Determination of the allowable minimum thickness of protective coating for welding in carbon dioxide

S B Sapozhkov\textsuperscript{1,2}, S I Arendateleva\textsuperscript{1} and O V Ushakova\textsuperscript{1}

\textsuperscript{1}Yaroslav-the-Wise Novgorod State University, ul. B. St. Peterburgskaya, 41 173003, Veliky Novgorod, Russia

\textsuperscript{2}E-mail: ssb@novsu.ru

Abstract. Among industrial technologies, carbon dioxide welding occupies a leading position. However, this welding method is characterized by increased spattering of metal and splashing it on the welded piece of work. A protective coating layer applied to metal is effective means of preventing the consequences of this disadvantage. The paper developed the method for determining the minimum allowable thickness of the coating, sufficient to prevent the interaction of molten metal drops with the surface of the welded pieces of work.

1. Introduction

As is known, protective coatings are used to protect the surface of welded products and welding equipment from splashes of molten metal during welding in CO\textsubscript{2} [1–5].

However, the thickness of required coating layer is assigned only on the basis of experience. In this case, a small thickness of the coating leads to poor quality protection of the surface of the piece of work, a large layer thickness to excessive consumption of the coating [1].

Currently, there are a number of methods for determining the thickness of the protective coating [1, 6], but the disadvantages of these methods are the lack of specific recommendations for calculating the thickness of the coating depending on the thickness of the metal being welded.

2. Main part

The task of the article was to determine the allowable minimum thickness of protective coating layer depending on welding mode, thermophysical characteristics of the coating, the temperature of drop at the moment of contact, the contact diameter of the interaction of drop with the surface of the piece of work to be welded and the thickness of the metal to be welded.

In solving the problem, it was assumed that:

1. At the moment of flying a drop from the arc gap, the amount of heat contained in it is determined by the equation:

\[ q = IU\eta, \]  \hspace{1cm} (1)

where \( q \) is the amount of heat introduced by the arc into the metal of the electrode per unit of time, J/s; \( I \) is welding current, A; \( U \) is arc voltage, V; \( \eta \) is effective efficiency of heating of the electrode metal by electric arc.

2. During the flying until the moment of contact with the surface of the metal being welded, the drop loses some of the heat to radiant and convective heat transfer. The specific flux of total heat transfer by drop to radiative and convective heat exchange with the environment is determined by the equation:
where \( \alpha \) is total surface heat transfer coefficient which is the sum of the coefficients of convective heat transfer and radiant heat transfer; \( T_k \) and \( T_o \) are drop temperature at the moment of flying from the electrode and the environment, respectively, °C.

3. It follows from the boundary adiabatic condition of the 3-rd kind that drops during flying cool insignificantly, i.e. we have: \( a \to 0 \).

4. The amount of heat contained in drop at the moment of contact with the surface of the welded pieces of work is determined by the equation:

\[
q_k = q - q_{To}.
\] (3)

5. Energy heat content of drop should be less than the amount of heat required for decomposition and evaporation of the protective coating layer \( \delta \).

To determine the thickness of the protective coating layer, we considered the process of temperature increment on the plate surface at the moment of introduction of heat from normally circular source with the condition that it spreads in depth in time \( t_0 \) in the direction of axis \( OZ \) (figure 1).

Such a process is expressed by the equation:

\[
\Delta T = \frac{2Q}{cp} \frac{e^{-R_s^2/[4a(t + t_0)]} e^{-z^2/(4\pi at)}}{4\pi a(t + t_0)} (4\pi at)^{1/2},
\] (4)

where \( \Delta T \) is the temperature increment at the considered point, °C; \( Q \) is the heat contained in drop at the point of contact with the surface of the metal being welded (enthalpy \( \Delta H \)), J; \( cp \) is the product of the heat capacity by the density of the droplet material, J/deg cm³; \( R_s \) is the radial distance from the considered point to the axis of the imprint of drop (radius of the imprint of the drop), cm; \( a \) is the coefficient of thermal diffusivity, cm² / s; \( t \) is the time counted from the moment of introduction of heat, s; \( z \) is the depth to which heat is distributed (thickness of the metal being welded), cm; \( k \) is the concentration coefficient of the heat flux of drop.

Time \( t_0 \), from which the heat propagates in depth along \( OZ \) axis, is determined by the equation [6–9]:

\[
t_0 = 1/(4ak),
\] (5)

where \( a \) is thermal diffusivity of the protective coating, \( k \) is concentration coefficient of the heat flux of drop and is determined by the equation:
where $dk$ is contact diameter of interaction of drop with surface, cm.

If you specify the condition that $q$ is the amount of heat contained in drop at the moment of its contact with the surface of the welded piece of work; $cp$ is the volumetric heat capacity of the protective coating; $r$ is the radius of the drop; $t$ is the time elapsed since the contact of the droplet with the protective coating, and $z$ is the depth to which the heat transferred by the drop to the protective coating layer extends, then it can be assumed that $z$ will be the thickness of the layer of protective coating necessary to prevent splashing on the surface of the welded part (hereinafter $\delta$).

By mathematical transformations, the equation was obtained:

$$
\delta = \sqrt{\frac{\ln \left( \frac{(IU\eta)dk}{cp\pi T_\delta} \right)}{k}}
$$

The complexity of further determining the thickness of the protective coating layer lies in the absence of data on the volumetric heat capacity and thermal diffusivity of the coatings used to protect the surface of the welded products. The coefficient of thermal diffusivity is determined by the equation:

$$
\alpha = \lambda / cp .
$$

The density of protective coatings $p$ was determined experimentally by equation:

$$
p = \frac{m}{Q},
$$

where $m$ is the mass of the protective coating, kg, $Q$ is the mass volume of the protective coating, m$^3$

The specific heat capacity of the protective coatings was determined by calorimetric measurement (through the heat of combustion of the material under study).

To determine the thermal conductivity coefficient $\lambda$, the plate method was used [8]. The principle diagram of the device is presented in figure 2.

Figure 2. Scheme of device for determining the coefficient of thermal conductivity of protective coatings on the plate principle [9].
Here, in the middle, there is flat electric heater 1, test sample 2 and refrigerator 3 above it. To compensate for heat leakage, additional electric heaters 4–5 are installed from below and from the sides. The device is carefully isolated from heat loss to the external environment, \( t_1 - t_5 \) — thermoelements for temperature measurement. At steady state of the system, all the heat released in the main heater 1 will pass through the sample and will be absorbed by the refrigerator. Since the amount of heat released is \( H \) and the temperatures \( t_1 \) and \( t_2 \) are known, the thermal conductivity coefficient is determined from the following relationship:

\[
\lambda = \frac{H \delta_0}{F(t_1 - t_2)},
\]

(10)

where \( F \) is the surface area of the main heater, \( \text{mm}^2 \); \( H \) is the thermal power of the heater; \( \delta_0 \) is the thickness of the layer of the protective coating under investigation, \( \text{mm} \).

The following equation was used to determine \( H \):

\[
H = I^2 R,
\]

(11)

where \( I \) is the electric current value, \( \text{A} \); \( R = U/I \) is the electrical resistance of the heater, \( \text{V/A} \).

Measurements of \( I \) and \( U \), \( t_1 \) and \( t_2 \) should be made only after the temperature \( t_3 \) is equal to \( t_1 \), and the temperature \( t_4 \) is equal to \( t_5 \). Only in this case, all the heat released in the main heater 1 really passes through test sample 2 [8].

According to the method described above, the thermophysical properties of a number of protective coatings were determined, the data of which are summarized in table 1.

**Table 1.** Volumetric heat capacity of protective coatings.

| S No. | Coating composition | \( cp \), J/deg cm\(^3 \) |
|-------|---------------------|---------------------------|
| 1     | Sulfite-alcohol bard (GOST 8578) – 140g, soap – 30g, soda ash – 25g, water – 1000g | 928.1 |
| 2     | Sulfite-alcohol bard (GOST 8578)-60 – 100g, soap – 25–45g, soda ash – 15–25g, kaolin – 25–50g, water – 1000g | 985.5 |
| 3     | 50-80g of sulphite-alcohol bards (GOST 8578), 30-40g of soap, 15–20g of soda ash and 30–60 g of abrasive waste (Patent No. 2134186), water –1000 g. | 1254.5 |
| 4     | Zircon (TsMTU 4469-54) – 40%, polyvinyl butyral (GOST 9439) – 3%, solvent – 646 (GOST 18188) – 57% | 1101.1 |

Using thermal diffusivity and volumetric heat capacity \( cp \) of protective coatings according to equation (7), calculations were carried out to determine the minimum layer of protective coatings. These calculations are summarized in table 2.

**Table 2.** Minimum layer of protective coatings.

| S No. | Coating thickness, mm | Error in % |
|-------|-----------------------|------------|
|       | Theoretic | Experimental |          |
| 1     | 0.0348 | 0.0366 | 5.2 |
| 2     | 0.024076 | 0.0273 | 13.4 |
| 3     | 0.02418 | 0.0252 | 4.04 |
| 4     | 0.05548 | 0.0614 | 10.7 |
Based on calculated data, nomograms of the dependence of the thickness of the protective layer of coating on the thickness of the product being welded (figure 3, a) and welding current (figure 3, b) were constructed.

![Nomogram](image_url)

**Figure 3.** Nomograms of dependence of the thickness of the protective coating on thickness of the piece of work to be welded (a) (for designations, see table 1) and for coating No. 4 on the welding current (b)

To determine the error of the measurement results and the data obtained by calculation, the results were processed according to the method proposed in [7–8]. Such processing of the results consists in estimating the value of the sample mean (arithmetic average) and determining its accuracy.

Analysis of theoretical and experimental data showed that the allowable minimum coating thickness, sufficient to prevent strong adhesion of drops to the surface, for water-based coatings reaches 200 or more microns, for solvent-based coatings –646 ranges from a few microns to several tens of microns, and coatings based on liquid glass – from 20 to 30 microns.
3. Conclusions

1. Method has been developed for determining the allowable minimum layer thickness of protective coating depending on the welding mode, thermal characteristics of the coating, drop temperature at the moment of contact, the contact diameter of the interaction between drop and surface, and the thickness of the piece of work being welded. It has been established that the allowable minimum coating thickness, sufficient to prevent durable adhesion of drops to the surface, for water-based coatings reaches 200 and more microns, for solvent-based coatings –646 ranges from a few microns to several tens of microns, and for coatings based on liquid glass – from 20 to 30 microns.

2. It has been established that the strength of adhesion of splashes with the surface of piece of work being welded and the nature of their interaction in the contact zone are determined by the following factors: the nature of the contacting materials, the energy heat content of drop, which is sufficient to destroy the oxide films, the surface roughness and contact diameter of interaction.

References

[1] Fedko V Т, Sapozhkov S B, Sokolov P D and Yastrebov А P 2004 Elements of theory and technology of anti-spatter surface shielding when welding in carbon dioxide Monograph (Tomsk: TSU Publishing) p 138

[2] Solonenko O P, Kudinov V V, Smirnov A V, Cherepanov A N, Popov V N, Mikhalchenko A A and Kartaev E V 2005 Micro-Metallurgy of Splats: Theory, Computer Simulation and Experiment JSME Inter. J. Ser. B Vol. 48 3 pp 366–380 DOI: 10.1299/jsmeb.48.366

[3] Knotek O and Elsing R 1987 Monte Carlo Simulation of Lamellar Structure of Thermally Sprayed Coatings Surf. Coat. Technol 32 p 261–271

[4] Ghafoori-Azar R, Mostaghimi J, Chandra S and Chamchi M A 2003 Stochastic Model to Simulation of a Thermal Spray Coating J. of Thermal Spray Techn. Vol 12 (1) p 53–69

[5] Steinke T B, Ker M 2006 Monte Carlo Simulation of Thermal Sprayed Coatings Proc. ITSC’06 Seattle (USA, May 15–18) p 329–334

[6] Fedko V T and Sapozhkov S B 1997 Processing the results of a passive experiment by studying the dependence of the thickness of the protective coating layer on the varying value of thermal conductivity of this coating Proc. of the 10th scientific. conf. (Urga: Published TPU) p 81–83

[7] Fedko V T, Tomas K I and Sapozhkov S B 1998 Protecting the surfaces of welded components against molten metal splashes in CO2 welding Welding International 1 p 58–62

[8] Sapozhkov S B and Fedko V T 2002 Determination of coating thickness to protect the surface from molten metal splashes when welding in carbon dioxide Metal technology 5 p 12–16

[9] Mikheev M A, Mikheeva I M 1961 Short course of heat transfer: Textbook for non-energy specialties (M.–L.: Gosenergoizdat publishing) p 180–182