficient of melting for different electrode diameters.

In addition, we have derived a formula for calculating the wire feed speed \([\text{m/min}]\) using regression analysis of our experimental data

\[ V_{\text{w}} = (0.055 \pm 0.005) \frac{4}{\pi d_e^2} \frac{I_{\text{w}}^{1.365 \pm 0.05}}{L_{\text{e}}^{0.314 \pm 0.09}} \]  \hspace{1cm} (19)

where \( k = 6000 \) when the electrode size is set in centimeters. The dependence obtained was in good agreement with the data of many studies. Comparison of the calculated data to the known studies shows that the relative error does not exceed 5%.

Conclusions

1) It was shown that the coefficient of melting has nonlinear dependence upon density of welding current. The nonlinear dependence one can explain by the influence of changed enthalpy of electrode droplets, which in its turn is caused by the changing of welding current.

The existence of the minimum of the coefficient of melting is caused by the maximum of the enthalpy of electrode droplets.

2) The deterministic and stochastic expressions were elaborated to calculate a coefficient of solid wire melting during CO\(_2\) welding. The deterministic expression describes the heat processes developing in three major heat sources: an anode arc region, an electrode extension, and a contact tube-wire. The regression relationship was derived to describe the processes of heat absorption in an electrode extension. Simple stochastic expressions described an influence of welding current, an electrode diameter, and an electrode extension on the coefficient of melting.

3) During welding, the variance of such parameters as welding current, electrode extension, and its temperature leads to the variance of the coefficient of melting, which in its turn leads to a deviation from the design value of the coefficient of melting. Assuming that the variance of the welding current is equal to 25 \( A^2\), the variance of electrode extension is equal to 10\(^{-2}\) cm, and the variance temperature of electrode extension is equal to 100 \( K^2\), the calculations of the deviation from the design value of the CM have been made for welding wire \( d = 1.2 \) mm. It was shown that deviation of the CM changed from 0.5 g/(A-h) at low currents up to 2 g/(A-h) at 330 A. Thus, in the worst case, the relative error of calculation is not more than 8%. This result can be considered quite acceptable for practical calculations.

4) In spite of the lack of accurate data on the enthalpy of droplets and electrode extension temperature of studied welding wires, the equations derived in this study allow us to qualitatively and correctly describe the change in the coefficient of melting as a function of welding current.

5) The deterministic expression of the coefficient of melting, including the connection between the enthalpy of electrode droplets and welding parameters (electrode diameter and density of welding current), allows one to calculate it with the relative error, which is no bigger than 10%. The relative error of calculating the coefficient of melting by using the stochastic expression does not exceed 13%.
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References