Melting dynamics of electrodes, additive materials in welding

V L Fedyaev1,*; E R Galimov2; A V Belyaev2; and L V Sirotkina3

1IME – Subdivision of FIC KazanSC of RAS, Lobachevsky street, 2/31, 420111 Kazan, Russia
2Kazan National Research Technical University named after A.N. Tupolev – KAI, K. Marx, 10, 420111 Kazan, Russia
3Kazan State Energy University, Krasnoselskaya ul., 51, 420066 Kazan, Russia

*V.L.Fedyaev@yandex.ru

Abstract. We consider electric arc, electroslag welding with a consumable electrode, as well as other types of welding (gas, plasma, etc.) using rod filler materials. Two schemes of the corresponding type of welding are distinguished - the first, when an electrode has a finite length, the location of the current lead relative to it is stationary. In the second case, the electrode moves relative to the place of current supply in such a way that the length of the part of the electrode from its end to the place of current supply during welding varies little. A number of assumptions are made, a mathematical description of the heating and melting of the electrodes, filler materials due to the heat of the welding sources, and ohmic resistance is presented. Relations are given for estimating the temperature distribution along the length of an electrode, filler rods, and their melting rate.

1. Introduction

Various types of fusion welding are widely used at enterprises of almost all sectors of the economy [1, 2]. Of these, manual arc welding with a consumable electrode remains the most common, while semi-automatic and automatic welding, including in a protective gas, is increasingly used. At the same time, the problems of obtaining reliable defect-free welded joints, increasing welding productivity, as well as reducing the technological impact on the environment are still relevant. The solution to these problems is impossible without a detailed analysis of the features of the processes occurring during welding, including heating and melting of melting electrodes, filler materials [3 - 7].

2. Main part

Further focusing on electric arc welding methods (manual, semi-automatic, automatic welding), filler materials, such as an electrode, rod, plate, wire, will be called electrodes. Following [3, 4], we single out two schemes for applying them. The first is that in the process of manual arc welding as the end of the electrode melts, the electrode metal enters the weld pool, the distance from the end of it to the current supply device decreases. When implementing the second scheme, which is typical for semi-automatic, automatic arc welding, the electrode moves relative to the current supply point in such a way that, during normal operation, the electrode extension length remains practically unchanged.

The first scheme. In order to simplify the subsequent calculations, we reverse the motion, assuming that the electrode with the current-carrying device is at rest, and the heat source with power \( q \) acting on
the end face from the arc side moves with speed \( w \). In this case, the heat received through the end to the electrode during the time \( d\tau \) will be:

\[
dQ = q d\tau. \tag{1}
\]

This heat is consumed, first of all, for heating the electrode and melting its material near the end. The corresponding heat fractions are determined by the ratios:

\[
dQ_L = wpLSD\tau, \quad dQ_I = cpV \cdot dT. \tag{2}
\]

Here \( \rho, c, L \) is the average density, specific heat, latent specific heat of fusion of the electrode material; \( V = lS \) – electrode volume; \( S \) is the cross-sectional area of the electrode; \( l = l(\tau) = l_0 - w\tau \) – the current length of the electrode from its end to the point of current supply; \( l_0 \) – the initial length of the active part of the electrode; \( T = T(\tau) \) is the average temperature of the electrode of length \( l \).

However, it is known that

\[
w \approx \overline{q}/\rho(cT_v + L),
\]

where \( \overline{q} = q/S \) is the specific thermal power characterizing the heat input to the electrode through its end.

In addition, when an electric current flows in the electrode over time \( d\tau \), Joule heat is generated, defined by the ratio:

\[
dQ_e = (T^2/\sigma)Vd\tau. \tag{3}
\]

Here \( T = I/S \) is the electric current density, \( I \) is the current strength in the electrode, \( \sigma \) is the specific electrical conductivity of the electrode material.

During welding, the main heat loss is due to heat transfer on the surface of the active part of the electrode with the environment due to convection and radiation. On average, these losses over time \( d\tau \) are estimated as:

\[
dQ_n = \alpha(\overline{T} - T_v)S_n d\tau, \tag{4}
\]

Where \( \alpha = \alpha_k + \alpha_r \); \( \alpha_k \), \( \alpha_r \) are the coefficients characterizing the components of these losses, \( S_n = S_k(\tau) = l(\tau) \cdot P \) is the area of the lateral surface of the active part of the electrode, \( P \) is the perimeter of the cross section of the electrode, \( T_v \) is the average temperature of the surrounding air.

Having the expressions (1) - (4), substituting them in the equation of the thermal balance of the electrode, making certain transformations, to find the dependence \( T = T(\tau) \) we get the ratio:

\[
d\overline{T} = \alpha_e d\tau/(l_0 - w\tau) + (\beta_e - \gamma_e(\tau))d\tau. \tag{5}
\]

Here are the coefficients \( \alpha_e = (q - wpLS)/\kappa \), \( \beta_e = \overline{T}^2S/(\sigma\kappa) \), function \( \gamma_e(\tau) = \alpha P(\overline{T}(\tau) - T_v)/\kappa \), \( \kappa = cpS \).

At first, for the sake of simplicity, we assume that the heat exchange of the active part of the electrode with the environment is small, \( \gamma_e \approx 0 \), and the parameters \( c, \rho, \sigma, w \) are equal to the average value during the arc burning. As a result of integration of equation (5) simplified in this way, we find:

\[
T = T_v(\tau) = T_0 - \frac{\alpha_e}{w} \ln \left(1 - \frac{w\tau}{l_0}\right) + \beta_e \tau \approx T_v + \beta_e \tau. \tag{6}
\]
Where \( \beta_\alpha = \beta_\varepsilon + \alpha_\varepsilon / l_0, \, w\tau / l_0 << 1 \).

In order to further refine this solution, we substitute its formula for \( \gamma_\varepsilon (\tau) \) and additionally assume that the coefficients \( \alpha_\varepsilon, \, \alpha_\varepsilon \) are close to the average values, as a result of (6) we obtain:

\[
\overline{T} = \overline{T}(\tau) = -\frac{\alpha_\varepsilon}{w} \ln \left( 1 - \frac{w\tau}{l_0} \right) + \beta_\varepsilon \tau + \delta_\varepsilon (\tau) \approx T_0 + \beta_\varepsilon \tau - \delta_\varepsilon (\tau). \tag{7}
\]

Here is the correction term

\[
\delta_\varepsilon (\tau) = \alpha P \tau (T_0 - T_c + 0,5\beta_\varepsilon \tau) / \kappa. \tag{8}
\]

In the case when the electrode is not preheated, \( T_0 \approx T_c \), the relation (8) is simplified,

\[
\overline{T} = \overline{T}(\tau) \approx T_0 + \beta_\varepsilon g_\varepsilon \tau, \tag{9}
\]

where \( g_\varepsilon = g_\varepsilon (\tau) = 1 - \alpha_\varepsilon P \tau / 2\kappa \).

Expression (9) makes it easy to estimate the time of thermal saturation \( \overline{T} \) of the material of the active part of the electrode, starting from which the average temperature changes little over time: \( \tau_s = \kappa / (\alpha P) \).

In this case, the length of the remaining part of the electrode will be: \( l_s = l_0 - w\tau_s \).

Since the temperature field stabilizes during this period, we assume that along the length \( l \) of the remaining part of the electrode, the temperature varies linearly:

\[
T = T(l) = T_n - (T_n - T_s)l / l_n.
\]

From here, the temperature of the electrode in the current supply section \( T_i \) will be:

\[
T_i = T_i (\tau) = 2\overline{T}(\tau) - T_s (\tau > \tau_s).
\]

Here, the average temperature of the electrode \( \overline{T} \) is determined by the formula (9).

**The second scheme.** As the electrode melts due to its movement relative to the current-conducting device, the length of the active part remains constant, equal to \( l_0 \). In accordance with the equation of its heat balance, we have:

\[
d\overline{T} = \beta_\varepsilon d\tau - \gamma_\varepsilon (\tau) d\tau. \tag{10}
\]

As in the case of the previous scheme, we first set \( \gamma_\varepsilon (\tau) = 0 \), then we determine the solution of equation (10) in a first approximation:

\[
\overline{T} = \overline{T}(\tau) = T_0 + \beta_\varepsilon \tau. \tag{11}
\]

Substituting (11) into \( \gamma_\varepsilon (\tau) \), integrating the resulting equation, we find:

\[
\overline{T} = \overline{T}(\tau) = T_0 + \beta_\varepsilon - \delta_\varepsilon (\tau). \tag{12}
\]

It should be noted that solutions (11), (12) coincide in form with approximate relations (6), (7) obtained from exact relations for small values of the parameter \( w\tau / l_0 \).

The temperature field in the active part of the electrode (wire) of length \( l_0 \) of circular cross section with area \( S \) moving relative to the current supply with a speed \( w \) is estimated by reversing the movement. In this case, we assume that a flat heat source with intensity \( \overline{q} \) and the place of current supply move relative to the wire with speed \( w \). In order to take into account the latent heat of fusion of the material
of the wire at its end, we replace $\vec{q}$ it with $\vec{q} = (q - wpLS)/S = \vec{q} - wpL$. In addition, we take into account the Joule heat, which increases the average temperature of the wire by

$$\bar{T}_d = l_o T^2/(w c p \sigma).$$

Hence, when the active section of the wire is quasi-stationary heated in the moving coordinate system $Oz$, the origin of which is located at the location of the welding heat source, and is directed towards the current-carrying device on the $z$ axis, we obtain the temperature distribution in the wire [3-5]:

$$T = T_h + \bar{T}_d + \frac{2q_L}{c p \sqrt{w^2 + 4ab}} \exp\left[-\frac{wz}{2a\left(1 + \sqrt{1 + \frac{4ab}{w^2}}\right)}\right] \left(0 < z \leq l_o\right),$$

where $a = \lambda/(c p)$ is the thermal conductivity coefficient of the wire material, is the thermal conductivity coefficient, $b = \alpha P/(c p S)$ is the parameter characterizing the convective and radiant heat transfer on the surface of the active part of the wire with the environment, $P$ is the perimeter of the wire cross section.

In special cases, when the heat transfer intensity on the surface of the wire is small $(b \approx 0)$, the values are also small $wz/a$, the temperature of the wire is estimated, respectively, using the expressions:

$$T \approx T_h + \bar{T}_d + \frac{2q_L}{c p w} \exp\left(-\frac{wz}{a}\right),$$

$$T \approx T_h + \bar{T}_d + \frac{2q_L}{c p w} \left(1 - \frac{wz}{a}\right) \left(0 < z \leq l_o\right).$$

From (14) it is seen that the temperature dependence $T = T(z)$ is close to linear.

The above solutions are applicable for estimating the temperature of uncovered melting electrodes, rods, etc. In practice, coated electrodes and powder welding materials are increasingly being used. In order to take into account the peculiarities of the composition and arrangement of these materials in the obtained ratios, it is necessary to replace the parameters $c$, $\rho$, $T_m$, $\sigma$, $I$ with effective ones: specific heat capacity $c_n$, density $\rho_n$, melting temperature $T_m$, specific latent heat of fusion $L_n$, conductivity $\sigma_n$, current $I_n$, using, in particular, formulas of the form:

$$p_{ef} = \epsilon_n p_n + (1 - \epsilon_n) p,$$

where $\epsilon_n = S_n/(S + S_n)$ is the volume fraction of the coating material in the electrode; $S_n$, $S$ is the area of the layer of the cross section of the coating, the metal of the electrode; $p_n$, $p$ are the indicated thermophysical and electrodynamic parameters of the coating, the metal of the electrode.

3. Conclusions

The regularities of the occurrence of thermal processes in the electrodes and filler materials are established, when during welding the place of the current lead relative to them either does not move or moves at the speed of the welding heat source. The obtained solutions allow us to evaluate the dynamics of these processes, to predict the welding performance, the chemical composition of the weld material, including taking into account the properties of the coating material.

References

[1] Chernyshov G G 2003 Welding: Welding and cutting of metals (Moscow: Publishing Center "Academy") 496 p
[2] Aleshin N P, Chernyshov G G, Gladkov E A et. al. 2004 *Welding. Cutting. Control* (Moscow: Mashinostroenie) 480 p
[3] Frolov V V 1988 *Theory of welding processes* (Moscow: Higher School) 559 p
[4] Bagryansky K V, Dobrotina Z A, Khrenov K K 1976 *Theory of welding processes* (Moscow: Visha School) 424 p
[5] Fedosov S A, Oskin I E 2014 *Basics of welding technology* (Moscow: Mechanical Engineering) 125 p
[6] Kulikov V P 2016 *Technology of fusion welding and thermal cutting* (Moscow: INFRA-M) 463 p
[7] Zorin N E 2017 *Material science welding. Fusion welding* (Moscow: Lan) 164 p