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Physicochemical patterns of the spread of a molten metal drop over a solid metal surface during MAG welding

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Abstract. In this paper, theoretical and experimental studies of the kinetics of the spreading of liquid drops of molten metal over a solid metal surface in the absence of extraneous (external) driving forces of hydrostatic pressure, gravity, etc. In the kinetic mode, wetting appears as the spreading of liquids on a solid surface. Wetting and spreading are spontaneous processes occurring due to a decrease in the surface energy of the Gibbs system

1. Introduction

The interaction of molten metal drops with a solid metal surface during MAG welding is a complex physicochemical problem, the scientific and applied solution of which has greatly increased in recent years due to the continuously expanding application of this type of welding in industry. The strength of the connection of a drop of molten metal with a solid metal surface depends on the area of their physicochemical interaction [2–5].

Surface phenomena and especially the phenomena of spreading (wetting) of hot metal drops on a solid metal surface during MAG welding are not well understood.

It is known that, when drops of molten metal come into contact with a solid metal surface, various physicochemical processes can occur: corrosion, adsorption decrease in strength due to a sharp decrease in free energy at the "drop-to-surface" interface, and others. The spreading of a molten metal drop on the surface plays a very important role in all these processes. Along with a purely surface distribution, molten metal atoms can penetrate a solid metal surface through regular volume diffusion, as well as through diffusion along grain boundaries and other structural defects, which in some cases leads to strong adhesion of drops to the surface. The patterns of volume diffusion have been studied in detail [5–10], while the issues of the spreading of molten metal drops over the surface during MAG welding, despite their great importance, have been paid much less attention until recently.

2. The main part

If a drop of metal in the molten state spreads over the surface of a solid metal, then the wetting pattern is affected by a number of conditions, from which it is necessary to distinguish:

1) the presence of an oxide film on the metal surface;
2) the presence of affinity of one metal to another, which determines the value of the contact angle;
3) the proximity of the melting points.

The high affinity of metals to oxygen, up to very high temperatures, leads to the formation of oxide films on the surface in an air atmosphere. In practice, the presence of an oxide or adsorbed film in metals reduces the adhesion of drops to the surface during MAG welding.

We will consider the influence of the micro relief of a solid surface on the nature of the distribution of liquid metal. When analyzing the behavior of a liquid on a solid surface, the relationship between the quantities σ_s, σ_l and σ_{sl} is usually considered, and (σ_s and σ_l are the specific free surface energies of the solid body and the liquid at the interface with the medium in which the experiment is conducted; σ_{sl} is the free energy at the interface) (see figure 1).

It is assumed that if

$$\sigma_s > \sigma_{sl} + \sigma_l, \tag{1}$$

then, there is complete wetting, i.e. a drop of liquid will spread over a solid surface in the form of a gradually thinning phase layer. Otherwise, i.e. at

$$\sigma_s < \sigma_{sl} + \sigma_l \,, \tag{2}$$

a drop with a finite edge angle is formed. Under these conditions, the spread of liquid metal can occur only by surface diffusion.

Thus, an analysis of the wetting conditions leads to the conclusion that it is possible in principle to have two qualitatively different forms of liquid distribution over a solid surface: spreading (viscous flow in a continuous phase layer) and surface diffusion (atom migration).

However, inequalities (1) and (2) are valid only for a perfectly smooth surface of a solid body. Since in real conditions each solid surface has its specific micro relief characteristic, for the correct description of the liquid distribution it is necessary, along with the physical properties of the system, also to take into account the geometric features of the surface.

P. A. Rebinder [1] considers the additional friction force acting along the contour, the magnitude of which is related to the degree of surface roughness. This force inhibits the advancement of the front of the spreading drop and leads to the fact that the contact angle during spreading is larger than when the drop flows out (wetting hysteresis). B.V. Deryagin, while theoretically investigating the dependence of the contact angle θon the micro relief, came to the conclusion that, under the condition $\text{К}cos\theta \geq 1$, liquid can spread on a rough surface along micro cavities and grooves (K is the roughness coefficient, i.e. the ratio of the true surface to the apparent, θ is the contact angle on a perfectly smooth surface).

From the condition $\text{К}\cos\theta \geq 1$ it follows that at acute wetting angles on an ideally smooth surface (i.e., at $cos\,\theta > 0$) it is in principle always possible to create such a micro relief that the liquid will spread

This position can be illustrated by the following scheme: let there be a longitudinal groove on the surface of a solid body with a cross section in the form of an isosceles triangle and with an angle ϕ at the apex (figure 1, a). Let also this liquid form an acute angle θ on a smooth surface of the same material. In the absence of extraneous forces, the spreading is thermodynamically possible when it is accompanied by a decrease in the free energy of the system.

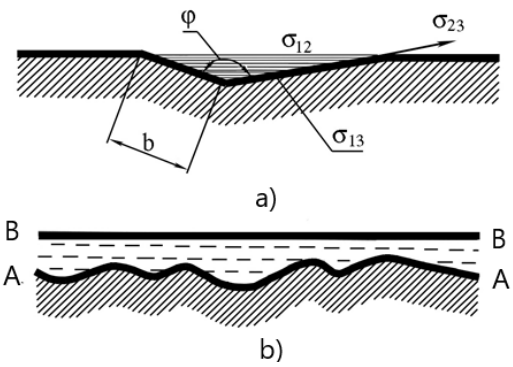

Figure 1. Schemes: a – to determine the conditions for the spreading of fluid along the groove; b – to estimate the value $\Delta\sigma$. AA is the surface of a solid; BB is a liquid surface.

In relation to the considered geometry of the groove, spreading along it will take place if

$$\sigma_s \cdot b > \sigma_{sl} \cdot b + \sigma_l \cdot b(\sin \varphi/2). \quad (3)$$

Since for a perfectly smooth surface $\sigma_s - \sigma_{sl} = \sigma_l \cdot \cos \theta$, we obtain the following equation of fluid spreading along the groove:

$$\varphi < 180^0 - 2\theta. \quad (4)$$

Relation (4) thus determines the critical value of the input angle φ at the apex of micro deeps on the surface of a solid body, at which a transition from one form of surface distribution - diffusion, to another – viscous spreading, is possible.

The loss of surface energy during spreading ($\Delta\sigma$) can be estimated as follows. Taking into account the micro relief of a solid surface (figure 1, b)

$$\Delta\sigma = \text{К}\sigma_s - (\text{К}\sigma_{sl} + \sigma_l). \quad (5)$$

In static conditions (motionless drop on a smooth surface) $\sigma_s - \sigma_{sl} = \sigma_l \cdot \cos \theta$. It follows that

$$\Delta\sigma = \sigma_l(\text{К} \cos \theta - 1). \quad (6)$$

All values included in relation (6) are available for direct experimental determination. The value of the roughness coefficient Кcan be found using micro profilograms of a solid surface, the analysis of which allows for a very accurate determination of the value К as the ratio of the actual surface area to “geometric”. For example, the roughness coefficients К for various surfaces are as follows [2–3]:

in delivery condition $\text{К} = 2.95$;
sandblasted $\text{К} = 3.21$;
ground $\text{К} = 2.65$;
machined with an emery wheel $\text{К} = 3.72$.

At present, there is no unified theory of the crystal lattice; therefore, the values of the surface energy of solid bodies calculated by different authors vary greatly. The most promising is the thermodynamic method based on the analysis of surface and bulk properties of solids. On this basis, equations are derived that relate the surface tension of the crystal to the surface tension of its own melt. The equation for determining the coefficient of surface tension of solid metals at the boundary with its own melt, expressed in terms of the coefficient of surface melt, is as follows

$$\sigma_l = \sigma_s \frac{L}{\lambda_c} = \sigma_l \sqrt[3]{\left(\frac{\rho_s}{\rho_l}\right)} \frac{L}{\lambda_V}, \quad (7)$$

where σ_{sl} – the surface tension coefficient of the crystal at the boundary with its own melt;
σ_s – crystal surface tension coefficient;
σ_l – melt surface tension coefficient at the boundary with intrinsic vapor;
ρ_s and ρ_l – crystal and melt density, respectively;
λ_c – heat of sublimation;
λ_V – heat of vaporization;
L– heat of melting.

The equations of the surface tension coefficients of solid metals at the interface with intrinsic vapor have the form

$$\sigma_s = \sigma_l \sqrt[3]{\left(\frac{\rho_s}{\rho_l}\right)^2 \frac{\lambda_c}{\lambda_V}}. \quad (8)$$

The values of the surface tension coefficients for iron, determined by these equations, are as follows: $\sigma_s = 1582$ MJ/m^2; $\sigma_l = 1840$ MJ/m^2; $\sigma_{sl} = 46$ MJ/m^2.

Knowing the values of the surface tension coefficients and the roughness coefficient, we can calculate the values of the wetting angle of a molten metal drop of various surfaces of the welded products by the following equation:

$$cos\,\theta = \frac{\frac{\sigma_S - \sigma_{\mathrm{sl}}}{\sigma_l} + 1}{\mathrm{K}}. \qquad (9)$$

Table 1. Wetting angle values for various surfaces.

	Surface condition			
	In delivery condition	Ground	Sandblasted	Machined with an emery wheel
Roughness coefficient	2.95	2.65	3.21	3.72
Theoretical wetting angle, deg	51.6	46.1	55.1	60.4
The average value of the experimental contact angle, deg	53.3	47.8	57.7	63.0
Error, %	3.26	3.73	4.82	4.27

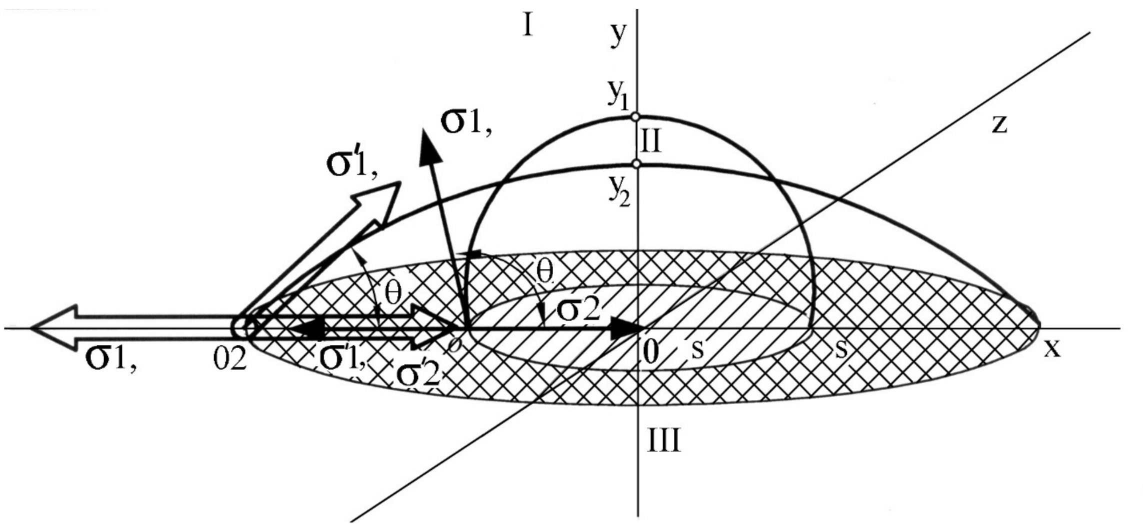

Figure 2. The spreading of the drop when changing the wetting angles and surface tension.

Table 2. The dependence of the wetting angle on the diameter of the drop print.

Diameter of a drop print, mm	The wetting angle, deg			
	The state of the surface of the welded metal			
	Ground	In delivery	Sandblasted	Machined with an emery wheel
1.8	49.0	50.0	59.5	61.0
2.0	41.0	49.0	56.0	73.0
2.2	50.7	50.0	63.5	56.0
2.5	42.0	51.3	59.5	61.25
2.7	51.0	58.0	57.3	54.0
3.0	44.25	51.0	52.5	54.5
3.2	40.0	57.0	54.5	59.0
3.5	39.0	48.0	59.0	65.35
3.8	51.0	45.0	45.0	58.5
4.0	45.6	47.5	60.5	53.22
4.3	38.0	48	58.5	57.0

To confirm the theoretical data on the spreading of a drop on the surface of the metal being welded, experimental studies were performed on the MAG welding of samples made of St3 steel in the delivery condition, machined with an emery wheel, sandblasted and ground. Welding was carried out by a PDG-508UZ semiautomatic device with a VDU-504 power source using Sv-08G2S wire with a diameter of 1.6 mm. Welding modes were $I_w = 320\ldots330$ A, $U_w = 32\ldots34$ V under normal conditions [3, 9].

3. Conclusion

The values of the contact angles for various surfaces of the welded products, determined by theoretical calculation and experimental studies, are given in table. 1. However, as shown by experimental data (table 2), the wetting angle θ also depends on the diameter of the drop print. With an increase in the print diameter, the wetting angle slightly decreases. On the surface treated with an emery wheel, a small angle of wettability is observed, and therefore, the adhesion force of drops of molten metal to the surface will be less. The ground surface is wetted better, which means that the complexity of manufacturing products with a ground surface increases.

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