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Heat transfer in a liquid droplet hanging at the tip of an electrode during arc welding

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Abstract. The motion of melted metal in a droplet hanging at the tip of an arc electrode during arc welding is considered. The motion is induced by a surface tension gradient due to the non-uniformly heated surface of the droplet. It is shown that the melt flow is confined within a narrow boundary layer. The thickness of this layer and the melt velocity within it are estimated. The influence of the metal motion on heat transfer in the droplet is considered. A simple formula for effective thermal conductivity, which takes into account thermocapillary convection, is obtained. Estimates show that, for conditions typical for arc welding, the effective coefficient of thermal conduction exceeds the normal value by approximately tenfold. Calculated heat fluxes agree with those obtained from the observed electrode melting rates.

1. Introduction

During consumable electrode arc welding, the electrode (usually the anode) is heated by heat from the arc and by Joule heating. The electrode melts and a liquid droplet forms at the tip of the electrode. When this droplet becomes big enough, gravity and electromagnetic force detach it from the electrode and the droplet becomes part of the welding pool. The effectiveness and the quality of the welding process depend on droplet parameters such as size, speed and heat content. The processes of mass and heat transfer in the droplet, which determine these parameters, are, therefore, very important. A great deal of literature is dedicated to their description; see, for example, [1].

Heat transfer in the solid portion of the electrode is relatively simple. The heat which the electrode receives from the surrounding plasma and the heat generated within the electrode by resistance heating are transferred by thermal conduction to the cooled end of the electrode. Heat transfer in the liquid droplet is much more complex. The droplet is subjected to many forces: buoyancy, the Lorentz force (the force of interaction of the current with the magnetic field created by this current), capillary and thermocapillary forces. The result is that the melt in the droplet moves and this motion intensifies heat transfer. A simple heat transfer model, based on thermal conduction only, is insufficient to describe the observed heat fluxes. This was shown convincingly by Waszink and Van den Heuvel [2] who compared the heat flux provided by the thermal conduction to the solid-liquid boundary, with the power necessary to melt the electrode at the observed rate. According to their estimations, the thermal conduction would have to be increased ten to twenty times to be able to supply the necessary heat flux. The authors suggested melt convection caused by the Lorentz force as a possible mechanism responsible for the heat transfer intensification.

The Lorentz force is not the only one which can set the melt into motion and in this way intensify the heat transfer. Another such force is the thermocapillary force the surface stress arising due to the gradient of the surface tension coefficient. The order of magnitude of this force was estimated in [3] where it was shown that this force can also be very important.

The melt motion caused by the thermocapillary force is considered in this paper in more detail. Its influence on heat transfer is estimated. It is shown that thermocapillary convection is sufficiently intensive to explain the observed electrode melting rates.

2. Estimation of flow parameters and heat transfer intensity

The heat flux from the surrounding plasma to the electrode is sufficiently high to cause the droplet surface to become very hot. The interface between molten droplet and the solid wire is at the melting pint, whereas results of calorimetric measurements [4] and direct pyrometric measurements [5] have indicated that the temperature of the hottest point of the surface is close to boiling point. Therefore, the difference in temperature of different parts of the droplet surface may be as much as 1300 K⁺. A large

[†] Hereafter all numerical values are related to the most common combination: plasma gas, Ar; electrode material, steel. Parameters of steel used in the calculations are listed in table 1.

Table 1. Steel parameters used in calculations.

T _m	1800 K [6]
ρ	7 g cm ^{−3} [6]
κ	0.4 W cm ⁻¹ K ⁻¹ [6]
α	0.05 cm ² s ⁻¹ [6]
ν	0.005 cm ² s ⁻¹ [1]
$d\sigma/dT$	0.35 mN m ⁻¹ K ⁻¹ [7]
H	1.2 kJ g ⁻¹ [6]

gradient of surface tension coefficient σ corresponds to this temperature difference. This results in a strong stress $\nabla \sigma$ directed from the locations with a lower σ towards those with the higher σ , i.e. to the coolest part of the surface. There is no force in the immobile liquid that can balance this stress, so thermocapillary motion arises in the liquid (Marangoni effect).

The flow pattern is shown in figure 1. The liquid moves from the hottest central part of the surface towards the liquid–solid interface, dives into the droplet and returns back through the droplet volume. During this circulation, the liquid transfers heat from the surface layer to the droplet volume adjacent to the solid–liquid interface. The intensity of this heat transfer depends on the speed of melt circulation and on the amount of liquid involved in the motion. Let us estimate these parameters.

As we will see later, the Reynolds number of the flow is high. This means that the melt moves within a relatively thin layer close to the surface and that the boundary layer approximation is applicable. This also means that one can neglect the droplet curvature. However, even in a boundary layer approximation, the problem is too complex. We limit ourselves to estimations valid within an order of magnitude. Dimensional analysis (see, for example, [8]) is used for this estimation. For thermocapillary motion in microgravity, this method has been used in [9], where it has been proven to give a good approximation to the numerical solution of the exact hydrodynamic equations.

There is no characteristic length in the problem. Therefore, all the flow parameters should depend on x, the distance along the surface from the centre line of the droplet. The Reynolds number is, therefore, Re = xv/v, where v is the kinematic viscosity. In boundary layer theory [8] the layer thickness is $\delta \sim x/\sqrt{Re}$. At the surface the stress balance condition should be satisfied:

$$\rho v \frac{v}{\delta} \sim \mathrm{d}\sigma/\mathrm{d}x \tag{1}$$

here ρ is the melt density. From equation (1) we obtain the following formulae: for velocity

$$v \sim \left(\frac{x}{\nu}\right)^{1/3} \left(\frac{1}{\rho} \frac{\mathrm{d}\sigma}{\mathrm{d}x}\right)^{2/3} \tag{2}$$

and for the layer thickness

$$\delta \sim \left(\rho v^2 x \middle/ \frac{\mathrm{d}\sigma}{\mathrm{d}x}\right)^{1/3}$$
. (3)

Let us substitute in (2) and (3) the gradient of surface tension $d\sigma/dx$ by $\Delta\sigma/R$, where $\Delta\sigma$ is the σ difference



Figure 1. Schematic of the melt motion in a droplet. Left of the centre shows the flow pattern. Right of the centre shows the coordinates used and the velocity distribution in the boundary layer. $\nabla \sigma$ shows the direction of the gradient of surface tension, *d* is the electrode wire diameter and v_w is wire feed rate.

between its maximum value at the solid-liquid interface and its minimum value at the hottest spot of the surface. Here *R* is the radius of the droplet. We have the following estimations for v and δ :

$$v \sim \left(\frac{R}{\nu}\right)^{1/3} \left(\frac{1}{\rho} \frac{\Delta\sigma}{R}\right)^{2/3} \tag{4}$$

$$\delta \sim (\rho \nu^2 R^2 / \Delta \sigma)^{1/3}.$$
 (5)

Let τ be the duration the liquid particle at the surface is exposed to the heat flux from the plasma. One can estimate τ as R/v, the ratio of the particle path (of the order of the droplet radius *R*) to the particle velocity at about distance *R* from the droplet centre. We have

$$\tau \sim (\nu R^2)^{1/3} \left(\frac{R\rho}{\Delta\sigma}\right)^{2/3}.$$
 (6)

In order to determine how the motion of the liquid affects the heat transfer, the temperature distribution should be considered. For the sake of simplicity, as we have done with the flow problem, let us average the temperature distribution T(x, y) over x, the coordinate along the droplet surface: $\overline{T}(y) = \int T(x, y) dx / \int dx$. To obtain $\overline{T}(y)$, consider a liquid particle moving along the surface of the droplet at a depth y. It takes this particle time $\tau(y) \sim$ $R/v_x(y)$ to travel along the surface. During this travel, the particle accumulates an amount of heat $\rho C \overline{T}(y)$ (J m⁻³), where C is the specific heat and ρ is the melt density. After its travel beneath the surface, the particle dives inside the droplet and there it is cooled by sharing its excess heat with the rest of the droplet. The process of gaining and losing heat by the liquid in the boundary layer can be described by the equation:

$$\kappa \frac{\mathrm{d}^2 \bar{T}}{\mathrm{d}y^2} - \frac{\rho C \bar{T}}{R} v_x(y) = 0. \tag{7}$$

This equation should be solved with the following two boundary conditions. First, at the liquid-plasma boundary

$$-\kappa \frac{\mathrm{d}\bar{T}(0)}{\mathrm{d}y} = q \tag{8}$$

where q is the heat flux density at the surface. Second, beneath the viscous boundary layer, where there is no liquid motion along the surface, the heat is transferred by thermal conduction only. In our case, when convective heat transfer is much more intense than conductive heat transfer, one may neglect the heat flux due to conduction and put

$$\frac{\mathrm{d}\bar{T}(y_0)}{\mathrm{d}y} = 0. \tag{9}$$

Here y_0 is the distance from the surface where the velocity of the liquid becomes zero. The boundary condition (9) can be justified in another way. There is a flow of liquid in the core of the droplet toward the surface which, although slow, does not allow the heat to reach the central portion of the droplet [9].

Let us assume a linear distribution of the liquid velocity inside the boundary layer: $v_x(y) = v_x(0)(1 - y/y_0)$. The velocity profile inside the layer (the Blasius solution [10]) can be well approximated by the linear dependence with $y_0 = 3.16\delta$, where $\delta = x/\sqrt{Re}$ is the boundary layer thickness. With this approximation, equation (7) can be rewritten in the following dimensionless form

$$\frac{\mathrm{d}^2\theta}{\mathrm{d}\eta^2} - \left(1 - \frac{\eta}{\eta_0}\right)\theta = 0 \tag{10}$$

$$\theta'(0) = -1 \tag{11}$$

$$\theta'(\eta_0) = 0 \tag{12}$$

where we introduced

$$\eta = y/\delta_T$$
 $\delta_T = \sqrt{\alpha R/v_x(0)}$ (13)

$$\theta = \frac{\kappa T(\mathbf{y})}{\delta_T q} \tag{14}$$

$$\eta_0 = \frac{3.16\delta}{\delta_T} = 3.16\sqrt{Pr} \tag{15}$$

where $\alpha = \kappa/\rho C$ is the thermal diffusivity and *Pr* is the Prandtl number. Solution of equation (10) with the boundary conditions (11) and (12) can be easily obtained by expanding in series:

$$\theta = \sum_{n=0}^{\infty} a_n \eta^n.$$
 (16)

For coefficients a_n one has

$$a_1 = -1$$
 $a_2 = a_0/2$ (17)



Figure 2. Calculated $\theta_0(\eta_0)$ dependence.

$$a_n = \frac{1}{n(n-1)}(a_{n-2} - a_{n-3}/\eta_0).$$
(18)

The unknown coefficient a_0 should be chosen such that the boundary condition (12) is satisfied. The problem depends on the single parameter η_0 , which according to (15) is related to the Prandtl number Pr.

We are interested in $\theta(y = 0) = \theta_0$, since with the given heat flux density at the surface, the heat transfer intensity is characterized by the surface temperature. To take convection into account, let us introduce the effective thermal conductivity κ_{eff} by the formula

$$q = \frac{\kappa_{eff}\bar{T}(y=0)}{R}.$$
 (19)

Comparing this formula to (14) we see that

$$\frac{\kappa_{eff}}{\kappa} = \frac{R}{\delta_T} \frac{1}{\theta_0} = \frac{\sqrt{v_x(0)R}}{\alpha} \frac{1}{\theta_0}.$$
 (20)

By putting $v_x(y = 0)$ from equation (4) into (20) we have finally

$$\frac{\kappa_{eff}}{\kappa} = \left(\frac{R\Delta\sigma}{\rho\nu^2}\right)^{1/3} \left(\frac{\nu}{\alpha}\right)^{1/2} \frac{1}{\theta_0}.$$
 (21)

The calculated dependence $\theta_0(\eta_0)$ is shown in figure 2[†]. For liquid iron, $Pr \sim 0.1$, so that in our case η_0 is close to unity. From figure 2 one can see that $\theta_0(1) \sim 2.2$.

The following assumptions have been made when deriving this formula. First, we used the boundary layer approximation which is valid if $Re \gg 1$ and $RePr \gg 1$. However, in order for the flow to be laminar, the Reynolds number should not be too large. Second, it has been assumed that the droplet is uniformly covered with the arc attachment. Third, the droplet resides at the electrode tip during a limited time 1/f, where f is the droplet detachment frequency. Since the stationary

[†] It can be shown easily that $\theta_0 \sim 2/\eta_0$ when $\eta_0 \ll 1$ and that $\theta_0 \sim 1$ when $\eta_0 \gg 1$.

Current (A)	v_w (m min ⁻¹)	<i>R</i> (mm)	f (1 s ⁻¹)	<i>v</i> (m s ⁻¹)	Re	τ (S)	Q_{exp} (W)	Q (W)	Q _{eff} (W)
228	2.5	1.3	10	0.82	2100	1.6E – 02	7.03E + 02	1.96E + 02	1.91E + 03
241	2.8	1.1	15	0.87	1900	1.9E – 02	7.87E + 02	1.66E + 02	1.53E + 03
249	3.0	1.1	20	0.87	1900	2.5E – 02	8.43E + 02	1.66E + 02	1.53E + 03
264	3.2	0.96	29	0.91	1700	3.1E – 02	9.00E + 02	1.45E + 02	1.28E + 03
279	3.4	0.81	51	0.96	1600	4.3E – 02	9.55E + 02	1.22E + 02	1.02E + 03
304	3.8	0.49	260	1.13	1100	1.1E – 01	1.07E + 03	7.40E + 01	5.22E + 02
342	4.2	0.47	320	1.15	1100	1.3E – 01	1.18E + 03	7.10E + 01	5.00E + 02
365	4.5	0.48	331	1.14	1100	1.4E – 01	1.26E + 03	7.25E + 01	5.07E + 02
389	5.0	0.48	360	1.14	1100	1.5E – 01	1.41E + 03	7.25E + 01	5.07E + 02

Table 2. Details of calculations for the pure Ar case.

flow consideration has been used, it is necessary that the liquid particle circulation time τ be much smaller than the residence time, i.e. $f\tau \ll 1$. The validity of these assumptions is discussed later.

3. Comparison with data obtained from the observed electrode melting rates

The power delivered to the solid–liquid interface by thermal conduction can be calculated as

$$Q_T = \kappa S \Delta T / L \tag{22}$$

where *S* is the arc attachment area and *L* is the average distance from the heated surface to the interface boundary. When the droplet surface facing the arc is heated uniformly, *S* is about $2\pi R^2$ and *L* is about 3R/2. In this case Q_T is approximately $4\kappa R\Delta T$, the value used in our computations. The power consumed by wire melting, Q_{exp} , is determined by the wire feed rate, v_w , by the wire diameter, *d*, and by the energy of heating and melting of the electrode material, *H* (J g⁻¹):

$$Q_{exp} = \frac{\pi d^2}{4} \rho v_w H. \tag{23}$$

For comparison of Q_{exp} and Q_T we used data obtained in [11–13]. These experiments were conducted with a steel electrode of 1.6 mm diameter and with plasma gases of Ar, 98% Ar + 2 % O₂, and 95% Ar + 5 % O₂. The Q_T/Q_{exp} ratio calculated for conditions [11–13] with $\Delta T = 1200$ K is shown in figure 3 with open symbols. Convection has been taken into account by multiplying Q_T by the factor κ_{eff}/κ :

$$Q_{eff} = \kappa_{eff} / \kappa Q_T. \tag{24}$$

The Q_{eff}/Q_{exp} ratio calculated in this way is shown in figure 3 with full symbols. One can see that convection increases heat transfer intensity approximately tenfold.

As an example, the details of calculations for the pure Ar case are shown in table 2. It can be seen from this table that the Reynolds number is in the range 1000 to 2000, high enough for applicability of the boundary layer approximation, but not high enough for transition from laminar to turbulent flow to occur. Calculations showed that the droplet residence time is at least ten times larger than the liquid particle circulation time: $f\tau < 0.1$ (see table 2). As for conditions for uniform droplet coverage



Figure 3. Comparison of the power consumed by electrode melting, as obtained from the observed melting rates, with the calculated power delivered to the melting boundary by thermal conductivity (Q_T/Q_{exp} , open symbols) and by marangoni convection (Q_{eff}/Q_{exp} , full symbols). Experimental data are taken from: \bigcirc , [11, 12]; \triangle , [11, 12]; \Box , [13].

with the arc attachment, it is not fulfilled at relatively low currents, under ~ 250 A (see discussion below).

From figure 3 one can see that at currents above 250 A the ratio between Q_T and Q_{exp} is between 10 and 20. After the correction has been made, $Q_{eff} = \kappa_{eff} / \kappa Q_T$ is in correspondence with Q_{exp} . The difference of ~ 100% should be considered as satisfactory for estimations valid within an order of magnitude. It can be seen that for lower currents Q_{eff} substantially deviates from Q_{exp} . We believe that this is because formula (22) overestimates Q_T at these currents. There are two reasons for this. First, ΔT in the globular mode is substantially lower than 1200 K, the value we used for Q_T calculations. According to [4], ΔT is about 800 K in this mode. For this reason only, Q_T is overestimated by a factor of $1.5^{4/3} \sim 1.7$. Also, in the globular mode, the arc does not cover the whole droplet surface, but only part of it [11]. Formally, this is equivalent to some decrease of S and some increase of L in the formula (22). This means that Q_T should be additionally decreased. It is likely that both factors cause Q_T to be overestimated by several times. After taking this into account, the deviation of Q_{eff}/Q_{exp} from unity can be decreased. Although this correction improves the agreement between Q_{eff} and Q_{exp} , formula (21) does not describe the situation of partial coverage of the droplet by the arc.

At high currents, the shape of the suspended droplet deviates from spherical: the higher the current, the more the droplet becomes elongated in the direction of the current. When obtaining formula (21), a spherical droplet shape was not assumed. Therefore, this formula can be used for the elongated droplet as well. In this case, parameter R in equation (21) represents the droplet dimension in the direction of the temperature gradient. For high currents, when the droplet is elongated, the value of R obtained from the droplet volume measurements underestimates the suspended droplet dimension in the direction of the current. According to (21), this underestimates the correction factor κ_{eff}/κ . Therefore, taking droplet distortion at high currents into account leads to the increase in Q_{eff}/Q_{exp} and brings this ratio closer to unity.

4. Note on the role of the Lorentz force in heat transfer

Among forces capable of setting the melt in motion, Waszink and Van den Heuvel marked out the Lorentz force [2]. Up to now, heat transfer in a droplet due to the Lorentz force action has not been calculated. It has not even been estimated yet. It seems appropriate to give here some considerations on the role of the Lorentz force in heat transfer.

The Lorentz force is due to the interaction of the current in the droplet with the magnetic field created by this current. It has an order of magnitude $F_L \sim \mu_0 I^2/4\pi$, where *I* is the arc current and μ_0 is the permeability of free space. At high currents, F_L has the same order of magnitude as the thermocapillary force. However, this does not necessarily mean that the melt velocities caused by these forces are of the same order of magnitude. The distribution of the Lorentz force, even its sign, depends on the current distribution inside the droplet [14], which in turn depends on the processes in the adjacent plasma [15]. Also, the Lorentz force, contrary to the thermocapillary force, can be compensated to some degree by the pressure gradient. This can be seen from the following expression for the volumetric Lorentz force f_L :

$$f_L = B \times J = -\mu_0 J \times \operatorname{rot} J = \mu_0 \{1/2 \operatorname{grad}(J^2) + (J \cdot \nabla) J\}$$

where J is the current density and B is magnetic flux. One can see that if current lines are parallel, the vortex component of f_L is equal to zero. In this case the Lorentz force can be compensated by the pressure gradient completely.

The motion of liquid caused by the Lorentz force demands special consideration. In this paper, we would like to emphasize that the marangoni effect is of the correct order of magnitude to explain the observed electrode melting rates.

5. Conclusion

In this paper, a simple formula describing heat convection due to the marangoni effect in a droplet is obtained. The effective coefficient of thermal conduction is expressed as a function of viscosity of the liquid ν and the surface tension difference $\Delta\sigma$ along the droplet surface. The formula is applied to obtain the heat fluxes in the liquid metal droplet hanging at the tip of an electrode during welding. Both ν and $\Delta\sigma$ are not very well known at the very high temperatures existing at the droplet surface (nor is the temperature itself known). However, these parameters enter the formula with only a small exponent and therefore the result is not sensitive to the precise value of these parameters. Calculations based on this formula agree with data obtained from observed electrode melting rates.

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