KINETICS OF SATURATION OF LIQUID METAL FLOW WITH GASES

B. L. Bozhenko, L. I. Bedenko,
V. L. Kovtun, and G. G. Chernyshov

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An analysis of the kinetics of gas dissolution in a liquid metal flow is performed. It is shown that due to a high pouring rate and specific surface of the flow, the flow in the arc of molten filler metal, as distinct from the flow of liquid metal during its pouring, leads to intense saturation of the melt with gas.

The properties of metal in plasma-arc welding and pouring of pig iron, steels and alloys are largely determined by the degree of metal saturation with gases [1, 2]. In welding the saturation with gases primarily occurs during melting of filler metal and depends on the conditions of the welding zone protection [3]. In the process of plasma and arc welding, especially under forcing conditions, on the end of an axially delivered filler wire a cone of liquid metal is formed whose height attains 10-15 mm. This points to an intense axial flow of melt in the direction of the plasma flow. When iron, steels and alloys are poured, a high-speed flow of liquid metal is also formed, which makes contact with atmospheric air. Analysis of literature data showed that in the main the studies were concerned with the interaction of gases with a stagnant liquid metal [2, 3].

In the present work, the effect of flow velocity of liquid filler metal on its saturation with gases was evaluated.

The motion of liquid metal on melting of filler wire axially delivered to the arc (Fig. 1) is governed by the following forces: electromagnetic, friction of plasma against the flow surface, gravity, surface tension, and viscosity. The basic criteria that characterize the motion of liquid (Re, Fr) show (Table 1) that under the considered conditions of welding the forces of viscosity and gravity are 2 - 5 orders of magnitude smaller than inertia forces. As a result of smooth variation in the flow diameter along its length and high temperature of the melt, the surface tension forces are also negligibly small.

The vector of current density in the wire is virtually parallel to its longitudinal axis (Fig. 1); therefore volumetric electromagnetic forces have only a radial component, which in any section x = const is counterbalanced by an excess internal pressure. By assuming the current density distribution to be uniform over the section, we determine the excess pressure in the flow in a cylindrical coordinate system, according to the results of [4], as

$$p(r) = \frac{\mu_0 I^2}{4\pi^2 R^2}\left(1 - \frac{r^2}{R^2}\right),$$

where μ_0 is the magnetic permeability, H/m, I is the magnitude of the current through the cross section of the flow of radius R (Fig. 1), A. At x = 0, the excess pressure will be maximum. In the section x = L, the whole current will go into the arc plasma, reducing the excess pressure to a minimum. By virtue of the assumptions made, we can assume that the entire potential energy of the difference of pressures between the sections x = 0 and x = L will go over into kinetic energy of the flow. Therefore, the speed of the melt due to electromagnetic forces can be evaluated as

$$V_e = \sqrt{V_{nn}^2 + \frac{2\Delta p}{\rho_l}} = \sqrt{V_{nn}^2 + \frac{2}{\rho_l}\frac{\mu_0 I^2}{4\pi^2 R_e^2}\left(1 - \frac{r^2}{R^2}\right)},$$

where V_{nn} is the speed of electrode delivery, m/sec; ρ_l is the liquid metal density, kg/m^3; R_e is the electrode radius, m.

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TABLE 1. Basic Characteristics of Liquid Filler Metal Flow in Arc and Plasma Welding

Mass flow, 10^{-3} kg/sec	Flow diameter, 10^{-3} m/sec	Density of melt, kg/m^3	Flow velocity, m/sec	Melt viscosity, 10^{-7} m^2/sec	$F_r = \frac{V_f^2}{gd_f}$	$Re = \frac{V_f d_f}{\nu}$
2-7	0.6-1.6	4900-5500	0.4-5.0	1.2-4.0	10-4000	1600-25000

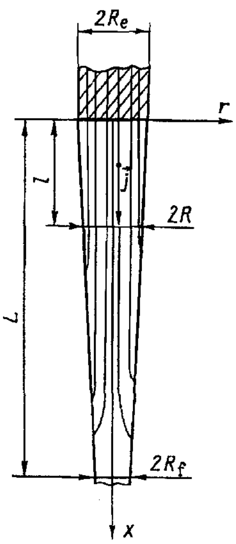


Fig. 1. Computational scheme of metal flow in plasma-arc welding.

The motion of liquid metal induced only by the plasma shear forces is Couette flow with linear velocity distribution [5]

$$V_\tau = V_{nn} r\tau/\mu,$$

where μ is the coefficient of dynamic viscosity, Pa·sec; τ is the shear stress on the flow surface, Pa.

It is customary to represent τ as part of the kinetic energy of the plasma flow

$$\tau = c_f \frac{\rho_p V_p^2}{2},$$

where ρ_p is the plasma density, kg/m^3; V_p is the plasma velocity, m/sec.

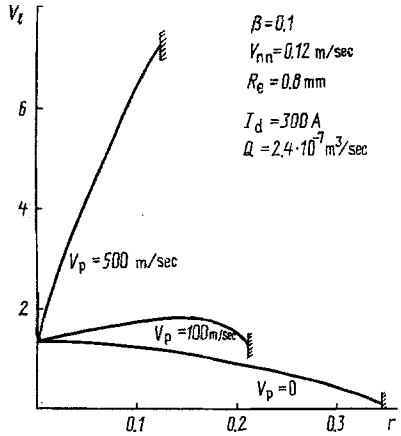
The friction factor c_f depends on the shape of the body and the conditions of flow past it. Due to high temperature, a "vapor jacket" is formed on the liquid metal surface, which lowers the friction. Therefore, when determining c_f [5], use was made of the additional coefficient β which takes into account the slip effect:

$$c_f = \beta \frac{0{,}644}{\sqrt{Re_p}},$$

where Re_p is the Reynolds number for plasma.

An indirect evaluation on the basis of the speed of droplet transfer in a plasma flow yields $\beta = 0.2 - 0.3$. Taking into account the fact that in the case of longitudinal flow past a cone the slip effect increases as against the flow past a sphere, we adopted in calculations that $\beta = 0.1$.

If metal evaporation is neglected, then beyond the zone of action of electromagnetic forces (x>L) the overall flow velocity $V_f(r) = V_e(r) + V_\tau(r)$ should satisfy the condition of constancy of the initial flow rate $Q = V_{nn}\pi R_e^2$. Therefore, the velocity profiles and the value of R were determined from the relation



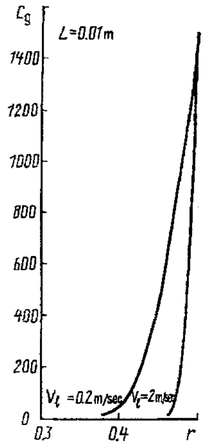


Fig. 2. Liquid metal velocity profiles at different plasma speeds V_l, m/sec; r, mm.

Fig. 3. Distribution of oxygen concentration at different flow velocities ($R_f = 0.5$ mm). C_g, kg/m^3.

$$2\pi \int_0^R V_l(r)\, r dr = Q.$$

The results of the calculations are presented in Fig. 2.

The intensity of the supply of gases by a plasma stream to an axial liquid metal flow is determined with allowance for high-velocity gas flows in plasma by convective diffusion [6]

$$I^{d}_{g\text{-}p} = \frac{k_f^{0,5} C_{g\text{-}p} V_p}{12{,}46 (\nu_p / D_{g\text{-}p})^{0,75}},$$

where I^d_{g-p} is the intensity of convective diffusion of gas from the plasma stream to the melt, kg/(m^2·sec); $C_{g\text{-}p}$ is the gas concentration in the plasma, kg/m^3; ν_p is the plasma viscosity, m^2/sec; $D_{g\text{-}p}$ is the coefficient of molecular diffusion of gas in the plasma, m^2/sec; k_f is a coefficient which depends on the conditions of plasma flow past the melt and which is determined from the relation

$$1/k_f^{0,5} = 4{,}13 \lg (\mathrm{Re}_p k_f).$$

The gas characteristics necessary for the calculations have been borrowed from [7-10], and the gas diffusion coefficients in plasma were calculated from the model of "rigid spheres" [11]. The results obtained show (Tables 2 and 3) that in the case of small concentration of active gas in plasma the values of I^d_{g-p}, and C_{g-l} may become substantial due to a high plasma velocity. Thus, the processes of mass transfer in a plasma flow do not restrict the intensity of saturation of liquid metal with gas. Let us consider the process of adsorption of gas particles by the melt surface.

It is known [12] that as the melt surface is saturated with gas particles, the rate of adsorption decreases. Then $I^a_g = I^d_{g-p}(1-z)P$, where I^a_g is the intensity of gas adsorption by the liquid metal surface, kg/(m^2·sec); z is the population of the melt surface with adsorbing-gas particles; P is the probability of gas particle adsorption by the melt surface.

By assuming the Maxwell-Boltzmann distribution of the kinetic energy of the gas particles and neglecting gas diffusion in the liquid metal, we obtain for a cylindrical flow

$$I^a_g = \frac{I^d_{g\text{-}p}}{1 + \dfrac{I^d_{g\text{-}p}\, d_g^2 L_{f\text{-}p}}{m_g V_l(R)}} \exp\left(-\frac{E_{ads.}}{RT_g}\right),$$

TABLE 2. Intensity of Gas Transfer to the Melt Surface by the Plasma Stream I^{d}_{g-p}, kg/(m^2·sec)

Diffusing gas	Composition of gas medium	V_p, m/sec				
		100	200	300	400	500
Nitrogen	N_2	0.31	0.45	0.58	0.68	0.78
	$Ar + 1\%\ N_2$	0.010	0.017	0.023	0.029	0.034
Oxygen	CO_2	0.54	0.94	1.29	1.58	1.93
	$Ar + 1\%\ O_2$	0.011	0.019	0.026	0.033	0.039

Note: $T_g = 5000$ K; $p_g = 1.013 \cdot 10^5$ Pa (concentration of diffusing gas in a mixture is given in vol. %).

TABLE 3. Maximum Possible Concentration of Gas in a Liquid Metal Flow with Convective Gas Diffusion from the Plasma C_{g-l}, %

Diffusing gas	Composition of gas medium	V_p, m/sec				
		100	200	300	400	500
Nitrogen	N_2	1.95	2.83	3.64	4.27	4.90
	$Ar + 1\%\ N_2$	0.06	0.11	0.14	0.18	0.21
Oxygen	CO_2	3.39	5.90	8.10	9.92	12.1
	$Ar + 1\%\ O_2$	0.07	0.12	0.16	0.21	0.25

Note: $G_f = 10^{-3}$ kg/sec; $L = 10 \cdot 10^{-3}$ m; $d_f = 2 \cdot 10^{-3}$ m; $T_g = 5000$ K; $p_g = 1.013 \cdot 10^5$ Pa.

where d_g and m_g are the diameter and mass of the adsorbed-gas particle, respectively, m and kg; L_{f-p} is the length of the liquid metal flow making contact with the plasma, m; $V_l(R)$ is the velocity of liquid metal on the cylinder surface, m/sec; E_{ads} is the activation energy of the process of gas adsorption by the melt, J/mole; R is the universal gas constant, J/(mole·K); T_g is the gas temperature, K.

When the temperature of a molecular gas increases, the process of gas dissociation starts. The atoms formed are adsorbed by the melt surface without barriers; therefore

$$I^{a}_{g} = \frac{I^{d}_{g-p}}{1 + \dfrac{I^{d}_{g-p}\, d_g^2\, L_{f-p}}{m_g V_l\,(R)}} \left[\alpha + (1-\alpha)\exp\left(-\frac{E_{ads}}{RT_g}\right)\right],$$

where α is the degree of gas dissociation.

Calculations show that when $V_l(R) \leq 10$ m/sec the flow length over which the process of adsorption virtually terminates because of melt surface saturation with gas particles amounts to only 10^{-4} m. Thus, the determining factor of liquid metal saturation with gas is the diffusion of gas particles in the melt. Similar conclusions for a stagnant liquid metal were obtained in [13, 14].

If we assume that the gas particles on the surface are packed just as densely as atoms in the melt, we obtain

$$C^{*}_{g-l} = \rho_l \frac{A_g}{A_m},$$

where C^{*}_{g-l} is the gas concentration in the liquid metal on the flow surface, kg/m^3; A_g and A_m are the atomic weights of the gas and the metal, amu.

TABLE 4. Saturation of Steel with Gas during Steel Pouring

Parameter	Gas							
	oxygen				nitrogen			
Mass flow, kg/sec	1		10		1		10	
Height of pouring, m	0.1	1.0	0.1	1.0	0.1	1.0	0.1	1.0
Concentration, %	0.0067	0.0140	0.0021	0.0044	0.0008	0.0027	0.0002	0.0009

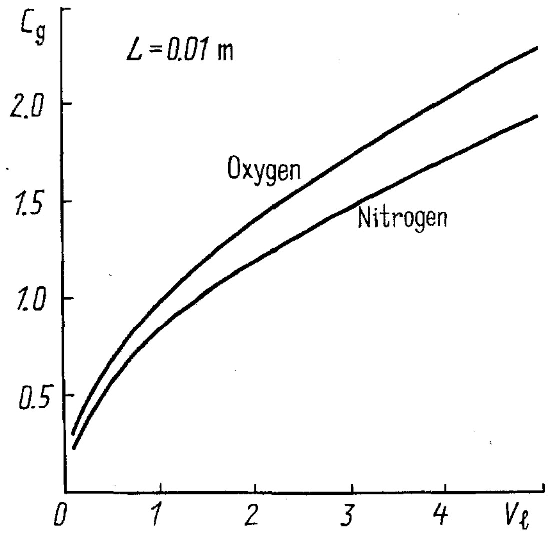


Fig. 4. Effect of the liquid metal flow velocity on its saturation with gases. C_g, %.

At T = 1809 - 3145 K, the maximum surface concentration of gas in liquid iron amounts to 1499 - 1940 kg/m^3 for oxygen and 1313 - 1698 kg/m^3 for nitrogen. Despite the fact that at T = 1853 K the oxygen and nitrogen solubilities are equal to only 13.4 and 2.7 kg/m^3 [15, 16], the actual concentration approaches the maximum possible value according to the packing density of atoms on the surface (for oxygen at T = 1853 K C^*_{g-l} = 1320 kg/m^3 [17]).

Experiments show that when an inert protecting gas (Ar) is used, the concentration of nitrogen in liquid filler metal can attain 0.3 - 0.4% due to air ejection into the zone of welding. When an active protecting gas (CO_2) is used, the oxygen which dissolves in liquid filler metal becomes bound into oxides by alloying elements (say, Si and Mn). In such a case, using the material balance equation, the oxygen concentration in liquid metal can be determined from the losses of alloying elements. When the filler metal is melted by a carbonic acid plasma arc, the oxygen concentration in the melt in forcing regimes may attain 1.2%, which is close to its solubility in liquid iron [15].

The saturation of a stagnant melt with gas is much smaller than that of a moving one. Thus, the oxygen dissolution intensity in liquid iron does not exceed $2.1 \cdot 10^{-3}$ kg/(m$^2 \cdot$sec) [18].

We consider the distribution of gas in a cylindrical liquid metal flow at any time instant t if the concentration on the surface is constant and equal to C^*_{g-l}. At t = 0, C_0 = const in the interior of the flow. In this case

$$\frac{\partial C(r,\ t)}{\partial t} = D\left(\frac{\partial^2 C(r,\ t)}{\partial r^2} + \frac{1}{r}\frac{\partial C(r,\ t)}{\partial r}\right),\quad 0 < r < R,$$

subject to the initial and boundary conditions

$$C(r,\ 0) = C_0;\ C(R,\ t) = C^*_{g-l};\ \frac{\partial C(0,\ t)}{\partial r} = 0;\ C(0,\ t) \neq \infty.$$

According to [19], evaluation of the depth of diffusional penetration by the formula $h = 4.714\sqrt{Dt}$ at $t = 0.001-0.005$ sec and $D = 10^{-8}$-10^{-7} m^2/sec shows that h is an order of magnitude smaller than R. By virtue of this fact we can use the solution of the second Fick law in linear formulation [20]

$$C(r, t) = C_0\left[1 - \Phi\left(\frac{r}{2\sqrt{Dt}}\right)\right],$$

where $\Phi(r/2\sqrt{Dt})$ is the Gauss integral. The distribution of concentration is shown in Fig. 3.

Having calculated the mass flow of diffusing gas and relating it to the liquid metal flow, we obtain the concentration of gas in the melt. The resulting effect of the metal flow velocity on metal saturation with gas is presented in Fig. 4. Estimates show a substantial effect of the melted-metal flow velocity. For example, at V_l up to 5 m/sec, the concentration of gases attains 2-2.5%.

During the pouring of liquid metal, its motion in air is equally accelerated, and at a constant flow rate the flow diameter and velocity are determined by the height of incidence. Since in this case the mass flow rates are 2 - 3 orders of magnitude higher than in arc welding, the saturation of melt with gas is insignificant (Table 4).

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