SURFACE SHAPE OF PHASE TRANSITION ON THE MOLTEN ELECTRODE END FACE FOR ARC WELDING IN A PROTECTIVE ATMOSPHERE

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The article examines the conjugate problem of the thermal state of the molten end face of a consumable electrode. The shapes are determined of the electrode front and of the free molten surface moving over it in the form of a film which later changes into a free jet.

The improvement of progressive methods of automatic welding in a protective atmosphere is closely associated with the analysis of the processes of heat and mass transfer — in our case of the molten electrode metal. It is known [1] that the most preferable transfer is the so-called jet transfer of liquid metal from the electrode to the welding seam, where the liquid film moving over the molten end face is the source of a free jet forming in the direction of the electrode axis. Jets form, and not drops, because the total effect of the electromagnetic volume forces in the film directed toward the axis and of the surface forces induced by the magnetic pressure in the weakly contracted arc is substantially larger than the forces of surface tension [2].

The conditions of the gas—liquid interface are also determined by the configuration of the molten surface over which the liquid film moves. In its turn, its thickness and the speed of motion determine the thermal resistance when the heat from the plasma is introduced and the overall power of the thermal sources distributed in the liquid phase of the electrode metal.

Thus, to find the speed and dimensions of the jet in dependence on the regime parameters of welding, the physical properties of the melt, and the protective atmosphere, we must solve the conjugate problem of magnetohydrodynamic heat and mass transfer of the melt along the molten surface and determine this surface, i.e., the mobile boundary of phase transition in the nonlinear problem of heat conductivity.

Statement of the Problem and Assumptions. In a semibounded metal cylinder of radius r_e with the physical properties of the substance c_T, ρ_T, λ_T, γ_T, the melt surface S_f spreads at the rate w_f. The surface S_q, orthogonal to the axis of the cross section, situated at the distance b from the apex of the surface S_f and bounding the region of the effect of the volume thermal sources whose density is constant in the bulk and is equal to j^2/γ_T, moves at the same speed. The melting point is T_f. The molten electrode front receives through the liquid film of the melt with the physical properties c_m, ρ_m, λ_m, γ_m, σ the thermal flux $q_s(\xi, \zeta)$ (Fig. 1). In the liquid film there exist heat sources because through it, like through the solid phase, an electric current flows. The free surface of the film has the temperature T_{vm}. We have to determine the molten surface S_f, the free surface of the liquid film S_v, and the cross section and speed of the jet forming at the apex of the melt surface.

We make the following assumptions: The temperature field as well as the distribution of the thermal fluxes and the current density in the plasma, and of the flow in the film, are axisymmetric; the physical properties of the solid and liquid phases do not depend on the temperature (only for the problem of the magnetohydrodynamic motion of the film); the magnetic field within the limits of the column of the arc and in the melt is formed only by the axial current component $j = j_z$; in the arc and in the melt there are no displacement currents, i.e., $\partial E/\partial\tau = 0$; instabilities in the plasma and in the film, induced by Θ-pinch, are out of the question; heat transfer from the plasma through the liquid film is effected solely by heat conduction on account of its small thickness.

Magnetohydrodynamic Motion in the Film. Mass flow of the melt through the live section of the film, orthogonal to the melt surface, is equal to

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$$G = 2\pi\rho_m \bar{w}\delta,$$

and its increase on an elementary area is

$$dG = 2\pi\rho_m r_1 d(\bar{w}\delta). \quad (1)$$

The increase in flow (1) is due to the heat introduced into the elementary volume $2\pi r_1 dr_1 \delta$ by liberation of heat and thermal conduction through the liquid film

$$dG = \frac{2\pi r_1 dr_1}{L_f}\left[\frac{\lambda_m(T_{1m} - T_f)}{\delta} + \frac{j^2\delta}{\gamma_m}\right]. \quad (2)$$

The mean speed in (1)

$$\bar{w} = \frac{1}{\delta}\int_0^\delta w d\zeta$$

can be found from the equation of laminar motion of the film

$$\eta\frac{d^2w}{d\zeta^2} = gz(\rho_m - \rho_g) - \text{grad}(p_a - p_v) + \mu_0(\mathbf{j}\times\mathbf{H}) + \sigma\,\text{grad}\left(\frac{1}{R_1} + \frac{1}{R_2}\right), \quad (3)$$

which was constructed with the assumption, usual in the examined situation, that the displacing forces of gravity, electromagnetic forces, forces of the magnetic pressure of the arc, and capillary forces are compensated only by viscous forces. When the thickness of the film δ is substantially smaller than the electrode radius r_e, the electromagnetic forces may be considered not to be dependent on δ, and the forces p_a, p_v, and $\sigma\text{grad}(R_1^{-1} + R_2^{-1})$ to be constant within the limits of each live section of the flux.

We integrate Eq. (3) with the following boundary conditions: $\zeta = 0$; $w = 0$; $\zeta = \delta$; $dw/d\zeta = 0$ (there is no viscous friction on the plasma–liquid interface). Then

$$w = \frac{1}{\eta_m}\left(\frac{\zeta^2 F}{2} + C_1\zeta + C_2\right),$$

where F is the right-hand side of Eq. (3). The integration constants C_1 and C_2 are determined for $\zeta = 0$, $w = 0$, $C_2 = 0$, and $\zeta = \delta$; $dw/d\varphi = 0$; $C_1 = -\delta F$. The curve of the speed of the melt in the film is described by the equation

$$w = \frac{F}{\eta}\left(\frac{\zeta^2}{2} - \delta\zeta\right),$$

and the mean speed by

$$\bar{w} = \frac{1}{\delta}\int_0^\delta w d\zeta = \frac{\delta^2 F}{3\eta}. \quad (4)$$

Substituting (4) into (2) yields the final form of the equation of the free film surface with the specified melt surface

$$\frac{\rho_m L_f d\delta}{\eta\left[\frac{\lambda_m}{\delta^3}(T_m - T_f) + \frac{j^2}{\gamma_m}\right]} = \frac{dr_1}{F}. \quad (5)$$

If we introduce the following notation:

$$A = \frac{\lambda_m(T_{1m} - T_f)\gamma_m}{j^2 r_e^2}, \quad B = \frac{L_f r_1^2 \rho_m \gamma_m}{\eta j^2}, \quad \bar{\delta} = \frac{\delta}{r_e}$$

and integrate (5), we obtain

$$B\int_0^{\bar{\delta}} \frac{\bar{\delta}^3 d\bar{\delta}}{A + \bar{\delta}^2} = \frac{B}{2}\left(\bar{\delta}^2 - A\ln\frac{A}{A + \bar{\delta}^2}\right) = \int_{r_e}^{r_1} F^{-1} dr_1. \quad (6)$$

We now turn to the right-hand part of Eq. (6).

We determine the electromagnetic forces in the film by assuming that the current density in the molten part of the electrode is constant. Such an assumption was found to be justified on the strength of calculations of the electric field in the electrode carried out on models of electrically conducting paper and networks of ohmic resistors. Here it should be noted that in the breaks of the threads at the boundaries of phase transitions, radial current components appeared which did not exceed 3-5% of the axial components. This means that the electromagnetic forces in the liquid metal are induced practically only by the components of the currents j_z.

The radial component of these forces is

$$f_m = \frac{\mu_0 I^2 k_m^2}{2\pi^2 r_1^3}, \tag{7}$$

where k_m is the proportion of the full current flowing through the liquid film. The value k_m can be determined in accordance with [3].

The gradient of the magnetic pressure of the arc [2] is equal to

$$\operatorname{grad} p_a = 0.384 \frac{\mu_0 I^2 \ln(1.3 s^2 r_1^2 + 1)}{\pi^2 r_e (1.3 s^2 r_1^2 + 1)} \left(\frac{r_e}{r_1}\right). \tag{8}$$

The gradient of the pressure on the free surface appearing as a result of the outflow of the metal vapors is equal to [3]

$$\operatorname{grad} p_v = \frac{2\Delta U^2 k_v^2 I^2 s^5}{\pi^2 L_f \rho_v} \exp(-2s^2 r_1^2). \tag{9}$$

Here k_v^2 is the proportion of energy introduced in welding that is expended on evaporation ($k_v^2 = 0.15-0.2$).

The gradient of the pressure caused by the effect of surface tension [3] is equal to

$$\operatorname{grad} p_\sigma = \frac{d}{dr_1}\left\{\sin(\operatorname{arctg} z')\frac{1}{r_1} + z''[1 + (z')^2]^{1.5}\right\}, \tag{10}$$

where $z = [(r_e - r_1/\sin\varphi) + \delta]\cos\varphi$ is the axial coordinate of the free surface; $\tan\varphi$ is the slope relative to the electrode axis tangential to the melt surface ($\tan\varphi = z' = dz/dr$).

The free surface of the liquid film, flowing down under the effect of the forces of gravity and the forces (7)-(10), is determined by the equation

$$\frac{B}{2}\left(\bar{\delta}^2 - \ln\frac{A}{A+\delta^2}\right) = \int_{r_e}^{r}\left\{\frac{\mu_0 I^2 (r_1^2 - r_f^2)}{2\pi^2 r_1^3} + 0.384\frac{\mu_0 I^2 s^2}{\pi^2 r_1}\right.$$

$$\left.\times \frac{\ln(1.3 s^2 r_1^2 + 1)}{1.3 s^2 r_1^2 + 1} + \frac{2\Delta U^2 k_v^2 I^2 s^5}{\pi^2 L_f^2 \rho_v}\exp(-2s^2 r_1^2) + \sin(\operatorname{arctg} z')\frac{1}{r_1} + z''[1 + (z')^2]^{1.5}\right\}^{-1} dr_1. \tag{11}$$

There is no difficulty in solving this equation with a computer; the solution is accompanied by an iteration process in which the free surface of some suitable continuous function is stipulated for calculating grad p_T, e.g.,

$$z = \cos\varphi\left[\frac{r_0 - r_1}{\sin\varphi} + \delta_0 r_1\left(\frac{r_e - r_1}{r_e \sin\varphi}\right)^2\right]. \tag{12}$$

Then the left-hand and right-hand parts of Eq. (11) are successively calculated. The convergence parameter are the values $\delta = \delta/r_0$ at the reference points of the specified surface of the melt.

The Temperature Field in the Solid and Liquid Phases. The process of heating the electrode with a movable molten end face is described in the general case by a nonlinear equation with a system of boundary conditions [5, 6]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left[\lambda(T) r\frac{\partial T}{\partial r}\right] + \frac{\partial}{\partial z}\left[\lambda(T)\frac{\partial T}{\partial z}\right] - c_{m,T}(T)\frac{\partial T}{\partial \tau}\rho_{m,T}(T) + \frac{j^2}{\gamma_{m,T}} = 0;$$

$$q_s + \frac{j^2 b}{\gamma_\tau} + \lambda(T)\frac{\partial T}{\partial n} = \rho_\tau(T) L_f \frac{\partial z}{\partial \tau};$$

$\tau \geqslant 0$; $r = r_1$; $\varkappa = \varkappa_1$ (surface of the liquid film); $q(\varkappa_1, r_1) = \alpha_1(T_g - T_{1,m}) + \varepsilon_1\varepsilon_2(T_g^4 - T_{1,m}^4)$; $\tau \geqslant 0$, $r = r_e$ (lateral surface of the electrode); $-\lambda_T(T)\ \partial T/\partial r = \alpha_2(T_2 - T_{wa})$ upon blowing protective gas around the part of the electrode protruding from the contact conductor; $\varkappa = 10r_e$, $0 \geqslant r \geqslant r_e$, $\tau \geqslant 0$; $T = T_0$ is the "cold" part of the electrode, sufficiently far from the zone of the contact conductor.

Here α_1 and α_2 are the heat-transfer coefficients from the plasma to the surface of the film and from the protective gas to the lateral surface of the electrode, respectively; T_2 and T_{wa} are the temperatures of the protective gas and of the lateral wall of the electrode, respectively; $\varkappa$ is the coordinate read off on the axis of the electrode from the pole point of the melting surface.

The melting front S_f moves at the speed $d_z/d\tau$, which is determined by the caloric power supplied to the end face and liberated at the segment of "escape" of the electrode wire, whose length is b.

The plasma temperature T_g on the surface of the liquid film is calculated in accordance with the recommendations of [4]:

$$T_g = T_{o,g} \exp(-s^2 r^2),$$

where $T_{o,g}$ is the plasma temperature on the axis of the arc.

Since for arc welding in a weakly contracting arc, the temperature of the gases surrounding the electrode is one order of magnitude higher than the temperature of the liquid metal, it is possible, without detriment to the accuracy of the calculation, to stipulate $T_{1,m}$ linearly changing from T_{wa} to the boiling point.

The distribution of $T_{1,m}$ is usually refined in the iteration process. On the segment of the contact conductor to the electrode, with $\varkappa = b$, the boundary conditions of the third kind are specified, taking into account of the thermal resistance of the contact between the surface of the contact conductor and the electrode.

The method of solving (13) with the aid of networks of ohmic resistors is explained in detail in [6]. The equations are linearized by an explicit procedure, and Liebmann's method was used to solve (13) by RR-networks (integrator BUSÉ-70).

When the problem is solved in the two-dimensional statement, the network of variable ohmic resistors consists of two parts: the sections of the solid and of the liquid phases. The elementary resistances were calculated in accordance with [7]. Near the line of phase transition $0.2r_e \geqslant \varkappa \geqslant 0.2r_e$, the pitch of the network is five times smaller than the pitch for the section $0 \leqslant \varkappa \leqslant b$, and with $b \leqslant \varkappa \leqslant 2b$, the axial sections of the meshes are 5 times longer than in the preceding region. To each nodal point of the network, two parallel branches with resistors were connected: One corresponded to the density of the distributed heat sources (it is constant in the volume of the section $0 \leqslant \varkappa \leqslant b$), whereas the resistance in the second branch corresponded to the time function of the temperature. At the boundary of the phase transition, the linear sink flow of heat through the resistors was specified, proportional to $(L_f/\lambda_T)(T_f - T_1)$.

The calculation procedure is carried out in the following sequence.

1. An arbitrary melt surface is specified (sphere, paraboloid), but close to the expected shape. 2. By solving Eq. (11), the mean speed $\bar{w}$ and the thickness of the film δ are found. 3. By calculating the resistance of the network, the boundary conditions, and the density of heat liberation, the electrical model of the object is assembled. 4. The temperature field is measured. The position of the melting surface is determined in coordinates for which $T = T_f$. 5. On the normal to it, the thickness of the liquid film δ is marked off, and thereby the free surface of the film is found. 6. The resistances of the network are corrected and transferred to the new position of the melting front of the circuit of linear sink flow of the heat. The conditions of ending the iteration process are $\Delta\varkappa/\delta(r=0.5\,r_e) \leqslant 0.5$. With this, the calculations for the first time step are finished.

During the subsequent time steps, the melting front remains immobile relative to the network, and a number of nodal points move toward it. The additional resistances, taking the change of temperature with time into account, are calculated with a view to the change in the number of nodes. Thus, the temperatures of each nodal point of the electrode in the system of coordinates that are immobile relative to its solid part change with time.

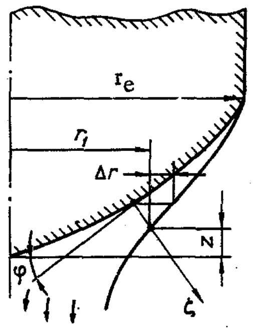

Fig. 1

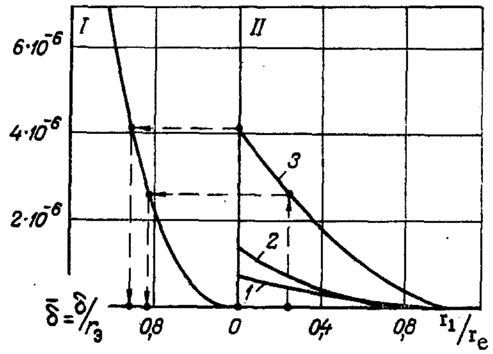

Fig. 2

Fig. 1. Diagram of jet formation at the molten electrode end face by a weakly contracting electric arc.

Fig. 2. Example of the graphic solution of (11).

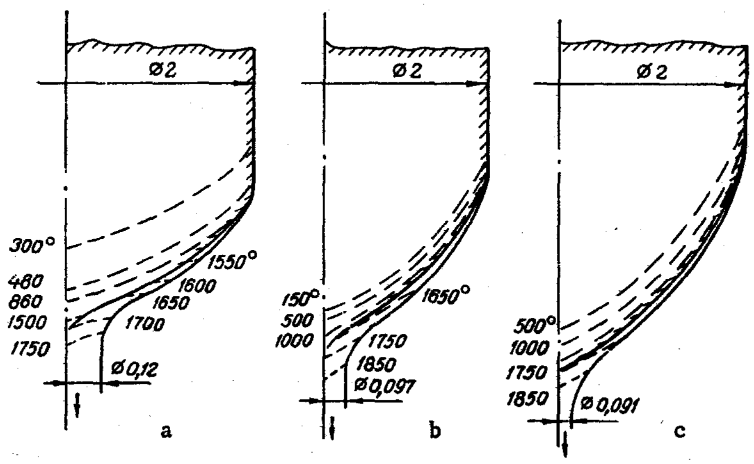

Fig. 3. Shape of the free surface of the melting-front film and the temperature field in the liquid and solid parts of the electrode: a) I = 300 A, $s^2 = 0.16 \cdot 10^{-6}$ m^{-2}; b) 350, $0.16 \cdot 10^{-6}$, respectively; c) 350, $0.13 \cdot 10^{-6}$.

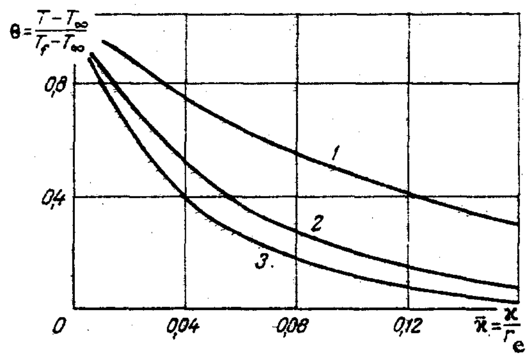

Fig. 4. Dimensionless temperature in the solid part on the axis of the molten electrode. 1) I = 200 A; 2) 300; 3) 350.

Now, if we keep track of the temperature of the points moving over the electrode in the system of coordinates $\varkappa$, r together with the melting front, we find that it does not change with time.

Results and Discussion. Figure 2 shows the graphic solution of Eq. (11) for $\rho_m = 7.2 \cdot 10^3$ kg/m^3, $\sigma = 600$ dyne/cm, I = 300, 350, and 450 A (curves 1, 2, and 3, respectively), ΔU = 36 V, $s^2 = 0.16 \cdot 10^6$ m^{-2}, L_f = 0.3142 J/kg, $r_e = 10^{-3}$ m, $\gamma_m = 0.6 \cdot 10^{-6}$ $\Omega \cdot$m. In part I of Fig. 2, the values of the left-hand part of Eq. (11) are marked, whereas in part II the values $r \int_1^{r_1/r_e} F^{-1} d\left(\frac{r}{r_e}\right)$ for the specified surface of phase transition are given. The dashed lines indicate the procedure of determining the thickness of the film δ corresponding to the radius r_1/r_e of the melting surface.

Figure 3a, b shows the shapes of the surface of the film and of the melting front for different current intensities I in the system of coordinates $\varkappa$, r; the "mobile" isotherms in the liquid and solid parts of the electrode are represented.

The results of the calculation show that in weakly contracting arcs, surrounding the end face of the electrode as well as its lateral surface, favorable conditions are created for organizing jet transfer of the electrode metal to the welded part. Whereas previously this kind of transfer was explained [1-3] only by the effect of magnetic pressure in the arc surrounding the electrode and in the melt, it is, as the data of Fig. 3 show, also determined by the density distribution of the thermal fluxes entering the molten end face. In contracting arcs, the thermal fluxes, with increasing coefficient s^2, are concentrated at the axis of the electrode, and the melting front therefore becomes blunted — the intensity of the axial component of the electromagnetic forces in the melt and of the forces induced by the magnetic pressure of the arc decreases against the background of the forces of surface tension (see Fig. 3b).

When $\sigma(R_1^{-1} + R_2^{-1}) > 0.5\rho_m\overline{w}$ ($\varkappa = 0$), drops of the melt may form on the melting surface [3]; in that case, the transfer of metal to the welding seam is called drop transfer. In weakly contracting arcs, with $s^2 = 0.13 \cdot 10^{-6}$ m^{-2}, the heat fluxes are sufficiently large on the lateral surface of the electrode. Then the melting front becomes sharp (see Fig. 3c) — the axial component of the electromagnetic forces and of the forces of arc pressure increases: the liquid metal is "pushed away" from the metal surface. The level of these forces exceeds the surface tension, and a jet forms at the apex of the melt surface. With current increasing to 350 A, the thickness of the film decreases at the peripheral sections and increases on the axial sections. This causes more intensive heat supply to the peripheral sections, and therefore the melt front becomes sharp. The jet diameter decreases with increasing current intensity. Thereby the speed of displacement of the melting front increases, as follows from (19). This speed increases even when the coefficient of contraction decreases, because of the extension of the surface of intake of the thermal flux in the sharpened molten end face.

The temperature fields are a notable feature of the electrode in the sliding system of coordinates $\varkappa$, r. They are characterized by large temperature gradients: up to 12,000 deg/mm. It follows from Fig. 4 that the level of the gradients increases with increasing arc current and electrode feed equal to the melting rate.

NOTATION

r, radius; T, temperature; c, heat capacity; ρ, density; λ, thermal conductivity; γ, electrical conductivity σ, surface tension; η, dynamic viscosity; q, thermal flux; j, current density; H, magnetic field strength; μ_0, magnetic permeability; w, speed; δ, thickness of the liquid film ξ, ζ, curvilinear coordinates; p, pressure; R_1, R_2, principal radii of curvature; φ, angular coordinate; s, coefficient of arc contraction [4]; ΔU, electrode voltage drop. Subscripts: o, axis of the arc electrode; a, arc; v, vapors on the saturation line; m, liquid phase; g, gas; e, electrode; f, melting surface; 1, surface of the film.

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