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EFFECT OF ELECTRODE DROPLET SIZE ON EVAPORATION AND FUME GENERATION IN GMAW

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ABSTRACT

The rate of fume generation in GMAW increases with evaporation from the molten droplet at the tip of the electrode. The rate of evaporation is controlled largely by the surface temperature of that droplet, which is determined by the heat and fluid flow in the molten metal. The application of the technique of Order of Magnitude Scaling shows that electromagnetic flows are dominant, and that convective currents can not be ignored. The effect of sulfur content in the filler wire, which affects the Marangoni flows, is discussed. Calculations indicate that the surface temperature at the tip of the electrode increases with droplet size. Because of the smaller droplet size less metal is vaporized; therefore, welding in spray transfer mode or with pulsed current generates less fume. This finding is in agreement with the lower fume formation rates observed experimentally with such conditions. Fume reduction strategies based on the above mentioned mechanism are discussed.

INTRODUCTION

Fumes generated during welding are objectionable and may influence the workers health. The protection of the welding operator from these fumes can seriously affect the economics of a welding process, even to the point of making that process uneconomical. There is thus a significant payoff in the reduction of welding fumes. This reduction is also desirable from a point of view of cleanliness of the operation, utilization of the material and balancing of the alloying elements. Processes in which the filler material acts as an electrode, such as GMAW or FCAW generate significantly more fumes than other processes such as GTAW. This paper will focus on fume generation during GMAW, however it should be possible to extend this approach to similar processes, such as FCAW.

The generation of fumes during GMAW has been extensively studied experimentally (Ref. 1, 2, 3, 4, 5) and theoretically (Ref. 6, 7, 8, 9). The focus of the work presented here is on the interactions between heat transfer and fluid flow in the electrode tip droplet. Only a few references have addressed these phenomena simultaneously (Ref. 8, 9, 10, 11, 12). The methodology employed here is the Order of Magnitude Scaling (OMS) of the constitutive differential equations (Ref. 13). This technique provides order of magnitude estimations of the unknowns of the problem, the range of validity of the estimations and a description of the dominant and balancing forces in the system. The application of this technique indicates that fluid flow in the droplet controls the temperature on the droplet, and thus the evaporation rate. In this analysis, the droplet will be considered as a system in steady state.

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MECHANISM OF FUME GENERATION

Fume particle formation can be placed into two categories: 1) from solids and liquids by mechanical means (for example, grinding or liquid atomization) and 2) from a vapor by condensation. Particles formed mechanically are rarely smaller than 1 micrometer in diameter. If they are indeed smaller, they are always found with particles 1 micrometer or larger. Particles created by condensation are 0.01 to 0.4 micrometer in diameter (Ref. 14).

Voitkevich (Ref. 3) experimentally found that the particle size of welding fume varies in the range of several hundredths to several tenths of a micrometer. In addition, the authors used transmission electron microscopy to study welding fume created under a variety of conditions and did not discover any particles larger than 0.5 micrometer.

It can be concluded that welding fume is formed solely by condensation from the vapor evolved during welding. Therefore, the fume formation rate in GMAW should be directly related to the vaporization rate from the welding droplet.

ANALYSIS OF THE DROPLET AT THE TIP OF THE ELECTRODE

It was mentioned above that the fume formation rate (FFR) is related to evaporation from the liquid at the tip of the electrode. This evaporation depends on the surface temperature and geometry of the liquid, which can be divided into three regimes (Figure 1):

Regime I: The anode spot covers only a fraction of the surface of the droplet. The electromagnetic forces stir the liquid inside the droplet creating two thermal boundary layers (TBL's) in the liquid, one at the anode (TBLa), and another at the solid-liquid interface with the wire (TBLw). Through the bulk of the droplet, the heat is transported by convection. This regime corresponds to the globular transfer mode

Regime II: The anode spot covers only a fraction of the surface of the droplet. Heat is transported through the bulk of the droplet by conduction (the TBL's are so thick that the convective region is suppressed). This regime corresponds to either globular or spray transfer mode.

Regime III: The anode spot completely covers the droplet and reaches the side of the wire. The wire melts forming a thin layer of liquid metal through which heat is transported by conduction. The molten liquid extends from the electrode forming a tail. Droplets detach from the tip of this tail.

The heat balance for the system is essentially the same for all three regimes:

$$Q_e = Q_w + Q_m + Q_v \qquad (1)$$

The heat input from the condensation of electrons (Q_e) is balanced by the heat conduced into the wire (Q_w), the heat necessary to melt and heat the liquid (Q_m) and the heat losses by vaporization (Q_v). In this analysis the heat transport by radiation and convection from the plasma is neglected. The heat generated by viscous dissipation and Joule effect inside the liquid will also be neglected.

The expression of heat condensation by the electrons (Q_e) is as follows (Ref. 15):

$$Q_e = I\left(\tfrac{3}{2} k_B T_e / e + \Phi\right) \qquad (2)$$

where I is the welding current, k_B is Boltzman's constant, T_e is the temperature of the electrons, e is the charge of the electron, and Φ is the work function of the material. For mild steel the magnitude in parenthesis of eq. 2 is $V_a = 6$ V (Ref. 10). For a given current and wire, the heat deposited by the electrons is determined independently of the droplet size and temperature and electrode extension.

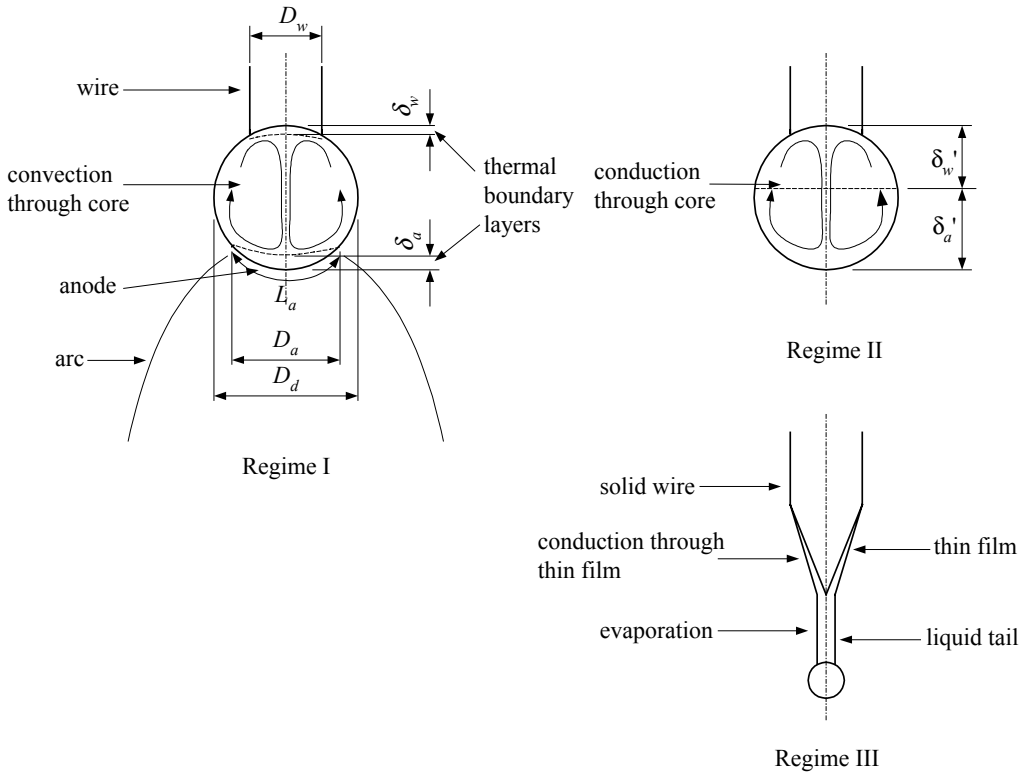

Figure 1
Heat transfer regimes in the GMAW electrode tip

The heat conduced into the wire (Q_w) has the following expression (Ref. 10):

$$Q_w = A_w V_w \rho_s \left[c_{ps}\left(T_m - T_c\right) + \beta\right] - \frac{I^2 L}{\sigma_e A_w}$$

where A_w is the cross sectional area of the wire, V_w is the wire feed speed, ρ_s is the density of the solid, c_{ps} is the specific heat of the solid, T_m is the melting temperature, T_c is the temperature of the wire at the contact tip, L is the effective wire extension, and σ_e is the electric conductivity. The parameter β is introduced by Waszink to account for the variation of electric conductivity with temperature. For a given wire, the heat conducted into it depends only on the current, electrode extension and the wire feed speed, and does not vary with droplet size or temperature.

The energy for melting and heating the wire (Q_m) has the following expression:

$$Q_m = A_w V_w \rho_s \left[\Delta H_m + c_{ps}\left(T_l - T_m\right)\right]$$

where ΔH_m is the latent heat of melting, and T_l is the average temperature of the bulk of liquid. The magnitude of Q_m depends on the droplet temperature.

The heat losses through vaporization (Q_v) have the following expression:

$$Q_v = \int_{A_v} q_v dA$$

where A_v is the area over which evaporation occurs, and q_v is the heat loss per unit area. The evaporation of metals into plasma is a very complex problem. Because vaporization does not occur into a vacuum, the rate of mass loss (thus energy loss) is lower than would be predicted by Langmuir's expression. The rate limiting factor is the diffusion of metal vapor through a diffusion boundary layer (DBL) of the gas on the surface of the liquid (Ref. 9, 16). As an approximation, in this work a fitting through Choo's calculated values for the evaporation of steel into argon will be used.

$$q_v = 1.661 \times 10^7 \left(T/T_b\right)^{10.033} \qquad (3)$$

where T_b is the boiling temperature. The units of q_v are W/m^2, and the temperatures are expressed in K. The large exponent in eq. 3 indicates that the evaporation rate depends very strongly on the surface temperature, for example a temperature decrease of 25% causes the evaporation rate to fall below 5% of is initial value. This fact will be used later to neglect the heat losses by evaporation from the colder parts of the liquid. The total heat losses through vaporization will thus depend on the surface area and temperature of the hot part of the liquid.

Equation 1 indicates that the heat input in excess of melting will be conducted through the wire, will be stored in the droplet and increase its temperature or will be evaporated. For a given current, to reduce the vaporization losses (which determine FFR), it is necessary to increase the heat conducted into the wire or the average temperature of the droplet.

Because of the steep dependence of vaporization losses with temperature, the temperature at the surface of the liquid will be almost constant, even if the vaporization losses vary significantly. The temperature of the liquid is contained between the surface temperature (approximately constant) and the melting temperature (constant). Therefore, in order to increase the heat stored in the liquid it is necessary to change its temperature distribution. The heat conducted into the wire is conditioned by the thermal barriers between the surface of the liquid and the solid wire, which are particular to each regime.

Regime I:

In this regime, heat transfer is controlled by the TBL's at the anode and solid-liquid interface. The heat transfer through them is estimated as:

$$Q_w = A_w k \left(T_l - T_m\right)/\delta_w$$

$$Q_e - Q_v = A_a k \left(T_a - T_l\right)/\delta_a$$

where k is the thermal conductivity of the liquid, A_a is the anode area, T_a is the temperature at the surface of the droplet at the anode, and δ_w and δ_a are the thickness of the TBL's at the wire and anode respectively.

For simplicity it will be assumed that over the anode area the current density is constant (J_a) and all of the evaporation occurs there. The rest of the surface of the droplet will be at the bulk temperature T_l, lower than the anode temperature, low enough to make the evaporation losses from outside the anode negligible.

The thickness of the TBL's depends on fluid flow inside the droplet. For fluids like molten metals, with a low Prandtl number (Pr), their thickness is related to that of the viscous boundary by a factor of $Pr^{-1/2}$ (Ref. 17), and it can be estimated as:

$$Q_w = 5\sqrt{\alpha D_w / (2V_{RC})}$$

$$Q_a = 5\sqrt{\alpha L_a / (2V_{RC})}$$

where α is the thermal diffusivity of the liquid, D_w is the diameter of the wire, L_a is the length of the anode arc (Figure 1) and V_{RC} is the characteristic radial velocity in the bulk of the liquid. This velocity was estimated by using OMS. Inside the droplet the electromagnetic forces are balanced by the inertial forces. Viscous effects and Marangoni driving forces play secondary roles. Estimation of the characteristic radial velocity gives:

$$V_{RC} = \frac{1}{2^{3/4}\pi}\sqrt{\frac{\mu_0 I^2 D_d \left|2(D_a - D_w)/(D_a + D_w)\right|}{\rho D_w{}^3 \left|1 + 2(D_a - D_w)/(D_a + D_w)\right|}}$$

where μ_0 is the magnetic permeability of vacuum, ρ is the density of the liquid, D_d is the droplet diameter, and D_a is the anode diameter.

The equations above show that by increasing current, the flow becomes proportionally faster and the boundary layers thinner, decreasing the resistance to heat flow. Increasing the droplet size has a similar effect. When the anode spot diameter is approximately the same as that of the wire, the flow is slower. For this narrow range of conditions Marangoni flows might be dominant. The recirculating flows can change their direction depending on the relative size of the anode and wire diameters.

Regime II

This regime is reached when the thickness of the two TBL's is larger than the droplet diameter. In this case there is no convection, but only conduction. For simplicity the formulation will be the same as that for regime I, but the thickness of the TBL's will be redefined:

$$\delta_a' = D_d / \left(1 + \sqrt{D_w / L_a}\right)$$

$$\delta_w' = D_d / \left(1 + \sqrt{L_a / D_w}\right)$$

This new definition have the property that $\delta'_a/\delta'_w=\delta_a/\delta_w$, and $\delta'_a+\delta'_w=D_d$. The redefined TBL's are thinner than those for regime I, thus the conductive thermal barrier is lower and the surface of the liquid in this regime will be colder than in regime I.

Regime III

This regime is reached when the arc completely covers the droplet and starts to heat the wire above. In this case two heat balances are necessary, one for the wire (eq. 4) and another for the liquid tail (eq. 5).

$$Q_{ew} = Q_w + Q_{mw} \tag{4}$$

$$Q_{et} = Q_{mt} + Q_v \tag{5}$$

where Q_{ew} and Q_{et} are the energy transported by electrons to the surface of the wire and tail respectively, and Q_{mw} and Q_{mt} are the energy of melting and heating the liquid in the wire and tail respectively.

In the balances above, it is assumed that there is no heat flow from the bulk of the liquid towards the wire, and that evaporation occurs only on the surface of the bulk of liquid. Because the liquid film covering the melting electrode is very thin, it will be assumed that it stores energy only in the form of latent heat of melting. The temperature of the tail will be assumed uniform throughout the volume.

The expression of the heat transported by electrons to the wire is:

$$Q_{ew} = C_1 A_{aw} J_a V_a$$

where A_{aw} is the surface area of the wire over which there is condensation of electrons. The factor C_1 accounts for errors in the estimation of anode area in the wire, and the lower current density through it. If the time to diffuse heat from the surface of the wire to its core is of the order of $D_w^2/4\alpha$, the anode area of the wire can be estimated as $A_{aw}=V_w D_w^2/4\alpha$.

In this regime the falling droplets have the same temperature as the liquid tail, so their surface should be included in calculation of the total generation of fume.

EFFECT OF PROCESS PARAMETERS IN FUME GENERATION

Table 1 below shows the variation of heat flow and temperature with the different regimes for a mild steel wire of diameter 1/16", under a current of 240 A and a wire feed speed of 2.9 m/min. Regime I corresponds to globular transfer; it is characterized by a ratio $\delta_a+\delta_w/D_d$ less than one, which indicates that there is a convective core between the two TBL's. In this regime the thermal barrier is highest and therefore the heat flow into the electrode (Q_w) is minimum. In regime II the thickness of the conductive thermal barrier is limited by the droplet size, therefore the heat transport to the wire is enhanced. Since more excess heat goes into the wire, the heat losses by evaporation are lower (therefore the FFR) . Since the diameter of the droplet is smaller than the diameter of the wire this case would correspond to spray transfer. In this case, the anode covers all of the

surface of the droplet A_d (the area taken by the wire must be subtracted), but it does not cover any part of the wire. Regime III corresponds to streaming spray transfer. In this case the part of the anode on the side of the electrode provides a very effective means of heat transport into the wire, therefore Q_w is the largest in this case. Also, the tail gets very hot storing energy in the form of temperature. These two effects reduce the heat losses due to evaporation by more than half.

Table 1: Variation of heat flow and temperatures with the different regimes

regime	D_d/D_w	$\delta_a+\delta_w/D_d$	$A_a/(A_d-A_w)$	L [mm]	T_a [K]	T_l [K]	Q_e [W]	Q_w [W]	Q_m [W]	Q_v [W]
I	2.09	0.61	0.15	28.1	4138	2333	1440	34	390	1016
II	0.92	2.19	1.00	27.5	4124	2354	1440	60	400	981
III	0.92	2.19	1.00	25.6	3716	3716	1440	130	1032	440

DISCUSSION

The trends indicated in Table 1 show a significant reduction in the vaporization losses with streaming spray transfer, and a moderate reduction with the transition from convective to conductive heat transfer. The model presented above is stationary, however the melting of the electrode and the production of droplets is of a cyclic, transient nature. In any regime, at the beginning of the formation of the droplets the anode root covers part of the electrode, just as in regime III, which corresponds to the lowest vaporization losses. As the droplet grows in diameter, it passes through regime II, until the droplet is large enough to have a convective core (regime I, with the highest vaporization losses). Thus, the instantaneous rate of evaporation losses increases as the droplet grows. The process of growth of the droplet is interrupted by its detachment. The earlier the droplet detaches, the lower the FFR. This might help explain why the use of pulsing in GMAW can have such an important effect in reduction of fumes.

Table 1 was constructed using the equations listed above, which incorporate many assumptions and simplifications. Perhaps the most important of these is the calculation of the evaporation heat losses. A better description of the process of evaporation would be desirable to increase the accuracy of the calculations. It might also help determine whether the temperature of the droplet is actually as far above the boiling point as the calculations indicate. Preliminary thermodynamic analyses of the composition of fumes also indicate temperatures close to 4000 K (Ref. 18). Numerical calculations by Haidar (Ref. 8) indicate average droplet temperatures between 2000 K and 2600 K, in agreement with the present calculations for regimes I and II. The calculated surface temperature would be lower if the heat losses by evaporation were higher than what eq. 3 predicts.

Another point that deserves especial attention is that the FFR predicted here is excessive in some cases by a factor of 10^{-2}. This is a problem also encountered by other researchers (Ref. 8, 10, 19), who suggested that the metal vapors might recondense on the surface of the weld pool.

CONCLUSIONS

The generation of fumes depends mainly on the evaporation of metal from the electrode. The amount evaporated depends on heat transfer through the droplet. Faster heat transfer implies lower droplet temperatures and less evaporation. The mechanism of heat transfer through the droplet can be divided in three different regimes. Regime I has the slowest rate, and corresponds to globular transfer with large droplets. Regime II is slightly faster than regime I, and corresponds to globular or spray transfer with small droplets. Regime III is the fastest regime because a fraction of the electrons condenses directly on the wire. This corresponds to the streaming spray transfer mode.

Regime III generates the least amount of fumes for a given current, and can be obtained by using thinner wire diameters. A decrease in the electrode extension increases the heat conducted through the wire, thus reducing the FFR. Such a decrease can be achieved by reducing the wire feed speed. Pulsing the current before or soon after the droplet reaches regime I can reduce FFR; however, detaching the droplet once it stayed at regime I for a relatively long time is not expected to yield significant improvements.

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